Supersymmetric Models implemented in SARAH

Version 2.2

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Abstract

This is an overview of all models which are part of the Mathematica package SARAH.

Contents

Chapter 1

Minimal Supersymmetric Standard Model

1.1 Superfields

1.1.1 Vector Superfields

SF	Spin $\frac{1}{2}$	Spin 1	$SU(N)$	Coupling	Name
$\hat{B}$	$\lambda_{\tilde{B}}$	B	$U(1)$	g_1	hypercharge
$\hat{W}$	$\lambda_{\tilde{W}}$	W^-	SU(2)	g_2	left
$\hat{g}$	$\lambda_{\tilde{g}}$	g	SU(3)	g_3	color

1.1.2 Chiral Superfields

SF	Spin 0	Spin $\frac{1}{2}$	Generations	$(U(1) \otimes \text{SU}(2) \otimes \text{SU}(3))$
$\hat{q}$	$\tilde{q}$	q	3	$(\frac{1}{6}, \mathbf{2}, \mathbf{3})$
$\hat{l}$	$\tilde{l}$	l	3	$(-\frac{1}{2}, \mathbf{2}, \mathbf{1})$
$\hat{H}_d$	H_d	$\tilde{H}_d$	1	$(-\frac{1}{2}, \mathbf{2}, \mathbf{1})$
$\hat{H}_u$	H_u	$\tilde{H}_u$	1	$(\frac{1}{2}, \mathbf{2}, \mathbf{1})$
$\hat{d}$	$\tilde{d}_R^*$	d_R^*	3	$(\frac{1}{3}, \mathbf{1}, \overline{\mathbf{3}})$
$\hat{u}$	$\tilde{u}_R^*$	u_R^*	3	$(-\frac{2}{3}, \mathbf{1}, \overline{\mathbf{3}})$
$\hat{e}$	$\tilde{e}_R^*$	e_R^*	3	$(1, \mathbf{1}, \mathbf{1})$

1.2 Superpotential and Lagrangian

1.2.1 Superpotential

$$W = Y_u\, \hat{u}\, \hat{q}\, \hat{H}_u \, - Y_d\, \hat{d}\, \hat{q}\, \hat{H}_d \, - Y_e\, \hat{e}\, \hat{l}\, \hat{H}_d \, + \mu\, \hat{H}_u\, \hat{H}_d \tag{1.1}$$

1.2.2 Softbreaking terms

$$L_{SB,W} = -H_d^0 H_u^0 B_\mu + H_d^- H_u^+ B_\mu + H_d^0 \tilde{d}^*_{R,i\alpha} \delta_{\alpha\beta} \tilde{d}_{L,j\beta} T_{d,ij} - H_d^- \tilde{d}^*_{R,i\alpha} \delta_{\alpha\beta} \tilde{u}_{L,j\beta} T_{d,ij}$$

$$
\begin{aligned}
& + H_d^0 \tilde{e}^*_{R,i} \tilde{e}_{L,j} T_{e,ij} - H_d^- \tilde{e}^*_{R,i} \tilde{\nu}_{L,j} T_{e,ij} - H_u^+ \tilde{u}^*_{R,i\alpha} \delta_{\alpha\beta} \tilde{d}_{L,j\beta} T_{u,ij} + H_u^0 \tilde{u}^*_{R,i\alpha} \delta_{\alpha\beta} \tilde{u}_{L,j\beta} T_{u,ij} + \text{h.c.} && (1.2) \\
L_{SB,\phi} = & - m_{H_d}^2 |H_d^0|^2 - m_{H_d}^2 |H_d^-|^2 - m_{H_u}^2 |H_u^0|^2 - m_{H_u}^2 |H_u^+|^2 - \tilde{d}^*_{L,j\beta} \delta_{\alpha\beta} m^2_{q,ij} \tilde{d}_{L,i\alpha} \\
& - \tilde{d}^*_{R,i\alpha} \delta_{\alpha\beta} m^2_{d,ij} \tilde{d}_{R,j\beta} - \tilde{e}^*_{L,j} m^2_{l,ij} \tilde{e}_{L,i} - \tilde{e}^*_{R,i} m^2_{e,ij} \tilde{e}_{R,j} - \tilde{u}^*_{L,j\beta} \delta_{\alpha\beta} m^2_{q,ij} \tilde{u}_{L,i\alpha} \\
& - \tilde{u}^*_{R,i\alpha} \delta_{\alpha\beta} m^2_{u,ij} \tilde{u}_{R,j\beta} - \tilde{\nu}^*_{L,j} m^2_{l,ij} \tilde{\nu}_{L,i} && (1.3) \\
L_{SB,\lambda} = & \frac{1}{2}\Big(-\lambda^2_{\tilde{B}} M_1 - M_2 \lambda^2_{\tilde{W},i} - M_3 \lambda^2_{\tilde{g},i} + \text{h.c.}\Big) && (1.4)
\end{aligned}
$$

1.2.3 Gauge fixing terms

Gauge fixing terms for eigenstates 'GaugeES'

$$
L_{GF} = -\frac{1}{2}\partial_\mu g \xi_G^{-1} - \frac{1}{2}\partial_\mu W^- \xi_W^{-1} \tag{1.5}
$$

Gauge fixing terms for eigenstates 'EWSB'

$$
L_{GF} = -\frac{1}{2}\partial_\mu \gamma \xi_P^{-1} - \frac{1}{2}\partial_\mu g \xi_G^{-1} - \frac{1}{2}\xi_Z^{-1}\Big(- A_1^0 m_Z \xi_Z + \partial_\mu Z\Big) - \xi_W^{-1}\Big(iH_1^- m_{W^-} \xi_W + \partial_\mu W^-\Big) \tag{1.6}
$$

1.2.4 Fields integrated out

None

1.3 Field Rotations

1.3.1 Rotations in gauge sector for eigenstates 'EWSB'

$$
\begin{aligned}
W^-_{1\rho} &= \frac{1}{\sqrt{2}} W^-_\rho + \frac{1}{\sqrt{2}} W^+_\rho && (1.7) \\
W^-_{2\rho} &= -i\frac{1}{\sqrt{2}} W^-_\rho + i\frac{1}{\sqrt{2}} W^+_\rho && (1.8) \\
W^-_{3\rho} &= \cos\Theta_W Z_\rho + \sin\Theta_W \gamma_\rho && (1.9) \\
B_\rho &= \cos\Theta_W \gamma_\rho - \sin\Theta_W Z_\rho && (1.10) \\
\lambda_{\tilde{W},1} &= \frac{1}{\sqrt{2}} \tilde{W}^- + \frac{1}{\sqrt{2}} \tilde{W}^+ && (1.11) \\
\lambda_{\tilde{W},2} &= -i\frac{1}{\sqrt{2}} \tilde{W}^- + i\frac{1}{\sqrt{2}} \tilde{W}^+ && (1.12) \\
\lambda_{\tilde{W},3} &= \tilde{W}^0 && (1.13)
\end{aligned}
$$

1.3.2 Rotations in Mass sector for eigenstates 'EWSB'

Mass Matrices for Scalars

- **Mass matrix for Down-Squarks**, Basis: $\left(\tilde{d}_{L,o_1\alpha_1}, \tilde{d}_{R,o_2\alpha_2}\right), \left(\tilde{d}^*_{L,p_1\beta_1}, \tilde{d}^*_{R,p_2\beta_2}\right)$

$$m^2_{\tilde{d}} = \begin{pmatrix} m_{11} & \frac{1}{\sqrt{2}}\delta_{\alpha_1\beta_2}\Big(v_d T_{d,p_2o_1} - v_u \mu^* Y_{d,p_2o_1}\Big) \\ \frac{1}{\sqrt{2}}\Big(v_d T^*_{d,o_2p_1} - v_u \mu Y^*_{d,o_2p_1}\Big)\delta_{\alpha_2\beta_1} & m_{22}\end{pmatrix} \tag{1.14}$$

$$m_{11} = \frac{1}{24}\delta_{\alpha_1\beta_1}\Big(12\Big(2m^2_{q,o_1p_1} + v_d^2\sum_{a=1}^{3} Y^*_{d,ap_1}Y_{d,ao_1}\Big) - \Big(3g_2^2 + g_1^2\Big)\Big(-v_u^2 + v_d^2\Big)\delta_{o_1p_1}\Big) \tag{1.15}$$

$$m_{22} = \frac{1}{12}\delta_{\alpha_2\beta_2}\Big(6\Big(2m^2_{d,p_2o_2} + v_d^2\sum_{a=1}^{3} Y^*_{d,o_2a}Y_{d,p_2a}\Big) + g_1^2\Big(-v_d^2 + v_u^2\Big)\delta_{o_2p_2}\Big) \tag{1.16}$$

This matrix is diagonalized by Z^D:

$$Z^D m^2_{\tilde{d}} Z^{D,\dagger} = m^{dia}_{2,\tilde{d}} \tag{1.17}$$

with

$$\tilde{d}_{L,i\alpha} = \sum_{t_2} Z^{D,*}_{ji}\tilde{d}_{j\alpha}\,, \qquad \tilde{d}_{R,i\alpha} = \sum_{t_2} Z^{D,*}_{ji}\tilde{d}_{j\alpha} \tag{1.18}$$

- **Mass matrix for Sneutrinos**, Basis: $\left(\tilde{\nu}_{L,o_1}\right), \left(\tilde{\nu}^*_{L,p_1}\right)$

$$m^2_{\tilde{\nu}} = \begin{pmatrix} \frac{1}{8}\Big(8m^2_{l,o_1p_1} + \Big(g_1^2 + g_2^2\Big)\Big(-v_u^2 + v_d^2\Big)\delta_{o_1p_1}\Big)\end{pmatrix} \tag{1.19}$$

This matrix is diagonalized by Z^V:

$$Z^V m^2_{\tilde{\nu}} Z^{V,\dagger} = m^{dia}_{2,\tilde{\nu}} \tag{1.20}$$

with

$$\tilde{\nu}_{L,i} = \sum_{t_2} Z^{V,*}_{ji}\tilde{\nu}_j \tag{1.21}$$

- **Mass matrix for Up-Squarks**, Basis: $\left(\tilde{u}_{L,o_1\alpha_1}, \tilde{u}_{R,o_2\alpha_2}\right), \left(\tilde{u}^*_{L,p_1\beta_1}, \tilde{u}^*_{R,p_2\beta_2}\right)$

$$m^2_{\tilde{u}} = \begin{pmatrix} m_{11} & \frac{1}{\sqrt{2}}\delta_{\alpha_1\beta_2}\Big(-v_d \mu^* Y_{u,p_2o_1} + v_u T_{u,p_2o_1}\Big) \\ \frac{1}{\sqrt{2}}\Big(-v_d \mu Y^*_{u,o_2p_1} + v_u T^*_{u,o_2p_1}\Big)\delta_{\alpha_2\beta_1} & m_{22}\end{pmatrix} \tag{1.22}$$

$$m_{11} = \frac{1}{24}\delta_{\alpha_1\beta_1}\Big(12\Big(2m^2_{q,o_1p_1} + v_u^2\sum_{a=1}^{3} Y^*_{u,ap_1}Y_{u,ao_1}\Big) - \Big(-3g_2^2 + g_1^2\Big)\Big(-v_u^2 + v_d^2\Big)\delta_{o_1p_1}\Big) \tag{1.23}$$

$$m_{22} = \frac{1}{6}\delta_{\alpha_2\beta_2}\Big(3v_u^2 \sum_{a=1}^{3} Y^*_{u,o_2 a} Y_{u,p_2 a} + 6 m^2_{u,p_2 o_2} + g_1^2\Big(-v_u^2 + v_d^2\Big)\delta_{o_2 p_2}\Big) \tag{1.24}$$

This matrix is diagonalized by Z^U:

$$Z^U m^2_{\tilde{u}} Z^{U,\dagger} = m^{dia}_{2,\tilde{u}} \tag{1.25}$$

with

$$\tilde{u}_{L,i\alpha} = \sum_{t_2} Z^{U,*}_{ji}\tilde{u}_{j\alpha}\,, \qquad \tilde{u}_{R,i\alpha} = \sum_{t_2} Z^{U,*}_{ji}\tilde{u}_{j\alpha} \tag{1.26}$$

- **Mass matrix for Sleptons**, Basis: $\left(\tilde{e}_{L,o_1}, \tilde{e}_{R,o_2}\right), \left(\tilde{e}^*_{L,p_1}, \tilde{e}^*_{R,p_2}\right)$

$$m^2_{\tilde{e}} = \left(\begin{array}{cc} m_{11} & \frac{1}{\sqrt{2}}\Big(v_d T_{e,p_2 o_1} - v_u \mu^* Y_{e,p_2 o_1}\Big) \\ \frac{1}{\sqrt{2}}\Big(v_d T^*_{e,o_2 p_1} - v_u \mu Y^*_{e,o_2 p_1}\Big) & m_{22}\end{array}\right) \tag{1.27}$$

$$m_{11} = \frac{1}{8}\Big(4v_d^2 \sum_{a=1}^{3} Y^*_{e,a p_1} Y_{e,a o_1} + 8 m^2_{l,o_1 p_1} + \Big(-g_2^2 + g_1^2\Big)\Big(-v_u^2 + v_d^2\Big)\delta_{o_1 p_1}\Big) \tag{1.28}$$

$$m_{22} = \frac{1}{4}\Big(2v_d^2 \sum_{a=1}^{3} Y^*_{e,o_2 a} Y_{e,p_2 a} + 4 m^2_{e,p_2 o_2} + g_1^2\Big(-v_d^2 + v_u^2\Big)\delta_{o_2 p_2}\Big) \tag{1.29}$$

This matrix is diagonalized by Z^E:

$$Z^E m^2_{\tilde{e}} Z^{E,\dagger} = m^{dia}_{2,\tilde{e}} \tag{1.30}$$

with

$$\tilde{e}_{L,i} = \sum_{t_2} Z^{E,*}_{ji}\tilde{e}_j\,, \qquad \tilde{e}_{R,i} = \sum_{t_2} Z^{E,*}_{ji}\tilde{e}_j \tag{1.31}$$

- **Mass matrix for Higgs**, Basis: $\left(\phi_d, \phi_u\right), \left(\phi_d, \phi_u\right)$

$$m^2_h = \left(\begin{array}{cc} \frac{1}{8}\Big(8m^2_{H_d} + 8|\mu|^2 + \Big(g_1^2 + g_2^2\Big)\Big(3v_d^2 - v_u^2\Big)\Big) & \frac{1}{4}\Big(-4\Re\Big(B_\mu\Big) - \Big(g_1^2 + g_2^2\Big)v_d v_u\Big) \\ \frac{1}{4}\Big(-4\Re\Big(B_\mu\Big) - \Big(g_1^2 + g_2^2\Big)v_d v_u\Big) & \frac{1}{8}\Big(8m^2_{H_u} + 8|\mu|^2 - \Big(g_1^2 + g_2^2\Big)\Big(-3v_u^2 + v_d^2\Big)\Big)\end{array}\right) \tag{1.32}$$

This matrix is diagonalized by Z^H:

$$Z^H m^2_h Z^{H,\dagger} = m^{dia}_{2,h} \tag{1.33}$$

with

$$\phi_d = \sum_{t_2} Z^H_{j1} h_j\,, \qquad \phi_u = \sum_{t_2} Z^H_{j2} h_j \tag{1.34}$$

The mixing matrix can be parametrized by

$$Z^H = \left(\begin{array}{cc} -\sin\alpha & \cos\alpha \\ \cos\alpha & \sin\alpha\end{array}\right) \tag{1.35}$$

- **Mass matrix for Pseudo-Scalar Higgs**, Basis: $(\sigma_d, \sigma_u), (\sigma_d, \sigma_u)$

$$m^2_{A^0} = \left(\begin{array}{cc} \frac{1}{8}\Big(8m^2_{H_d} + 8|\mu|^2 + \Big(g_1^2 + g_2^2\Big)\Big(- v_u^2 + v_d^2\Big)\Big) & \Re\Big(B_\mu\Big) \\ \Re\Big(B_\mu\Big) & \frac{1}{8}\Big(8m^2_{H_u} + 8|\mu|^2 - \Big(g_1^2 + g_2^2\Big)\Big(- v_u^2 + v_d^2\Big)\Big) \end{array} \right) \tag{1.36}$$

This matrix is diagonalized by Z^A:

$$Z^A m^2_{A^0} Z^{A,\dagger} = m^{dia}_{2,A^0} \tag{1.37}$$

with

$$\sigma_d = \sum_{t_2} Z^A_{j1} A^0_j\,, \qquad \sigma_u = \sum_{t_2} Z^A_{j2} A^0_j \tag{1.38}$$

The mixing matrix can be parametrized by

$$Z^A = \left(\begin{array}{cc} -\cos\beta & \sin\beta \\ \sin\beta & \cos\beta \end{array} \right) \tag{1.39}$$

- **Mass matrix for Charged Higgs**, Basis: $\left(H_d^-, H_u^{+,*}\right), \left(H_d^{-,*}, H_u^+\right)$

$$m^2_{H^-} = \left(\begin{array}{cc} m_{11} & \frac{1}{4} g_2^2 v_d v_u + B_\mu \\ \frac{1}{4} g_2^2 v_d v_u + B_\mu^* & m_{22} \end{array} \right) \tag{1.40}$$

$$m_{11} = \frac{1}{8}\Big(8m^2_{H_d} + 8|\mu|^2 + g_1^2 v_d^2 - g_1^2 v_u^2 + g_2^2 v_d^2 + g_2^2 v_u^2\Big) \tag{1.41}$$

$$m_{22} = \frac{1}{8}\Big(8m^2_{H_u} + 8|\mu|^2 - g_1^2 v_d^2 + g_1^2 v_u^2 + g_2^2 v_d^2 + g_2^2 v_u^2\Big) \tag{1.42}$$

This matrix is diagonalized by Z^+:

$$Z^+ m^2_{H^-} Z^{+,\dagger} = m^{dia}_{2,H^-} \tag{1.43}$$

with

$$H_d^- = \sum_{t_2} Z^{+,*}_{j1} H_j^-\,, \qquad H_u^+ = \sum_{t_2} Z^+_{j2} H_j^+ \tag{1.44}$$

The mixing matrix can be parametrized by

$$Z^+ = \left(\begin{array}{cc} -\cos\beta & \sin\beta \\ \sin\beta & \cos\beta \end{array} \right) \tag{1.45}$$

Mass Matrices for Fermions

- **Mass matrix for Neutralinos**, Basis: $\left(\lambda_{\tilde{B}}, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0\right), \left(\lambda_{\tilde{B}}, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0\right)$

$$m_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -\frac{1}{2} g_1 v_d & \frac{1}{2} g_1 v_u \\ 0 & M_2 & \frac{1}{2} g_2 v_d & -\frac{1}{2} g_2 v_u \\ -\frac{1}{2} g_1 v_d & \frac{1}{2} g_2 v_d & 0 & -\mu \\ \frac{1}{2} g_1 v_u & -\frac{1}{2} g_2 v_u & -\mu & 0 \end{pmatrix} \tag{1.46}$$

This matrix is diagonalized by N:

$$N m_{\tilde{\chi}^0} N^\dagger = m^{dia}_{\tilde{\chi}^0} \tag{1.47}$$

with

$$\lambda_{\tilde{B}} = \sum_{t_2} N^*_{j1} \lambda^0_j \,, \qquad \tilde{W}^0 = \sum_{t_2} N^*_{j2} \lambda^0_j \,, \qquad \tilde{H}^0_d = \sum_{t_2} N^*_{j3} \lambda^0_j \tag{1.48}$$

$$\tilde{H}^0_u = \sum_{t_2} N^*_{j4} \lambda^0_j \tag{1.49}$$

- **Mass matrix for Charginos**, Basis: $\left(\tilde{W}^-, \tilde{H}_d^-\right), \left(\tilde{W}^+, \tilde{H}_u^+\right)$

$$m_{\tilde{\chi}^-} = \begin{pmatrix} M_2 & \frac{1}{\sqrt{2}} g_2 v_u \\ \frac{1}{\sqrt{2}} g_2 v_d & \mu \end{pmatrix} \tag{1.50}$$

This matrix is diagonalized by U and V

$$U^* m_{\tilde{\chi}^-} V^\dagger = m^{dia}_{\tilde{\chi}^-} \tag{1.51}$$

with

$$\tilde{W}^- = \sum_{t_2} U^*_{j1} \lambda^-_j \,, \qquad \tilde{H}^-_d = \sum_{t_2} U^*_{j2} \lambda^-_j \tag{1.52}$$

$$\tilde{W}^+ = \sum_{t_2} V^*_{1j} \lambda^+_j \,, \qquad \tilde{H}^+_u = \sum_{t_2} V^*_{2j} \lambda^+_j \tag{1.53}$$

- **Mass matrix for Leptons**, Basis: $\left(e_{L,o_1}\right), \left(e^*_{R,p_1}\right)$

$$m_e = \begin{pmatrix} \frac{1}{\sqrt{2}} v_d Y_{e,p_1 o_1} \end{pmatrix} \tag{1.54}$$

This matrix is diagonalized by U^e_L and U^e_R

$$U^{e,*}_L m_e U^{e,\dagger}_R = m^{dia}_e \tag{1.55}$$

with

$$e_{L,i} = \sum_{t_2} U^{e,*}_{L,ji} E_{L,j} \tag{1.56}$$

$$e_{R,i} = \sum_{t_2} U^e_{R,ij} E^*_{R,j} \tag{1.57}$$

- **Mass matrix for Down-Quarks**, Basis: $\left(d_{L,o_1\alpha_1}\right),\left(d^*_{R,p_1\beta_1}\right)$

$$m_d = \left(\frac{1}{\sqrt{2}} v_d \delta_{\alpha_1\beta_1} Y_{d,p_1 o_1} \right) \tag{1.58}$$

This matrix is diagonalized by U^d_L and U^d_R

$$U^{d,*}_L m_d U^{d,\dagger}_R = m^{dia}_d \tag{1.59}$$

with

$$d_{L,i\alpha} = \sum_{t_2} U^{d,*}_{L,ji} D_{L,j\alpha} \tag{1.60}$$

$$d_{R,i\alpha} = \sum_{t_2} U^{d}_{R,ij} D^*_{R,j\alpha} \tag{1.61}$$

- **Mass matrix for Up-Quarks**, Basis: $\left(u_{L,o_1\alpha_1}\right),\left(u^*_{R,p_1\beta_1}\right)$

$$m_u = \left(\frac{1}{\sqrt{2}} v_u \delta_{\alpha_1\beta_1} Y_{u,p_1 o_1} \right) \tag{1.62}$$

This matrix is diagonalized by U^u_L and U^u_R

$$U^{u,*}_L m_u U^{u,\dagger}_R = m^{dia}_u \tag{1.63}$$

with

$$u_{L,i\alpha} = \sum_{t_2} U^{u,*}_{L,ji} U_{L,j\alpha} \tag{1.64}$$

$$u_{R,i\alpha} = \sum_{t_2} U^{u}_{R,ij} U^*_{R,j\alpha} \tag{1.65}$$

1.4 Vacuum Expectation Values

$$H^0_d = \frac{1}{\sqrt{2}}\phi_d + \frac{1}{\sqrt{2}}v_d + i\frac{1}{\sqrt{2}}\sigma_d \tag{1.66}$$

$$H^0_u = \frac{1}{\sqrt{2}}\phi_u + \frac{1}{\sqrt{2}}v_u + i\frac{1}{\sqrt{2}}\sigma_u \tag{1.67}$$

1.5 Tadpole Equations

$$\frac{\partial V}{\partial v_d} = \frac{1}{8}\Big(8v_d|\mu|^2 - 8v_u\Re\Big(B_\mu\Big) + v_d\Big(8m^2_{H_d} + g_1^2 v_d^2 - g_1^2 v_u^2 + g_2^2 v_d^2 - g_2^2 v_u^2\Big)\Big) \tag{1.68}$$

$$\frac{\partial V}{\partial v_u} = \frac{1}{8}\Big(- 8v_d\Re\Big(B_\mu\Big) + 8v_u|\mu|^2 + v_u\Big(8m^2_{H_u} - g_1^2 v_d^2 + g_1^2 v_u^2 - g_2^2 v_d^2 + g_2^2 v_u^2\Big)\Big) \tag{1.69}$$

1.6 Particle content for eigenstates 'EWSB'

Name	Type	complex/real	Generations	Indices
$\tilde{d}$	Scalar	complex	6	generation, color
$\tilde{\nu}$	Scalar	complex	3	generation
$\tilde{u}$	Scalar	complex	6	generation, color
$\tilde{e}$	Scalar	complex	6	generation
h	Scalar	real	2	generation
A^0	Scalar	real	2	generation
H^-	Scalar	complex	2	generation
ν	Fermion	Dirac	3	generation
$\tilde{g}$	Fermion	Majorana	8	generation
$\tilde{\chi}^0$	Fermion	Majorana	4	generation
$\tilde{\chi}^-$	Fermion	Dirac	2	generation
e	Fermion	Dirac	3	generation
d	Fermion	Dirac	3	generation, color
u	Fermion	Dirac	3	generation, color
g	Vector	real	8	generation, lorentz
W^-	Vector	complex	1	lorentz
γ	Vector	real	1	lorentz
Z	Vector	real	1	lorentz
η^G	Ghost	real	8	generation
η^-	Ghost	complex	1	
η^+	Ghost	complex	1	
η^γ	Ghost	real	1	
η^Z	Ghost	real	1	

1.7 Modelfile for SARAH

```
Off[General::spell]
Print["Model file for the MSSM loaded"];

ModelNameLaTeX ="MSSM";


(*-------------------------------------------*)
(*   Particle Content*)
(*-------------------------------------------*)

(* Gauge Superfields *)

Gauge[[1]]={B,   U[1], hypercharge, g1,False};
Gauge[[2]]={WB, SU[2], left,        g2,True};
Gauge[[3]]={G,  SU[3], color,       g3,False};


(* Chiral Superfields *)

Fields[[1]] = {{uL,  dL},  3, q,   1/6, 2, 3};
Fields[[2]] = {{vL,  eL},  3, l,  -1/2, 2, 1};
Fields[[3]] = {{Hd0, Hdm}, 1, Hd, -1/2, 2, 1};
Fields[[4]] = {{Hup, Hu0}, 1, Hu,  1/2, 2, 1};

Fields[[5]] = {conj[dR], 3, d,  1/3, 1, -3};
Fields[[6]] = {conj[uR], 3, u, -2/3, 1, -3};
Fields[[7]] = {conj[eR], 3, e,    1, 1,  1};


(*-----------------------------------------------------*)
(* Superpotential *)
(*-----------------------------------------------------*)


SuperPotential = { {{1, Yu},{u,q,Hu}}, {{-1,Yd},{d,q,Hd}},
                   {{-1,Ye},{e,l,Hd}}, {{1,\[Mu]},{Hu,Hd}}};


(*-------------------------------------------*)
(* Integrate Out or Delete Particles         *)
(*-------------------------------------------*)

IntegrateOut={};
DeleteParticles={};
```

```
(*-----------------------------------------------*)
(*   DEFINITION                                  *)
(*-----------------------------------------------*)

NameOfStates={GaugeES, EWSB};

(* ----- Before EWSB ----- *)


DEFINITION[GaugeES][GaugeFixing]=
{ {Der[VWB],  -1/(2 RXi[W])},
     {Der[VG],   -1/(2 RXi[G]) }};



(* ----- After EWSB ----- *)


(* Gauge Sector *)

DEFINITION[EWSB][GaugeSector]=
{{VWB,{1,{VWm,1/Sqrt[2]},{conj[VWm],1/Sqrt[2]}},
      {2,{VWm,-\[ImaginaryI]/Sqrt[2]},{conj[VWm],\[ImaginaryI]/Sqrt[2]}},
      {3,{VP,Sin[ThetaW]},{VZ,Cos[ThetaW]}}},
 {VB, {1,{VP,Cos[ThetaW]},{VZ,-Sin[ThetaW]}}},
 {fWB,{1,{fWm,1/Sqrt[2]},{fWp,1/Sqrt[2]}},
      {2,{fWm,-\[ImaginaryI]/Sqrt[2]},{fWp,\[ImaginaryI]/Sqrt[2]}},
      {3,{fW0,1}}}};




(* ----- VEVs ---- *)

DEFINITION[EWSB][VEVs]=
  {{SHd0, {vd, 1/Sqrt[2]}, {sigmad, \[ImaginaryI]/Sqrt[2]},{phid, \
1/Sqrt[2]}},
   {SHu0, {vu, 1/Sqrt[2]}, {sigmau, \[ImaginaryI]/Sqrt[2]},{phiu, \
1/Sqrt[2]}}};



(* ---- Mixings ---- *)

DEFINITION[EWSB][MatterSector]=
{    {{SdL, SdR}, {Sd, ZD}},
```

```
 {{SvL}, {Sv, ZV}},
     {{SuL, SuR}, {Su, ZU}},
     {{SeL, SeR}, {Se, ZE}},
     {{phid, phiu}, {hh, ZH}},
     {{sigmad, sigmau}, {Ah, ZA}},
     {{SHdm,conj[SHup]},{Hpm,ZP}},
     {{fB, fW0, FHd0, FHu0}, {L0, ZN}},
     {{{fWm, FHdm}, {fWp, FHup}}, {{Lm,UM}, {Lp,UP}}},
     {{{FeL},{conj[FeR]}},{{FEL,ZEL},{FER,ZER}}},
     {{{FdL},{conj[FdR]}},{{FDL,ZDL},{FDR,ZDR}}},
     {{{FuL},{conj[FuR]}},{{FUL,ZUL},{FUR,ZUR}}}      \
       };

DEFINITION[EWSB][Phases]=
{    {fG, PhaseGlu}
    };

(*--- Gauge Fixing ---- *)

DEFINITION[EWSB][GaugeFixing]=
  { {Der[VP],                                           - 1/(2 RXi[P])},
{Der[VWm]+\[ImaginaryI] Mass[VWm] RXi[W] Hpm[{1}],   - 1/(RXi[W])},
{Der[VZ] - Mass[VZ] RXi[Z] Ah[{1}],                 - 1/(2 RXi[Z])},
{Der[VG],                                           - 1/(2 RXi[G])}};


(*--------------------------------------------------------*)
(* Dirac-Spinors *)
(*--------------------------------------------------------*)

dirac[[1]] = {Fd,  FDL, conj[FDR]};
dirac[[2]] = {Fe,  FEL, conj[FER]};
dirac[[3]] = {Fu,  FUL, conj[FUR]};
dirac[[4]] = {Fv,  FvL, 0};
dirac[[5]] = {Chi, L0, conj[L0]};
dirac[[6]] = {Cha, Lm, conj[Lp]};
dirac[[7]] = {Glu, fG, conj[fG]};


(* Unbroken EW *)

dirac[[8]] = {Bino, fB, conj[fB]};
dirac[[9]] = {Wino, fWB, conj[fWB]};
dirac[[10]] = {H0, FHd0, conj[FHu0]};
dirac[[11]] = {HC, FHdm, conj[FHup]};
dirac[[12]] = {Fd1, FdL, 0};
dirac[[13]] = {Fd2, 0, FdR};
dirac[[14]] = {Fu1, FuL, 0};
```

```
dirac[[15]] = {Fu2, 0, FuR};
dirac[[16]] = {Fe1, FeL, 0};
dirac[[17]] = {Fe2, 0, FeR};




(*-----------------------------------------------------*)
(* Automatized Output        *)
(*-----------------------------------------------------*)

(*
makeOutput = {
                  {EWSB, {TeX, FeynArts}}
             };
            *)

SpectrumFile=None;
```

1.8 Implementation in SARAH

Model directory: MSSM

1.8.1 Particles for eigenstates 'GaugeES'

- Fermions

$\tilde{B} = \begin{pmatrix} \lambda_{\tilde{B}} \\ \lambda^*_{\tilde{B}} \end{pmatrix}$	$\texttt{Bino} = \begin{pmatrix} \texttt{fB} \\ \texttt{conj[fB]} \end{pmatrix}$
$d^1_{i\alpha} = \begin{pmatrix} d_{L,i\alpha} \\ 0 \end{pmatrix}$	$\texttt{Fd1[\{generation, color\}]} = \begin{pmatrix} \texttt{FdL[\{generation, color\}]} \\ 0 \end{pmatrix}$
$d^2_{i\alpha} = \begin{pmatrix} 0 \\ d_{R,i\alpha} \end{pmatrix}$	$\texttt{Fd2[\{generation, color\}]} = \begin{pmatrix} 0 \\ \texttt{FdR[\{generation, color\}]} \end{pmatrix}$
$e^1_{i} = \begin{pmatrix} e_{L,i} \\ 0 \end{pmatrix}$	$\texttt{Fe1[\{generation\}]} = \begin{pmatrix} \texttt{FeL[\{generation\}]} \\ 0 \end{pmatrix}$
$e^2_{i} = \begin{pmatrix} 0 \\ e_{R,i} \end{pmatrix}$	$\texttt{Fe2[\{generation\}]} = \begin{pmatrix} 0 \\ \texttt{FeR[\{generation\}]} \end{pmatrix}$
$u^1_{i\alpha} = \begin{pmatrix} u_{L,i\alpha} \\ 0 \end{pmatrix}$	$\texttt{Fu1[\{generation, color\}]} = \begin{pmatrix} \texttt{FuL[\{generation, color\}]} \\ 0 \end{pmatrix}$

$u^2_{i\alpha} = \begin{pmatrix} 0 \\ u_{R,i\alpha} \end{pmatrix}$	`Fu2[{generation, color}]` $= \begin{pmatrix} 0 \\ \texttt{FuR[\{generation, color\}]} \end{pmatrix}$
$\nu_i = \begin{pmatrix} \nu_{L,i} \\ 0 \end{pmatrix}$	`Fv[{generation}]` $= \begin{pmatrix} \texttt{FvL[\{generation\}]} \\ 0 \end{pmatrix}$
$\tilde{g}_i = \begin{pmatrix} \lambda_{\tilde{g},i} \\ \lambda^*_{\tilde{g},i} \end{pmatrix}$	`Glu[{generation}]` $= \begin{pmatrix} \texttt{fG[\{generation\}]} \\ \texttt{conj[fG[\{generation\}]]} \end{pmatrix}$
$\tilde{H}^0 = \begin{pmatrix} \tilde{H}^0_d \\ \tilde{H}^{0,*}_u \end{pmatrix}$	`H0` $= \begin{pmatrix} \texttt{FHd0} \\ \texttt{conj[FHu0]} \end{pmatrix}$
$\tilde{H}^- = \begin{pmatrix} \tilde{H}^-_d \\ \tilde{H}^{+,*}_u \end{pmatrix}$	`HC` $= \begin{pmatrix} \texttt{FHdm} \\ \texttt{conj[FHup]} \end{pmatrix}$
$\tilde{W}_i = \begin{pmatrix} \lambda_{\tilde{W},i} \\ \lambda^*_{\tilde{W},i} \end{pmatrix}$	`Wino[{generation}]` $= \begin{pmatrix} \texttt{fWB[\{generation\}]} \\ \texttt{conj[fWB[\{generation\}]]} \end{pmatrix}$

- Scalars

$\tilde{d}_{L,i\alpha}$	`SdL[{generation, color}]`	$\tilde{u}_{L,i\alpha}$	`SuL[{generation, color}]`
$\tilde{e}_{L,i}$	`SeL[{generation}]`	$\tilde{\nu}_{L,i}$	`SvL[{generation}]`
H^0_d	`SHd0`	H^-_d	`SHdm`
H^0_u	`SHu0`	H^+_u	`SHup`
$\tilde{d}_{R,i\alpha}$	`SdR[{generation, color}]`	$\tilde{u}_{R,i\alpha}$	`SuR[{generation, color}]`
$\tilde{e}_{R,i}$	`SeR[{generation}]`		

- Vector Bosons

B_ρ	`VB[{lorentz}]`	$W^-_{i\rho}$	`VWB[{generation, lorentz}]`
$g_{i\rho}$	`VG[{generation, lorentz}]`		

- Ghosts

η^B	`gB`	$\mathrm{gWB}\left(\{\mathrm{gt1}\}\right)$	`gWB[{generation}]`

η_i^G	gG[{generation}]

1.8.2 Particles for eigenstates 'EWSB'

- Fermions

$\tilde{\chi}_i^- = \begin{pmatrix} \lambda_i^- \\ \lambda_i^{+,*} \end{pmatrix}$	$\texttt{Cha[\{generation\}]} = \begin{pmatrix} \texttt{Lm[\{generation\}]} \\ \texttt{conj[Lp[\{generation\}]]} \end{pmatrix}$
$\tilde{\chi}_i^0 = \begin{pmatrix} \lambda_i^0 \\ \lambda_i^{0,*} \end{pmatrix}$	$\texttt{Chi[\{generation\}]} = \begin{pmatrix} \texttt{L0[\{generation\}]} \\ \texttt{conj[L0[\{generation\}]]} \end{pmatrix}$
$d_{i\alpha} = \begin{pmatrix} D_{L,i\alpha} \\ D_{R,i\alpha}^* \end{pmatrix}$	$\texttt{Fd[\{generation, color\}]} = \begin{pmatrix} \texttt{FDL[\{generation, color\}]} \\ \texttt{conj[FDR[\{generation, color\}]]} \end{pmatrix}$
$e_i = \begin{pmatrix} E_{L,i} \\ E_{R,i}^* \end{pmatrix}$	$\texttt{Fe[\{generation\}]} = \begin{pmatrix} \texttt{FEL[\{generation\}]} \\ \texttt{conj[FER[\{generation\}]]} \end{pmatrix}$
$u_{i\alpha} = \begin{pmatrix} U_{L,i\alpha} \\ U_{R,i\alpha}^* \end{pmatrix}$	$\texttt{Fu[\{generation, color\}]} = \begin{pmatrix} \texttt{FUL[\{generation, color\}]} \\ \texttt{conj[FUR[\{generation, color\}]]} \end{pmatrix}$
$\nu_i = \begin{pmatrix} \nu_{L,i} \\ 0 \end{pmatrix}$	$\texttt{Fv[\{generation\}]} = \begin{pmatrix} \texttt{FvL[\{generation\}]} \\ 0 \end{pmatrix}$
$\tilde{g}_i = \begin{pmatrix} \lambda_{\tilde{g},i} \\ \lambda_{\tilde{g},i}^* \end{pmatrix}$	$\texttt{Glu[\{generation\}]} = \begin{pmatrix} \texttt{fG[\{generation\}]} \\ \texttt{conj[fG[\{generation\}]]} \end{pmatrix}$

- Scalars

$\tilde{d}_{i\alpha}$	Sd[{generation, color}]	$\tilde{\nu}_i$	Sv[{generation}]
$\tilde{u}_{i\alpha}$	Su[{generation, color}]	$\tilde{e}_i$	Se[{generation}]
h_i	hh[{generation}]	A_i^0	Ah[{generation}]
H_i^-	Hpm[{generation}]		

- Vector Bosons

$g_{i\rho}$	VG[{generation, lorentz}]	W^-_ρ	VWm[{lorentz}]
γ_ρ	VP[{lorentz}]	Z_ρ	VZ[{lorentz}]

- Ghosts

η^G_i	gG[{generation}]	η^-	gWm
η^+	gWmC	η^γ	gP
η^Z	gZ		

1.8.3 Parameters

g_1	g1	g_2	g2	g_3	g3
Y_u	Yu	T_u	T[Yu]	Y_d	Yd
T_d	T[Yd]	Y_e	Ye	T_e	T[Ye]
μ	\[Mu]	B_μ	B[\[Mu]]	m_q^2	mq2
m_l^2	ml2	$m_{H_d}^2$	mHd2	$m_{H_u}^2$	mHu2
m_d^2	md2	m_u^2	mu2	m_e^2	me2
M_1	MassB	M_2	MassWB	M_3	MassG
v_d	vd	v_u	vu	Θ_W	ThetaW
$\phi_{\tilde{g}}$	PhaseGlu	Z^D	ZD	Z^V	ZV
Z^U	ZU	Z^E	ZE	Z^H	ZH
Z^A	ZA	Z^+	ZP	N	ZN
U	UM	V	UP	U_L^e	ZEL
U_R^e	ZER	U_L^d	ZDL	U_R^d	ZDR
U_L^u	ZUL	U_R^u	ZUR	α	\[Alpha]
β	\[Beta]				

Chapter 2

Minimal Supersymmetric Standard Model without flavor violation

2.1 Superfields

2.1.1 Vector Superfields

SF	Spin $\frac{1}{2}$	Spin 1	$SU(N)$	Coupling	Name
$\hat{B}$	$\lambda_{\tilde{B}}$	B	$U(1)$	g_1	hypercharge
$\hat{W}$	$\lambda_{\tilde{W}}$	W^-	SU(2)	g_2	left
$\hat{g}$	$\lambda_{\tilde{g}}$	g	SU(3)	g_3	color

2.1.2 Chiral Superfields

SF	Spin 0	Spin $\frac{1}{2}$	Generations	$(U(1) \otimes \mathrm{SU}(2) \otimes \mathrm{SU}(3))$
$\hat{q}$	$\tilde{q}$	q	3	$(\frac{1}{6}, \mathbf{2}, \mathbf{3})$
$\hat{l}$	$\tilde{l}$	l	3	$(-\frac{1}{2}, \mathbf{2}, \mathbf{1})$
$\hat{H}_d$	H_d	$\tilde{H}_d$	1	$(-\frac{1}{2}, \mathbf{2}, \mathbf{1})$
$\hat{H}_u$	H_u	$\tilde{H}_u$	1	$(\frac{1}{2}, \mathbf{2}, \mathbf{1})$
$\hat{d}$	$\tilde{d}_R^*$	d_R^*	3	$(\frac{1}{3}, \mathbf{1}, \overline{\mathbf{3}})$
$\hat{u}$	$\tilde{u}_R^*$	u_R^*	3	$(-\frac{2}{3}, \mathbf{1}, \overline{\mathbf{3}})$
$\hat{e}$	$\tilde{e}_R^*$	e_R^*	3	$(1, \mathbf{1}, \mathbf{1})$

2.2 Superpotential and Lagrangian

2.2.1 Superpotential

$$W = Y_u \, \hat{u} \, \hat{q} \, \hat{H}_u \, - Y_d \, \hat{d} \, \hat{q} \, \hat{H}_d \, - Y_e \, \hat{e} \, \hat{l} \, \hat{H}_d \, + \mu \, \hat{H}_u \, \hat{H}_d \tag{2.1}$$

2.2.2 Softbreaking terms

$$
\begin{aligned}
L_{SB,W} = & -H_d^0 H_u^0 B_\mu + H_d^- H_u^+ B_\mu + H_d^0 \tilde{d}^*_{R,i\alpha}\delta_{\alpha\beta}\delta_{ij}\tilde{d}_{L,j\beta}T_{d,ij} - H_d^- \tilde{d}^*_{R,i\alpha}\delta_{\alpha\beta}\delta_{ij}\tilde{u}_{L,j\beta}T_{d,ij} \\
& + H_d^0 \tilde{e}^*_{R,i}\delta_{ij}\tilde{e}_{L,j}T_{e,ij} - H_d^- \tilde{e}^*_{R,i}\delta_{ij}\tilde{\nu}_{L,j}T_{e,ij} - H_u^+ \tilde{u}^*_{R,i\alpha}\delta_{\alpha\beta}\delta_{ij}\tilde{d}_{L,j\beta}T_{u,ij} \\
& + H_u^0 \tilde{u}^*_{R,i\alpha}\delta_{\alpha\beta}\delta_{ij}\tilde{u}_{L,j\beta}T_{u,ij} + \text{h.c.} && (2.2) \\
L_{SB,\phi} = & -m^2_{H_d}|H_d^0|^2 - m^2_{H_d}|H_d^-|^2 - m^2_{H_u}|H_u^0|^2 - m^2_{H_u}|H_u^+|^2 - \tilde{d}^*_{L,j\beta}\delta_{\alpha\beta}\delta_{ij}m^2_{q,ij}\tilde{d}_{L,i\alpha} \\
& - \tilde{d}^*_{R,i\alpha}\delta_{\alpha\beta}\delta_{ij}m^2_{d,ij}\tilde{d}_{R,j\beta} - \tilde{e}^*_{L,j}\delta_{ij}m^2_{l,ij}\tilde{e}_{L,i} - \tilde{e}^*_{R,i}\delta_{ij}m^2_{e,ij}\tilde{e}_{R,j} \\
& - \tilde{u}^*_{L,j\beta}\delta_{\alpha\beta}\delta_{ij}m^2_{q,ij}\tilde{u}_{L,i\alpha} - \tilde{u}^*_{R,i\alpha}\delta_{\alpha\beta}\delta_{ij}m^2_{u,ij}\tilde{u}_{R,j\beta} - \tilde{\nu}^*_{L,j}\delta_{ij}m^2_{l,ij}\tilde{\nu}_{L,i} && (2.3) \\
L_{SB,\lambda} = & \frac{1}{2}\left(-\lambda^2_{\tilde{B}}M_1 - M_2\lambda^2_{\tilde{W},i} - M_3\lambda^2_{\tilde{g},i} + \text{h.c.}\right) && (2.4)
\end{aligned}
$$

2.2.3 Gauge fixing terms

Gauge fixing terms for eigenstates 'GaugeES'

$$L_{GF} = -\frac{1}{2}\partial_\mu g\xi_G^{-1} - \frac{1}{2}\partial_\mu W^-\xi_W^{-1} \tag{2.5}$$

Gauge fixing terms for eigenstates 'EWSB'

$$L_{GF} = -\frac{1}{2}\partial_\mu\gamma\xi_P^{-1} - \frac{1}{2}\partial_\mu g\xi_G^{-1} - \frac{1}{2}\xi_Z^{-1}\Big(-A_1^0 m_Z\xi_Z + \partial_\mu Z\Big) - \xi_W^{-1}\Big(iH_1^- m_{W^-}\xi_W + \partial_\mu W^-\Big) \tag{2.6}$$

2.2.4 Fields integrated out

None

2.3 Field Rotations

2.3.1 Rotations in gauge sector for eigenstates 'EWSB'

$$
\begin{aligned}
W^-_{1\rho} &= \frac{1}{\sqrt{2}}W^-_\rho + \frac{1}{\sqrt{2}}W^+_\rho && (2.7) \\
W^-_{2\rho} &= -i\frac{1}{\sqrt{2}}W^-_\rho + i\frac{1}{\sqrt{2}}W^+_\rho && (2.8) \\
W^-_{3\rho} &= \cos\Theta_W Z_\rho + \sin\Theta_W\gamma_\rho && (2.9) \\
B_\rho &= \cos\Theta_W\gamma_\rho - \sin\Theta_W Z_\rho && (2.10) \\
\lambda_{\tilde{W},1} &= \frac{1}{\sqrt{2}}\tilde{W}^- + \frac{1}{\sqrt{2}}\tilde{W}^+ && (2.11) \\
\lambda_{\tilde{W},2} &= -i\frac{1}{\sqrt{2}}\tilde{W}^- + i\frac{1}{\sqrt{2}}\tilde{W}^+ && (2.12) \\
\lambda_{\tilde{W},3} &= \tilde{W}^0 && (2.13)
\end{aligned}
$$

2.3.2 Rotations in Mass sector for eigenstates 'EWSB'

Mass Matrices for Scalars

- **Mass matrix for Down Squark**, Basis: $\left(\tilde{d}_{L,\alpha_1}, \tilde{d}_{R,\alpha_2}\right), \left(\tilde{d}^*_{L,\beta_1}, \tilde{d}^*_{R,\beta_2}\right)$

$$m^2_{\tilde{d}} = \begin{pmatrix} m_{11} & \frac{1}{\sqrt{2}}\delta_{\alpha_1\beta_2}\Big(v_d T_{d,11} - v_u \mu^* Y_{d,11}\Big) \\ \frac{1}{\sqrt{2}}\Big(v_d T^*_{d,11} - v_u \mu Y^*_{d,11}\Big)\delta_{\alpha_2\beta_1} & m_{22} \end{pmatrix} \tag{2.14}$$

$$m_{11} = \frac{1}{24}\delta_{\alpha_1\beta_1}\Big(12 v_d^2 |Y_{d,11}|^2 + 24 m^2_{q,11} - 3 g_2^2 v_d^2 + 3 g_2^2 v_u^2 + g_1^2\Big(- v_d^2 + v_u^2\Big)\Big) \tag{2.15}$$

$$m_{22} = \frac{1}{12}\delta_{\alpha_2\beta_2}\Big(12 m^2_{d,11} + 6 v_d^2 |Y_{d,11}|^2 + g_1^2\Big(- v_d^2 + v_u^2\Big)\Big) \tag{2.16}$$

This matrix is diagonalized by Z^D:

$$Z^D m^2_{\tilde{d}} Z^{D,\dagger} = m^{dia}_{2,\tilde{d}} \tag{2.17}$$

with

$$\tilde{d}_{L,\alpha} = \sum_{t_2} Z^{D,*}_{j1}\tilde{d}_{j\alpha}\,, \qquad \tilde{d}_{R,\alpha} = \sum_{t_2} Z^{D,*}_{j2}\tilde{d}_{j\alpha} \tag{2.18}$$

- **Mass matrix for Up Squark**, Basis: $\left(\tilde{u}_{L,\alpha_1}, \tilde{u}_{R,\alpha_2}\right), \left(\tilde{u}^*_{L,\beta_1}, \tilde{u}^*_{R,\beta_2}\right)$

$$m^2_{\tilde{u}} = \begin{pmatrix} m_{11} & \frac{1}{\sqrt{2}}\delta_{\alpha_1\beta_2}\Big(- v_d \mu^* Y_{u,11} + v_u T_{u,11}\Big) \\ \frac{1}{\sqrt{2}}\Big(- v_d \mu Y^*_{u,11} + v_u T^*_{u,11}\Big)\delta_{\alpha_2\beta_1} & m_{22} \end{pmatrix} \tag{2.19}$$

$$m_{11} = \frac{1}{24}\delta_{\alpha_1\beta_1}\Big(12 v_u^2 |Y_{u,11}|^2 + 3\Big(8 m^2_{q,11} + g_2^2\Big(- v_u^2 + v_d^2\Big)\Big) + g_1^2\Big(- v_d^2 + v_u^2\Big)\Big) \tag{2.20}$$

$$m_{22} = \frac{1}{6}\delta_{\alpha_2\beta_2}\Big(3 v_u^2 |Y_{u,11}|^2 + 6 m^2_{u,11} + g_1^2\Big(- v_u^2 + v_d^2\Big)\Big) \tag{2.21}$$

This matrix is diagonalized by Z^U:

$$Z^U m^2_{\tilde{u}} Z^{U,\dagger} = m^{dia}_{2,\tilde{u}} \tag{2.22}$$

with

$$\tilde{u}_{L,\alpha} = \sum_{t_2} Z^{U,*}_{j1}\tilde{u}_{j\alpha}\,, \qquad \tilde{u}_{R,\alpha} = \sum_{t_2} Z^{U,*}_{j2}\tilde{u}_{j\alpha} \tag{2.23}$$

- **Mass matrix for Selectron**, Basis: $\left(\tilde{e}_L, \tilde{e}_R\right), \left(\tilde{e}^*_L, \tilde{e}^*_R\right)$

$$m^2_{\tilde{e}} = \begin{pmatrix} m_{11} & \frac{1}{\sqrt{2}}\Big(v_d T_{e,11} - v_u \mu^* Y_{e,11}\Big) \\ \frac{1}{\sqrt{2}}\Big(v_d T^*_{e,11} - v_u \mu Y^*_{e,11}\Big) & m_{22} \end{pmatrix} \tag{2.24}$$

$$m_{11} = \frac{1}{8}\Big(4v_d^2|Y_{e,11}|^2 + 8m_{l,11}^2 + g_1^2\Big(-v_u^2 + v_d^2\Big) - g_2^2 v_d^2 + g_2^2 v_u^2\Big) \tag{2.25}$$

$$m_{22} = \frac{1}{4}\Big(2v_d^2|Y_{e,11}|^2 + 4m_{e,11}^2 + g_1^2\Big(-v_d^2 + v_u^2\Big)\Big) \tag{2.26}$$

This matrix is diagonalized by Z^E:

$$Z^E m_{\tilde{e}}^2 Z^{E,\dagger} = m_{2,\tilde{e}}^{dia} \tag{2.27}$$

with

$$\tilde{e}_L = \sum_{t_2} Z_{j1}^{E,*}\tilde{e}_j\,, \qquad \tilde{e}_R = \sum_{t_2} Z_{j2}^{E,*}\tilde{e}_j \tag{2.28}$$

- **Mass matrix for Smuon**, Basis: $(\tilde{\mu}_L, \tilde{\mu}_R)\,, (\tilde{\mu}_L^*, \tilde{\mu}_R^*)$

$$m_{\tilde{\mu}}^2 = \left(\begin{array}{cc} m_{11} & \frac{1}{\sqrt{2}}\Big(v_d T_{e,22} - v_u \mu^* Y_{e,22}\Big) \\ \frac{1}{\sqrt{2}}\Big(v_d T_{e,22}^* - v_u \mu Y_{e,22}^*\Big) & m_{22} \end{array}\right) \tag{2.29}$$

$$m_{11} = \frac{1}{8}\Big(4v_d^2|Y_{e,22}|^2 + 8m_{l,22}^2 + g_1^2\Big(-v_u^2 + v_d^2\Big) - g_2^2 v_d^2 + g_2^2 v_u^2\Big) \tag{2.30}$$

$$m_{22} = \frac{1}{4}\Big(2v_d^2|Y_{e,22}|^2 + 4m_{e,22}^2 + g_1^2\Big(-v_d^2 + v_u^2\Big)\Big) \tag{2.31}$$

This matrix is diagonalized by Z^μ:

$$Z^\mu m_{\tilde{\mu}}^2 Z^{\mu,\dagger} = m_{2,\tilde{\mu}}^{dia} \tag{2.32}$$

with

$$\tilde{\mu}_L = \sum_{t_2} Z_{j1}^{\mu,*}\tilde{\mu}_j\,, \qquad \tilde{\mu}_R = \sum_{t_2} Z_{j2}^{\mu,*}\tilde{\mu}_j \tag{2.33}$$

- **Mass matrix for Stau**, Basis: $(\tilde{\tau}_L, \tilde{\tau}_R)\,, (\tilde{\tau}_L^*, \tilde{\tau}_R^*)$

$$m_{\tilde{\tau}}^2 = \left(\begin{array}{cc} m_{11} & \frac{1}{\sqrt{2}}\Big(v_d T_{e,33} - v_u \mu^* Y_{e,33}\Big) \\ \frac{1}{\sqrt{2}}\Big(v_d T_{e,33}^* - v_u \mu Y_{e,33}^*\Big) & m_{22} \end{array}\right) \tag{2.34}$$

$$m_{11} = \frac{1}{8}\Big(4v_d^2|Y_{e,33}|^2 + 8m_{l,33}^2 + g_1^2\Big(-v_u^2 + v_d^2\Big) - g_2^2 v_d^2 + g_2^2 v_u^2\Big) \tag{2.35}$$

$$m_{22} = \frac{1}{4}\Big(2v_d^2|Y_{e,33}|^2 + 4m_{e,33}^2 + g_1^2\Big(-v_d^2 + v_u^2\Big)\Big) \tag{2.36}$$

This matrix is diagonalized by Z^τ:

$$Z^\tau m_{\tilde{\tau}}^2 Z^{\tau,\dagger} = m_{2,\tilde{\tau}}^{dia} \tag{2.37}$$

with

$$\tilde{\tau}_L = \sum_{t_2} Z_{j1}^{\tau,*}\tilde{\tau}_j\,, \qquad \tilde{\tau}_R = \sum_{t_2} Z_{j2}^{\tau,*}\tilde{\tau}_j \tag{2.38}$$

- **Mass matrix for Strange Squark**, Basis: $(\tilde{s}_{L,\alpha_1}, \tilde{s}_{R,\alpha_2}), \Big(\tilde{s}^*_{L,\beta_1}, \tilde{s}^*_{R,\beta_2}\Big)$

$$m^2_{\tilde{s}} = \left(\begin{array}{cc}m_{11} &\frac{1}{\sqrt{2}} \delta_{\alpha_1\beta_2} \Big(v_d T_{d,22} - v_u \mu^* Y_{d,22} \Big)\\
\frac{1}{\sqrt{2}} \Big(v_d T_{d,22}^* - v_u \mu Y_{d,22}^* \Big)\delta_{\alpha_2\beta_1} &m_{22}\end{array}\right) \tag{2.39}$$

$$m_{11} = \frac{1}{24} \delta_{\alpha_1\beta_1} \Big(12 v_{d}^{2} |Y_{d,22}|^2 + 24 m_{q,22}^2 -3 g_{2}^{2} v_{d}^{2} + 3 g_{2}^{2} v_{u}^{2} + g_{1}^{2} \Big(- v_{d}^{2} + v_{u}^{2}\Big)\Big) \tag{2.40}$$

$$m_{22} = \frac{1}{12} \delta_{\alpha_2\beta_2} \Big(12 m_{d,22}^2 + 6 v_{d}^{2} |Y_{d,22}|^2 + g_{1}^{2} \Big(- v_{d}^{2} + v_{u}^{2}\Big)\Big) \tag{2.41}$$

This matrix is diagonalized by Z^S:

$$Z^S m^2_{\tilde{s}} Z^{S,\dagger} = m^{dia}_{2,\tilde{s}} \tag{2.42}$$

with

$$\tilde{s}_{L,\alpha} = \sum_{t_2}Z^{S,*}_{j1}\tilde{s}_{j\alpha}\,, \qquad \tilde{s}_{R,\alpha} = \sum_{t_2}Z^{S,*}_{j2}\tilde{s}_{j\alpha} \tag{2.43}$$

- **Mass matrix for Charmed Squark**, Basis: $(\tilde{c}_{L,\alpha_1}, \tilde{c}_{R,\alpha_2}), \Big(\tilde{c}^*_{L,\beta_1}, \tilde{c}^*_{R,\beta_2}\Big)$

$$m^2_{\tilde{c}} = \left(\begin{array}{cc}m_{11} &\frac{1}{\sqrt{2}} \delta_{\alpha_1\beta_2} \Big(- v_d \mu^* Y_{u,22} + v_u T_{u,22} \Big)\\
\frac{1}{\sqrt{2}} \Big(- v_d \mu Y_{u,22}^* + v_u T_{u,22}^* \Big)\delta_{\alpha_2\beta_1} &m_{22}\end{array}\right) \tag{2.44}$$

$$m_{11} = \frac{1}{24} \delta_{\alpha_1\beta_1} \Big(12 v_{u}^{2} |Y_{u,22}|^2 + 3 \Big(8 m_{q,22}^2 + g_{2}^{2} \Big(- v_{u}^{2} + v_{d}^{2}\Big)\Big) + g_{1}^{2} \Big(- v_{d}^{2} + v_{u}^{2}\Big)\Big) \tag{2.45}$$

$$m_{22} = \frac{1}{6} \delta_{\alpha_2\beta_2} \Big(3 v_{u}^{2} |Y_{u,22}|^2 + 6 m_{u,22}^2 + g_{1}^{2} \Big(- v_{u}^{2} + v_{d}^{2}\Big)\Big) \tag{2.46}$$

This matrix is diagonalized by Z^C:

$$Z^C m^2_{\tilde{c}} Z^{C,\dagger} = m^{dia}_{2,\tilde{c}} \tag{2.47}$$

with

$$\tilde{c}_{L,\alpha} = \sum_{t_2}Z^{C,*}_{j1}\tilde{c}_{j\alpha}\,, \qquad \tilde{c}_{R,\alpha} = \sum_{t_2}Z^{C,*}_{j2}\tilde{c}_{j\alpha} \tag{2.48}$$

- **Mass matrix for Bottom Squark**, Basis: $\Big(\tilde{b}_{L,\alpha_1}, \tilde{b}_{R,\alpha_2}\Big), \Big(\tilde{b}^*_{L,\beta_1}, \tilde{b}^*_{R,\beta_2}\Big)$

$$m^2_{\tilde{b}} = \left(\begin{array}{cc}m_{11} &\frac{1}{\sqrt{2}} \delta_{\alpha_1\beta_2} \Big(v_d T_{d,33} - v_u \mu^* Y_{d,33} \Big)\\
\frac{1}{\sqrt{2}} \Big(v_d T_{d,33}^* - v_u \mu Y_{d,33}^* \Big)\delta_{\alpha_2\beta_1} &m_{22}\end{array}\right) \tag{2.49}$$

$$m_{11} = \frac{1}{24}\delta_{\alpha_1\beta_1}\Big(12v_d^2|Y_{d,33}|^2 + 24m_{q,33}^2 - 3g_2^2v_d^2 + 3g_2^2v_u^2 + g_1^2\Big(-v_d^2 + v_u^2\Big)\Big) \tag{2.50}$$

$$m_{22} = \frac{1}{12}\delta_{\alpha_2\beta_2}\Big(12m_{d,33}^2 + 6v_d^2|Y_{d,33}|^2 + g_1^2\Big(-v_d^2 + v_u^2\Big)\Big) \tag{2.51}$$

This matrix is diagonalized by Z^B:

$$Z^B m_{\tilde{b}}^2 Z^{B,\dagger} = m_{2,\tilde{b}}^{dia} \tag{2.52}$$

with

$$\tilde{b}_{L,\alpha} = \sum_{t_2} Z_{j1}^{B,*}\tilde{b}_{j\alpha}\,, \qquad \tilde{b}_{R,\alpha} = \sum_{t_2} Z_{j2}^{B,*}\tilde{b}_{j\alpha} \tag{2.53}$$

- **Mass matrix for Top Squark**, Basis: $\left(\tilde{t}_{L,\alpha_1}, \tilde{t}_{R,\alpha_2}\right), \left(\tilde{t}^*_{L,\beta_1}, \tilde{t}^*_{R,\beta_2}\right)$

$$m_{\tilde{t}}^2 = \begin{pmatrix} m_{11} & \frac{1}{\sqrt{2}}\delta_{\alpha_1\beta_2}\Big(-v_d\mu^*Y_{u,33} + v_uT_{u,33}\Big) \\ \frac{1}{\sqrt{2}}\Big(-v_d\mu Y_{u,33}^* + v_uT_{u,33}^*\Big)\delta_{\alpha_2\beta_1} & m_{22} \end{pmatrix} \tag{2.54}$$

$$m_{11} = \frac{1}{24}\delta_{\alpha_1\beta_1}\Big(12v_u^2|Y_{u,33}|^2 + 3\Big(8m_{q,33}^2 + g_2^2\Big(-v_u^2 + v_d^2\Big)\Big) + g_1^2\Big(-v_d^2 + v_u^2\Big)\Big) \tag{2.55}$$

$$m_{22} = \frac{1}{6}\delta_{\alpha_2\beta_2}\Big(3v_u^2|Y_{u,33}|^2 + 6m_{u,33}^2 + g_1^2\Big(-v_u^2 + v_d^2\Big)\Big) \tag{2.56}$$

This matrix is diagonalized by Z^T:

$$Z^T m_{\tilde{t}}^2 Z^{T,\dagger} = m_{2,\tilde{t}}^{dia} \tag{2.57}$$

with

$$\tilde{t}_{L,\alpha} = \sum_{t_2} Z_{j1}^{T,*}\tilde{t}_{j\alpha}\,, \qquad \tilde{t}_{R,\alpha} = \sum_{t_2} Z_{j2}^{T,*}\tilde{t}_{j\alpha} \tag{2.58}$$

- **Mass matrix for Higgs**, Basis: $\left(\phi_d, \phi_u\right), \left(\phi_d, \phi_u\right)$

$$m_h^2 = \begin{pmatrix} \frac{1}{8}\Big(8m_{H_d}^2 + 8|\mu|^2 + \Big(g_1^2 + g_2^2\Big)\Big(3v_d^2 - v_u^2\Big)\Big) & \frac{1}{4}\Big(-4\Re\Big(B_\mu\Big) - \Big(g_1^2 + g_2^2\Big)v_dv_u\Big) \\ \frac{1}{4}\Big(-4\Re\Big(B_\mu\Big) - \Big(g_1^2 + g_2^2\Big)v_dv_u\Big) & \frac{1}{8}\Big(8m_{H_u}^2 + 8|\mu|^2 - \Big(g_1^2 + g_2^2\Big)\Big(-3v_u^2 + v_d^2\Big)\Big) \end{pmatrix} \tag{2.59}$$

This matrix is diagonalized by Z^H:

$$Z^H m_h^2 Z^{H,\dagger} = m_{2,h}^{dia} \tag{2.60}$$

with

$$\phi_d = \sum_{t_2} Z_{j1}^H h_j\,, \qquad \phi_u = \sum_{t_2} Z_{j2}^H h_j \tag{2.61}$$

The mixing matrix can be parametrized by

$$Z^H = \begin{pmatrix} -\sin\alpha & \cos\alpha \\ \cos\alpha & \sin\alpha \end{pmatrix} \tag{2.62}$$

- **Mass matrix for Pseudo-Scalar Higgs**, Basis: $(\sigma_d, \sigma_u), (\sigma_d, \sigma_u)$

$$m^2_{A^0} = \begin{pmatrix} \frac{1}{8}\Big(8m^2_{H_d} + 8|\mu|^2 + \Big(g_1^2 + g_2^2\Big)\Big(- v_u^2 + v_d^2\Big)\Big) & \Re\Big(B_\mu\Big) \\ \Re\Big(B_\mu\Big) & \frac{1}{8}\Big(8m^2_{H_u} + 8|\mu|^2 - \Big(g_1^2 + g_2^2\Big)\Big(- v_u^2 + v_d^2\Big)\Big) \end{pmatrix} \tag{2.63}$$

This matrix is diagonalized by Z^A:

$$Z^A m^2_{A^0} Z^{A,\dagger} = m^{dia}_{2,A^0} \tag{2.64}$$

with

$$\sigma_d = \sum_{t_2} Z^A_{j1} A^0_j\,, \qquad \sigma_u = \sum_{t_2} Z^A_{j2} A^0_j \tag{2.65}$$

The mixing matrix can be parametrized by

$$Z^A = \begin{pmatrix} -\cos\beta & \sin\beta \\ \sin\beta & \cos\beta \end{pmatrix} \tag{2.66}$$

- **Mass matrix for Charged Higgs**, Basis: $\left(H_d^-, H_u^{+,*}\right), \left(H_d^{-,*}, H_u^+\right)$

$$m^2_{H^-} = \begin{pmatrix} m_{11} & \frac{1}{4}g_2^2 v_d v_u + B_\mu \\ \frac{1}{4}g_2^2 v_d v_u + B^*_\mu & m_{22} \end{pmatrix} \tag{2.67}$$

$$m_{11} = \frac{1}{8}\Big(8m^2_{H_d} + 8|\mu|^2 + g_1^2 v_d^2 - g_1^2 v_u^2 + g_2^2 v_d^2 + g_2^2 v_u^2\Big) \tag{2.68}$$

$$m_{22} = \frac{1}{8}\Big(8m^2_{H_u} + 8|\mu|^2 - g_1^2 v_d^2 + g_1^2 v_u^2 + g_2^2 v_d^2 + g_2^2 v_u^2\Big) \tag{2.69}$$

This matrix is diagonalized by Z^+:

$$Z^+ m^2_{H^-} Z^{+,\dagger} = m^{dia}_{2,H^-} \tag{2.70}$$

with

$$H_d^- = \sum_{t_2} Z^{+,*}_{j1} H_j^-\,, \qquad H_u^+ = \sum_{t_2} Z^+_{j2} H_j^+ \tag{2.71}$$

The mixing matrix can be parametrized by

$$Z^+ = \begin{pmatrix} -\cos\beta & \sin\beta \\ \sin\beta & \cos\beta \end{pmatrix} \tag{2.72}$$

Mass Matrices for Fermions

- **Mass matrix for Neutralinos**, Basis: $\left(\lambda_{\tilde{B}}, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0\right), \left(\lambda_{\tilde{B}}, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0\right)$

$$m_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -\frac{1}{2}g_1 v_d & \frac{1}{2}g_1 v_u \\ 0 & M_2 & \frac{1}{2}g_2 v_d & -\frac{1}{2}g_2 v_u \\ -\frac{1}{2}g_1 v_d & \frac{1}{2}g_2 v_d & 0 & -\mu \\ \frac{1}{2}g_1 v_u & -\frac{1}{2}g_2 v_u & -\mu & 0 \end{pmatrix} \tag{2.73}$$

This matrix is diagonalized by N:

$$N m_{\tilde{\chi}^0} N^\dagger = m_{\tilde{\chi}^0}^{dia} \tag{2.74}$$

with

$$\lambda_{\tilde{B}} = \sum_{t_2} N_{j1}^* \lambda_j^0\,, \qquad \tilde{W}^0 = \sum_{t_2} N_{j2}^* \lambda_j^0\,, \qquad \tilde{H}_d^0 = \sum_{t_2} N_{j3}^* \lambda_j^0 \tag{2.75}$$

$$\tilde{H}_u^0 = \sum_{t_2} N_{j4}^* \lambda_j^0 \tag{2.76}$$

- **Mass matrix for Charginos**, Basis: $\left(\tilde{W}^-, \tilde{H}_d^-\right), \left(\tilde{W}^+, \tilde{H}_u^+\right)$

$$m_{\tilde{\chi}^-} = \begin{pmatrix} M_2 & \frac{1}{\sqrt{2}}g_2 v_u \\ \frac{1}{\sqrt{2}}g_2 v_d & \mu \end{pmatrix} \tag{2.77}$$

This matrix is diagonalized by U and V

$$U^* m_{\tilde{\chi}^-} V^\dagger = m_{\tilde{\chi}^-}^{dia} \tag{2.78}$$

with

$$\tilde{W}^- = \sum_{t_2} U_{j1}^* \lambda_j^-\,, \qquad \tilde{H}_d^- = \sum_{t_2} U_{j2}^* \lambda_j^- \tag{2.79}$$

$$\tilde{W}^+ = \sum_{t_2} V_{1j}^* \lambda_j^+\,, \qquad \tilde{H}_u^+ = \sum_{t_2} V_{2j}^* \lambda_j^+ \tag{2.80}$$

2.4 Vacuum Expectation Values

$$H_d^0 = \frac{1}{\sqrt{2}}\phi_d + \frac{1}{\sqrt{2}}v_d + i\frac{1}{\sqrt{2}}\sigma_d \tag{2.81}$$

$$H_u^0 = \frac{1}{\sqrt{2}}\phi_u + \frac{1}{\sqrt{2}}v_u + i\frac{1}{\sqrt{2}}\sigma_u \tag{2.82}$$

2.5 Tadpole Equations

$$\frac{\partial V}{\partial v_d} = \frac{1}{8}\Big(8 v_d |\mu|^2 - 8 v_u \Re\Big(B_\mu\Big) + v_d \Big(8 m_{H_d}^2 + g_1^2 v_d^2 - g_1^2 v_u^2 + g_2^2 v_d^2 - g_2^2 v_u^2\Big)\Big) \tag{2.83}$$

$$\frac{\partial V}{\partial v_u} = \frac{1}{8}\Big(- 8 v_d \Re\Big(B_\mu\Big) + 8 v_u |\mu|^2 + v_u \Big(8 m_{H_u}^2 - g_1^2 v_d^2 + g_1^2 v_u^2 - g_2^2 v_d^2 + g_2^2 v_u^2\Big)\Big) \tag{2.84}$$

2.6 Particle content for eigenstates 'EWSB'

Name	Type	complex/real	Generations	Indices
$\tilde{\nu}_e$	Scalar	complex	1	
$\tilde{\nu}_\mu$	Scalar	complex	1	
$\tilde{\nu}_\tau$	Scalar	complex	1	
$\tilde{d}$	Scalar	complex	2	generation, color
$\tilde{u}$	Scalar	complex	2	generation, color
$\tilde{e}$	Scalar	complex	2	generation
$\tilde{\mu}$	Scalar	complex	2	generation
$\tilde{\tau}$	Scalar	complex	2	generation
$\tilde{s}$	Scalar	complex	2	generation, color
$\tilde{c}$	Scalar	complex	2	generation, color
$\tilde{b}$	Scalar	complex	2	generation, color
$\tilde{t}$	Scalar	complex	2	generation, color
h	Scalar	real	2	generation
A^0	Scalar	real	2	generation
H^-	Scalar	complex	2	generation
$\tilde{g}$	Fermion	Majorana	8	generation
d	Fermion	Dirac	1	color
s	Fermion	Dirac	1	color
b	Fermion	Dirac	1	color
u	Fermion	Dirac	1	color
c	Fermion	Dirac	1	color
t	Fermion	Dirac	1	color
ν_e	Fermion	Dirac	1	
ν_μ	Fermion	Dirac	1	
ν_τ	Fermion	Dirac	1	
e	Fermion	Dirac	1	
m	Fermion	Dirac	1	
τ	Fermion	Dirac	1	

$\tilde{\chi}^0$	Fermion	Majorana	4	generation
$\tilde{\chi}^-$	Fermion	Dirac	2	generation
g	Vector	real	8	generation, lorentz
W^-	Vector	complex	1	lorentz
γ	Vector	real	1	lorentz
Z	Vector	real	1	lorentz
η^G	Ghost	real	8	generation
η^-	Ghost	complex	1	
η^+	Ghost	complex	1	
η^γ	Ghost	real	1	
η^Z	Ghost	real	1	

2.7 Modelfile for SARAH

```
Off[General::spell]
Print["Model file for the MSSM loaded"];

ModelNameLaTeX ="MSSM";


(*-------------------------------------------*)
(*   Particle Content*)
(*-------------------------------------------*)

(* Gauge Superfields *)

Gauge[[1]]={B,   U[1], hypercharge, g1,False};
Gauge[[2]]={WB, SU[2], left,        g2,True};
Gauge[[3]]={G,  SU[3], color,       g3,False};


(* Chiral Superfields *)

Fields[[1]] = {{uL0,  dL0},  3, q,   1/6, 2, 3};
Fields[[2]] = {{vL0,  eL0},  3, l,  -1/2, 2, 1};
Fields[[3]] = {{Hd0, Hdm}, 1, Hd, -1/2, 2, 1};
Fields[[4]] = {{Hup, Hu0}, 1, Hu,  1/2, 2, 1};

Fields[[5]] = {conj[dR0], 3, d,  1/3, 1, -3};
Fields[[6]] = {conj[uR0], 3, u, -2/3, 1, -3};
Fields[[7]] = {conj[eR0], 3, e,    1, 1,  1};



(*-----------------------------------------------------*)
(* Superpotential *)
(*-----------------------------------------------------*)


SuperPotential = { {{1, Yu},{u,q,Hu}}, {{-1,Yd},{d,q,Hd}},
                   {{-1,Ye},{e,l,Hd}}, {{1,\[Mu]},{Hu,Hd}}  };


(*-------------------------------------------*)
(* Integrate Out or Delete Particles         *)
(*-------------------------------------------*)

IntegrateOut={};
```

```
DeleteParticles={};


(*--------------------------------------------------*)
(*   DEFINITION                                     *)
(*--------------------------------------------------*)

NameOfStates={GaugeES, EWSB};

(* ----- Before EWSB ----- *)


DEFINITION[GaugeES][GaugeFixing]=
{ {Der[VWB],  -1/(2 RXi[W])},
     {Der[VG],   -1/(2 RXi[G]) }};




(* ----- After EWSB ----- *)


(* Gauge Sector *)

DEFINITION[EWSB][GaugeSector]=
{{VWB,{1,{VWm,1/Sqrt[2]},{conj[VWm],1/Sqrt[2]}},
      {2,{VWm,-\[ImaginaryI]/Sqrt[2]},{conj[VWm],\[ImaginaryI]/Sqrt[2]}},
      {3,{VP,Sin[ThetaW]},{VZ,Cos[ThetaW]}}},
 {VB, {1,{VP,Cos[ThetaW]},{VZ,-Sin[ThetaW]}}},
 {fWB,{1,{fWm,1/Sqrt[2]},{fWp,1/Sqrt[2]}},
      {2,{fWm,-\[ImaginaryI]/Sqrt[2]},{fWp,\[ImaginaryI]/Sqrt[2]}},
      {3,{fW0,1}}}};




(* ----- VEVs ---- *)

DEFINITION[EWSB][VEVs]=
  {{SHd0, {vd, 1/Sqrt[2]}, {sigmad, \[ImaginaryI]/Sqrt[2]},{phid, \
1/Sqrt[2]}},
   {SHu0, {vu, 1/Sqrt[2]}, {sigmau, \[ImaginaryI]/Sqrt[2]},{phiu, \
1/Sqrt[2]}}};


(* ----- Flavors ---- *)

DEFINITION[EWSB][Flavors]=
{{FdR0,{FdR,FsR,FbR}},
```

```
 {FdL0,{FdL,FsL,FbL}},
 {FuL0,{FuL,FcL,FtL}},
 {FuR0,{FuR,FcR,FtR}},
 {FvL0,{FveL,FvmL,FvtL}},
 {SdR0,{SdR,SsR,SbR}},
 {SdL0,{SdL,SsL,SbL}},
 {SuL0,{SuL,ScL,StL}},
 {SuR0,{SuR,ScR,StR}},
 {FeL0,{FeL,FmL,FtauL}},
 {FeR0,{FeR,FmR,FtauR}},
 {SeR0,{SeR,SmR,StauR}},
 {SeL0,{SeL,SmL,StauL}},
 {SvL0,{SveL,SvmL,SvtL}}};

(* ---- Mixings ---- *)

DEFINITION[EWSB][MatterSector]=
{    {{SdL, SdR}, {Sd, ZD}},
     {{SuL, SuR}, {Su, ZU}},
     {{SeL, SeR}, {Se, ZE}},
     {{SmL, SmR}, {Sm, ZM}},
     {{StauL, StauR}, {Stau, ZTau}},
 {{SsL, SsR}, {Ss, ZS}},
     {{ScL, ScR}, {Sc, ZC}},
 {{SbL, SbR}, {Sb, ZB}},
     {{StL, StR}, {St, ZT}},
     {{phid, phiu}, {hh, ZH}},
     {{sigmad, sigmau}, {Ah, ZA}},
     {{SHdm,conj[SHup]},{Hpm,ZP}},
     {{fB, fW0, FHd0, FHu0}, {L0, ZN}},
     {{{fWm, FHdm}, {fWp, FHup}}, {{Lm,UM}, {Lp,UP}}}      \
       };

DEFINITION[EWSB][Phases]=
{    {fG, PhaseGlu}
    };


(*--- Gauge Fixing ---- *)

DEFINITION[EWSB][GaugeFixing]=
  { {Der[VP],                                          - 1/(2 RXi[P])},
{Der[VWm]+\[ImaginaryI] Mass[VWm] RXi[W] Hpm[{1}],   - 1/(RXi[W])},
{Der[VZ] - Mass[VZ] RXi[Z] Ah[{1}],                  - 1/(2 RXi[Z])},
{Der[VG],                                            - 1/(2 RXi[G])}};


(*------------------------------------------------------*)
```

```
(* Dirac-Spinors *)
(*------------------------------------------------------*)

dirac[[1]] = {Fd,  FdL, FdR};
dirac[[2]] = {Fb,  FbL, FbR};
dirac[[3]] = {Fs,  FsL, FsR};
dirac[[4]] = {Fc,  FcL, FcR};
dirac[[5]] = {Ft,  FtL, FtR};
dirac[[6]] = {Fm,  FmL, FmR};
dirac[[7]] = {Ftau,  FtauL, FtauR};
dirac[[8]] = {Fe,  FeL, FeR};
dirac[[9]] = {Fu,  FuL, FuR};
dirac[[10]] = {Fve,  FveL, 0};
dirac[[11]] = {Fvm,  FvmL, 0};
dirac[[12]] = {Fvt,  FvtL, 0};
dirac[[13]] = {Chi, L0, conj[L0]};
dirac[[14]] = {Cha, Lm, conj[Lp]};
dirac[[15]] = {Glu, fG, conj[fG]};
dirac[[16]] = {Bino, fB, conj[fB]};
dirac[[17]] = {Wino, fWB, conj[fWB]};
dirac[[18]] = {H0, FHd0, conj[FHu0]};
dirac[[19]] = {HC, FHdm, conj[FHup]};

dirac[[20]] = {Fd1, FdL0, 0};
dirac[[21]] = {Fd2, 0, FdR0};
dirac[[22]] = {Fu1, FuL0, 0};
dirac[[23]] = {Fu2, 0, FuR0};
dirac[[24]] = {Fe1, FeL0, 0};
dirac[[25]] = {Fe2, 0, FeR0};
dirac[[26]] = {Fv, FvL0,0};



(*------------------------------------------------------*)
(* Automatized Output        *)
(*------------------------------------------------------*)

(*
makeOutput = {
                   {EWSB, {TeX, FeynArts}}
             };
            *)

SpectrumFile=None;
```

2.8 Implementation in SARAH

Model directory: `MSSM/NoFV`

2.8.1 Particles for eigenstates 'GaugeES'

- Fermions

$$
\begin{array}{rr}
\tilde{B} = \begin{pmatrix} \lambda_{\tilde{B}} \\ \lambda^*_{\tilde{B}} \end{pmatrix} & \texttt{Bino} = \begin{pmatrix} \texttt{fB} \\ \texttt{conj[fB]} \end{pmatrix} \\
d^1_{i\alpha} = \begin{pmatrix} d_{L,i\alpha} \\ 0 \end{pmatrix} & \texttt{Fd1[\{generation, color\}]} = \begin{pmatrix} \texttt{FdL0[\{generation, color\}]} \\ 0 \end{pmatrix} \\
d^2_{i\alpha} = \begin{pmatrix} 0 \\ d_{R,i\alpha} \end{pmatrix} & \texttt{Fd2[\{generation, color\}]} = \begin{pmatrix} 0 \\ \texttt{FdR0[\{generation, color\}]} \end{pmatrix} \\
e^1_{i} = \begin{pmatrix} e_{L,i} \\ 0 \end{pmatrix} & \texttt{Fe1[\{generation\}]} = \begin{pmatrix} \texttt{FeL0[\{generation\}]} \\ 0 \end{pmatrix} \\
e^2_{i} = \begin{pmatrix} 0 \\ e_{R,i} \end{pmatrix} & \texttt{Fe2[\{generation\}]} = \begin{pmatrix} 0 \\ \texttt{FeR0[\{generation\}]} \end{pmatrix} \\
u^1_{i\alpha} = \begin{pmatrix} u_{L,i\alpha} \\ 0 \end{pmatrix} & \texttt{Fu1[\{generation, color\}]} = \begin{pmatrix} \texttt{FuL0[\{generation, color\}]} \\ 0 \end{pmatrix} \\
u^2_{i\alpha} = \begin{pmatrix} 0 \\ u_{R,i\alpha} \end{pmatrix} & \texttt{Fu2[\{generation, color\}]} = \begin{pmatrix} 0 \\ \texttt{FuR0[\{generation, color\}]} \end{pmatrix} \\
\nu_{i} = \begin{pmatrix} \nu_i \\ 0 \end{pmatrix} & \texttt{Fv[\{generation\}]} = \begin{pmatrix} \texttt{FvL0[\{generation\}]} \\ 0 \end{pmatrix} \\
\tilde{g}_{i} = \begin{pmatrix} \lambda_{\tilde{g},i} \\ \lambda^*_{\tilde{g},i} \end{pmatrix} & \texttt{Glu[\{generation\}]} = \begin{pmatrix} \texttt{fG[\{generation\}]} \\ \texttt{conj[fG[\{generation\}]]} \end{pmatrix} \\
\tilde{H}^0 = \begin{pmatrix} \tilde{H}^0_d \\ \tilde{H}^{0,*}_u \end{pmatrix} & \texttt{H0} = \begin{pmatrix} \texttt{FHd0} \\ \texttt{conj[FHu0]} \end{pmatrix} \\
\tilde{H}^- = \begin{pmatrix} \tilde{H}^-_d \\ \tilde{H}^{+,*}_u \end{pmatrix} & \texttt{HC} = \begin{pmatrix} \texttt{FHdm} \\ \texttt{conj[FHup]} \end{pmatrix} \\
\tilde{W}_{i} = \begin{pmatrix} \lambda_{\tilde{W},i} \\ \lambda^*_{\tilde{W},i} \end{pmatrix} & \texttt{Wino[\{generation\}]} = \begin{pmatrix} \texttt{fWB[\{generation\}]} \\ \texttt{conj[fWB[\{generation\}]]} \end{pmatrix}
\end{array}
$$

- Scalars

$\tilde{d}_{L,i\alpha}$	`SdL0[{generation, color}]`	$\tilde{u}_{L,i\alpha}$	`SuL0[{generation, color}]`
$\tilde{e}_{L,i}$	`SeL0[{generation}]`	$\tilde{\nu}_{L,i}$	`SvL0[{generation}]`
H_d^0	`SHd0`	H_d^-	`SHdm`
H_u^0	`SHu0`	H_u^+	`SHup`
$\tilde{d}_{R,i\alpha}$	`SdR0[{generation, color}]`	$\tilde{u}_{R,i\alpha}$	`SuR0[{generation, color}]`
$\tilde{e}_{R,i}$	`SeR0[{generation}]`		

- Vector Bosons

B_ρ	`VB[{lorentz}]`	$W^-_{i\rho}$	`VWB[{generation, lorentz}]`
$g_{i\rho}$	`VG[{generation, lorentz}]`		

- Ghosts

η^B	`gB`	$\mathrm{gWB}\left(\{\mathrm{gt1}\}\right)$	`gWB[{generation}]`
η^G_i	`gG[{generation}]`		

2.8.2 Particles for eigenstates 'EWSB'

- Fermions

$\tilde{\chi}_i^- = \begin{pmatrix} \lambda_i^- \\ \lambda_i^{+,*} \end{pmatrix}$	$\texttt{Cha[\{generation\}]} = \begin{pmatrix} \texttt{Lm[\{generation\}]} \\ \texttt{conj[Lp[\{generation\}]]} \end{pmatrix}$
$\tilde{\chi}_i^0 = \begin{pmatrix} \lambda_i^0 \\ \lambda_i^{0,*} \end{pmatrix}$	$\texttt{Chi[\{generation\}]} = \begin{pmatrix} \texttt{L0[\{generation\}]} \\ \texttt{conj[L0[\{generation\}]]} \end{pmatrix}$
$b_\alpha = \begin{pmatrix} b_{L,\alpha} \\ b_{R,\alpha} \end{pmatrix}$	$\texttt{Fb[\{color\}]} = \begin{pmatrix} \texttt{FbL[\{color\}]} \\ \texttt{FbR[\{color\}]} \end{pmatrix}$
$c_\alpha = \begin{pmatrix} c_{L,\alpha} \\ c_{R,\alpha} \end{pmatrix}$	$\texttt{Fc[\{color\}]} = \begin{pmatrix} \texttt{FcL[\{color\}]} \\ \texttt{FcR[\{color\}]} \end{pmatrix}$
$d_\alpha = \begin{pmatrix} d_{L,\alpha} \\ d_{R,\alpha} \end{pmatrix}$	$\texttt{Fd[\{color\}]} = \begin{pmatrix} \texttt{FdL[\{color\}]} \\ \texttt{FdR[\{color\}]} \end{pmatrix}$

$e = \begin{pmatrix} e_L \\ e_R \end{pmatrix}$	$\texttt{Fe} = \begin{pmatrix} \texttt{FeL} \\ \texttt{FeR} \end{pmatrix}$
$m = \begin{pmatrix} \mu_L \\ \mu_R \end{pmatrix}$	$\texttt{Fm} = \begin{pmatrix} \texttt{FmL} \\ \texttt{FmR} \end{pmatrix}$
$s_\alpha = \begin{pmatrix} s_{L,\alpha} \\ s_{R,\alpha} \end{pmatrix}$	$\texttt{Fs[\{color\}]} = \begin{pmatrix} \texttt{FsL[\{color\}]} \\ \texttt{FsR[\{color\}]} \end{pmatrix}$
$t_\alpha = \begin{pmatrix} t_{L,\alpha} \\ t_{R,\alpha} \end{pmatrix}$	$\texttt{Ft[\{color\}]} = \begin{pmatrix} \texttt{FtL[\{color\}]} \\ \texttt{FtR[\{color\}]} \end{pmatrix}$
$\tau = \begin{pmatrix} \tau_L \\ \tau_R \end{pmatrix}$	$\texttt{Ftau} = \begin{pmatrix} \texttt{FtauL} \\ \texttt{FtauR} \end{pmatrix}$
$u_\alpha = \begin{pmatrix} u_{L,\alpha} \\ u_{R,\alpha} \end{pmatrix}$	$\texttt{Fu[\{color\}]} = \begin{pmatrix} \texttt{FuL[\{color\}]} \\ \texttt{FuR[\{color\}]} \end{pmatrix}$
$\nu_e = \begin{pmatrix} \nu_e \\ 0 \end{pmatrix}$	$\texttt{Fve} = \begin{pmatrix} \texttt{FveL} \\ \texttt{0} \end{pmatrix}$
$\nu_\mu = \begin{pmatrix} \nu_\mu \\ 0 \end{pmatrix}$	$\texttt{Fvm} = \begin{pmatrix} \texttt{FvmL} \\ \texttt{0} \end{pmatrix}$
$\nu_\tau = \begin{pmatrix} \nu_\tau \\ 0 \end{pmatrix}$	$\texttt{Fvt} = \begin{pmatrix} \texttt{FvtL} \\ \texttt{0} \end{pmatrix}$
$\tilde{g}_i = \begin{pmatrix} \lambda_{\tilde{g},i} \\ \lambda^*_{\tilde{g},i} \end{pmatrix}$	$\texttt{Glu[\{generation\}]} = \begin{pmatrix} \texttt{fG[\{generation\}]} \\ \texttt{conj[fG[\{generation\}]]} \end{pmatrix}$

- Scalars

$\tilde{\nu}_e$	SveL	$\tilde{\nu}_\mu$	SvmL
$\tilde{\nu}_\tau$	SvtL	$\tilde{d}_{i\alpha}$	Sd[{generation, color}]
$\tilde{u}_{i\alpha}$	Su[{generation, color}]	$\tilde{e}_i$	Se[{generation}]
$\tilde{\mu}_i$	Sm[{generation}]	$\tilde{\tau}_i$	Stau[{generation}]
$\tilde{s}_{i\alpha}$	Ss[{generation, color}]	$\tilde{c}_{i\alpha}$	Sc[{generation, color}]
$\tilde{b}_{i\alpha}$	Sb[{generation, color}]	$\tilde{t}_{i\alpha}$	St[{generation, color}]
h_i	hh[{generation}]	A^0_i	Ah[{generation}]
H^-_i	Hpm[{generation}]		

- Vector Bosons

$g_{i\rho}$	`VG[{generation, lorentz}]`	W^-_ρ	`VWm[{lorentz}]`
γ_ρ	`VP[{lorentz}]`	Z_ρ	`VZ[{lorentz}]`

- Ghosts

η^G_i	`gG[{generation}]`	η^-	`gWm`
η^+	`gWmC`	η^γ	`gP`
η^Z	`gZ`		

2.8.3 Parameters

g_1	`g1`	g_2	`g2`	g_3	`g3`
Y_u	`Yu`	T_u	`T[Yu]`	Y_d	`Yd`
T_d	`T[Yd]`	Y_e	`Ye`	T_e	`T[Ye]`
μ	`\[Mu]`	B_μ	`B[\[Mu]]`	m_q^2	`mq2`
m_l^2	`ml2`	$m_{H_d}^2$	`mHd2`	$m_{H_u}^2$	`mHu2`
m_d^2	`md2`	m_u^2	`mu2`	m_e^2	`me2`
M_1	`MassB`	M_2	`MassWB`	M_3	`MassG`
v_d	`vd`	v_u	`vu`	Θ_W	`ThetaW`
$\phi_{\tilde{g}}$	`PhaseGlu`	Z^D	`ZD`	Z^U	`ZU`
Z^E	`ZE`	Z^μ	`ZM`	Z^τ	`ZTau`
Z^S	`ZS`	Z^C	`ZC`	Z^B	`ZB`
Z^T	`ZT`	Z^H	`ZH`	Z^A	`ZA`
Z^+	`ZP`	N	`ZN`	U	`UM`
V	`UP`	α	`\[Alpha]`	β	`\[Beta]`

Chapter 3

Minimal Supersymmetric Standard Model in SCKM basis

3.1 Superfields

3.1.1 Vector Superfields

SF	Spin $\frac{1}{2}$	Spin 1	$SU(N)$	Coupling	Name
$\hat{B}$	$\lambda_{\tilde{B}}$	B	$U(1)$	g_1	hypercharge
$\hat{W}$	$\lambda_{\tilde{W}}$	W^-	SU(2)	g_2	left
$\hat{g}$	$\lambda_{\tilde{g}}$	g	SU(3)	g_3	color

3.1.2 Chiral Superfields

SF	Spin 0	Spin $\frac{1}{2}$	Generations	$(U(1)\otimes$ SU(2) $\otimes$ SU(3))
$\hat{q}$	Sq0	Fq0	3	$(\frac{1}{6},\mathbf{2},\mathbf{3})$
$\hat{l}$	$\tilde{l}$	l	3	$(-\frac{1}{2},\mathbf{2},\mathbf{1})$
$\hat{H}_d$	H_d	$\tilde{H}_d$	1	$(-\frac{1}{2},\mathbf{2},\mathbf{1})$
$\hat{H}_u$	H_u	$\tilde{H}_u$	1	$(\frac{1}{2},\mathbf{2},\mathbf{1})$
$\hat{d}$	$\tilde{d}_R^{0,*}$	d_R^*	3	$(\frac{1}{3},\mathbf{1},\overline{\mathbf{3}})$
$\hat{u}$	$\tilde{u}_R^{0,*}$	u_R^*	3	$(-\frac{2}{3},\mathbf{1},\overline{\mathbf{3}})$
$\hat{e}$	$\tilde{e}_R^*$	e_R^*	3	$(1,\mathbf{1},\mathbf{1})$

3.2 Superpotential and Lagrangian

3.2.1 Superpotential

$$W = Y_u^0\,\hat{q}\,\hat{H}_u\,\hat{u}\, - Y_d^0\,\hat{q}\,\hat{H}_d\,\hat{d}\, - Y_e\,\hat{l}\,\hat{H}_d\,\hat{e}\, + \mu\,\hat{H}_u\,\hat{H}_d \tag{3.1}$$

3.2.2 Softbreaking terms

$$
\begin{aligned}
L_{SB,W} = & - H_d^0 H_u^0 B_\mu + H_d^- H_u^+ B_\mu + H_d^0 \tilde{d}_{R,k\gamma}^{0,*} \delta_{\alpha\gamma} \tilde{d}_{L,i\alpha}^0 T_{d,ik}^0 - H_d^- \tilde{d}_{R,k\gamma}^{0,*} \delta_{\alpha\gamma} \tilde{u}_{L,i\alpha}^0 T_{d,ik}^0 \\
& + H_d^0 \tilde{e}_{R,k}^* \tilde{e}_{L,i} T_{e,ik} - H_d^- \tilde{e}_{R,k}^* \tilde{\nu}_{L,i} T_{e,ik} - H_u^+ \tilde{u}_{R,k\gamma}^{0,*} \delta_{\alpha\gamma} \tilde{d}_{L,i\alpha}^0 T_{u,ik}^0 \\
& + H_u^0 \tilde{u}_{R,k\gamma}^{0,*} \delta_{\alpha\gamma} \tilde{u}_{L,i\alpha}^0 T_{u,ik}^0 + \text{h.c.} \qquad (3.2)\\
L_{SB,\phi} = & - m_{H_d}^2 |H_d^0|^2 - m_{H_d}^2 |H_d^-|^2 - m_{H_u}^2 |H_u^0|^2 - m_{H_u}^2 |H_u^+|^2 - \tilde{d}_{L,j\beta}^{0,*} \delta_{\alpha\beta} m_{\tilde{q},ij}^{0,2} \tilde{d}_{L,i\alpha}^0 \\
& - \tilde{d}_{R,i\alpha}^{0,*} \delta_{\alpha\beta} m_{\tilde{d},ij}^{0,2} \tilde{d}_{R,j\beta}^0 - \tilde{e}_{L,j}^* m_{l,ij}^2 \tilde{e}_{L,i} - \tilde{e}_{R,i}^* m_{e,ij}^2 \tilde{e}_{R,j} - \tilde{u}_{L,j\beta}^{0,*} \delta_{\alpha\beta} m_{\tilde{q},ij}^{0,2} \tilde{u}_{L,i\alpha}^0 \\
& - \tilde{u}_{R,i\alpha}^{0,*} \delta_{\alpha\beta} m_{\tilde{u},ij}^{0,2} \tilde{u}_{R,j\beta}^0 - \tilde{\nu}_{L,j}^* m_{l,ij}^2 \tilde{\nu}_{L,i} \qquad (3.3)\\
L_{SB,\lambda} = & \frac{1}{2}\Big(-\lambda_{\tilde{B}}^2 M_1 - M_2 \lambda_{\tilde{W},i}^2 - M_3 \lambda_{\tilde{g},i}^2 + \text{h.c.}\Big) \qquad (3.4)
\end{aligned}
$$

3.2.3 Gauge fixing terms

Gauge fixing terms for eigenstates 'GaugeES'

$$L_{GF} = -\frac{1}{2}\partial_\mu g \xi_G^{-1} - \frac{1}{2}\partial_\mu W^- \xi_W^{-1} \qquad (3.5)$$

Gauge fixing terms for eigenstates 'EWSB'

$$L_{GF} = -\frac{1}{2}\partial_\mu \gamma \xi_P^{-1} - \frac{1}{2}\partial_\mu g \xi_G^{-1} - \frac{1}{2}\xi_Z^{-1}\Big(- A_1^0 m_Z \xi_Z + \partial_\mu Z\Big) - \xi_W^{-1}\Big(iH_1^- m_{W^-} \xi_W + \partial_\mu W^-\Big) \qquad (3.6)$$

3.2.4 Fields integrated out

None

3.3 Field Rotations

3.3.1 Rotations in gauge sector for eigenstates 'EWSB'

$$
\begin{aligned}
W_{1\rho}^- &= \frac{1}{\sqrt{2}} W_\rho^- + \frac{1}{\sqrt{2}} W_\rho^+ && (3.7)\\
W_{2\rho}^- &= -i\frac{1}{\sqrt{2}} W_\rho^- + i\frac{1}{\sqrt{2}} W_\rho^+ && (3.8)\\
W_{3\rho}^- &= \cos\Theta_W Z_\rho + \sin\Theta_W \gamma_\rho && (3.9)\\
B_\rho &= \cos\Theta_W \gamma_\rho - \sin\Theta_W Z_\rho && (3.10)\\
\lambda_{\tilde{W},1} &= \frac{1}{\sqrt{2}} \tilde{W}^- + \frac{1}{\sqrt{2}} \tilde{W}^+ && (3.11)\\
\lambda_{\tilde{W},2} &= -i\frac{1}{\sqrt{2}} \tilde{W}^- + i\frac{1}{\sqrt{2}} \tilde{W}^+ && (3.12)\\
\lambda_{\tilde{W},3} &= \tilde{W}^0 && (3.13)
\end{aligned}
$$

3.3.2 Rotations in Mass sector for eigenstates 'EWSB'

Mass Matrices for Scalars

- **Mass matrix for Down-Squarks**, Basis: $\left(\tilde{d}_{L,o_1\alpha_1}, \tilde{d}_{R,o_2\alpha_2}\right), \left(\tilde{d}^*_{L,p_1\beta_1}, \tilde{d}^*_{R,p_2\beta_2}\right)$

$$m^2_{\tilde{d}} = \left(\begin{array}{cc} m_{11} & \frac{1}{\sqrt{2}} \delta_{\alpha_1\beta_2} \delta_{o_1p_2} \Big(v_d T_{d,o_1o_1} - v_u \mu^* Y_{d,o_1o_1}\Big) \\ \frac{1}{\sqrt{2}} \Big(v_d T^*_{d,o_2o_2} - v_u \mu Y^*_{d,o_2o_2}\Big) \delta_{\alpha_2\beta_1} \delta_{o_2p_1} & m_{22} \end{array} \right) \tag{3.14}$$

$$m_{11} = \frac{1}{24} \delta_{\alpha_1\beta_1} \delta_{o_1p_1} \Big(12 v_d^2 |Y_{d,o_1o_1}|^2 + 24 m^2_{q,o_1o_1} - \Big(3 g_2^2 + g_1^2\Big)\Big(- v_u^2 + v_d^2\Big)\Big) \tag{3.15}$$

$$m_{22} = \frac{1}{12} \delta_{\alpha_2\beta_2} \delta_{o_2p_2} \Big(12 m^2_{d,o_2o_2} + 6 v_d^2 |Y_{d,o_2o_2}|^2 + g_1^2 \Big(- v_d^2 + v_u^2\Big)\Big) \tag{3.16}$$

This matrix is diagonalized by Z^D:

$$Z^D m^2_{\tilde{d}} Z^{D,\dagger} = m^{dia}_{2,\tilde{d}} \tag{3.17}$$

with

$$\tilde{d}_{L,i\alpha} = \sum_{t_2} Z^{D,*}_{ji} \tilde{d}_{j\alpha}\,, \qquad \tilde{d}_{R,i\alpha} = \sum_{t_2} Z^{D,*}_{ji} \tilde{d}_{j\alpha} \tag{3.18}$$

- **Mass matrix for Up-Squarks**, Basis: $\left(\tilde{u}_{L,o_1\alpha_1}, \tilde{u}_{R,o_2\alpha_2}\right), \left(\tilde{u}^*_{L,p_1\beta_1}, \tilde{u}^*_{R,p_2\beta_2}\right)$

$$m^2_{\tilde{u}} = \left(\begin{array}{cc} m_{11} & \frac{1}{\sqrt{2}} \delta_{\alpha_1\beta_2} \delta_{o_1p_2} \Big(- v_d \mu^* Y_{u,o_1o_1} + v_u T_{u,o_1o_1}\Big) \\ \frac{1}{\sqrt{2}} \Big(- v_d \mu Y^*_{u,o_2o_2} + v_u T^*_{u,o_2o_2}\Big) \delta_{\alpha_2\beta_1} \delta_{o_2p_1} & m_{22} \end{array} \right) \tag{3.19}$$

$$m_{11} = \frac{1}{24} \delta_{\alpha_1\beta_1} \Big(\Big(12 v_u^2 |Y_{u,o_1o_1}|^2 - \Big(- 3 g_2^2 + g_1^2\Big)\Big(- v_u^2 + v_d^2\Big)\Big)\delta_{o_1p_1} + 24 \sum_{a=1}^{3} V^{CKM}_{o_1a} V^{CKM,*}_{p_1a} m^2_{q,aa}\Big) \tag{3.20}$$

$$m_{22} = \frac{1}{6} \delta_{\alpha_2\beta_2} \delta_{o_2p_2} \Big(3 v_u^2 |Y_{u,o_2o_2}|^2 + 6 m^2_{u,o_2o_2} + g_1^2 \Big(- v_u^2 + v_d^2\Big)\Big) \tag{3.21}$$

This matrix is diagonalized by Z^U:

$$Z^U m^2_{\tilde{u}} Z^{U,\dagger} = m^{dia}_{2,\tilde{u}} \tag{3.22}$$

with

$$\tilde{u}_{L,i\alpha} = \sum_{t_2} Z^{U,*}_{ji} \tilde{u}_{j\alpha}\,, \qquad \tilde{u}_{R,i\alpha} = \sum_{t_2} Z^{U,*}_{ji} \tilde{u}_{j\alpha} \tag{3.23}$$

- **Mass matrix for Sleptons**, Basis: $\left(\tilde{e}_{L,o_1}, \tilde{e}_{R,o_2}\right), \left(\tilde{e}^*_{L,p_1}, \tilde{e}^*_{R,p_2}\right)$

$$m^2_{\tilde{e}} = \left(\begin{array}{cc} m_{11} & \frac{1}{\sqrt{2}} \Big(v_d T_{e,o_1p_2} - v_u \mu^* Y_{e,o_1p_2}\Big) \\ \frac{1}{\sqrt{2}} \Big(v_d T^*_{e,p_1o_2} - v_u \mu Y^*_{e,p_1o_2}\Big) & m_{22} \end{array} \right) \tag{3.24}$$

$$m_{11} = \frac{1}{8}\Big(4v_d^2 \sum_{a=1}^{3} Y^*_{e,p_1 a} Y_{e,o_1 a} + 8 m^2_{l,o_1 p_1} + \Big(- g_2^2 + g_1^2\Big)\Big(- v_u^2 + v_d^2\Big)\delta_{o_1 p_1}\Big) \tag{3.25}$$

$$m_{22} = \frac{1}{4}\Big(2v_d^2 \sum_{a=1}^{3} Y^*_{e,a o_2} Y_{e,a p_2} + 4 m^2_{e,p_2 o_2} + g_1^2\Big(- v_d^2 + v_u^2\Big)\delta_{o_2 p_2}\Big) \tag{3.26}$$

This matrix is diagonalized by Z^E:

$$Z^E m^2_{\tilde{e}} Z^{E,\dagger} = m^{dia}_{2,\tilde{e}} \tag{3.27}$$

with

$$\tilde{e}_{L,i} = \sum_{t_2} Z^{E,*}_{ji} \tilde{e}_j \,, \qquad \tilde{e}_{R,i} = \sum_{t_2} Z^{E,*}_{ji} \tilde{e}_j \tag{3.28}$$

- **Mass matrix for Sneutrinos**, Basis: $\left(\tilde{\nu}_{L,o_1}\right), \left(\tilde{\nu}^*_{L,p_1}\right)$

$$m^2_{\tilde{\nu}} = \left(\begin{array}{c} \frac{1}{8}\Big(8 m^2_{l,o_1 p_1} + \Big(g_1^2 + g_2^2\Big)\Big(- v_u^2 + v_d^2\Big)\delta_{o_1 p_1}\Big) \end{array} \right) \tag{3.29}$$

This matrix is diagonalized by Z^V:

$$Z^V m^2_{\tilde{\nu}} Z^{V,\dagger} = m^{dia}_{2,\tilde{\nu}} \tag{3.30}$$

with

$$\tilde{\nu}_{L,i} = \sum_{t_2} Z^{V,*}_{ji} \tilde{\nu}_j \tag{3.31}$$

- **Mass matrix for Higgs**, Basis: $\left(\phi_d, \phi_u\right), \left(\phi_d, \phi_u\right)$

$$m^2_h = \left(\begin{array}{cc} \frac{1}{8}\Big(8 m^2_{H_d} + 8|\mu|^2 + \Big(g_1^2 + g_2^2\Big)\Big(3v_d^2 - v_u^2\Big)\Big) & \frac{1}{4}\Big(- 4\Re\Big(B_\mu\Big) - \Big(g_1^2 + g_2^2\Big) v_d v_u\Big) \\ \frac{1}{4}\Big(- 4\Re\Big(B_\mu\Big) - \Big(g_1^2 + g_2^2\Big) v_d v_u\Big) & \frac{1}{8}\Big(8 m^2_{H_u} + 8|\mu|^2 - \Big(g_1^2 + g_2^2\Big)\Big(- 3v_u^2 + v_d^2\Big)\Big) \end{array} \right) \tag{3.32}$$

This matrix is diagonalized by Z^H:

$$Z^H m^2_h Z^{H,\dagger} = m^{dia}_{2,h} \tag{3.33}$$

with

$$\phi_d = \sum_{t_2} Z^H_{j1} h_j \,, \qquad \phi_u = \sum_{t_2} Z^H_{j2} h_j \tag{3.34}$$

The mixing matrix can be parametrized by

$$Z^H = \left(\begin{array}{cc} -\sin\alpha & \cos\alpha \\ \cos\alpha & \sin\alpha \end{array} \right) \tag{3.35}$$

- **Mass matrix for Pseudo-Scalar Higgs**, Basis: $\left(\sigma_d, \sigma_u\right), \left(\sigma_d, \sigma_u\right)$

$$m^2_{A^0} = \left(\begin{array}{cc} \frac{1}{8}\Big(8 m_{H_d}^2 + 8 |\mu|^2 + \Big(g_{1}^{2} + g_{2}^{2}\Big)\Big(- v_{u}^{2} + v_{d}^{2}\Big)\Big) & \Re\Big(B_{\mu}\Big) \\ \Re\Big(B_{\mu}\Big) & \frac{1}{8}\Big(8 m_{H_u}^2 + 8 |\mu|^2 - \Big(g_{1}^{2} + g_{2}^{2}\Big)\Big(- v_{u}^{2} + v_{d}^{2}\Big)\Big) \end{array} \right) \tag{3.36}$$

This matrix is diagonalized by Z^A:

$$Z^A m^2_{A^0} Z^{A,\dagger} = m^{dia}_{2,A^0} \tag{3.37}$$

with

$$\sigma_{d} = \sum_{t_2}Z_{{j 1}}^{A}A^0_{{j}}\,, \qquad \sigma_{u} = \sum_{t_2}Z_{{j 2}}^{A}A^0_{{j}} \tag{3.38}$$

The mixing matrix can be parametrized by

$$Z^A = \left(\begin{array}{cc} -\cos\beta & \sin\beta \\ \sin\beta & \cos\beta \end{array} \right) \tag{3.39}$$

- **Mass matrix for Charged Higgs**, Basis: $\left(H_d^-, H_u^{+,*}\right), \left(H_d^{-,*}, H_u^+\right)$

$$m^2_{H^-} = \left(\begin{array}{cc} m_{11} & \frac{1}{4} g_{2}^{2} v_d v_u + B_{\mu} \\ \frac{1}{4} g_{2}^{2} v_d v_u + B_{\mu}^* & m_{22} \end{array} \right) \tag{3.40}$$

$$m_{11} = \frac{1}{8}\Big(8 m_{H_d}^2 + 8 |\mu|^2 + g_{1}^{2} v_{d}^{2} - g_{1}^{2} v_{u}^{2} + g_{2}^{2} v_{d}^{2} + g_{2}^{2} v_{u}^{2}\Big) \tag{3.41}$$

$$m_{22} = \frac{1}{8}\Big(8 m_{H_u}^2 + 8 |\mu|^2 - g_{1}^{2} v_{d}^{2} + g_{1}^{2} v_{u}^{2} + g_{2}^{2} v_{d}^{2} + g_{2}^{2} v_{u}^{2}\Big) \tag{3.42}$$

This matrix is diagonalized by Z^+:

$$Z^+ m^2_{H^-} Z^{+,\dagger} = m^{dia}_{2,H^-} \tag{3.43}$$

with

$$H_d^- = \sum_{t_2}Z_{{j 1}}^{+,*}H^-_{{j}}\,, \qquad H_u^+ = \sum_{t_2}Z_{{j 2}}^{+}H^+_{{j}} \tag{3.44}$$

The mixing matrix can be parametrized by

$$Z^+ = \left(\begin{array}{cc} -\cos\beta & \sin\beta \\ \sin\beta & \cos\beta \end{array} \right) \tag{3.45}$$

Mass Matrices for Fermions

- **Mass matrix for Neutralinos**, Basis: $\left(\lambda_{\tilde{B}}, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0\right), \left(\lambda_{\tilde{B}}, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0\right)$

$$m_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -\frac{1}{2} g_1 v_d & \frac{1}{2} g_1 v_u \\ 0 & M_2 & \frac{1}{2} g_2 v_d & -\frac{1}{2} g_2 v_u \\ -\frac{1}{2} g_1 v_d & \frac{1}{2} g_2 v_d & 0 & -\mu \\ \frac{1}{2} g_1 v_u & -\frac{1}{2} g_2 v_u & -\mu & 0 \end{pmatrix} \tag{3.46}$$

This matrix is diagonalized by N:

$$N m_{\tilde{\chi}^0} N^{\dagger} = m^{dia}_{\tilde{\chi}^0} \tag{3.47}$$

with

$$\lambda_{\tilde{B}} = \sum_{t_2} N^*_{j1} \lambda^0_j\,, \qquad \tilde{W}^0 = \sum_{t_2} N^*_{j2} \lambda^0_j\,, \qquad \tilde{H}^0_d = \sum_{t_2} N^*_{j3} \lambda^0_j \tag{3.48}$$

$$\tilde{H}^0_u = \sum_{t_2} N^*_{j4} \lambda^0_j \tag{3.49}$$

- **Mass matrix for Charginos**, Basis: $\left(\tilde{W}^-, \tilde{H}_d^-\right), \left(\tilde{W}^+, \tilde{H}_u^+\right)$

$$m_{\tilde{\chi}^-} = \begin{pmatrix} M_2 & \frac{1}{\sqrt{2}} g_2 v_u \\ \frac{1}{\sqrt{2}} g_2 v_d & \mu \end{pmatrix} \tag{3.50}$$

This matrix is diagonalized by U and V

$$U^* m_{\tilde{\chi}^-} V^{\dagger} = m^{dia}_{\tilde{\chi}^-} \tag{3.51}$$

with

$$\tilde{W}^- = \sum_{t_2} U^*_{j1} \lambda^-_j\,, \qquad \tilde{H}^-_d = \sum_{t_2} U^*_{j2} \lambda^-_j \tag{3.52}$$

$$\tilde{W}^+ = \sum_{t_2} V^*_{1j} \lambda^+_j\,, \qquad \tilde{H}^+_u = \sum_{t_2} V^*_{2j} \lambda^+_j \tag{3.53}$$

- **Mass matrix for Leptons**, Basis: $\left(e_{L,o_1}\right), \left(e^*_{R,p_1}\right)$

$$m_e = \begin{pmatrix} \frac{1}{\sqrt{2}} v_d Y_{e,o_1 p_1} \end{pmatrix} \tag{3.54}$$

This matrix is diagonalized by U^e_L and U^e_R

$$U^{e,*}_L m_e U^{e,\dagger}_R = m^{dia}_e \tag{3.55}$$

with

$$e_{L,i} = \sum_{t_2} U^{e,*}_{L,ji} E_{L,j} \tag{3.56}$$

$$e_{R,i} = \sum_{t_2} U^{e}_{R,ij} E^*_{R,j} \tag{3.57}$$

3.4 Vacuum Expectation Values

3.4.1 VEVs for eigenstates 'EWSB'

$$H_d^0 = \frac{1}{\sqrt{2}}\phi_d + \frac{1}{\sqrt{2}}v_d + i\frac{1}{\sqrt{2}}\sigma_d \tag{3.58}$$

$$H_u^0 = \frac{1}{\sqrt{2}}\phi_u + \frac{1}{\sqrt{2}}v_u + i\frac{1}{\sqrt{2}}\sigma_u \tag{3.59}$$

3.5 Tadpole Equations

3.5.1 Tadpole Equations for eigenstates 'SCKM'

$$\frac{\partial V}{\partial v_d} = \frac{1}{8}\Big(- 4 v_u \Big(B_{\mu} + B_{\mu}^*\Big) + \Big(g_{1}^{2} + g_{2}^{2}\Big)v_{d}^{3} + v_d \Big(8 m_{H_d}^2 + 8 |\mu|^2 - \Big(g_{1}^{2} + g_{2}^{2}\Big)v_{u}^{2}\Big)\Big) \tag{3.60}$$

$$\frac{\partial V}{\partial v_u} = \frac{1}{8}\Big(- 8 v_d \Re\Big(B_{\mu}\Big) + v_u \Big(8 m_{H_u}^2 + 8 |\mu|^2 - \Big(g_{1}^{2} + g_{2}^{2}\Big)\Big(- v_{u}^{2} + v_{d}^{2}\Big)\Big)\Big) \tag{3.61}$$

3.5.2 Tadpole Equations for eigenstates 'EWSB'

$$\frac{\partial V}{\partial v_d} = \frac{1}{8}\Big(8 v_d |\mu|^2 - 8 v_u \Re\Big(B_{\mu}\Big) + v_d \Big(8 m_{H_d}^2 + g_{1}^{2} v_{d}^{2} - g_{1}^{2} v_{u}^{2} + g_{2}^{2} v_{d}^{2} - g_{2}^{2} v_{u}^{2}\Big)\Big) \tag{3.62}$$

$$\frac{\partial V}{\partial v_u} = \frac{1}{8}\Big(- 8 v_d \Re\Big(B_{\mu}\Big) + 8 v_u |\mu|^2 + v_u \Big(8 m_{H_u}^2 - g_{1}^{2} v_{d}^{2} + g_{1}^{2} v_{u}^{2} - g_{2}^{2} v_{d}^{2} + g_{2}^{2} v_{u}^{2}\Big)\Big) \tag{3.63}$$

3.6 Particle content for eigenstates 'EWSB'

Name	Type	complex/real	Generations	Indices
$\tilde{d}$	Scalar	complex	6	generation, color
$\tilde{u}$	Scalar	complex	6	generation, color
$\tilde{e}$	Scalar	complex	6	generation
$\tilde{\nu}$	Scalar	complex	3	generation
h	Scalar	real	2	generation
A^0	Scalar	real	2	generation
H^-	Scalar	complex	2	generation
ν	Fermion	Dirac	3	generation
$\tilde{g}$	Fermion	Majorana	8	generation
d	Fermion	Dirac	3	generation, color
u	Fermion	Dirac	3	generation, color
$\tilde{\chi}^0$	Fermion	Majorana	4	generation
$\tilde{\chi}^-$	Fermion	Dirac	2	generation

e	Fermion	Dirac	3	generation
g	Vector	real	8	generation, lorentz
W^-	Vector	complex	1	lorentz
γ	Vector	real	1	lorentz
Z	Vector	real	1	lorentz
η^G	Ghost	real	8	generation
η^-	Ghost	complex	1	
η^+	Ghost	complex	1	
η^γ	Ghost	real	1	
η^Z	Ghost	real	1	

3.7 Modelfile for SARAH

```
Off[General::spell]
Print["Model file for the MSSM (CKM) loaded"];

ModelNameLaTeX ="MSSM (CKM)";


(*-------------------------------------------*)
(*   Particle Content*)
(*-------------------------------------------*)

(* Gauge Superfields *)

Gauge[[1]]={B,   U[1], hypercharge, g1,False};
Gauge[[2]]={WB, SU[2], left,        g2,True};
Gauge[[3]]={G,  SU[3], color,       g3,False};


(* Chiral Superfields *)

Fields[[1]] = {{uL0,  dL0},  3, q0,   1/6, 2, 3};
Fields[[2]] = {{vL,  eL},  3, l,  -1/2, 2, 1};
Fields[[3]] = {{Hd0, Hdm}, 1, Hd, -1/2, 2, 1};
Fields[[4]] = {{Hup, Hu0}, 1, Hu,  1/2, 2, 1};

Fields[[5]] = {conj[dR0], 3, d0,  1/3, 1, -3};
Fields[[6]] = {conj[uR0], 3, u0, -2/3, 1, -3};
Fields[[7]] = {conj[eR], 3, e,    1, 1,  1};

(*-----------------------------------------------------*)
(* Superpotential *)
(*-----------------------------------------------------*)

SuperPotential = { {{1, Yu0},{q0,Hu,u0}}, {{-1,Yd0},{q0,Hd,d0}},
                   {{-1,Ye},{l,Hd,e}}, {{1,\[Mu]},{Hu,Hd}}  };

(*-------------------------------------------*)
(* Integrate Out or Delete Particles         *)
(*-------------------------------------------*)

IntegrateOut={};
DeleteParticles={};
```

```
(*-----------------------------------------------*)
(*   DEFINITION                                   *)
(*-----------------------------------------------*)

NameOfStates={GaugeES,SCKM, EWSB};

DEFINITION[GaugeES][GaugeFixing]=
{ {Der[VWB],  -1/(2 RXi[W])},
     {Der[VG],   -1/(2 RXi[G]) }};


(*--- Matter Sector ---- *)


DEFINITION[SCKM][MatterSector]=
    {{{SdL0}, {SdL, Vd}},
     {{SuL0}, {SuL, Vu}},
     {{SdR0}, {SdR, Ud}},
     {{SuR0}, {SuR, Uu}},
     {{AdL0}, {AdL, Vd}},
     {{AuL0}, {AuL, Vu}},
     {{AdR0}, {AdR, Ud}},
     {{AuR0}, {AuR, Uu}},
     {{{FdL0}, {FdR0}}, {{FdL,Vd}, {FdR,Ud}}},
     {{{FuL0}, {FuR0}}, {{FuL,Vu}, {FuR,Uu}}}};



(*--- Gauge Sector ---- *)


DEFINITION[EWSB][GaugeSector]=
{ {VWB, {1,{VWm,1/Sqrt[2]},{conj[VWm],1/Sqrt[2]}},
        {2,{VWm,-\[ImaginaryI]/Sqrt[2]},{conj[VWm],\[ImaginaryI]/Sqrt[2]}},
        {3,{VP, Sin[ThetaW]},{VZ, Cos[ThetaW]}}},
  {VB,  {1,{VP, Cos[ThetaW]},{VZ,-Sin[ThetaW]}}},
  {fWB, {1,{fWm,1/Sqrt[2]}, {fWp,1/Sqrt[2]}},
        {2,{fWm,-\[ImaginaryI]/Sqrt[2]},{fWp,\[ImaginaryI]/Sqrt[2]}},
        {3,{fW0,1}}}                                                  \
      };




(*--- VEVs ---- *)
```

```
DEFINITION[EWSB][VEVs]=
{    {SHd0, {vd, 1/Sqrt[2]}, {sigmad, \[ImaginaryI]/Sqrt[2]},{phid, \
1/Sqrt[2]}},
     {SHu0, {vu, 1/Sqrt[2]}, {sigmau, \[ImaginaryI]/Sqrt[2]},{phiu, \
1/Sqrt[2]}}     };



(*--- Matter Sector ---- *)


DEFINITION[EWSB][MatterSector]=
{    {{SdL, SdR}, {Sd, ZD}},
     {{SuL, SuR}, {Su, ZU}},
     {{SeL, SeR}, {Se, ZE}},
     {{SvL}, {Sv, ZV}},
     {{phid, phiu}, {hh, ZH}},
     {{sigmad, sigmau}, {Ah, ZA}},
     {{SHdm,conj[SHup]},{Hpm,ZP}},
     {{fB, fW0, FHd0, FHu0}, {L0, ZN}},
     {{{fWm, FHdm}, {fWp, FHup}}, {{Lm,UM}, {Lp,UP}}},
     {{{FeL},{conj[FeR]}},{{FEL,ZEL},{FER,ZER}}}
       };


(*--- Gauge Fixing ---- *)


DEFINITION[EWSB][GaugeFixing]=
  { {Der[VP],                                          - 1/(2 RXi[P])},
{Der[VWm]+\[ImaginaryI] Mass[VWm] RXi[W] Hpm[{1}],   - 1/(RXi[W])},
{Der[VZ] - Mass[VZ] RXi[Z] Ah[{1}],                  - 1/(2 RXi[Z])},
{Der[VG],                                            - 1/(2 RXi[G])}};

DEFINITION[EWSB][Phases]=
{    {fG, PhaseGlu}
    };

(*-------------------------------------------------------*)
(* Dirac-Spinors *)
(*-------------------------------------------------------*)

dirac[[1]] = {Fd,  FdL, FdR};
dirac[[2]] = {Fe,  FEL, conj[FER]};
dirac[[3]] = {Fu,  FuL, FuR};
dirac[[4]] = {Fv,  FvL, 0};
dirac[[5]] = {Chi, L0, conj[L0]};
dirac[[6]] = {Cha, Lm, conj[Lp]};
```

```
dirac[[7]] = {Glu, fG, conj[fG]};

(* Unbroken EW *)

dirac[[8]] = {Bino, fB, conj[fB]};
dirac[[9]] = {Wino, fWB, conj[fWB]};
dirac[[10]] = {H0, FHd0, conj[FHu0]};
dirac[[11]] = {HC, FHdm, conj[FHup]};
dirac[[12]] = {Fd1, FdL0, 0};
dirac[[13]] = {Fd2, 0, FdR0};
dirac[[14]] = {Fu1, FuL0, 0};
dirac[[15]] = {Fu2, 0, FuR0};
dirac[[16]] = {Fe1, FeL, 0};
dirac[[17]] = {Fe2, 0, FeR};



(*----------------------------------------------------*)
(* Automatized Output        *)
(*----------------------------------------------------*)

(*
makeOutput = {
                    {EWSB, {TeX, FeynArts}}
             };
            *)

SpectrumFile= None;
```

3.8 Implementation in SARAH

Model directory: MSSM/CKM

3.8.1 Particles for eigenstates 'GaugeES'

- Fermions

$\tilde{B} = \begin{pmatrix} \lambda_{\tilde{B}} \\ \lambda^*_{\tilde{B}} \end{pmatrix}$	$\texttt{Bino} = \begin{pmatrix} \texttt{fB} \\ \texttt{conj[fB]} \end{pmatrix}$
$d^1_{i\alpha} = \begin{pmatrix} d_{L,i\alpha} \\ 0 \end{pmatrix}$	$\texttt{Fd1[\{generation, color\}]} = \begin{pmatrix} \texttt{FdL0[\{generation, color\}]} \\ 0 \end{pmatrix}$

$d^2_{i\alpha} = \begin{pmatrix} 0 \\ d_{R,i\alpha} \end{pmatrix}$	$\texttt{Fd2[\{generation, color\}]} = \begin{pmatrix} \texttt{0} \\ \texttt{FdR0[\{generation, color\}]} \end{pmatrix}$
$e^1_i = \begin{pmatrix} e_{L,i} \\ 0 \end{pmatrix}$	$\texttt{Fe1[\{generation\}]} = \begin{pmatrix} \texttt{FeL[\{generation\}]} \\ \texttt{0} \end{pmatrix}$
$e^2_i = \begin{pmatrix} 0 \\ e_{R,i} \end{pmatrix}$	$\texttt{Fe2[\{generation\}]} = \begin{pmatrix} \texttt{0} \\ \texttt{FeR[\{generation\}]} \end{pmatrix}$
$u^1_{i\alpha} = \begin{pmatrix} u_{L,i\alpha} \\ 0 \end{pmatrix}$	$\texttt{Fu1[\{generation, color\}]} = \begin{pmatrix} \texttt{FuL0[\{generation, color\}]} \\ \texttt{0} \end{pmatrix}$
$u^2_{i\alpha} = \begin{pmatrix} 0 \\ u_{R,i\alpha} \end{pmatrix}$	$\texttt{Fu2[\{generation, color\}]} = \begin{pmatrix} \texttt{0} \\ \texttt{FuR0[\{generation, color\}]} \end{pmatrix}$
$\nu_i = \begin{pmatrix} \nu_{L,i} \\ 0 \end{pmatrix}$	$\texttt{Fv[\{generation\}]} = \begin{pmatrix} \texttt{FvL[\{generation\}]} \\ \texttt{0} \end{pmatrix}$
$\tilde{g}_i = \begin{pmatrix} \lambda_{\tilde{g},i} \\ \lambda^*_{\tilde{g},i} \end{pmatrix}$	$\texttt{Glu[\{generation\}]} = \begin{pmatrix} \texttt{fG[\{generation\}]} \\ \texttt{conj[fG[\{generation\}]]} \end{pmatrix}$
$\tilde{H}^0 = \begin{pmatrix} \tilde{H}^0_d \\ \tilde{H}^{0,*}_u \end{pmatrix}$	$\texttt{H0} = \begin{pmatrix} \texttt{FHd0} \\ \texttt{conj[FHu0]} \end{pmatrix}$
$\tilde{H}^- = \begin{pmatrix} \tilde{H}^-_d \\ \tilde{H}^{+,*}_u \end{pmatrix}$	$\texttt{HC} = \begin{pmatrix} \texttt{FHdm} \\ \texttt{conj[FHup]} \end{pmatrix}$
$\tilde{W}_i = \begin{pmatrix} \lambda_{\tilde{W},i} \\ \lambda^*_{\tilde{W},i} \end{pmatrix}$	$\texttt{Wino[\{generation\}]} = \begin{pmatrix} \texttt{fWB[\{generation\}]} \\ \texttt{conj[fWB[\{generation\}]]} \end{pmatrix}$

- Scalars

$\tilde{d}^0_{L,i\alpha}$	SdL0[{generation, color}]	$\tilde{u}^0_{L,i\alpha}$	SuL0[{generation, color}]
$\tilde{e}_{L,i}$	SeL[{generation}]	$\tilde{\nu}_{L,i}$	SvL[{generation}]
H^0_d	SHd0	H^-_d	SHdm
H^0_u	SHu0	H^+_u	SHup
$\tilde{d}^0_{R,i\alpha}$	SdR0[{generation, color}]	$\tilde{u}^0_{R,i\alpha}$	SuR0[{generation, color}]
$\tilde{e}_{R,i}$	SeR[{generation}]		

- Vector Bosons

B_ρ	`VB[{lorentz}]`	$W^-_{i\rho}$	`VWB[{generation, lorentz}]`
$g_{i\rho}$	`VG[{generation, lorentz}]`		

- Ghosts

η^B	`gB`	$\mathrm{gWB}\left(\{\mathrm{gt1}\}\right)$	`gWB[{generation}]`
η^G_i	`gG[{generation}]`		

3.8.2 Particles for eigenstates 'SCKM'

- Fermions

$\tilde{B} = \begin{pmatrix} \lambda_{\tilde{B}} \\ \lambda^*_{\tilde{B}} \end{pmatrix}$	$\texttt{Bino} = \begin{pmatrix} \texttt{fB} \\ \texttt{conj[fB]} \end{pmatrix}$
$d_{i\alpha} = \begin{pmatrix} D_{L,i\alpha} \\ D_{R,i\alpha} \end{pmatrix}$	$\texttt{Fd[\{generation, color\}]} = \begin{pmatrix} \texttt{FdL[\{generation, color\}]} \\ \texttt{FdR[\{generation, color\}]} \end{pmatrix}$
$e^1_i = \begin{pmatrix} e_{L,i} \\ 0 \end{pmatrix}$	$\texttt{Fe1[\{generation\}]} = \begin{pmatrix} \texttt{FeL[\{generation\}]} \\ 0 \end{pmatrix}$
$e^2_i = \begin{pmatrix} 0 \\ e_{R,i} \end{pmatrix}$	$\texttt{Fe2[\{generation\}]} = \begin{pmatrix} 0 \\ \texttt{FeR[\{generation\}]} \end{pmatrix}$
$u_{i\alpha} = \begin{pmatrix} U_{L,i\alpha} \\ U_{R,i\alpha} \end{pmatrix}$	$\texttt{Fu[\{generation, color\}]} = \begin{pmatrix} \texttt{FuL[\{generation, color\}]} \\ \texttt{FuR[\{generation, color\}]} \end{pmatrix}$
$\nu_i = \begin{pmatrix} \nu_{L,i} \\ 0 \end{pmatrix}$	$\texttt{Fv[\{generation\}]} = \begin{pmatrix} \texttt{FvL[\{generation\}]} \\ 0 \end{pmatrix}$
$\tilde{g}_i = \begin{pmatrix} \lambda_{\tilde{g},i} \\ \lambda^*_{\tilde{g},i} \end{pmatrix}$	$\texttt{Glu[\{generation\}]} = \begin{pmatrix} \texttt{fG[\{generation\}]} \\ \texttt{conj[fG[\{generation\}]]} \end{pmatrix}$
$\tilde{H}^0 = \begin{pmatrix} \tilde{H}^0_d \\ \tilde{H}^{0,*}_u \end{pmatrix}$	$\texttt{H0} = \begin{pmatrix} \texttt{FHd0} \\ \texttt{conj[FHu0]} \end{pmatrix}$
$\tilde{H}^- = \begin{pmatrix} \tilde{H}^-_d \\ \tilde{H}^{+,*}_u \end{pmatrix}$	$\texttt{HC} = \begin{pmatrix} \texttt{FHdm} \\ \texttt{conj[FHup]} \end{pmatrix}$
$\tilde{W}_i = \begin{pmatrix} \lambda_{\tilde{W},i} \\ \lambda^*_{\tilde{W},i} \end{pmatrix}$	$\texttt{Wino[\{generation\}]} = \begin{pmatrix} \texttt{fWB[\{generation\}]} \\ \texttt{conj[fWB[\{generation\}]]} \end{pmatrix}$

- Scalars

$\tilde{e}_{L,i}$	`SeL[{generation}]`	$\tilde{\nu}_{L,i}$	`SvL[{generation}]`
H_d^0	`SHd0`	H_d^-	`SHdm`
H_u^0	`SHu0`	H_u^+	`SHup`
$\tilde{e}_{R,i}$	`SeR[{generation}]`	$\tilde{d}_{L,i\alpha}$	`SdL[{generation, color}]`
$\tilde{u}_{L,i\alpha}$	`SuL[{generation, color}]`	$\tilde{d}_{R,i\alpha}$	`SdR[{generation, color}]`
$\tilde{u}_{R,i\alpha}$	`SuR[{generation, color}]`		

- Vector Bosons

B_ρ	`VB[{lorentz}]`	$W_{i\rho}^-$	`VWB[{generation, lorentz}]`
$g_{i\rho}$	`VG[{generation, lorentz}]`		

- Ghosts

η^B	`gB`	$\mathrm{gWB}\Big(\{\mathrm{gt1}\}\Big)$	`gWB[{generation}]`
η_i^G	`gG[{generation}]`		

3.8.3 Particles for eigenstates 'EWSB'

- Fermions

$\tilde{\chi}_i^- = \begin{pmatrix} \lambda_i^- \\ \lambda_i^{+,*} \end{pmatrix}$	`Cha[{generation}]` $= \begin{pmatrix} \texttt{Lm[\{generation\}]} \\ \texttt{conj[Lp[\{generation\}]]} \end{pmatrix}$
$\tilde{\chi}_i^0 = \begin{pmatrix} \lambda_i^0 \\ \lambda_i^{0,*} \end{pmatrix}$	`Chi[{generation}]` $= \begin{pmatrix} \texttt{L0[\{generation\}]} \\ \texttt{conj[L0[\{generation\}]]} \end{pmatrix}$
$d_{i\alpha} = \begin{pmatrix} D_{L,i\alpha} \\ D_{R,i\alpha} \end{pmatrix}$	`Fd[{generation, color}]` $= \begin{pmatrix} \texttt{FdL[\{generation, color\}]} \\ \texttt{FdR[\{generation, color\}]} \end{pmatrix}$

$e_i = \begin{pmatrix} E_{L,i} \\ E^*_{R,i} \end{pmatrix}$	`Fe[{generation}]` $= \begin{pmatrix} \texttt{FEL[\{generation\}]} \\ \texttt{conj[FER[\{generation\}]]} \end{pmatrix}$
$u_{i\alpha} = \begin{pmatrix} U_{L,i\alpha} \\ U_{R,i\alpha} \end{pmatrix}$	`Fu[{generation, color}]` $= \begin{pmatrix} \texttt{FuL[\{generation, color\}]} \\ \texttt{FuR[\{generation, color\}]} \end{pmatrix}$
$\nu_i = \begin{pmatrix} \nu_{L,i} \\ 0 \end{pmatrix}$	`Fv[{generation}]` $= \begin{pmatrix} \texttt{FvL[\{generation\}]} \\ \texttt{0} \end{pmatrix}$
$\tilde{g}_i = \begin{pmatrix} \lambda_{\tilde{g},i} \\ \lambda^*_{\tilde{g},i} \end{pmatrix}$	`Glu[{generation}]` $= \begin{pmatrix} \texttt{fG[\{generation\}]} \\ \texttt{conj[fG[\{generation\}]]} \end{pmatrix}$

- Scalars

$\tilde{d}_{i\alpha}$	`Sd[{generation, color}]`	$\tilde{u}_{i\alpha}$	`Su[{generation, color}]`
$\tilde{e}_i$	`Se[{generation}]`	$\tilde{\nu}_i$	`Sv[{generation}]`
h_i	`hh[{generation}]`	A^0_i	`Ah[{generation}]`
H^-_i	`Hpm[{generation}]`		

- Vector Bosons

$g_{i\rho}$	`VG[{generation, lorentz}]`	W^-_ρ	`VWm[{lorentz}]`
γ_ρ	`VP[{lorentz}]`	Z_ρ	`VZ[{lorentz}]`

- Ghosts

η^G_i	`gG[{generation}]`	η^-	`gWm`
η^+	`gWmC`	η^γ	`gP`
η^Z	`gZ`		

3.8.4 Parameters

g_1	g1	g_2	g2	g_3	g3
Y_u^0	Yu0	T_u^0	T[Yu0]	Y_d^0	Yd0
T_d^0	T[Yd0]	Y_e	Ye	T_e	T[Ye]
μ	\[Mu]	B_μ	B[\[Mu]]	$m_{\tilde{q}}^{0,2}$	mq02
m_l^2	ml2	$m_{H_d}^2$	mHd2	$m_{H_u}^2$	mHu2
$m_{\tilde{d}}^{0,2}$	md02	$m_{\tilde{u}}^{0,2}$	mu02	m_e^2	me2
M_1	MassB	M_2	MassWB	M_3	MassG
V_d	Vd	V_u	Vu	U_d	Ud
U_u	Uu	v_d	vd	v_u	vu
Θ_W	ThetaW	$\phi_{\tilde{g}}$	PhaseGlu	Z^D	ZD
Z^U	ZU	Z^E	ZE	Z^V	ZV
Z^H	ZH	Z^A	ZA	Z^+	ZP
N	ZN	U	UM	V	UP
U_L^e	ZEL	U_R^e	ZER	α	\[Alpha]
β	\[Beta]	V^{CKM}	CKM	Y_u	Yu
Y_d	Yd	T_d	T[Yd]	T_u	T[Yu]
m_q^2	mq2	m_u^2	mu2	m_d^2	md2

Chapter 4

Minimal Supersymmetric Standard Model with CP violation

4.1 Superfields

4.1.1 Vector Superfields

SF	Spin $\frac{1}{2}$	Spin 1	$SU(N)$	Coupling	Name
$\hat{B}$	$\lambda_{\tilde{B}}$	B	$U(1)$	g_1	hypercharge
$\hat{W}$	$\lambda_{\tilde{W}}$	W^-	SU(2)	g_2	left
$\hat{g}$	$\lambda_{\tilde{g}}$	g	SU(3)	g_3	color

4.1.2 Chiral Superfields

SF	Spin 0	Spin $\frac{1}{2}$	Generations	$(U(1)\otimes$ SU(2) $\otimes$ SU(3)$)$
$\hat{q}$	$\tilde{q}$	q	3	$(\frac{1}{6},\mathbf{2},\mathbf{3})$
$\hat{l}$	$\tilde{l}$	l	3	$(-\frac{1}{2},\mathbf{2},\mathbf{1})$
$\hat{H}_d$	H_d	$\tilde{H}_d$	1	$(-\frac{1}{2},\mathbf{2},\mathbf{1})$
$\hat{H}_u$	H_u	$\tilde{H}_u$	1	$(\frac{1}{2},\mathbf{2},\mathbf{1})$
$\hat{d}$	$\tilde{d}_R^*$	d_R^*	3	$(\frac{1}{3},\mathbf{1},\overline{\mathbf{3}})$
$\hat{u}$	$\tilde{u}_R^*$	u_R^*	3	$(-\frac{2}{3},\mathbf{1},\overline{\mathbf{3}})$
$\hat{e}$	$\tilde{e}_R^*$	e_R^*	3	$(1,\mathbf{1},\mathbf{1})$

4.2 Superpotential and Lagrangian

4.2.1 Superpotential

$$W = Y_u\,\hat{u}\,\hat{q}\,\hat{H}_u\,-Y_d\,\hat{d}\,\hat{q}\,\hat{H}_d\,-Y_e\,\hat{e}\,\hat{l}\,\hat{H}_d\,+\mu\,\hat{H}_u\,\hat{H}_d \tag{4.1}$$

4.2.2 Softbreaking terms

$$\begin{aligned}
L_{SB,W} =& - H_d^0 H_u^0 B_\mu + H_d^- H_u^+ B_\mu + H_d^0 \tilde{d}^*_{R,i\alpha} \delta_{\alpha\beta} \tilde{d}_{L,j\beta} T_{d,ij} - H_d^- \tilde{d}^*_{R,i\alpha} \delta_{\alpha\beta} \tilde{u}_{L,j\beta} T_{d,ij} \\
&+ H_d^0 \tilde{e}^*_{R,i} \tilde{e}_{L,j} T_{e,ij} - H_d^- \tilde{e}^*_{R,i} \tilde{\nu}_{L,j} T_{e,ij} - H_u^+ \tilde{u}^*_{R,i\alpha} \delta_{\alpha\beta} \tilde{d}_{L,j\beta} T_{u,ij} + H_u^0 \tilde{u}^*_{R,i\alpha} \delta_{\alpha\beta} \tilde{u}_{L,j\beta} T_{u,ij} + \text{h.c.} \qquad (4.2)
\end{aligned}$$

$$\begin{aligned}
L_{SB,\phi} =& - m_{H_d}^2 |H_d^0|^2 - m_{H_d}^2 |H_d^-|^2 - m_{H_u}^2 |H_u^0|^2 - m_{H_u}^2 |H_u^+|^2 - \tilde{d}^*_{L,j\beta} \delta_{\alpha\beta} m^2_{q,ij} \tilde{d}_{L,i\alpha} \\
&- \tilde{d}^*_{R,i\alpha} \delta_{\alpha\beta} m^2_{d,ij} \tilde{d}_{R,j\beta} - \tilde{e}^*_{L,j} m^2_{l,ij} \tilde{e}_{L,i} - \tilde{e}^*_{R,i} m^2_{e,ij} \tilde{e}_{R,j} - \tilde{u}^*_{L,j\beta} \delta_{\alpha\beta} m^2_{q,ij} \tilde{u}_{L,i\alpha} \\
&- \tilde{u}^*_{R,i\alpha} \delta_{\alpha\beta} m^2_{u,ij} \tilde{u}_{R,j\beta} - \tilde{\nu}^*_{L,j} m^2_{l,ij} \tilde{\nu}_{L,i} \qquad (4.3)
\end{aligned}$$

$$L_{SB,\lambda} = \frac{1}{2}\Big(-\lambda_{\tilde{B}}^2 M_1 - M_2 \lambda_{\tilde{W},i}^2 - M_3 \lambda_{\tilde{g},i}^2 + \text{h.c.}\Big) \qquad (4.4)$$

4.2.3 Gauge fixing terms

Gauge fixing terms for eigenstates 'GaugeES'

$$L_{GF} = -\frac{1}{2}\partial_\mu g \xi_G^{-1} - \frac{1}{2}\partial_\mu W^- \xi_W^{-1} \qquad (4.5)$$

Gauge fixing terms for eigenstates 'EWSB'

$$L_{GF} = -\frac{1}{2}\partial_\mu \gamma \xi_P^{-1} - \frac{1}{2}\partial_\mu g \xi_G^{-1} - \frac{1}{2}\xi_Z^{-1}\Big(-h_1 m_Z \xi_Z + \partial_\mu Z\Big) - \xi_W^{-1}\Big(i H_1^- m_{W^-} \xi_W + \partial_\mu W^-\Big) \qquad (4.6)$$

4.2.4 Fields integrated out

None

4.3 Field Rotations

4.3.1 Rotations in gauge sector for eigenstates 'EWSB'

$$W^-_{1\rho} = \frac{1}{\sqrt{2}} W^-_\rho + \frac{1}{\sqrt{2}} W^+_\rho \qquad (4.7)$$

$$W^-_{2\rho} = -i\frac{1}{\sqrt{2}} W^-_\rho + i\frac{1}{\sqrt{2}} W^+_\rho \qquad (4.8)$$

$$W^-_{3\rho} = \cos\Theta_W Z_\rho + \sin\Theta_W \gamma_\rho \qquad (4.9)$$

$$B_\rho = \cos\Theta_W \gamma_\rho - \sin\Theta_W Z_\rho \qquad (4.10)$$

$$\lambda_{\tilde{W},1} = \frac{1}{\sqrt{2}}\tilde{W}^- + \frac{1}{\sqrt{2}}\tilde{W}^+ \qquad (4.11)$$

$$\lambda_{\tilde{W},2} = -i\frac{1}{\sqrt{2}}\tilde{W}^- + i\frac{1}{\sqrt{2}}\tilde{W}^+ \qquad (4.12)$$

$$\lambda_{\tilde{W},3} = \tilde{W}^0 \qquad (4.13)$$

4.3.2 Rotations in Mass sector for eigenstates 'EWSB'

Mass Matrices for Scalars

- **Mass matrix for Down-Squarks**, Basis: $\left(\tilde{d}_{L,o_1\alpha_1}, \tilde{d}_{R,o_2\alpha_2}\right), \left(\tilde{d}^*_{L,p_1\beta_1}, \tilde{d}^*_{R,p_2\beta_2}\right)$

$$m^2_{\tilde{d}} = \left(\begin{array}{cc} m_{11} & \frac{1}{\sqrt{2}}\delta_{\alpha_1\beta_2}\Big(v_d T_{d,p_2o_1} - v_u\mu^* Y_{d,p_2o_1}\Big) \\ \frac{1}{\sqrt{2}}\Big(v_d T^*_{d,o_2p_1} - v_u\mu Y^*_{d,o_2p_1}\Big)\delta_{\alpha_2\beta_1} & m_{22} \end{array} \right) \tag{4.14}$$

$$m_{11} = \frac{1}{24}\delta_{\alpha_1\beta_1}\Big(12\Big(2m^2_{q,o_1p_1} + v_d^2\sum_{a=1}^{3}Y^*_{d,ap_1}Y_{d,ao_1}\Big) - \Big(3g_2^2 + g_1^2\Big)\Big(-v_u^2 + v_d^2\Big)\delta_{o_1p_1}\Big) \tag{4.15}$$

$$m_{22} = \frac{1}{12}\delta_{\alpha_2\beta_2}\Big(6\Big(2m^2_{d,p_2o_2} + v_d^2\sum_{a=1}^{3}Y^*_{d,o_2a}Y_{d,p_2a}\Big) + g_1^2\Big(-v_d^2 + v_u^2\Big)\delta_{o_2p_2}\Big) \tag{4.16}$$

This matrix is diagonalized by Z^D:

$$Z^D m^2_{\tilde{d}} Z^{D,\dagger} = m^{dia}_{2,\tilde{d}} \tag{4.17}$$

with

$$\tilde{d}_{L,i\alpha} = \sum_{t_2} Z^{D,*}_{ji}\tilde{d}_{j\alpha}\,, \qquad \tilde{d}_{R,i\alpha} = \sum_{t_2} Z^{D,*}_{ji}\tilde{d}_{j\alpha} \tag{4.18}$$

- **Mass matrix for Up-Squarks**, Basis: $\left(\tilde{u}_{L,o_1\alpha_1}, \tilde{u}_{R,o_2\alpha_2}\right), \left(\tilde{u}^*_{L,p_1\beta_1}, \tilde{u}^*_{R,p_2\beta_2}\right)$

$$m^2_{\tilde{u}} = \left(\begin{array}{cc} m_{11} & \frac{1}{\sqrt{2}}\delta_{\alpha_1\beta_2}\Big(-v_d\mu^* Y_{u,p_2o_1} + v_u T_{u,p_2o_1}\Big) \\ \frac{1}{\sqrt{2}}\Big(-v_d\mu Y^*_{u,o_2p_1} + v_u T^*_{u,o_2p_1}\Big)\delta_{\alpha_2\beta_1} & m_{22} \end{array} \right) \tag{4.19}$$

$$m_{11} = \frac{1}{24}\delta_{\alpha_1\beta_1}\Big(12\Big(2m^2_{q,o_1p_1} + v_u^2\sum_{a=1}^{3}Y^*_{u,ap_1}Y_{u,ao_1}\Big) - \Big(-3g_2^2 + g_1^2\Big)\Big(-v_u^2 + v_d^2\Big)\delta_{o_1p_1}\Big) \tag{4.20}$$

$$m_{22} = \frac{1}{6}\delta_{\alpha_2\beta_2}\Big(3v_u^2\sum_{a=1}^{3}Y^*_{u,o_2a}Y_{u,p_2a} + 6m^2_{u,p_2o_2} + g_1^2\Big(-v_u^2 + v_d^2\Big)\delta_{o_2p_2}\Big) \tag{4.21}$$

This matrix is diagonalized by Z^U:

$$Z^U m^2_{\tilde{u}} Z^{U,\dagger} = m^{dia}_{2,\tilde{u}} \tag{4.22}$$

with

$$\tilde{u}_{L,i\alpha} = \sum_{t_2} Z^{U,*}_{ji}\tilde{u}_{j\alpha}\,, \qquad \tilde{u}_{R,i\alpha} = \sum_{t_2} Z^{U,*}_{ji}\tilde{u}_{j\alpha} \tag{4.23}$$

- **Mass matrix for Sleptons**, Basis: $\left(\tilde{e}_{L,o_1}, \tilde{e}_{R,o_2}\right), \left(\tilde{e}^*_{L,p_1}, \tilde{e}^*_{R,p_2}\right)$

$$m^2_{\tilde{e}} = \begin{pmatrix} m_{11} & \frac{1}{\sqrt{2}}\Big(v_d T_{e,p_2 o_1} - v_u \mu^* Y_{e,p_2 o_1}\Big) \\ \frac{1}{\sqrt{2}}\Big(v_d T^*_{e,o_2 p_1} - v_u \mu Y^*_{e,o_2 p_1}\Big) & m_{22} \end{pmatrix} \tag{4.24}$$

$$m_{11} = \frac{1}{8}\Big(4 v_d^2 \sum_{a=1}^{3} Y^*_{e,a p_1} Y_{e,a o_1} + 8 m^2_{l,o_1 p_1} + \Big(-g_2^2 + g_1^2\Big)\Big(-v_u^2 + v_d^2\Big)\delta_{o_1 p_1}\Big) \tag{4.25}$$

$$m_{22} = \frac{1}{4}\Big(2 v_d^2 \sum_{a=1}^{3} Y^*_{e,o_2 a} Y_{e,p_2 a} + 4 m^2_{e,p_2 o_2} + g_1^2\Big(-v_d^2 + v_u^2\Big)\delta_{o_2 p_2}\Big) \tag{4.26}$$

This matrix is diagonalized by Z^E:

$$Z^E m^2_{\tilde{e}} Z^{E,\dagger} = m^{dia}_{2,\tilde{e}} \tag{4.27}$$

with

$$\tilde{e}_{L,i} = \sum_{t_2} Z^{E,*}_{ji} \tilde{e}_j\,, \qquad \tilde{e}_{R,i} = \sum_{t_2} Z^{E,*}_{ji} \tilde{e}_j \tag{4.28}$$

- **Mass matrix for Sneutrinos**, Basis: $\left(\tilde{\nu}_{L,o_1}\right), \left(\tilde{\nu}^*_{L,p_1}\right)$

$$m^2_{\tilde{\nu}} = \begin{pmatrix} \frac{1}{8}\Big(8 m^2_{l,o_1 p_1} + \Big(g_1^2 + g_2^2\Big)\Big(-v_u^2 + v_d^2\Big)\delta_{o_1 p_1}\Big) \end{pmatrix} \tag{4.29}$$

This matrix is diagonalized by Z^V:

$$Z^V m^2_{\tilde{\nu}} Z^{V,\dagger} = m^{dia}_{2,\tilde{\nu}} \tag{4.30}$$

with

$$\tilde{\nu}_{L,i} = \sum_{t_2} Z^{V,*}_{ji} \tilde{\nu}_j \tag{4.31}$$

- **Mass matrix for Higgs**, Basis: $\left(\phi_d, \phi_u, \sigma_d, \sigma_u\right), \left(\phi_d, \phi_u, \sigma_d, \sigma_u\right)$

$$m^2_h = \begin{pmatrix} m_{11} & m^*_{21} & 0 & -\frac{i}{2}\Big(-B^*_\mu + B_\mu\Big) \\ m_{21} & m_{22} & -\frac{i}{2}\Big(-B^*_\mu + B_\mu\Big) & 0 \\ 0 & -\frac{i}{2}\Big(-B^*_\mu + B_\mu\Big) & m_{33} & \Re\Big(B_\mu\Big) \\ -\frac{i}{2}\Big(-B^*_\mu + B_\mu\Big) & 0 & \Re\Big(B_\mu\Big) & m_{44} \end{pmatrix} \tag{4.32}$$

$$m_{11} = \frac{1}{8}\Big(8 m^2_{H_d} + 8|\mu|^2 + \Big(g_1^2 + g_2^2\Big)\Big(3 v_d^2 - v_u^2\Big)\Big) \tag{4.33}$$

$$m_{21} = \frac{1}{4}\Big(- 4\Re\Big(B_\mu\Big) - \Big(g_1^2 + g_2^2\Big)v_d v_u\Big) \tag{4.34}$$

$$m_{22} = \frac{1}{8}\Big(8m_{H_u}^2 + 8|\mu|^2 - \Big(g_1^2 + g_2^2\Big)\Big(- 3v_u^2 + v_d^2\Big)\Big) \tag{4.35}$$

$$m_{33} = \frac{1}{8}\Big(8m_{H_d}^2 + 8|\mu|^2 + \Big(g_1^2 + g_2^2\Big)\Big(- v_u^2 + v_d^2\Big)\Big) \tag{4.36}$$

$$m_{44} = \frac{1}{8}\Big(8m_{H_u}^2 + 8|\mu|^2 - \Big(g_1^2 + g_2^2\Big)\Big(- v_u^2 + v_d^2\Big)\Big) \tag{4.37}$$

This matrix is diagonalized by Z^H:

$$Z^H m_h^2 Z^{H,\dagger} = m_{2,h}^{dia} \tag{4.38}$$

with

$$\phi_d = \sum_{t_2} Z_{j1}^{H,*} h_j\,, \qquad \phi_u = \sum_{t_2} Z_{j2}^{H,*} h_j\,, \qquad \sigma_d = \sum_{t_2} Z_{j3}^{H,*} h_j \tag{4.39}$$

$$\sigma_u = \sum_{t_2} Z_{j4}^{H,*} h_j \tag{4.40}$$

- **Mass matrix for Charged Higgs**, Basis: $\left(H_d^-, H_u^{+,*}\right), \left(H_d^{-,*}, H_u^+\right)$

$$m_{H^-}^2 = \begin{pmatrix} m_{11} & \frac{1}{4}g_2^2 v_d v_u + B_\mu \\ \frac{1}{4}g_2^2 v_d v_u + B_\mu^* & m_{22} \end{pmatrix} \tag{4.41}$$

$$m_{11} = \frac{1}{8}\Big(8m_{H_d}^2 + 8|\mu|^2 + g_1^2 v_d^2 - g_1^2 v_u^2 + g_2^2 v_d^2 + g_2^2 v_u^2\Big) \tag{4.42}$$

$$m_{22} = \frac{1}{8}\Big(8m_{H_u}^2 + 8|\mu|^2 - g_1^2 v_d^2 + g_1^2 v_u^2 + g_2^2 v_d^2 + g_2^2 v_u^2\Big) \tag{4.43}$$

This matrix is diagonalized by Z^+:

$$Z^+ m_{H^-}^2 Z^{+,\dagger} = m_{2,H^-}^{dia} \tag{4.44}$$

with

$$H_d^- = \sum_{t_2} Z_{j1}^{+,*} H_j^-\,, \qquad H_u^+ = \sum_{t_2} Z_{j2}^{+} H_j^+ \tag{4.45}$$

The mixing matrix can be parametrized by

$$Z^+ = \begin{pmatrix} -\cos\beta & \sin\beta \\ \sin\beta & \cos\beta \end{pmatrix} \tag{4.46}$$

Mass Matrices for Fermions

- **Mass matrix for Neutralinos**, Basis: $\left(\lambda_{\tilde{B}}, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0\right), \left(\lambda_{\tilde{B}}, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0\right)$

$$m_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -\frac{1}{2}g_1 v_d & \frac{1}{2}g_1 v_u \\ 0 & M_2 & \frac{1}{2}g_2 v_d & -\frac{1}{2}g_2 v_u \\ -\frac{1}{2}g_1 v_d & \frac{1}{2}g_2 v_d & 0 & -\mu \\ \frac{1}{2}g_1 v_u & -\frac{1}{2}g_2 v_u & -\mu & 0 \end{pmatrix} \tag{4.47}$$

This matrix is diagonalized by N:

$$N m_{\tilde{\chi}^0} N^{\dagger} = m^{dia}_{\tilde{\chi}^0} \tag{4.48}$$

with

$$\lambda_{\tilde{B}} = \sum_{t_2} N^*_{j1}\lambda^0_j\,, \qquad \tilde{W}^0 = \sum_{t_2} N^*_{j2}\lambda^0_j\,, \qquad \tilde{H}^0_d = \sum_{t_2} N^*_{j3}\lambda^0_j \tag{4.49}$$

$$\tilde{H}^0_u = \sum_{t_2} N^*_{j4}\lambda^0_j \tag{4.50}$$

- **Mass matrix for Charginos**, Basis: $\left(\tilde{W}^-, \tilde{H}^-_d\right), \left(\tilde{W}^+, \tilde{H}^+_u\right)$

$$m_{\tilde{\chi}^-} = \begin{pmatrix} M_2 & \frac{1}{\sqrt{2}} g_2 v_u \\ \frac{1}{\sqrt{2}} g_2 v_d & \mu \end{pmatrix} \tag{4.51}$$

This matrix is diagonalized by U and V

$$U^* m_{\tilde{\chi}^-} V^{\dagger} = m^{dia}_{\tilde{\chi}^-} \tag{4.52}$$

with

$$\tilde{W}^- = \sum_{t_2} U^*_{j1}\lambda^-_j\,, \qquad \tilde{H}^-_d = \sum_{t_2} U^*_{j2}\lambda^-_j \tag{4.53}$$

$$\tilde{W}^+ = \sum_{t_2} V^*_{1j}\lambda^+_j\,, \qquad \tilde{H}^+_u = \sum_{t_2} V^*_{2j}\lambda^+_j \tag{4.54}$$

- **Mass matrix for Leptons**, Basis: $\left(e_{L,o_1}\right), \left(e^*_{R,p_1}\right)$

$$m_e = \begin{pmatrix} \frac{1}{\sqrt{2}} v_d Y_{e,p_1 o_1} \end{pmatrix} \tag{4.55}$$

This matrix is diagonalized by U^e_L and U^e_R

$$U^{e,*}_L m_e U^{e,\dagger}_R = m^{dia}_e \tag{4.56}$$

with

$$e_{L,i} = \sum_{t_2} U^{e,*}_{L,ji} E_{L,j} \tag{4.57}$$

$$e_{R,i} = \sum_{t_2} U^{e}_{R,ij} E^*_{R,j} \tag{4.58}$$

- **Mass matrix for Down-Quarks**, Basis: $\left(d_{L,o_1\alpha_1}\right), \left(d^*_{R,p_1\beta_1}\right)$

$$m_d = \begin{pmatrix} \frac{1}{\sqrt{2}} v_d \delta_{\alpha_1\beta_1} Y_{d,p_1 o_1} \end{pmatrix} \tag{4.59}$$

This matrix is diagonalized by U^d_L and U^d_R

$$U^{d,*}_L m_d U^{d,\dagger}_R = m^{dia}_d \tag{4.60}$$

with

$$d_{L,i\alpha} = \sum_{t_2} U^{d,*}_{L,ji} D_{L,j\alpha} \tag{4.61}$$

$$d_{R,i\alpha} = \sum_{t_2} U^{d}_{R,ij} D^*_{R,j\alpha} \tag{4.62}$$

- **Mass matrix for Up-Quarks**, Basis: $\left(u_{L,o_1\alpha_1}\right), \left(u^*_{R,p_1\beta_1}\right)$

$$m_u = \left(\begin{array}{c} \frac{1}{\sqrt{2}} v_u \delta_{\alpha_1\beta_1} Y_{u,p_1 o_1} \end{array} \right) \tag{4.63}$$

This matrix is diagonalized by U^u_L and U^u_R

$$U^{u,*}_L m_u U^{u,\dagger}_R = m^{dia}_u \tag{4.64}$$

with

$$u_{L,i\alpha} = \sum_{t_2} U^{u,*}_{L,ji} U_{L,j\alpha} \tag{4.65}$$

$$u_{R,i\alpha} = \sum_{t_2} U^{u}_{R,ij} U^*_{R,j\alpha} \tag{4.66}$$

4.4 Vacuum Expectation Values

$$H^0_d = \frac{1}{\sqrt{2}}\phi_d + \frac{1}{\sqrt{2}} v_d + i\frac{1}{\sqrt{2}}\sigma_d \tag{4.67}$$

$$H^0_u = \frac{1}{\sqrt{2}}\phi_u + \frac{1}{\sqrt{2}} v_u + i\frac{1}{\sqrt{2}}\sigma_u \tag{4.68}$$

4.5 Tadpole Equations

$$\frac{\partial V}{\partial v_d} = \frac{1}{8}\Big(8 v_d |\mu|^2 - 8 v_u \Re\Big(B_\mu\Big) + v_d\Big(8 m^2_{H_d} + g_1^2 v_d^2 - g_1^2 v_u^2 + g_2^2 v_d^2 - g_2^2 v_u^2\Big)\Big) \tag{4.69}$$

$$\frac{\partial V}{\partial v_u} = \frac{1}{8}\Big(- 8 v_d \Re\Big(B_\mu\Big) + 8 v_u |\mu|^2 + v_u\Big(8 m^2_{H_u} - g_1^2 v_d^2 + g_1^2 v_u^2 - g_2^2 v_d^2 + g_2^2 v_u^2\Big)\Big) \tag{4.70}$$

4.6 Particle content for eigenstates 'EWSB'

Name	Type	complex/real	Generations	Indices

$\tilde{d}$	Scalar	complex	6	generation, color
$\tilde{u}$	Scalar	complex	6	generation, color
$\tilde{e}$	Scalar	complex	6	generation
$\tilde{\nu}$	Scalar	complex	3	generation
h	Scalar	real	4	generation
H^-	Scalar	complex	2	generation
ν	Fermion	Dirac	3	generation
$\tilde{g}$	Fermion	Majorana	8	generation
$\tilde{\chi}^0$	Fermion	Majorana	4	generation
$\tilde{\chi}^-$	Fermion	Dirac	2	generation
e	Fermion	Dirac	3	generation
d	Fermion	Dirac	3	generation, color
u	Fermion	Dirac	3	generation, color
g	Vector	real	8	generation, lorentz
W^-	Vector	complex	1	lorentz
γ	Vector	real	1	lorentz
Z	Vector	real	1	lorentz
η^G	Ghost	real	8	generation
η^-	Ghost	complex	1	
η^+	Ghost	complex	1	
η^γ	Ghost	real	1	
η^Z	Ghost	real	1	

4.7 Modelfile for SARAH

```
Off[General::spell]
Print["Model file for the MSSM loaded"];

ModelNameLaTeX ="MSSM-CPV";


(*-------------------------------------------*)
(*   Particle Content*)
(*-------------------------------------------*)

(* Gauge Superfields *)

Gauge[[1]]={B,   U[1], hypercharge, g1,False};
Gauge[[2]]={WB, SU[2], left,        g2,True};
Gauge[[3]]={G,  SU[3], color,       g3,False};


(* Chiral Superfields *)

Fields[[1]] = {{uL,  dL},  3, q,   1/6, 2, 3};
Fields[[2]] = {{vL,  eL},  3, l,  -1/2, 2, 1};
Fields[[3]] = {{Hd0, Hdm}, 1, Hd, -1/2, 2, 1};
Fields[[4]] = {{Hup, Hu0}, 1, Hu,  1/2, 2, 1};

Fields[[5]] = {conj[dR], 3, d,  1/3, 1, -3};
Fields[[6]] = {conj[uR], 3, u, -2/3, 1, -3};
Fields[[7]] = {conj[eR], 3, e,    1, 1,  1};


(*-----------------------------------------------------*)
(* Superpotential *)
(*-----------------------------------------------------*)


SuperPotential = { {{1, Yu},{u,q,Hu}}, {{-1,Yd},{d,q,Hd}},
                   {{-1,Ye},{e,l,Hd}}, {{1,\[Mu]},{Hu,Hd}}  };


(*-------------------------------------------*)
(* Integrate Out or Delete Particles         *)
(*-------------------------------------------*)

IntegrateOut={};
DeleteParticles={};
```

```
(*-----------------------------------------------*)
(*   DEFINITION                                   *)
(*-----------------------------------------------*)

NameOfStates={GaugeES,EWSB};

DEFINITION[GaugeES][GaugeFixing]=
{ {Der[VWB],  -1/(2 RXi[W])},
     {Der[VG],   -1/(2 RXi[G]) }};

(* Gauge Sector *)

DEFINITION[EWSB][GaugeSector]=
{{VWB,{1,{VWm,1/Sqrt[2]},{conj[VWm],1/Sqrt[2]}},
      {2,{VWm,-\[ImaginaryI]/Sqrt[2]},{conj[VWm],\[ImaginaryI]/Sqrt[2]}},
      {3,{VP,Sin[ThetaW]},{VZ,Cos[ThetaW]}}},
 {VB, {1,{VP,Cos[ThetaW]},{VZ,-Sin[ThetaW]}}},
 {fWB,{1,{fWm,1/Sqrt[2]},{fWp,1/Sqrt[2]}},
      {2,{fWm,-\[ImaginaryI]/Sqrt[2]},{fWp,\[ImaginaryI]/Sqrt[2]}},
      {3,{fW0,1}}}};




(* ----- VEVs ---- *)

DEFINITION[EWSB][VEVs]=
  {{SHd0, {vd, 1/Sqrt[2]}, {sigmad, \[ImaginaryI]/Sqrt[2]},{phid, \
1/Sqrt[2]}},
   {SHu0, {vu, 1/Sqrt[2]}, {sigmau, \[ImaginaryI]/Sqrt[2]},{phiu, \
1/Sqrt[2]}}};



(* ---- Mixings ---- *)

DEFINITION[EWSB][MatterSector]=
{    {{SdL, SdR}, {Sd, ZD}},
     {{SuL, SuR}, {Su, ZU}},
     {{SeL, SeR}, {Se, ZE}},
     {{SvL}, {Sv, ZV}},
     {{phid, phiu, sigmad, sigmau}, {hh, ZH}},
     {{SHdm,conj[SHup]},{Hpm,ZP}},
     {{fB, fW0, FHd0, FHu0}, {L0, ZN}},
     {{{fWm, FHdm}, {fWp, FHup}}, {{Lm,UM}, {Lp,UP}}},
     {{{FeL},{conj[FeR]}},{{FEL,ZEL},{FER,ZER}}},
```

```
     {{{FdL},{conj[FdR]}},{{FDL,ZDL},{FDR,ZDR}}},
     {{{FuL},{conj[FuR]}},{{FUL,ZUL},{FUR,ZUR}}}
       };


(*--- Gauge Fixing ---- *)

DEFINITION[EWSB][GaugeFixing]=
  { {Der[VP],                                           - 1/(2 RXi[P])},
{Der[VWm]+\[ImaginaryI] Mass[VWm] RXi[W] Hpm[{1}],   - 1/(RXi[W])},
{Der[VZ] - Mass[VZ] RXi[Z] hh[{1}],                 - 1/(2 RXi[Z])},
{Der[VG],                                           - 1/(2 RXi[G])}};


DEFINITION[EWSB][Phases]=
{    {fG, PhaseGlu}
    };



(*-------------------------------------------------------*)
(* Dirac-Spinors *)
(*-------------------------------------------------------*)

dirac[[1]] = {Fd,  FDL, conj[FDR]};
dirac[[2]] = {Fe,  FEL, conj[FER]};
dirac[[3]] = {Fu,  FUL, conj[FUR]};
dirac[[4]] = {Fv,  FvL, 0};
dirac[[5]] = {Chi, L0, conj[L0]};
dirac[[6]] = {Cha, Lm, conj[Lp]};
dirac[[7]] = {Glu, fG, conj[fG]};


(* Unbroken EW *)

dirac[[8]] = {Bino, fB, conj[fB]};
dirac[[9]] = {Wino, fWB, conj[fWB]};
dirac[[10]] = {H0, FHd0, conj[FHu0]};
dirac[[11]] = {HC, FHdm, conj[FHup]};
dirac[[12]] = {Fd1, FdL, 0};
dirac[[13]] = {Fd2, 0, FdR};
dirac[[14]] = {Fu1, FuL, 0};
dirac[[15]] = {Fu2, 0, FuR};
dirac[[16]] = {Fe1, FeL, 0};
dirac[[17]] = {Fe2, 0, FeR};


(*-------------------------------------------------------*)
```

```
(* Automatized Output        *)
(*--------------------------------------------------*)

(*
makeOutput = {
                   {EWSB, {TeX, FeynArts}}
             };
            *)

SpectrumFile= None;
```

4.8 Implementation in SARAH

Model directory: MSSM/CPV

4.8.1 Particles for eigenstates 'GaugeES'

- Fermions

$\tilde{B} = \begin{pmatrix} \lambda_{\tilde{B}} \\ \lambda^*_{\tilde{B}} \end{pmatrix}$	$\texttt{Bino} = \begin{pmatrix} \texttt{fB} \\ \texttt{conj[fB]} \end{pmatrix}$
$d^1_{i\alpha} = \begin{pmatrix} d_{L,i\alpha} \\ 0 \end{pmatrix}$	$\texttt{Fd1[\{generation, color\}]} = \begin{pmatrix} \texttt{FdL[\{generation, color\}]} \\ 0 \end{pmatrix}$
$d^2_{i\alpha} = \begin{pmatrix} 0 \\ d_{R,i\alpha} \end{pmatrix}$	$\texttt{Fd2[\{generation, color\}]} = \begin{pmatrix} 0 \\ \texttt{FdR[\{generation, color\}]} \end{pmatrix}$
$e^1_i = \begin{pmatrix} e_{L,i} \\ 0 \end{pmatrix}$	$\texttt{Fe1[\{generation\}]} = \begin{pmatrix} \texttt{FeL[\{generation\}]} \\ 0 \end{pmatrix}$
$e^2_i = \begin{pmatrix} 0 \\ e_{R,i} \end{pmatrix}$	$\texttt{Fe2[\{generation\}]} = \begin{pmatrix} 0 \\ \texttt{FeR[\{generation\}]} \end{pmatrix}$
$u^1_{i\alpha} = \begin{pmatrix} u_{L,i\alpha} \\ 0 \end{pmatrix}$	$\texttt{Fu1[\{generation, color\}]} = \begin{pmatrix} \texttt{FuL[\{generation, color\}]} \\ 0 \end{pmatrix}$
$u^2_{i\alpha} = \begin{pmatrix} 0 \\ u_{R,i\alpha} \end{pmatrix}$	$\texttt{Fu2[\{generation, color\}]} = \begin{pmatrix} 0 \\ \texttt{FuR[\{generation, color\}]} \end{pmatrix}$
$\nu_i = \begin{pmatrix} \nu_{L,i} \\ 0 \end{pmatrix}$	$\texttt{Fv[\{generation\}]} = \begin{pmatrix} \texttt{FvL[\{generation\}]} \\ 0 \end{pmatrix}$
$\tilde{g}_i = \begin{pmatrix} \lambda_{\tilde{g},i} \\ \lambda^*_{\tilde{g},i} \end{pmatrix}$	$\texttt{Glu[\{generation\}]} = \begin{pmatrix} \texttt{fG[\{generation\}]} \\ \texttt{conj[fG[\{generation\}]]} \end{pmatrix}$

$\tilde{H}^0 = \begin{pmatrix} \tilde{H}_d^0 \\ \tilde{H}_u^{0,*} \end{pmatrix}$	`H0` $=$ $\begin{pmatrix} \texttt{FHd0} \\ \texttt{conj[FHu0]} \end{pmatrix}$
$\tilde{H}^- = \begin{pmatrix} \tilde{H}_d^- \\ \tilde{H}_u^{+,*} \end{pmatrix}$	`HC` $=$ $\begin{pmatrix} \texttt{FHdm} \\ \texttt{conj[FHup]} \end{pmatrix}$
$\tilde{W}_i = \begin{pmatrix} \lambda_{\tilde{W},i} \\ \lambda^*_{\tilde{W},i} \end{pmatrix}$	`Wino[{generation}]` $=$ $\begin{pmatrix} \texttt{fWB[\{generation\}]} \\ \texttt{conj[fWB[\{generation\}]]} \end{pmatrix}$

- Scalars

$\tilde{d}_{L,i\alpha}$	`SdL[{generation, color}]`	$\tilde{u}_{L,i\alpha}$	`SuL[{generation, color}]`
$\tilde{e}_{L,i}$	`SeL[{generation}]`	$\tilde{\nu}_{L,i}$	`SvL[{generation}]`
H_d^0	`SHd0`	H_d^-	`SHdm`
H_u^0	`SHu0`	H_u^+	`SHup`
$\tilde{d}_{R,i\alpha}$	`SdR[{generation, color}]`	$\tilde{u}_{R,i\alpha}$	`SuR[{generation, color}]`
$\tilde{e}_{R,i}$	`SeR[{generation}]`		

- Vector Bosons

B_ρ	`VB[{lorentz}]`	$W^-_{i\rho}$	`VWB[{generation, lorentz}]`
$g_{i\rho}$	`VG[{generation, lorentz}]`		

- Ghosts

η^B	`gB`	$\mathrm{gWB}\Big(\{\mathrm{gt1}\}\Big)$	`gWB[{generation}]`
η^G_i	`gG[{generation}]`		

4.8.2 Particles for eigenstates 'EWSB'

- Fermions

$\tilde{\chi}^-_i = \begin{pmatrix} \lambda^-_i \\ \lambda^{+,*}_i \end{pmatrix}$	`Cha[{generation}]` =	$\begin{pmatrix} \texttt{Lm[\{generation\}]} \\ \texttt{conj[Lp[\{generation\}]]} \end{pmatrix}$
$\tilde{\chi}^0_i = \begin{pmatrix} \lambda^0_i \\ \lambda^{0,*}_i \end{pmatrix}$	`Chi[{generation}]` =	$\begin{pmatrix} \texttt{L0[\{generation\}]} \\ \texttt{conj[L0[\{generation\}]]} \end{pmatrix}$
$d_{i\alpha} = \begin{pmatrix} D_{L,i\alpha} \\ D^*_{R,i\alpha} \end{pmatrix}$	`Fd[{generation, color}]` =	$\begin{pmatrix} \texttt{FDL[\{generation, color\}]} \\ \texttt{conj[FDR[\{generation, color\}]]} \end{pmatrix}$
$e_i = \begin{pmatrix} E_{L,i} \\ E^*_{R,i} \end{pmatrix}$	`Fe[{generation}]` =	$\begin{pmatrix} \texttt{FEL[\{generation\}]} \\ \texttt{conj[FER[\{generation\}]]} \end{pmatrix}$
$u_{i\alpha} = \begin{pmatrix} U_{L,i\alpha} \\ U^*_{R,i\alpha} \end{pmatrix}$	`Fu[{generation, color}]` =	$\begin{pmatrix} \texttt{FUL[\{generation, color\}]} \\ \texttt{conj[FUR[\{generation, color\}]]} \end{pmatrix}$
$\nu_i = \begin{pmatrix} \nu_{L,i} \\ 0 \end{pmatrix}$	`Fv[{generation}]` =	$\begin{pmatrix} \texttt{FvL[\{generation\}]} \\ 0 \end{pmatrix}$
$\tilde{g}_i = \begin{pmatrix} \lambda_{\tilde{g},i} \\ \lambda^*_{\tilde{g},i} \end{pmatrix}$	`Glu[{generation}]` =	$\begin{pmatrix} \texttt{fG[\{generation\}]} \\ \texttt{conj[fG[\{generation\}]]} \end{pmatrix}$

- Scalars

$\tilde{d}_{i\alpha}$	`Sd[{generation, color}]`	$\tilde{u}_{i\alpha}$	`Su[{generation, color}]`
$\tilde{e}_i$	`Se[{generation}]`	$\tilde{\nu}_i$	`Sv[{generation}]`
h_i	`hh[{generation}]`	H^-_i	`Hpm[{generation}]`

- Vector Bosons

$g_{i\rho}$	`VG[{generation, lorentz}]`	W^-_ρ	`VWm[{lorentz}]`
γ_ρ	`VP[{lorentz}]`	Z_ρ	`VZ[{lorentz}]`

- Ghosts

η_i^G	gG[{generation}]	η^-	gWm
η^+	gWmC	η^γ	gP
η^Z	gZ		

4.8.3 Parameters

g_1	g1	g_2	g2	g_3	g3
Y_u	Yu	T_u	T[Yu]	Y_d	Yd
T_d	T[Yd]	Y_e	Ye	T_e	T[Ye]
μ	\[Mu]	B_μ	B[\[Mu]]	m_q^2	mq2
m_l^2	ml2	$m_{H_d}^2$	mHd2	$m_{H_u}^2$	mHu2
m_d^2	md2	m_u^2	mu2	m_e^2	me2
M_1	MassB	M_2	MassWB	M_3	MassG
v_d	vd	v_u	vu	Θ_W	ThetaW
$\phi_{\tilde{g}}$	PhaseGlu	Z^D	ZD	Z^U	ZU
Z^E	ZE	Z^V	ZV	Z^H	ZH
Z^+	ZP	N	ZN	U	UM
V	UP	U_L^e	ZEL	U_R^e	ZER
U_L^d	ZDL	U_R^d	ZDR	U_L^u	ZUL
U_R^u	ZUR	β	\[Beta]		

Chapter 5

Minimal Supersymmetric Standard Model with Heavy gluino

5.1 Superfields

5.1.1 Vector Superfields

SF	Spin $\frac{1}{2}$	Spin 1	$SU(N)$	Coupling	Name
$\hat{B}$	$\lambda_{\tilde{B}}$	B	$U(1)$	g_1	hypercharge
$\hat{W}$	$\lambda_{\tilde{W}}$	W^-	SU(2)	g_2	left
$\hat{g}$	$\lambda_{\tilde{g}}$	g	SU(3)	g_3	color

5.1.2 Chiral Superfields

SF	Spin 0	Spin $\frac{1}{2}$	Generations	$(U(1) \otimes \mathrm{SU}(2) \otimes \mathrm{SU}(3))$
$\hat{q}$	$\tilde{q}$	q	3	$(\frac{1}{6}, \mathbf{2}, \mathbf{3})$
$\hat{l}$	$\tilde{l}$	l	3	$(-\frac{1}{2}, \mathbf{2}, \mathbf{1})$
$\hat{H}_d$	H_d	$\tilde{H}_d$	1	$(-\frac{1}{2}, \mathbf{2}, \mathbf{1})$
$\hat{H}_u$	H_u	$\tilde{H}_u$	1	$(\frac{1}{2}, \mathbf{2}, \mathbf{1})$
$\hat{d}$	$\tilde{d}_R^*$	d_R^*	3	$(\frac{1}{3}, \mathbf{1}, \overline{\mathbf{3}})$
$\hat{u}$	$\tilde{u}_R^*$	u_R^*	3	$(-\frac{2}{3}, \mathbf{1}, \overline{\mathbf{3}})$
$\hat{e}$	$\tilde{e}_R^*$	e_R^*	3	$(1, \mathbf{1}, \mathbf{1})$

5.2 Superpotential and Lagrangian

5.2.1 Superpotential

$$W = Y_u\, \hat{u}\, \hat{q}\, \hat{H}_u \, - Y_d\, \hat{d}\, \hat{q}\, \hat{H}_d \, - Y_e\, \hat{e}\, \hat{l}\, \hat{H}_d \, + \mu\, \hat{H}_u\, \hat{H}_d \tag{5.1}$$

5.2.2 Softbreaking terms

$$\begin{aligned}L_{SB,W} = & - H_d^0 H_u^0 B_\mu + H_d^- H_u^+ B_\mu + H_d^0 \tilde{d}^*_{R,i\alpha} \delta_{\alpha\beta} \tilde{d}_{L,j\beta} T_{d,ij} - H_d^- \tilde{d}^*_{R,i\alpha} \delta_{\alpha\beta} \tilde{u}_{L,j\beta} T_{d,ij} \\ & + H_d^0 \tilde{e}^*_{R,i} \tilde{e}_{L,j} T_{e,ij} - H_d^- \tilde{e}^*_{R,i} \tilde{\nu}_{L,j} T_{e,ij} - H_u^+ \tilde{u}^*_{R,i\alpha} \delta_{\alpha\beta} \tilde{d}_{L,j\beta} T_{u,ij} + H_u^0 \tilde{u}^*_{R,i\alpha} \delta_{\alpha\beta} \tilde{u}_{L,j\beta} T_{u,ij} + \text{h.c.}\end{aligned} \tag{5.2}$$

$$\begin{aligned}L_{SB,\phi} = & - m^2_{H_d} |H_d^0|^2 - m^2_{H_d} |H_d^-|^2 - m^2_{H_u} |H_u^0|^2 - m^2_{H_u} |H_u^+|^2 - \tilde{d}^*_{L,j\beta} \delta_{\alpha\beta} m^2_{q,ij} \tilde{d}_{L,i\alpha} \\ & - \tilde{d}^*_{R,i\alpha} \delta_{\alpha\beta} m^2_{d,ij} \tilde{d}_{R,j\beta} - \tilde{e}^*_{L,j} m^2_{l,ij} \tilde{e}_{L,i} - \tilde{e}^*_{R,i} m^2_{e,ij} \tilde{e}_{R,j} - \tilde{u}^*_{L,j\beta} \delta_{\alpha\beta} m^2_{q,ij} \tilde{u}_{L,i\alpha} \\ & - \tilde{u}^*_{R,i\alpha} \delta_{\alpha\beta} m^2_{u,ij} \tilde{u}_{R,j\beta} - \tilde{\nu}^*_{L,j} m^2_{l,ij} \tilde{\nu}_{L,i}\end{aligned} \tag{5.3}$$

$$L_{SB,\lambda} = \frac{1}{2}\Big(-\lambda^2_{\tilde{B}} M_1 - M_2 \lambda^2_{\tilde{W},i} - M_3 \lambda^2_{\tilde{g},i} + \text{h.c.}\Big) \tag{5.4}$$

5.2.3 Gauge fixing terms

Gauge fixing terms for eigenstates 'GaugeES'

$$L_{GF} = -\frac{1}{2}\partial_\mu g \xi_G^{-1} - \frac{1}{2}\partial_\mu W^- \xi_W^{-1} \tag{5.5}$$

Gauge fixing terms for eigenstates 'EWSB'

$$L_{GF} = -\frac{1}{2}\partial_\mu \gamma \xi_P^{-1} - \frac{1}{2}\partial_\mu g \xi_G^{-1} - \frac{1}{2}\xi_Z^{-1}\Big(- A_1^0 m_Z \xi_Z + \partial_\mu Z\Big) - \xi_W^{-1}\Big(i H_1^- m_{W^-} \xi_W + \partial_\mu W^-\Big) \tag{5.6}$$

5.2.4 Fields integrated out

a) $\lambda_{\tilde{g}}$

5.3 Field Rotations

5.3.1 Rotations in gauge sector for eigenstates 'EWSB'

$$W^-_{1\rho} = \frac{1}{\sqrt{2}} W^-_\rho + \frac{1}{\sqrt{2}} W^+_\rho \tag{5.7}$$

$$W^-_{2\rho} = -i\frac{1}{\sqrt{2}} W^-_\rho + i\frac{1}{\sqrt{2}} W^+_\rho \tag{5.8}$$

$$W^-_{3\rho} = \cos\Theta_W Z_\rho + \sin\Theta_W \gamma_\rho \tag{5.9}$$

$$B_\rho = \cos\Theta_W \gamma_\rho - \sin\Theta_W Z_\rho \tag{5.10}$$

$$\lambda_{\tilde{W},1} = \frac{1}{\sqrt{2}} \tilde{W}^- + \frac{1}{\sqrt{2}} \tilde{W}^+ \tag{5.11}$$

$$\lambda_{\tilde{W},2} = -i\frac{1}{\sqrt{2}} \tilde{W}^- + i\frac{1}{\sqrt{2}} \tilde{W}^+ \tag{5.12}$$

$$\lambda_{\tilde{W},3} = \tilde{W}^0 \tag{5.13}$$

5.3.2 Rotations in Mass sector for eigenstates 'EWSB'

Mass Matrices for Scalars

- **Mass matrix for Down-Squarks**, Basis: $\Big(\tilde{d}_{L,o_1\alpha_1}, \tilde{d}_{R,o_2\alpha_2}\Big), \Big(\tilde{d}^*_{L,p_1\beta_1}, \tilde{d}^*_{R,p_2\beta_2}\Big)$

$$m^2_{\tilde{d}} = \begin{pmatrix} m_{11} & \frac{1}{\sqrt{2}}\delta_{\alpha_1\beta_2}\Big(v_d T_{d,p_2o_1} - v_u\mu^* Y_{d,p_2o_1}\Big) \\ \frac{1}{\sqrt{2}}\Big(v_d T^*_{d,o_2p_1} - v_u\mu Y^*_{d,o_2p_1}\Big)\delta_{\alpha_2\beta_1} & m_{22} \end{pmatrix} \tag{5.14}$$

$$m_{11} = \frac{1}{24}\delta_{\alpha_1\beta_1}\Big(12\Big(2m^2_{q,o_1p_1} + v_d^2\sum_{a=1}^{3} Y^*_{d,ap_1}Y_{d,ao_1}\Big) - \Big(3g_2^2 + g_1^2\Big)\Big(- v_u^2 + v_d^2\Big)\delta_{o_1p_1}\Big) \tag{5.15}$$

$$m_{22} = \frac{1}{12}\delta_{\alpha_2\beta_2}\Big(6\Big(2m^2_{d,p_2o_2} + v_d^2\sum_{a=1}^{3} Y^*_{d,o_2a}Y_{d,p_2a}\Big) + g_1^2\Big(- v_d^2 + v_u^2\Big)\delta_{o_2p_2}\Big) \tag{5.16}$$

This matrix is diagonalized by Z^D:

$$Z^D m^2_{\tilde{d}} Z^{D,\dagger} = m^{dia}_{2,\tilde{d}} \tag{5.17}$$

with

$$\tilde{d}_{L,i\alpha} = \sum_{t_2} Z^{D,*}_{ji}\tilde{d}_{j\alpha}\,, \qquad \tilde{d}_{R,i\alpha} = \sum_{t_2} Z^{D,*}_{ji}\tilde{d}_{j\alpha} \tag{5.18}$$

- **Mass matrix for Up-Squarks**, Basis: $(\tilde{u}_{L,o_1\alpha_1}, \tilde{u}_{R,o_2\alpha_2}), \Big(\tilde{u}^*_{L,p_1\beta_1}, \tilde{u}^*_{R,p_2\beta_2}\Big)$

$$m^2_{\tilde{u}} = \begin{pmatrix} m_{11} & \frac{1}{\sqrt{2}}\delta_{\alpha_1\beta_2}\Big(- v_d\mu^* Y_{u,p_2o_1} + v_u T_{u,p_2o_1}\Big) \\ \frac{1}{\sqrt{2}}\Big(- v_d\mu Y^*_{u,o_2p_1} + v_u T^*_{u,o_2p_1}\Big)\delta_{\alpha_2\beta_1} & m_{22} \end{pmatrix} \tag{5.19}$$

$$m_{11} = \frac{1}{24}\delta_{\alpha_1\beta_1}\Big(12\Big(2m^2_{q,o_1p_1} + v_u^2\sum_{a=1}^{3} Y^*_{u,ap_1}Y_{u,ao_1}\Big) - \Big(- 3g_2^2 + g_1^2\Big)\Big(- v_u^2 + v_d^2\Big)\delta_{o_1p_1}\Big) \tag{5.20}$$

$$m_{22} = \frac{1}{6}\delta_{\alpha_2\beta_2}\Big(3v_u^2\sum_{a=1}^{3} Y^*_{u,o_2a}Y_{u,p_2a} + 6m^2_{u,p_2o_2} + g_1^2\Big(- v_u^2 + v_d^2\Big)\delta_{o_2p_2}\Big) \tag{5.21}$$

This matrix is diagonalized by Z^U:

$$Z^U m^2_{\tilde{u}} Z^{U,\dagger} = m^{dia}_{2,\tilde{u}} \tag{5.22}$$

with

$$\tilde{u}_{L,i\alpha} = \sum_{t_2} Z^{U,*}_{ji}\tilde{u}_{j\alpha}\,, \qquad \tilde{u}_{R,i\alpha} = \sum_{t_2} Z^{U,*}_{ji}\tilde{u}_{j\alpha} \tag{5.23}$$

- **Mass matrix for Sleptons**, Basis: $\left(\tilde{e}_{L,o_1}, \tilde{e}_{R,o_2}\right), \left(\tilde{e}^*_{L,p_1}, \tilde{e}^*_{R,p_2}\right)$

$$m^2_{\tilde{e}} = \begin{pmatrix} m_{11} & \frac{1}{\sqrt{2}}\Big(v_d T_{e,p_2 o_1} - v_u \mu^* Y_{e,p_2 o_1}\Big) \\ \frac{1}{\sqrt{2}}\Big(v_d T^*_{e,o_2 p_1} - v_u \mu Y^*_{e,o_2 p_1}\Big) & m_{22} \end{pmatrix} \tag{5.24}$$

$$m_{11} = \frac{1}{8}\Big(4v_d^2 \sum_{a=1}^{3} Y^*_{e,ap_1} Y_{e,ao_1} + 8m^2_{l,o_1 p_1} + \Big(-g_2^2 + g_1^2\Big)\Big(-v_u^2 + v_d^2\Big)\delta_{o_1 p_1}\Big) \tag{5.25}$$

$$m_{22} = \frac{1}{4}\Big(2v_d^2 \sum_{a=1}^{3} Y^*_{e,o_2 a} Y_{e,p_2 a} + 4m^2_{e,p_2 o_2} + g_1^2\Big(-v_d^2 + v_u^2\Big)\delta_{o_2 p_2}\Big) \tag{5.26}$$

This matrix is diagonalized by Z^E:

$$Z^E m^2_{\tilde{e}} Z^{E,\dagger} = m^{dia}_{2,\tilde{e}} \tag{5.27}$$

with

$$\tilde{e}_{L,i} = \sum_{t_2} Z^{E,*}_{ji} \tilde{e}_j\,, \qquad \tilde{e}_{R,i} = \sum_{t_2} Z^{E,*}_{ji} \tilde{e}_j \tag{5.28}$$

- **Mass matrix for Higgs**, Basis: $\left(\phi_d, \phi_u\right), \left(\phi_d, \phi_u\right)$

$$m^2_h = \begin{pmatrix} \frac{1}{8}\Big(8m^2_{H_d} + 8|\mu|^2 + \Big(g_1^2 + g_2^2\Big)\Big(3v_d^2 - v_u^2\Big)\Big) & \frac{1}{4}\Big(-4\Re\Big(B_\mu\Big) - \Big(g_1^2 + g_2^2\Big)v_d v_u\Big) \\ \frac{1}{4}\Big(-4\Re\Big(B_\mu\Big) - \Big(g_1^2 + g_2^2\Big)v_d v_u\Big) & \frac{1}{8}\Big(8m^2_{H_u} + 8|\mu|^2 - \Big(g_1^2 + g_2^2\Big)\Big(-3v_u^2 + v_d^2\Big)\Big) \end{pmatrix} \tag{5.29}$$

This matrix is diagonalized by Z^H:

$$Z^H m^2_h Z^{H,\dagger} = m^{dia}_{2,h} \tag{5.30}$$

with

$$\phi_d = \sum_{t_2} Z^H_{j1} h_j\,, \qquad \phi_u = \sum_{t_2} Z^H_{j2} h_j \tag{5.31}$$

The mixing matrix can be parametrized by

$$Z^H = \begin{pmatrix} -\sin\alpha & \cos\alpha \\ \cos\alpha & \sin\alpha \end{pmatrix} \tag{5.32}$$

- **Mass matrix for Pseudo-Scalar Higgs**, Basis: $\left(\sigma_d, \sigma_u\right), \left(\sigma_d, \sigma_u\right)$

$$m^2_{A^0} = \begin{pmatrix} \frac{1}{8}\Big(8m^2_{H_d} + 8|\mu|^2 + \Big(g_1^2 + g_2^2\Big)\Big(-v_u^2 + v_d^2\Big)\Big) & \Re\Big(B_\mu\Big) \\ \Re\Big(B_\mu\Big) & \frac{1}{8}\Big(8m^2_{H_u} + 8|\mu|^2 - \Big(g_1^2 + g_2^2\Big)\Big(-v_u^2 + v_d^2\Big)\Big) \end{pmatrix} \tag{5.33}$$

This matrix is diagonalized by Z^A:

$$Z^A m^2_{A^0} Z^{A,\dagger} = m^{dia}_{2,A^0} \tag{5.34}$$

with

$$\sigma_d = \sum_{t_2} Z^A_{j1} A^0_j\,, \qquad \sigma_u = \sum_{t_2} Z^A_{j2} A^0_j \tag{5.35}$$

The mixing matrix can be parametrized by

$$Z^A = \begin{pmatrix} -\cos\beta & \sin\beta \\ \sin\beta & \cos\beta \end{pmatrix} \tag{5.36}$$

- **Mass matrix for Charged Higgs**, Basis: $\left(H_d^-, H_u^{+,*}\right), \left(H_d^{-,*}, H_u^+\right)$

$$m^2_{H^-} = \begin{pmatrix} m_{11} & \frac{1}{4}g_2^2 v_d v_u + B_\mu \\ \frac{1}{4}g_2^2 v_d v_u + B_\mu^* & m_{22} \end{pmatrix} \tag{5.37}$$

$$m_{11} = \frac{1}{8}\Big(8m^2_{H_d} + 8|\mu|^2 + g_1^2 v_d^2 - g_1^2 v_u^2 + g_2^2 v_d^2 + g_2^2 v_u^2\Big) \tag{5.38}$$

$$m_{22} = \frac{1}{8}\Big(8m^2_{H_u} + 8|\mu|^2 - g_1^2 v_d^2 + g_1^2 v_u^2 + g_2^2 v_d^2 + g_2^2 v_u^2\Big) \tag{5.39}$$

This matrix is diagonalized by Z^+:

$$Z^+ m^2_{H^-} Z^{+,\dagger} = m^{dia}_{2,H^-} \tag{5.40}$$

with

$$H_d^- = \sum_{t_2} Z^{+,*}_{j1} H_j^-\,, \qquad H_u^+ = \sum_{t_2} Z^+_{j2} H_j^+ \tag{5.41}$$

The mixing matrix can be parametrized by

$$Z^+ = \begin{pmatrix} -\cos\beta & \sin\beta \\ \sin\beta & \cos\beta \end{pmatrix} \tag{5.42}$$

Mass Matrices for Fermions

- **Mass matrix for Neutralinos**, Basis: $\left(\lambda_{\tilde{B}}, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0\right), \left(\lambda_{\tilde{B}}, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0\right)$

$$m_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -\frac{1}{2}g_1 v_d & \frac{1}{2}g_1 v_u \\ 0 & M_2 & \frac{1}{2}g_2 v_d & -\frac{1}{2}g_2 v_u \\ -\frac{1}{2}g_1 v_d & \frac{1}{2}g_2 v_d & 0 & -\mu \\ \frac{1}{2}g_1 v_u & -\frac{1}{2}g_2 v_u & -\mu & 0 \end{pmatrix} \tag{5.43}$$

This matrix is diagonalized by N:

$$N m_{\tilde{\chi}^0} N^\dagger = m^{dia}_{\tilde{\chi}^0} \tag{5.44}$$

with

$$\lambda_{\tilde{B}} = \sum_{t_2} N^*_{j1}\lambda^0_j\,, \qquad \tilde{W}^0 = \sum_{t_2} N^*_{j2}\lambda^0_j\,, \qquad \tilde{H}^0_d = \sum_{t_2} N^*_{j3}\lambda^0_j \tag{5.45}$$

$$\tilde{H}^0_u = \sum_{t_2} N^*_{j4}\lambda^0_j \tag{5.46}$$

- **Mass matrix for Charginos**, Basis: $\Big(\tilde{W}^-, \tilde{H}^-_d\Big), \Big(\tilde{W}^+, \tilde{H}^+_u\Big)$

$$m_{\tilde{\chi}^-} = \begin{pmatrix} M_2 & \frac{1}{\sqrt{2}} g_2 v_u \\ \frac{1}{\sqrt{2}} g_2 v_d & \mu \end{pmatrix} \tag{5.47}$$

This matrix is diagonalized by U and V

$$U^* m_{\tilde{\chi}^-} V^\dagger = m^{dia}_{\tilde{\chi}^-} \tag{5.48}$$

with

$$\tilde{W}^- = \sum_{t_2} U^*_{j1}\lambda^-_j\,, \qquad \tilde{H}^-_d = \sum_{t_2} U^*_{j2}\lambda^-_j \tag{5.49}$$

$$\tilde{W}^+ = \sum_{t_2} V^*_{1j}\lambda^+_j\,, \qquad \tilde{H}^+_u = \sum_{t_2} V^*_{2j}\lambda^+_j \tag{5.50}$$

5.4 Vacuum Expectation Values

$$H^0_d = \frac{1}{\sqrt{2}}\phi_d + \frac{1}{\sqrt{2}} v_d + i\frac{1}{\sqrt{2}}\sigma_d \tag{5.51}$$

$$H^0_u = \frac{1}{\sqrt{2}}\phi_u + \frac{1}{\sqrt{2}} v_u + i\frac{1}{\sqrt{2}}\sigma_u \tag{5.52}$$

5.5 Tadpole Equations

$$\frac{\partial V}{\partial v_d} = \frac{1}{8}\Big(8 v_d |\mu|^2 - 8 v_u \Re\Big(B_\mu\Big) + v_d\Big(8 m^2_{H_d} + g_1^2 v_d^2 - g_1^2 v_u^2 + g_2^2 v_d^2 - g_2^2 v_u^2\Big)\Big) \tag{5.53}$$

$$\frac{\partial V}{\partial v_u} = \frac{1}{8}\Big(- 8 v_d \Re\Big(B_\mu\Big) + 8 v_u |\mu|^2 + v_u\Big(8 m^2_{H_u} - g_1^2 v_d^2 + g_1^2 v_u^2 - g_2^2 v_d^2 + g_2^2 v_u^2\Big)\Big) \tag{5.54}$$

5.6 Particle content for eigenstates 'EWSB'

Name	Type	complex/real	Generations	Indices
$\tilde{\nu}_L$	Scalar	complex	3	generation
$\tilde{d}$	Scalar	complex	6	generation, color
$\tilde{u}$	Scalar	complex	6	generation, color
$\tilde{e}$	Scalar	complex	6	generation
h	Scalar	real	2	generation
A^0	Scalar	real	2	generation
H^-	Scalar	complex	2	generation
d	Fermion	Dirac	3	generation, color
u	Fermion	Dirac	3	generation, color
e	Fermion	Dirac	3	generation
ν	Fermion	Dirac	3	generation
d^2	Fermion	Dirac	3	generation, color
u^2	Fermion	Dirac	3	generation, color
e^2	Fermion	Dirac	3	generation
$\tilde{\chi}^0$	Fermion	Majorana	4	generation
$\tilde{\chi}^-$	Fermion	Dirac	2	generation
g	Vector	real	8	generation, lorentz
W^-	Vector	complex	1	lorentz
γ	Vector	real	1	lorentz
Z	Vector	real	1	lorentz
η^G	Ghost	real	8	generation
η^-	Ghost	complex	1	
η^+	Ghost	complex	1	
η^γ	Ghost	real	1	
η^Z	Ghost	real	1	

5.7 Modelfile for SARAH

```
Off[General::spell]
Print["Model file for the MSSM loaded"];

ModelNameLaTeX ="MSSM";


(*-------------------------------------------*)
(*   Particle Content*)
(*-------------------------------------------*)

(* Gauge Superfields *)

Gauge[[1]]={B,   U[1], hypercharge, g1,False};
Gauge[[2]]={WB, SU[2], left,        g2,True};
Gauge[[3]]={G,  SU[3], color,       g3,False};


(* Chiral Superfields *)

Fields[[1]] = {{uL,  dL},  3, q,   1/6, 2, 3};
Fields[[2]] = {{vL,  eL},  3, l,  -1/2, 2, 1};
Fields[[3]] = {{Hd0, Hdm}, 1, Hd, -1/2, 2, 1};
Fields[[4]] = {{Hup, Hu0}, 1, Hu,  1/2, 2, 1};

Fields[[5]] = {conj[dR], 3, d,  1/3, 1, -3};
Fields[[6]] = {conj[uR], 3, u, -2/3, 1, -3};
Fields[[7]] = {conj[eR], 3, e,    1, 1,  1};


(*-----------------------------------------------------*)
(* Superpotential *)
(*-----------------------------------------------------*)


SuperPotential = { {{1, Yu},{u,q,Hu}}, {{-1,Yd},{d,q,Hd}},
                   {{-1,Ye},{e,l,Hd}}, {{1,\[Mu]},{Hu,Hd}}  };


(*-------------------------------------------*)
(* Integrate Out or Delete Particles         *)
(*-------------------------------------------*)

IntegrateOut={fG};
DeleteParticles={};
```

```
(*--------------------------------------------*)
(*   DEFINITION                               *)
(*--------------------------------------------*)

NameOfStates={GaugeES, EWSB};

(* ----- Before EWSB ----- *)


DEFINITION[GaugeES][GaugeFixing]=
{ {Der[VWB],  -1/(2 RXi[W])},
     {Der[VG],   -1/(2 RXi[G]) }};



(* ----- After EWSB ----- *)


(* Gauge Sector *)

DEFINITION[EWSB][GaugeSector]=
{{VWB,{1,{VWm,1/Sqrt[2]},{conj[VWm],1/Sqrt[2]}},
      {2,{VWm,-\[ImaginaryI]/Sqrt[2]},{conj[VWm],\[ImaginaryI]/Sqrt[2]}},
      {3,{VP,Sin[ThetaW]},{VZ,Cos[ThetaW]}}},
 {VB, {1,{VP,Cos[ThetaW]},{VZ,-Sin[ThetaW]}}},
 {fWB,{1,{fWm,1/Sqrt[2]},{fWp,1/Sqrt[2]}},
      {2,{fWm,-\[ImaginaryI]/Sqrt[2]},{fWp,\[ImaginaryI]/Sqrt[2]}},
      {3,{fW0,1}}}};




(* ----- VEVs ---- *)

DEFINITION[EWSB][VEVs]=
  {{SHd0, {vd, 1/Sqrt[2]}, {sigmad, \[ImaginaryI]/Sqrt[2]},{phid, \
1/Sqrt[2]}},
   {SHu0, {vu, 1/Sqrt[2]}, {sigmau, \[ImaginaryI]/Sqrt[2]},{phiu, \
1/Sqrt[2]}}};



(* ---- Mixings ---- *)

DEFINITION[EWSB][MatterSector]=
{    {{SdL, SdR}, {Sd, ZD}},
```

```
     {{SuL, SuR}, {Su, ZU}},
     {{SeL, SeR}, {Se, ZE}},
     {{phid, phiu}, {hh, ZH}},
     {{sigmad, sigmau}, {Ah, ZA}},
     {{SHdm,conj[SHup]},{Hpm,ZP}},
     {{fB, fW0, FHd0, FHu0}, {L0, ZN}},
     {{{fWm, FHdm}, {fWp, FHup}}, {{Lm,UM}, {Lp,UP}}}      \
       };


(*--- Gauge Fixing ---- *)

DEFINITION[EWSB][GaugeFixing]=
  { {Der[VP],                                           - 1/(2 RXi[P])},
{Der[VWm]+\[ImaginaryI] Mass[VWm] RXi[W] Hpm[{1}],   - 1/(RXi[W])},
{Der[VZ] - Mass[VZ] RXi[Z] Ah[{1}],                 - 1/(2 RXi[Z])},
{Der[VG],                                           - 1/(2 RXi[G])}};


(*-------------------------------------------------------*)
(* Dirac-Spinors *)
(*-------------------------------------------------------*)

dirac[[1]] = {Fd,  FdL, FdR};
dirac[[2]] = {Fe,  FeL, FeR};
dirac[[3]] = {Fu,  FuL, FuR};
dirac[[4]] = {Fv,  FvL, 0};
dirac[[5]] = {Chi, L0, conj[L0]};
dirac[[6]] = {Cha, Lm, conj[Lp]};
dirac[[7]] = {Glu, fG, conj[fG]};

(* Unbroken EW *)

dirac[[8]] = {Bino, fB, conj[fB]};
dirac[[9]] = {Wino, fWB, conj[fWB]};
dirac[[10]] = {H0, FHd0, conj[FHu0]};
dirac[[11]] = {HC, FHdm, conj[FHup]};
dirac[[12]] = {Fd1, FdL, 0};
dirac[[13]] = {Fd2, 0, FdR};
dirac[[14]] = {Fu1, FuL, 0};
dirac[[15]] = {Fu2, 0, FuR};
dirac[[16]] = {Fe1, FeL, 0};
dirac[[17]] = {Fe2, 0, FeR};




(*-------------------------------------------------------*)
```

```
(* Automatized Output        *)
(*-----------------------------------------------------*)

(*
makeOutput = {
                  {EWSB, {TeX, FeynArts}}
             };
            *)

SpectrumFile=None;
```

5.8 Implementation in SARAH

Model directory: `MSSM/HeavyGluino`

5.8.1 Particles for eigenstates 'GaugeES'

- Fermions

$\tilde{B} = \begin{pmatrix} \lambda_{\tilde{B}} \\ \lambda^*_{\tilde{B}} \end{pmatrix}$	$\texttt{Bino} = \begin{pmatrix} \texttt{fB} \\ \texttt{conj[fB]} \end{pmatrix}$
$d_{i\alpha} = \begin{pmatrix} d_{L,i\alpha} \\ d_{R,i\alpha} \end{pmatrix}$	$\texttt{Fd[\{generation, color\}]} = \begin{pmatrix} \texttt{FdL[\{generation, color\}]} \\ \texttt{FdR[\{generation, color\}]} \end{pmatrix}$
$e_i = \begin{pmatrix} e_{L,i} \\ e_{R,i} \end{pmatrix}$	$\texttt{Fe[\{generation\}]} = \begin{pmatrix} \texttt{FeL[\{generation\}]} \\ \texttt{FeR[\{generation\}]} \end{pmatrix}$
$u_{i\alpha} = \begin{pmatrix} u_{L,i\alpha} \\ u_{R,i\alpha} \end{pmatrix}$	$\texttt{Fu[\{generation, color\}]} = \begin{pmatrix} \texttt{FuL[\{generation, color\}]} \\ \texttt{FuR[\{generation, color\}]} \end{pmatrix}$
$\nu_i = \begin{pmatrix} \text{FvL}\Big(\{\text{gt1}\}\Big) \\ 0 \end{pmatrix}$	$\texttt{Fv[\{generation\}]} = \begin{pmatrix} \texttt{FvL[\{generation\}]} \\ 0 \end{pmatrix}$
$\tilde{H}^0 = \begin{pmatrix} \tilde{H}^0_d \\ \tilde{H}^{0,*}_u \end{pmatrix}$	$\texttt{H0} = \begin{pmatrix} \texttt{FHd0} \\ \texttt{conj[FHu0]} \end{pmatrix}$
$\tilde{H}^- = \begin{pmatrix} \tilde{H}^-_d \\ \tilde{H}^{+,*}_u \end{pmatrix}$	$\texttt{HC} = \begin{pmatrix} \texttt{FHdm} \\ \texttt{conj[FHup]} \end{pmatrix}$
$\tilde{W}_i = \begin{pmatrix} \lambda_{\tilde{W},i} \\ \lambda^*_{\tilde{W},i} \end{pmatrix}$	$\texttt{Wino[\{generation\}]} = \begin{pmatrix} \texttt{fWB[\{generation\}]} \\ \texttt{conj[fWB[\{generation\}]]} \end{pmatrix}$

- Scalars

$\tilde{d}_{L,i\alpha}$	`SdL[{generation, color}]`	$\tilde{u}_{L,i\alpha}$	`SuL[{generation, color}]`
$\tilde{e}_{L,i}$	`SeL[{generation}]`	$\tilde{\nu}_{L,i}$	`SvL[{generation}]`
H_d^0	`SHd0`	H_d^-	`SHdm`
H_u^0	`SHu0`	H_u^+	`SHup`
$\tilde{d}_{R,i\alpha}$	`SdR[{generation, color}]`	$\tilde{u}_{R,i\alpha}$	`SuR[{generation, color}]`
$\tilde{e}_{R,i}$	`SeR[{generation}]`		

- Vector Bosons

B_ρ	`VB[{lorentz}]`	$W_{i\rho}^-$	`VWB[{generation, lorentz}]`
$g_{i\rho}$	`VG[{generation, lorentz}]`		

- Ghosts

η^B	`gB`	$\mathrm{gWB}\left(\{\mathrm{gt1}\}\right)$	`gWB[{generation}]`
η_i^G	`gG[{generation}]`		

5.8.2 Particles for eigenstates 'EWSB'

- Fermions

$\tilde{\chi}_i^- = \begin{pmatrix} \lambda_i^- \\ \lambda_i^{+,*} \end{pmatrix}$	$\texttt{Cha[\{generation\}]} = \begin{pmatrix} \texttt{Lm[\{generation\}]} \\ \texttt{conj[Lp[\{generation\}]]} \end{pmatrix}$
$\tilde{\chi}_i^0 = \begin{pmatrix} \lambda_i^0 \\ \lambda_i^{0,*} \end{pmatrix}$	$\texttt{Chi[\{generation\}]} = \begin{pmatrix} \texttt{L0[\{generation\}]} \\ \texttt{conj[L0[\{generation\}]]} \end{pmatrix}$
$d_{i\alpha} = \begin{pmatrix} d_{L,i\alpha} \\ d_{R,i\alpha} \end{pmatrix}$	$\texttt{Fd[\{generation, color\}]} = \begin{pmatrix} \texttt{FdL[\{generation, color\}]} \\ \texttt{FdR[\{generation, color\}]} \end{pmatrix}$

$e_i = \begin{pmatrix} e_{L,i} \\ e_{R,i} \end{pmatrix}$	`Fe[{generation}]` $= \begin{pmatrix} \texttt{FeL[\{generation\}]} \\ \texttt{FeR[\{generation\}]} \end{pmatrix}$
$u_{i\alpha} = \begin{pmatrix} u_{L,i\alpha} \\ u_{R,i\alpha} \end{pmatrix}$	`Fu[{generation, color}]` $= \begin{pmatrix} \texttt{FuL[\{generation, color\}]} \\ \texttt{FuR[\{generation, color\}]} \end{pmatrix}$
$\nu_i = \begin{pmatrix} \mathrm{FvL}\left(\{\mathrm{gt1}\}\right) \\ 0 \end{pmatrix}$	`Fv[{generation}]` $= \begin{pmatrix} \texttt{FvL[\{generation\}]} \\ \texttt{0} \end{pmatrix}$

- Scalars

$\tilde{\nu}_{L,i}$	`SvL[{generation}]`	$\tilde{d}_{i\alpha}$	`Sd[{generation, color}]`
$\tilde{u}_{i\alpha}$	`Su[{generation, color}]`	$\tilde{e}_i$	`Se[{generation}]`
h_i	`hh[{generation}]`	A_i^0	`Ah[{generation}]`
H_i^-	`Hpm[{generation}]`		

- Vector Bosons

$g_{i\rho}$	`VG[{generation, lorentz}]`	W_ρ^-	`VWm[{lorentz}]`
γ_ρ	`VP[{lorentz}]`	Z_ρ	`VZ[{lorentz}]`

- Ghosts

η_i^G	`gG[{generation}]`	η^-	`gWm`
η^+	`gWmC`	η^γ	`gP`
η^Z	`gZ`		

5.8.3 Parameters

g_1	`g1`	g_2	`g2`	g_3	`g3`

Y_u	Yu	T_u	T[Yu]	Y_d	Yd
T_d	T[Yd]	Y_e	Ye	T_e	T[Ye]
μ	\[Mu]	B_μ	B[\[Mu]]	m_q^2	mq2
m_l^2	ml2	$m_{H_d}^2$	mHd2	$m_{H_u}^2$	mHu2
m_d^2	md2	m_u^2	mu2	m_e^2	me2
M_1	MassB	M_2	MassWB	M_3	MassG
v_d	vd	v_u	vu	Θ_W	ThetaW
Z^D	ZD	Z^U	ZU	Z^E	ZE
Z^H	ZH	Z^A	ZA	Z^+	ZP
N	ZN	U	UM	V	UP
α	\[Alpha]	β	\[Beta]		

Chapter 6

The MSSM with bilinear R-parity violation

6.1 Superfields

6.1.1 Vector Superfields

SF	Spin $\frac{1}{2}$	Spin 1	$SU(N)$	Coupling	Name
$\hat{B}$	$\lambda_{\tilde{B}}$	B	$U(1)$	g_1	hypercharge
$\hat{W}$	$\lambda_{\tilde{W}}$	W^-	SU(2)	g_2	left
$\hat{g}$	$\lambda_{\tilde{g}}$	g	SU(3)	g_3	color

6.1.2 Chiral Superfields

SF	Spin 0	Spin $\frac{1}{2}$	Generations	$(U(1)\otimes \text{SU}(2)\otimes \text{SU}(3))$
$\hat{q}$	$\tilde{q}$	q	3	$(\frac{1}{6},\mathbf{2},\mathbf{3})$
$\hat{l}$	$\tilde{l}$	l	3	$(-\frac{1}{2},\mathbf{2},\mathbf{1})$
$\hat{H}_d$	H_d	$\tilde{H}_d$	1	$(-\frac{1}{2},\mathbf{2},\mathbf{1})$
$\hat{H}_u$	H_u	$\tilde{H}_u$	1	$(\frac{1}{2},\mathbf{2},\mathbf{1})$
$\hat{d}$	$\tilde{d}_R^*$	d_R^*	3	$(\frac{1}{3},\mathbf{1},\overline{\mathbf{3}})$
$\hat{u}$	$\tilde{u}_R^*$	u_R^*	3	$(-\frac{2}{3},\mathbf{1},\overline{\mathbf{3}})$
$\hat{e}$	$\tilde{e}_R^*$	e_R^*	3	$(1,\mathbf{1},\mathbf{1})$

6.2 Superpotential and Lagrangian

6.2.1 Superpotential

$$W = Y_u\,\hat{q}\,\hat{H}_u\,\hat{u}\,-Y_d\,\hat{q}\,\hat{H}_d\,\hat{d}\,-Y_e\,\hat{l}\,\hat{H}_d\,\hat{e}\,+\mu\,\hat{H}_u\,\hat{H}_d\,+\epsilon\,\hat{l}\,\hat{H}_u \tag{6.1}$$

6.2.2 Softbreaking terms

$$L_{SB,W} = -\,H_d^0 H_u^0 B_\mu + H_d^- H_u^+ B_\mu - H_u^+ \tilde{e}_{L,i} B_{\epsilon,i} + H_u^0 \tilde{\nu}_{L,i} B_{\epsilon,i} + H_d^0 \tilde{d}^*_{R,k\gamma}\delta_{\alpha\gamma}\tilde{d}_{L,i\alpha} T_{d,ik}$$

$$
\begin{aligned}
& - H_d^- \tilde{d}^*_{R,k\gamma} \delta_{\alpha\gamma} \tilde{u}_{L,i\alpha} T_{d,ik} + H_d^0 \tilde{e}^*_{R,k} \tilde{e}_{L,i} T_{e,ik} - H_d^- \tilde{e}^*_{R,k} \tilde{\nu}_{L,i} T_{e,ik} - H_u^+ \tilde{u}^*_{R,k\gamma} \delta_{\alpha\gamma} \tilde{d}_{L,i\alpha} T_{u,ik} \\
& + H_u^0 \tilde{u}^*_{R,k\gamma} \delta_{\alpha\gamma} \tilde{u}_{L,i\alpha} T_{u,ik} + \text{h.c.}
\end{aligned} \tag{6.2}
$$

$$
\begin{aligned}
L_{SB,\phi} = & - m^2_{H_d} |H_d^0|^2 - m^2_{H_d} |H_d^-|^2 - m^2_{H_u} |H_u^0|^2 - m^2_{H_u} |H_u^+|^2 - \tilde{d}^*_{L,j\beta} \delta_{\alpha\beta} m^2_{q,ij} \tilde{d}_{L,i\alpha} \\
& - \tilde{d}^*_{R,i\alpha} \delta_{\alpha\beta} m^2_{d,ij} \tilde{d}_{R,j\beta} - \tilde{e}^*_{L,j} m^2_{l,ij} \tilde{e}_{L,i} - \tilde{e}^*_{R,i} m^2_{e,ij} \tilde{e}_{R,j} - \tilde{u}^*_{L,j\beta} \delta_{\alpha\beta} m^2_{q,ij} \tilde{u}_{L,i\alpha} \\
& - \tilde{u}^*_{R,i\alpha} \delta_{\alpha\beta} m^2_{u,ij} \tilde{u}_{R,j\beta} - \tilde{\nu}^*_{L,j} m^2_{l,ij} \tilde{\nu}_{L,i}
\end{aligned} \tag{6.3}
$$

$$
L_{SB,\lambda} = \frac{1}{2} \left(-\lambda^2_{\tilde{B}} M_1 - M_2 \lambda^2_{\tilde{W},i} - M_3 \lambda^2_{\tilde{g},i} + \text{h.c.} \right) \tag{6.4}
$$

6.2.3 Gauge fixing terms

Gauge fixing terms for eigenstates 'GaugeES'

$$
L_{GF} = -\frac{1}{2} \partial_\mu g \xi_G^{-1} - \frac{1}{2} \partial_\mu W^- \xi_W^{-1} \tag{6.5}
$$

Gauge fixing terms for eigenstates 'EWSB'

$$
L_{GF} = -\frac{1}{2} \partial_\mu \gamma \xi_P^{-1} - \frac{1}{2} \partial_\mu g \xi_G^{-1} - \frac{1}{2} \xi_Z^{-1} \Big(- A_1^0 m_Z \xi_Z + \partial_\mu Z \Big) - \xi_W^{-1} \Big(i H_1^- m_{W^-} \xi_W + \partial_\mu W^- \Big) \tag{6.6}
$$

6.2.4 Fields integrated out

None

6.3 Field Rotations

6.3.1 Rotations in gauge sector for eigenstates 'EWSB'

$$
W^-_{1\rho} = \frac{1}{\sqrt{2}} W^-_\rho + \frac{1}{\sqrt{2}} W^+_\rho \tag{6.7}
$$

$$
W^-_{2\rho} = -i \frac{1}{\sqrt{2}} W^-_\rho + i \frac{1}{\sqrt{2}} W^+_\rho \tag{6.8}
$$

$$
W^-_{3\rho} = \cos\Theta_W Z_\rho + \sin\Theta_W \gamma_\rho \tag{6.9}
$$

$$
B_\rho = \cos\Theta_W \gamma_\rho - \sin\Theta_W Z_\rho \tag{6.10}
$$

$$
\lambda_{\tilde{W},1} = \frac{1}{\sqrt{2}} \tilde{W}^- + \frac{1}{\sqrt{2}} \tilde{W}^+ \tag{6.11}
$$

$$
\lambda_{\tilde{W},2} = -i \frac{1}{\sqrt{2}} \tilde{W}^- + i \frac{1}{\sqrt{2}} \tilde{W}^+ \tag{6.12}
$$

$$
\lambda_{\tilde{W},3} = \tilde{W}^0 \tag{6.13}
$$

6.3.2 Rotations in Mass sector for eigenstates 'EWSB'

Mass Matrices for Scalars

- **Mass matrix for Down-Squarks**, Basis: $\left(\tilde{d}_{L,o_1\alpha_1}, \tilde{d}_{R,o_2\alpha_2}\right), \left(\tilde{d}^*_{L,p_1\beta_1}, \tilde{d}^*_{R,p_2\beta_2}\right)$

$$m^2_{\tilde{d}} = \begin{pmatrix} m_{11} & \frac{1}{\sqrt{2}}\delta_{\alpha_1\beta_2}\Big(v_d T_{d,o_1p_2} - v_u \mu^* Y_{d,o_1p_2}\Big) \\ \frac{1}{\sqrt{2}}\Big(v_d T^*_{d,p_1o_2} - v_u \mu Y^*_{d,p_1o_2}\Big)\delta_{\alpha_2\beta_1} & m_{22} \end{pmatrix} \tag{6.14}$$

$$m_{11} = \frac{1}{24}\delta_{\alpha_1\beta_1}\Big(12\Big(2m^2_{q,o_1p_1} + v_d^2\sum_{a=1}^{3} Y^*_{d,p_1a}Y_{d,o_1a}\Big) - \Big(3g_2^2 + g_1^2\Big)\delta_{o_1p_1}\Big(- v_u^2 + v_d^2 + \sum_{a=1}^{3} v_{L,a}^2\Big)\Big) \tag{6.15}$$

$$m_{22} = \frac{1}{12}\delta_{\alpha_2\beta_2}\Big(6\Big(2m^2_{d,p_2o_2} + v_d^2\sum_{a=1}^{3} Y^*_{d,ao_2}Y_{d,ap_2}\Big) - g_1^2\delta_{o_2p_2}\Big(- v_u^2 + v_d^2 + \sum_{a=1}^{3} v_{L,a}^2\Big)\Big) \tag{6.16}$$

This matrix is diagonalized by Z^D:

$$Z^D m^2_{\tilde{d}} Z^{D,\dagger} = m^{dia}_{2,\tilde{d}} \tag{6.17}$$

with

$$\tilde{d}_{L,i\alpha} = \sum_{t_2} Z^{D,*}_{ji}\tilde{d}_{j\alpha}\,, \qquad \tilde{d}_{R,i\alpha} = \sum_{t_2} Z^{D,*}_{ji}\tilde{d}_{j\alpha} \tag{6.18}$$

- **Mass matrix for Up-Squarks**, Basis: $\left(\tilde{u}_{L,o_1\alpha_1}, \tilde{u}_{R,o_2\alpha_2}\right), \left(\tilde{u}^*_{L,p_1\beta_1}, \tilde{u}^*_{R,p_2\beta_2}\right)$

$$m^2_{\tilde{u}} = \begin{pmatrix} m_{11} & m^*_{21} \\ m_{21} & m_{22} \end{pmatrix} \tag{6.19}$$

$$m_{11} = \frac{1}{24}\delta_{\alpha_1\beta_1}\Big(12\Big(2m^2_{q,o_1p_1} + v_u^2\sum_{a=1}^{3} Y^*_{u,p_1a}Y_{u,o_1a}\Big) - \Big(- 3g_2^2 + g_1^2\Big)\delta_{o_1p_1}\Big(- v_u^2 + v_d^2 + \sum_{a=1}^{3} v_{L,a}^2\Big)\Big) \tag{6.20}$$

$$m_{21} = \frac{1}{\sqrt{2}}\delta_{\alpha_2\beta_1}\Big(v_u T^*_{u,p_1o_2} + Y^*_{u,p_1o_2}\Big(- v_d\mu + \sum_{a=1}^{3} v_{L,a}\epsilon_a\Big)\Big) \tag{6.21}$$

$$m_{22} = \frac{1}{6}\delta_{\alpha_2\beta_2}\Big(3v_u^2\sum_{a=1}^{3} Y^*_{u,ao_2}Y_{u,ap_2} + 6m^2_{u,p_2o_2} + g_1^2\delta_{o_2p_2}\Big(- v_u^2 + v_d^2 + \sum_{a=1}^{3} v_{L,a}^2\Big)\Big) \tag{6.22}$$

This matrix is diagonalized by Z^U:

$$Z^U m^2_{\tilde{u}} Z^{U,\dagger} = m^{dia}_{2,\tilde{u}} \tag{6.23}$$

with

$$\tilde{u}_{L,i\alpha} = \sum_{t_2} Z^{U,*}_{ji}\tilde{u}_{j\alpha}\,, \qquad \tilde{u}_{R,i\alpha} = \sum_{t_2} Z^{U,*}_{ji}\tilde{u}_{j\alpha} \tag{6.24}$$

- **Mass matrix for Higgs**, Basis: $\left(\phi_d, \phi_u, \phi_{L,o_3}\right), \left(\phi_d, \phi_u, \phi_{L,p_3}\right)$

$$m_h^2 = \begin{pmatrix} m_{11} & m_{21}^* & m_{31}^* \\ m_{21} & m_{22} & m_{32}^* \\ m_{31} & m_{32} & m_{33} \end{pmatrix} \tag{6.25}$$

$$m_{11} = \frac{1}{8}\Big(3g_1^2 v_d^2 + 3g_2^2 v_d^2 + 8m_{H_d}^2 + 8|\mu|^2 + \Big(g_1^2 + g_2^2\Big)\sum_{a=1}^{3} v_{L,a}^2 - g_1^2 v_u^2 - g_2^2 v_u^2\Big) \tag{6.26}$$

$$m_{21} = \frac{1}{4}\Big(- 4\Re\Big(B_\mu\Big) - \Big(g_1^2 + g_2^2\Big)v_d v_u\Big) \tag{6.27}$$

$$m_{22} = \frac{1}{8}\Big(3g_1^2 v_u^2 + 3g_2^2 v_u^2 + 8m_{H_u}^2 + 8|\mu|^2 + 8\sum_{a=1}^{3}|\epsilon_a|^2 - \Big(g_1^2 + g_2^2\Big)\sum_{a=1}^{3} v_{L,a}^2 - g_1^2 v_d^2 - g_2^2 v_d^2\Big) \tag{6.28}$$

$$m_{31} = \frac{1}{4}\Big(- 2\mu^* \epsilon_{o_3} - 2\mu \epsilon_{o_3}^* + 4\Re\Big(m_{lH,o_3}^2\Big) + g_1^2 v_d \sum_{a=1}^{3} v_{L,a} + g_2^2 v_d \sum_{a=1}^{3} v_{L,a}\Big) \tag{6.29}$$

$$m_{32} = -\frac{1}{4}\Big(g_1^2 + g_2^2\Big)v_u \sum_{a=1}^{3} v_{L,a} + \Re\Big(B_{\epsilon,o_3}\Big) \tag{6.30}$$

$$\begin{aligned} m_{33} = &\frac{1}{8}\Big(\Big(g_1^2 + g_2^2\Big)\delta_{o_3 p_3}\Big(- v_u^2 + v_d^2 + \sum_{a=1}^{3} v_{L,a}^2\Big) \\ &+ 2\Big(2\epsilon_{o_3}^* \epsilon_{p_3} + 2\epsilon_{p_3}^* \epsilon_{o_3} + 2m_{l,o_3 p_3}^2 + 2m_{l,p_3 o_3}^2 + g_1^2 \sum_{a=1}^{3} v_{L,a} \sum_{b=1}^{3} v_{L,b} + g_2^2 \sum_{a=1}^{3} v_{L,a} \sum_{b=1}^{3} v_{L,b}\Big)\Big) \end{aligned} \tag{6.31}$$

This matrix is diagonalized by Z^H:

$$Z^H m_h^2 Z^{H,\dagger} = m_{2,h}^{dia} \tag{6.32}$$

with

$$\phi_d = \sum_{t_2} Z_{j1}^H h_j\,, \qquad \phi_u = \sum_{t_2} Z_{j2}^H h_j\,, \qquad \phi_{L,i} = \sum_{t_2} Z_{ji}^H h_j \tag{6.33}$$

- **Mass matrix for Pseudo-Scalar Higgs**, Basis: $\left(\sigma_d, \sigma_u, \sigma_{L,o_3}\right), \left(\sigma_d, \sigma_u, \sigma_{L,p_3}\right)$

$$m_{A^0}^2 = \begin{pmatrix} m_{11} & \Re\Big(B_\mu\Big) & m_{31}^* \\ \Re\Big(B_\mu\Big) & m_{22} & -\Re\Big(B_{\epsilon,p_3}\Big) \\ m_{31} & -\Re\Big(B_{\epsilon,o_3}\Big) & m_{33} \end{pmatrix} \tag{6.34}$$

$$m_{11} = \frac{1}{8}\Big(8m_{H_d}^2 + 8|\mu|^2 + \Big(g_1^2 + g_2^2\Big)\sum_{a=1}^{3} v_{L,a}^2 + g_1^2 v_d^2 - g_1^2 v_u^2 + g_2^2 v_d^2 - g_2^2 v_u^2\Big) \tag{6.35}$$

$$m_{22} = \frac{1}{8}\Big(8m_{H_u}^2 + 8|\mu|^2 + 8\sum_{a=1}^{3}|\epsilon_a|^2 - \Big(g_1^2 + g_2^2\Big)\sum_{a=1}^{3}v_{L,a}^2 - g_1^2 v_d^2 + g_1^2 v_u^2 - g_2^2 v_d^2 + g_2^2 v_u^2\Big) \tag{6.36}$$

$$m_{31} = \frac{1}{2}\Big(2\Re\Big(m_{lH,o_3}^2\Big) - \mu^*\epsilon_{o_3} - \mu\epsilon_{o_3}^*\Big) \tag{6.37}$$

$$m_{33} = \frac{1}{8}\Big(4\Big(\epsilon_{o_3}^*\epsilon_{p_3} + \epsilon_{p_3}^*\epsilon_{o_3} + m_{l,o_3p_3}^2 + m_{l,p_3o_3}^2\Big) + \Big(g_1^2 + g_2^2\Big)\delta_{o_3p_3}\Big(-v_u^2 + v_d^2 + \sum_{a=1}^{3}v_{L,a}^2\Big)\Big) \tag{6.38}$$

This matrix is diagonalized by Z^A:

$$Z^A m_{A^0}^2 Z^{A,\dagger} = m_{2,A^0}^{dia} \tag{6.39}$$

with

$$\sigma_d = \sum_{t_2} Z_{j1}^A A_j^0\,, \qquad \sigma_u = \sum_{t_2} Z_{j2}^A A_j^0\,, \qquad \sigma_{L,i} = \sum_{t_2} Z_{ji}^A A_j^0 \tag{6.40}$$

- **Mass matrix for Charged Higgs**, Basis: $\Big(H_d^-, H_u^{+,*}, \tilde{e}_{L,o_3}, \tilde{e}_{R,o_4}\Big), \Big(H_d^{-,*}, H_u^+, \tilde{e}_{L,p_3}^*, \tilde{e}_{R,p_4}^*\Big)$

$$m_{H^-}^2 = \begin{pmatrix} m_{11} & \frac{1}{4}g_2^2 v_d v_u + B_\mu & m_{31}^* & m_{41}^* \\ \frac{1}{4}g_2^2 v_d v_u + B_\mu^* & m_{22} & m_{32}^* & m_{42}^* \\ m_{31} & m_{32} & m_{33} & m_{43}^* \\ m_{41} & m_{42} & m_{43} & m_{44} \end{pmatrix} \tag{6.41}$$

$$\begin{aligned} m_{11} = \frac{1}{8}\Big(&8m_{H_d}^2 + g_1^2 v_d^2 + g_2^2 v_d^2 - g_1^2 v_u^2 + g_2^2 v_u^2 + 8|\mu|^2 + \Big(-g_2^2 + g_1^2\Big)\sum_{a=1}^{3}v_{L,a}^2 \\ &+ 4\sum_{c=1}^{3}\sum_{b=1}^{3}\sum_{a=1}^{3}Y_{e,ca}^* Y_{e,ba} v_{L,b} v_{L,c}\Big) \end{aligned} \tag{6.42}$$

$$m_{22} = \frac{1}{8}\Big(8m_{H_u}^2 + 8|\mu|^2 + 8\sum_{a=1}^{3}|\epsilon_a|^2 + \Big(-g_1^2 + g_2^2\Big)\sum_{a=1}^{3}v_{L,a}^2 - g_1^2 v_d^2 + g_1^2 v_u^2 + g_2^2 v_d^2 + g_2^2 v_u^2\Big) \tag{6.43}$$

$$m_{31} = \frac{1}{4}\Big(-2v_d\sum_{b=1}^{3}\sum_{a=1}^{3}Y_{e,ba}^* Y_{e,o_3a} v_{L,b} - 4\mu^*\epsilon_{o_3} + g_2^2 v_d\sum_{a=1}^{3}v_{L,a}\Big) + m_{lH,o_3}^{2,*} \tag{6.44}$$

$$m_{32} = -B_{\epsilon,o_3} + \frac{1}{4}g_2^2 v_u\sum_{a=1}^{3}v_{L,a} \tag{6.45}$$

$$m_{33} = \frac{1}{8}\Big(2g_2^2\sum_{a=1}^{3}v_{L,a}\sum_{b=1}^{3}v_{L,b} + 4v_d^2\sum_{a=1}^{3}Y_{e,p_3a}^* Y_{e,o_3a} + 8\epsilon_{p_3}^*\epsilon_{o_3} + 8m_{l,o_3p_3}^2 + \Big(-g_2^2 + g_1^2\Big)\delta_{o_3p_3}\Big(-v_u^2 + v_d^2 + \sum_{a=1}^{3}v_{L,a}^2\Big)\Big) \tag{6.46}$$

$$m_{41} = -\frac{1}{\sqrt{2}}\Big(v_u\sum_{a=1}^{3}Y_{e,ao_4}^*\epsilon_a + \sum_{a=1}^{3}T_{e,ao_4}^* v_{L,a}\Big) \tag{6.47}$$

$$m_{42} = -\frac{1}{\sqrt{2}}\Big(\mu\sum_{a=1}^{3}Y_{e,ao_4}^* v_{L,a} + v_d\sum_{a=1}^{3}Y_{e,ao_4}^*\epsilon_a\Big) \tag{6.48}$$

$$m_{43} = \frac{1}{\sqrt{2}}\Big(v_d T^*_{e,p_3 o_4} - v_u \mu Y^*_{e,p_3 o_4}\Big) \tag{6.49}$$

$$m_{44} = \frac{1}{4}\Big(2\Big(2m^2_{e,p_4 o_4} + \sum_{a=1}^{3} v_{L,a} Y_{e,a p_4} \sum_{b=1}^{3} Y^*_{e,b o_4} v_{L,b} + v_d^2 \sum_{a=1}^{3} Y^*_{e,a o_4} Y_{e,a p_4}\Big) - g_1^2 \delta_{o_4 p_4}\Big(- v_u^2 + v_d^2 + \sum_{a=1}^{3} v^2_{L,a}\Big)\Big) \tag{6.50}$$

This matrix is diagonalized by Z^+:

$$Z^+ m^2_{H^-} Z^{+,\dagger} = m^{dia}_{2,H^-} \tag{6.51}$$

with

$$H_d^- = \sum_{t_2} Z^{+,*}_{j1} H_j^- \,, \qquad H_u^+ = \sum_{t_2} Z^{+}_{j2} H_j^+ \,, \qquad \tilde{e}_{L,i} = \sum_{t_2} Z^{+,*}_{ji} H_j^- \tag{6.52}$$

$$\tilde{e}_{R,i} = \sum_{t_2} Z^{+,*}_{ji} H_j^- \tag{6.53}$$

Mass Matrices for Fermions

- **Mass matrix for Neutralinos**, Basis: $\Big(\nu_{L,o_1}, \lambda_{\tilde{B}}, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0\Big), \Big(\nu_{L,p_1}, \lambda_{\tilde{B}}, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0\Big)$

$$m_{\tilde{\chi}^0} = \begin{pmatrix} 0 & -\frac{1}{2} g_1 \sum_{a=1}^3 v_{L,a} & \frac{1}{2} g_2 \sum_{a=1}^3 v_{L,a} & 0 & \epsilon_{o_1} \\ -\frac{1}{2} g_1 \sum_{a=1}^3 v_{L,a} & M_1 & 0 & -\frac{1}{2} g_1 v_d & \frac{1}{2} g_1 v_u \\ \frac{1}{2} g_2 \sum_{a=1}^3 v_{L,a} & 0 & M_2 & \frac{1}{2} g_2 v_d & -\frac{1}{2} g_2 v_u \\ 0 & -\frac{1}{2} g_1 v_d & \frac{1}{2} g_2 v_d & 0 & -\mu \\ \epsilon_{p_1} & \frac{1}{2} g_1 v_u & -\frac{1}{2} g_2 v_u & -\mu & 0 \end{pmatrix} \tag{6.54}$$

This matrix is diagonalized by N:

$$N m_{\tilde{\chi}^0} N^\dagger = m^{dia}_{\tilde{\chi}^0} \tag{6.55}$$

with

$$\nu_{L,i} = \sum_{t_2} N^*_{ji} \lambda_j^0 \,, \qquad \lambda_{\tilde{B}} = \sum_{t_2} N^*_{j4} \lambda_j^0 \,, \qquad \tilde{W}^0 = \sum_{t_2} N^*_{j5} \lambda_j^0 \tag{6.56}$$

$$\tilde{H}_d^0 = \sum_{t_2} N^*_{j6} \lambda_j^0 \,, \qquad \tilde{H}_u^0 = \sum_{t_2} N^*_{j7} \lambda_j^0 \tag{6.57}$$

- **Mass matrix for Charginos**, Basis: $\Big(e_{L,o_1}, \tilde{W}^-, \tilde{H}_d^-\Big), \Big(e^*_{R,p_1}, \tilde{W}^+, \tilde{H}_u^+\Big)$

$$m_{\tilde{\chi}^-} = \begin{pmatrix} \frac{1}{\sqrt{2}} v_d Y_{e,o_1 p_1} & \frac{1}{\sqrt{2}} g_2 \sum_{a=1}^3 v_{L,a} & -\epsilon_{o_1} \\ 0 & M_2 & \frac{1}{\sqrt{2}} g_2 v_u \\ -\frac{1}{\sqrt{2}} \sum_{a=1}^3 v_{L,a} Y_{e,a p_1} & \frac{1}{\sqrt{2}} g_2 v_d & \mu \end{pmatrix} \tag{6.58}$$

This matrix is diagonalized by U and V

$$U^* m_{\tilde{\chi}^-} V^\dagger = m^{dia}_{\tilde{\chi}^-} \tag{6.59}$$

with

$$e_{L,i} = \sum_{t_2} U^*_{ji}\lambda^-_j\,, \qquad \tilde{W}^- = \sum_{t_2} U^*_{j4}\lambda^-_j\,, \qquad \tilde{H}^-_d = \sum_{t_2} U^*_{j5}\lambda^-_j \tag{6.60}$$

$$e_{R,i} = \sum_{t_2} V_{ij}\lambda^{+,*}_j\,, \qquad \tilde{W}^+ = \sum_{t_2} V^*_{4j}\lambda^+_j\,, \qquad \tilde{H}^+_u = \sum_{t_2} V^*_{5j}\lambda^+_j \tag{6.61}$$

- **Mass matrix for Down-Quarks**, Basis: $\left(d_{L,o_1\alpha_1}\right), \left(d^*_{R,p_1\beta_1}\right)$

$$m_d = \begin{pmatrix} \frac{1}{\sqrt{2}}v_d\delta_{\alpha_1\beta_1}Y_{d,o_1p_1} \end{pmatrix} \tag{6.62}$$

This matrix is diagonalized by U^d_L and U^d_R

$$U^{d,*}_L m_d U^{d,\dagger}_R = m^{dia}_d \tag{6.63}$$

with

$$d_{L,i\alpha} = \sum_{t_2} U^{d,*}_{L,ji} D_{L,j\alpha} \tag{6.64}$$

$$d_{R,i\alpha} = \sum_{t_2} U^d_{R,ij} D^*_{R,j\alpha} \tag{6.65}$$

- **Mass matrix for Up-Quarks**, Basis: $\left(u_{L,o_1\alpha_1}\right), \left(u^*_{R,p_1\beta_1}\right)$

$$m_u = \begin{pmatrix} \frac{1}{\sqrt{2}}v_u\delta_{\alpha_1\beta_1}Y_{u,o_1p_1} \end{pmatrix} \tag{6.66}$$

This matrix is diagonalized by U^u_L and U^u_R

$$U^{u,*}_L m_u U^{u,\dagger}_R = m^{dia}_u \tag{6.67}$$

with

$$u_{L,i\alpha} = \sum_{t_2} U^{u,*}_{L,ji} U_{L,j\alpha} \tag{6.68}$$

$$u_{R,i\alpha} = \sum_{t_2} U^u_{R,ij} U^*_{R,j\alpha} \tag{6.69}$$

6.4 Vacuum Expectation Values

$$H^0_d = \frac{1}{\sqrt{2}}\phi_d + \frac{1}{\sqrt{2}}v_d + i\frac{1}{\sqrt{2}}\sigma_d \tag{6.70}$$

$$H^0_u = \frac{1}{\sqrt{2}}\phi_u + \frac{1}{\sqrt{2}}v_u + i\frac{1}{\sqrt{2}}\sigma_u \tag{6.71}$$

$$\tilde{\nu}_L = \frac{1}{\sqrt{2}}\phi_L + \frac{1}{\sqrt{2}}v_L + i\frac{1}{\sqrt{2}}\sigma_L \tag{6.72}$$

6.5 Tadpole Equations

$$\frac{\partial V}{\partial v_d} = \frac{1}{8}\Big(8m_{H_d}^2 v_d + g_1^2 v_d^3 + g_2^2 v_d^3 - g_1^2 v_d v_u^2 - g_2^2 v_d v_u^2 - 8 v_u \Re\Big(B_\mu\Big) + 4\sum_{a=1}^{3} m_{lH,a}^{2,*} v_{L,a}$$
$$- 4\mu\sum_{a=1}^{3}\epsilon_a^* v_{L,a} + 4\sum_{a=1}^{3} m_{lH,a}^2 v_{L,a} + g_1^2 v_d \sum_{a=1}^{3} v_{L,a}^2 + g_2^2 v_d \sum_{a=1}^{3} v_{L,a}^2 + \mu^*\Big(-4\sum_{a=1}^{3} v_{L,a}\epsilon_a + 8 v_d \mu\Big)\Big) \tag{6.73}$$

$$\frac{\partial V}{\partial v_u} = \frac{1}{8}\Big(8m_{H_u}^2 v_u - g_1^2 v_d^2 v_u - g_2^2 v_d^2 v_u + g_1^2 v_u^3 + g_2^2 v_u^3 + 8 v_u |\mu|^2 - 8 v_d \Re\Big(B_\mu\Big)$$
$$+ 8 v_u \sum_{a=1}^{3} |\epsilon_a|^2 + 4\sum_{a=1}^{3} B_{\epsilon,a}^* v_{L,a} - g_1^2 v_u \sum_{a=1}^{3} v_{L,a}^2 - g_2^2 v_u \sum_{a=1}^{3} v_{L,a}^2 + 4\sum_{a=1}^{3} v_{L,a} B_{\epsilon,a}\Big) \tag{6.74}$$

$$\frac{\partial V}{\partial v_L} = \frac{1}{8}\Big(4 v_u B_{\epsilon,i}^* + 8 v_d \Re\Big(m_{lH,i}^2\Big) + 4\sum_{a=1}^{3} m_{l,ia}^2 v_{L,a} + 4\sum_{a=1}^{3} m_{l,ai}^2 v_{L,a} + \epsilon_i^*\Big(4\sum_{a=1}^{3} v_{L,a}\epsilon_a - 4 v_d \mu\Big) + g_1^2 v_d^2 v_{L,i}$$
$$+ g_2^2 v_d^2 v_{L,i} - g_1^2 v_u^2 v_{L,i} - g_2^2 v_u^2 v_{L,i} + g_1^2 \sum_{a=1}^{3} v_{L,a}^2 v_{L,i} + g_2^2 \sum_{a=1}^{3} v_{L,a}^2 v_{L,i} - 4 v_d \mu^* \epsilon_i$$
$$+ 4\sum_{a=1}^{3}\epsilon_a^* v_{L,a}\epsilon_i + 4 v_u B_{\epsilon,i}\Big) \tag{6.75}$$

6.6 Particle content for eigenstates 'EWSB'

Name	Type	complex/real	Generations	Indices
$\tilde{d}$	Scalar	complex	6	generation, color
$\tilde{u}$	Scalar	complex	6	generation, color
h	Scalar	real	5	generation
A^0	Scalar	real	5	generation
H^-	Scalar	complex	8	generation
$\tilde{g}$	Fermion	Majorana	8	generation
$\tilde{\chi}^0$	Fermion	Majorana	7	generation
$\tilde{\chi}^-$	Fermion	Dirac	5	generation
d	Fermion	Dirac	3	generation, color
u	Fermion	Dirac	3	generation, color
g	Vector	real	8	generation, lorentz
W^-	Vector	complex	1	lorentz
γ	Vector	real	1	lorentz
Z	Vector	real	1	lorentz
η^G	Ghost	real	8	generation
η^-	Ghost	complex	1	

η^+	Ghost	complex	1
η^γ	Ghost	real	1
η^Z	Ghost	real	1

6.7 Modelfile for SARAH

```
Off[General::spell]
Print["Model file for the MSSM loaded"];

ModelNameLaTeX ="MSSM-BiRpV";


(*-------------------------------------------*)
(*   Particle Content*)
(*-------------------------------------------*)

(* Gauge Superfields *)

Gauge[[1]]={B,   U[1], hypercharge, g1,False};
Gauge[[2]]={WB, SU[2], left,        g2,True};
Gauge[[3]]={G,  SU[3], color,       g3,False};


(* Chiral Superfields *)

Fields[[1]] = {{uL,  dL},  3, q,   1/6, 2, 3};
Fields[[2]] = {{vL,  eL},  3, l,  -1/2, 2, 1};
Fields[[3]] = {{Hd0, Hdm}, 1, Hd, -1/2, 2, 1};
Fields[[4]] = {{Hup, Hu0}, 1, Hu,  1/2, 2, 1};

Fields[[5]] = {conj[dR], 3, d,  1/3, 1, -3};
Fields[[6]] = {conj[uR], 3, u, -2/3, 1, -3};
Fields[[7]] = {conj[eR], 3, e,    1, 1,  1};


(*----------------------------------------------------*)
(* Superpotential *)
(*----------------------------------------------------*)

SuperPotential = { {{1, Yu},{q,Hu,u}}, {{-1,Yd},{q,Hd,d}},
                   {{-1,Ye},{l,Hd,e}}, {{1,\[Mu]},{Hu,Hd}},
                   {{1,\[Epsilon]},{l,Hu}}};


(*-------------------------------------------*)
(* Integrate Out or Delete Particles         *)
(*-------------------------------------------*)

IntegrateOut={};
DeleteParticles={};
```

```
(*-----------------------------------------------*)
(*   DEFINITION                                   *)
(*-----------------------------------------------*)

NameOfStates={GaugeES,EWSB};

DEFINITION[GaugeES][GaugeFixing]=
{ {Der[VWB],  -1/(2 RXi[W])},
     {Der[VG],   -1/(2 RXi[G]) }};

DEFINITION[GaugeES][Additional]=
 {{{conj[SvL], SHd0}, {1, mHL2}},
  {{conj[SeL], SHdm}, {1, mHL2}}};

(* Gauge Sector *)

DEFINITION[EWSB][GaugeSector]=
{{VWB,{1,{VWm,1/Sqrt[2]},{conj[VWm],1/Sqrt[2]}},
      {2,{VWm,-\[ImaginaryI]/Sqrt[2]},{conj[VWm],\[ImaginaryI]/Sqrt[2]}},
      {3,{VP,Sin[ThetaW]},{VZ,Cos[ThetaW]}}},
 {VB, {1,{VP,Cos[ThetaW]},{VZ,-Sin[ThetaW]}}},
 {fWB,{1,{fWm,1/Sqrt[2]},{fWp,1/Sqrt[2]}},
      {2,{fWm,-\[ImaginaryI]/Sqrt[2]},{fWp,\[ImaginaryI]/Sqrt[2]}},
      {3,{fW0,1}}}};




(* ----- VEVs ---- *)

DEFINITION[EWSB][VEVs]=
{    {SHd0, {vd, 1/Sqrt[2]}, {sigmad, \[ImaginaryI]/Sqrt[2]},{phid, \
1/Sqrt[2]}},
     {SHu0, {vu, 1/Sqrt[2]}, {sigmau, \[ImaginaryI]/Sqrt[2]},{phiu, \
1/Sqrt[2]}},
     {SvL, {vL, 1/Sqrt[2]}, {sigmaL, \[ImaginaryI]/Sqrt[2]},{phiL, \
1/Sqrt[2]}}     };


DEFINITION[EWSB][Phases]=
{    {fG, PhaseGlu}
    };


DEFINITION[EWSB][MatterSector]=
{    {{SdL, SdR}, {Sd, ZD}},
```

```
     {{SuL, SuR}, {Su, ZU}},
     {{phid, phiu,phiL}, {hh, ZH}},
     {{sigmad, sigmau,sigmaL}, {Ah, ZA}},
     {{SHdm,conj[SHup],SeL,SeR},{Hpm,ZP}},
     {{FvL,fB, fW0, FHd0, FHu0}, {L0, ZN}},
     {{{FeL,fWm, FHdm}, {conj[FeR],fWp, FHup}},  {{Lm,UM}, {Lp,UP}}},
     {{{FdL},{conj[FdR]}},{{FDL,ZDL},{FDR,ZDR}}},
     {{{FuL},{conj[FuR]}},{{FUL,ZUL},{FUR,ZUR}}}
       };


(*--- Gauge Fixing ---- *)

DEFINITION[EWSB][GaugeFixing]=
  { {Der[VP],                                           - 1/(2 RXi[P])},
{Der[VWm]+\[ImaginaryI] Mass[VWm] RXi[W] Hpm[{1}],   - 1/(RXi[W])},
{Der[VZ] - Mass[VZ] RXi[Z] Ah[{1}],                 - 1/(2 RXi[Z])},
{Der[VG],                                           - 1/(2 RXi[G])}};

(*--------------------------------------------------------*)
(* Dirac-Spinors *)
(*--------------------------------------------------------*)

dirac[[1]] = {Fd,  FDL, conj[FDR]};
dirac[[2]] = {Fu,  FUL, conj[FUR]};
dirac[[3]] = {Chi, L0, conj[L0]};
dirac[[4]] = {Cha, Lm, conj[Lp]};
dirac[[5]] = {Glu, fG, conj[fG]};

(* Unbroken EW *)

dirac[[6]] = {Bino, fB, conj[fB]};
dirac[[7]] = {Wino, fWB, conj[fWB]};
dirac[[8]] = {H0, FHd0, conj[FHu0]};
dirac[[9]] = {HC, FHdm, conj[FHup]};
dirac[[10]] = {Fd1, FdL, 0};
dirac[[11]] = {Fd2, 0, FdR};
dirac[[12]] = {Fu1, FuL, 0};
dirac[[13]] = {Fu2, 0, FuR};
dirac[[14]] = {Fe1, FeL, 0};
dirac[[15]] = {Fe2, 0, FeR};
dirac[[16]] = {Fv, FvL, 0};


(*--------------------------------------------------------*)
(* Automatized Output        *)
(*--------------------------------------------------------*)
```

```
(*
makeOutput = {
                    {EWSB, {TeX, FeynArts}}
              };
             *)

SpectrumFile= None;
```

6.8 Implementation in SARAH

Model directory: `MSSM-RpV/Bi`

6.8.1 Particles for eigenstates 'GaugeES'

- Fermions

$\tilde{B} = \begin{pmatrix} \lambda_{\tilde{B}} \\ \lambda^*_{\tilde{B}} \end{pmatrix}$	$\texttt{Bino} = \begin{pmatrix} \texttt{fB} \\ \texttt{conj[fB]} \end{pmatrix}$
$d^1_{i\alpha} = \begin{pmatrix} d_{L,i\alpha} \\ 0 \end{pmatrix}$	$\texttt{Fd1[\{generation, color\}]} = \begin{pmatrix} \texttt{FdL[\{generation, color\}]} \\ 0 \end{pmatrix}$
$d^2_{i\alpha} = \begin{pmatrix} 0 \\ d_{R,i\alpha} \end{pmatrix}$	$\texttt{Fd2[\{generation, color\}]} = \begin{pmatrix} 0 \\ \texttt{FdR[\{generation, color\}]} \end{pmatrix}$
$e^1_i = \begin{pmatrix} e_{L,i} \\ 0 \end{pmatrix}$	$\texttt{Fe1[\{generation\}]} = \begin{pmatrix} \texttt{FeL[\{generation\}]} \\ 0 \end{pmatrix}$
$e^2_i = \begin{pmatrix} 0 \\ e_{R,i} \end{pmatrix}$	$\texttt{Fe2[\{generation\}]} = \begin{pmatrix} 0 \\ \texttt{FeR[\{generation\}]} \end{pmatrix}$
$u^1_{i\alpha} = \begin{pmatrix} u_{L,i\alpha} \\ 0 \end{pmatrix}$	$\texttt{Fu1[\{generation, color\}]} = \begin{pmatrix} \texttt{FuL[\{generation, color\}]} \\ 0 \end{pmatrix}$
$u^2_{i\alpha} = \begin{pmatrix} 0 \\ u_{R,i\alpha} \end{pmatrix}$	$\texttt{Fu2[\{generation, color\}]} = \begin{pmatrix} 0 \\ \texttt{FuR[\{generation, color\}]} \end{pmatrix}$
$\nu_i = \begin{pmatrix} \nu_{L,i} \\ 0 \end{pmatrix}$	$\texttt{Fv[\{generation\}]} = \begin{pmatrix} \texttt{FvL[\{generation\}]} \\ 0 \end{pmatrix}$
$\tilde{g}_i = \begin{pmatrix} \lambda_{\tilde{g},i} \\ \lambda^*_{\tilde{g},i} \end{pmatrix}$	$\texttt{Glu[\{generation\}]} = \begin{pmatrix} \texttt{fG[\{generation\}]} \\ \texttt{conj[fG[\{generation\}]]} \end{pmatrix}$
$\tilde{H}^0 = \begin{pmatrix} \tilde{H}^0_d \\ \tilde{H}^{0,*}_u \end{pmatrix}$	$\texttt{H0} = \begin{pmatrix} \texttt{FHd0} \\ \texttt{conj[FHu0]} \end{pmatrix}$

$\tilde{H}^- = \begin{pmatrix} \tilde{H}_d^- \\ \tilde{H}_u^{+,*} \end{pmatrix}$	$\texttt{HC} = \begin{pmatrix} \texttt{FHdm} \\ \texttt{conj[FHup]} \end{pmatrix}$
$\tilde{W}_i = \begin{pmatrix} \lambda_{\tilde{W},i} \\ \lambda^*_{\tilde{W},i} \end{pmatrix}$	$\texttt{Wino[\{generation\}]} = \begin{pmatrix} \texttt{fWB[\{generation\}]} \\ \texttt{conj[fWB[\{generation\}]]} \end{pmatrix}$

- Scalars

$\tilde{d}_{L,i\alpha}$	`SdL[{generation, color}]`	$\tilde{u}_{L,i\alpha}$	`SuL[{generation, color}]`
$\tilde{e}_{L,i}$	`SeL[{generation}]`	$\tilde{\nu}_{L,i}$	`SvL[{generation}]`
H_d^0	`SHd0`	H_d^-	`SHdm`
H_u^0	`SHu0`	H_u^+	`SHup`
$\tilde{d}_{R,i\alpha}$	`SdR[{generation, color}]`	$\tilde{u}_{R,i\alpha}$	`SuR[{generation, color}]`
$\tilde{e}_{R,i}$	`SeR[{generation}]`		

- Vector Bosons

B_ρ	`VB[{lorentz}]`	$W^-_{i\rho}$	`VWB[{generation, lorentz}]`
$g_{i\rho}$	`VG[{generation, lorentz}]`		

- Ghosts

η^B	`gB`	$\mathrm{gWB}\Big(\{\mathrm{gt1}\}\Big)$	`gWB[{generation}]`
η^G_i	`gG[{generation}]`		

6.8.2 Particles for eigenstates 'EWSB'

- Fermions

$\tilde{\chi}^-_i = \begin{pmatrix} \lambda^-_i \\ \lambda^{+,*}_i \end{pmatrix}$	`Cha[{generation}]`	=	`( Lm[{generation}] , conj[Lp[{generation}]] )`
$\tilde{\chi}^0_i = \begin{pmatrix} \lambda^0_i \\ \lambda^{0,*}_i \end{pmatrix}$	`Chi[{generation}]`	=	`( L0[{generation}] , conj[L0[{generation}]] )`
$d_{i\alpha} = \begin{pmatrix} D_{L,i\alpha} \\ D^*_{R,i\alpha} \end{pmatrix}$	`Fd[{generation, color}]`	=	`( FDL[{generation, color}] , conj[FDR[{generation, color}]] )`
$u_{i\alpha} = \begin{pmatrix} U_{L,i\alpha} \\ U^*_{R,i\alpha} \end{pmatrix}$	`Fu[{generation, color}]`	=	`( FUL[{generation, color}] , conj[FUR[{generation, color}]] )`
$\tilde{g}_i = \begin{pmatrix} \lambda_{\tilde{g},i} \\ \lambda^*_{\tilde{g},i} \end{pmatrix}$	`Glu[{generation}]`	=	`( fG[{generation}] , conj[fG[{generation}]] )`

- Scalars

$\tilde{d}_{i\alpha}$	Sd[{generation, color}]	$\tilde{u}_{i\alpha}$	Su[{generation, color}]
h_i	hh[{generation}]	A^0_i	Ah[{generation}]
H^-_i	Hpm[{generation}]		

- Vector Bosons

$g_{i\rho}$	VG[{generation, lorentz}]	W^-_ρ	VWm[{lorentz}]
γ_ρ	VP[{lorentz}]	Z_ρ	VZ[{lorentz}]

- Ghosts

η^G_i	gG[{generation}]	η^-	gWm
η^+	gWmC	η^γ	gP
η^Z	gZ		

6.8.3 Parameters

g_1	`g1`	g_2	`g2`	g_3	`g3`
Y_u	`Yu`	T_u	`T[Yu]`	Y_d	`Yd`
T_d	`T[Yd]`	Y_e	`Ye`	T_e	`T[Ye]`
μ	`\[Mu]`	B_μ	`B[\[Mu]]`	ϵ	`\[Epsilon]`
B_ϵ	`B[\[Epsilon]]`	m_q^2	`mq2`	m_l^2	`ml2`
$m_{H_d}^2$	`mHd2`	$m_{H_u}^2$	`mHu2`	m_d^2	`md2`
m_u^2	`mu2`	m_e^2	`me2`	M_1	`MassB`
M_2	`MassWB`	M_3	`MassG`	m_{lH}^2	`mHL2`
v_d	`vd`	v_u	`vu`	v_L	`vL`
Θ_W	`ThetaW`	$\phi_{\tilde{g}}$	`PhaseGlu`	Z^D	`ZD`
Z^U	`ZU`	Z^H	`ZH`	Z^A	`ZA`
Z^+	`ZP`	N	`ZN`	U	`UM`
V	`UP`	U_L^d	`ZDL`	U_R^d	`ZDR`
U_L^u	`ZUL`	U_R^u	`ZUR`		

Chapter 7

The MSSM with R-parity and lepton number violation

7.1 Superfields

7.1.1 Vector Superfields

SF	Spin $\frac{1}{2}$	Spin 1	$SU(N)$	Coupling	Name
$\hat{B}$	$\lambda_{\tilde{B}}$	B	$U(1)$	g_1	hypercharge
$\hat{W}$	$\lambda_{\tilde{W}}$	W^-	SU(2)	g_2	left
$\hat{g}$	$\lambda_{\tilde{g}}$	g	SU(3)	g_3	color

7.1.2 Chiral Superfields

SF	Spin 0	Spin $\frac{1}{2}$	Generations	$(U(1)\otimes \mathrm{SU}(2)\otimes \mathrm{SU}(3))$
$\hat{q}$	$\tilde{q}$	q	3	$(\frac{1}{6},\mathbf{2},\mathbf{3})$
$\hat{l}$	$\tilde{l}$	l	3	$(-\frac{1}{2},\mathbf{2},\mathbf{1})$
$\hat{H}_d$	H_d	$\tilde{H}_d$	1	$(-\frac{1}{2},\mathbf{2},\mathbf{1})$
$\hat{H}_u$	H_u	$\tilde{H}_u$	1	$(\frac{1}{2},\mathbf{2},\mathbf{1})$
$\hat{d}$	$\tilde{d}_R^*$	d_R^*	3	$(\frac{1}{3},\mathbf{1},\overline{\mathbf{3}})$
$\hat{u}$	$\tilde{u}_R^*$	u_R^*	3	$(-\frac{2}{3},\mathbf{1},\overline{\mathbf{3}})$
$\hat{e}$	$\tilde{e}_R^*$	e_R^*	3	$(1,\mathbf{1},\mathbf{1})$

7.2 Superpotential and Lagrangian

7.2.1 Superpotential

$$W = Y_u\,\hat{q}\,\hat{H}_u\,\hat{u}\, - Y_d\,\hat{q}\,\hat{H}_d\,\hat{d}\, - Y_e\,\hat{l}\,\hat{H}_d\,\hat{e}\, + \mu\,\hat{H}_u\,\hat{H}_d\, + \epsilon\,\hat{l}\,\hat{H}_u\, + \frac{1}{2}\lambda_1\,\hat{l}\,\hat{l}\,\hat{e}\, + \lambda_2\,\hat{l}\,\hat{q}\,\hat{d} \tag{7.1}$$

7.2.2 Softbreaking terms

$$
\begin{aligned}
L_{SB,W} = & -H_d^0 H_u^0 B_\mu + H_d^- H_u^+ B_\mu - H_u^+ \tilde{e}_{L,i} B_{\epsilon,i} + H_u^0 \tilde{\nu}_{L,i} B_{\epsilon,i} \\
& + \frac{1}{2}\Big(- \tilde{e}^*_{R,k} \tilde{e}_{L,i} \tilde{\nu}_{L,j} T_{\lambda_1,ijk} + \tilde{e}^*_{R,k} \tilde{e}_{L,j} \tilde{\nu}_{L,i} T_{\lambda_1,ijk}\Big) - \tilde{d}^*_{R,k\gamma} \delta_{\beta\gamma} \tilde{e}_{L,i} \tilde{u}_{L,j\beta} T_{\lambda_2,ijk} \\
& + \tilde{d}^*_{R,k\gamma} \delta_{\beta\gamma} \tilde{d}_{L,j\beta} \tilde{\nu}_{L,i} T_{\lambda_2,ijk} + H_d^0 \tilde{d}^*_{R,k\gamma} \delta_{\alpha\gamma} \tilde{d}_{L,i\alpha} T_{d,ik} - H_d^- \tilde{d}^*_{R,k\gamma} \delta_{\alpha\gamma} \tilde{u}_{L,i\alpha} T_{d,ik} \\
& + H_d^0 \tilde{e}^*_{R,k} \tilde{e}_{L,i} T_{e,ik} - H_d^- \tilde{e}^*_{R,k} \tilde{\nu}_{L,i} T_{e,ik} - H_u^+ \tilde{u}^*_{R,k\gamma} \delta_{\alpha\gamma} \tilde{d}_{L,i\alpha} T_{u,ik} + H_u^0 \tilde{u}^*_{R,k\gamma} \delta_{\alpha\gamma} \tilde{u}_{L,i\alpha} T_{u,ik} + \text{h.c.} \qquad (7.2) \\
L_{SB,\phi} = & -m^2_{H_d} |H_d^0|^2 - m^2_{H_d} |H_d^-|^2 - m^2_{H_u} |H_u^0|^2 - m^2_{H_u} |H_u^+|^2 - \tilde{d}^*_{L,j\beta} \delta_{\alpha\beta} m^2_{q,ij} \tilde{d}_{L,i\alpha} \\
& - \tilde{d}^*_{R,i\alpha} \delta_{\alpha\beta} m^2_{d,ij} \tilde{d}_{R,j\beta} - \tilde{e}^*_{L,j} m^2_{l,ij} \tilde{e}_{L,i} - \tilde{e}^*_{R,i} m^2_{e,ij} \tilde{e}_{R,j} - \tilde{u}^*_{L,j\beta} \delta_{\alpha\beta} m^2_{q,ij} \tilde{u}_{L,i\alpha} \\
& - \tilde{u}^*_{R,i\alpha} \delta_{\alpha\beta} m^2_{u,ij} \tilde{u}_{R,j\beta} - \tilde{\nu}^*_{L,j} m^2_{l,ij} \tilde{\nu}_{L,i} \qquad (7.3) \\
L_{SB,\lambda} = & \frac{1}{2}\Big(-\lambda^2_{\tilde{B}} M_1 - M_2 \lambda^2_{\tilde{W},i} - M_3 \lambda^2_{\tilde{g},i} + \text{h.c.}\Big) \qquad (7.4)
\end{aligned}
$$

7.2.3 Gauge fixing terms

Gauge fixing terms for eigenstates 'GaugeES'

$$L_{GF} = -\frac{1}{2}\partial_\mu g \xi_G^{-1} - \frac{1}{2}\partial_\mu W^- \xi_W^{-1} \qquad (7.5)$$

Gauge fixing terms for eigenstates 'EWSB'

$$L_{GF} = -\frac{1}{2}\partial_\mu \gamma \xi_P^{-1} - \frac{1}{2}\partial_\mu g \xi_G^{-1} - \frac{1}{2}\xi_Z^{-1}\Big(- A_1^0 m_Z \xi_Z + \partial_\mu Z\Big) - \xi_W^{-1}\Big(i H_1^- m_{W^-} \xi_W + \partial_\mu W^-\Big) \qquad (7.6)$$

7.2.4 Fields integrated out

None

7.3 Field Rotations

7.3.1 Rotations in gauge sector for eigenstates 'EWSB'

$$
\begin{aligned}
W^-_{1\rho} &= \frac{1}{\sqrt{2}} W^-_\rho + \frac{1}{\sqrt{2}} W^+_\rho && (7.7) \\
W^-_{2\rho} &= -i\frac{1}{\sqrt{2}} W^-_\rho + i\frac{1}{\sqrt{2}} W^+_\rho && (7.8) \\
W^-_{3\rho} &= \cos\Theta_W Z_\rho + \sin\Theta_W \gamma_\rho && (7.9) \\
B_\rho &= \cos\Theta_W \gamma_\rho - \sin\Theta_W Z_\rho && (7.10) \\
\lambda_{\tilde{W},1} &= \frac{1}{\sqrt{2}} \tilde{W}^- + \frac{1}{\sqrt{2}} \tilde{W}^+ && (7.11) \\
\lambda_{\tilde{W},2} &= -i\frac{1}{\sqrt{2}} \tilde{W}^- + i\frac{1}{\sqrt{2}} \tilde{W}^+ && (7.12) \\
\lambda_{\tilde{W},3} &= \tilde{W}^0 && (7.13)
\end{aligned}
$$

7.3.2 Rotations in Mass sector for eigenstates 'EWSB'

Mass Matrices for Scalars

- **Mass matrix for Down-Squarks**, Basis: $\left(\tilde{d}_{L,o_1\alpha_1}, \tilde{d}_{R,o_2\alpha_2}\right), \left(\tilde{d}^*_{L,p_1\beta_1}, \tilde{d}^*_{R,p_2\beta_2}\right)$

$$m^2_{\tilde{d}} = \left(\begin{array}{cc} m_{11} & m^*_{21} \\ m_{21} & m_{22} \end{array}\right) \tag{7.14}$$

$$\begin{aligned} m_{11} = & \frac{1}{24}\delta_{\alpha_1\beta_1}\Big(- \Big(3g_2^2 + g_1^2\Big)\delta_{o_1p_1}\Big(- v_u^2 + v_d^2 + \sum_{a=1}^{3} v_{L,a}^2\Big) \\ & + 12\Big(2m^2_{q,o_1p_1} + v_d^2 \sum_{a=1}^{3} Y^*_{d,p_1a} Y_{d,o_1a} + v_d \sum_{b=1}^{3}\sum_{a=1}^{3} Y^*_{d,p_1a}\lambda_{2,bo_1a} v_{L,b} + v_d \sum_{b=1}^{3}\sum_{a=1}^{3}\lambda^*_{2,bp_1a} Y_{d,o_1a} v_{L,b} \\ & + \sum_{c=1}^{3}\sum_{b=1}^{3}\sum_{a=1}^{3}\lambda^*_{2,cp_1a}\lambda_{2,bo_1a} v_{L,b} v_{L,c}\Big)\Big) \end{aligned} \tag{7.15}$$

$$m_{21} = \frac{1}{\sqrt{2}}\delta_{\alpha_2\beta_1}\Big(v_d T^*_{d,p_1o_2} - v_u\mu Y^*_{d,p_1o_2} + v_u \sum_{a=1}^{3}\lambda^*_{2,ap_1o_2}\epsilon_a + \sum_{a=1}^{3} T_{\lambda,2^*_{ap_1o_2}} v_{L,a}\Big) \tag{7.16}$$

$$\begin{aligned} m_{22} = & \frac{1}{12}\Big(6v_d\Big(\sum_{a=1}^{3} Y^*_{d,ao_2}\sum_{c=1}^{3}\sum_{b=1}^{3}\lambda_{2,cbp_2} v_{L,c} + \sum_{a=1}^{3} Y_{d,ap_2}\sum_{c=1}^{3}\sum_{b=1}^{3}\lambda^*_{2,cbo_2} v_{L,c}\Big) \\ & + \delta_{\alpha_2\beta_2}\Big(6\Big(2m^2_{d,p_2o_2} + v_d^2\sum_{a=1}^{3} Y^*_{d,ao_2} Y_{d,ap_2} + \sum_{c=1}^{3}\sum_{b=1}^{3}\sum_{a=1}^{3}\lambda^*_{2,cao_2}\lambda_{2,bap_2} v_{L,b} v_{L,c}\Big) - g_1^2\delta_{o_2p_2}\Big(- v_u^2 + v_d^2 + \sum_{a=1}^{3} v_{L,a}^2\Big)\Big)\Big) \end{aligned} \tag{7.17}$$

This matrix is diagonalized by Z^D:

$$Z^D m^2_{\tilde{d}} Z^{D,\dagger} = m^{dia}_{2,\tilde{d}} \tag{7.18}$$

with

$$\tilde{d}_{L,i\alpha} = \sum_{t_2} Z^{D,*}_{ji}\tilde{d}_{j\alpha}\,, \qquad \tilde{d}_{R,i\alpha} = \sum_{t_2} Z^{D,*}_{ji}\tilde{d}_{j\alpha} \tag{7.19}$$

- **Mass matrix for Up-Squarks**, Basis: $\left(\tilde{u}_{L,o_1\alpha_1}, \tilde{u}_{R,o_2\alpha_2}\right), \left(\tilde{u}^*_{L,p_1\beta_1}, \tilde{u}^*_{R,p_2\beta_2}\right)$

$$m^2_{\tilde{u}} = \left(\begin{array}{cc} m_{11} & m^*_{21} \\ m_{21} & m_{22} \end{array}\right) \tag{7.20}$$

$$m_{11} = \frac{1}{24}\delta_{\alpha_1\beta_1}\Big(12\Big(2m^2_{q,o_1p_1} + v_u^2\sum_{a=1}^{3} Y^*_{u,p_1a} Y_{u,o_1a}\Big) - \Big(- 3g_2^2 + g_1^2\Big)\delta_{o_1p_1}\Big(- v_u^2 + v_d^2 + \sum_{a=1}^{3} v_{L,a}^2\Big)\Big) \tag{7.21}$$

$$m_{21} = \frac{1}{\sqrt{2}} \delta_{\alpha_2 \beta_1} \Big(v_u T^*_{u,p_1 o_2} + Y^*_{u,p_1 o_2} \Big(- v_d \mu + \sum_{a=1}^{3} v_{L,a} \epsilon_a \Big) \Big) \tag{7.22}$$

$$m_{22} = \frac{1}{6} \delta_{\alpha_2 \beta_2} \Big(3 v_u^2 \sum_{a=1}^{3} Y^*_{u,a o_2} Y_{u,a p_2} + 6 m^2_{u,p_2 o_2} + g_1^2 \delta_{o_2 p_2} \Big(- v_u^2 + v_d^2 + \sum_{a=1}^{3} v_{L,a}^2 \Big) \Big) \tag{7.23}$$

This matrix is diagonalized by Z^U:

$$Z^U m^2_{\tilde{u}} Z^{U,\dagger} = m^{dia}_{2,\tilde{u}} \tag{7.24}$$

with

$$\tilde{u}_{L,i\alpha} = \sum_{t_2} Z^{U,*}_{ji} \tilde{u}_{j\alpha} \,, \qquad \tilde{u}_{R,i\alpha} = \sum_{t_2} Z^{U,*}_{ji} \tilde{u}_{j\alpha} \tag{7.25}$$

- **Mass matrix for Higgs**, Basis: $(\phi_d, \phi_u, \phi_{L,o_3}), (\phi_d, \phi_u, \phi_{L,p_3})$

$$m_h^2 = \begin{pmatrix} m_{11} & m^*_{21} & m^*_{31} \\ m_{21} & m_{22} & m^*_{32} \\ m_{31} & m_{32} & m_{33} \end{pmatrix} \tag{7.26}$$

$$m_{11} = \frac{1}{8} \Big(3 g_1^2 v_d^2 + 3 g_2^2 v_d^2 + 8 m^2_{H_d} + 8 |\mu|^2 + \Big(g_1^2 + g_2^2 \Big) \sum_{a=1}^{3} v_{L,a}^2 - g_1^2 v_u^2 - g_2^2 v_u^2 \Big) \tag{7.27}$$

$$m_{21} = \frac{1}{4} \Big(- 4 \Re \Big(B_\mu \Big) - \Big(g_1^2 + g_2^2 \Big) v_d v_u \Big) \tag{7.28}$$

$$m_{22} = \frac{1}{8} \Big(3 g_1^2 v_u^2 + 3 g_2^2 v_u^2 + 8 m^2_{H_u} + 8 |\mu|^2 + 8 \sum_{a=1}^{3} |\epsilon_a|^2 - \Big(g_1^2 + g_2^2 \Big) \sum_{a=1}^{3} v_{L,a}^2 - g_1^2 v_d^2 - g_2^2 v_d^2 \Big) \tag{7.29}$$

$$m_{31} = \frac{1}{4} \Big(- 2 \mu^* \epsilon_{o_3} - 2 \mu \epsilon^*_{o_3} + 4 \Re \Big(m^2_{lH,o_3} \Big) + g_1^2 v_d \sum_{a=1}^{3} v_{L,a} + g_2^2 v_d \sum_{a=1}^{3} v_{L,a} \Big) \tag{7.30}$$

$$m_{32} = - \frac{1}{4} \Big(g_1^2 + g_2^2 \Big) v_u \sum_{a=1}^{3} v_{L,a} + \Re \Big(B_{\epsilon,o_3} \Big) \tag{7.31}$$

$$\begin{aligned} m_{33} = \frac{1}{8} \Big(\Big(g_1^2 + g_2^2 \Big) \delta_{o_3 p_3} \Big(- v_u^2 + v_d^2 + \sum_{a=1}^{3} v_{L,a}^2 \Big) \\ + 2 \Big(2 \epsilon^*_{o_3} \epsilon_{p_3} + 2 \epsilon^*_{p_3} \epsilon_{o_3} + 2 m^2_{l,o_3 p_3} + 2 m^2_{l,p_3 o_3} + g_1^2 \sum_{a=1}^{3} v_{L,a} \sum_{b=1}^{3} v_{L,b} + g_2^2 \sum_{a=1}^{3} v_{L,a} \sum_{b=1}^{3} v_{L,b} \Big) \Big) \end{aligned} \tag{7.32}$$

This matrix is diagonalized by Z^H:

$$Z^H m_h^2 Z^{H,\dagger} = m^{dia}_{2,h} \tag{7.33}$$

with

$$\phi_d = \sum_{t_2} Z^H_{j1} h_j \,, \qquad \phi_u = \sum_{t_2} Z^H_{j2} h_j \,, \qquad \phi_{L,i} = \sum_{t_2} Z^H_{ji} h_j \tag{7.34}$$

- **Mass matrix for Pseudo-Scalar Higgs**, Basis: $(\sigma_d, \sigma_u, \sigma_{L,o_3}), (\sigma_d, \sigma_u, \sigma_{L,p_3})$

$$m^2_{A^0} = \begin{pmatrix} m_{11} & \Re\Big(B_\mu\Big) & m^*_{31} \\ \Re\Big(B_\mu\Big) & m_{22} & -\Re\Big(B_{\epsilon,p_3}\Big) \\ m_{31} & -\Re\Big(B_{\epsilon,o_3}\Big) & m_{33} \end{pmatrix} \tag{7.35}$$

$$m_{11} = \frac{1}{8}\Big(8m^2_{H_d} + 8|\mu|^2 + \Big(g_1^2 + g_2^2\Big)\sum_{a=1}^{3} v^2_{L,a} + g_1^2 v_d^2 - g_1^2 v_u^2 + g_2^2 v_d^2 - g_2^2 v_u^2\Big) \tag{7.36}$$

$$m_{22} = \frac{1}{8}\Big(8m^2_{H_u} + 8|\mu|^2 + 8\sum_{a=1}^{3}|\epsilon_a|^2 - \Big(g_1^2 + g_2^2\Big)\sum_{a=1}^{3} v^2_{L,a} - g_1^2 v_d^2 + g_1^2 v_u^2 - g_2^2 v_d^2 + g_2^2 v_u^2\Big) \tag{7.37}$$

$$m_{31} = \frac{1}{2}\Big(2\Re\Big(m^2_{lH,o_3}\Big) - \mu^*\epsilon_{o_3} - \mu\epsilon^*_{o_3}\Big) \tag{7.38}$$

$$m_{33} = \frac{1}{8}\Big(4\Big(\epsilon^*_{o_3}\epsilon_{p_3} + \epsilon^*_{p_3}\epsilon_{o_3} + m^2_{l,o_3p_3} + m^2_{l,p_3o_3}\Big) + \Big(g_1^2 + g_2^2\Big)\delta_{o_3p_3}\Big(- v_u^2 + v_d^2 + \sum_{a=1}^{3} v^2_{L,a}\Big)\Big) \tag{7.39}$$

This matrix is diagonalized by Z^A:

$$Z^A m^2_{A^0} Z^{A,\dagger} = m^{dia}_{2,A^0} \tag{7.40}$$

with

$$\sigma_d = \sum_{t_2} Z^A_{j1} A^0_j\,, \qquad \sigma_u = \sum_{t_2} Z^A_{j2} A^0_j\,, \qquad \sigma_{L,i} = \sum_{t_2} Z^A_{ji} A^0_j \tag{7.41}$$

- **Mass matrix for Charged Higgs**, Basis: $\Big(H_d^-, H_u^{+,*}, \tilde{e}_{L,o_3}, \tilde{e}_{R,o_4}\Big), \Big(H_d^{-,*}, H_u^+, \tilde{e}^*_{L,p_3}, \tilde{e}^*_{R,p_4}\Big)$

$$m^2_{H^-} = \begin{pmatrix} m_{11} & \frac{1}{4}g_2^2 v_d v_u + B_\mu & m^*_{31} & m^*_{41} \\ \frac{1}{4}g_2^2 v_d v_u + B^*_\mu & m_{22} & m^*_{32} & m^*_{42} \\ m_{31} & m_{32} & m_{33} & m^*_{43} \\ m_{41} & m_{42} & m_{43} & m_{44} \end{pmatrix} \tag{7.42}$$

$$\begin{aligned} m_{11} = \frac{1}{8}\Big(&8m^2_{H_d} + g_1^2 v_d^2 + g_2^2 v_d^2 - g_1^2 v_u^2 + g_2^2 v_u^2 + 8|\mu|^2 + \Big(- g_2^2 + g_1^2\Big)\sum_{a=1}^{3} v^2_{L,a} \\ &+ 4\sum_{c=1}^{3}\sum_{b=1}^{3}\sum_{a=1}^{3} Y^*_{e,ca} Y_{e,ba} v_{L,b} v_{L,c}\Big) \end{aligned} \tag{7.43}$$

$$m_{22} = \frac{1}{8}\Big(8m^2_{H_u} + 8|\mu|^2 + 8\sum_{a=1}^{3}|\epsilon_a|^2 + \Big(- g_1^2 + g_2^2\Big)\sum_{a=1}^{3} v^2_{L,a} - g_1^2 v_d^2 + g_1^2 v_u^2 + g_2^2 v_d^2 + g_2^2 v_u^2\Big) \tag{7.44}$$

$$m_{31} = \frac{1}{4}\Big(4m^{2,*}_{lH,o_3} + g_2^2 v_d \sum_{a=1}^{3} v_{L,a} - 2v_d \sum_{b=1}^{3}\sum_{a=1}^{3} Y^*_{e,ba} Y_{e,o_3a} v_{L,b} + \sum_{c=1}^{3}\sum_{b=1}^{3}\sum_{a=1}^{3} Y^*_{e,ca}\lambda_{1,o_3ba} v_{L,b} v_{L,c}$$

$$- \sum_{c=1}^{3}\sum_{b=1}^{3}\sum_{a=1}^{3} Y^*_{e,ca}\lambda_{1,bo_3a}v_{L,b}v_{L,c} - 4\mu^*\epsilon_{o_3}\Big) \tag{7.45}$$

$$m_{32} = -B_{\epsilon,o_3} + \frac{1}{4}g_2^2 v_u \sum_{a=1}^{3} v_{L,a} \tag{7.46}$$

$$\begin{aligned} m_{33} = \frac{1}{8}\Big(&8m^2_{l,o_3p_3} + \Big(-g_2^2+g_1^2\Big)\delta_{o_3p_3}\Big(-v_u^2+v_d^2+\sum_{a=1}^{3}v^2_{L,a}\Big) + 4v_d^2\sum_{a=1}^{3}Y^*_{e,p_3a}Y_{e,o_3a} + 2g_2^2\sum_{a=1}^{3}v_{L,a}\sum_{b=1}^{3}v_{L,b} \\ &- 2v_d\sum_{b=1}^{3}\sum_{a=1}^{3}Y^*_{e,p_3a}\lambda_{1,o_3ba}v_{L,b} + 2v_d\sum_{b=1}^{3}\sum_{a=1}^{3}Y^*_{e,p_3a}\lambda_{1,bo_3a}v_{L,b} - 2v_d\sum_{b=1}^{3}\sum_{a=1}^{3}\lambda^*_{1,p_3ba}Y_{e,o_3a}v_{L,b} \\ &+ 2v_d\sum_{b=1}^{3}\sum_{a=1}^{3}\lambda^*_{1,bp_3a}Y_{e,o_3a}v_{L,b} + \sum_{c=1}^{3}\sum_{b=1}^{3}\sum_{a=1}^{3}\lambda^*_{1,p_3ca}\lambda_{1,o_3ba}v_{L,b}v_{L,c} - \sum_{c=1}^{3}\sum_{b=1}^{3}\sum_{a=1}^{3}\lambda^*_{1,cp_3a}\lambda_{1,o_3ba}v_{L,b}v_{L,c} \\ &- \sum_{c=1}^{3}\sum_{b=1}^{3}\sum_{a=1}^{3}\lambda^*_{1,p_3ca}\lambda_{1,bo_3a}v_{L,b}v_{L,c} + \sum_{c=1}^{3}\sum_{b=1}^{3}\sum_{a=1}^{3}\lambda^*_{1,cp_3a}\lambda_{1,bo_3a}v_{L,b}v_{L,c} + 8\epsilon^*_{p_3}\epsilon_{o_3}\Big) \end{aligned} \tag{7.47}$$

$$m_{41} = -\frac{1}{\sqrt{2}}\Big(v_u\sum_{a=1}^{3}Y^*_{e,ao_4}\epsilon_a + \sum_{a=1}^{3}T^*_{e,ao_4}v_{L,a}\Big) \tag{7.48}$$

$$m_{42} = -\frac{1}{2}\frac{1}{\sqrt{2}}\Big(2\mu\sum_{a=1}^{3}Y^*_{e,ao_4}v_{L,a} + 2v_d\sum_{a=1}^{3}Y^*_{e,ao_4}\epsilon_a + \sum_{a=1}^{3}\epsilon_a\sum_{c=1}^{3}\sum_{b=1}^{3}\lambda^*_{1,cbo_4}v_{L,c} - \sum_{b=1}^{3}\sum_{a=1}^{3}\lambda^*_{1,abo_4}\epsilon_a v_{L,b}\Big) \tag{7.49}$$

$$m_{43} = \frac{1}{2}\frac{1}{\sqrt{2}}\Big(2v_dT^*_{e,p_3o_4} - 2v_u\mu Y^*_{e,p_3o_4} - \sum_{a=1}^{3}T_{\lambda,1^*_{p_3ao_4}}v_{L,a} - v_u\sum_{a=1}^{3}\epsilon_a\sum_{b=1}^{3}\lambda^*_{1,p_3bo_4} + v_u\sum_{a=1}^{3}\lambda^*_{1,ap_3o_4}\epsilon_a + \sum_{a=1}^{3}T_{\lambda,1^*_{ap_3o_4}}v_{L,a}\Big) \tag{7.50}$$

$$\begin{aligned} m_{44} = \frac{1}{8}\Big(&8m^2_{e,p_4o_4} - 2g_1^2\delta_{o_4p_4}\Big(-v_u^2+v_d^2+\sum_{a=1}^{3}v^2_{L,a}\Big) + 4v_d^2\sum_{a=1}^{3}Y^*_{e,ao_4}Y_{e,ap_4} + 4\sum_{a=1}^{3}v_{L,a}Y_{e,ap_4}\sum_{b=1}^{3}Y^*_{e,bo_4}v_{L,b} \\ &- 2v_d\sum_{b=1}^{3}\sum_{a=1}^{3}Y^*_{e,ao_4}\lambda_{1,abp_4}v_{L,b} - 2v_d\sum_{b=1}^{3}\sum_{a=1}^{3}\lambda^*_{1,abo_4}Y_{e,ap_4}v_{L,b} + 2v_d\sum_{a=1}^{3}Y_{e,ap_4}\sum_{c=1}^{3}\sum_{b=1}^{3}\lambda^*_{1,cbo_4}v_{L,c} \\ &+ 2v_d\sum_{a=1}^{3}Y^*_{e,ao_4}\sum_{c=1}^{3}\sum_{b=1}^{3}\lambda_{1,cbp_4}v_{L,c} + \sum_{c=1}^{3}\sum_{b=1}^{3}\sum_{a=1}^{3}\lambda^*_{1,aco_4}\lambda_{1,abp_4}v_{L,b}v_{L,c} + \sum_{c=1}^{3}\sum_{b=1}^{3}\sum_{a=1}^{3}\lambda^*_{1,cao_4}\lambda_{1,bap_4}v_{L,b}v_{L,c} \\ &- \sum_{c=1}^{3}\sum_{b=1}^{3}\lambda_{1,cbp_4}v_{L,c}\sum_{d=1}^{3}\sum_{a=1}^{3}\lambda^*_{1,ado_4}v_{L,d} - \sum_{c=1}^{3}\sum_{a=1}^{3}\lambda_{1,acp_4}v_{L,c}\sum_{d=1}^{3}\sum_{b=1}^{3}\lambda^*_{1,dbo_4}v_{L,d}\Big) \end{aligned} \tag{7.51}$$

This matrix is diagonalized by Z^+:

$$Z^+ m^2_{H^-} Z^{+,\dagger} = m^{dia}_{2,H^-} \tag{7.52}$$

with

$$H_d^- = \sum_{t_2} Z^{+,*}_{j1}H_j^-\,, \qquad H_u^+ = \sum_{t_2} Z^{+}_{j2}H_j^+\,, \qquad \tilde{e}_{L,i} = \sum_{t_2} Z^{+,*}_{ji}H_j^- \tag{7.53}$$

$$\tilde{e}_{R,i} = \sum_{t_2} Z^{+,*}_{ji}H_j^- \tag{7.54}$$

Mass Matrices for Fermions

- **Mass matrix for Neutralinos**, Basis: $\left(\nu_{L,o_1}, \lambda_{\tilde{B}}, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0\right), \left(\nu_{L,p_1}, \lambda_{\tilde{B}}, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0\right)$

$$m_{\tilde{\chi}^0} = \begin{pmatrix} 0 & -\frac{1}{2}g_1 \sum_{a=1}^3 v_{L,a} & \frac{1}{2}g_2 \sum_{a=1}^3 v_{L,a} & 0 & \epsilon_{o_1} \\ -\frac{1}{2}g_1 \sum_{a=1}^3 v_{L,a} & M_1 & 0 & -\frac{1}{2}g_1 v_d & \frac{1}{2}g_1 v_u \\ \frac{1}{2}g_2 \sum_{a=1}^3 v_{L,a} & 0 & M_2 & \frac{1}{2}g_2 v_d & -\frac{1}{2}g_2 v_u \\ 0 & -\frac{1}{2}g_1 v_d & \frac{1}{2}g_2 v_d & 0 & -\mu \\ \epsilon_{p_1} & \frac{1}{2}g_1 v_u & -\frac{1}{2}g_2 v_u & -\mu & 0 \end{pmatrix} \tag{7.55}$$

This matrix is diagonalized by N:

$$N m_{\tilde{\chi}^0} N^{\dagger} = m^{dia}_{\tilde{\chi}^0} \tag{7.56}$$

with

$$\nu_{L,i} = \sum_{t_2} N^*_{ji}\lambda^0_j\,, \qquad \lambda_{\tilde{B}} = \sum_{t_2} N^*_{j4}\lambda^0_j\,, \qquad \tilde{W}^0 = \sum_{t_2} N^*_{j5}\lambda^0_j \tag{7.57}$$

$$\tilde{H}^0_d = \sum_{t_2} N^*_{j6}\lambda^0_j\,, \qquad \tilde{H}^0_u = \sum_{t_2} N^*_{j7}\lambda^0_j \tag{7.58}$$

- **Mass matrix for Charginos**, Basis: $\left(e_{L,o_1}, \tilde{W}^-, \tilde{H}_d^-\right), \left(e^*_{R,p_1}, \tilde{W}^+, \tilde{H}_u^+\right)$

$$m_{\tilde{\chi}^-} = \begin{pmatrix} m_{11} & \frac{1}{\sqrt{2}}g_2 \sum_{a=1}^3 v_{L,a} & -\epsilon_{o_1} \\ 0 & M_2 & \frac{1}{\sqrt{2}}g_2 v_u \\ -\frac{1}{\sqrt{2}} \sum_{a=1}^3 v_{L,a} Y_{e,ap_1} & \frac{1}{\sqrt{2}}g_2 v_d & \mu \end{pmatrix} \tag{7.59}$$

$$m_{11} = \frac{1}{2}\frac{1}{\sqrt{2}}\Big(2v_d Y_{e,o_1p_1} - \sum_{a=1}^{3}\lambda_{1,o_1ap_1}v_{L,a} + \sum_{a=1}^{3}\lambda_{1,ao_1p_1}v_{L,a}\Big) \tag{7.60}$$

This matrix is diagonalized by U and V

$$U^* m_{\tilde{\chi}^-} V^{\dagger} = m^{dia}_{\tilde{\chi}^-} \tag{7.61}$$

with

$$e_{L,i} = \sum_{t_2} U^*_{ji}\lambda^-_j\,, \qquad \tilde{W}^- = \sum_{t_2} U^*_{j4}\lambda^-_j\,, \qquad \tilde{H}^-_d = \sum_{t_2} U^*_{j5}\lambda^-_j \tag{7.62}$$

$$e_{R,i} = \sum_{t_2} V_{ij}\lambda^{+,*}_j\,, \qquad \tilde{W}^+ = \sum_{t_2} V^*_{4j}\lambda^+_j\,, \qquad \tilde{H}^+_u = \sum_{t_2} V^*_{5j}\lambda^+_j \tag{7.63}$$

- **Mass matrix for Down-Quarks**, Basis: $\left(d_{L,o_1\alpha_1}\right), \left(d^*_{R,p_1\beta_1}\right)$

$$m_d = \begin{pmatrix} \frac{1}{\sqrt{2}}\delta_{\alpha_1\beta_1}\Big(v_d Y_{d,o_1p_1} + \sum_{a=1}^3 \lambda_{2,ao_1p_1}v_{L,a}\Big) \end{pmatrix} \tag{7.64}$$

This matrix is diagonalized by U^d_L and U^d_R

$$U^{d,*}_L m_d U^{d,\dagger}_R = m^{dia}_d \tag{7.65}$$

with

$$d_{L,i\alpha} = \sum_{t_2} U^{d,*}_{L,ji} D_{L,j\alpha} \tag{7.66}$$

$$d_{R,i\alpha} = \sum_{t_2} U^{d}_{R,ij} D^*_{R,j\alpha} \tag{7.67}$$

- **Mass matrix for Up-Quarks**, Basis: $(u_{L,o_1\alpha_1})\,, \Big(u^*_{R,p_1\beta_1}\Big)$

$$m_u = \left(\begin{array}{c} \frac{1}{\sqrt{2}} v_u \delta_{\alpha_1\beta_1} Y_{u,o_1p_1} \end{array} \right) \tag{7.68}$$

This matrix is diagonalized by U^u_L and U^u_R

$$U^{u,*}_L m_u U^{u,\dagger}_R = m^{dia}_u \tag{7.69}$$

with

$$u_{L,i\alpha} = \sum_{t_2} U^{u,*}_{L,ji} U_{L,j\alpha} \tag{7.70}$$

$$u_{R,i\alpha} = \sum_{t_2} U^{u}_{R,ij} U^*_{R,j\alpha} \tag{7.71}$$

7.4 Vacuum Expectation Values

$$H^0_d = \frac{1}{\sqrt{2}}\phi_d + \frac{1}{\sqrt{2}}v_d + i\frac{1}{\sqrt{2}}\sigma_d \tag{7.72}$$

$$H^0_u = \frac{1}{\sqrt{2}}\phi_u + \frac{1}{\sqrt{2}}v_u + i\frac{1}{\sqrt{2}}\sigma_u \tag{7.73}$$

$$\tilde{\nu}_L = \frac{1}{\sqrt{2}}\phi_L + \frac{1}{\sqrt{2}}v_L + i\frac{1}{\sqrt{2}}\sigma_L \tag{7.74}$$

7.5 Tadpole Equations

$$\frac{\partial V}{\partial v_d} = \frac{1}{8}\Big(8m^2_{H_d}v_d + g_1^2 v_d^3 + g_2^2 v_d^3 - g_1^2 v_d v_u^2 - g_2^2 v_d v_u^2 - 8v_u \Re\Big(B_\mu\Big) + 4\sum_{a=1}^{3} m^{2,*}_{lH,a} v_{L,a}$$
$$- 4\mu \sum_{a=1}^{3} \epsilon^*_a v_{L,a} + 4\sum_{a=1}^{3} m^2_{lH,a} v_{L,a} + g_1^2 v_d \sum_{a=1}^{3} v^2_{L,a} + g_2^2 v_d \sum_{a=1}^{3} v^2_{L,a} + \mu^*\Big(-4\sum_{a=1}^{3} v_{L,a}\epsilon_a + 8v_d\mu\Big)\Big) \tag{7.75}$$

$$\frac{\partial V}{\partial v_u} = \frac{1}{8}\Big(8m^2_{H_u}v_u - g_1^2 v_d^2 v_u - g_2^2 v_d^2 v_u + g_1^2 v_u^3 + g_2^2 v_u^3 + 8v_u|\mu|^2 - 8v_d\Re\Big(B_\mu\Big)$$

$$+ 8v_u \sum_{a=1}^{3} |\epsilon_a|^2 + 4\sum_{a=1}^{3} B^*_{\epsilon,a} v_{L,a} - g_1^2 v_u \sum_{a=1}^{3} v^2_{L,a} - g_2^2 v_u \sum_{a=1}^{3} v^2_{L,a} + 4\sum_{a=1}^{3} v_{L,a} B_{\epsilon,a}\Big) \tag{7.76}$$

$$\frac{\partial V}{\partial v_L} = \frac{1}{8}\Big(4v_u B^*_{\epsilon,i} + 8v_d \Re\Big(m^2_{lH,i}\Big) + 4\sum_{a=1}^{3} m^2_{l,ia} v_{L,a} + 4\sum_{a=1}^{3} m^2_{l,ai} v_{L,a} + \epsilon_i^*\Big(4\sum_{a=1}^{3} v_{L,a}\epsilon_a - 4v_d\mu\Big) + g_1^2 v_d^2 v_{L,i}$$

$$+ g_2^2 v_d^2 v_{L,i} - g_1^2 v_u^2 v_{L,i} - g_2^2 v_u^2 v_{L,i} + g_1^2 \sum_{a=1}^{3} v^2_{L,a} v_{L,i} + g_2^2 \sum_{a=1}^{3} v^2_{L,a} v_{L,i} - 4v_d \mu^* \epsilon_i$$

$$+ 4\sum_{a=1}^{3} \epsilon_a^* v_{L,a}\epsilon_i + 4v_u B_{\epsilon,i}\Big) \tag{7.77}$$

7.6 Particle content for eigenstates 'EWSB'

Name	Type	complex/real	Generations	Indices
$\tilde{d}$	Scalar	complex	6	generation, color
$\tilde{u}$	Scalar	complex	6	generation, color
h	Scalar	real	5	generation
A^0	Scalar	real	5	generation
H^-	Scalar	complex	8	generation
$\tilde{g}$	Fermion	Majorana	8	generation
$\tilde{\chi}^0$	Fermion	Majorana	7	generation
$\tilde{\chi}^-$	Fermion	Dirac	5	generation
d	Fermion	Dirac	3	generation, color
u	Fermion	Dirac	3	generation, color
g	Vector	real	8	generation, lorentz
W^-	Vector	complex	1	lorentz
γ	Vector	real	1	lorentz
Z	Vector	real	1	lorentz
η^G	Ghost	real	8	generation
η^-	Ghost	complex	1	
η^+	Ghost	complex	1	
η^γ	Ghost	real	1	
η^Z	Ghost	real	1	

7.7 Modelfile for SARAH

```
Off[General::spell]
Print["Model file for the MSSM loaded"];

ModelNameLaTeX ="MSSM-BiRpV";


(*-------------------------------------------*)
(*   Particle Content*)
(*-------------------------------------------*)

(* Gauge Superfields *)

Gauge[[1]]={B,   U[1], hypercharge, g1,False};
Gauge[[2]]={WB, SU[2], left,        g2,True};
Gauge[[3]]={G,  SU[3], color,       g3,False};


(* Chiral Superfields *)

Fields[[1]] = {{uL,  dL},  3, q,   1/6, 2, 3};
Fields[[2]] = {{vL,  eL},  3, l,  -1/2, 2, 1};
Fields[[3]] = {{Hd0, Hdm}, 1, Hd, -1/2, 2, 1};
Fields[[4]] = {{Hup, Hu0}, 1, Hu,  1/2, 2, 1};

Fields[[5]] = {conj[dR], 3, d,  1/3, 1, -3};
Fields[[6]] = {conj[uR], 3, u, -2/3, 1, -3};
Fields[[7]] = {conj[eR], 3, e,    1, 1,  1};


(*-----------------------------------------------------*)
(* Superpotential *)
(*-----------------------------------------------------*)

SuperPotential = { {{1, Yu},{q,Hu,u}}, {{-1,Yd},{q,Hd,d}},
                   {{-1,Ye},{l,Hd,e}}, {{1,\[Mu]},{Hu,Hd}},
                   {{1,\[Epsilon]},{l,Hu}}, {{1/2,L1},{l,l,e}},
                   {{1,L2},{l,q,d}}};


(*-------------------------------------------*)
(* Integrate Out or Delete Particles        *)
(*-------------------------------------------*)

IntegrateOut={};
```

```
DeleteParticles={};


(*-----------------------------------------------*)
(*   DEFINITION                                  *)
(*-----------------------------------------------*)

NameOfStates={GaugeES,EWSB};

DEFINITION[GaugeES][GaugeFixing]=
{ {Der[VWB],  -1/(2 RXi[W])},
     {Der[VG],   -1/(2 RXi[G]) }};

DEFINITION[GaugeES][Additional]=
 {{{conj[SvL], SHd0}, {1, mHL2}},
  {{conj[SeL], SHdm}, {1, mHL2}}};

(* Gauge Sector *)

DEFINITION[EWSB][GaugeSector]=
{{VWB,{1,{VWm,1/Sqrt[2]},{conj[VWm],1/Sqrt[2]}},
      {2,{VWm,-\[ImaginaryI]/Sqrt[2]},{conj[VWm],\[ImaginaryI]/Sqrt[2]}},
      {3,{VP,Sin[ThetaW]},{VZ,Cos[ThetaW]}}},
 {VB, {1,{VP,Cos[ThetaW]},{VZ,-Sin[ThetaW]}}},
 {fWB,{1,{fWm,1/Sqrt[2]},{fWp,1/Sqrt[2]}},
      {2,{fWm,-\[ImaginaryI]/Sqrt[2]},{fWp,\[ImaginaryI]/Sqrt[2]}},
      {3,{fW0,1}}}};




(* ----- VEVs ---- *)

DEFINITION[EWSB][VEVs]=
{    {SHd0, {vd, 1/Sqrt[2]}, {sigmad, \[ImaginaryI]/Sqrt[2]},{phid, \
1/Sqrt[2]}},
     {SHu0, {vu, 1/Sqrt[2]}, {sigmau, \[ImaginaryI]/Sqrt[2]},{phiu, \
1/Sqrt[2]}},
     {SvL, {vL, 1/Sqrt[2]}, {sigmaL, \[ImaginaryI]/Sqrt[2]},{phiL, \
1/Sqrt[2]}}     };


DEFINITION[EWSB][Phases]=
{    {fG, PhaseGlu}
    };


DEFINITION[EWSB][MatterSector]=
```

```
{    {{SdL, SdR}, {Sd, ZD}},
     {{SuL, SuR}, {Su, ZU}},
     {{phid, phiu,phiL}, {hh, ZH}},
     {{sigmad, sigmau,sigmaL}, {Ah, ZA}},
     {{SHdm,conj[SHup],SeL,SeR},{Hpm,ZP}},
     {{FvL,fB, fW0, FHd0, FHu0}, {L0, ZN}},
     {{{FeL,fWm, FHdm}, {conj[FeR],fWp, FHup}},  {{Lm,UM}, {Lp,UP}}},
     {{{FdL},{conj[FdR]}},{{FDL,ZDL},{FDR,ZDR}}},
     {{{FuL},{conj[FuR]}},{{FUL,ZUL},{FUR,ZUR}}}
       };


(*--- Gauge Fixing ---- *)

DEFINITION[EWSB][GaugeFixing]=
  { {Der[VP],                                          - 1/(2 RXi[P])},
{Der[VWm]+\[ImaginaryI] Mass[VWm] RXi[W] Hpm[{1}],   - 1/(RXi[W])},
{Der[VZ] - Mass[VZ] RXi[Z] Ah[{1}],                  - 1/(2 RXi[Z])},
{Der[VG],                                            - 1/(2 RXi[G])}};

(*------------------------------------------------------*)
(* Dirac-Spinors *)
(*------------------------------------------------------*)

dirac[[1]] = {Fd,  FDL, conj[FDR]};
dirac[[2]] = {Fu,  FUL, conj[FUR]};
dirac[[3]] = {Chi, L0, conj[L0]};
dirac[[4]] = {Cha, Lm, conj[Lp]};
dirac[[5]] = {Glu, fG, conj[fG]};

(* Unbroken EW *)

dirac[[6]] = {Bino, fB, conj[fB]};
dirac[[7]] = {Wino, fWB, conj[fWB]};
dirac[[8]] = {H0, FHd0, conj[FHu0]};
dirac[[9]] = {HC, FHdm, conj[FHup]};
dirac[[10]] = {Fd1, FdL, 0};
dirac[[11]] = {Fd2, 0, FdR};
dirac[[12]] = {Fu1, FuL, 0};
dirac[[13]] = {Fu2, 0, FuR};
dirac[[14]] = {Fe1, FeL, 0};
dirac[[15]] = {Fe2, 0, FeR};
dirac[[16]] = {Fv, FvL, 0};


(*------------------------------------------------------*)
(* Automatized Output        *)
(*------------------------------------------------------*)
```

```
(*
makeOutput = {
                    {EWSB, {TeX, FeynArts}}
             };
            *)

SpectrumFile= None;
```

7.8 Implementation in SARAH

Model directory: `MSSM-RpV/LnV`

7.8.1 Particles for eigenstates 'GaugeES'

- Fermions

$\tilde{B} = \begin{pmatrix} \lambda_{\tilde{B}} \\ \lambda^*_{\tilde{B}} \end{pmatrix}$	$\texttt{Bino} = \begin{pmatrix} \texttt{fB} \\ \texttt{conj[fB]} \end{pmatrix}$
$d^1_{i\alpha} = \begin{pmatrix} d_{L,i\alpha} \\ 0 \end{pmatrix}$	$\texttt{Fd1[\{generation, color\}]} = \begin{pmatrix} \texttt{FdL[\{generation, color\}]} \\ 0 \end{pmatrix}$
$d^2_{i\alpha} = \begin{pmatrix} 0 \\ d_{R,i\alpha} \end{pmatrix}$	$\texttt{Fd2[\{generation, color\}]} = \begin{pmatrix} 0 \\ \texttt{FdR[\{generation, color\}]} \end{pmatrix}$
$e^1_{i} = \begin{pmatrix} e_{L,i} \\ 0 \end{pmatrix}$	$\texttt{Fe1[\{generation\}]} = \begin{pmatrix} \texttt{FeL[\{generation\}]} \\ 0 \end{pmatrix}$
$e^2_{i} = \begin{pmatrix} 0 \\ e_{R,i} \end{pmatrix}$	$\texttt{Fe2[\{generation\}]} = \begin{pmatrix} 0 \\ \texttt{FeR[\{generation\}]} \end{pmatrix}$
$u^1_{i\alpha} = \begin{pmatrix} u_{L,i\alpha} \\ 0 \end{pmatrix}$	$\texttt{Fu1[\{generation, color\}]} = \begin{pmatrix} \texttt{FuL[\{generation, color\}]} \\ 0 \end{pmatrix}$
$u^2_{i\alpha} = \begin{pmatrix} 0 \\ u_{R,i\alpha} \end{pmatrix}$	$\texttt{Fu2[\{generation, color\}]} = \begin{pmatrix} 0 \\ \texttt{FuR[\{generation, color\}]} \end{pmatrix}$
$\nu_{i} = \begin{pmatrix} \nu_{L,i} \\ 0 \end{pmatrix}$	$\texttt{Fv[\{generation\}]} = \begin{pmatrix} \texttt{FvL[\{generation\}]} \\ 0 \end{pmatrix}$
$\tilde{g}_{i} = \begin{pmatrix} \lambda_{\tilde{g},i} \\ \lambda^*_{\tilde{g},i} \end{pmatrix}$	$\texttt{Glu[\{generation\}]} = \begin{pmatrix} \texttt{fG[\{generation\}]} \\ \texttt{conj[fG[\{generation\}]]} \end{pmatrix}$
$\tilde{H}^0 = \begin{pmatrix} \tilde{H}^0_d \\ \tilde{H}^{0,*}_u \end{pmatrix}$	$\texttt{H0} = \begin{pmatrix} \texttt{FHd0} \\ \texttt{conj[FHu0]} \end{pmatrix}$

$\tilde{H}^- = \begin{pmatrix} \tilde{H}_d^- \\ \tilde{H}_u^{+,*} \end{pmatrix}$	`HC` $= \begin{pmatrix} \texttt{FHdm} \\ \texttt{conj[FHup]} \end{pmatrix}$
$\tilde{W}_i = \begin{pmatrix} \lambda_{\tilde{W},i} \\ \lambda^*_{\tilde{W},i} \end{pmatrix}$	`Wino[{generation}]` $= \begin{pmatrix} \texttt{fWB[\{generation\}]} \\ \texttt{conj[fWB[\{generation\}]]} \end{pmatrix}$

- Scalars

$\tilde{d}_{L,i\alpha}$	`SdL[{generation, color}]`	$\tilde{u}_{L,i\alpha}$	`SuL[{generation, color}]`
$\tilde{e}_{L,i}$	`SeL[{generation}]`	$\tilde{\nu}_{L,i}$	`SvL[{generation}]`
H_d^0	`SHd0`	H_d^-	`SHdm`
H_u^0	`SHu0`	H_u^+	`SHup`
$\tilde{d}_{R,i\alpha}$	`SdR[{generation, color}]`	$\tilde{u}_{R,i\alpha}$	`SuR[{generation, color}]`
$\tilde{e}_{R,i}$	`SeR[{generation}]`		

- Vector Bosons

B_ρ	`VB[{lorentz}]`	$W^-_{i\rho}$	`VWB[{generation, lorentz}]`
$g_{i\rho}$	`VG[{generation, lorentz}]`		

- Ghosts

η^B	`gB`	$\text{gWB}\Big(\{\text{gt1}\}\Big)$	`gWB[{generation}]`
η^G_i	`gG[{generation}]`		

7.8.2 Particles for eigenstates 'EWSB'

- Fermions

$\tilde{\chi}^-_i = \begin{pmatrix} \lambda^-_i \\ \lambda^{+,*}_i \end{pmatrix}$	`Cha[{generation}]` = (`Lm[{generation}]` , `conj[Lp[{generation}]]`)
$\tilde{\chi}^0_i = \begin{pmatrix} \lambda^0_i \\ \lambda^{0,*}_i \end{pmatrix}$	`Chi[{generation}]` = (`L0[{generation}]` , `conj[L0[{generation}]]`)
$d_{i\alpha} = \begin{pmatrix} D_{L,i\alpha} \\ D^*_{R,i\alpha} \end{pmatrix}$	`Fd[{generation, color}]` = (`FDL[{generation, color}]` , `conj[FDR[{generation, color}]]`)
$u_{i\alpha} = \begin{pmatrix} U_{L,i\alpha} \\ U^*_{R,i\alpha} \end{pmatrix}$	`Fu[{generation, color}]` = (`FUL[{generation, color}]` , `conj[FUR[{generation, color}]]`)
$\tilde{g}_i = \begin{pmatrix} \lambda_{\tilde{g},i} \\ \lambda^*_{\tilde{g},i} \end{pmatrix}$	`Glu[{generation}]` = (`fG[{generation}]` , `conj[fG[{generation}]]`)

- Scalars

$\tilde{d}_{i\alpha}$	Sd[{generation, color}]	$\tilde{u}_{i\alpha}$	Su[{generation, color}]
h_i	hh[{generation}]	A^0_i	Ah[{generation}]
H^-_i	Hpm[{generation}]		

- Vector Bosons

$g_{i\rho}$	VG[{generation, lorentz}]	W^-_ρ	VWm[{lorentz}]
γ_ρ	VP[{lorentz}]	Z_ρ	VZ[{lorentz}]

- Ghosts

η^G_i	gG[{generation}]	η^-	gWm
η^+	gWmC	η^γ	gP
η^Z	gZ		

7.8.3 Parameters

g_1	g1	g_2	g2	g_3	g3
Y_u	Yu	T_u	T[Yu]	Y_d	Yd
T_d	T[Yd]	Y_e	Ye	T_e	T[Ye]
μ	\[Mu]	B_μ	B[\[Mu]]	ϵ	\[Epsilon]
B_ϵ	B[\[Epsilon]]	λ_1	L1	T_{λ_1}	T[L1]
λ_2	L2	T_{λ_2}	T[L2]	m_q^2	mq2
m_l^2	ml2	$m_{H_d}^2$	mHd2	$m_{H_u}^2$	mHu2
m_d^2	md2	m_u^2	mu2	m_e^2	me2
M_1	MassB	M_2	MassWB	M_3	MassG
m_{lH}^2	mHL2	v_d	vd	v_u	vu
v_L	vL	Θ_W	ThetaW	$\phi_{\tilde{g}}$	PhaseGlu
Z^D	ZD	Z^U	ZU	Z^H	ZH
Z^A	ZA	Z^+	ZP	N	ZN
U	UM	V	UP	U_L^d	ZDL
U_R^d	ZDR	U_L^u	ZUL	U_R^u	ZUR

Chapter 8

The MSSM with R-parity and baryon number violation

8.1 Superfields

8.1.1 Vector Superfields

SF	Spin $\frac{1}{2}$	Spin 1	$SU(N)$	Coupling	Name
$\hat{B}$	$\lambda_{\tilde{B}}$	B	$U(1)$	g_1	hypercharge
$\hat{W}$	$\lambda_{\tilde{W}}$	W^-	SU(2)	g_2	left
$\hat{g}$	$\lambda_{\tilde{g}}$	g	SU(3)	g_3	color

8.1.2 Chiral Superfields

SF	Spin 0	Spin $\frac{1}{2}$	Generations	$(U(1)\otimes \text{SU}(2)\otimes \text{SU}(3))$
$\hat{q}$	$\tilde{q}$	q	3	$(\frac{1}{6},\mathbf{2},\mathbf{3})$
$\hat{l}$	$\tilde{l}$	l	3	$(-\frac{1}{2},\mathbf{2},\mathbf{1})$
$\hat{H}_d$	H_d	$\tilde{H}_d$	1	$(-\frac{1}{2},\mathbf{2},\mathbf{1})$
$\hat{H}_u$	H_u	$\tilde{H}_u$	1	$(\frac{1}{2},\mathbf{2},\mathbf{1})$
$\hat{d}$	$\tilde{d}_R^*$	d_R^*	3	$(\frac{1}{3},\mathbf{1},\overline{\mathbf{3}})$
$\hat{u}$	$\tilde{u}_R^*$	u_R^*	3	$(-\frac{2}{3},\mathbf{1},\overline{\mathbf{3}})$
$\hat{e}$	$\tilde{e}_R^*$	e_R^*	3	$(1,\mathbf{1},\mathbf{1})$

8.2 Superpotential and Lagrangian

8.2.1 Superpotential

$$W = Y_u\,\hat{u}\,\hat{q}\,\hat{H}_u\, - Y_d\,\hat{d}\,\hat{q}\,\hat{H}_d\, - Y_e\,\hat{e}\,\hat{l}\,\hat{H}_d\, + \mu\,\hat{H}_u\,\hat{H}_d\, + \frac{1}{2}\lambda_3\,\hat{d}\,\hat{d}\,\hat{u} \tag{8.1}$$

8.2.2 Softbreaking terms

$$
\begin{aligned}
L_{SB,W} = & - H_d^0 H_u^0 B_\mu + H_d^- H_u^+ B_\mu + \frac{1}{2}\tilde{d}^*_{R,i\alpha}\tilde{d}^*_{R,j\beta}\tilde{u}^*_{R,k\gamma}\epsilon^{\alpha\beta\gamma}T_{\lambda_3,ijk} + H_d^0\tilde{d}^*_{R,i\alpha}\delta_{\alpha\beta}\tilde{d}_{L,j\beta}T_{d,ij} \\
& - H_d^-\tilde{d}^*_{R,i\alpha}\delta_{\alpha\beta}\tilde{u}_{L,j\beta}T_{d,ij} + H_d^0\tilde{e}^*_{R,i}\tilde{e}_{L,j}T_{e,ij} - H_d^-\tilde{e}^*_{R,i}\tilde{\nu}_{L,j}T_{e,ij} - H_u^+\tilde{u}^*_{R,i\alpha}\delta_{\alpha\beta}\tilde{d}_{L,j\beta}T_{u,ij} \\
& + H_u^0\tilde{u}^*_{R,i\alpha}\delta_{\alpha\beta}\tilde{u}_{L,j\beta}T_{u,ij} + \text{h.c.}
\end{aligned} \tag{8.2}
$$

$$
\begin{aligned}
L_{SB,\phi} = & - m^2_{H_d}|H_d^0|^2 - m^2_{H_d}|H_d^-|^2 - m^2_{H_u}|H_u^0|^2 - m^2_{H_u}|H_u^+|^2 - \tilde{d}^*_{L,j\beta}\delta_{\alpha\beta}m^2_{q,ij}\tilde{d}_{L,i\alpha} \\
& - \tilde{d}^*_{R,i\alpha}\delta_{\alpha\beta}m^2_{d,ij}\tilde{d}_{R,j\beta} - \tilde{e}^*_{L,j}m^2_{l,ij}\tilde{e}_{L,i} - \tilde{e}^*_{R,i}m^2_{e,ij}\tilde{e}_{R,j} - \tilde{u}^*_{L,j\beta}\delta_{\alpha\beta}m^2_{q,ij}\tilde{u}_{L,i\alpha} \\
& - \tilde{u}^*_{R,i\alpha}\delta_{\alpha\beta}m^2_{u,ij}\tilde{u}_{R,j\beta} - \tilde{\nu}^*_{L,j}m^2_{l,ij}\tilde{\nu}_{L,i}
\end{aligned} \tag{8.3}
$$

$$
L_{SB,\lambda} = \frac{1}{2}\Big(-\lambda^2_{\tilde{B}}M_1 - M_2\lambda^2_{\tilde{W},i} - M_3\lambda^2_{\tilde{g},i} + \text{h.c.}\Big) \tag{8.4}
$$

8.2.3 Gauge fixing terms

Gauge fixing terms for eigenstates 'GaugeES'

$$
L_{GF} = -\frac{1}{2}\partial_\mu g\xi_G^{-1} - \frac{1}{2}\partial_\mu W^-\xi_W^{-1} \tag{8.5}
$$

Gauge fixing terms for eigenstates 'EWSB'

$$
L_{GF} = -\frac{1}{2}\partial_\mu\gamma\xi_P^{-1} - \frac{1}{2}\partial_\mu g\xi_G^{-1} - \frac{1}{2}\xi_Z^{-1}\Big(-A_1^0 m_Z\xi_Z + \partial_\mu Z\Big) - \xi_W^{-1}\Big(iH_1^- m_{W^-}\xi_W + \partial_\mu W^-\Big) \tag{8.6}
$$

8.2.4 Fields integrated out

None

8.3 Field Rotations

8.3.1 Rotations in gauge sector for eigenstates 'EWSB'

$$
W^-_{1\rho} = \frac{1}{\sqrt{2}}W^-_\rho + \frac{1}{\sqrt{2}}W^+_\rho \tag{8.7}
$$

$$
W^-_{2\rho} = -i\frac{1}{\sqrt{2}}W^-_\rho + i\frac{1}{\sqrt{2}}W^+_\rho \tag{8.8}
$$

$$
W^-_{3\rho} = \cos\Theta_W Z_\rho + \sin\Theta_W\gamma_\rho \tag{8.9}
$$

$$
B_\rho = \cos\Theta_W\gamma_\rho - \sin\Theta_W Z_\rho \tag{8.10}
$$

$$
\lambda_{\tilde{W},1} = \frac{1}{\sqrt{2}}\tilde{W}^- + \frac{1}{\sqrt{2}}\tilde{W}^+ \tag{8.11}
$$

$$
\lambda_{\tilde{W},2} = -i\frac{1}{\sqrt{2}}\tilde{W}^- + i\frac{1}{\sqrt{2}}\tilde{W}^+ \tag{8.12}
$$

$$
\lambda_{\tilde{W},3} = \tilde{W}^0 \tag{8.13}
$$

8.3.2 Rotations in Mass sector for eigenstates 'EWSB'

Mass Matrices for Scalars

- **Mass matrix for Down-Squarks**, Basis: $\left(\tilde{d}_{L,o_1\alpha_1}, \tilde{d}_{R,o_2\alpha_2}\right), \left(\tilde{d}^*_{L,p_1\beta_1}, \tilde{d}^*_{R,p_2\beta_2}\right)$

$$m^2_{\tilde{d}} = \begin{pmatrix} m_{11} & \frac{1}{\sqrt{2}}\delta_{\alpha_1\beta_2}\Big(v_d T_{d,p_2o_1} - v_u\mu^* Y_{d,p_2o_1}\Big) \\ \frac{1}{\sqrt{2}}\Big(v_d T^*_{d,o_2p_1} - v_u\mu Y^*_{d,o_2p_1}\Big)\delta_{\alpha_2\beta_1} & m_{22} \end{pmatrix} \tag{8.14}$$

$$m_{11} = \frac{1}{24}\delta_{\alpha_1\beta_1}\Big(12\Big(2m^2_{q,o_1p_1} + v_d^2\sum_{a=1}^{3} Y^*_{d,ap_1} Y_{d,ao_1}\Big) - \Big(3g_2^2 + g_1^2\Big)\Big(-v_u^2 + v_d^2\Big)\delta_{o_1p_1}\Big) \tag{8.15}$$

$$m_{22} = \frac{1}{12}\delta_{\alpha_2\beta_2}\Big(6\Big(2m^2_{d,p_2o_2} + v_d^2\sum_{a=1}^{3} Y^*_{d,o_2a} Y_{d,p_2a}\Big) + g_1^2\Big(-v_d^2 + v_u^2\Big)\delta_{o_2p_2}\Big) \tag{8.16}$$

This matrix is diagonalized by Z^D:

$$Z^D m^2_{\tilde{d}} Z^{D,\dagger} = m^{dia}_{2,\tilde{d}} \tag{8.17}$$

with

$$\tilde{d}_{L,i\alpha} = \sum_{t_2} Z^{D,*}_{ji}\tilde{d}_{j\alpha}\,, \qquad \tilde{d}_{R,i\alpha} = \sum_{t_2} Z^{D,*}_{ji}\tilde{d}_{j\alpha} \tag{8.18}$$

- **Mass matrix for Sneutrinos**, Basis: $\left(\tilde{\nu}_{L,o_1}\right), \left(\tilde{\nu}^*_{L,p_1}\right)$

$$m^2_{\tilde{\nu}} = \begin{pmatrix} \frac{1}{8}\Big(8m^2_{l,o_1p_1} + \Big(g_1^2 + g_2^2\Big)\Big(-v_u^2 + v_d^2\Big)\delta_{o_1p_1}\Big) \end{pmatrix} \tag{8.19}$$

This matrix is diagonalized by Z^V:

$$Z^V m^2_{\tilde{\nu}} Z^{V,\dagger} = m^{dia}_{2,\tilde{\nu}} \tag{8.20}$$

with

$$\tilde{\nu}_{L,i} = \sum_{t_2} Z^{V,*}_{ji}\tilde{\nu}_j \tag{8.21}$$

- **Mass matrix for Up-Squarks**, Basis: $\left(\tilde{u}_{L,o_1\alpha_1}, \tilde{u}_{R,o_2\alpha_2}\right), \left(\tilde{u}^*_{L,p_1\beta_1}, \tilde{u}^*_{R,p_2\beta_2}\right)$

$$m^2_{\tilde{u}} = \begin{pmatrix} m_{11} & \frac{1}{\sqrt{2}}\delta_{\alpha_1\beta_2}\Big(-v_d\mu^* Y_{u,p_2o_1} + v_u T_{u,p_2o_1}\Big) \\ \frac{1}{\sqrt{2}}\Big(-v_d\mu Y^*_{u,o_2p_1} + v_u T^*_{u,o_2p_1}\Big)\delta_{\alpha_2\beta_1} & m_{22} \end{pmatrix} \tag{8.22}$$

$$m_{11} = \frac{1}{24}\delta_{\alpha_1\beta_1}\Big(12\Big(2m^2_{q,o_1p_1} + v_u^2\sum_{a=1}^{3} Y^*_{u,ap_1} Y_{u,ao_1}\Big) - \Big(-3g_2^2 + g_1^2\Big)\Big(-v_u^2 + v_d^2\Big)\delta_{o_1p_1}\Big) \tag{8.23}$$

$$m_{22} = \frac{1}{6}\delta_{\alpha_2\beta_2}\Big(3v_u^2\sum_{a=1}^{3}Y^*_{u,o_2a}Y_{u,p_2a} + 6m^2_{u,p_2o_2} + g_1^2\Big(-v_u^2+v_d^2\Big)\delta_{o_2p_2}\Big) \tag{8.24}$$

This matrix is diagonalized by Z^U:

$$Z^U m^2_{\tilde{u}} Z^{U,\dagger} = m^{dia}_{2,\tilde{u}} \tag{8.25}$$

with

$$\tilde{u}_{L,i\alpha} = \sum_{t_2} Z^{U,*}_{ji}\tilde{u}_{j\alpha}\,, \qquad \tilde{u}_{R,i\alpha} = \sum_{t_2} Z^{U,*}_{ji}\tilde{u}_{j\alpha} \tag{8.26}$$

- **Mass matrix for Sleptons**, Basis: $\left(\tilde{e}_{L,o_1},\tilde{e}_{R,o_2}\right),\left(\tilde{e}^*_{L,p_1},\tilde{e}^*_{R,p_2}\right)$

$$m^2_{\tilde{e}} = \begin{pmatrix} m_{11} & \frac{1}{\sqrt{2}}\Big(v_d T_{e,p_2o_1} - v_u\mu^* Y_{e,p_2o_1}\Big) \\ \frac{1}{\sqrt{2}}\Big(v_d T^*_{e,o_2p_1} - v_u\mu Y^*_{e,o_2p_1}\Big) & m_{22}\end{pmatrix} \tag{8.27}$$

$$m_{11} = \frac{1}{8}\Big(4v_d^2\sum_{a=1}^{3}Y^*_{e,ap_1}Y_{e,ao_1} + 8m^2_{l,o_1p_1} + \Big(-g_2^2+g_1^2\Big)\Big(-v_u^2+v_d^2\Big)\delta_{o_1p_1}\Big) \tag{8.28}$$

$$m_{22} = \frac{1}{4}\Big(2v_d^2\sum_{a=1}^{3}Y^*_{e,o_2a}Y_{e,p_2a} + 4m^2_{e,p_2o_2} + g_1^2\Big(-v_d^2+v_u^2\Big)\delta_{o_2p_2}\Big) \tag{8.29}$$

This matrix is diagonalized by Z^E:

$$Z^E m^2_{\tilde{e}} Z^{E,\dagger} = m^{dia}_{2,\tilde{e}} \tag{8.30}$$

with

$$\tilde{e}_{L,i} = \sum_{t_2} Z^{E,*}_{ji}\tilde{e}_j\,, \qquad \tilde{e}_{R,i} = \sum_{t_2} Z^{E,*}_{ji}\tilde{e}_j \tag{8.31}$$

- **Mass matrix for Higgs**, Basis: $\left(\phi_d,\phi_u\right),\left(\phi_d,\phi_u\right)$

$$m^2_h = \begin{pmatrix} \frac{1}{8}\Big(8m^2_{H_d} + 8|\mu|^2 + \Big(g_1^2+g_2^2\Big)\Big(3v_d^2 - v_u^2\Big)\Big) & \frac{1}{4}\Big(-4\Re\Big(B_\mu\Big) - \Big(g_1^2+g_2^2\Big)v_dv_u\Big) \\ \frac{1}{4}\Big(-4\Re\Big(B_\mu\Big) - \Big(g_1^2+g_2^2\Big)v_dv_u\Big) & \frac{1}{8}\Big(8m^2_{H_u} + 8|\mu|^2 - \Big(g_1^2+g_2^2\Big)\Big(-3v_u^2+v_d^2\Big)\Big)\end{pmatrix} \tag{8.32}$$

This matrix is diagonalized by Z^H:

$$Z^H m^2_h Z^{H,\dagger} = m^{dia}_{2,h} \tag{8.33}$$

with

$$\phi_d = \sum_{t_2} Z^H_{j1}h_j\,, \qquad \phi_u = \sum_{t_2} Z^H_{j2}h_j \tag{8.34}$$

The mixing matrix can be parametrized by

$$Z^H = \begin{pmatrix} -\sin\alpha & \cos\alpha \\ \cos\alpha & \sin\alpha \end{pmatrix} \tag{8.35}$$

- **Mass matrix for Pseudo-Scalar Higgs**, Basis: $\left(\sigma_d, \sigma_u\right), \left(\sigma_d, \sigma_u\right)$

$$m^2_{A^0} = \begin{pmatrix} \frac{1}{8}\Big(8 m_{H_d}^2 + 8|\mu|^2 + \Big(g_1^2 + g_2^2\Big)\Big(- v_u^2 + v_d^2\Big)\Big) & \Re\Big(B_\mu\Big) \\ \Re\Big(B_\mu\Big) & \frac{1}{8}\Big(8 m_{H_u}^2 + 8|\mu|^2 - \Big(g_1^2 + g_2^2\Big)\Big(- v_u^2 + v_d^2\Big)\Big) \end{pmatrix} \tag{8.36}$$

This matrix is diagonalized by Z^A:

$$Z^A m^2_{A^0} Z^{A,\dagger} = m^{dia}_{2,A^0} \tag{8.37}$$

with

$$\sigma_d = \sum_{t_2} Z^A_{j1} A^0_j \,, \qquad \sigma_u = \sum_{t_2} Z^A_{j2} A^0_j \tag{8.38}$$

The mixing matrix can be parametrized by

$$Z^A = \begin{pmatrix} -\cos\beta & \sin\beta \\ \sin\beta & \cos\beta \end{pmatrix} \tag{8.39}$$

- **Mass matrix for Charged Higgs**, Basis: $\left(H_d^-, H_u^{+,*}\right), \left(H_d^{-,*}, H_u^+\right)$

$$m^2_{H^-} = \begin{pmatrix} m_{11} & \frac{1}{4} g_2^2 v_d v_u + B_\mu \\ \frac{1}{4} g_2^2 v_d v_u + B_\mu^* & m_{22} \end{pmatrix} \tag{8.40}$$

$$m_{11} = \frac{1}{8}\Big(8 m_{H_d}^2 + 8|\mu|^2 + g_1^2 v_d^2 - g_1^2 v_u^2 + g_2^2 v_d^2 + g_2^2 v_u^2\Big) \tag{8.41}$$

$$m_{22} = \frac{1}{8}\Big(8 m_{H_u}^2 + 8|\mu|^2 - g_1^2 v_d^2 + g_1^2 v_u^2 + g_2^2 v_d^2 + g_2^2 v_u^2\Big) \tag{8.42}$$

This matrix is diagonalized by Z^+:

$$Z^+ m^2_{H^-} Z^{+,\dagger} = m^{dia}_{2,H^-} \tag{8.43}$$

with

$$H_d^- = \sum_{t_2} Z^{+,*}_{j1} H_j^- \,, \qquad H_u^+ = \sum_{t_2} Z^+_{j2} H_j^+ \tag{8.44}$$

The mixing matrix can be parametrized by

$$Z^+ = \begin{pmatrix} -\cos\beta & \sin\beta \\ \sin\beta & \cos\beta \end{pmatrix} \tag{8.45}$$

Mass Matrices for Fermions

- **Mass matrix for Neutralinos**, Basis: $\left(\lambda_{\tilde{B}}, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0\right), \left(\lambda_{\tilde{B}}, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0\right)$

$$m_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -\frac{1}{2}g_1 v_d & \frac{1}{2}g_1 v_u \\ 0 & M_2 & \frac{1}{2}g_2 v_d & -\frac{1}{2}g_2 v_u \\ -\frac{1}{2}g_1 v_d & \frac{1}{2}g_2 v_d & 0 & -\mu \\ \frac{1}{2}g_1 v_u & -\frac{1}{2}g_2 v_u & -\mu & 0 \end{pmatrix} \tag{8.46}$$

This matrix is diagonalized by N:

$$N m_{\tilde{\chi}^0} N^\dagger = m^{dia}_{\tilde{\chi}^0} \tag{8.47}$$

with

$$\lambda_{\tilde{B}} = \sum_{t_2} N^*_{j1}\lambda^0_j\,, \qquad \tilde{W}^0 = \sum_{t_2} N^*_{j2}\lambda^0_j\,, \qquad \tilde{H}^0_d = \sum_{t_2} N^*_{j3}\lambda^0_j \tag{8.48}$$

$$\tilde{H}^0_u = \sum_{t_2} N^*_{j4}\lambda^0_j \tag{8.49}$$

- **Mass matrix for Charginos**, Basis: $\left(\tilde{W}^-, \tilde{H}_d^-\right), \left(\tilde{W}^+, \tilde{H}_u^+\right)$

$$m_{\tilde{\chi}^-} = \begin{pmatrix} M_2 & \frac{1}{\sqrt{2}}g_2 v_u \\ \frac{1}{\sqrt{2}}g_2 v_d & \mu \end{pmatrix} \tag{8.50}$$

This matrix is diagonalized by U and V

$$U^* m_{\tilde{\chi}^-} V^\dagger = m^{dia}_{\tilde{\chi}^-} \tag{8.51}$$

with

$$\tilde{W}^- = \sum_{t_2} U^*_{j1}\lambda^-_j\,, \qquad \tilde{H}^-_d = \sum_{t_2} U^*_{j2}\lambda^-_j \tag{8.52}$$

$$\tilde{W}^+ = \sum_{t_2} V^*_{1j}\lambda^+_j\,, \qquad \tilde{H}^+_u = \sum_{t_2} V^*_{2j}\lambda^+_j \tag{8.53}$$

- **Mass matrix for Leptons**, Basis: $\left(e_{L,o_1}\right), \left(e^*_{R,p_1}\right)$

$$m_e = \begin{pmatrix} \frac{1}{\sqrt{2}} v_d Y_{e,p_1 o_1} \end{pmatrix} \tag{8.54}$$

This matrix is diagonalized by U^e_L and U^e_R

$$U^{e,*}_L m_e U^{e,\dagger}_R = m^{dia}_e \tag{8.55}$$

with

$$e_{L,i} = \sum_{t_2} U^{e,*}_{L,ji} E_{L,j} \tag{8.56}$$

$$e_{R,i} = \sum_{t_2} U^{e}_{R,ij} E^*_{R,j} \tag{8.57}$$

- **Mass matrix for Down-Quarks**, Basis: $\left(d_{L,o_1\alpha_1}\right), \left(d^*_{R,p_1\beta_1}\right)$

$$m_d = \left(\begin{array}{c} \frac{1}{\sqrt{2}} v_d \delta_{\alpha_1\beta_1} Y_{d,p_1 o_1} \end{array} \right) \tag{8.58}$$

This matrix is diagonalized by U^d_L and U^d_R

$$U^{d,*}_L m_d U^{d,\dagger}_R = m^{dia}_d \tag{8.59}$$

with

$$d_{L,i\alpha} = \sum_{t_2} U^{d,*}_{L,ji} D_{L,j\alpha} \tag{8.60}$$

$$d_{R,i\alpha} = \sum_{t_2} U^{d}_{R,ij} D^*_{R,j\alpha} \tag{8.61}$$

- **Mass matrix for Up-Quarks**, Basis: $\left(u_{L,o_1\alpha_1}\right), \left(u^*_{R,p_1\beta_1}\right)$

$$m_u = \left(\begin{array}{c} \frac{1}{\sqrt{2}} v_u \delta_{\alpha_1\beta_1} Y_{u,p_1 o_1} \end{array} \right) \tag{8.62}$$

This matrix is diagonalized by U^u_L and U^u_R

$$U^{u,*}_L m_u U^{u,\dagger}_R = m^{dia}_u \tag{8.63}$$

with

$$u_{L,i\alpha} = \sum_{t_2} U^{u,*}_{L,ji} U_{L,j\alpha} \tag{8.64}$$

$$u_{R,i\alpha} = \sum_{t_2} U^{u}_{R,ij} U^*_{R,j\alpha} \tag{8.65}$$

8.4 Vacuum Expectation Values

$$H^0_d = \frac{1}{\sqrt{2}}\phi_d + \frac{1}{\sqrt{2}}v_d + i\frac{1}{\sqrt{2}}\sigma_d \tag{8.66}$$

$$H^0_u = \frac{1}{\sqrt{2}}\phi_u + \frac{1}{\sqrt{2}}v_u + i\frac{1}{\sqrt{2}}\sigma_u \tag{8.67}$$

8.5 Tadpole Equations

$$\frac{\partial V}{\partial v_d} = \frac{1}{8}\Big(8 v_d |\mu|^2 - 8 v_u \Re\Big(B_\mu\Big) + v_d\Big(8 m^2_{H_d} + g_1^2 v_d^2 - g_1^2 v_u^2 + g_2^2 v_d^2 - g_2^2 v_u^2\Big)\Big) \tag{8.68}$$

$$\frac{\partial V}{\partial v_u} = \frac{1}{8}\Big(- 8 v_d \Re\Big(B_\mu\Big) + 8 v_u |\mu|^2 + v_u\Big(8 m^2_{H_u} - g_1^2 v_d^2 + g_1^2 v_u^2 - g_2^2 v_d^2 + g_2^2 v_u^2\Big)\Big) \tag{8.69}$$

8.6 Particle content for eigenstates 'EWSB'

Name	Type	complex/real	Generations	Indices
$\tilde{d}$	Scalar	complex	6	generation, color
$\tilde{\nu}$	Scalar	complex	3	generation
$\tilde{u}$	Scalar	complex	6	generation, color
$\tilde{e}$	Scalar	complex	6	generation
h	Scalar	real	2	generation
A^0	Scalar	real	2	generation
H^-	Scalar	complex	2	generation
ν	Fermion	Dirac	3	generation
$\tilde{g}$	Fermion	Majorana	8	generation
$\tilde{\chi}^0$	Fermion	Majorana	4	generation
$\tilde{\chi}^-$	Fermion	Dirac	2	generation
e	Fermion	Dirac	3	generation
d	Fermion	Dirac	3	generation, color
u	Fermion	Dirac	3	generation, color
g	Vector	real	8	generation, lorentz
W^-	Vector	complex	1	lorentz
γ	Vector	real	1	lorentz
Z	Vector	real	1	lorentz
η^G	Ghost	real	8	generation
η^-	Ghost	complex	1	
η^+	Ghost	complex	1	
η^γ	Ghost	real	1	
η^Z	Ghost	real	1	

8.7 Modelfile for SARAH

```
Off[General::spell]
Print["Model file for the MSSM loaded"];

ModelNameLaTeX ="MSSM";


(*-------------------------------------------*)
(*   Particle Content*)
(*-------------------------------------------*)

(* Gauge Superfields *)

Gauge[[1]]={B,   U[1], hypercharge, g1,False};
Gauge[[2]]={WB, SU[2], left,        g2,True};
Gauge[[3]]={G,  SU[3], color,       g3,False};


(* Chiral Superfields *)

Fields[[1]] = {{uL,  dL},  3, q,   1/6, 2, 3};
Fields[[2]] = {{vL,  eL},  3, l,  -1/2, 2, 1};
Fields[[3]] = {{Hd0, Hdm}, 1, Hd, -1/2, 2, 1};
Fields[[4]] = {{Hup, Hu0}, 1, Hu,  1/2, 2, 1};

Fields[[5]] = {conj[dR], 3, d,  1/3, 1, -3};
Fields[[6]] = {conj[uR], 3, u, -2/3, 1, -3};
Fields[[7]] = {conj[eR], 3, e,    1, 1,  1};


(*------------------------------------------------------*)
(* Superpotential *)
(*------------------------------------------------------*)


SuperPotential = { {{1, Yu},{u,q,Hu}}, {{-1,Yd},{d,q,Hd}},
                   {{-1,Ye},{e,l,Hd}}, {{1,\[Mu]},{Hu,Hd}},
                   {{1/2, Lambda3},{d,d,u}}};


(*-------------------------------------------*)
(* Integrate Out or Delete Particles        *)
(*-------------------------------------------*)

IntegrateOut={};
```

```
DeleteParticles={};


(*--------------------------------------------*)
(*   DEFINITION                               *)
(*--------------------------------------------*)

NameOfStates={GaugeES, EWSB};

(* ----- Before EWSB ----- *)


DEFINITION[GaugeES][GaugeFixing]=
{ {Der[VWB],  -1/(2 RXi[W])},
     {Der[VG],   -1/(2 RXi[G]) }};

(* ----- After EWSB ----- *)


(* Gauge Sector *)

DEFINITION[EWSB][GaugeSector]=
{{VWB,{1,{VWm,1/Sqrt[2]},{conj[VWm],1/Sqrt[2]}},
      {2,{VWm,-\[ImaginaryI]/Sqrt[2]},{conj[VWm],\[ImaginaryI]/Sqrt[2]}},
      {3,{VP,Sin[ThetaW]},{VZ,Cos[ThetaW]}}},
 {VB, {1,{VP,Cos[ThetaW]},{VZ,-Sin[ThetaW]}}},
 {fWB,{1,{fWm,1/Sqrt[2]},{fWp,1/Sqrt[2]}},
      {2,{fWm,-\[ImaginaryI]/Sqrt[2]},{fWp,\[ImaginaryI]/Sqrt[2]}},
      {3,{fW0,1}}}};




(* ----- VEVs ---- *)

DEFINITION[EWSB][VEVs]=
  {{SHd0, {vd, 1/Sqrt[2]}, {sigmad, \[ImaginaryI]/Sqrt[2]},{phid, \
1/Sqrt[2]}},
   {SHu0, {vu, 1/Sqrt[2]}, {sigmau, \[ImaginaryI]/Sqrt[2]},{phiu, \
1/Sqrt[2]}}};



(* ---- Mixings ---- *)

DEFINITION[EWSB][MatterSector]=
{    {{SdL, SdR}, {Sd, ZD}},
 {{SvL}, {Sv, ZV}},
```

```
     {{SuL, SuR}, {Su, ZU}},
     {{SeL, SeR}, {Se, ZE}},
     {{phid, phiu}, {hh, ZH}},
     {{sigmad, sigmau}, {Ah, ZA}},
     {{SHdm,conj[SHup]},{Hpm,ZP}},
     {{fB, fW0, FHd0, FHu0}, {L0, ZN}},
     {{{fWm, FHdm}, {fWp, FHup}}, {{Lm,UM}, {Lp,UP}}},
     {{{FeL},{conj[FeR]}},{{FEL,ZEL},{FER,ZER}}},
     {{{FdL},{conj[FdR]}},{{FDL,ZDL},{FDR,ZDR}}},
     {{{FuL},{conj[FuR]}},{{FUL,ZUL},{FUR,ZUR}}}      \
       };

DEFINITION[EWSB][Phases]=
{    {fG, PhaseGlu}
    };

(*--- Gauge Fixing ---- *)

DEFINITION[EWSB][GaugeFixing]=
  { {Der[VP],                                            - 1/(2 RXi[P])},
{Der[VWm]+\[ImaginaryI] Mass[VWm] RXi[W] Hpm[{1}],   - 1/(RXi[W])},
{Der[VZ] - Mass[VZ] RXi[Z] Ah[{1}],                 - 1/(2 RXi[Z])},
{Der[VG],                                           - 1/(2 RXi[G])}};


(*------------------------------------------------------*)
(* Dirac-Spinors *)
(*------------------------------------------------------*)

dirac[[1]] = {Fd,  FDL, conj[FDR]};
dirac[[2]] = {Fe,  FEL, conj[FER]};
dirac[[3]] = {Fu,  FUL, conj[FUR]};
dirac[[4]] = {Fv,  FvL, 0};
dirac[[5]] = {Chi, L0, conj[L0]};
dirac[[6]] = {Cha, Lm, conj[Lp]};
dirac[[7]] = {Glu, fG, conj[fG]};


(* Unbroken EW *)

dirac[[8]] = {Bino, fB, conj[fB]};
dirac[[9]] = {Wino, fWB, conj[fWB]};
dirac[[10]] = {H0, FHd0, conj[FHu0]};
dirac[[11]] = {HC, FHdm, conj[FHup]};
dirac[[12]] = {Fd1, FdL, 0};
dirac[[13]] = {Fd2, 0, FdR};
dirac[[14]] = {Fu1, FuL, 0};
dirac[[15]] = {Fu2, 0, FuR};
```

```
dirac[[16]] = {Fe1, FeL, 0};
dirac[[17]] = {Fe2, 0, FeR};




(*-------------------------------------------------*)
(* Automatized Output        *)
(*-------------------------------------------------*)

(*
makeOutput = {
                    {EWSB, {TeX, FeynArts}}
             };
            *)

SpectrumFile=None;
```

8.8 Implementation in SARAH

Model directory: `MSSM-RpV/BnV`

8.8.1 Particles for eigenstates 'GaugeES'

- Fermions

$\tilde{B} = \begin{pmatrix} \lambda_{\tilde{B}} \\ \lambda^*_{\tilde{B}} \end{pmatrix}$	$\texttt{Bino} = \begin{pmatrix} \texttt{fB} \\ \texttt{conj[fB]} \end{pmatrix}$
$d^1_{i\alpha} = \begin{pmatrix} d_{L,i\alpha} \\ 0 \end{pmatrix}$	$\texttt{Fd1[\{generation, color\}]} = \begin{pmatrix} \texttt{FdL[\{generation, color\}]} \\ 0 \end{pmatrix}$
$d^2_{i\alpha} = \begin{pmatrix} 0 \\ d_{R,i\alpha} \end{pmatrix}$	$\texttt{Fd2[\{generation, color\}]} = \begin{pmatrix} 0 \\ \texttt{FdR[\{generation, color\}]} \end{pmatrix}$
$e^1_i = \begin{pmatrix} e_{L,i} \\ 0 \end{pmatrix}$	$\texttt{Fe1[\{generation\}]} = \begin{pmatrix} \texttt{FeL[\{generation\}]} \\ 0 \end{pmatrix}$
$e^2_i = \begin{pmatrix} 0 \\ e_{R,i} \end{pmatrix}$	$\texttt{Fe2[\{generation\}]} = \begin{pmatrix} 0 \\ \texttt{FeR[\{generation\}]} \end{pmatrix}$
$u^1_{i\alpha} = \begin{pmatrix} u_{L,i\alpha} \\ 0 \end{pmatrix}$	$\texttt{Fu1[\{generation, color\}]} = \begin{pmatrix} \texttt{FuL[\{generation, color\}]} \\ 0 \end{pmatrix}$

$u^2_{i\alpha} = \begin{pmatrix} 0 \\ u_{R,i\alpha} \end{pmatrix}$	$\texttt{Fu2[\{generation, color\}]} = \begin{pmatrix} 0 \\ \texttt{FuR[\{generation, color\}]} \end{pmatrix}$
$\nu_i = \begin{pmatrix} \nu_{L,i} \\ 0 \end{pmatrix}$	$\texttt{Fv[\{generation\}]} = \begin{pmatrix} \texttt{FvL[\{generation\}]} \\ 0 \end{pmatrix}$
$\tilde{g}_i = \begin{pmatrix} \lambda_{\tilde{g},i} \\ \lambda^*_{\tilde{g},i} \end{pmatrix}$	$\texttt{Glu[\{generation\}]} = \begin{pmatrix} \texttt{fG[\{generation\}]} \\ \texttt{conj[fG[\{generation\}]]} \end{pmatrix}$
$\tilde{H}^0 = \begin{pmatrix} \tilde{H}^0_d \\ \tilde{H}^{0,*}_u \end{pmatrix}$	$\texttt{H0} = \begin{pmatrix} \texttt{FHd0} \\ \texttt{conj[FHu0]} \end{pmatrix}$
$\tilde{H}^- = \begin{pmatrix} \tilde{H}^-_d \\ \tilde{H}^{+,*}_u \end{pmatrix}$	$\texttt{HC} = \begin{pmatrix} \texttt{FHdm} \\ \texttt{conj[FHup]} \end{pmatrix}$
$\tilde{W}_i = \begin{pmatrix} \lambda_{\tilde{W},i} \\ \lambda^*_{\tilde{W},i} \end{pmatrix}$	$\texttt{Wino[\{generation\}]} = \begin{pmatrix} \texttt{fWB[\{generation\}]} \\ \texttt{conj[fWB[\{generation\}]]} \end{pmatrix}$

- Scalars

$\tilde{d}_{L,i\alpha}$	`SdL[{generation, color}]`	$\tilde{u}_{L,i\alpha}$	`SuL[{generation, color}]`
$\tilde{e}_{L,i}$	`SeL[{generation}]`	$\tilde{\nu}_{L,i}$	`SvL[{generation}]`
H^0_d	`SHd0`	H^-_d	`SHdm`
H^0_u	`SHu0`	H^+_u	`SHup`
$\tilde{d}_{R,i\alpha}$	`SdR[{generation, color}]`	$\tilde{u}_{R,i\alpha}$	`SuR[{generation, color}]`
$\tilde{e}_{R,i}$	`SeR[{generation}]`		

- Vector Bosons

B_ρ	`VB[{lorentz}]`	$W^-_{i\rho}$	`VWB[{generation, lorentz}]`
$g_{i\rho}$	`VG[{generation, lorentz}]`		

- Ghosts

η^B	`gB`	$\mathrm{gWB}\Big(\{\mathrm{gt1}\}\Big)$	`gWB[{generation}]`

η_i^G	gG[{generation}]	

8.8.2 Particles for eigenstates 'EWSB'

- Fermions

$\tilde{\chi}_i^- = \begin{pmatrix} \lambda_i^- \\ \lambda_i^{+,*} \end{pmatrix}$	Cha[{generation}] $= \begin{pmatrix} \texttt{Lm[\{generation\}]} \\ \texttt{conj[Lp[\{generation\}]]} \end{pmatrix}$
$\tilde{\chi}_i^0 = \begin{pmatrix} \lambda_i^0 \\ \lambda_i^{0,*} \end{pmatrix}$	Chi[{generation}] $= \begin{pmatrix} \texttt{L0[\{generation\}]} \\ \texttt{conj[L0[\{generation\}]]} \end{pmatrix}$
$d_{i\alpha} = \begin{pmatrix} D_{L,i\alpha} \\ D^*_{R,i\alpha} \end{pmatrix}$	Fd[{generation, color}] $= \begin{pmatrix} \texttt{FDL[\{generation, color\}]} \\ \texttt{conj[FDR[\{generation, color\}]]} \end{pmatrix}$
$e_i = \begin{pmatrix} E_{L,i} \\ E^*_{R,i} \end{pmatrix}$	Fe[{generation}] $= \begin{pmatrix} \texttt{FEL[\{generation\}]} \\ \texttt{conj[FER[\{generation\}]]} \end{pmatrix}$
$u_{i\alpha} = \begin{pmatrix} U_{L,i\alpha} \\ U^*_{R,i\alpha} \end{pmatrix}$	Fu[{generation, color}] $= \begin{pmatrix} \texttt{FUL[\{generation, color\}]} \\ \texttt{conj[FUR[\{generation, color\}]]} \end{pmatrix}$
$\nu_i = \begin{pmatrix} \nu_{L,i} \\ 0 \end{pmatrix}$	Fv[{generation}] $= \begin{pmatrix} \texttt{FvL[\{generation\}]} \\ \texttt{0} \end{pmatrix}$
$\tilde{g}_i = \begin{pmatrix} \lambda_{\tilde{g},i} \\ \lambda^*_{\tilde{g},i} \end{pmatrix}$	Glu[{generation}] $= \begin{pmatrix} \texttt{fG[\{generation\}]} \\ \texttt{conj[fG[\{generation\}]]} \end{pmatrix}$

- Scalars

$\tilde{d}_{i\alpha}$	Sd[{generation, color}]	$\tilde{\nu}_i$	Sv[{generation}]
$\tilde{u}_{i\alpha}$	Su[{generation, color}]	$\tilde{e}_i$	Se[{generation}]
h_i	hh[{generation}]	A_i^0	Ah[{generation}]
H_i^-	Hpm[{generation}]		

- Vector Bosons

$g_{i\rho}$	`VG[{generation, lorentz}]`	W^-_ρ	`VWm[{lorentz}]`
γ_ρ	`VP[{lorentz}]`	Z_ρ	`VZ[{lorentz}]`

- Ghosts

η^G_i	`gG[{generation}]`	η^-	`gWm`
η^+	`gWmC`	η^γ	`gP`
η^Z	`gZ`		

8.8.3 Parameters

g_1	`g1`	g_2	`g2`	g_3	`g3`
Y_u	`Yu`	T_u	`T[Yu]`	Y_d	`Yd`
T_d	`T[Yd]`	Y_e	`Ye`	T_e	`T[Ye]`
μ	`\[Mu]`	B_μ	`B[\[Mu]]`	λ_3	`Lambda3`
T_{λ_3}	`T[Lambda3]`	m_q^2	`mq2`	m_l^2	`ml2`
$m_{H_d}^2$	`mHd2`	$m_{H_u}^2$	`mHu2`	m_d^2	`md2`
m_u^2	`mu2`	m_e^2	`me2`	M_1	`MassB`
M_2	`MassWB`	M_3	`MassG`	v_d	`vd`
v_u	`vu`	Θ_W	`ThetaW`	$\phi_{\tilde{g}}$	`PhaseGlu`
Z^D	`ZD`	Z^V	`ZV`	Z^U	`ZU`
Z^E	`ZE`	Z^H	`ZH`	Z^A	`ZA`
Z^+	`ZP`	N	`ZN`	U	`UM`
V	`UP`	U_L^e	`ZEL`	U_R^e	`ZER`
U_L^d	`ZDL`	U_R^d	`ZDR`	U_L^u	`ZUL`
U_R^u	`ZUR`	α	`\[Alpha]`	β	`\[Beta]`
$Lambda3[1]$	`Lambda3[1]`	$Lambda3[2]$	`Lambda3[2]`	$Lambda3[3]$	`Lambda3[3]`
$T[Lambda3][1]$	`T[Lambda3][1]`	$T[Lambda3][2]$	`T[Lambda3][2]`	$T[Lambda3][3]$	`T[Lambda3][3]`

Chapter 9

The Next-to-Minimal Supersymmetric Standard Model

9.1 Superfields

9.1.1 Vector Superfields

SF	Spin $\frac{1}{2}$	Spin 1	$SU(N)$	Coupling	Name
$\hat{B}$	$\lambda_{\tilde{B}}$	B	$U(1)$	g_1	hypercharge
$\hat{W}$	$\lambda_{\tilde{W}}$	W^-	SU(2)	g_2	left
$\hat{g}$	$\lambda_{\tilde{g}}$	g	SU(3)	g_3	color

9.1.2 Chiral Superfields

SF	Spin 0	Spin $\frac{1}{2}$	Generations	$(U(1)\otimes \text{SU}(2)\otimes \text{SU}(3))$
$\hat{q}$	$\tilde{q}$	q	3	$(\frac{1}{6},\mathbf{2},\mathbf{3})$
$\hat{l}$	$\tilde{l}$	l	3	$(-\frac{1}{2},\mathbf{2},\mathbf{1})$
$\hat{H}_d$	H_d	$\tilde{H}_d$	1	$(-\frac{1}{2},\mathbf{2},\mathbf{1})$
$\hat{H}_u$	H_u	$\tilde{H}_u$	1	$(\frac{1}{2},\mathbf{2},\mathbf{1})$
$\hat{d}$	$\tilde{d}_R^*$	d_R^*	3	$(\frac{1}{3},\mathbf{1},\overline{\mathbf{3}})$
$\hat{u}$	$\tilde{u}_R^*$	u_R^*	3	$(-\frac{2}{3},\mathbf{1},\overline{\mathbf{3}})$
$\hat{e}$	$\tilde{e}_R^*$	e_R^*	3	$(1,\mathbf{1},\mathbf{1})$
$\hat{s}$	S	$\tilde{S}$	1	$(0,\mathbf{1},\mathbf{1})$

9.2 Superpotential and Lagrangian

9.2.1 Superpotential

$$W = Y_u\,\hat{q}\,\hat{H}_u\,\hat{u}\,-Y_d\,\hat{q}\,\hat{H}_d\,\hat{d}\,-Y_e\,\hat{l}\,\hat{H}_d\,\hat{e}\,+\lambda\,\hat{H}_u\,\hat{H}_d\,\hat{s}\,+\frac{1}{3}\kappa\,\hat{s}\,\hat{s}\,\hat{s} \tag{9.1}$$

9.2.2 Softbreaking terms

$$
\begin{aligned}
L_{SB,W} =& +\frac{1}{3}S^3T_\kappa - H_d^0H_u^0ST_\lambda + H_d^-H_u^+ST_\lambda + H_d^0\tilde{d}^*_{R,k\gamma}\delta_{\alpha\gamma}\tilde{d}_{L,i\alpha}T_{d,ik} - H_d^-\tilde{d}^*_{R,k\gamma}\delta_{\alpha\gamma}\tilde{u}_{L,i\alpha}T_{d,ik} \\
&+ H_d^0\tilde{e}^*_{R,k}\tilde{e}_{L,i}T_{e,ik} - H_d^-\tilde{e}^*_{R,k}\tilde{\nu}_{L,i}T_{e,ik} - H_u^+\tilde{u}^*_{R,k\gamma}\delta_{\alpha\gamma}\tilde{d}_{L,i\alpha}T_{u,ik} + H_u^0\tilde{u}^*_{R,k\gamma}\delta_{\alpha\gamma}\tilde{u}_{L,i\alpha}T_{u,ik} + \text{h.c.} \qquad (9.2)\\
L_{SB,\phi} =& - m^2_{H_d}|H_d^0|^2 - m^2_{H_d}|H_d^-|^2 - m^2_{H_u}|H_u^0|^2 - m^2_{H_u}|H_u^+|^2 - m^2_S|S|^2 \\
&- \tilde{d}^*_{L,j\beta}\delta_{\alpha\beta}m^2_{q,ij}\tilde{d}_{L,i\alpha} - \tilde{d}^*_{R,i\alpha}\delta_{\alpha\beta}m^2_{d,ij}\tilde{d}_{R,j\beta} - \tilde{e}^*_{L,j}m^2_{l,ij}\tilde{e}_{L,i} - \tilde{e}^*_{R,i}m^2_{e,ij}\tilde{e}_{R,j} \\
&- \tilde{u}^*_{L,j\beta}\delta_{\alpha\beta}m^2_{q,ij}\tilde{u}_{L,i\alpha} - \tilde{u}^*_{R,i\alpha}\delta_{\alpha\beta}m^2_{u,ij}\tilde{u}_{R,j\beta} - \tilde{\nu}^*_{L,j}m^2_{l,ij}\tilde{\nu}_{L,i} \qquad (9.3)\\
L_{SB,\lambda} =& \frac{1}{2}\left(-\lambda^2_{\tilde{B}}M_1 - M_2\lambda^2_{\tilde{W},i} - M_3\lambda^2_{\tilde{g},i} + \text{h.c.}\right) \qquad (9.4)
\end{aligned}
$$

9.2.3 Gauge fixing terms

Gauge fixing terms for eigenstates 'GaugeES'

$$L_{GF} = -\frac{1}{2}\partial_\mu g\xi_G^{-1} - \frac{1}{2}\partial_\mu W^-\xi_W^{-1} \qquad (9.5)$$

Gauge fixing terms for eigenstates 'EWSB'

$$L_{GF} = -\frac{1}{2}\partial_\mu\gamma\xi_P^{-1} - \frac{1}{2}\partial_\mu g\xi_G^{-1} - \frac{1}{2}\xi_Z^{-1}\Big(-A_1^0m_Z\xi_Z + \partial_\mu Z\Big) - \xi_W^{-1}\Big(iH_1^-m_{W^-}\xi_W + \partial_\mu W^-\Big) \qquad (9.6)$$

9.2.4 Fields integrated out

None

9.3 Field Rotations

9.3.1 Rotations in gauge sector for eigenstates 'EWSB'

$$
\begin{aligned}
W^-_{1\rho} &= \frac{1}{\sqrt{2}}W^-_\rho + \frac{1}{\sqrt{2}}W^+_\rho && (9.7)\\
W^-_{2\rho} &= -i\frac{1}{\sqrt{2}}W^-_\rho + i\frac{1}{\sqrt{2}}W^+_\rho && (9.8)\\
W^-_{3\rho} &= \cos\Theta_W Z_\rho + \sin\Theta_W\gamma_\rho && (9.9)\\
B_\rho &= \cos\Theta_W\gamma_\rho - \sin\Theta_W Z_\rho && (9.10)\\
\lambda_{\tilde{W},1} &= \frac{1}{\sqrt{2}}\tilde{W}^- + \frac{1}{\sqrt{2}}\tilde{W}^+ && (9.11)\\
\lambda_{\tilde{W},2} &= -i\frac{1}{\sqrt{2}}\tilde{W}^- + i\frac{1}{\sqrt{2}}\tilde{W}^+ && (9.12)\\
\lambda_{\tilde{W},3} &= \tilde{W}^0 && (9.13)
\end{aligned}
$$

9.3.2 Rotations in Mass sector for eigenstates 'EWSB'

Mass Matrices for Scalars

- **Mass matrix for Down-Squarks**, Basis: $\left(\tilde{d}_{L,o_1\alpha_1}, \tilde{d}_{R,o_2\alpha_2}\right), \left(\tilde{d}^*_{L,p_1\beta_1}, \tilde{d}^*_{R,p_2\beta_2}\right)$

$$m^2_{\tilde{d}} = \left(\begin{array}{cc} m_{11} & \frac{1}{2}\delta_{\alpha_1\beta_2}\Big(\sqrt{2}v_d T_{d,o_1p_2} - v_s v_u \lambda^* Y_{d,o_1p_2}\Big) \\ \frac{1}{2}\Big(\sqrt{2}v_d T^*_{d,p_1o_2} - v_s v_u \lambda Y^*_{d,p_1o_2}\Big)\delta_{\alpha_2\beta_1} & m_{22} \end{array} \right) \tag{9.14}$$

$$m_{11} = \frac{1}{24}\delta_{\alpha_1\beta_1}\Big(12\Big(2m^2_{q,o_1p_1} + v_d^2 \sum_{a=1}^{3} Y^*_{d,p_1a} Y_{d,o_1a}\Big) - \Big(3g_2^2 + g_1^2\Big)\Big(- v_u^2 + v_d^2\Big)\delta_{o_1p_1}\Big) \tag{9.15}$$

$$m_{22} = \frac{1}{12}\delta_{\alpha_2\beta_2}\Big(6\Big(2m^2_{d,p_2o_2} + v_d^2 \sum_{a=1}^{3} Y^*_{d,ao_2} Y_{d,ap_2}\Big) + g_1^2\Big(- v_d^2 + v_u^2\Big)\delta_{o_2p_2}\Big) \tag{9.16}$$

This matrix is diagonalized by Z^D:

$$Z^D m^2_{\tilde{d}} Z^{D,\dagger} = m^{dia}_{2,\tilde{d}} \tag{9.17}$$

with

$$\tilde{d}_{L,i\alpha} = \sum_{t_2} Z^{D,*}_{ji} \tilde{d}_{j\alpha}\,, \qquad \tilde{d}_{R,i\alpha} = \sum_{t_2} Z^{D,*}_{ji} \tilde{d}_{j\alpha} \tag{9.18}$$

- **Mass matrix for Sneutrinos**, Basis: $\left(\tilde{\nu}_{L,o_1}\right), \left(\tilde{\nu}^*_{L,p_1}\right)$

$$m^2_{\tilde{\nu}} = \left(\begin{array}{c} \frac{1}{8}\Big(8m^2_{l,o_1p_1} + \Big(g_1^2 + g_2^2\Big)\Big(- v_u^2 + v_d^2\Big)\delta_{o_1p_1}\Big) \end{array} \right) \tag{9.19}$$

This matrix is diagonalized by Z^V:

$$Z^V m^2_{\tilde{\nu}} Z^{V,\dagger} = m^{dia}_{2,\tilde{\nu}} \tag{9.20}$$

with

$$\tilde{\nu}_{L,i} = \sum_{t_2} Z^{V,*}_{ji} \tilde{\nu}_j \tag{9.21}$$

- **Mass matrix for Up-Squarks**, Basis: $\left(\tilde{u}_{L,o_1\alpha_1}, \tilde{u}_{R,o_2\alpha_2}\right), \left(\tilde{u}^*_{L,p_1\beta_1}, \tilde{u}^*_{R,p_2\beta_2}\right)$

$$m^2_{\tilde{u}} = \left(\begin{array}{cc} m_{11} & \frac{1}{2}\delta_{\alpha_1\beta_2}\Big(\sqrt{2}v_u T_{u,o_1p_2} - v_d v_s \lambda^* Y_{u,o_1p_2}\Big) \\ \frac{1}{2}\Big(\sqrt{2}v_u T^*_{u,p_1o_2} - v_d v_s \lambda Y^*_{u,p_1o_2}\Big)\delta_{\alpha_2\beta_1} & m_{22} \end{array} \right) \tag{9.22}$$

$$m_{11} = \frac{1}{24}\delta_{\alpha_1\beta_1}\Big(12\Big(2m^2_{q,o_1p_1} + v_u^2 \sum_{a=1}^{3} Y^*_{u,p_1a} Y_{u,o_1a}\Big) - \Big(- 3g_2^2 + g_1^2\Big)\Big(- v_u^2 + v_d^2\Big)\delta_{o_1p_1}\Big) \tag{9.23}$$

$$m_{22} = \frac{1}{6}\delta_{\alpha_2\beta_2}\Big(3v_u^2\sum_{a=1}^{3}Y^*_{u,ao_2}Y_{u,ap_2} + 6m^2_{u,p_2o_2} + g_1^2\Big(-v_u^2+v_d^2\Big)\delta_{o_2p_2}\Big) \tag{9.24}$$

This matrix is diagonalized by Z^U:

$$Z^U m^2_{\tilde{u}} Z^{U,\dagger} = m^{dia}_{2,\tilde{u}} \tag{9.25}$$

with

$$\tilde{u}_{L,i\alpha} = \sum_{t_2} Z^{U,*}_{ji}\tilde{u}_{j\alpha}\,, \qquad \tilde{u}_{R,i\alpha} = \sum_{t_2} Z^{U,*}_{ji}\tilde{u}_{j\alpha} \tag{9.26}$$

- **Mass matrix for Sleptons**, Basis: $\left(\tilde{e}_{L,o_1}, \tilde{e}_{R,o_2}\right), \left(\tilde{e}^*_{L,p_1}, \tilde{e}^*_{R,p_2}\right)$

$$m^2_{\tilde{e}} = \begin{pmatrix} m_{11} & -\frac{1}{2}v_s v_u \lambda^* Y_{e,o_1p_2} + \frac{1}{\sqrt{2}}v_d T_{e,o_1p_2} \\ -\frac{1}{2}v_s v_u \lambda Y^*_{e,p_1o_2} + \frac{1}{\sqrt{2}}v_d T^*_{e,p_1o_2} & m_{22} \end{pmatrix} \tag{9.27}$$

$$m_{11} = \frac{1}{8}\Big(4v_d^2\sum_{a=1}^{3}Y^*_{e,p_1a}Y_{e,o_1a} + 8m^2_{l,o_1p_1} + \Big(-g_2^2+g_1^2\Big)\Big(-v_u^2+v_d^2\Big)\delta_{o_1p_1}\Big) \tag{9.28}$$

$$m_{22} = \frac{1}{4}\Big(2v_d^2\sum_{a=1}^{3}Y^*_{e,ao_2}Y_{e,ap_2} + 4m^2_{e,p_2o_2} + g_1^2\Big(-v_d^2+v_u^2\Big)\delta_{o_2p_2}\Big) \tag{9.29}$$

This matrix is diagonalized by Z^E:

$$Z^E m^2_{\tilde{e}} Z^{E,\dagger} = m^{dia}_{2,\tilde{e}} \tag{9.30}$$

with

$$\tilde{e}_{L,i} = \sum_{t_2} Z^{E,*}_{ji}\tilde{e}_j\,, \qquad \tilde{e}_{R,i} = \sum_{t_2} Z^{E,*}_{ji}\tilde{e}_j \tag{9.31}$$

- **Mass matrix for Higgs**, Basis: $\left(\phi_d, \phi_u, \phi_s\right), \left(\phi_d, \phi_u, \phi_s\right)$

$$m^2_h = \begin{pmatrix} m_{11} & m^*_{21} & m^*_{31} \\ m_{21} & m_{22} & m^*_{32} \\ m_{31} & m_{32} & m_{33} \end{pmatrix} \tag{9.32}$$

$$m_{11} = \frac{1}{8}\Big(4\Big(v_s^2+v_u^2\Big)|\lambda|^2 + 8m^2_{H_d} + \Big(g_1^2+g_2^2\Big)\Big(3v_d^2-v_u^2\Big)\Big) \tag{9.33}$$

$$m_{21} = \frac{1}{4}\Big(-2\sqrt{2}v_s\Re\Big(T_\lambda\Big) + \Big(4v_dv_u\lambda - v_s^2\kappa\Big)\lambda^* - g_1^2v_dv_u - g_2^2v_dv_u - v_s^2\lambda\kappa^*\Big) \tag{9.34}$$

$$m_{22} = \frac{1}{8}\Big(4\Big(v_d^2+v_s^2\Big)|\lambda|^2 + 8m^2_{H_u} - \Big(g_1^2+g_2^2\Big)\Big(-3v_u^2+v_d^2\Big)\Big) \tag{9.35}$$

$$m_{31} = \frac{1}{2}\Big(\Big(2v_d v_s \lambda - v_s v_u \kappa\Big)\lambda^* - \sqrt{2}v_u \Re\Big(T_\lambda\Big) - v_s v_u \lambda \kappa^*\Big) \tag{9.36}$$

$$m_{32} = \frac{1}{2}\Big(\Big(2v_s v_u \lambda - v_d v_s \kappa\Big)\lambda^* - \sqrt{2}v_d \Re\Big(T_\lambda\Big) - v_d v_s \lambda \kappa^*\Big) \tag{9.37}$$

$$m_{33} = \frac{1}{2}\Big(2\Big(\sqrt{2}v_s \Re\Big(T_\kappa\Big) + m_S^2\Big) + \Big(6v_s^2 \kappa - v_d v_u \lambda\Big)\kappa^* + \Big(v_d^2 \lambda - v_d v_u \kappa + v_u^2 \lambda\Big)\lambda^*\Big) \tag{9.38}$$

This matrix is diagonalized by Z^H:

$$Z^H m_h^2 Z^{H,\dagger} = m_{2,h}^{dia} \tag{9.39}$$

with

$$\phi_d = \sum_{t_2} Z_{j1}^H h_j \,, \qquad \phi_u = \sum_{t_2} Z_{j2}^H h_j \,, \qquad \phi_s = \sum_{t_2} Z_{j3}^H h_j \tag{9.40}$$

- **Mass matrix for Pseudo-Scalar Higgs**, Basis: $(\sigma_d, \sigma_u, \sigma_s)\,, (\sigma_d, \sigma_u, \sigma_s)$

$$m_{A^0}^2 = \begin{pmatrix} m_{11} & m_{21}^* & m_{31}^* \\ m_{21} & m_{22} & m_{32}^* \\ m_{31} & m_{32} & m_{33} \end{pmatrix} \tag{9.41}$$

$$m_{11} = \frac{1}{8}\Big(4\Big(v_s^2 + v_u^2\Big)|\lambda|^2 + 8m_{H_d}^2 + \Big(g_1^2 + g_2^2\Big)\Big(- v_u^2 + v_d^2\Big)\Big) \tag{9.42}$$

$$m_{21} = \frac{1}{4}v_s\Big(2\sqrt{2}\Re\Big(T_\lambda\Big) + v_s \kappa \lambda^* + v_s \lambda \kappa^*\Big) \tag{9.43}$$

$$m_{22} = \frac{1}{8}\Big(4\Big(v_d^2 + v_s^2\Big)|\lambda|^2 + 8m_{H_u}^2 - \Big(g_1^2 + g_2^2\Big)\Big(- v_u^2 + v_d^2\Big)\Big) \tag{9.44}$$

$$m_{31} = -\frac{1}{2}v_u\Big(- \sqrt{2}\Re\Big(T_\lambda\Big) + v_s \kappa \lambda^* + v_s \lambda \kappa^*\Big) \tag{9.45}$$

$$m_{32} = -\frac{1}{2}v_d\Big(- \sqrt{2}\Re\Big(T_\lambda\Big) + v_s \kappa \lambda^* + v_s \lambda \kappa^*\Big) \tag{9.46}$$

$$m_{33} = \frac{1}{2}\Big(2\Big(- \sqrt{2}v_s \Re\Big(T_\kappa\Big) + m_S^2\Big) + \Big(2v_s^2 \kappa + v_d v_u \lambda\Big)\kappa^* + \Big(v_d^2 \lambda + v_d v_u \kappa + v_u^2 \lambda\Big)\lambda^*\Big) \tag{9.47}$$

This matrix is diagonalized by Z^A:

$$Z^A m_{A^0}^2 Z^{A,\dagger} = m_{2,A^0}^{dia} \tag{9.48}$$

with

$$\sigma_d = \sum_{t_2} Z_{j1}^A A_j^0 \,, \qquad \sigma_u = \sum_{t_2} Z_{j2}^A A_j^0 \,, \qquad \sigma_s = \sum_{t_2} Z_{j3}^A A_j^0 \tag{9.49}$$

- **Mass matrix for Charged Higgs**, Basis: $\Big(H_d^-, H_u^{+,*}\Big)\,, \Big(H_d^{-,*}, H_u^+\Big)$

$$m_{H^-}^2 = \begin{pmatrix} m_{11} & m_{21}^* \\ m_{21} & m_{22} \end{pmatrix} \tag{9.50}$$

$$m_{11} = \frac{1}{8}\Big(4v_s^2|\lambda|^2 + 8m_{H_d}^2 + g_1^2 v_d^2 - g_1^2 v_u^2 + g_2^2 v_d^2 + g_2^2 v_u^2\Big) \tag{9.51}$$

$$m_{21} = \frac{1}{4}\Big(2\sqrt{2}v_s T_\lambda^* + 2\Big(- v_d v_u \lambda + v_s^2 \kappa\Big)\lambda^* + g_2^2 v_d v_u\Big) \tag{9.52}$$

$$m_{22} = \frac{1}{8}\Big(4v_s^2|\lambda|^2 + 8m_{H_u}^2 - g_1^2 v_d^2 + g_1^2 v_u^2 + g_2^2 v_d^2 + g_2^2 v_u^2\Big) \tag{9.53}$$

This matrix is diagonalized by Z^+:

$$Z^+ m_{H^-}^2 Z^{+,\dagger} = m_{2,H^-}^{dia} \tag{9.54}$$

with

$$H_d^- = \sum_{t_2} Z_{j1}^{+,*} H_j^- \,, \qquad H_u^+ = \sum_{t_2} Z_{j2}^{+} H_j^+ \tag{9.55}$$

The mixing matrix can be parametrized by

$$Z^+ = \begin{pmatrix} -\cos\beta & \sin\beta \\ \sin\beta & \cos\beta \end{pmatrix} \tag{9.56}$$

Mass Matrices for Fermions

- **Mass matrix for Neutralinos**, Basis: $\Big(\lambda_{\tilde{B}}, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0, \tilde{S}\Big), \Big(\lambda_{\tilde{B}}, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0, \tilde{S}\Big)$

$$m_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -\frac{1}{2}g_1 v_d & \frac{1}{2}g_1 v_u & 0 \\ 0 & M_2 & \frac{1}{2}g_2 v_d & -\frac{1}{2}g_2 v_u & 0 \\ -\frac{1}{2}g_1 v_d & \frac{1}{2}g_2 v_d & 0 & -\frac{1}{\sqrt{2}}v_s\lambda & -\frac{1}{\sqrt{2}}v_u\lambda \\ \frac{1}{2}g_1 v_u & -\frac{1}{2}g_2 v_u & -\frac{1}{\sqrt{2}}v_s\lambda & 0 & -\frac{1}{\sqrt{2}}v_d\lambda \\ 0 & 0 & -\frac{1}{\sqrt{2}}v_u\lambda & -\frac{1}{\sqrt{2}}v_d\lambda & \sqrt{2}v_s\kappa \end{pmatrix} \tag{9.57}$$

This matrix is diagonalized by N:

$$N m_{\tilde{\chi}^0} N^\dagger = m_{\tilde{\chi}^0}^{dia} \tag{9.58}$$

with

$$\lambda_{\tilde{B}} = \sum_{t_2} N_{j1}^* \lambda_j^0 \,, \qquad \tilde{W}^0 = \sum_{t_2} N_{j2}^* \lambda_j^0 \,, \qquad \tilde{H}_d^0 = \sum_{t_2} N_{j3}^* \lambda_j^0 \tag{9.59}$$

$$\tilde{H}_u^0 = \sum_{t_2} N_{j4}^* \lambda_j^0 \,, \qquad \tilde{S} = \sum_{t_2} N_{j5}^* \lambda_j^0 \tag{9.60}$$

- **Mass matrix for Charginos**, Basis: $\Big(\tilde{W}^-, \tilde{H}_d^-\Big), \Big(\tilde{W}^+, \tilde{H}_u^+\Big)$

$$m_{\tilde{\chi}^-} = \begin{pmatrix} M_2 & \frac{1}{\sqrt{2}}g_2 v_u \\ \frac{1}{\sqrt{2}}g_2 v_d & \frac{1}{\sqrt{2}}v_s\lambda \end{pmatrix} \tag{9.61}$$

This matrix is diagonalized by U and V

$$U^* m_{\tilde{\chi}^-} V^\dagger = m^{dia}_{\tilde{\chi}^-} \tag{9.62}$$

with

$$\tilde{W}^- = \sum_{t_2} U^*_{j1}\lambda^-_j\,, \qquad \tilde{H}^-_d = \sum_{t_2} U^*_{j2}\lambda^-_j \tag{9.63}$$

$$\tilde{W}^+ = \sum_{t_2} V^*_{1j}\lambda^+_j\,, \qquad \tilde{H}^+_u = \sum_{t_2} V^*_{2j}\lambda^+_j \tag{9.64}$$

- **Mass matrix for Leptons**, Basis: $\left(e_{L,o_1}\right), \left(e^*_{R,p_1}\right)$

$$m_e = \left(\begin{array}{c} \frac{1}{\sqrt{2}} v_d Y_{e,o_1 p_1} \end{array} \right) \tag{9.65}$$

This matrix is diagonalized by U^e_L and U^e_R

$$U^{e,*}_L m_e U^{e,\dagger}_R = m^{dia}_e \tag{9.66}$$

with

$$e_{L,i} = \sum_{t_2} U^{e,*}_{L,ji} E_{L,j} \tag{9.67}$$

$$e_{R,i} = \sum_{t_2} U^{e}_{R,ij} E^*_{R,j} \tag{9.68}$$

- **Mass matrix for Down-Quarks**, Basis: $\left(d_{L,o_1\alpha_1}\right), \left(d^*_{R,p_1\beta_1}\right)$

$$m_d = \left(\begin{array}{c} \frac{1}{\sqrt{2}} v_d \delta_{\alpha_1\beta_1} Y_{d,o_1 p_1} \end{array} \right) \tag{9.69}$$

This matrix is diagonalized by U^d_L and U^d_R

$$U^{d,*}_L m_d U^{d,\dagger}_R = m^{dia}_d \tag{9.70}$$

with

$$d_{L,i\alpha} = \sum_{t_2} U^{d,*}_{L,ji} D_{L,j\alpha} \tag{9.71}$$

$$d_{R,i\alpha} = \sum_{t_2} U^{d}_{R,ij} D^*_{R,j\alpha} \tag{9.72}$$

- **Mass matrix for Up-Quarks**, Basis: $\left(u_{L,o_1\alpha_1}\right), \left(u^*_{R,p_1\beta_1}\right)$

$$m_u = \left(\begin{array}{c} \frac{1}{\sqrt{2}} v_u \delta_{\alpha_1\beta_1} Y_{u,o_1 p_1} \end{array} \right) \tag{9.73}$$

This matrix is diagonalized by U^u_L and U^u_R

$$U^{u,*}_L m_u U^{u,\dagger}_R = m^{dia}_u \tag{9.74}$$

with

$$u_{L,i\alpha} = \sum_{t_2} U^{u,*}_{L,ji} U_{L,j\alpha} \tag{9.75}$$

$$u_{R,i\alpha} = \sum_{t_2} U^{u}_{R,ij} U^{*}_{R,j\alpha} \tag{9.76}$$

9.4 Vacuum Expectation Values

$$H^0_d = \frac{1}{\sqrt{2}}\phi_d + \frac{1}{\sqrt{2}}v_d + i\frac{1}{\sqrt{2}}\sigma_d \tag{9.77}$$

$$H^0_u = \frac{1}{\sqrt{2}}\phi_u + \frac{1}{\sqrt{2}}v_u + i\frac{1}{\sqrt{2}}\sigma_u \tag{9.78}$$

$$S = \frac{1}{\sqrt{2}}\phi_s + \frac{1}{\sqrt{2}}v_s + i\frac{1}{\sqrt{2}}\sigma_s \tag{9.79}$$

9.5 Tadpole Equations

$$\begin{aligned}\frac{\partial V}{\partial v_d} = \frac{1}{8}\Big(&8m^2_{H_d}v_d + g_1^2 v_d^3 + g_2^2 v_d^3 - g_1^2 v_d v_u^2 - g_2^2 v_d v_u^2 - 2v_s^2 v_u \lambda\kappa^* \\ &+ \Big(4v_d v_u^2 \lambda + v_s^2\Big(-2v_u\kappa + 4v_d\lambda\Big)\Big)\lambda^* - 4\sqrt{2}v_s v_u \Re\Big(T_\lambda\Big)\Big)\end{aligned} \tag{9.80}$$

$$\begin{aligned}\frac{\partial V}{\partial v_u} = \frac{1}{8}\Big(&8m^2_{H_u}v_u - g_1^2 v_d^2 v_u - g_2^2 v_d^2 v_u + g_1^2 v_u^3 + g_2^2 v_u^3 - 2v_d v_s^2 \lambda\kappa^* \\ &+ \Big(-2v_d v_s^2\kappa + 4v_d^2 v_u\lambda + 4v_s^2 v_u\lambda\Big)\lambda^* - 4\sqrt{2}v_d v_s \Re\Big(T_\lambda\Big)\Big)\end{aligned} \tag{9.81}$$

$$\begin{aligned}\frac{\partial V}{\partial v_s} = \frac{1}{4}\Big(&4m^2_S v_s + \Big(-2v_d v_s v_u\lambda + 4v_s^3\kappa\Big)\kappa^* + 2v_s\Big(v_d^2\lambda - v_d v_u\kappa + v_u^2\lambda\Big)\lambda^* - \sqrt{2}v_d v_u T^*_\lambda \\ &+ 2\sqrt{2}v_s^2\Re\Big(T_\kappa\Big) - \sqrt{2}v_d v_u T_\lambda\Big)\end{aligned} \tag{9.82}$$

9.6 Particle content for eigenstates 'EWSB'

Name	Type	complex/real	Generations	Indices
$\tilde{d}$	Scalar	complex	6	generation, color
$\tilde{\nu}$	Scalar	complex	3	generation
$\tilde{u}$	Scalar	complex	6	generation, color
$\tilde{e}$	Scalar	complex	6	generation
h	Scalar	real	3	generation

A^0	Scalar	real	3	generation
H^-	Scalar	complex	2	generation
ν	Fermion	Dirac	3	generation
$\tilde{g}$	Fermion	Majorana	8	generation
$\tilde{\chi}^0$	Fermion	Majorana	5	generation
$\tilde{\chi}^-$	Fermion	Dirac	2	generation
e	Fermion	Dirac	3	generation
d	Fermion	Dirac	3	generation, color
u	Fermion	Dirac	3	generation, color
g	Vector	real	8	generation, lorentz
W^-	Vector	complex	1	lorentz
γ	Vector	real	1	lorentz
Z	Vector	real	1	lorentz
η^G	Ghost	real	8	generation
η^-	Ghost	complex	1	
η^+	Ghost	complex	1	
η^γ	Ghost	real	1	
η^Z	Ghost	real	1	

9.7 Modelfile for SARAH

9.8 Implementation in SARAH

Model directory: `NMSSM/One_Rotation`

9.8.1 Particles for eigenstates 'GaugeES'

- Fermions

$\tilde{B} = \begin{pmatrix} \lambda_{\tilde{B}} \\ \lambda^*_{\tilde{B}} \end{pmatrix}$	$\texttt{Bino} = \begin{pmatrix} \texttt{fB} \\ \texttt{conj[fB]} \end{pmatrix}$
$d^1_{i\alpha} = \begin{pmatrix} d_{L,i\alpha} \\ 0 \end{pmatrix}$	$\texttt{Fd1[\{generation, color\}]} = \begin{pmatrix} \texttt{FdL[\{generation, color\}]} \\ 0 \end{pmatrix}$
$d^2_{i\alpha} = \begin{pmatrix} 0 \\ d_{R,i\alpha} \end{pmatrix}$	$\texttt{Fd2[\{generation, color\}]} = \begin{pmatrix} 0 \\ \texttt{FdR[\{generation, color\}]} \end{pmatrix}$
$e^1_i = \begin{pmatrix} e_{L,i} \\ 0 \end{pmatrix}$	$\texttt{Fe1[\{generation\}]} = \begin{pmatrix} \texttt{FeL[\{generation\}]} \\ 0 \end{pmatrix}$
$e^2_i = \begin{pmatrix} 0 \\ e_{R,i} \end{pmatrix}$	$\texttt{Fe2[\{generation\}]} = \begin{pmatrix} 0 \\ \texttt{FeR[\{generation\}]} \end{pmatrix}$
$u^1_{i\alpha} = \begin{pmatrix} u_{L,i\alpha} \\ 0 \end{pmatrix}$	$\texttt{Fu1[\{generation, color\}]} = \begin{pmatrix} \texttt{FuL[\{generation, color\}]} \\ 0 \end{pmatrix}$
$u^2_{i\alpha} = \begin{pmatrix} 0 \\ u_{R,i\alpha} \end{pmatrix}$	$\texttt{Fu2[\{generation, color\}]} = \begin{pmatrix} 0 \\ \texttt{FuR[\{generation, color\}]} \end{pmatrix}$
$\nu_i = \begin{pmatrix} \nu_{L,i} \\ 0 \end{pmatrix}$	$\texttt{Fv[\{generation\}]} = \begin{pmatrix} \texttt{FvL[\{generation\}]} \\ 0 \end{pmatrix}$
$\tilde{g}_i = \begin{pmatrix} \lambda_{\tilde{g},i} \\ \lambda^*_{\tilde{g},i} \end{pmatrix}$	$\texttt{Glu[\{generation\}]} = \begin{pmatrix} \texttt{fG[\{generation\}]} \\ \texttt{conj[fG[\{generation\}]]} \end{pmatrix}$
$\tilde{H}^0 = \begin{pmatrix} \tilde{H}^0_u \\ \tilde{H}^{0,*}_d \end{pmatrix}$	$\texttt{H0} = \begin{pmatrix} \texttt{FHu0} \\ \texttt{conj[FHd0]} \end{pmatrix}$
$\tilde{H}^- = \begin{pmatrix} \tilde{H}^+_u \\ \tilde{H}^{-,*}_d \end{pmatrix}$	$\texttt{HC} = \begin{pmatrix} \texttt{FHup} \\ \texttt{conj[FHdm]} \end{pmatrix}$
$\tilde{S} = \begin{pmatrix} \tilde{S} \\ \tilde{S}^* \end{pmatrix}$	$\texttt{S} = \begin{pmatrix} \texttt{FsR} \\ \texttt{conj[FsR]} \end{pmatrix}$
$\tilde{W}_i = \begin{pmatrix} \lambda_{\tilde{W},i} \\ \lambda^*_{\tilde{W},i} \end{pmatrix}$	$\texttt{Wino[\{generation\}]} = \begin{pmatrix} \texttt{fWB[\{generation\}]} \\ \texttt{conj[fWB[\{generation\}]]} \end{pmatrix}$

- Scalars

$\tilde{d}_{L,i\alpha}$	`SdL[{generation, color}]`	$\tilde{u}_{L,i\alpha}$	`SuL[{generation, color}]`
$\tilde{e}_{L,i}$	`SeL[{generation}]`	$\tilde{\nu}_{L,i}$	`SvL[{generation}]`
H_d^0	`SHd0`	H_d^-	`SHdm`
H_u^0	`SHu0`	H_u^+	`SHup`
$\tilde{d}_{R,i\alpha}$	`SdR[{generation, color}]`	$\tilde{u}_{R,i\alpha}$	`SuR[{generation, color}]`
$\tilde{e}_{R,i}$	`SeR[{generation}]`	S	`SsR`

- Vector Bosons

B_ρ	`VB[{lorentz}]`	$W^-_{i\rho}$	`VWB[{generation, lorentz}]`
$g_{i\rho}$	`VG[{generation, lorentz}]`		

- Ghosts

η^B	`gB`	$\mathrm{gWB}\Big(\{\mathrm{gt1}\}\Big)$	`gWB[{generation}]`
η^G_i	`gG[{generation}]`		

9.8.2 Particles for eigenstates `'EWSB'`

- Fermions

$\tilde{\chi}_i^- = \begin{pmatrix} \lambda_i^- \\ \lambda_i^{+,*} \end{pmatrix}$	$\texttt{Cha[\{generation\}]} = \begin{pmatrix} \texttt{Lm[\{generation\}]} \\ \texttt{conj[Lp[\{generation\}]]} \end{pmatrix}$
$\tilde{\chi}_i^0 = \begin{pmatrix} \lambda_i^0 \\ \lambda_i^{0,*} \end{pmatrix}$	$\texttt{Chi[\{generation\}]} = \begin{pmatrix} \texttt{L0[\{generation\}]} \\ \texttt{conj[L0[\{generation\}]]} \end{pmatrix}$
$d_{i\alpha} = \begin{pmatrix} D_{L,i\alpha} \\ D^*_{R,i\alpha} \end{pmatrix}$	$\texttt{Fd[\{generation, color\}]} = \begin{pmatrix} \texttt{FDL[\{generation, color\}]} \\ \texttt{conj[FDR[\{generation, color\}]]} \end{pmatrix}$

$e_i = \begin{pmatrix} E_{L,i} \\ E^*_{R,i} \end{pmatrix}$	`Fe[{generation}]` $= \begin{pmatrix} \texttt{FEL[\{generation\}]} \\ \texttt{conj[FER[\{generation\}]]} \end{pmatrix}$
$u_{i\alpha} = \begin{pmatrix} U_{L,i\alpha} \\ U^*_{R,i\alpha} \end{pmatrix}$	`Fu[{generation, color}]` $= \begin{pmatrix} \texttt{FUL[\{generation, color\}]} \\ \texttt{conj[FUR[\{generation, color\}]]} \end{pmatrix}$
$\nu_i = \begin{pmatrix} \nu_{L,i} \\ 0 \end{pmatrix}$	`Fv[{generation}]` $= \begin{pmatrix} \texttt{FvL[\{generation\}]} \\ 0 \end{pmatrix}$
$\tilde{g}_i = \begin{pmatrix} \lambda_{\tilde{g},i} \\ \lambda^*_{\tilde{g},i} \end{pmatrix}$	`Glu[{generation}]` $= \begin{pmatrix} \texttt{fG[\{generation\}]} \\ \texttt{conj[fG[\{generation\}]]} \end{pmatrix}$

- Scalars

$\tilde{d}_{i\alpha}$	`Sd[{generation, color}]`	$\tilde{\nu}_i$	`Sv[{generation}]`
$\tilde{u}_{i\alpha}$	`Su[{generation, color}]`	$\tilde{e}_i$	`Se[{generation}]`
h_i	`hh[{generation}]`	A^0_i	`Ah[{generation}]`
H^-_i	`Hpm[{generation}]`		

- Vector Bosons

$g_{i\rho}$	`VG[{generation, lorentz}]`	W^-_ρ	`VWm[{lorentz}]`
γ_ρ	`VP[{lorentz}]`	Z_ρ	`VZ[{lorentz}]`

- Ghosts

η^G_i	`gG[{generation}]`	η^-	`gWm`
η^+	`gWmC`	η^γ	`gP`
η^Z	`gZ`		

9.8.3 Parameters

g_1	`g1`	g_2	`g2`	g_3	`g3`
Y_u	`Yu`	T_u	`T[Yu]`	Y_d	`Yd`
T_d	`T[Yd]`	Y_e	`Ye`	T_e	`T[Ye]`
λ	`\[Lambda]`	T_λ	`T[\[Lambda]]`	κ	`\[Kappa]`
T_κ	`T[\[Kappa]]`	m_q^2	`mq2`	m_l^2	`ml2`
$m_{H_d}^2$	`mHd2`	$m_{H_u}^2$	`mHu2`	m_d^2	`md2`
m_u^2	`mu2`	m_e^2	`me2`	m_S^2	`ms2`
M_1	`MassB`	M_2	`MassWB`	M_3	`MassG`
v_d	`vd`	v_u	`vu`	v_s	`vS`
Θ_W	`ThetaW`	$\phi_{\tilde{g}}$	`PhaseGlu`	Z^D	`ZD`
Z^V	`ZV`	Z^U	`ZU`	Z^E	`ZE`
Z^H	`ZH`	Z^A	`ZA`	Z^+	`ZP`
N	`ZN`	U	`UM`	V	`UP`
U_L^e	`ZEL`	U_R^e	`ZER`	U_L^d	`ZDL`
U_R^d	`ZDR`	U_L^u	`ZUL`	U_R^u	`ZUR`
β	`\[Beta]`				

Chapter 10

The Next-to-Minimal Supersymmetric Standard Model in SCKM basis

10.1 Superfields

10.1.1 Vector Superfields

SF	Spin $\frac{1}{2}$	Spin 1	$SU(N)$	Coupling	Name
$\hat{B}$	$\lambda_{\tilde{B}}$	B	$U(1)$	g_1	hypercharge
$\hat{W}$	$\lambda_{\tilde{W}}$	W^-	SU(2)	g_2	left
$\hat{g}$	$\lambda_{\tilde{g}}$	g	SU(3)	g_3	color

10.1.2 Chiral Superfields

SF	Spin 0	Spin $\frac{1}{2}$	Generations	$(U(1) \otimes \text{SU}(2) \otimes \text{SU}(3))$
$\hat{q}$	Sq0	q^0	3	$(\frac{1}{6}, \mathbf{2}, \mathbf{3})$
$\hat{l}$	$\tilde{l}$	l	3	$(-\frac{1}{2}, \mathbf{2}, \mathbf{1})$
$\hat{H}_d$	H_d	$\tilde{H}_d$	1	$(-\frac{1}{2}, \mathbf{2}, \mathbf{1})$
$\hat{H}_u$	H_u	$\tilde{H}_u$	1	$(\frac{1}{2}, \mathbf{2}, \mathbf{1})$
$\hat{d}$	$\tilde{d}_R^{0,*}$	d_R^*	3	$(\frac{1}{3}, \mathbf{1}, \overline{\mathbf{3}})$
$\hat{u}$	$\tilde{u}_R^{0,*}$	u_R^*	3	$(-\frac{2}{3}, \mathbf{1}, \overline{\mathbf{3}})$
$\hat{e}$	$\tilde{e}_R^*$	e_R^*	3	$(1, \mathbf{1}, \mathbf{1})$
$\hat{s}$	S	$\tilde{S}$	1	$(0, \mathbf{1}, \mathbf{1})$

10.2 Superpotential and Lagrangian

10.2.1 Superpotential

$$W = Y_u^0\, \hat{q}\, \hat{H}_u\, \hat{u}\, - Y_d^0\, \hat{q}\, \hat{H}_d\, \hat{d}\, - Y_e\, \hat{l}\, \hat{H}_d\, \hat{e}\, + \lambda\, \hat{H}_u\, \hat{H}_d\, \hat{s}\, + \frac{1}{3}\kappa\, \hat{s}\, \hat{s}\, \hat{s} \tag{10.1}$$

10.2.2 Softbreaking terms

$$L_{SB,W} = +\frac{1}{3}S^3 T_\kappa - H_d^0 H_u^0 S T_\lambda + H_d^- H_u^+ S T_\lambda + H_d^0 \tilde{d}^{0,*}_{R,k\gamma}\delta_{\alpha\gamma}\tilde{d}^0_{L,i\alpha}T^0_{d,ik}$$
$$- H_d^- \tilde{d}^{0,*}_{R,k\gamma}\delta_{\alpha\gamma}\tilde{u}^0_{L,i\alpha}T^0_{d,ik} + H_d^0 \tilde{e}^*_{R,k}\tilde{e}_{L,i}T_{e,ik} - H_d^- \tilde{e}^*_{R,k}\tilde{\nu}_{L,i}T_{e,ik}$$
$$- H_u^+ \tilde{u}^{0,*}_{R,k\gamma}\delta_{\alpha\gamma}\tilde{d}^0_{L,i\alpha}T^0_{u,ik} + H_u^0 \tilde{u}^{0,*}_{R,k\gamma}\delta_{\alpha\gamma}\tilde{u}^0_{L,i\alpha}T^0_{u,ik} + \text{h.c.} \tag{10.2}$$
$$L_{SB,\phi} = - m^2_{H_d}|H_d^0|^2 - m^2_{H_d}|H_d^-|^2 - m^2_{H_u}|H_u^0|^2 - m^2_{H_u}|H_u^+|^2 - m^2_S|S|^2$$
$$- \tilde{d}^{0,*}_{L,j\beta}\delta_{\alpha\beta}m^{0,2}_{\tilde{q},ij}\tilde{d}^0_{L,i\alpha} - \tilde{d}^{0,*}_{R,i\alpha}\delta_{\alpha\beta}m^{0,2}_{\tilde{d},ij}\tilde{d}^0_{R,j\beta} - \tilde{e}^*_{L,j}m^2_{l,ij}\tilde{e}_{L,i} - \tilde{e}^*_{R,i}m^2_{e,ij}\tilde{e}_{R,j}$$
$$- \tilde{u}^{0,*}_{L,j\beta}\delta_{\alpha\beta}m^{0,2}_{\tilde{q},ij}\tilde{u}^0_{L,i\alpha} - \tilde{u}^{0,*}_{R,i\alpha}\delta_{\alpha\beta}m^{0,2}_{\tilde{u},ij}\tilde{u}^0_{R,j\beta} - \tilde{\nu}^*_{L,j}m^2_{l,ij}\tilde{\nu}_{L,i} \tag{10.3}$$
$$L_{SB,\lambda} = \frac{1}{2}\left(-\lambda^2_{\tilde{B}}M_1 - M_2\lambda^2_{\tilde{W},i} - M_3\lambda^2_{\tilde{g},i} + \text{h.c.}\right) \tag{10.4}$$

10.2.3 Gauge fixing terms

Gauge fixing terms for eigenstates 'GaugeES'

$$L_{GF} = -\frac{1}{2}\partial_\mu g \xi_G^{-1} - \frac{1}{2}\partial_\mu W^- \xi_W^{-1} \tag{10.5}$$

Gauge fixing terms for eigenstates 'EWSB'

$$L_{GF} = -\frac{1}{2}\partial_\mu \gamma \xi_P^{-1} - \frac{1}{2}\partial_\mu g \xi_G^{-1} - \frac{1}{2}\xi_Z^{-1}\Big(-A_1^0 m_Z \xi_Z + \partial_\mu Z\Big) - \xi_W^{-1}\Big(iH_1^- m_{W^-}\xi_W + \partial_\mu W^-\Big) \tag{10.6}$$

10.2.4 Fields integrated out

None

10.3 Field Rotations

10.3.1 Rotations in gauge sector for eigenstates 'EWSB'

$$W^-_{1\rho} = \frac{1}{\sqrt{2}}W^-_\rho + \frac{1}{\sqrt{2}}W^+_\rho \tag{10.7}$$
$$W^-_{2\rho} = -i\frac{1}{\sqrt{2}}W^-_\rho + i\frac{1}{\sqrt{2}}W^+_\rho \tag{10.8}$$
$$W^-_{3\rho} = \cos\Theta_W Z_\rho + \sin\Theta_W \gamma_\rho \tag{10.9}$$
$$B_\rho = \cos\Theta_W \gamma_\rho - \sin\Theta_W Z_\rho \tag{10.10}$$
$$\lambda_{\tilde{W},1} = \frac{1}{\sqrt{2}}\tilde{W}^- + \frac{1}{\sqrt{2}}\tilde{W}^+ \tag{10.11}$$
$$\lambda_{\tilde{W},2} = -i\frac{1}{\sqrt{2}}\tilde{W}^- + i\frac{1}{\sqrt{2}}\tilde{W}^+ \tag{10.12}$$
$$\lambda_{\tilde{W},3} = \tilde{W}^0 \tag{10.13}$$

10.3.2 Rotations in Mass sector for eigenstates 'EWSB'

Mass Matrices for Scalars

- **Mass matrix for Down-Squarks**, Basis: $\Big(\tilde{d}_{L,o_1\alpha_1}, \tilde{d}_{R,o_2\alpha_2}\Big), \Big(\tilde{d}^*_{L,p_1\beta_1}, \tilde{d}^*_{R,p_2\beta_2}\Big)$

$$m^2_{\tilde{d}} = \begin{pmatrix} m_{11} & \frac{1}{2}\delta_{\alpha_1\beta_2}\delta_{o_1p_2}\Big(\sqrt{2}v_d T_{d,o_1o_1} - v_s v_u \lambda^* Y_{d,o_1o_1}\Big) \\ m_{21} & m_{22} \end{pmatrix} \tag{10.14}$$

$$m_{11} = \frac{1}{24}\delta_{\alpha_1\beta_1}\delta_{o_1p_1}\Big(12v_d^2|Y_{d,o_1o_1}|^2 + 24m^2_{q,o_1o_1} - \Big(3g_2^2 + g_1^2\Big)\Big(-v_u^2 + v_d^2\Big)\Big) \tag{10.15}$$

$$m_{21} = \frac{1}{2}\Big(\sqrt{2}v_d T^*_{d,o_2o_2} - v_s v_u \lambda Y^*_{d,o_2o_2}\Big)\delta_{\alpha_2\beta_1}\delta_{o_2p_1} \tag{10.16}$$

$$m_{22} = \frac{1}{12}\delta_{\alpha_2\beta_2}\delta_{o_2p_2}\Big(12m^2_{d,o_2o_2} + 6v_d^2|Y_{d,o_2o_2}|^2 + g_1^2\Big(-v_d^2 + v_u^2\Big)\Big) \tag{10.17}$$

This matrix is diagonalized by Z^D:

$$Z^D m^2_{\tilde{d}} Z^{D,\dagger} = m^{dia}_{2,\tilde{d}} \tag{10.18}$$

with

$$\tilde{d}_{L,i\alpha} = \sum_{t_2} Z^{D,*}_{ji}\tilde{d}_{j\alpha}\,, \qquad \tilde{d}_{R,i\alpha} = \sum_{t_2} Z^{D,*}_{ji}\tilde{d}_{j\alpha} \tag{10.19}$$

- **Mass matrix for Sneutrinos**, Basis: $(\tilde{\nu}_{L,o_1}), (\tilde{\nu}^*_{L,p_1})$

$$m^2_{\tilde{\nu}} = \begin{pmatrix} \frac{1}{8}\Big(8m^2_{l,o_1p_1} + \Big(g_1^2 + g_2^2\Big)\Big(-v_u^2 + v_d^2\Big)\delta_{o_1p_1}\Big) \end{pmatrix} \tag{10.20}$$

This matrix is diagonalized by Z^V:

$$Z^V m^2_{\tilde{\nu}} Z^{V,\dagger} = m^{dia}_{2,\tilde{\nu}} \tag{10.21}$$

with

$$\tilde{\nu}_{L,i} = \sum_{t_2} Z^{V,*}_{ji}\tilde{\nu}_j \tag{10.22}$$

- **Mass matrix for Up-Squarks**, Basis: $(\tilde{u}_{L,o_1\alpha_1}, \tilde{u}_{R,o_2\alpha_2}), \Big(\tilde{u}^*_{L,p_1\beta_1}, \tilde{u}^*_{R,p_2\beta_2}\Big)$

$$m^2_{\tilde{u}} = \begin{pmatrix} m_{11} & \frac{1}{2}\delta_{\alpha_1\beta_2}\delta_{o_1p_2}\Big(\sqrt{2}v_u T_{u,o_1o_1} - v_d v_s \lambda^* Y_{u,o_1o_1}\Big) \\ m_{21} & m_{22} \end{pmatrix} \tag{10.23}$$

$$m_{11} = \frac{1}{24}\delta_{\alpha_1\beta_1}\Big(\Big(12v_u^2|Y_{u,o_1o_1}|^2 - \Big(-3g_2^2 + g_1^2\Big)\Big(-v_u^2 + v_d^2\Big)\Big)\delta_{o_1p_1} + 24\sum_{a=1}^{3} V^{CKM}_{o_1a}V^{CKM,*}_{p_1a}m^2_{q,aa}\Big) \tag{10.24}$$

$$m_{21} = \frac{1}{2}\Big(\sqrt{2} v_u T^*_{u,o_2 o_2} - v_d v_s \lambda Y^*_{u,o_2 o_2}\Big)\delta_{\alpha_2\beta_1}\delta_{o_2 p_1} \tag{10.25}$$

$$m_{22} = \frac{1}{6}\delta_{\alpha_2\beta_2}\delta_{o_2 p_2}\Big(3 v_u^2 |Y_{u,o_2 o_2}|^2 + 6 m^2_{u,o_2 o_2} + g_1^2\Big(-v_u^2 + v_d^2\Big)\Big) \tag{10.26}$$

This matrix is diagonalized by Z^U:

$$Z^U m^2_{\tilde{u}} Z^{U,\dagger} = m^{dia}_{2,\tilde{u}} \tag{10.27}$$

with

$$\tilde{u}_{L,i\alpha} = \sum_{t_2} Z^{U,*}_{ji}\tilde{u}_{j\alpha}\,, \qquad \tilde{u}_{R,i\alpha} = \sum_{t_2} Z^{U,*}_{ji}\tilde{u}_{j\alpha} \tag{10.28}$$

- **Mass matrix for Sleptons**, Basis: $\left(\tilde{e}_{L,o_1}, \tilde{e}_{R,o_2}\right), \left(\tilde{e}^*_{L,p_1}, \tilde{e}^*_{R,p_2}\right)$

$$m^2_{\tilde{e}} = \begin{pmatrix} m_{11} & -\frac{1}{2} v_s v_u \lambda^* Y_{e,o_1 p_2} + \frac{1}{\sqrt{2}} v_d T_{e,o_1 p_2} \\ -\frac{1}{2} v_s v_u \lambda Y^*_{e,p_1 o_2} + \frac{1}{\sqrt{2}} v_d T^*_{e,p_1 o_2} & m_{22} \end{pmatrix} \tag{10.29}$$

$$m_{11} = \frac{1}{8}\Big(4 v_d^2 \sum_{a=1}^{3} Y^*_{e,p_1 a} Y_{e,o_1 a} + 8 m^2_{l,o_1 p_1} + \Big(-g_2^2 + g_1^2\Big)\Big(-v_u^2 + v_d^2\Big)\delta_{o_1 p_1}\Big) \tag{10.30}$$

$$m_{22} = \frac{1}{4}\Big(2 v_d^2 \sum_{a=1}^{3} Y^*_{e,a o_2} Y_{e,a p_2} + 4 m^2_{e,p_2 o_2} + g_1^2\Big(-v_d^2 + v_u^2\Big)\delta_{o_2 p_2}\Big) \tag{10.31}$$

This matrix is diagonalized by Z^E:

$$Z^E m^2_{\tilde{e}} Z^{E,\dagger} = m^{dia}_{2,\tilde{e}} \tag{10.32}$$

with

$$\tilde{e}_{L,i} = \sum_{t_2} Z^{E,*}_{ji}\tilde{e}_j\,, \qquad \tilde{e}_{R,i} = \sum_{t_2} Z^{E,*}_{ji}\tilde{e}_j \tag{10.33}$$

- **Mass matrix for Higgs**, Basis: $\left(\phi_d, \phi_u, \phi_s\right), \left(\phi_d, \phi_u, \phi_s\right)$

$$m^2_h = \begin{pmatrix} m_{11} & m^*_{21} & m^*_{31} \\ m_{21} & m_{22} & m^*_{32} \\ m_{31} & m_{32} & m_{33} \end{pmatrix} \tag{10.34}$$

$$m_{11} = \frac{1}{8}\Big(4\Big(v_s^2 + v_u^2\Big)|\lambda|^2 + 8 m^2_{H_d} + \Big(g_1^2 + g_2^2\Big)\Big(3 v_d^2 - v_u^2\Big)\Big) \tag{10.35}$$

$$m_{21} = \frac{1}{4}\Big(-2\sqrt{2} v_s \Re\Big(T_\lambda\Big) + \Big(4 v_d v_u \lambda - v_s^2 \kappa\Big)\lambda^* - g_1^2 v_d v_u - g_2^2 v_d v_u - v_s^2 \lambda \kappa^*\Big) \tag{10.36}$$

$$m_{22} = \frac{1}{8}\Big(4\Big(v_d^2 + v_s^2\Big)|\lambda|^2 + 8 m^2_{H_u} - \Big(g_1^2 + g_2^2\Big)\Big(-3 v_u^2 + v_d^2\Big)\Big) \tag{10.37}$$

$$m_{31} = \frac{1}{2}\Big(\Big(2v_d v_s \lambda - v_s v_u \kappa\Big)\lambda^* - \sqrt{2} v_u \Re\Big(T_\lambda\Big) - v_s v_u \lambda \kappa^*\Big) \tag{10.38}$$

$$m_{32} = \frac{1}{2}\Big(\Big(2v_s v_u \lambda - v_d v_s \kappa\Big)\lambda^* - \sqrt{2} v_d \Re\Big(T_\lambda\Big) - v_d v_s \lambda \kappa^*\Big) \tag{10.39}$$

$$m_{33} = \frac{1}{2}\Big(2\Big(\sqrt{2} v_s \Re\Big(T_\kappa\Big) + m_S^2\Big) + \Big(6v_s^2 \kappa - v_d v_u \lambda\Big)\kappa^* + \Big(v_d^2 \lambda - v_d v_u \kappa + v_u^2 \lambda\Big)\lambda^*\Big) \tag{10.40}$$

This matrix is diagonalized by Z^H:

$$Z^H m_h^2 Z^{H,\dagger} = m^{dia}_{2,h} \tag{10.41}$$

with

$$\phi_d = \sum_{t_2} Z^H_{j1} h_j\,, \qquad \phi_u = \sum_{t_2} Z^H_{j2} h_j\,, \qquad \phi_s = \sum_{t_2} Z^H_{j3} h_j \tag{10.42}$$

- **Mass matrix for Pseudo-Scalar Higgs**, Basis: $(\sigma_d, \sigma_u, \sigma_s), (\sigma_d, \sigma_u, \sigma_s)$

$$m^2_{A^0} = \begin{pmatrix} m_{11} & m_{21}^* & m_{31}^* \\ m_{21} & m_{22} & m_{32}^* \\ m_{31} & m_{32} & m_{33} \end{pmatrix} \tag{10.43}$$

$$m_{11} = \frac{1}{8}\Big(4\Big(v_s^2 + v_u^2\Big)|\lambda|^2 + 8m_{H_d}^2 + \Big(g_1^2 + g_2^2\Big)\Big(-v_u^2 + v_d^2\Big)\Big) \tag{10.44}$$

$$m_{21} = \frac{1}{4} v_s\Big(2\sqrt{2}\Re\Big(T_\lambda\Big) + v_s \kappa \lambda^* + v_s \lambda \kappa^*\Big) \tag{10.45}$$

$$m_{22} = \frac{1}{8}\Big(4\Big(v_d^2 + v_s^2\Big)|\lambda|^2 + 8m_{H_u}^2 - \Big(g_1^2 + g_2^2\Big)\Big(-v_u^2 + v_d^2\Big)\Big) \tag{10.46}$$

$$m_{31} = -\frac{1}{2} v_u\Big(-\sqrt{2}\Re\Big(T_\lambda\Big) + v_s \kappa \lambda^* + v_s \lambda \kappa^*\Big) \tag{10.47}$$

$$m_{32} = -\frac{1}{2} v_d\Big(-\sqrt{2}\Re\Big(T_\lambda\Big) + v_s \kappa \lambda^* + v_s \lambda \kappa^*\Big) \tag{10.48}$$

$$m_{33} = \frac{1}{2}\Big(2\Big(-\sqrt{2} v_s \Re\Big(T_\kappa\Big) + m_S^2\Big) + \Big(2v_s^2 \kappa + v_d v_u \lambda\Big)\kappa^* + \Big(v_d^2 \lambda + v_d v_u \kappa + v_u^2 \lambda\Big)\lambda^*\Big) \tag{10.49}$$

This matrix is diagonalized by Z^A:

$$Z^A m^2_{A^0} Z^{A,\dagger} = m^{dia}_{2,A^0} \tag{10.50}$$

with

$$\sigma_d = \sum_{t_2} Z^A_{j1} A^0_j\,, \qquad \sigma_u = \sum_{t_2} Z^A_{j2} A^0_j\,, \qquad \sigma_s = \sum_{t_2} Z^A_{j3} A^0_j \tag{10.51}$$

- **Mass matrix for Charged Higgs**, Basis: $\Big(H_d^-, H_u^{+,*}\Big), \Big(H_d^{-,*}, H_u^+\Big)$

$$m^2_{H^-} = \begin{pmatrix} m_{11} & m_{21}^* \\ m_{21} & m_{22} \end{pmatrix} \tag{10.52}$$

$$m_{11} = \frac{1}{8}\Big(4v_s^2|\lambda|^2 + 8m_{H_d}^2 + g_1^2 v_d^2 - g_1^2 v_u^2 + g_2^2 v_d^2 + g_2^2 v_u^2\Big) \tag{10.53}$$

$$m_{21} = \frac{1}{4}\Big(2\sqrt{2}v_s T_\lambda^* + 2\Big(- v_d v_u \lambda + v_s^2 \kappa\Big)\lambda^* + g_2^2 v_d v_u\Big) \tag{10.54}$$

$$m_{22} = \frac{1}{8}\Big(4v_s^2|\lambda|^2 + 8m_{H_u}^2 - g_1^2 v_d^2 + g_1^2 v_u^2 + g_2^2 v_d^2 + g_2^2 v_u^2\Big) \tag{10.55}$$

This matrix is diagonalized by Z^+:

$$Z^+ m_{H^-}^2 Z^{+,\dagger} = m_{2,H^-}^{dia} \tag{10.56}$$

with

$$H_d^- = \sum_{t_2} Z_{j1}^{+,*} H_j^- \,, \qquad H_u^+ = \sum_{t_2} Z_{j2}^{+} H_j^+ \tag{10.57}$$

The mixing matrix can be parametrized by

$$Z^+ = \left(\begin{array}{cc} -\cos\beta & \sin\beta \\ \sin\beta & \cos\beta \end{array}\right) \tag{10.58}$$

Mass Matrices for Fermions

- **Mass matrix for Neutralinos**, Basis: $\Big(\lambda_{\tilde{B}}, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0, \tilde{S}\Big), \Big(\lambda_{\tilde{B}}, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0, \tilde{S}\Big)$

$$m_{\tilde{\chi}^0} = \left(\begin{array}{ccccc} M_1 & 0 & -\frac{1}{2}g_1 v_d & \frac{1}{2}g_1 v_u & 0 \\ 0 & M_2 & \frac{1}{2}g_2 v_d & -\frac{1}{2}g_2 v_u & 0 \\ -\frac{1}{2}g_1 v_d & \frac{1}{2}g_2 v_d & 0 & -\frac{1}{\sqrt{2}}v_s\lambda & -\frac{1}{\sqrt{2}}v_u\lambda \\ \frac{1}{2}g_1 v_u & -\frac{1}{2}g_2 v_u & -\frac{1}{\sqrt{2}}v_s\lambda & 0 & -\frac{1}{\sqrt{2}}v_d\lambda \\ 0 & 0 & -\frac{1}{\sqrt{2}}v_u\lambda & -\frac{1}{\sqrt{2}}v_d\lambda & \sqrt{2}v_s\kappa \end{array}\right) \tag{10.59}$$

This matrix is diagonalized by N:

$$N m_{\tilde{\chi}^0} N^\dagger = m_{\tilde{\chi}^0}^{dia} \tag{10.60}$$

with

$$\lambda_{\tilde{B}} = \sum_{t_2} N_{j1}^* \lambda_j^0 \,, \qquad \tilde{W}^0 = \sum_{t_2} N_{j2}^* \lambda_j^0 \,, \qquad \tilde{H}_d^0 = \sum_{t_2} N_{j3}^* \lambda_j^0 \tag{10.61}$$

$$\tilde{H}_u^0 = \sum_{t_2} N_{j4}^* \lambda_j^0 \,, \qquad \tilde{S} = \sum_{t_2} N_{j5}^* \lambda_j^0 \tag{10.62}$$

- **Mass matrix for Charginos**, Basis: $\Big(\tilde{W}^-, \tilde{H}_d^-\Big), \Big(\tilde{W}^+, \tilde{H}_u^+\Big)$

$$m_{\tilde{\chi}^-} = \left(\begin{array}{cc} M_2 & \frac{1}{\sqrt{2}}g_2 v_u \\ \frac{1}{\sqrt{2}}g_2 v_d & \frac{1}{\sqrt{2}}v_s\lambda \end{array}\right) \tag{10.63}$$

This matrix is diagonalized by U and V

$$U^* m_{\tilde{\chi}^-} V^\dagger = m^{dia}_{\tilde{\chi}^-} \tag{10.64}$$

with

$$\tilde{W}^- = \sum_{t_2} U^*_{j1}\lambda^-_j \,, \qquad \tilde{H}^-_d = \sum_{t_2} U^*_{j2}\lambda^-_j \tag{10.65}$$

$$\tilde{W}^+ = \sum_{t_2} V^*_{1j}\lambda^+_j \,, \qquad \tilde{H}^+_u = \sum_{t_2} V^*_{2j}\lambda^+_j \tag{10.66}$$

- **Mass matrix for Leptons**, Basis: $\left(e_{L,o_1}\right), \left(e^*_{R,p_1}\right)$

$$m_e = \left(\begin{array}{c} \frac{1}{\sqrt{2}} v_d Y_{e,o_1 p_1} \end{array} \right) \tag{10.67}$$

This matrix is diagonalized by U^e_L and U^e_R

$$U^{e,*}_L m_e U^{e,\dagger}_R = m^{dia}_e \tag{10.68}$$

with

$$e_{L,i} = \sum_{t_2} U^{e,*}_{L,ji} E_{L,j} \tag{10.69}$$

$$e_{R,i} = \sum_{t_2} U^e_{R,ij} E^*_{R,j} \tag{10.70}$$

10.4 Vacuum Expectation Values

10.4.1 VEVs for eigenstates 'EWSB'

$$H^0_d = \frac{1}{\sqrt{2}}\phi_d + \frac{1}{\sqrt{2}} v_d + i\frac{1}{\sqrt{2}}\sigma_d \tag{10.71}$$

$$H^0_u = \frac{1}{\sqrt{2}}\phi_u + \frac{1}{\sqrt{2}} v_u + i\frac{1}{\sqrt{2}}\sigma_u \tag{10.72}$$

$$S = \frac{1}{\sqrt{2}}\phi_s + \frac{1}{\sqrt{2}} v_s + i\frac{1}{\sqrt{2}}\sigma_s \tag{10.73}$$

10.5 Tadpole Equations

10.5.1 Tadpole Equations for eigenstates 'SCKM'

$$\begin{aligned}\frac{\partial V}{\partial v_d} &= \frac{1}{8}\Big(\Big(g_1^2 + g_2^2\Big) v_d^3 + v_d\Big(4\Big(v_s^2 + v_u^2\Big)|\lambda|^2 + 8 m^2_{H_d} - \Big(g_1^2 + g_2^2\Big) v_u^2\Big) \\ &- 2 v_s v_u \Big(2\sqrt{2}\Re\Big(T_\lambda\Big) + v_s \kappa \lambda^* + v_s \lambda \kappa^*\Big)\Big) \end{aligned}\tag{10.74}$$

$$\frac{\partial V}{\partial v_u} = \frac{1}{8}\Big(8 m^2_{H_u} v_u - g_1^2 v_d^2 v_u - g_2^2 v_d^2 v_u + g_1^2 v_u^3 + g_2^2 v_u^3 - 2 v_d v_s^2 \lambda \kappa^*$$

$$+ \Big(- 2 v_d v_s^2 \kappa + 4 v_d^2 v_u \lambda + 4 v_s^2 v_u \lambda \Big) \lambda^* - 4 \sqrt{2} v_d v_s \Re\Big(T_\lambda\Big)\Big) \quad (10.75)$$

$$\frac{\partial V}{\partial v_s} = \frac{1}{4}\Big(4 v_s^3 |\kappa|^2 + 2 v_s \Big(2 m_S^2 + \Big(v_d^2 \lambda - v_d v_u \kappa + v_u^2 \lambda\Big)\lambda^* - v_d v_u \lambda \kappa^*\Big) + \sqrt{2} v_s^2 \Big(T_\kappa^* + T_\kappa\Big)$$
$$- \sqrt{2} v_d v_u \Big(T_\lambda^* + T_\lambda\Big)\Big) \quad (10.76)$$

10.5.2 Tadpole Equations for eigenstates 'EWSB'

$$\frac{\partial V}{\partial v_d} = \frac{1}{8}\Big(8 m_{H_d}^2 v_d + g_1^2 v_d^3 + g_2^2 v_d^3 - g_1^2 v_d v_u^2 - g_2^2 v_d v_u^2 - 2 v_s^2 v_u \lambda \kappa^*$$
$$+ \Big(4 v_d v_u^2 \lambda + v_s^2 \Big(- 2 v_u \kappa + 4 v_d \lambda\Big)\Big)\lambda^* - 4 \sqrt{2} v_s v_u \Re\Big(T_\lambda\Big)\Big) \quad (10.77)$$

$$\frac{\partial V}{\partial v_u} = \frac{1}{8}\Big(8 m_{H_u}^2 v_u - g_1^2 v_d^2 v_u - g_2^2 v_d^2 v_u + g_1^2 v_u^3 + g_2^2 v_u^3 - 2 v_d v_s^2 \lambda \kappa^*$$
$$+ \Big(- 2 v_d v_s^2 \kappa + 4 v_d^2 v_u \lambda + 4 v_s^2 v_u \lambda\Big)\lambda^* - 4 \sqrt{2} v_d v_s \Re\Big(T_\lambda\Big)\Big) \quad (10.78)$$

$$\frac{\partial V}{\partial v_s} = \frac{1}{4}\Big(4 m_S^2 v_s + \Big(- 2 v_d v_s v_u \lambda + 4 v_s^3 \kappa\Big)\kappa^* + 2 v_s \Big(v_d^2 \lambda - v_d v_u \kappa + v_u^2 \lambda\Big)\lambda^* - \sqrt{2} v_d v_u T_\lambda^*$$
$$+ 2 \sqrt{2} v_s^2 \Re\Big(T_\kappa\Big) - \sqrt{2} v_d v_u T_\lambda\Big) \quad (10.79)$$

10.6 Particle content for eigenstates 'EWSB'

Name	Type	complex/real	Generations	Indices
$\tilde{d}$	Scalar	complex	6	generation, color
$\tilde{\nu}$	Scalar	complex	3	generation
$\tilde{u}$	Scalar	complex	6	generation, color
$\tilde{e}$	Scalar	complex	6	generation
h	Scalar	real	3	generation
A^0	Scalar	real	3	generation
H^-	Scalar	complex	2	generation
ν	Fermion	Dirac	3	generation
$\tilde{g}$	Fermion	Majorana	8	generation
d	Fermion	Dirac	3	generation, color
u	Fermion	Dirac	3	generation, color
$\tilde{\chi}^0$	Fermion	Majorana	5	generation
$\tilde{\chi}^-$	Fermion	Dirac	2	generation
e	Fermion	Dirac	3	generation
g	Vector	real	8	generation, lorentz
W^-	Vector	complex	1	lorentz
γ	Vector	real	1	lorentz

Z	Vector	real	1	lorentz
η^G	Ghost	real	8	generation
η^-	Ghost	complex	1	
η^+	Ghost	complex	1	
η^γ	Ghost	real	1	
η^Z	Ghost	real	1	

10.7 Modelfile for SARAH

10.8 Implementation in SARAH

Model directory: `NMSSM/CKM`

10.8.1 Particles for eigenstates 'GaugeES'

- Fermions

$$\tilde{B} = \begin{pmatrix} \lambda_{\tilde{B}} \\ \lambda^*_{\tilde{B}} \end{pmatrix} \qquad \texttt{Bino} = \begin{pmatrix} \texttt{fB} \\ \texttt{conj[fB]} \end{pmatrix}$$

$$d^1_{i\alpha} = \begin{pmatrix} d_{L,i\alpha} \\ 0 \end{pmatrix} \qquad \texttt{Fd1[\{generation, color\}]} = \begin{pmatrix} \texttt{FdL0[\{generation, color\}]} \\ 0 \end{pmatrix}$$

$$d^2_{i\alpha} = \begin{pmatrix} 0 \\ d_{R,i\alpha} \end{pmatrix} \qquad \texttt{Fd2[\{generation, color\}]} = \begin{pmatrix} 0 \\ \texttt{FdR0[\{generation, color\}]} \end{pmatrix}$$

$$e^1_{i} = \begin{pmatrix} e_{L,i} \\ 0 \end{pmatrix} \qquad \texttt{Fe1[\{generation\}]} = \begin{pmatrix} \texttt{FeL[\{generation\}]} \\ 0 \end{pmatrix}$$

$$e^2_{i} = \begin{pmatrix} 0 \\ e_{R,i} \end{pmatrix} \qquad \texttt{Fe2[\{generation\}]} = \begin{pmatrix} 0 \\ \texttt{FeR[\{generation\}]} \end{pmatrix}$$

$$u^1_{i\alpha} = \begin{pmatrix} u_{L,i\alpha} \\ 0 \end{pmatrix} \qquad \texttt{Fu1[\{generation, color\}]} = \begin{pmatrix} \texttt{FuL0[\{generation, color\}]} \\ 0 \end{pmatrix}$$

$$u^2_{i\alpha} = \begin{pmatrix} 0 \\ u_{R,i\alpha} \end{pmatrix} \qquad \texttt{Fu2[\{generation, color\}]} = \begin{pmatrix} 0 \\ \texttt{FuR0[\{generation, color\}]} \end{pmatrix}$$

$$\nu_{i} = \begin{pmatrix} \nu_{L,i} \\ 0 \end{pmatrix} \qquad \texttt{Fv[\{generation\}]} = \begin{pmatrix} \texttt{FvL[\{generation\}]} \\ 0 \end{pmatrix}$$

$$\tilde{g}_{i} = \begin{pmatrix} \lambda_{\tilde{g},i} \\ \lambda^*_{\tilde{g},i} \end{pmatrix} \qquad \texttt{Glu[\{generation\}]} = \begin{pmatrix} \texttt{fG[\{generation\}]} \\ \texttt{conj[fG[\{generation\}]]} \end{pmatrix}$$

$$\tilde{H}^0 = \begin{pmatrix} \tilde{H}^0_d \\ \tilde{H}^{0,*}_u \end{pmatrix} \qquad \texttt{H0} = \begin{pmatrix} \texttt{FHd0} \\ \texttt{conj[FHu0]} \end{pmatrix}$$

$$\tilde{H}^- = \begin{pmatrix} \tilde{H}^-_d \\ \tilde{H}^{+,*}_u \end{pmatrix} \qquad \texttt{HC} = \begin{pmatrix} \texttt{FHdm} \\ \texttt{conj[FHup]} \end{pmatrix}$$

$$\tilde{S} = \begin{pmatrix} \tilde{S} \\ \tilde{S}^* \end{pmatrix} \qquad \texttt{S} = \begin{pmatrix} \texttt{FsR} \\ \texttt{conj[FsR]} \end{pmatrix}$$

$$\tilde{W}_{i} = \begin{pmatrix} \lambda_{\tilde{W},i} \\ \lambda^*_{\tilde{W},i} \end{pmatrix} \qquad \texttt{Wino[\{generation\}]} = \begin{pmatrix} \texttt{fWB[\{generation\}]} \\ \texttt{conj[fWB[\{generation\}]]} \end{pmatrix}$$

- Scalars

$\tilde{d}^0_{L,i\alpha}$	SdL0[{generation, color}]	$\tilde{u}^0_{L,i\alpha}$	SuL0[{generation, color}]
$\tilde{e}_{L,i}$	SeL[{generation}]	$\tilde{\nu}_{L,i}$	SvL[{generation}]
H^0_d	SHd0	H^-_d	SHdm
H^0_u	SHu0	H^+_u	SHup
$\tilde{d}^0_{R,i\alpha}$	SdR0[{generation, color}]	$\tilde{u}^0_{R,i\alpha}$	SuR0[{generation, color}]
$\tilde{e}_{R,i}$	SeR[{generation}]	S	SsR

- Vector Bosons

B_ρ	VB[{lorentz}]	$W^-_{i\rho}$	VWB[{generation, lorentz}]
$g_{i\rho}$	VG[{generation, lorentz}]		

- Ghosts

η^B	gB	$\mathrm{gWB}\Big(\{\mathrm{gt1}\}\Big)$	gWB[{generation}]
η^G_i	gG[{generation}]		

10.8.2 Particles for eigenstates 'SCKM'

- Fermions

$\tilde{B} = \begin{pmatrix} \lambda_{\tilde{B}} \\ \lambda^*_{\tilde{B}} \end{pmatrix}$	$\texttt{Bino} = \begin{pmatrix} \texttt{fB} \\ \texttt{conj[fB]} \end{pmatrix}$
$d_{i\alpha} = \begin{pmatrix} D_{L,i\alpha} \\ D_{R,i\alpha} \end{pmatrix}$	$\texttt{Fd[\{generation, color\}]} = \begin{pmatrix} \texttt{FdL[\{generation, color\}]} \\ \texttt{FdR[\{generation, color\}]} \end{pmatrix}$
$e^1_i = \begin{pmatrix} e_{L,i} \\ 0 \end{pmatrix}$	$\texttt{Fe1[\{generation\}]} = \begin{pmatrix} \texttt{FeL[\{generation\}]} \\ 0 \end{pmatrix}$

$e^2_i = \begin{pmatrix} 0 \\ e_{R,i} \end{pmatrix}$	$\texttt{Fe2[\{generation\}]} = \begin{pmatrix} \texttt{0} \\ \texttt{FeR[\{generation\}]} \end{pmatrix}$
$u_{i\alpha} = \begin{pmatrix} U_{L,i\alpha} \\ U_{R,i\alpha} \end{pmatrix}$	$\texttt{Fu[\{generation, color\}]} = \begin{pmatrix} \texttt{FuL[\{generation, color\}]} \\ \texttt{FuR[\{generation, color\}]} \end{pmatrix}$
$\nu_i = \begin{pmatrix} \nu_{L,i} \\ 0 \end{pmatrix}$	$\texttt{Fv[\{generation\}]} = \begin{pmatrix} \texttt{FvL[\{generation\}]} \\ \texttt{0} \end{pmatrix}$
$\tilde{g}_i = \begin{pmatrix} \lambda_{\tilde{g},i} \\ \lambda^*_{\tilde{g},i} \end{pmatrix}$	$\texttt{Glu[\{generation\}]} = \begin{pmatrix} \texttt{fG[\{generation\}]} \\ \texttt{conj[fG[\{generation\}]]} \end{pmatrix}$
$\tilde{H}^0 = \begin{pmatrix} \tilde{H}^0_d \\ \tilde{H}^{0,*}_u \end{pmatrix}$	$\texttt{H0} = \begin{pmatrix} \texttt{FHd0} \\ \texttt{conj[FHu0]} \end{pmatrix}$
$\tilde{H}^- = \begin{pmatrix} \tilde{H}^-_d \\ \tilde{H}^{+,*}_u \end{pmatrix}$	$\texttt{HC} = \begin{pmatrix} \texttt{FHdm} \\ \texttt{conj[FHup]} \end{pmatrix}$
$\tilde{S} = \begin{pmatrix} \tilde{S} \\ \tilde{S}^* \end{pmatrix}$	$\texttt{S} = \begin{pmatrix} \texttt{FsR} \\ \texttt{conj[FsR]} \end{pmatrix}$
$\tilde{W}_i = \begin{pmatrix} \lambda_{\tilde{W},i} \\ \lambda^*_{\tilde{W},i} \end{pmatrix}$	$\texttt{Wino[\{generation\}]} = \begin{pmatrix} \texttt{fWB[\{generation\}]} \\ \texttt{conj[fWB[\{generation\}]]} \end{pmatrix}$

- Scalars

$\tilde{e}_{L,i}$	`SeL[{generation}]`	$\tilde{\nu}_{L,i}$	`SvL[{generation}]`
H^0_d	`SHd0`	H^-_d	`SHdm`
H^0_u	`SHu0`	H^+_u	`SHup`
$\tilde{e}_{R,i}$	`SeR[{generation}]`	S	`SsR`
$\tilde{d}_{L,i\alpha}$	`SdL[{generation, color}]`	$\tilde{u}_{L,i\alpha}$	`SuL[{generation, color}]`
$\tilde{d}_{R,i\alpha}$	`SdR[{generation, color}]`	$\tilde{u}_{R,i\alpha}$	`SuR[{generation, color}]`

- Vector Bosons

B_ρ	`VB[{lorentz}]`	$W^-_{i\rho}$	`VWB[{generation, lorentz}]`
$g_{i\rho}$	`VG[{generation, lorentz}]`		

- Ghosts

η^B	gB	$\mathrm{gWB}\Big(\{\mathrm{gt1}\}\Big)$	gWB[{generation}]
η^G_i	gG[{generation}]		

10.8.3 Particles for eigenstates 'EWSB'

- Fermions

$\tilde{\chi}^-_i = \begin{pmatrix} \lambda^-_i \\ \lambda^{+,*}_i \end{pmatrix}$	$\texttt{Cha[\{generation\}]} = \begin{pmatrix} \texttt{Lm[\{generation\}]} \\ \texttt{conj[Lp[\{generation\}]]} \end{pmatrix}$
$\tilde{\chi}^0_i = \begin{pmatrix} \lambda^0_i \\ \lambda^{0,*}_i \end{pmatrix}$	$\texttt{Chi[\{generation\}]} = \begin{pmatrix} \texttt{L0[\{generation\}]} \\ \texttt{conj[L0[\{generation\}]]} \end{pmatrix}$
$d_{i\alpha} = \begin{pmatrix} D_{L,i\alpha} \\ D_{R,i\alpha} \end{pmatrix}$	$\texttt{Fd[\{generation, color\}]} = \begin{pmatrix} \texttt{FdL[\{generation, color\}]} \\ \texttt{FdR[\{generation, color\}]} \end{pmatrix}$
$e_i = \begin{pmatrix} E_{L,i} \\ E^*_{R,i} \end{pmatrix}$	$\texttt{Fe[\{generation\}]} = \begin{pmatrix} \texttt{FEL[\{generation\}]} \\ \texttt{conj[FER[\{generation\}]]} \end{pmatrix}$
$u_{i\alpha} = \begin{pmatrix} U_{L,i\alpha} \\ U_{R,i\alpha} \end{pmatrix}$	$\texttt{Fu[\{generation, color\}]} = \begin{pmatrix} \texttt{FuL[\{generation, color\}]} \\ \texttt{FuR[\{generation, color\}]} \end{pmatrix}$
$\nu_i = \begin{pmatrix} \nu_{L,i} \\ 0 \end{pmatrix}$	$\texttt{Fv[\{generation\}]} = \begin{pmatrix} \texttt{FvL[\{generation\}]} \\ 0 \end{pmatrix}$
$\tilde{g}_i = \begin{pmatrix} \lambda_{\tilde{g},i} \\ \lambda^*_{\tilde{g},i} \end{pmatrix}$	$\texttt{Glu[\{generation\}]} = \begin{pmatrix} \texttt{fG[\{generation\}]} \\ \texttt{conj[fG[\{generation\}]]} \end{pmatrix}$

- Scalars

$\tilde{d}_{i\alpha}$	Sd[{generation, color}]	$\tilde{\nu}_i$	Sv[{generation}]
$\tilde{u}_{i\alpha}$	Su[{generation, color}]	$\tilde{e}_i$	Se[{generation}]
h_i	hh[{generation}]	A^0_i	Ah[{generation}]
H^-_i	Hpm[{generation}]		

- Vector Bosons

$g_{i\rho}$	`VG[{generation, lorentz}]`	W^-_ρ	`VWm[{lorentz}]`
γ_ρ	`VP[{lorentz}]`	Z_ρ	`VZ[{lorentz}]`

- Ghosts

η^G_i	`gG[{generation}]`	η^-	`gWm`
η^+	`gWmC`	η^γ	`gP`
η^Z	`gZ`		

10.8.4 Parameters

g_1	`g1`	g_2	`g2`	g_3	`g3`
Y_u^0	`Yu0`	T_u^0	`T[Yu0]`	Y_d^0	`Yd0`
T_d^0	`T[Yd0]`	Y_e	`Ye`	T_e	`T[Ye]`
λ	`\[Lambda]`	T_λ	`T[\[Lambda]]`	κ	`\[Kappa]`
T_κ	`T[\[Kappa]]`	$m_{\tilde{q}}^{0,2}$	`mq02`	m_l^2	`ml2`
$m_{H_d}^2$	`mHd2`	$m_{H_u}^2$	`mHu2`	$m_{\tilde{d}}^{0,2}$	`md02`
$m_{\tilde{u}}^{0,2}$	`mu02`	m_e^2	`me2`	m_S^2	`ms2`
M_1	`MassB`	M_2	`MassWB`	M_3	`MassG`
V_d	`Vd`	V_u	`Vu`	U_d	`Ud`
U_u	`Uu`	v_d	`vd`	v_u	`vu`
v_s	`vS`	Θ_W	`ThetaW`	$\phi_{\tilde{g}}$	`PhaseGlu`
Z^D	`ZD`	Z^V	`ZV`	Z^U	`ZU`
Z^E	`ZE`	Z^H	`ZH`	Z^A	`ZA`
Z^+	`ZP`	N	`ZN`	U	`UM`
V	`UP`	U_L^e	`ZEL`	U_R^e	`ZER`
β	`\[Beta]`	V^{CKM}	`CKM`	Y_u	`Yu`
Y_d	`Yd`	T_d	`T[Yd]`	T_u	`T[Yu]`
m_q^2	`mq2`	m_u^2	`mu2`	m_d^2	`md2`

Chapter 11

The Next-to-Minimal Supersymmetric Standard Model with CP violation

11.1 Superfields

11.1.1 Vector Superfields

SF	Spin $\frac{1}{2}$	Spin 1	$SU(N)$	Coupling	Name
$\hat{B}$	$\lambda_{\tilde{B}}$	B	$U(1)$	g_1	hypercharge
$\hat{W}$	$\lambda_{\tilde{W}}$	W^-	SU(2)	g_2	left
$\hat{g}$	$\lambda_{\tilde{g}}$	g	SU(3)	g_3	color

11.1.2 Chiral Superfields

SF	Spin 0	Spin $\frac{1}{2}$	Generations	$(U(1)\otimes \text{SU}(2)\otimes \text{SU}(3))$
$\hat{q}$	$\tilde{q}$	q	3	$(\frac{1}{6},\mathbf{2},\mathbf{3})$
$\hat{l}$	$\tilde{l}$	l	3	$(-\frac{1}{2},\mathbf{2},\mathbf{1})$
$\hat{H}_d$	H_d	$\tilde{H}_d$	1	$(-\frac{1}{2},\mathbf{2},\mathbf{1})$
$\hat{H}_u$	H_u	$\tilde{H}_u$	1	$(\frac{1}{2},\mathbf{2},\mathbf{1})$
$\hat{d}$	$\tilde{d}_R^*$	d_R^*	3	$(\frac{1}{3},\mathbf{1},\overline{\mathbf{3}})$
$\hat{u}$	$\tilde{u}_R^*$	u_R^*	3	$(-\frac{2}{3},\mathbf{1},\overline{\mathbf{3}})$
$\hat{e}$	$\tilde{e}_R^*$	e_R^*	3	$(1,\mathbf{1},\mathbf{1})$
$\hat{s}$	S	$\tilde{S}$	1	$(0,\mathbf{1},\mathbf{1})$

11.2 Superpotential and Lagrangian

11.2.1 Superpotential

$$W = Y_u\,\hat{q}\,\hat{H}_u\,\hat{u}\,-Y_d\,\hat{q}\,\hat{H}_d\,\hat{d}\,-Y_e\,\hat{l}\,\hat{H}_d\,\hat{e}\,+\lambda\,\hat{H}_u\,\hat{H}_d\,\hat{s}\,+\frac{1}{3}\kappa\,\hat{s}\,\hat{s}\,\hat{s} \tag{11.1}$$

11.2.2 Softbreaking terms

$$
\begin{aligned}
L_{SB,W} = &+\frac{1}{3}S^3 T_\kappa - H_d^0 H_u^0 S T_\lambda + H_d^- H_u^+ S T_\lambda + H_d^0 \tilde{d}^*_{R,k\gamma}\delta_{\alpha\gamma}\tilde{d}_{L,i\alpha}T_{d,ik} - H_d^- \tilde{d}^*_{R,k\gamma}\delta_{\alpha\gamma}\tilde{u}_{L,i\alpha}T_{d,ik} \\
&+ H_d^0 \tilde{e}^*_{R,k}\tilde{e}_{L,i}T_{e,ik} - H_d^- \tilde{e}^*_{R,k}\tilde{\nu}_{L,i}T_{e,ik} - H_u^+ \tilde{u}^*_{R,k\gamma}\delta_{\alpha\gamma}\tilde{d}_{L,i\alpha}T_{u,ik} + H_u^0 \tilde{u}^*_{R,k\gamma}\delta_{\alpha\gamma}\tilde{u}_{L,i\alpha}T_{u,ik} + \text{h.c.} \qquad (11.2)
\end{aligned}
$$

$$
\begin{aligned}
L_{SB,\phi} = &- m^2_{H_d}|H_d^0|^2 - m^2_{H_d}|H_d^-|^2 - m^2_{H_u}|H_u^0|^2 - m^2_{H_u}|H_u^+|^2 - m^2_S|S|^2 \\
&- \tilde{d}^*_{L,j\beta}\delta_{\alpha\beta}m^2_{q,ij}\tilde{d}_{L,i\alpha} - \tilde{d}^*_{R,i\alpha}\delta_{\alpha\beta}m^2_{d,ij}\tilde{d}_{R,j\beta} - \tilde{e}^*_{L,j}m^2_{l,ij}\tilde{e}_{L,i} - \tilde{e}^*_{R,i}m^2_{e,ij}\tilde{e}_{R,j} \\
&- \tilde{u}^*_{L,j\beta}\delta_{\alpha\beta}m^2_{q,ij}\tilde{u}_{L,i\alpha} - \tilde{u}^*_{R,i\alpha}\delta_{\alpha\beta}m^2_{u,ij}\tilde{u}_{R,j\beta} - \tilde{\nu}^*_{L,j}m^2_{l,ij}\tilde{\nu}_{L,i} \qquad (11.3)
\end{aligned}
$$

$$
L_{SB,\lambda} = \frac{1}{2}\left(-\lambda^2_{\tilde{B}}M_1 - M_2\lambda^2_{\tilde{W},i} - M_3\lambda^2_{\tilde{g},i} + \text{h.c.}\right) \qquad (11.4)
$$

11.2.3 Gauge fixing terms

Gauge fixing terms for eigenstates 'GaugeES'

$$
L_{GF} = -\frac{1}{2}\partial_\mu g\xi_G^{-1} - \frac{1}{2}\partial_\mu W^-\xi_W^{-1} \qquad (11.5)
$$

Gauge fixing terms for eigenstates 'EWSB'

$$
L_{GF} = -\frac{1}{2}\partial_\mu\gamma\xi_P^{-1} - \frac{1}{2}\partial_\mu g\xi_G^{-1} - \frac{1}{2}\xi_Z^{-1}\Big(-h_1 m_Z\xi_Z + \partial_\mu Z\Big) - \xi_W^{-1}\Big(iH_1^- m_{W^-}\xi_W + \partial_\mu W^-\Big) \qquad (11.6)
$$

11.2.4 Fields integrated out

None

11.3 Field Rotations

11.3.1 Rotations in gauge sector for eigenstates 'EWSB'

$$
W^-_{1\rho} = \frac{1}{\sqrt{2}}W^-_\rho + \frac{1}{\sqrt{2}}W^+_\rho \qquad (11.7)
$$

$$
W^-_{2\rho} = -i\frac{1}{\sqrt{2}}W^-_\rho + i\frac{1}{\sqrt{2}}W^+_\rho \qquad (11.8)
$$

$$
W^-_{3\rho} = \cos\Theta_W Z_\rho + \sin\Theta_W\gamma_\rho \qquad (11.9)
$$

$$
B_\rho = \cos\Theta_W\gamma_\rho - \sin\Theta_W Z_\rho \qquad (11.10)
$$

$$
\lambda_{\tilde{W},1} = \frac{1}{\sqrt{2}}\tilde{W}^- + \frac{1}{\sqrt{2}}\tilde{W}^+ \qquad (11.11)
$$

$$
\lambda_{\tilde{W},2} = -i\frac{1}{\sqrt{2}}\tilde{W}^- + i\frac{1}{\sqrt{2}}\tilde{W}^+ \qquad (11.12)
$$

$$
\lambda_{\tilde{W},3} = \tilde{W}^0 \qquad (11.13)
$$

11.3.2 Rotations in Mass sector for eigenstates 'EWSB'

Mass Matrices for Scalars

- **Mass matrix for Down-Squarks**, Basis: $\left(\tilde{d}_{L,o_1\alpha_1}, \tilde{d}_{R,o_2\alpha_2}\right), \left(\tilde{d}^*_{L,p_1\beta_1}, \tilde{d}^*_{R,p_2\beta_2}\right)$

$$m^2_{\tilde{d}} = \begin{pmatrix} m_{11} & \frac{1}{2}\delta_{\alpha_1\beta_2}\Big(\sqrt{2}v_d T_{d,o_1p_2} - v_s v_u \lambda^* Y_{d,o_1p_2}\Big) \\ \frac{1}{2}\Big(\sqrt{2}v_d T^*_{d,p_1o_2} - v_s v_u \lambda Y^*_{d,p_1o_2}\Big)\delta_{\alpha_2\beta_1} & m_{22} \end{pmatrix} \tag{11.14}$$

$$m_{11} = \frac{1}{24}\delta_{\alpha_1\beta_1}\Big(12\Big(2m^2_{q,o_1p_1} + v_d^2\sum_{a=1}^{3} Y^*_{d,p_1a}Y_{d,o_1a}\Big) - \Big(3g_2^2 + g_1^2\Big)\Big(-v_u^2 + v_d^2\Big)\delta_{o_1p_1}\Big) \tag{11.15}$$

$$m_{22} = \frac{1}{12}\delta_{\alpha_2\beta_2}\Big(6\Big(2m^2_{d,p_2o_2} + v_d^2\sum_{a=1}^{3} Y^*_{d,ao_2}Y_{d,ap_2}\Big) + g_1^2\Big(-v_d^2 + v_u^2\Big)\delta_{o_2p_2}\Big) \tag{11.16}$$

This matrix is diagonalized by Z^D:

$$Z^D m^2_{\tilde{d}} Z^{D,\dagger} = m^{dia}_{2,\tilde{d}} \tag{11.17}$$

with

$$\tilde{d}_{L,i\alpha} = \sum_{t_2} Z^{D,*}_{ji}\tilde{d}_{j\alpha}\,, \qquad \tilde{d}_{R,i\alpha} = \sum_{t_2} Z^{D,*}_{ji}\tilde{d}_{j\alpha} \tag{11.18}$$

- **Mass matrix for Up-Squarks**, Basis: $\left(\tilde{u}_{L,o_1\alpha_1}, \tilde{u}_{R,o_2\alpha_2}\right), \left(\tilde{u}^*_{L,p_1\beta_1}, \tilde{u}^*_{R,p_2\beta_2}\right)$

$$m^2_{\tilde{u}} = \begin{pmatrix} m_{11} & \frac{1}{2}\delta_{\alpha_1\beta_2}\Big(\sqrt{2}v_u T_{u,o_1p_2} - v_d v_s \lambda^* Y_{u,o_1p_2}\Big) \\ \frac{1}{2}\Big(\sqrt{2}v_u T^*_{u,p_1o_2} - v_d v_s \lambda Y^*_{u,p_1o_2}\Big)\delta_{\alpha_2\beta_1} & m_{22} \end{pmatrix} \tag{11.19}$$

$$m_{11} = \frac{1}{24}\delta_{\alpha_1\beta_1}\Big(12\Big(2m^2_{q,o_1p_1} + v_u^2\sum_{a=1}^{3} Y^*_{u,p_1a}Y_{u,o_1a}\Big) - \Big(-3g_2^2 + g_1^2\Big)\Big(-v_u^2 + v_d^2\Big)\delta_{o_1p_1}\Big) \tag{11.20}$$

$$m_{22} = \frac{1}{6}\delta_{\alpha_2\beta_2}\Big(3v_u^2\sum_{a=1}^{3} Y^*_{u,ao_2}Y_{u,ap_2} + 6m^2_{u,p_2o_2} + g_1^2\Big(-v_u^2 + v_d^2\Big)\delta_{o_2p_2}\Big) \tag{11.21}$$

This matrix is diagonalized by Z^U:

$$Z^U m^2_{\tilde{u}} Z^{U,\dagger} = m^{dia}_{2,\tilde{u}} \tag{11.22}$$

with

$$\tilde{u}_{L,i\alpha} = \sum_{t_2} Z^{U,*}_{ji}\tilde{u}_{j\alpha}\,, \qquad \tilde{u}_{R,i\alpha} = \sum_{t_2} Z^{U,*}_{ji}\tilde{u}_{j\alpha} \tag{11.23}$$

- **Mass matrix for Sneutrinos**, Basis: $\left(\tilde{\nu}_{L,o_1}\right), \left(\tilde{\nu}^*_{L,p_1}\right)$

$$m^2_{\tilde{\nu}} = \left(\begin{array}{c} \frac{1}{8}\Big(8 m^2_{l,o_1 p_1} + \Big(g_1^2 + g_2^2\Big)\Big(- v_u^2 + v_d^2\Big)\delta_{o_1 p_1}\Big) \end{array} \right) \tag{11.24}$$

This matrix is diagonalized by Z^V:

$$Z^V m^2_{\tilde{\nu}} Z^{V,\dagger} = m^{dia}_{2,\tilde{\nu}} \tag{11.25}$$

with

$$\tilde{\nu}_{L,i} = \sum_{t_2} Z^{V,*}_{ji} \tilde{\nu}_j \tag{11.26}$$

- **Mass matrix for Sleptons**, Basis: $\left(\tilde{e}_{L,o_1}, \tilde{e}_{R,o_2}\right), \left(\tilde{e}^*_{L,p_1}, \tilde{e}^*_{R,p_2}\right)$

$$m^2_{\tilde{e}} = \left(\begin{array}{cc} m_{11} & -\frac{1}{2} v_s v_u \lambda^* Y_{e,o_1 p_2} + \frac{1}{\sqrt{2}} v_d T_{e,o_1 p_2} \\ -\frac{1}{2} v_s v_u \lambda Y^*_{e,p_1 o_2} + \frac{1}{\sqrt{2}} v_d T^*_{e,p_1 o_2} & m_{22} \end{array} \right) \tag{11.27}$$

$$m_{11} = \frac{1}{8}\Big(4 v_d^2 \sum_{a=1}^{3} Y^*_{e,p_1 a} Y_{e,o_1 a} + 8 m^2_{l,o_1 p_1} + \Big(- g_2^2 + g_1^2\Big)\Big(- v_u^2 + v_d^2\Big)\delta_{o_1 p_1}\Big) \tag{11.28}$$

$$m_{22} = \frac{1}{4}\Big(2 v_d^2 \sum_{a=1}^{3} Y^*_{e,a o_2} Y_{e,a p_2} + 4 m^2_{e,p_2 o_2} + g_1^2 \Big(- v_d^2 + v_u^2\Big)\delta_{o_2 p_2}\Big) \tag{11.29}$$

This matrix is diagonalized by Z^E:

$$Z^E m^2_{\tilde{e}} Z^{E,\dagger} = m^{dia}_{2,\tilde{e}} \tag{11.30}$$

with

$$\tilde{e}_{L,i} = \sum_{t_2} Z^{E,*}_{ji} \tilde{e}_j\,, \qquad \tilde{e}_{R,i} = \sum_{t_2} Z^{E,*}_{ji} \tilde{e}_j \tag{11.31}$$

- **Mass matrix for Higgs**, Basis: $\left(\phi_d, \phi_u, \phi_s, \sigma_d, \sigma_u, \sigma_s\right), \left(\phi_d, \phi_u, \phi_s, \sigma_d, \sigma_u, \sigma_s\right)$

$$m^2_h = \left(\begin{array}{cccccc} m_{11} & m^*_{21} & m^*_{31} & 0 & m^*_{51} & m^*_{61} \\ m_{21} & m_{22} & m^*_{32} & m^*_{42} & 0 & m^*_{62} \\ m_{31} & m_{32} & m_{33} & m^*_{43} & m^*_{53} & m^*_{63} \\ 0 & m_{42} & m_{43} & m_{44} & m^*_{54} & m^*_{64} \\ m_{51} & 0 & m_{53} & m_{54} & m_{55} & m^*_{65} \\ m_{61} & m_{62} & m_{63} & m_{64} & m_{65} & m_{66} \end{array} \right) \tag{11.32}$$

$$m_{11} = \frac{1}{8}\Big(4\Big(v_s^2 + v_u^2\Big)|\lambda|^2 + 8 m^2_{H_d} + \Big(g_1^2 + g_2^2\Big)\Big(3 v_d^2 - v_u^2\Big)\Big) \tag{11.33}$$

$$m_{21} = \frac{1}{4}\Big(- 2\sqrt{2} v_s \Re\Big(T_{\lambda}\Big) + \Big(4 v_d v_u \lambda - v_{s}^{2} \kappa \Big)\lambda^* - g_{1}^{2} v_d v_u - g_{2}^{2} v_d v_u - v_{s}^{2} \lambda \kappa^* \Big) \tag{11.34}$$

$$m_{22} = \frac{1}{8}\Big(4\Big(v_{d}^{2} + v_{s}^{2}\Big)|\lambda|^2 + 8 m_{H_u}^2 - \Big(g_{1}^{2} + g_{2}^{2}\Big)\Big(- 3 v_{u}^{2} + v_{d}^{2}\Big)\Big) \tag{11.35}$$

$$m_{31} = \frac{1}{2}\Big(\Big(2 v_d v_s \lambda - v_s v_u \kappa \Big)\lambda^* - \sqrt{2} v_u \Re\Big(T_{\lambda}\Big) - v_s v_u \lambda \kappa^* \Big) \tag{11.36}$$

$$m_{32} = \frac{1}{2}\Big(\Big(2 v_s v_u \lambda - v_d v_s \kappa \Big)\lambda^* - \sqrt{2} v_d \Re\Big(T_{\lambda}\Big) - v_d v_s \lambda \kappa^* \Big) \tag{11.37}$$

$$m_{33} = \frac{1}{2}\Big(2\Big(\sqrt{2} v_s \Re\Big(T_{\kappa}\Big) + m_{S}^{2}\Big) + \Big(6 v_{s}^{2} \kappa - v_d v_u \lambda \Big)\kappa^* + \Big(v_{d}^{2} \lambda - v_d v_u \kappa + v_{u}^{2} \lambda \Big)\lambda^* \Big) \tag{11.38}$$

$$m_{42} = -\frac{i}{4} v_s \Big(\sqrt{2}\Big(- T_{\lambda}^{*} + T_{\lambda}\Big) - v_s \kappa \lambda^* + v_s \lambda \kappa^* \Big) \tag{11.39}$$

$$m_{43} = -\frac{i}{4} v_u \Big(- 2 v_s \kappa \lambda^* + 2 v_s \lambda \kappa^* + \sqrt{2}\Big(- T_{\lambda}^{*} + T_{\lambda}\Big)\Big) \tag{11.40}$$

$$m_{44} = \frac{1}{8}\Big(4\Big(v_{s}^{2} + v_{u}^{2}\Big)|\lambda|^2 + 8 m_{H_d}^2 + \Big(g_{1}^{2} + g_{2}^{2}\Big)\Big(- v_{u}^{2} + v_{d}^{2}\Big)\Big) \tag{11.41}$$

$$m_{51} = -\frac{i}{4} v_s \Big(\sqrt{2}\Big(- T_{\lambda}^{*} + T_{\lambda}\Big) - v_s \kappa \lambda^* + v_s \lambda \kappa^* \Big) \tag{11.42}$$

$$m_{53} = -\frac{i}{4} v_d \Big(- 2 v_s \kappa \lambda^* + 2 v_s \lambda \kappa^* + \sqrt{2}\Big(- T_{\lambda}^{*} + T_{\lambda}\Big)\Big) \tag{11.43}$$

$$m_{54} = \frac{1}{4} v_s \Big(2\sqrt{2}\Re\Big(T_{\lambda}\Big) + v_s \kappa \lambda^* + v_s \lambda \kappa^* \Big) \tag{11.44}$$

$$m_{55} = \frac{1}{8}\Big(4\Big(v_{d}^{2} + v_{s}^{2}\Big)|\lambda|^2 + 8 m_{H_u}^2 - \Big(g_{1}^{2} + g_{2}^{2}\Big)\Big(- v_{u}^{2} + v_{d}^{2}\Big)\Big) \tag{11.45}$$

$$m_{61} = \frac{i}{4} v_u \Big(- 2 v_s \kappa \lambda^* + 2 v_s \lambda \kappa^* + \sqrt{2}\Big(- T_{\lambda} + T_{\lambda}^{*}\Big)\Big) \tag{11.46}$$

$$m_{62} = \frac{i}{4} v_d \Big(- 2 v_s \kappa \lambda^* + 2 v_s \lambda \kappa^* + \sqrt{2}\Big(- T_{\lambda} + T_{\lambda}^{*}\Big)\Big) \tag{11.47}$$

$$m_{63} = \frac{i}{2}\Big(\sqrt{2} v_s \Big(- T_{\kappa}^{*} + T_{\kappa}\Big) - v_d v_u \kappa \lambda^* + v_d v_u \lambda \kappa^* \Big) \tag{11.48}$$

$$m_{64} = -\frac{1}{2} v_u \Big(- \sqrt{2}\Re\Big(T_{\lambda}\Big) + v_s \kappa \lambda^* + v_s \lambda \kappa^* \Big) \tag{11.49}$$

$$m_{65} = -\frac{1}{2} v_d \Big(- \sqrt{2}\Re\Big(T_{\lambda}\Big) + v_s \kappa \lambda^* + v_s \lambda \kappa^* \Big) \tag{11.50}$$

$$m_{66} = \frac{1}{2}\Big(2\Big(- \sqrt{2} v_s \Re\Big(T_{\kappa}\Big) + m_{S}^{2}\Big) + \Big(2 v_{s}^{2} \kappa + v_d v_u \lambda \Big)\kappa^* + \Big(v_{d}^{2} \lambda + v_d v_u \kappa + v_{u}^{2} \lambda \Big)\lambda^* \Big) \tag{11.51}$$

This matrix is diagonalized by Z^H:

$$Z^H m^2_h Z^{H,\dagger} = m^{dia}_{2,h} \tag{11.52}$$

with

$$\phi_d = \sum_{t_2} Z^{H,*}_{j1} h_j \,, \qquad \phi_u = \sum_{t_2} Z^{H,*}_{j2} h_j \,, \qquad \phi_s = \sum_{t_2} Z^{H,*}_{j3} h_j \tag{11.53}$$

$$\sigma_d = \sum_{t_2} Z^{H,*}_{j4} h_j \,, \qquad \sigma_u = \sum_{t_2} Z^{H,*}_{j5} h_j \,, \qquad \sigma_s = \sum_{t_2} Z^{H,*}_{j6} h_j \tag{11.54}$$

- **Mass matrix for Charged Higgs**, Basis: $\left(H_d^-, H_u^{+,*}\right), \left(H_d^{-,*}, H_u^+\right)$

$$m^2_{H^-} = \begin{pmatrix} m_{11} & m^*_{21} \\ m_{21} & m_{22} \end{pmatrix} \tag{11.55}$$

$$m_{11} = \frac{1}{8}\Big(4v_s^2|\lambda|^2 + 8m^2_{H_d} + g_1^2 v_d^2 - g_1^2 v_u^2 + g_2^2 v_d^2 + g_2^2 v_u^2\Big) \tag{11.56}$$

$$m_{21} = \frac{1}{4}\Big(2\sqrt{2}v_s T^*_\lambda + 2\Big(-v_d v_u \lambda + v_s^2 \kappa\Big)\lambda^* + g_2^2 v_d v_u\Big) \tag{11.57}$$

$$m_{22} = \frac{1}{8}\Big(4v_s^2|\lambda|^2 + 8m^2_{H_u} - g_1^2 v_d^2 + g_1^2 v_u^2 + g_2^2 v_d^2 + g_2^2 v_u^2\Big) \tag{11.58}$$

This matrix is diagonalized by Z^+:

$$Z^+ m^2_{H^-} Z^{+,\dagger} = m^{dia}_{2,H^-} \tag{11.59}$$

with

$$H_d^- = \sum_{t_2} Z^{+,*}_{j1} H_j^-\,, \qquad H_u^+ = \sum_{t_2} Z^+_{j2} H_j^+ \tag{11.60}$$

The mixing matrix can be parametrized by

$$Z^+ = \begin{pmatrix} -\cos\beta & \sin\beta \\ \sin\beta & \cos\beta \end{pmatrix} \tag{11.61}$$

Mass Matrices for Fermions

- **Mass matrix for Neutralinos**, Basis: $\left(\lambda_{\tilde{B}}, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0, \tilde{S}^*\right), \left(\lambda_{\tilde{B}}, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0, \tilde{S}^*\right)$

$$m_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -\frac{1}{2}g_1 v_d & \frac{1}{2}g_1 v_u & 0 \\ 0 & M_2 & \frac{1}{2}g_2 v_d & -\frac{1}{2}g_2 v_u & 0 \\ -\frac{1}{2}g_1 v_d & \frac{1}{2}g_2 v_d & 0 & -\frac{1}{\sqrt{2}}v_s\lambda & 0 \\ \frac{1}{2}g_1 v_u & -\frac{1}{2}g_2 v_u & -\frac{1}{\sqrt{2}}v_s\lambda & 0 & 0 \\ 0 & 0 & 0 & 0 & \sqrt{2}v_s\kappa^* \end{pmatrix} \tag{11.62}$$

This matrix is diagonalized by N:

$$N m_{\tilde{\chi}^0} N^\dagger = m^{dia}_{\tilde{\chi}^0} \tag{11.63}$$

with

$$\lambda_{\tilde{B}} = \sum_{t_2} N^*_{j1}\lambda^0_j\,, \qquad \tilde{W}^0 = \sum_{t_2} N^*_{j2}\lambda^0_j\,, \qquad \tilde{H}^0_d = \sum_{t_2} N^*_{j3}\lambda^0_j \tag{11.64}$$

$$\tilde{H}^0_u = \sum_{t_2} N^*_{j4}\lambda^0_j\,, \qquad \tilde{S} = \sum_{t_2} N_{j5}\lambda^{0,*}_j \tag{11.65}$$

- **Mass matrix for Charginos**, Basis: $\left(\tilde{W}^-, \tilde{H}_d^-\right), \left(\tilde{W}^+, \tilde{H}_u^+\right)$

$$m_{\tilde{\chi}^-} = \begin{pmatrix} M_2 & \frac{1}{\sqrt{2}} g_2 v_u \\ \frac{1}{\sqrt{2}} g_2 v_d & \frac{1}{\sqrt{2}} v_s \lambda \end{pmatrix} \tag{11.66}$$

This matrix is diagonalized by U and V

$$U^* m_{\tilde{\chi}^-} V^\dagger = m^{dia}_{\tilde{\chi}^-} \tag{11.67}$$

with

$$\tilde{W}^- = \sum_{t_2} U^*_{j1} \lambda^-_j \, , \qquad \tilde{H}^-_d = \sum_{t_2} U^*_{j2} \lambda^-_j \tag{11.68}$$

$$\tilde{W}^+ = \sum_{t_2} V^*_{1j} \lambda^+_j \, , \qquad \tilde{H}^+_u = \sum_{t_2} V^*_{2j} \lambda^+_j \tag{11.69}$$

- **Mass matrix for Leptons**, Basis: $\left(e_{L,o_1}\right), \left(e^*_{R,p_1}\right)$

$$m_e = \begin{pmatrix} \frac{1}{\sqrt{2}} v_d Y_{e,o_1 p_1} \end{pmatrix} \tag{11.70}$$

This matrix is diagonalized by U^e_L and U^e_R

$$U^{e,*}_L m_e U^{e,\dagger}_R = m^{dia}_e \tag{11.71}$$

with

$$e_{L,i} = \sum_{t_2} U^{e,*}_{L,ji} E_{L,j} \tag{11.72}$$

$$e_{R,i} = \sum_{t_2} U^e_{R,ij} E^*_{R,j} \tag{11.73}$$

- **Mass matrix for Down-Quarks**, Basis: $\left(d_{L,o_1\alpha_1}\right), \left(d^*_{R,p_1\beta_1}\right)$

$$m_d = \begin{pmatrix} \frac{1}{\sqrt{2}} v_d \delta_{\alpha_1\beta_1} Y_{d,o_1 p_1} \end{pmatrix} \tag{11.74}$$

This matrix is diagonalized by U^d_L and U^d_R

$$U^{d,*}_L m_d U^{d,\dagger}_R = m^{dia}_d \tag{11.75}$$

with

$$d_{L,i\alpha} = \sum_{t_2} U^{d,*}_{L,ji} D_{L,j\alpha} \tag{11.76}$$

$$d_{R,i\alpha} = \sum_{t_2} U^d_{R,ij} D^*_{R,j\alpha} \tag{11.77}$$

- **Mass matrix for Up-Quarks**, Basis: $(u_{L,o_1\alpha_1}), \left(u^*_{R,p_1\beta_1}\right)$

$$m_u = \left(\frac{1}{\sqrt{2}} v_u \delta_{\alpha_1\beta_1} Y_{u,o_1p_1} \right) \tag{11.78}$$

This matrix is diagonalized by U^u_L and U^u_R

$$U^{u,*}_L m_u U^{u,\dagger}_R = m^{dia}_u \tag{11.79}$$

with

$$u_{L,i\alpha} = \sum_{t_2} U^{u,*}_{L,ji} U_{L,j\alpha} \tag{11.80}$$

$$u_{R,i\alpha} = \sum_{t_2} U^{u}_{R,ij} U^*_{R,j\alpha} \tag{11.81}$$

11.4 Vacuum Expectation Values

$$H^0_d = \frac{1}{\sqrt{2}}\phi_d + \frac{1}{\sqrt{2}} v_d + i\frac{1}{\sqrt{2}}\sigma_d \tag{11.82}$$

$$H^0_u = \frac{1}{\sqrt{2}}\phi_u + \frac{1}{\sqrt{2}} v_u + i\frac{1}{\sqrt{2}}\sigma_u \tag{11.83}$$

$$S = \frac{1}{\sqrt{2}}\phi_s + \frac{1}{\sqrt{2}} v_s + i\frac{1}{\sqrt{2}}\sigma_s \tag{11.84}$$

11.5 Tadpole Equations

$$\begin{aligned}\frac{\partial V}{\partial v_d} &= \frac{1}{8}\Big(8 m^2_{H_d} v_d + g_1^2 v_d^3 + g_2^2 v_d^3 - g_1^2 v_d v_u^2 - g_2^2 v_d v_u^2 - 2 v_s^2 v_u \lambda \kappa^* \\ &+ \Big(4 v_d v_u^2 \lambda + v_s^2 \Big(-2 v_u \kappa + 4 v_d \lambda\Big)\Big)\lambda^* - 4\sqrt{2} v_s v_u \Re\Big(T_\lambda\Big)\Big)\end{aligned} \tag{11.85}$$

$$\begin{aligned}\frac{\partial V}{\partial v_u} &= \frac{1}{8}\Big(8 m^2_{H_u} v_u - g_1^2 v_d^2 v_u - g_2^2 v_d^2 v_u + g_1^2 v_u^3 + g_2^2 v_u^3 - 2 v_d v_s^2 \lambda \kappa^* \\ &+ \Big(-2 v_d v_s^2 \kappa + 4 v_d^2 v_u \lambda + 4 v_s^2 v_u \lambda\Big)\lambda^* - 4\sqrt{2} v_d v_s \Re\Big(T_\lambda\Big)\Big)\end{aligned} \tag{11.86}$$

$$\begin{aligned}\frac{\partial V}{\partial v_s} &= \frac{1}{4}\Big(4 m^2_S v_s + \Big(-2 v_d v_s v_u \lambda + 4 v_s^3 \kappa\Big)\kappa^* + 2 v_s \Big(v_d^2 \lambda - v_d v_u \kappa + v_u^2 \lambda\Big)\lambda^* - \sqrt{2} v_d v_u T^*_\lambda \\ &+ 2\sqrt{2} v_s^2 \Re\Big(T_\kappa\Big) - \sqrt{2} v_d v_u T_\lambda\Big)\end{aligned} \tag{11.87}$$

11.6 Particle content for eigenstates 'EWSB'

Name	Type	complex/real	Generations	Indices

$\tilde{d}$	Scalar	complex	6	generation, color
$\tilde{u}$	Scalar	complex	6	generation, color
$\tilde{\nu}$	Scalar	complex	3	generation
$\tilde{e}$	Scalar	complex	6	generation
h	Scalar	real	6	generation
H^-	Scalar	complex	2	generation
ν	Fermion	Dirac	3	generation
$\tilde{g}$	Fermion	Majorana	8	generation
$\tilde{\chi}^0$	Fermion	Majorana	5	generation
$\tilde{\chi}^-$	Fermion	Dirac	2	generation
e	Fermion	Dirac	3	generation
d	Fermion	Dirac	3	generation, color
u	Fermion	Dirac	3	generation, color
g	Vector	real	8	generation, lorentz
W^-	Vector	complex	1	lorentz
γ	Vector	real	1	lorentz
Z	Vector	real	1	lorentz
η^G	Ghost	real	8	generation
η^-	Ghost	complex	1	
η^+	Ghost	complex	1	
η^γ	Ghost	real	1	
η^Z	Ghost	real	1	

11.7 Modelfile for SARAH

11.8 Implementation in SARAH

Model directory: NMSSM/CPV

11.8.1 Particles for eigenstates 'GaugeES'

- Fermions

$\tilde{B} = \begin{pmatrix} \lambda_{\tilde{B}} \\ \lambda^*_{\tilde{B}} \end{pmatrix}$	$\texttt{Bino} = \begin{pmatrix} \texttt{fB} \\ \texttt{conj[fB]} \end{pmatrix}$
$d^1_{i\alpha} = \begin{pmatrix} d_{L,i\alpha} \\ 0 \end{pmatrix}$	$\texttt{Fd1[\{generation, color\}]} = \begin{pmatrix} \texttt{FdL[\{generation, color\}]} \\ 0 \end{pmatrix}$
$d^2_{i\alpha} = \begin{pmatrix} 0 \\ d_{R,i\alpha} \end{pmatrix}$	$\texttt{Fd2[\{generation, color\}]} = \begin{pmatrix} 0 \\ \texttt{FdR[\{generation, color\}]} \end{pmatrix}$
$e^1_i = \begin{pmatrix} e_{L,i} \\ 0 \end{pmatrix}$	$\texttt{Fe1[\{generation\}]} = \begin{pmatrix} \texttt{FeL[\{generation\}]} \\ 0 \end{pmatrix}$
$e^2_i = \begin{pmatrix} 0 \\ e_{R,i} \end{pmatrix}$	$\texttt{Fe2[\{generation\}]} = \begin{pmatrix} 0 \\ \texttt{FeR[\{generation\}]} \end{pmatrix}$
$u^1_{i\alpha} = \begin{pmatrix} u_{L,i\alpha} \\ 0 \end{pmatrix}$	$\texttt{Fu1[\{generation, color\}]} = \begin{pmatrix} \texttt{FuL[\{generation, color\}]} \\ 0 \end{pmatrix}$
$u^2_{i\alpha} = \begin{pmatrix} 0 \\ u_{R,i\alpha} \end{pmatrix}$	$\texttt{Fu2[\{generation, color\}]} = \begin{pmatrix} 0 \\ \texttt{FuR[\{generation, color\}]} \end{pmatrix}$
$\nu_i = \begin{pmatrix} \nu_{L,i} \\ 0 \end{pmatrix}$	$\texttt{Fv[\{generation\}]} = \begin{pmatrix} \texttt{FvL[\{generation\}]} \\ 0 \end{pmatrix}$
$\tilde{g}_i = \begin{pmatrix} \lambda_{\tilde{g},i} \\ \lambda^*_{\tilde{g},i} \end{pmatrix}$	$\texttt{Glu[\{generation\}]} = \begin{pmatrix} \texttt{fG[\{generation\}]} \\ \texttt{conj[fG[\{generation\}]]} \end{pmatrix}$
$\tilde{H}^0 = \begin{pmatrix} \tilde{H}^0_d \\ \tilde{H}^{0,*}_u \end{pmatrix}$	$\texttt{H0} = \begin{pmatrix} \texttt{FHd0} \\ \texttt{conj[FHu0]} \end{pmatrix}$
$\tilde{H}^- = \begin{pmatrix} \tilde{H}^-_d \\ \tilde{H}^{+,*}_u \end{pmatrix}$	$\texttt{HC} = \begin{pmatrix} \texttt{FHdm} \\ \texttt{conj[FHup]} \end{pmatrix}$
$\tilde{S} = \begin{pmatrix} \tilde{S} \\ \tilde{S}^* \end{pmatrix}$	$\texttt{S} = \begin{pmatrix} \texttt{FsR} \\ \texttt{conj[FsR]} \end{pmatrix}$
$\tilde{W}_i = \begin{pmatrix} \lambda_{\tilde{W},i} \\ \lambda^*_{\tilde{W},i} \end{pmatrix}$	$\texttt{Wino[\{generation\}]} = \begin{pmatrix} \texttt{fWB[\{generation\}]} \\ \texttt{conj[fWB[\{generation\}]]} \end{pmatrix}$

- Scalars

$\tilde{d}_{L,i\alpha}$	SdL[{generation, color}]	$\tilde{u}_{L,i\alpha}$	SuL[{generation, color}]
$\tilde{e}_{L,i}$	SeL[{generation}]	$\tilde{\nu}_{L,i}$	SvL[{generation}]
H_d^0	SHd0	H_d^-	SHdm
H_u^0	SHu0	H_u^+	SHup
$\tilde{d}_{R,i\alpha}$	SdR[{generation, color}]	$\tilde{u}_{R,i\alpha}$	SuR[{generation, color}]
$\tilde{e}_{R,i}$	SeR[{generation}]	S	SsR

- Vector Bosons

B_ρ	VB[{lorentz}]	$W^-_{i\rho}$	VWB[{generation, lorentz}]
$g_{i\rho}$	VG[{generation, lorentz}]		

- Ghosts

η^B	gB	$\mathrm{gWB}\Big(\{\mathrm{gt1}\}\Big)$	gWB[{generation}]
η^G_i	gG[{generation}]		

11.8.2 Particles for eigenstates 'EWSB'

- Fermions

$\tilde{\chi}^-_i = \begin{pmatrix} \lambda^-_i \\ \lambda^{+,*}_i \end{pmatrix}$	$\texttt{Cha[\{generation\}]} = \begin{pmatrix} \texttt{Lm[\{generation\}]} \\ \texttt{conj[Lp[\{generation\}]]} \end{pmatrix}$
$\tilde{\chi}^0_i = \begin{pmatrix} \lambda^0_i \\ \lambda^{0,*}_i \end{pmatrix}$	$\texttt{Chi[\{generation\}]} = \begin{pmatrix} \texttt{L0[\{generation\}]} \\ \texttt{conj[L0[\{generation\}]]} \end{pmatrix}$
$d_{i\alpha} = \begin{pmatrix} D_{L,i\alpha} \\ D^*_{R,i\alpha} \end{pmatrix}$	$\texttt{Fd[\{generation, color\}]} = \begin{pmatrix} \texttt{FDL[\{generation, color\}]} \\ \texttt{conj[FDR[\{generation, color\}]]} \end{pmatrix}$

$e_i = \begin{pmatrix} E_{L,i} \\ E^*_{R,i} \end{pmatrix}$	Fe[{generation}] = $\begin{pmatrix} \texttt{FEL[\{generation\}]} \\ \texttt{conj[FER[\{generation\}]]} \end{pmatrix}$
$u_{i\alpha} = \begin{pmatrix} U_{L,i\alpha} \\ U^*_{R,i\alpha} \end{pmatrix}$	Fu[{generation, color}] = $\begin{pmatrix} \texttt{FUL[\{generation, color\}]} \\ \texttt{conj[FUR[\{generation, color\}]]} \end{pmatrix}$
$\nu_i = \begin{pmatrix} \nu_{L,i} \\ 0 \end{pmatrix}$	Fv[{generation}] = $\begin{pmatrix} \texttt{FvL[\{generation\}]} \\ \texttt{0} \end{pmatrix}$
$\tilde{g}_i = \begin{pmatrix} \lambda_{\tilde{g},i} \\ \lambda^*_{\tilde{g},i} \end{pmatrix}$	Glu[{generation}] = $\begin{pmatrix} \texttt{fG[\{generation\}]} \\ \texttt{conj[fG[\{generation\}]]} \end{pmatrix}$

- Scalars

$\tilde{d}_{i\alpha}$	Sd[{generation, color}]	$\tilde{u}_{i\alpha}$	Su[{generation, color}]
$\tilde{\nu}_i$	Sv[{generation}]	$\tilde{e}_i$	Se[{generation}]
h_i	hh[{generation}]	H^-_i	Hpm[{generation}]

- Vector Bosons

$g_{i\rho}$	VG[{generation, lorentz}]	W^-_ρ	VWm[{lorentz}]
γ_ρ	VP[{lorentz}]	Z_ρ	VZ[{lorentz}]

- Ghosts

η^G_i	gG[{generation}]	η^-	gWm
η^+	gWmC	η^γ	gP
η^Z	gZ		

11.8.3 Parameters

g_1	g1	g_2	g2	g_3	g3
Y_u	Yu	T_u	T[Yu]	Y_d	Yd
T_d	T[Yd]	Y_e	Ye	T_e	T[Ye]
λ	\[Lambda]	T_λ	T[\[Lambda]]	κ	\[Kappa]
T_κ	T[\[Kappa]]	m_q^2	mq2	m_l^2	ml2
$m_{H_d}^2$	mHd2	$m_{H_u}^2$	mHu2	m_d^2	md2
m_u^2	mu2	m_e^2	me2	m_S^2	ms2
M_1	MassB	M_2	MassWB	M_3	MassG
v_d	vd	v_u	vu	v_s	vS
Θ_W	ThetaW	$\phi_{\tilde{g}}$	PhaseGlu	Z^D	ZD
Z^U	ZU	Z^V	ZV	Z^E	ZE
Z^H	ZH	Z^+	ZP	N	ZN
U	UM	V	UP	U_L^e	ZEL
U_R^e	ZER	U_L^d	ZDL	U_R^d	ZDR
U_L^u	ZUL	U_R^u	ZUR	β	\[Beta]

Chapter 12

The Next-to-Minimal Supersymmetric Standard Model with two rotations in pseudo-scalar sector

12.1 Superfields

12.1.1 Vector Superfields

SF	Spin $\frac{1}{2}$	Spin 1	$SU(N)$	Coupling	Name
$\hat{B}$	$\lambda_{\tilde{B}}$	B	$U(1)$	g_1	hypercharge
$\hat{W}$	$\lambda_{\tilde{W}}$	W^-	SU(2)	g_2	left
$\hat{g}$	$\lambda_{\tilde{g}}$	g	SU(3)	g_3	color

12.1.2 Chiral Superfields

SF	Spin 0	Spin $\frac{1}{2}$	Generations	$(U(1)\otimes$ SU(2) $\otimes$ SU(3)$)$
$\hat{q}$	$\tilde{q}$	q	3	$(\frac{1}{6},\mathbf{2},\mathbf{3})$
$\hat{l}$	$\tilde{l}$	l	3	$(-\frac{1}{2},\mathbf{2},\mathbf{1})$
$\hat{H}_d$	H_d	$\tilde{H}_d$	1	$(-\frac{1}{2},\mathbf{2},\mathbf{1})$
$\hat{H}_u$	H_u	$\tilde{H}_u$	1	$(\frac{1}{2},\mathbf{2},\mathbf{1})$
$\hat{d}$	$\tilde{d}_R^*$	d_R^*	3	$(\frac{1}{3},\mathbf{1},\overline{\mathbf{3}})$
$\hat{u}$	$\tilde{u}_R^*$	u_R^*	3	$(-\frac{2}{3},\mathbf{1},\overline{\mathbf{3}})$
$\hat{e}$	$\tilde{e}_R^*$	e_R^*	3	$(1,\mathbf{1},\mathbf{1})$
$\hat{s}$	S	$\tilde{S}$	1	$(0,\mathbf{1},\mathbf{1})$

12.2 Superpotential and Lagrangian

12.2.1 Superpotential

$$W = Y_u\,\hat{q}\,\hat{H}_u\,\hat{u}\, - Y_d\,\hat{q}\,\hat{H}_d\,\hat{d}\, - Y_e\,\hat{l}\,\hat{H}_d\,\hat{e}\, + \lambda\,\hat{H}_u\,\hat{H}_d\,\hat{s}\, + \frac{1}{3}\kappa\,\hat{s}\,\hat{s}\,\hat{s} \tag{12.1}$$

12.2.2 Softbreaking terms

$$\begin{aligned} L_{SB,W} = &+ \frac{1}{3}S^3 T_\kappa - H_d^0 H_u^0 S T_\lambda + H_d^- H_u^+ S T_\lambda + H_d^0 \tilde{d}^*_{R,k\gamma}\delta_{\alpha\gamma}\tilde{d}_{L,i\alpha}T_{d,ik} - H_d^- \tilde{d}^*_{R,k\gamma}\delta_{\alpha\gamma}\tilde{u}_{L,i\alpha}T_{d,ik} \\ &+ H_d^0 \tilde{e}^*_{R,k}\tilde{e}_{L,i}T_{e,ik} - H_d^- \tilde{e}^*_{R,k}\tilde{\nu}_{L,i}T_{e,ik} - H_u^+ \tilde{u}^*_{R,k\gamma}\delta_{\alpha\gamma}\tilde{d}_{L,i\alpha}T_{u,ik} + H_u^0 \tilde{u}^*_{R,k\gamma}\delta_{\alpha\gamma}\tilde{u}_{L,i\alpha}T_{u,ik} + \text{h.c.} \end{aligned} \tag{12.2}$$

$$\begin{aligned} L_{SB,\phi} = &- m_{H_d}^2 |H_d^0|^2 - m_{H_d}^2 |H_d^-|^2 - m_{H_u}^2 |H_u^0|^2 - m_{H_u}^2 |H_u^+|^2 - m_S^2 |S|^2 \\ &- \tilde{d}^*_{L,j\beta}\delta_{\alpha\beta}m^2_{q,ij}\tilde{d}_{L,i\alpha} - \tilde{d}^*_{R,i\alpha}\delta_{\alpha\beta}m^2_{d,ij}\tilde{d}_{R,j\beta} - \tilde{e}^*_{L,j}m^2_{l,ij}\tilde{e}_{L,i} - \tilde{e}^*_{R,i}m^2_{e,ij}\tilde{e}_{R,j} \\ &- \tilde{u}^*_{L,j\beta}\delta_{\alpha\beta}m^2_{q,ij}\tilde{u}_{L,i\alpha} - \tilde{u}^*_{R,i\alpha}\delta_{\alpha\beta}m^2_{u,ij}\tilde{u}_{R,j\beta} - \tilde{\nu}^*_{L,j}m^2_{l,ij}\tilde{\nu}_{L,i} \end{aligned} \tag{12.3}$$

$$L_{SB,\lambda} = \frac{1}{2}\Big(-\lambda_{\tilde{B}}^2 M_1 - M_2\lambda^2_{\tilde{W},i} - M_3\lambda^2_{\tilde{g},i} + \text{h.c.}\Big) \tag{12.4}$$

12.2.3 Gauge fixing terms

Gauge fixing terms for eigenstates 'GaugeES'

$$L_{GF} = -\frac{1}{2}\partial_\mu g \xi_G^{-1} - \frac{1}{2}\partial_\mu W^- \xi_W^{-1} \tag{12.5}$$

Gauge fixing terms for eigenstates 'TEMP'

$$L_{GF} = -\frac{1}{2}\partial_\mu \gamma \xi_P^{-1} - \frac{1}{2}\partial_\mu g \xi_G^{-1} - \frac{1}{2}\xi_Z^{-1}\Big(-A^0_{T,1}m_Z\xi_Z + \partial_\mu Z\Big) - \partial_\mu W^- \xi_W^{-1} \tag{12.6}$$

Gauge fixing terms for eigenstates 'EWSB'

$$L_{GF} = -\frac{1}{2}\partial_\mu \gamma \xi_P^{-1} - \frac{1}{2}\partial_\mu g \xi_G^{-1} - \frac{1}{2}\xi_Z^{-1}\Big(-A^0_1 m_Z\xi_Z + \partial_\mu Z\Big) - \xi_W^{-1}\Big(iH_1^- m_{W^-}\xi_W + \partial_\mu W^-\Big) \tag{12.7}$$

12.2.4 Fields integrated out

None

12.3 Field Rotations

12.3.1 Rotations in Mass sector for eigenstates 'EWSB'

Mass Matrices for Scalars

- **Mass matrix for Pseudo-Scalar Higgs**, Basis: $\left(A^0_{T,o_1},\sigma_s\right),\left(A^0_{T,p_1},\sigma_s\right)$

$$m^2_{A^0} = \begin{pmatrix} m_{11} & m^*_{21} \\ m_{21} & m_{22} \end{pmatrix} \tag{12.8}$$

$$\begin{aligned} m_{11} &= \frac{1}{8}\Big(Z^T_{o_1 1}\Big(2v_s\Big(\sqrt{2}\Big(T^*_\lambda + T_\lambda\Big) + v_s\kappa\lambda^* + v_s\lambda\kappa^*\Big)Z^T_{p_1 2} + \Big(4\Big(v_s^2+v_u^2\Big)|\lambda|^2 + 8m^2_{H_d} + \Big(g_1^2+g_2^2\Big)\Big(-v_u^2+v_d^2\Big)\Big)Z^T_{p_1 1}\Big) \\ &+ Z^T_{o_1 2}\Big(2v_s^2\lambda\kappa^* Z^T_{p_1 1} + 4\sqrt{2}v_s\Re\Big(T_\lambda\Big)Z^T_{p_1 1} + 8m^2_{H_u}Z^T_{p_1 2} - g_1^2 v_d^2 Z^T_{p_1 2} - g_2^2 v_d^2 Z^T_{p_1 2} + g_1^2 v_u^2 Z^T_{p_1 2} \\ &+ g_2^2 v_u^2 Z^T_{p_1 2} + 2\lambda^*\Big(2\Big(v_d^2+v_s^2\Big)\lambda Z^T_{p_1 2} + v_s^2\kappa Z^T_{p_1 1}\Big)\Big)\Big) \end{aligned} \tag{12.9}$$

$$m_{21} = \frac{1}{4}\Big(-2v_s\kappa\lambda^*\Big(v_d Z^T_{p_1 2} + v_u Z^T_{p_1 1}\Big) - 2v_s\lambda\kappa^*\Big(v_d Z^T_{p_1 2} + v_u Z^T_{p_1 1}\Big) + \sqrt{2}\Big(2v_u\Re\Big(T_\lambda\Big)Z^T_{p_1 1} + v_d\Big(T^*_\lambda + T_\lambda\Big)Z^T_{p_1 2}\Big)\Big) \tag{12.10}$$

$$m_{22} = \frac{1}{2}\Big(2\Big(-\sqrt{2}v_s\Re\Big(T_\kappa\Big) + m_S^2\Big) + \Big(2v_s^2\kappa + v_d v_u\lambda\Big)\kappa^* + \Big(v_d^2\lambda + v_d v_u\kappa + v_u^2\lambda\Big)\lambda^*\Big) \tag{12.11}$$

This matrix is diagonalized by Z^A:

$$Z^A m^2_{A^0} Z^{A,\dagger} = m^{dia}_{2,A^0} \tag{12.12}$$

with

$$A^0_{T,i} = \sum_{t_2} Z^A_{ji} A^0_j\,, \qquad \sigma_s = \sum_{t_2} Z^A_{j3} A^0_j \tag{12.13}$$

The mixing matrix can be parametrized by

$$Z^A = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi & \cos\phi \end{pmatrix} \tag{12.14}$$

Mass Matrices for Fermions

- No Fermion Mixings

12.4 Vacuum Expectation Values

12.5 Tadpole Equations

12.5.1 Tadpole Equations for eigenstates 'TEMP'

$$\frac{\partial V}{\partial v_d} = \frac{1}{8}\Big(8m^2_{H_d}v_d + g_1^2 v_d^3 + g_2^2 v_d^3 - g_1^2 v_d v_u^2 - g_2^2 v_d v_u^2 - 2v_s^2 v_u\lambda\kappa^*$$

$$+\Big(4v_d v_u^2\lambda + v_s^2\Big(-2v_u\kappa + 4v_d\lambda\Big)\Big)\lambda^* - 4\sqrt{2}v_s v_u \Re\Big(T_\lambda\Big)\Big) \tag{12.15}$$

$$\frac{\partial V}{\partial v_u} = \frac{1}{8}\Big(8m_{H_u}^2 v_u - g_1^2 v_d^2 v_u - g_2^2 v_d^2 v_u + g_1^2 v_u^3 + g_2^2 v_u^3 - 2v_d v_s^2\lambda\kappa^* + \Big(-2v_d v_s^2\kappa + 4v_d^2 v_u\lambda + 4v_s^2 v_u\lambda\Big)\lambda^* - 4\sqrt{2}v_d v_s\Re\Big(T_\lambda\Big)\Big) \tag{12.16}$$

$$\frac{\partial V}{\partial v_s} = \frac{1}{4}\Big(4m_S^2 v_s + \Big(-2v_d v_s v_u\lambda + 4v_s^3\kappa\Big)\kappa^* + 2v_s\Big(v_d^2\lambda - v_d v_u\kappa + v_u^2\lambda\Big)\lambda^* - \sqrt{2}v_d v_u T_\lambda^* + 2\sqrt{2}v_s^2\Re\Big(T_\kappa\Big) - \sqrt{2}v_d v_u T_\lambda\Big) \tag{12.17}$$

12.5.2 Tadpole Equations for eigenstates 'EWSB'

$$\frac{\partial V}{\partial v_d} = \frac{1}{8}\Big(8m_{H_d}^2 v_d + g_1^2 v_d^3 + g_2^2 v_d^3 - g_1^2 v_d v_u^2 - g_2^2 v_d v_u^2 - 2v_s^2 v_u\lambda\kappa^* + \Big(4v_d v_u^2\lambda + v_s^2\Big(-2v_u\kappa + 4v_d\lambda\Big)\Big)\lambda^* - 4\sqrt{2}v_s v_u \Re\Big(T_\lambda\Big)\Big) \tag{12.18}$$

$$\frac{\partial V}{\partial v_u} = \frac{1}{8}\Big(8m_{H_u}^2 v_u - g_1^2 v_d^2 v_u - g_2^2 v_d^2 v_u + g_1^2 v_u^3 + g_2^2 v_u^3 - 2v_d v_s^2\lambda\kappa^* + \Big(-2v_d v_s^2\kappa + 4v_d^2 v_u\lambda + 4v_s^2 v_u\lambda\Big)\lambda^* - 4\sqrt{2}v_d v_s\Re\Big(T_\lambda\Big)\Big) \tag{12.19}$$

$$\frac{\partial V}{\partial v_s} = \frac{1}{4}\Big(4m_S^2 v_s + \Big(-2v_d v_s v_u\lambda + 4v_s^3\kappa\Big)\kappa^* + 2v_s\Big(v_d^2\lambda - v_d v_u\kappa + v_u^2\lambda\Big)\lambda^* - \sqrt{2}v_d v_u T_\lambda^* + 2\sqrt{2}v_s^2\Re\Big(T_\kappa\Big) - \sqrt{2}v_d v_u T_\lambda\Big) \tag{12.20}$$

12.6 Particle content for eigenstates 'EWSB'

Name	Type	complex/real	Generations	Indices
$\tilde{d}$	Scalar	complex	6	generation, color
$\tilde{u}$	Scalar	complex	6	generation, color
$\tilde{e}$	Scalar	complex	6	generation
$\tilde{\nu}$	Scalar	complex	3	generation
h	Scalar	real	3	generation
H^-	Scalar	complex	2	generation
A^0	Scalar	real	3	generation
ν	Fermion	Dirac	3	generation
$\tilde{g}$	Fermion	Majorana	8	generation
$\tilde{\chi}^0$	Fermion	Majorana	5	generation
$\tilde{\chi}^-$	Fermion	Dirac	2	generation
e	Fermion	Dirac	3	generation
d	Fermion	Dirac	3	generation, color
u	Fermion	Dirac	3	generation, color

g	Vector	real	8	generation, lorentz
W^-	Vector	complex	1	lorentz
γ	Vector	real	1	lorentz
Z	Vector	real	1	lorentz
η^G	Ghost	real	8	generation
η^-	Ghost	complex	1	
η^+	Ghost	complex	1	
η^γ	Ghost	real	1	
η^Z	Ghost	real	1	

12.7 Modelfile for SARAH

12.8 Implementation in SARAH

Model directory: NMSSM/Two_Rotations

12.8.1 Particles for eigenstates 'GaugeES'

- Fermions

$\tilde{B} = \begin{pmatrix} \lambda_{\tilde{B}} \\ \lambda^*_{\tilde{B}} \end{pmatrix}$	$\texttt{Bino} = \begin{pmatrix} \texttt{fB} \\ \texttt{conj[fB]} \end{pmatrix}$
$d^1_{i\alpha} = \begin{pmatrix} d_{L,i\alpha} \\ 0 \end{pmatrix}$	$\texttt{Fd1[\{generation, color\}]} = \begin{pmatrix} \texttt{FdL[\{generation, color\}]} \\ 0 \end{pmatrix}$
$d^2_{i\alpha} = \begin{pmatrix} 0 \\ d_{R,i\alpha} \end{pmatrix}$	$\texttt{Fd2[\{generation, color\}]} = \begin{pmatrix} 0 \\ \texttt{FdR[\{generation, color\}]} \end{pmatrix}$
$e^1_{i} = \begin{pmatrix} e_{L,i} \\ 0 \end{pmatrix}$	$\texttt{Fe1[\{generation\}]} = \begin{pmatrix} \texttt{FeL[\{generation\}]} \\ 0 \end{pmatrix}$
$e^2_{i} = \begin{pmatrix} 0 \\ e_{R,i} \end{pmatrix}$	$\texttt{Fe2[\{generation\}]} = \begin{pmatrix} 0 \\ \texttt{FeR[\{generation\}]} \end{pmatrix}$
$u^1_{i\alpha} = \begin{pmatrix} u_{L,i\alpha} \\ 0 \end{pmatrix}$	$\texttt{Fu1[\{generation, color\}]} = \begin{pmatrix} \texttt{FuL[\{generation, color\}]} \\ 0 \end{pmatrix}$
$u^2_{i\alpha} = \begin{pmatrix} 0 \\ u_{R,i\alpha} \end{pmatrix}$	$\texttt{Fu2[\{generation, color\}]} = \begin{pmatrix} 0 \\ \texttt{FuR[\{generation, color\}]} \end{pmatrix}$
$\nu_{i} = \begin{pmatrix} \nu_{L,i} \\ 0 \end{pmatrix}$	$\texttt{Fv[\{generation\}]} = \begin{pmatrix} \texttt{FvL[\{generation\}]} \\ 0 \end{pmatrix}$
$\tilde{g}_{i} = \begin{pmatrix} \lambda_{\tilde{g},i} \\ \lambda^*_{\tilde{g},i} \end{pmatrix}$	$\texttt{Glu[\{generation\}]} = \begin{pmatrix} \texttt{fG[\{generation\}]} \\ \texttt{conj[fG[\{generation\}]]} \end{pmatrix}$
$\tilde{H}^0 = \begin{pmatrix} \tilde{H}^0_d \\ \tilde{H}^{0,*}_u \end{pmatrix}$	$\texttt{H0} = \begin{pmatrix} \texttt{FHd0} \\ \texttt{conj[FHu0]} \end{pmatrix}$
$\tilde{H}^- = \begin{pmatrix} \tilde{H}^-_d \\ \tilde{H}^{+,*}_u \end{pmatrix}$	$\texttt{HC} = \begin{pmatrix} \texttt{FHdm} \\ \texttt{conj[FHup]} \end{pmatrix}$
$\tilde{S} = \begin{pmatrix} \tilde{S} \\ \tilde{S}^* \end{pmatrix}$	$\texttt{S} = \begin{pmatrix} \texttt{FsR} \\ \texttt{conj[FsR]} \end{pmatrix}$
$\tilde{W}_{i} = \begin{pmatrix} \lambda_{\tilde{W},i} \\ \lambda^*_{\tilde{W},i} \end{pmatrix}$	$\texttt{Wino[\{generation\}]} = \begin{pmatrix} \texttt{fWB[\{generation\}]} \\ \texttt{conj[fWB[\{generation\}]]} \end{pmatrix}$

- Scalars

$\tilde{d}_{L,i\alpha}$	`SdL[{generation, color}]`	$\tilde{u}_{L,i\alpha}$	`SuL[{generation, color}]`
$\tilde{e}_{L,i}$	`SeL[{generation}]`	$\tilde{\nu}_{L,i}$	`SvL[{generation}]`
H_d^0	`SHd0`	H_d^-	`SHdm`
H_u^0	`SHu0`	H_u^+	`SHup`
$\tilde{d}_{R,i\alpha}$	`SdR[{generation, color}]`	$\tilde{u}_{R,i\alpha}$	`SuR[{generation, color}]`
$\tilde{e}_{R,i}$	`SeR[{generation}]`	S	`SsR`

- Vector Bosons

B_ρ	`VB[{lorentz}]`	$W_{i\rho}^-$	`VWB[{generation, lorentz}]`
$g_{i\rho}$	`VG[{generation, lorentz}]`		

- Ghosts

η^B	`gB`	$\mathrm{gWB}\Big(\{\mathrm{gt1}\}\Big)$	`gWB[{generation}]`
η_i^G	`gG[{generation}]`		

12.8.2 Particles for eigenstates 'TEMP'

- Fermions

$\tilde{\chi}_i^- = \begin{pmatrix} \lambda_i^- \\ \lambda_i^{+,*} \end{pmatrix}$	$\texttt{Cha[\{generation\}]} = \begin{pmatrix} \texttt{Lm[\{generation\}]} \\ \texttt{conj[Lp[\{generation\}]]} \end{pmatrix}$
$\tilde{\chi}_i^0 = \begin{pmatrix} \lambda_i^0 \\ \lambda_i^{0,*} \end{pmatrix}$	$\texttt{Chi[\{generation\}]} = \begin{pmatrix} \texttt{L0[\{generation\}]} \\ \texttt{conj[L0[\{generation\}]]} \end{pmatrix}$
$d_{i\alpha} = \begin{pmatrix} D_{L,i\alpha} \\ D_{R,i\alpha}^* \end{pmatrix}$	$\texttt{Fd[\{generation, color\}]} = \begin{pmatrix} \texttt{FDL[\{generation, color\}]} \\ \texttt{conj[FDR[\{generation, color\}]]} \end{pmatrix}$

$e_i = \begin{pmatrix} E_{L,i} \\ E^*_{R,i} \end{pmatrix}$	`Fe[{generation}]` $= \begin{pmatrix} \texttt{FEL[\{generation\}]} \\ \texttt{conj[FER[\{generation\}]]} \end{pmatrix}$
$u_{i\alpha} = \begin{pmatrix} U_{L,i\alpha} \\ U^*_{R,i\alpha} \end{pmatrix}$	`Fu[{generation, color}]` $= \begin{pmatrix} \texttt{FUL[\{generation, color\}]} \\ \texttt{conj[FUR[\{generation, color\}]]} \end{pmatrix}$
$\nu_i = \begin{pmatrix} \nu_{L,i} \\ 0 \end{pmatrix}$	`Fv[{generation}]` $= \begin{pmatrix} \texttt{FvL[\{generation\}]} \\ \texttt{0} \end{pmatrix}$
$\tilde{g}_i = \begin{pmatrix} \lambda_{\tilde{g},i} \\ \lambda^*_{\tilde{g},i} \end{pmatrix}$	`Glu[{generation}]` $= \begin{pmatrix} \texttt{fG[\{generation\}]} \\ \texttt{conj[fG[\{generation\}]]} \end{pmatrix}$

- Scalars

σ_s	`sigmaS`	$\tilde{d}_{i\alpha}$	`Sd[{generation, color}]`
$\tilde{u}_{i\alpha}$	`Su[{generation, color}]`	$\tilde{e}_i$	`Se[{generation}]`
$\tilde{\nu}_i$	`Sv[{generation}]`	h_i	`hh[{generation}]`
$A^0_{T,i}$	`AhT[{generation}]`	H^-_i	`Hpm[{generation}]`

- Vector Bosons

$g_{i\rho}$	`VG[{generation, lorentz}]`	W^-_ρ	`VWm[{lorentz}]`
γ_ρ	`VP[{lorentz}]`	Z_ρ	`VZ[{lorentz}]`

- Ghosts

η^G_i	`gG[{generation}]`	η^-	`gWm`
η^+	`gWmC`	η^γ	`gP`
η^Z	`gZ`		

12.8.3 Particles for eigenstates 'EWSB'

- Fermions

$\tilde{\chi}_i^- = \begin{pmatrix} \lambda_i^- \\ \lambda_i^{+,*} \end{pmatrix}$	`Cha[{generation}]` $= \begin{pmatrix}$ `Lm[{generation}]` $\\$ `conj[Lp[{generation}]]` $\end{pmatrix}$
$\tilde{\chi}_i^0 = \begin{pmatrix} \lambda_i^0 \\ \lambda_i^{0,*} \end{pmatrix}$	`Chi[{generation}]` $= \begin{pmatrix}$ `L0[{generation}]` $\\$ `conj[L0[{generation}]]` $\end{pmatrix}$
$d_{i\alpha} = \begin{pmatrix} D_{L,i\alpha} \\ D^*_{R,i\alpha} \end{pmatrix}$	`Fd[{generation, color}]` $= \begin{pmatrix}$ `FDL[{generation, color}]` $\\$ `conj[FDR[{generation, color}]]` $\end{pmatrix}$
$e_i = \begin{pmatrix} E_{L,i} \\ E^*_{R,i} \end{pmatrix}$	`Fe[{generation}]` $= \begin{pmatrix}$ `FEL[{generation}]` $\\$ `conj[FER[{generation}]]` $\end{pmatrix}$
$u_{i\alpha} = \begin{pmatrix} U_{L,i\alpha} \\ U^*_{R,i\alpha} \end{pmatrix}$	`Fu[{generation, color}]` $= \begin{pmatrix}$ `FUL[{generation, color}]` $\\$ `conj[FUR[{generation, color}]]` $\end{pmatrix}$
$\nu_i = \begin{pmatrix} \nu_{L,i} \\ 0 \end{pmatrix}$	`Fv[{generation}]` $= \begin{pmatrix}$ `FvL[{generation}]` $\\$ `0` $\end{pmatrix}$
$\tilde{g}_i = \begin{pmatrix} \lambda_{\tilde{g},i} \\ \lambda^*_{\tilde{g},i} \end{pmatrix}$	`Glu[{generation}]` $= \begin{pmatrix}$ `fG[{generation}]` $\\$ `conj[fG[{generation}]]` $\end{pmatrix}$

- Scalars

$\tilde{d}_{i\alpha}$	`Sd[{generation, color}]`	$\tilde{u}_{i\alpha}$	`Su[{generation, color}]`
$\tilde{e}_i$	`Se[{generation}]`	$\tilde{\nu}_i$	`Sv[{generation}]`
h_i	`hh[{generation}]`	H_i^-	`Hpm[{generation}]`
A_i^0	`Ah[{generation}]`		

- Vector Bosons

$g_{i\rho}$	`VG[{generation, lorentz}]`	W_ρ^-	`VWm[{lorentz}]`
γ_ρ	`VP[{lorentz}]`	Z_ρ	`VZ[{lorentz}]`

- Ghosts

η_i^G	gG[{generation}]	η^-	gWm
η^+	gWmC	η^γ	gP
η^Z	gZ		

12.8.4 Parameters

g_1	g1	g_2	g2	g_3	g3
Y_u	Yu	T_u	T[Yu]	Y_d	Yd
T_d	T[Yd]	Y_e	Ye	T_e	T[Ye]
λ	\[Lambda]	T_λ	T[\[Lambda]]	κ	\[Kappa]
T_κ	T[\[Kappa]]	m_q^2	mq2	m_l^2	ml2
$m_{H_d}^2$	mHd2	$m_{H_u}^2$	mHu2	m_d^2	md2
m_u^2	mu2	m_e^2	me2	m_S^2	ms2
M_1	MassB	M_2	MassWB	M_3	MassG
v_d	vd	v_u	vu	v_s	vS
Θ_W	ThetaW	Z^D	ZD	Z^U	ZU
Z^E	ZE	Z^V	ZV	Z^H	ZH
Z^T	ZT	Z^+	ZP	N	ZN
U	UM	V	UP	U_L^e	ZEL
U_R^e	ZER	U_L^d	ZDL	U_R^d	ZDR
U_L^u	ZUL	U_R^u	ZUR	β	\[Beta]
$\phi_{\tilde{g}}$	PhaseGlu	Z^A	ZA	ϕ	\[Phi]

Chapter 13

The near-to-Minimal Supersymmetric Standard Model

13.1 Superfields

13.1.1 Vector Superfields

SF	Spin $\frac{1}{2}$	Spin 1	$SU(N)$	Coupling	Name
$\hat{B}$	$\lambda_{\tilde{B}}$	B	$U(1)$	g_1	hypercharge
$\hat{W}$	$\lambda_{\tilde{W}}$	W^-	SU(2)	g_2	left
$\hat{g}$	$\lambda_{\tilde{g}}$	g	SU(3)	g_3	color

13.1.2 Chiral Superfields

SF	Spin 0	Spin $\frac{1}{2}$	Generations	$(U(1)\otimes \text{SU}(2)\otimes \text{SU}(3))$
$\hat{q}$	$\tilde{q}$	q	3	$(\frac{1}{6},\mathbf{2},\mathbf{3})$
$\hat{l}$	$\tilde{l}$	l	3	$(-\frac{1}{2},\mathbf{2},\mathbf{1})$
$\hat{H}_d$	H_d	$\tilde{H}_d$	1	$(-\frac{1}{2},\mathbf{2},\mathbf{1})$
$\hat{H}_u$	H_u	$\tilde{H}_u$	1	$(\frac{1}{2},\mathbf{2},\mathbf{1})$
$\hat{d}$	$\tilde{d}_R^*$	d_R^*	3	$(\frac{1}{3},\mathbf{1},\overline{\mathbf{3}})$
$\hat{u}$	$\tilde{u}_R^*$	u_R^*	3	$(-\frac{2}{3},\mathbf{1},\overline{\mathbf{3}})$
$\hat{e}$	$\tilde{e}_R^*$	e_R^*	3	$(1,\mathbf{1},\mathbf{1})$
$\hat{s}$	S	$\tilde{S}$	1	$(0,\mathbf{1},\mathbf{1})$

13.2 Superpotential and Lagrangian

13.2.1 Superpotential

$$W = Y_u\,\hat{q}\,\hat{H}_u\,\hat{u}\, - Y_d\,\hat{q}\,\hat{H}_d\,\hat{d}\, - Y_e\,\hat{l}\,\hat{H}_d\,\hat{e}\, + \lambda\,\hat{H}_u\,\hat{H}_d\,\hat{s}\, + \xi\,\hat{s} \tag{13.1}$$

13.2.2 Softbreaking terms

$$\begin{aligned} L_{SB,W} = &+ SL_\xi - H_d^0 H_u^0 S T_\lambda + H_d^- H_u^+ S T_\lambda + H_d^0 \tilde{d}^*_{R,k\gamma}\delta_{\alpha\gamma}\tilde{d}_{L,i\alpha}T_{d,ik} - H_d^- \tilde{d}^*_{R,k\gamma}\delta_{\alpha\gamma}\tilde{u}_{L,i\alpha}T_{d,ik} \\ &+ H_d^0 \tilde{e}^*_{R,k}\tilde{e}_{L,i}T_{e,ik} - H_d^- \tilde{e}^*_{R,k}\tilde{\nu}_{L,i}T_{e,ik} - H_u^+ \tilde{u}^*_{R,k\gamma}\delta_{\alpha\gamma}\tilde{d}_{L,i\alpha}T_{u,ik} + H_u^0 \tilde{u}^*_{R,k\gamma}\delta_{\alpha\gamma}\tilde{u}_{L,i\alpha}T_{u,ik} + \text{h.c.} \end{aligned} \tag{13.2}$$

$$\begin{aligned} L_{SB,\phi} = &- m^2_{H_d}|H_d^0|^2 - m^2_{H_d}|H_d^-|^2 - m^2_{H_u}|H_u^0|^2 - m^2_{H_u}|H_u^+|^2 - m_S^2|S|^2 \\ &- \tilde{d}^*_{L,j\beta}\delta_{\alpha\beta}m^2_{q,ij}\tilde{d}_{L,i\alpha} - \tilde{d}^*_{R,i\alpha}\delta_{\alpha\beta}m^2_{d,ij}\tilde{d}_{R,j\beta} - \tilde{e}^*_{L,j}m^2_{l,ij}\tilde{e}_{L,i} - \tilde{e}^*_{R,i}m^2_{e,ij}\tilde{e}_{R,j} \\ &- \tilde{u}^*_{L,j\beta}\delta_{\alpha\beta}m^2_{q,ij}\tilde{u}_{L,i\alpha} - \tilde{u}^*_{R,i\alpha}\delta_{\alpha\beta}m^2_{u,ij}\tilde{u}_{R,j\beta} - \tilde{\nu}^*_{L,j}m^2_{l,ij}\tilde{\nu}_{L,i} \end{aligned} \tag{13.3}$$

$$L_{SB,\lambda} = \frac{1}{2}\left(-\lambda^2_{\tilde{B}}M_1 - M_2\lambda^2_{\tilde{W},i} - M_3\lambda^2_{\tilde{g},i} + \text{h.c.}\right) \tag{13.4}$$

13.2.3 Gauge fixing terms

Gauge fixing terms for eigenstates 'GaugeES'

$$L_{GF} = -\frac{1}{2}\partial_\mu g\xi_G^{-1} - \frac{1}{2}\partial_\mu W^- \xi_W^{-1} \tag{13.5}$$

Gauge fixing terms for eigenstates 'EWSB'

$$L_{GF} = -\frac{1}{2}\partial_\mu \gamma\xi_P^{-1} - \frac{1}{2}\partial_\mu g\xi_G^{-1} - \frac{1}{2}\xi_Z^{-1}\Big(-A_1^0 m_Z\xi_Z + \partial_\mu Z\Big) - \xi_W^{-1}\Big(iH_1^- m_{W^-}\xi_W + \partial_\mu W^-\Big) \tag{13.6}$$

13.2.4 Fields integrated out

None

13.3 Field Rotations

13.3.1 Rotations in gauge sector for eigenstates 'EWSB'

$$W^-_{1\rho} = \frac{1}{\sqrt{2}}W^-_\rho + \frac{1}{\sqrt{2}}W^+_\rho \tag{13.7}$$

$$W^-_{2\rho} = -i\frac{1}{\sqrt{2}}W^-_\rho + i\frac{1}{\sqrt{2}}W^+_\rho \tag{13.8}$$

$$W^-_{3\rho} = \cos\Theta_W Z_\rho + \sin\Theta_W \gamma_\rho \tag{13.9}$$

$$B_\rho = \cos\Theta_W \gamma_\rho - \sin\Theta_W Z_\rho \tag{13.10}$$

$$\lambda_{\tilde{W},1} = \frac{1}{\sqrt{2}}\tilde{W}^- + \frac{1}{\sqrt{2}}\tilde{W}^+ \tag{13.11}$$

$$\lambda_{\tilde{W},2} = -i\frac{1}{\sqrt{2}}\tilde{W}^- + i\frac{1}{\sqrt{2}}\tilde{W}^+ \tag{13.12}$$

$$\lambda_{\tilde{W},3} = \tilde{W}^0 \tag{13.13}$$

13.3.2 Rotations in Mass sector for eigenstates 'EWSB'

Mass Matrices for Scalars

- **Mass matrix for Down-Squarks**, Basis: $\left(\tilde{d}_{L,o_1\alpha_1}, \tilde{d}_{R,o_2\alpha_2}\right), \left(\tilde{d}^*_{L,p_1\beta_1}, \tilde{d}^*_{R,p_2\beta_2}\right)$

$$m^2_{\tilde{d}} = \left(\begin{array}{cc} m_{11} & \frac{1}{2}\delta_{\alpha_1\beta_2}\Big(\sqrt{2}v_d T_{d,o_1p_2} - v_s v_u \lambda^* Y_{d,o_1p_2}\Big) \\ \frac{1}{2}\Big(\sqrt{2}v_d T^*_{d,p_1o_2} - v_s v_u \lambda Y^*_{d,p_1o_2}\Big)\delta_{\alpha_2\beta_1} & m_{22} \end{array} \right) \tag{13.14}$$

$$m_{11} = \frac{1}{24}\delta_{\alpha_1\beta_1}\Big(12\Big(2m^2_{q,o_1p_1} + v_d^2\sum_{a=1}^{3} Y^*_{d,p_1a}Y_{d,o_1a}\Big) - \Big(3g_2^2 + g_1^2\Big)\Big(-v_u^2 + v_d^2\Big)\delta_{o_1p_1}\Big) \tag{13.15}$$

$$m_{22} = \frac{1}{12}\delta_{\alpha_2\beta_2}\Big(6\Big(2m^2_{d,p_2o_2} + v_d^2\sum_{a=1}^{3} Y^*_{d,ao_2}Y_{d,ap_2}\Big) + g_1^2\Big(-v_d^2 + v_u^2\Big)\delta_{o_2p_2}\Big) \tag{13.16}$$

This matrix is diagonalized by Z^D:

$$Z^D m^2_{\tilde{d}} Z^{D,\dagger} = m^{dia}_{2,\tilde{d}} \tag{13.17}$$

with

$$\tilde{d}_{L,i\alpha} = \sum_{t_2} Z^{D,*}_{ji}\tilde{d}_{j\alpha}\,, \qquad \tilde{d}_{R,i\alpha} = \sum_{t_2} Z^{D,*}_{ji}\tilde{d}_{j\alpha} \tag{13.18}$$

- **Mass matrix for Sneutrinos**, Basis: $\left(\tilde{\nu}_{L,o_1}\right), \left(\tilde{\nu}^*_{L,p_1}\right)$

$$m^2_{\tilde{\nu}} = \left(\begin{array}{c} \frac{1}{8}\Big(8m^2_{l,o_1p_1} + \Big(g_1^2 + g_2^2\Big)\Big(-v_u^2 + v_d^2\Big)\delta_{o_1p_1}\Big) \end{array} \right) \tag{13.19}$$

This matrix is diagonalized by Z^V:

$$Z^V m^2_{\tilde{\nu}} Z^{V,\dagger} = m^{dia}_{2,\tilde{\nu}} \tag{13.20}$$

with

$$\tilde{\nu}_{L,i} = \sum_{t_2} Z^{V,*}_{ji}\tilde{\nu}_j \tag{13.21}$$

- **Mass matrix for Up-Squarks**, Basis: $\left(\tilde{u}_{L,o_1\alpha_1}, \tilde{u}_{R,o_2\alpha_2}\right), \left(\tilde{u}^*_{L,p_1\beta_1}, \tilde{u}^*_{R,p_2\beta_2}\right)$

$$m^2_{\tilde{u}} = \left(\begin{array}{cc} m_{11} & \frac{1}{2}\delta_{\alpha_1\beta_2}\Big(\sqrt{2}v_u T_{u,o_1p_2} - v_d v_s \lambda^* Y_{u,o_1p_2}\Big) \\ \frac{1}{2}\Big(\sqrt{2}v_u T^*_{u,p_1o_2} - v_d v_s \lambda Y^*_{u,p_1o_2}\Big)\delta_{\alpha_2\beta_1} & m_{22} \end{array} \right) \tag{13.22}$$

$$m_{11} = \frac{1}{24}\delta_{\alpha_1\beta_1}\Big(12\Big(2m^2_{q,o_1p_1} + v_u^2\sum_{a=1}^{3} Y^*_{u,p_1a}Y_{u,o_1a}\Big) - \Big(-3g_2^2 + g_1^2\Big)\Big(-v_u^2 + v_d^2\Big)\delta_{o_1p_1}\Big) \tag{13.23}$$

$$m_{22} = \frac{1}{6}\delta_{\alpha_2\beta_2}\Big(3v_u^2\sum_{a=1}^{3}Y^*_{u,ao_2}Y_{u,ap_2} + 6m^2_{u,p_2o_2} + g_1^2\Big(-v_u^2+v_d^2\Big)\delta_{o_2p_2}\Big) \tag{13.24}$$

This matrix is diagonalized by Z^U:

$$Z^U m^2_{\tilde{u}} Z^{U,\dagger} = m^{dia}_{2,\tilde{u}} \tag{13.25}$$

with

$$\tilde{u}_{L,i\alpha} = \sum_{t_2} Z^{U,*}_{ji}\tilde{u}_{j\alpha}\,, \qquad \tilde{u}_{R,i\alpha} = \sum_{t_2} Z^{U,*}_{ji}\tilde{u}_{j\alpha} \tag{13.26}$$

- **Mass matrix for Sleptons**, Basis: $\left(\tilde{e}_{L,o_1}, \tilde{e}_{R,o_2}\right), \left(\tilde{e}^*_{L,p_1}, \tilde{e}^*_{R,p_2}\right)$

$$m^2_{\tilde{e}} = \begin{pmatrix} m_{11} & -\frac{1}{2}v_s v_u \lambda^* Y_{e,o_1p_2} + \frac{1}{\sqrt{2}}v_d T_{e,o_1p_2} \\ -\frac{1}{2}v_s v_u \lambda Y^*_{e,p_1o_2} + \frac{1}{\sqrt{2}}v_d T^*_{e,p_1o_2} & m_{22}\end{pmatrix} \tag{13.27}$$

$$m_{11} = \frac{1}{8}\Big(4v_d^2\sum_{a=1}^{3}Y^*_{e,p_1a}Y_{e,o_1a} + 8m^2_{l,o_1p_1} + \Big(-g_2^2+g_1^2\Big)\Big(-v_u^2+v_d^2\Big)\delta_{o_1p_1}\Big) \tag{13.28}$$

$$m_{22} = \frac{1}{4}\Big(2v_d^2\sum_{a=1}^{3}Y^*_{e,ao_2}Y_{e,ap_2} + 4m^2_{e,p_2o_2} + g_1^2\Big(-v_d^2+v_u^2\Big)\delta_{o_2p_2}\Big) \tag{13.29}$$

This matrix is diagonalized by Z^E:

$$Z^E m^2_{\tilde{e}} Z^{E,\dagger} = m^{dia}_{2,\tilde{e}} \tag{13.30}$$

with

$$\tilde{e}_{L,i} = \sum_{t_2} Z^{E,*}_{ji}\tilde{e}_j\,, \qquad \tilde{e}_{R,i} = \sum_{t_2} Z^{E,*}_{ji}\tilde{e}_j \tag{13.31}$$

- **Mass matrix for Higgs**, Basis: $\left(\phi_d, \phi_u, \phi_s\right), \left(\phi_d, \phi_u, \phi_s\right)$

$$m^2_h = \begin{pmatrix} m_{11} & m^*_{21} & -\frac{1}{\sqrt{2}}v_u\Re\Big(T_\lambda\Big) + v_d v_s|\lambda|^2 \\ m_{21} & m_{22} & -\frac{1}{\sqrt{2}}v_d\Re\Big(T_\lambda\Big) + v_s v_u|\lambda|^2 \\ -\frac{1}{\sqrt{2}}v_u\Re\Big(T_\lambda\Big) + v_d v_s|\lambda|^2 & -\frac{1}{\sqrt{2}}v_d\Re\Big(T_\lambda\Big) + v_s v_u|\lambda|^2 & \frac{1}{2}\Big(2m_S^2 + \Big(v_d^2+v_u^2\Big)|\lambda|^2\Big)\end{pmatrix} \tag{13.32}$$

$$m_{11} = \frac{1}{8}\Big(4\Big(v_s^2+v_u^2\Big)|\lambda|^2 + 8m^2_{H_d} + \Big(g_1^2+g_2^2\Big)\Big(3v_d^2-v_u^2\Big)\Big) \tag{13.33}$$

$$m_{21} = \frac{1}{4}\Big(-2\Big(-2v_d v_u\lambda + \xi\Big)\lambda^* - 2\lambda\xi^* - 2\sqrt{2}v_s\Re\Big(T_\lambda\Big) - g_1^2 v_d v_u - g_2^2 v_d v_u\Big) \tag{13.34}$$

$$m_{22} = \frac{1}{8}\Big(4\Big(v_d^2+v_s^2\Big)|\lambda|^2 + 8m^2_{H_u} - \Big(g_1^2+g_2^2\Big)\Big(-3v_u^2+v_d^2\Big)\Big) \tag{13.35}$$

This matrix is diagonalized by Z^H:

$$Z^H m_h^2 Z^{H,\dagger} = m_{2,h}^{dia} \tag{13.36}$$

with

$$\phi_d = \sum_{t_2} Z_{j1}^{H,*} h_j\,, \qquad \phi_u = \sum_{t_2} Z_{j2}^{H,*} h_j\,, \qquad \phi_s = \sum_{t_2} Z_{j3}^{H,*} h_j \tag{13.37}$$

- **Mass matrix for Pseudo-Scalar Higgs**, Basis: $(\sigma_d, \sigma_u, \sigma_s)\,, (\sigma_d, \sigma_u, \sigma_s)$

$$m_{A^0}^2 = \left(\begin{array}{ccc} m_{11} & \frac{1}{2}\Big(\lambda\xi^* + \sqrt{2} v_s \Re\Big(T_\lambda\Big) + \xi\lambda^*\Big) & \frac{1}{\sqrt{2}} v_u \Re\Big(T_\lambda\Big) \\ \frac{1}{2}\Big(\lambda\xi^* + \sqrt{2} v_s \Re\Big(T_\lambda\Big) + \xi\lambda^*\Big) & m_{22} & \frac{1}{\sqrt{2}} v_d \Re\Big(T_\lambda\Big) \\ \frac{1}{\sqrt{2}} v_u \Re\Big(T_\lambda\Big) & \frac{1}{\sqrt{2}} v_d \Re\Big(T_\lambda\Big) & \frac{1}{2}\Big(2m_S^2 + \Big(v_d^2 + v_u^2\Big)|\lambda|^2\Big) \end{array}\right) \tag{13.38}$$

$$m_{11} = \frac{1}{8}\Big(4\Big(v_s^2 + v_u^2\Big)|\lambda|^2 + 8m_{H_d}^2 + \Big(g_1^2 + g_2^2\Big)\Big(-v_u^2 + v_d^2\Big)\Big) \tag{13.39}$$

$$m_{22} = \frac{1}{8}\Big(4\Big(v_d^2 + v_s^2\Big)|\lambda|^2 + 8m_{H_u}^2 - \Big(g_1^2 + g_2^2\Big)\Big(-v_u^2 + v_d^2\Big)\Big) \tag{13.40}$$

This matrix is diagonalized by Z^A:

$$Z^A m_{A^0}^2 Z^{A,\dagger} = m_{2,A^0}^{dia} \tag{13.41}$$

with

$$\sigma_d = \sum_{t_2} Z_{j1}^{A,*} A_j^0\,, \qquad \sigma_u = \sum_{t_2} Z_{j2}^{A,*} A_j^0\,, \qquad \sigma_s = \sum_{t_2} Z_{j3}^{A,*} A_j^0 \tag{13.42}$$

- **Mass matrix for Charged Higgs**, Basis: $\Big(H_d^-, H_u^{+,*}\Big)\,, \Big(H_d^{-,*}, H_u^+\Big)$

$$m_{H^-}^2 = \left(\begin{array}{cc} m_{11} & m_{21}^* \\ m_{21} & m_{22} \end{array}\right) \tag{13.43}$$

$$m_{11} = \frac{1}{8}\Big(4v_s^2|\lambda|^2 + 8m_{H_d}^2 + g_1^2 v_d^2 - g_1^2 v_u^2 + g_2^2 v_d^2 + g_2^2 v_u^2\Big) \tag{13.44}$$

$$m_{21} = \frac{1}{4}\Big(2\sqrt{2} v_s T_\lambda^* + \Big(-2v_d v_u \lambda + 4\xi\Big)\lambda^* + g_2^2 v_d v_u\Big) \tag{13.45}$$

$$m_{22} = \frac{1}{8}\Big(4v_s^2|\lambda|^2 + 8m_{H_u}^2 - g_1^2 v_d^2 + g_1^2 v_u^2 + g_2^2 v_d^2 + g_2^2 v_u^2\Big) \tag{13.46}$$

This matrix is diagonalized by Z^+:

$$Z^+ m_{H^-}^2 Z^{+,\dagger} = m_{2,H^-}^{dia} \tag{13.47}$$

with

$$H_d^- = \sum_{t_2} Z_{j1}^{+,*} H_j^-\,, \qquad H_u^+ = \sum_{t_2} Z_{j2}^{+} H_j^+ \tag{13.48}$$

The mixing matrix can be parametrized by

$$Z^+ = \left(\begin{array}{cc} -\cos\beta & \sin\beta \\ \sin\beta & \cos\beta \end{array}\right) \tag{13.49}$$

Mass Matrices for Fermions

- **Mass matrix for Neutralinos**, Basis: $\left(\lambda_{\tilde{B}}, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0, \tilde{S}\right), \left(\lambda_{\tilde{B}}, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0, \tilde{S}\right)$

$$m_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -\frac{1}{2}g_1 v_d & \frac{1}{2}g_1 v_u & 0 \\ 0 & M_2 & \frac{1}{2}g_2 v_d & -\frac{1}{2}g_2 v_u & 0 \\ -\frac{1}{2}g_1 v_d & \frac{1}{2}g_2 v_d & 0 & -\frac{1}{\sqrt{2}}v_s\lambda & -\frac{1}{\sqrt{2}}v_u\lambda \\ \frac{1}{2}g_1 v_u & -\frac{1}{2}g_2 v_u & -\frac{1}{\sqrt{2}}v_s\lambda & 0 & -\frac{1}{\sqrt{2}}v_d\lambda \\ 0 & 0 & -\frac{1}{\sqrt{2}}v_u\lambda & -\frac{1}{\sqrt{2}}v_d\lambda & 0 \end{pmatrix} \tag{13.50}$$

This matrix is diagonalized by N:

$$N m_{\tilde{\chi}^0} N^\dagger = m^{dia}_{\tilde{\chi}^0} \tag{13.51}$$

with

$$\lambda_{\tilde{B}} = \sum_{t_2} N^*_{j1}\lambda^0_j\,, \qquad \tilde{W}^0 = \sum_{t_2} N^*_{j2}\lambda^0_j\,, \qquad \tilde{H}^0_d = \sum_{t_2} N^*_{j3}\lambda^0_j \tag{13.52}$$

$$\tilde{H}^0_u = \sum_{t_2} N^*_{j4}\lambda^0_j\,, \qquad \tilde{S} = \sum_{t_2} N^*_{j5}\lambda^0_j \tag{13.53}$$

- **Mass matrix for Charginos**, Basis: $\left(\tilde{W}^-, \tilde{H}_d^-\right), \left(\tilde{W}^+, \tilde{H}_u^+\right)$

$$m_{\tilde{\chi}^-} = \begin{pmatrix} M_2 & \frac{1}{\sqrt{2}}g_2 v_u \\ \frac{1}{\sqrt{2}}g_2 v_d & \frac{1}{\sqrt{2}}v_s\lambda \end{pmatrix} \tag{13.54}$$

This matrix is diagonalized by U and V

$$U^* m_{\tilde{\chi}^-} V^\dagger = m^{dia}_{\tilde{\chi}^-} \tag{13.55}$$

with

$$\tilde{W}^- = \sum_{t_2} U^*_{j1}\lambda^-_j\,, \qquad \tilde{H}^-_d = \sum_{t_2} U^*_{j2}\lambda^-_j \tag{13.56}$$

$$\tilde{W}^+ = \sum_{t_2} V^*_{1j}\lambda^+_j\,, \qquad \tilde{H}^+_u = \sum_{t_2} V^*_{2j}\lambda^+_j \tag{13.57}$$

- **Mass matrix for Leptons**, Basis: $\left(e_{L,o_1}\right), \left(e^*_{R,p_1}\right)$

$$m_e = \begin{pmatrix} \frac{1}{\sqrt{2}}v_d Y_{e,o_1 p_1} \end{pmatrix} \tag{13.58}$$

This matrix is diagonalized by U^e_L and U^e_R

$$U^{e,*}_L m_e U^{e,\dagger}_R = m^{dia}_e \tag{13.59}$$

with

$$e_{L,i} = \sum_{t_2} U^{e,*}_{L,ji} E_{L,j} \tag{13.60}$$

$$e_{R,i} = \sum_{t_2} U^{e}_{R,ij} E^*_{R,j} \tag{13.61}$$

- **Mass matrix for Down-Quarks**, Basis: $\left(d_{L,o_1\alpha_1}\right), \left(d^*_{R,p_1\beta_1}\right)$

$$m_d = \left(\begin{array}{c} \frac{1}{\sqrt{2}} v_d \delta_{\alpha_1\beta_1} Y_{d,o_1 p_1} \end{array} \right) \tag{13.62}$$

This matrix is diagonalized by U^d_L and U^d_R

$$U^{d,*}_L m_d U^{d,\dagger}_R = m^{dia}_d \tag{13.63}$$

with

$$d_{L,i\alpha} = \sum_{t_2} U^{d,*}_{L,ji} D_{L,j\alpha} \tag{13.64}$$

$$d_{R,i\alpha} = \sum_{t_2} U^{d}_{R,ij} D^*_{R,j\alpha} \tag{13.65}$$

- **Mass matrix for Up-Quarks**, Basis: $\left(u_{L,o_1\alpha_1}\right), \left(u^*_{R,p_1\beta_1}\right)$

$$m_u = \left(\begin{array}{c} \frac{1}{\sqrt{2}} v_u \delta_{\alpha_1\beta_1} Y_{u,o_1 p_1} \end{array} \right) \tag{13.66}$$

This matrix is diagonalized by U^u_L and U^u_R

$$U^{u,*}_L m_u U^{u,\dagger}_R = m^{dia}_u \tag{13.67}$$

with

$$u_{L,i\alpha} = \sum_{t_2} U^{u,*}_{L,ji} U_{L,j\alpha} \tag{13.68}$$

$$u_{R,i\alpha} = \sum_{t_2} U^{u}_{R,ij} U^*_{R,j\alpha} \tag{13.69}$$

13.4 Vacuum Expectation Values

$$H^0_d = \frac{1}{\sqrt{2}}\phi_d + \frac{1}{\sqrt{2}} v_d + i\frac{1}{\sqrt{2}}\sigma_d \tag{13.70}$$

$$H^0_u = \frac{1}{\sqrt{2}}\phi_u + \frac{1}{\sqrt{2}} v_u + i\frac{1}{\sqrt{2}}\sigma_u \tag{13.71}$$

$$S = \frac{1}{\sqrt{2}}\phi_s + \frac{1}{\sqrt{2}} v_s + i\frac{1}{\sqrt{2}}\sigma_s \tag{13.72}$$

13.5 Tadpole Equations

$$\frac{\partial V}{\partial v_d} = \frac{1}{8}\Big(8m_{H_d}^2 v_d + g_1^2 v_d^3 + g_2^2 v_d^3 - g_1^2 v_d v_u^2 - g_2^2 v_d v_u^2 - 4v_u\lambda\xi^* \\ + \Big(4v_d\Big(v_s^2+v_u^2\Big)\lambda - 4\xi v_u\Big)\lambda^* - 4\sqrt{2}v_s v_u \Re\Big(T_\lambda\Big)\Big) \tag{13.73}$$

$$\frac{\partial V}{\partial v_u} = \frac{1}{8}\Big(8m_{H_u}^2 v_u - g_1^2 v_d^2 v_u - g_2^2 v_d^2 v_u + g_1^2 v_u^3 + g_2^2 v_u^3 - 4v_d\lambda\xi^* \\ + \Big(4\Big(v_d^2+v_s^2\Big)v_u\lambda - 4\xi v_d\Big)\lambda^* - 4\sqrt{2}v_d v_s \Re\Big(T_\lambda\Big)\Big) \tag{13.74}$$

$$\frac{\partial V}{\partial v_s} = \frac{1}{4}\Big(2v_s\Big(v_d^2+v_u^2\Big)|\lambda|^2 + 4m_S^2 v_s + 4\sqrt{2}\Re\Big(L_\xi\Big) - \sqrt{2}v_d v_u T_\lambda - \sqrt{2}v_d v_u T_\lambda^*\Big) \tag{13.75}$$

13.6 Particle content for eigenstates 'EWSB'

Name	Type	complex/real	Generations	Indices
$\tilde{d}$	Scalar	complex	6	generation, color
$\tilde{\nu}$	Scalar	complex	3	generation
$\tilde{u}$	Scalar	complex	6	generation, color
$\tilde{e}$	Scalar	complex	6	generation
h	Scalar	real	3	generation
A^0	Scalar	real	3	generation
H^-	Scalar	complex	2	generation
ν	Fermion	Dirac	3	generation
$\tilde{g}$	Fermion	Majorana	8	generation
$\tilde{\chi}^0$	Fermion	Majorana	5	generation
$\tilde{\chi}^-$	Fermion	Dirac	2	generation
e	Fermion	Dirac	3	generation
d	Fermion	Dirac	3	generation, color
u	Fermion	Dirac	3	generation, color
g	Vector	real	8	generation, lorentz
W^-	Vector	complex	1	lorentz
γ	Vector	real	1	lorentz
Z	Vector	real	1	lorentz
η^G	Ghost	real	8	generation
η^-	Ghost	complex	1	
η^+	Ghost	complex	1	
η^γ	Ghost	real	1	
η^Z	Ghost	real	1	

13.7 Modelfile for SARAH

```
Off[General::spell]
Print["Model file for the near-to-minimal MSSM loaded"];

ModelNameLaTeX ="near-to-minimal MSSM";


(*-------------------------------------------*)
(*   Particle Content*)
(*-------------------------------------------*)

(* Gauge Superfields *)

Gauge[[1]]={B,   U[1], hypercharge, g1,False};
Gauge[[2]]={WB, SU[2], left,        g2,True};
Gauge[[3]]={G,  SU[3], color,       g3,False};


(* Chiral Superfields *)

Fields[[1]] = {{uL,  dL},  3, q,   1/6, 2, 3};
Fields[[2]] = {{vL,  eL},  3, l,  -1/2, 2, 1};
Fields[[3]] = {{Hd0, Hdm}, 1, Hd, -1/2, 2, 1};
Fields[[4]] = {{Hup, Hu0}, 1, Hu,  1/2, 2, 1};

Fields[[5]] = {conj[dR], 3, d,  1/3, 1, -3};
Fields[[6]] = {conj[uR], 3, u, -2/3, 1, -3};
Fields[[7]] = {conj[eR], 3, e,    1, 1,  1};
Fields[[8]] = {sR, 1, s,    0, 1,  1};


(*----------------------------------------------------*)
(* Superpotential *)
(*----------------------------------------------------*)

SuperPotential = { {{1, Yu},{q,Hu,u}}, {{-1,Yd},{q,Hd,d}},
                   {{-1,Ye},{l,Hd,e}},
                   {{1,\[Lambda]},{Hu,Hd,s}},
                   {{1,Tad},{s}}};


(*-------------------------------------------*)
(* Integrate Out or Delete Particles         *)
(*-------------------------------------------*)
```

```
IntegrateOut={};
DeleteParticles={};


(*----------------------------------------------*)
(*   DEFINITION                                 *)
(*----------------------------------------------*)

NameOfStates={GaugeES, EWSB};

(* ----- Before EWSB ----- *)


DEFINITION[GaugeES][GaugeFixing]=
{ {Der[VWB],  -1/(2 RXi[W])},
     {Der[VG],   -1/(2 RXi[G]) }};

(* ----- After EWSB ----- *)

DEFINITION[EWSB][GaugeSector]=
{{VWB,{1,{VWm,1/Sqrt[2]},{conj[VWm],1/Sqrt[2]}},
      {2,{VWm,-\[ImaginaryI]/Sqrt[2]},{conj[VWm],\[ImaginaryI]/Sqrt[2]}},
      {3,{VP,Sin[ThetaW]},{VZ,Cos[ThetaW]}}},
 {VB, {1,{VP,Cos[ThetaW]},{VZ,-Sin[ThetaW]}}},
 {fWB,{1,{fWm,1/Sqrt[2]},{fWp,1/Sqrt[2]}},
      {2,{fWm,-\[ImaginaryI]/Sqrt[2]},{fWp,\[ImaginaryI]/Sqrt[2]}},
      {3,{fW0,1}}}};



DEFINITION[EWSB][VEVs]=
{    {SHd0, {vd, 1/Sqrt[2]}, {sigmad, \[ImaginaryI]/Sqrt[2]},{phid, \
\
1/Sqrt[2]}},
     {SHu0, {vu, 1/Sqrt[2]}, {sigmau, \[ImaginaryI]/Sqrt[2]},{phiu, \
\
1/Sqrt[2]}},
     {SsR, {vS, 1/Sqrt[2]}, {sigmaS, \[ImaginaryI]/Sqrt[2]},{phiS, \
\
1/Sqrt[2]}}     };



DEFINITION[EWSB][MatterSector]=

{    {{SdL, SdR}, {Sd, ZD}},
     {{SvL}, {Sv, ZV}},
     {{SuL, SuR}, {Su, ZU}},
```

```
     {{SeL, SeR}, {Se, ZE}},
     {{phid, phiu, phiS}, {hh, ZH}},
     {{sigmad, sigmau,sigmaS}, {Ah, ZA}},
     {{SHdm,conj[SHup]},{Hpm,ZP}},
     {{fB, fW0, FHd0, FHu0,FsR}, {L0, ZN}},
     {{{fWm, FHdm}, {fWp, FHup}}, {{Lm,UM}, {Lp,UP}}},
     {{{FeL},{conj[FeR]}},{{FEL,ZEL},{FER,ZER}}},
     {{{FdL},{conj[FdR]}},{{FDL,ZDL},{FDR,ZDR}}},
     {{{FuL},{conj[FuR]}},{{FUL,ZUL},{FUR,ZUR}}}
   };

DEFINITION[EWSB][Phases]=
{    {fG, PhaseGlu}
    };

DEFINITION[EWSB][GaugeFixing]=
  { {Der[VP],                                           - 1/(2 RXi[P])},
{Der[VWm]+\[ImaginaryI] Mass[VWm] RXi[W] Hpm[{1}],   - 1/(RXi[W])},
{Der[VZ] - Mass[VZ] RXi[Z] Ah[{1}],                 - 1/(2 RXi[Z])},
{Der[VG],                                           - 1/(2 RXi[G])}};

(*-------------------------------------------------------*)
(* Dirac-Spinors *)
(*-------------------------------------------------------*)

dirac[[1]] = {Fd,  FDL, conj[FDR]};
dirac[[2]] = {Fe,  FEL, conj[FER]};
dirac[[3]] = {Fu,  FUL, conj[FUR]};
dirac[[4]] = {Fv,  FvL, 0};
dirac[[5]] = {Chi, L0, conj[L0]};
dirac[[6]] = {Cha, Lm, conj[Lp]};
dirac[[7]] = {Glu, fG, conj[fG]};
dirac[[8]] = {Bino, fB, conj[fB]};
dirac[[9]] = {Wino, fWB, conj[fWB]};
dirac[[10]] = {H0, FHu0, conj[FHd0]};
dirac[[11]] = {HC, FHup, conj[FHdm]};
dirac[[12]] = {S, FsR, conj[FsR]};

(* Unbroken EW *)

dirac[[13]] = {Fd1, FdL, 0};
dirac[[14]] = {Fd2, 0, FdR};
dirac[[15]] = {Fu1, FuL, 0};
dirac[[16]] = {Fu2, 0, FuR};
dirac[[17]] = {Fe1, FeL, 0};
dirac[[18]] = {Fe2, 0, FeR};

(*-------------------------------------------------------*)
```

```
(* Automatized Output       *)
(*--------------------------------------------------*)

(*
makeOutput = {
                    {EWSB, {TeX, FeynArts}}
             };

            *)

SpectrumFile= None;
```

13.8 Implementation in SARAH

Model directory: `near-MSSM`

13.8.1 Particles for eigenstates 'GaugeES'

- Fermions

$\tilde{B} = \begin{pmatrix} \lambda_{\tilde{B}} \\ \lambda^*_{\tilde{B}} \end{pmatrix}$	`Bino` $= \begin{pmatrix} \texttt{fB} \\ \texttt{conj[fB]} \end{pmatrix}$
$d^1_{i\alpha} = \begin{pmatrix} d_{L,i\alpha} \\ 0 \end{pmatrix}$	`Fd1[{generation, color}]` $= \begin{pmatrix} \texttt{FdL[\{generation, color\}]} \\ 0 \end{pmatrix}$
$d^2_{i\alpha} = \begin{pmatrix} 0 \\ d_{R,i\alpha} \end{pmatrix}$	`Fd2[{generation, color}]` $= \begin{pmatrix} 0 \\ \texttt{FdR[\{generation, color\}]} \end{pmatrix}$
$e^1_{i} = \begin{pmatrix} e_{L,i} \\ 0 \end{pmatrix}$	`Fe1[{generation}]` $= \begin{pmatrix} \texttt{FeL[\{generation\}]} \\ 0 \end{pmatrix}$
$e^2_{i} = \begin{pmatrix} 0 \\ e_{R,i} \end{pmatrix}$	`Fe2[{generation}]` $= \begin{pmatrix} 0 \\ \texttt{FeR[\{generation\}]} \end{pmatrix}$
$u^1_{i\alpha} = \begin{pmatrix} u_{L,i\alpha} \\ 0 \end{pmatrix}$	`Fu1[{generation, color}]` $= \begin{pmatrix} \texttt{FuL[\{generation, color\}]} \\ 0 \end{pmatrix}$
$u^2_{i\alpha} = \begin{pmatrix} 0 \\ u_{R,i\alpha} \end{pmatrix}$	`Fu2[{generation, color}]` $= \begin{pmatrix} 0 \\ \texttt{FuR[\{generation, color\}]} \end{pmatrix}$
$\nu_{i} = \begin{pmatrix} \nu_{L,i} \\ 0 \end{pmatrix}$	`Fv[{generation}]` $= \begin{pmatrix} \texttt{FvL[\{generation\}]} \\ 0 \end{pmatrix}$

$\tilde{g}_i = \begin{pmatrix} \lambda_{\tilde{g},i} \\ \lambda^*_{\tilde{g},i} \end{pmatrix}$	`Glu[{generation}]` $= \begin{pmatrix} \texttt{fG[\{generation\}]} \\ \texttt{conj[fG[\{generation\}]]} \end{pmatrix}$
$\tilde{H}^0 = \begin{pmatrix} \tilde{H}^0_u \\ \tilde{H}^{0,*}_d \end{pmatrix}$	`H0` $= \begin{pmatrix} \texttt{FHu0} \\ \texttt{conj[FHd0]} \end{pmatrix}$
$\tilde{H}^- = \begin{pmatrix} \tilde{H}^+_u \\ \tilde{H}^{-,*}_d \end{pmatrix}$	`HC` $= \begin{pmatrix} \texttt{FHup} \\ \texttt{conj[FHdm]} \end{pmatrix}$
$\tilde{S} = \begin{pmatrix} \tilde{S} \\ \tilde{S}^* \end{pmatrix}$	`S` $= \begin{pmatrix} \texttt{FsR} \\ \texttt{conj[FsR]} \end{pmatrix}$
$\tilde{W}_i = \begin{pmatrix} \lambda_{\tilde{W},i} \\ \lambda^*_{\tilde{W},i} \end{pmatrix}$	`Wino[{generation}]` $= \begin{pmatrix} \texttt{fWB[\{generation\}]} \\ \texttt{conj[fWB[\{generation\}]]} \end{pmatrix}$

- Scalars

$\tilde{d}_{L,i\alpha}$	`SdL[{generation, color}]`	$\tilde{u}_{L,i\alpha}$	`SuL[{generation, color}]`
$\tilde{e}_{L,i}$	`SeL[{generation}]`	$\tilde{\nu}_{L,i}$	`SvL[{generation}]`
H^0_d	`SHd0`	H^-_d	`SHdm`
H^0_u	`SHu0`	H^+_u	`SHup`
$\tilde{d}_{R,i\alpha}$	`SdR[{generation, color}]`	$\tilde{u}_{R,i\alpha}$	`SuR[{generation, color}]`
$\tilde{e}_{R,i}$	`SeR[{generation}]`	S	`SsR`

- Vector Bosons

B_ρ	`VB[{lorentz}]`	$W^-_{i\rho}$	`VWB[{generation, lorentz}]`
$g_{i\rho}$	`VG[{generation, lorentz}]`		

- Ghosts

η^B	`gB`	$\text{gWB}\Big(\{\text{gt1}\}\Big)$	`gWB[{generation}]`
η^G_i	`gG[{generation}]`		

13.8.2 Particles for eigenstates 'EWSB'

- Fermions

$\tilde{\chi}_i^- = \begin{pmatrix} \lambda_i^- \\ \lambda_i^{+,*} \end{pmatrix}$	`Cha[{generation}]` $= \begin{pmatrix}$ `Lm[{generation}]` $\\$ `conj[Lp[{generation}]]` $\end{pmatrix}$
$\tilde{\chi}_i^0 = \begin{pmatrix} \lambda_i^0 \\ \lambda_i^{0,*} \end{pmatrix}$	`Chi[{generation}]` $= \begin{pmatrix}$ `L0[{generation}]` $\\$ `conj[L0[{generation}]]` $\end{pmatrix}$
$d_{i\alpha} = \begin{pmatrix} D_{L,i\alpha} \\ D^*_{R,i\alpha} \end{pmatrix}$	`Fd[{generation, color}]` $= \begin{pmatrix}$ `FDL[{generation, color}]` $\\$ `conj[FDR[{generation, color}]]` $\end{pmatrix}$
$e_i = \begin{pmatrix} E_{L,i} \\ E^*_{R,i} \end{pmatrix}$	`Fe[{generation}]` $= \begin{pmatrix}$ `FEL[{generation}]` $\\$ `conj[FER[{generation}]]` $\end{pmatrix}$
$u_{i\alpha} = \begin{pmatrix} U_{L,i\alpha} \\ U^*_{R,i\alpha} \end{pmatrix}$	`Fu[{generation, color}]` $= \begin{pmatrix}$ `FUL[{generation, color}]` $\\$ `conj[FUR[{generation, color}]]` $\end{pmatrix}$
$\nu_i = \begin{pmatrix} \nu_{L,i} \\ 0 \end{pmatrix}$	`Fv[{generation}]` $= \begin{pmatrix}$ `FvL[{generation}]` $\\$ `0` $\end{pmatrix}$
$\tilde{g}_i = \begin{pmatrix} \lambda_{\tilde{g},i} \\ \lambda^*_{\tilde{g},i} \end{pmatrix}$	`Glu[{generation}]` $= \begin{pmatrix}$ `fG[{generation}]` $\\$ `conj[fG[{generation}]]` $\end{pmatrix}$

- Scalars

$\tilde{d}_{i\alpha}$	`Sd[{generation, color}]`	$\tilde{\nu}_i$	`Sv[{generation}]`
$\tilde{u}_{i\alpha}$	`Su[{generation, color}]`	$\tilde{e}_i$	`Se[{generation}]`
h_i	`hh[{generation}]`	A_i^0	`Ah[{generation}]`
H_i^-	`Hpm[{generation}]`		

- Vector Bosons

$g_{i\rho}$	`VG[{generation, lorentz}]`	W_ρ^-	`VWm[{lorentz}]`
γ_ρ	`VP[{lorentz}]`	Z_ρ	`VZ[{lorentz}]`

- Ghosts

η_i^G	gG[{generation}]	η^-	gWm
η^+	gWmC	η^γ	gP
η^Z	gZ		

13.8.3 Parameters

g_1	g1	g_2	g2	g_3	g3
Y_u	Yu	T_u	T[Yu]	Y_d	Yd
T_d	T[Yd]	Y_e	Ye	T_e	T[Ye]
λ	\[Lambda]	T_λ	T[\[Lambda]]	ξ	Tad
L_ξ	L[Tad]	m_q^2	mq2	m_l^2	ml2
$m_{H_d}^2$	mHd2	$m_{H_u}^2$	mHu2	m_d^2	md2
m_u^2	mu2	m_e^2	me2	m_S^2	ms2
M_1	MassB	M_2	MassWB	M_3	MassG
v_d	vd	v_u	vu	v_s	vS
Θ_W	ThetaW	$\phi_{\tilde{g}}$	PhaseGlu	Z^D	ZD
Z^V	ZV	Z^U	ZU	Z^E	ZE
Z^H	ZH	Z^A	ZA	Z^+	ZP
N	ZN	U	UM	V	UP
U_L^e	ZEL	U_R^e	ZER	U_L^d	ZDL
U_R^d	ZDR	U_L^u	ZUL	U_R^u	ZUR
β	\[Beta]				

Chapter 14

The Singlet extended Minimal Supersymmetric Standard Model

14.1 Superfields

14.1.1 Vector Superfields

SF	Spin $\frac{1}{2}$	Spin 1	$SU(N)$	Coupling	Name
$\hat{B}$	$\lambda_{\tilde{B}}$	B	$U(1)$	g_1	hypercharge
$\hat{W}$	$\lambda_{\tilde{W}}$	W^-	SU(2)	g_2	left
$\hat{g}$	$\lambda_{\tilde{g}}$	g	SU(3)	g_3	color

14.1.2 Chiral Superfields

SF	Spin 0	Spin $\frac{1}{2}$	Generations	$(U(1)\otimes \mathrm{SU}(2)\otimes \mathrm{SU}(3))$
$\hat{q}$	$\tilde{q}$	q	3	$(\frac{1}{6},\mathbf{2},\mathbf{3})$
$\hat{l}$	$\tilde{l}$	l	3	$(-\frac{1}{2},\mathbf{2},\mathbf{1})$
$\hat{H}_d$	H_d	$\tilde{H}_d$	1	$(-\frac{1}{2},\mathbf{2},\mathbf{1})$
$\hat{H}_u$	H_u	$\tilde{H}_u$	1	$(\frac{1}{2},\mathbf{2},\mathbf{1})$
$\hat{d}$	$\tilde{d}_R^*$	d_R^*	3	$(\frac{1}{3},\mathbf{1},\overline{\mathbf{3}})$
$\hat{u}$	$\tilde{u}_R^*$	u_R^*	3	$(-\frac{2}{3},\mathbf{1},\overline{\mathbf{3}})$
$\hat{e}$	$\tilde{e}_R^*$	e_R^*	3	$(1,\mathbf{1},\mathbf{1})$
$\hat{s}$	S	$\tilde{S}$	1	$(0,\mathbf{1},\mathbf{1})$

14.2 Superpotential and Lagrangian

14.2.1 Superpotential

$$W = Y_u\,\hat{q}\,\hat{H}_u\,\hat{u}\,-Y_d\,\hat{q}\,\hat{H}_d\,\hat{d}\,-Y_e\,\hat{l}\,\hat{H}_d\,\hat{e}\,+\lambda\,\hat{H}_u\,\hat{H}_d\,\hat{s}\,+\frac{1}{3}\kappa\,\hat{s}\,\hat{s}\,\hat{s}\,+L_1\,\hat{s}\,+\frac{1}{2}M_S\,\hat{s}\,\hat{s}$$

$$+\mu\,\hat{H}_u\,\hat{H}_d \tag{14.1}$$

14.2.2 Softbreaking terms

$$\begin{aligned}
L_{SB,W} = &+\frac{1}{2}S^2 B_S - H_d^0 H_u^0 B_\mu + H_d^- H_u^+ B_\mu + S\xi_1 + \frac{1}{3}S^3 T_\kappa - H_d^0 H_u^0 S T_\lambda + H_d^- H_u^+ S T_\lambda \\
&+ H_d^0 \tilde{d}^*_{R,k\gamma}\delta_{\alpha\gamma}\tilde{d}_{L,i\alpha}T_{d,ik} - H_d^- \tilde{d}^*_{R,k\gamma}\delta_{\alpha\gamma}\tilde{u}_{L,i\alpha}T_{d,ik} + H_d^0 \tilde{e}^*_{R,k}\tilde{e}_{L,i}T_{e,ik} - H_d^- \tilde{e}^*_{R,k}\tilde{\nu}_{L,i}T_{e,ik} \\
&- H_u^+ \tilde{u}^*_{R,k\gamma}\delta_{\alpha\gamma}\tilde{d}_{L,i\alpha}T_{u,ik} + H_u^0 \tilde{u}^*_{R,k\gamma}\delta_{\alpha\gamma}\tilde{u}_{L,i\alpha}T_{u,ik} + \text{h.c.}
\end{aligned} \tag{14.2}$$

$$\begin{aligned}
L_{SB,\phi} = &- m_{H_d}^2|H_d^0|^2 - m_{H_d}^2|H_d^-|^2 - m_{H_u}^2|H_u^0|^2 - m_{H_u}^2|H_u^+|^2 - m_S^2|S|^2 \\
&- \tilde{d}^*_{L,j\beta}\delta_{\alpha\beta}m^2_{q,ij}\tilde{d}_{L,i\alpha} - \tilde{d}^*_{R,i\alpha}\delta_{\alpha\beta}m^2_{d,ij}\tilde{d}_{R,j\beta} - \tilde{e}^*_{L,j}m^2_{l,ij}\tilde{e}_{L,i} - \tilde{e}^*_{R,i}m^2_{e,ij}\tilde{e}_{R,j} \\
&- \tilde{u}^*_{L,j\beta}\delta_{\alpha\beta}m^2_{q,ij}\tilde{u}_{L,i\alpha} - \tilde{u}^*_{R,i\alpha}\delta_{\alpha\beta}m^2_{u,ij}\tilde{u}_{R,j\beta} - \tilde{\nu}^*_{L,j}m^2_{l,ij}\tilde{\nu}_{L,i}
\end{aligned} \tag{14.3}$$

$$L_{SB,\lambda} = \frac{1}{2}\Big(-\lambda^2_{\tilde{B}}M_1 - M_2\lambda^2_{\tilde{W},i} - M_3\lambda^2_{\tilde{g},i} + \text{h.c.}\Big) \tag{14.4}$$

14.2.3 Gauge fixing terms

Gauge fixing terms for eigenstates 'GaugeES'

$$L_{GF} = -\frac{1}{2}\partial_\mu g \xi_G^{-1} - \frac{1}{2}\partial_\mu W^- \xi_W^{-1} \tag{14.5}$$

Gauge fixing terms for eigenstates 'EWSB'

$$L_{GF} = -\frac{1}{2}\partial_\mu \gamma \xi_P^{-1} - \frac{1}{2}\partial_\mu g \xi_G^{-1} - \frac{1}{2}\xi_Z^{-1}\Big(-A_1^0 m_Z \xi_Z + \partial_\mu Z\Big) - \xi_W^{-1}\Big(iH_1^- m_{W^-}\xi_W + \partial_\mu W^-\Big) \tag{14.6}$$

14.2.4 Fields integrated out

None

14.3 Field Rotations

14.3.1 Rotations in gauge sector for eigenstates 'EWSB'

$$W^-_{1\rho} = \frac{1}{\sqrt{2}}W^-_\rho + \frac{1}{\sqrt{2}}W^+_\rho \tag{14.7}$$

$$W^-_{2\rho} = -i\frac{1}{\sqrt{2}}W^-_\rho + i\frac{1}{\sqrt{2}}W^+_\rho \tag{14.8}$$

$$W^-_{3\rho} = \cos\Theta_W Z_\rho + \sin\Theta_W \gamma_\rho \tag{14.9}$$

$$B_\rho = \cos\Theta_W \gamma_\rho - \sin\Theta_W Z_\rho \tag{14.10}$$

$$\lambda_{\tilde{W},1} = \frac{1}{\sqrt{2}}\tilde{W}^- + \frac{1}{\sqrt{2}}\tilde{W}^+ \tag{14.11}$$

$$\lambda_{\tilde{W},2} = -i\frac{1}{\sqrt{2}}\tilde{W}^- + i\frac{1}{\sqrt{2}}\tilde{W}^+ \tag{14.12}$$

$$\lambda_{\tilde{W},3} = \tilde{W}^0 \tag{14.13}$$

14.3.2 Rotations in Mass sector for eigenstates 'EWSB'

Mass Matrices for Scalars

- **Mass matrix for Down-Squarks**, Basis: $\left(\tilde{d}_{L,o_1\alpha_1}, \tilde{d}_{R,o_2\alpha_2}\right), \left(\tilde{d}^*_{L,p_1\beta_1}, \tilde{d}^*_{R,p_2\beta_2}\right)$

$$m^2_{\tilde{d}} = \begin{pmatrix} m_{11} & m^*_{21} \\ m_{21} & m_{22} \end{pmatrix} \tag{14.14}$$

$$m_{11} = \frac{1}{24}\delta_{\alpha_1\beta_1}\Big(12\Big(2m^2_{q,o_1p_1} + v_d^2\sum_{a=1}^{3} Y^*_{d,p_1a}Y_{d,o_1a}\Big) - \Big(3g_2^2 + g_1^2\Big)\Big(-v_u^2 + v_d^2\Big)\delta_{o_1p_1}\Big) \tag{14.15}$$

$$m_{21} = -\frac{1}{2}\Big(-\sqrt{2}v_dT^*_{d,p_1o_2} + v_u\Big(\sqrt{2}\mu + v_s\lambda\Big)Y^*_{d,p_1o_2}\Big)\delta_{\alpha_2\beta_1} \tag{14.16}$$

$$m_{22} = \frac{1}{12}\delta_{\alpha_2\beta_2}\Big(6\Big(2m^2_{d,p_2o_2} + v_d^2\sum_{a=1}^{3} Y^*_{d,ao_2}Y_{d,ap_2}\Big) + g_1^2\Big(-v_d^2 + v_u^2\Big)\delta_{o_2p_2}\Big) \tag{14.17}$$

This matrix is diagonalized by Z^D:

$$Z^D m^2_{\tilde{d}} Z^{D,\dagger} = m^{dia}_{2,\tilde{d}} \tag{14.18}$$

with

$$\tilde{d}_{L,i\alpha} = \sum_{t_2} Z^{D,*}_{ji}\tilde{d}_{j\alpha}\,, \qquad \tilde{d}_{R,i\alpha} = \sum_{t_2} Z^{D,*}_{ji}\tilde{d}_{j\alpha} \tag{14.19}$$

- **Mass matrix for Sneutrinos**, Basis: $(\tilde{\nu}_{L,o_1}), (\tilde{\nu}^*_{L,p_1})$

$$m^2_{\tilde{\nu}} = \Big(\tfrac{1}{8}\Big(8m^2_{l,o_1p_1} + \Big(g_1^2 + g_2^2\Big)\Big(-v_u^2 + v_d^2\Big)\delta_{o_1p_1}\Big) \Big) \tag{14.20}$$

This matrix is diagonalized by Z^V:

$$Z^V m^2_{\tilde{\nu}} Z^{V,\dagger} = m^{dia}_{2,\tilde{\nu}} \tag{14.21}$$

with

$$\tilde{\nu}_{L,i} = \sum_{t_2} Z^{V,*}_{ji}\tilde{\nu}_j \tag{14.22}$$

- **Mass matrix for Up-Squarks**, Basis: $(\tilde{u}_{L,o_1\alpha_1}, \tilde{u}_{R,o_2\alpha_2}), \left(\tilde{u}^*_{L,p_1\beta_1}, \tilde{u}^*_{R,p_2\beta_2}\right)$

$$m^2_{\tilde{u}} = \begin{pmatrix} m_{11} & m^*_{21} \\ m_{21} & m_{22} \end{pmatrix} \tag{14.23}$$

$$m_{11} = \frac{1}{24}\delta_{\alpha_1\beta_1}\Big(12\Big(2m^2_{q,o_1p_1} + v_u^2\sum_{a=1}^{3} Y^*_{u,p_1a}Y_{u,o_1a}\Big) - \Big(-3g_2^2 + g_1^2\Big)\Big(-v_u^2 + v_d^2\Big)\delta_{o_1p_1}\Big) \tag{14.24}$$

$$m_{21} = -\frac{1}{2}\Big(- \sqrt{2} v_u T^*_{u,p_1 o_2} + v_d \Big(\sqrt{2} \mu + v_s \lambda \Big) Y^*_{u,p_1 o_2}\Big) \delta_{\alpha_2 \beta_1} \tag{14.25}$$

$$m_{22} = \frac{1}{6} \delta_{\alpha_2 \beta_2} \Big(3 v_u^2 \sum_{a=1}^{3} Y^*_{u,a o_2} Y_{u,a p_2} + 6 m^2_{u,p_2 o_2} + g_1^2 \Big(- v_u^2 + v_d^2\Big) \delta_{o_2 p_2}\Big) \tag{14.26}$$

This matrix is diagonalized by Z^U:

$$Z^U m^2_{\tilde{u}} Z^{U,\dagger} = m^{dia}_{2,\tilde{u}} \tag{14.27}$$

with

$$\tilde{u}_{L,i\alpha} = \sum_{t_2} Z^{U,*}_{ji} \tilde{u}_{j\alpha}\,, \qquad \tilde{u}_{R,i\alpha} = \sum_{t_2} Z^{U,*}_{ji} \tilde{u}_{j\alpha} \tag{14.28}$$

- **Mass matrix for Sleptons**, Basis: $\left(\tilde{e}_{L,o_1}, \tilde{e}_{R,o_2}\right), \left(\tilde{e}^*_{L,p_1}, \tilde{e}^*_{R,p_2}\right)$

$$m^2_{\tilde{e}} = \begin{pmatrix} m_{11} & m^*_{21} \\ \frac{1}{2}\Big(\sqrt{2} v_d T^*_{e,p_1 o_2} - v_u \Big(\sqrt{2}\mu + v_s \lambda\Big) Y^*_{e,p_1 o_2}\Big) & m_{22} \end{pmatrix} \tag{14.29}$$

$$m_{11} = \frac{1}{8}\Big(4 v_d^2 \sum_{a=1}^{3} Y^*_{e,p_1 a} Y_{e,o_1 a} + 8 m^2_{l,o_1 p_1} + \Big(- g_2^2 + g_1^2\Big)\Big(- v_u^2 + v_d^2\Big)\delta_{o_1 p_1}\Big) \tag{14.30}$$

$$m_{22} = \frac{1}{4}\Big(2 v_d^2 \sum_{a=1}^{3} Y^*_{e,a o_2} Y_{e,a p_2} + 4 m^2_{e,p_2 o_2} + g_1^2 \Big(- v_d^2 + v_u^2\Big)\delta_{o_2 p_2}\Big) \tag{14.31}$$

This matrix is diagonalized by Z^E:

$$Z^E m^2_{\tilde{e}} Z^{E,\dagger} = m^{dia}_{2,\tilde{e}} \tag{14.32}$$

with

$$\tilde{e}_{L,i} = \sum_{t_2} Z^{E,*}_{ji} \tilde{e}_j\,, \qquad \tilde{e}_{R,i} = \sum_{t_2} Z^{E,*}_{ji} \tilde{e}_j \tag{14.33}$$

- **Mass matrix for Higgs**, Basis: $\left(\phi_d, \phi_u, \phi_s\right), \left(\phi_d, \phi_u, \phi_s\right)$

$$m^2_h = \begin{pmatrix} m_{11} & m^*_{21} & m^*_{31} \\ m_{21} & m_{22} & m^*_{32} \\ m_{31} & m_{32} & m_{33} \end{pmatrix} \tag{14.34}$$

$$\begin{aligned} m_{11} = \frac{1}{8}\Big(& 8 m^2_{H_d} + 3 g_1^2 v_d^2 + 3 g_2^2 v_d^2 - g_1^2 v_u^2 - g_2^2 v_u^2 + 4\Big(\sqrt{2} v_s \mu + v_s^2 \lambda + v_u^2 \lambda\Big)\lambda^* \\ & + 4\Big(2\mu + \sqrt{2} v_s \lambda\Big)\mu^*\Big) \end{aligned} \tag{14.35}$$

$$m_{21} = \frac{1}{4}\Big(- g_1^2 v_d v_u - g_2^2 v_d v_u + 4 v_d v_u |\lambda|^2 - 2\lambda L_1^* - \sqrt{2} v_s \lambda M_S^* - v_s^2 \lambda \kappa^* - 2 L_1 \lambda^*$$
$$- \sqrt{2} M_S v_s \lambda^* - v_s^2 \kappa \lambda^* - \sqrt{2} v_s T_\lambda^* - 4\Re\Big(B_\mu\Big) - \sqrt{2} v_s T_\lambda\Big) \tag{14.36}$$
$$m_{22} = \frac{1}{8}\Big(8 m_{H_u}^2 - g_1^2 v_d^2 - g_2^2 v_d^2 + 3 g_1^2 v_u^2 + 3 g_2^2 v_u^2 + 4\Big(v_d^2 \lambda + v_s\Big(\sqrt{2}\mu + v_s \lambda\Big)\Big)\lambda^*$$
$$+ 4\Big(2\mu + \sqrt{2} v_s \lambda\Big)\mu^*\Big) \tag{14.37}$$
$$m_{31} = \frac{1}{4}\Big(4 v_d v_s |\lambda|^2 - \sqrt{2} v_u \lambda M_S^* - 2 v_s v_u \lambda \kappa^* - \sqrt{2} M_S v_u \lambda^* - 2 v_s v_u \kappa \lambda^* + 2\sqrt{2} v_d \mu \lambda^*$$
$$+ 2\sqrt{2} v_d \lambda \mu^* - 2\sqrt{2} v_u \Re\Big(T_\lambda\Big)\Big) \tag{14.38}$$
$$m_{32} = \frac{1}{4}\Big(4 v_s v_u |\lambda|^2 - \sqrt{2} v_d \lambda M_S^* - 2 v_d v_s \lambda \kappa^* - \sqrt{2} M_S v_d \lambda^* - 2 v_d v_s \kappa \lambda^* + 2\sqrt{2} v_u \mu \lambda^*$$
$$+ 2\sqrt{2} v_u \lambda \mu^* - 2\sqrt{2} v_d \Re\Big(T_\lambda\Big)\Big) \tag{14.39}$$
$$m_{33} = \frac{1}{2}\Big(2 m_S^2 + 6 v_s^2 |\kappa|^2 + v_d^2 |\lambda|^2 + v_u^2 |\lambda|^2 + 2\kappa L_1^* + \Big(2 M_S + 3\sqrt{2} v_s \kappa\Big) M_S^* + 2 L_1 \kappa^* + 3\sqrt{2} M_S v_s \kappa^*$$
$$- v_d v_u \lambda \kappa^* - v_d v_u \kappa \lambda^* + \sqrt{2} v_s T_\kappa^* + 2\Re\Big(B_S\Big) + \sqrt{2} v_s T_\kappa\Big) \tag{14.40}$$

This matrix is diagonalized by Z^H:

$$Z^H m_h^2 Z^{H,\dagger} = m_{2,h}^{dia} \tag{14.41}$$

with

$$\phi_d = \sum_{t_2} Z_{j1}^{H,*} h_j\,, \qquad \phi_u = \sum_{t_2} Z_{j2}^{H,*} h_j\,, \qquad \phi_s = \sum_{t_2} Z_{j3}^{H,*} h_j \tag{14.42}$$

- **Mass matrix for Pseudo-Scalar Higgs**, Basis: $(\sigma_d, \sigma_u, \sigma_s)\,, (\sigma_d, \sigma_u, \sigma_s)$

$$m_{A^0}^2 = \begin{pmatrix} m_{11} & m_{21}^* & m_{31}^* \\ m_{21} & m_{22} & m_{32}^* \\ m_{31} & m_{32} & m_{33} \end{pmatrix} \tag{14.43}$$

$$m_{11} = \frac{1}{8}\Big(8 m_{H_d}^2 + g_1^2 v_d^2 + g_2^2 v_d^2 - g_1^2 v_u^2 - g_2^2 v_u^2 + 4\Big(\sqrt{2} v_s \mu + v_s^2 \lambda + v_u^2 \lambda\Big)\lambda^*$$
$$+ 4\Big(2\mu + \sqrt{2} v_s \lambda\Big)\mu^*\Big) \tag{14.44}$$
$$m_{21} = \frac{1}{4}\Big(2 L_1 \lambda^* + 2\lambda L_1^* + 4\Re\Big(B_\mu\Big) + \sqrt{2} M_S v_s \lambda^* + \sqrt{2} v_s \lambda M_S^* + \sqrt{2} v_s T_\lambda + \sqrt{2} v_s T_\lambda^* + v_s^2 \kappa \lambda^* + v_s^2 \lambda \kappa^*\Big) \tag{14.45}$$
$$m_{22} = \frac{1}{8}\Big(8 m_{H_u}^2 - g_1^2 v_d^2 - g_2^2 v_d^2 + g_1^2 v_u^2 + g_2^2 v_u^2 + 4\Big(v_d^2 \lambda + v_s\Big(\sqrt{2}\mu + v_s \lambda\Big)\Big)\lambda^*$$
$$+ 4\Big(2\mu + \sqrt{2} v_s \lambda\Big)\mu^*\Big) \tag{14.46}$$
$$m_{31} = -\frac{1}{4} v_u \Big(- 2\sqrt{2}\Re\Big(T_\lambda\Big) + 2 v_s \kappa \lambda^* + 2 v_s \lambda \kappa^* + \sqrt{2}\lambda M_S^* + \sqrt{2} M_S \lambda^*\Big) \tag{14.47}$$

$$m_{32} = -\frac{1}{4}v_d\Big(- 2\sqrt{2}\Re\Big(T_\lambda\Big) + 2v_s\kappa\lambda^* + 2v_s\lambda\kappa^* + \sqrt{2}\lambda M_S^* + \sqrt{2}M_S\lambda^*\Big) \tag{14.48}$$

$$m_{33} = \frac{1}{2}\Big(2m_S^2 + 2v_s^2|\kappa|^2 + v_d^2|\lambda|^2 + v_u^2|\lambda|^2 - 2\kappa L_1^* + \Big(2M_S + \sqrt{2}v_s\kappa\Big)M_S^* - 2L_1\kappa^* + \sqrt{2}M_S v_s\kappa^* + v_d v_u\lambda\kappa^* + v_d v_u\kappa\lambda^* - \sqrt{2}v_s T_\kappa^* - 2\Re\Big(B_S\Big) - \sqrt{2}v_s T_\kappa\Big) \tag{14.49}$$

This matrix is diagonalized by Z^A:

$$Z^A m^2_{A^0} Z^{A,\dagger} = m^{dia}_{2,A^0} \tag{14.50}$$

with

$$\sigma_d = \sum_{t_2} Z^{A,*}_{j1} A^0_j\,, \qquad \sigma_u = \sum_{t_2} Z^{A,*}_{j2} A^0_j\,, \qquad \sigma_s = \sum_{t_2} Z^{A,*}_{j3} A^0_j \tag{14.51}$$

- **Mass matrix for Charged Higgs**, Basis: $\Big(H_d^-, H_u^{+,*}\Big), \Big(H_d^{-,*}, H_u^+\Big)$

$$m^2_{H^-} = \begin{pmatrix} m_{11} & m^*_{21} \\ m_{21} & m_{22} \end{pmatrix} \tag{14.52}$$

$$m_{11} = \frac{1}{8}\Big(4\Big(2\mu + \sqrt{2}v_s\lambda\Big)\mu^* + 4v_s\Big(\sqrt{2}\mu + v_s\lambda\Big)\lambda^* + 8m^2_{H_d} + g_1^2v_d^2 - g_1^2v_u^2 + g_2^2v_d^2 + g_2^2v_u^2\Big) \tag{14.53}$$

$$m_{21} = \frac{1}{4}\Big(2\Big(2L_1 + \sqrt{2}M_S v_s - v_d v_u\lambda + v_s^2\kappa\Big)\lambda^* + 2\sqrt{2}v_s T_\lambda^* + 4B_\mu^* + g_2^2 v_d v_u\Big) \tag{14.54}$$

$$m_{22} = \frac{1}{8}\Big(4\Big(2\mu + \sqrt{2}v_s\lambda\Big)\mu^* + 4v_s\Big(\sqrt{2}\mu + v_s\lambda\Big)\lambda^* + 8m^2_{H_u} - g_1^2v_d^2 + g_1^2v_u^2 + g_2^2v_d^2 + g_2^2v_u^2\Big) \tag{14.55}$$

This matrix is diagonalized by Z^+:

$$Z^+ m^2_{H^-} Z^{+,\dagger} = m^{dia}_{2,H^-} \tag{14.56}$$

with

$$H_d^- = \sum_{t_2} Z^{+,*}_{j1} H_j^-\,, \qquad H_u^+ = \sum_{t_2} Z^+_{j2} H_j^+ \tag{14.57}$$

The mixing matrix can be parametrized by

$$Z^+ = \begin{pmatrix} -\cos\beta & \sin\beta \\ \sin\beta & \cos\beta \end{pmatrix} \tag{14.58}$$

Mass Matrices for Fermions

- **Mass matrix for Neutralinos**, Basis: $\Big(\lambda_{\tilde{B}}, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0, \tilde{S}\Big), \Big(\lambda_{\tilde{B}}, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0, \tilde{S}\Big)$

$$m_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -\frac{1}{2}g_1 v_d & \frac{1}{2}g_1 v_u & 0 \\ 0 & M_2 & \frac{1}{2}g_2 v_d & -\frac{1}{2}g_2 v_u & 0 \\ -\frac{1}{2}g_1 v_d & \frac{1}{2}g_2 v_d & 0 & -\frac{1}{\sqrt{2}}v_s\lambda - \mu & -\frac{1}{\sqrt{2}}v_u\lambda \\ \frac{1}{2}g_1 v_u & -\frac{1}{2}g_2 v_u & -\frac{1}{\sqrt{2}}v_s\lambda - \mu & 0 & -\frac{1}{\sqrt{2}}v_d\lambda \\ 0 & 0 & -\frac{1}{\sqrt{2}}v_u\lambda & -\frac{1}{\sqrt{2}}v_d\lambda & \sqrt{2}v_s\kappa + M_S \end{pmatrix} \tag{14.59}$$

This matrix is diagonalized by N:

$$N m_{\tilde{\chi}^0} N^{\dagger} = m^{dia}_{\tilde{\chi}^0} \tag{14.60}$$

with

$$\lambda_{\tilde{B}} = \sum_{t_2} N^*_{j1}\lambda^0_j\,, \qquad \tilde{W}^0 = \sum_{t_2} N^*_{j2}\lambda^0_j\,, \qquad \tilde{H}^0_d = \sum_{t_2} N^*_{j3}\lambda^0_j \tag{14.61}$$

$$\tilde{H}^0_u = \sum_{t_2} N^*_{j4}\lambda^0_j\,, \qquad \tilde{S} = \sum_{t_2} N^*_{j5}\lambda^0_j \tag{14.62}$$

- **Mass matrix for Charginos**, Basis: $\left(\tilde{W}^-, \tilde{H}^-_d\right), \left(\tilde{W}^+, \tilde{H}^+_u\right)$

$$m_{\tilde{\chi}^-} = \begin{pmatrix} M_2 & \frac{1}{\sqrt{2}} g_2 v_u \\ \frac{1}{\sqrt{2}} g_2 v_d & \frac{1}{\sqrt{2}} v_s \lambda + \mu \end{pmatrix} \tag{14.63}$$

This matrix is diagonalized by U and V

$$U^* m_{\tilde{\chi}^-} V^{\dagger} = m^{dia}_{\tilde{\chi}^-} \tag{14.64}$$

with

$$\tilde{W}^- = \sum_{t_2} U^*_{j1}\lambda^-_j\,, \qquad \tilde{H}^-_d = \sum_{t_2} U^*_{j2}\lambda^-_j \tag{14.65}$$

$$\tilde{W}^+ = \sum_{t_2} V^*_{1j}\lambda^+_j\,, \qquad \tilde{H}^+_u = \sum_{t_2} V^*_{2j}\lambda^+_j \tag{14.66}$$

- **Mass matrix for Leptons**, Basis: $\left(e_{L,o_1}\right), \left(e^*_{R,p_1}\right)$

$$m_e = \begin{pmatrix} \frac{1}{\sqrt{2}} v_d Y_{e,o_1 p_1} \end{pmatrix} \tag{14.67}$$

This matrix is diagonalized by U^e_L and U^e_R

$$U^{e,*}_L m_e U^{e,\dagger}_R = m^{dia}_e \tag{14.68}$$

with

$$e_{L,i} = \sum_{t_2} U^{e,*}_{L,ji} E_{L,j} \tag{14.69}$$

$$e_{R,i} = \sum_{t_2} U^{e}_{R,ij} E^*_{R,j} \tag{14.70}$$

- **Mass matrix for Down-Quarks**, Basis: $\left(d_{L,o_1\alpha_1}\right), \left(d^*_{R,p_1\beta_1}\right)$

$$m_d = \begin{pmatrix} \frac{1}{\sqrt{2}} v_d \delta_{\alpha_1\beta_1} Y_{d,o_1 p_1} \end{pmatrix} \tag{14.71}$$

This matrix is diagonalized by U^d_L and U^d_R

$$U^{d,*}_L m_d U^{d,\dagger}_R = m^{dia}_d \tag{14.72}$$

with

$$d_{L,i\alpha} = \sum_{t_2} U^{d,*}_{L,ji} D_{L,j\alpha} \tag{14.73}$$

$$d_{R,i\alpha} = \sum_{t_2} U^{d}_{R,ij} D^*_{R,j\alpha} \tag{14.74}$$

- **Mass matrix for Up-Quarks**, Basis: $\left(u_{L,o_1\alpha_1}\right), \left(u^*_{R,p_1\beta_1}\right)$

$$m_u = \left(\begin{array}{c} \frac{1}{\sqrt{2}} v_u \delta_{\alpha_1\beta_1} Y_{u,o_1p_1} \end{array} \right) \tag{14.75}$$

This matrix is diagonalized by U^u_L and U^u_R

$$U^{u,*}_L m_u U^{u,\dagger}_R = m^{dia}_u \tag{14.76}$$

with

$$u_{L,i\alpha} = \sum_{t_2} U^{u,*}_{L,ji} U_{L,j\alpha} \tag{14.77}$$

$$u_{R,i\alpha} = \sum_{t_2} U^{u}_{R,ij} U^*_{R,j\alpha} \tag{14.78}$$

14.4 Vacuum Expectation Values

$$H^0_d = \frac{1}{\sqrt{2}}\phi_d + \frac{1}{\sqrt{2}}v_d + i\frac{1}{\sqrt{2}}\sigma_d \tag{14.79}$$

$$H^0_u = \frac{1}{\sqrt{2}}\phi_u + \frac{1}{\sqrt{2}}v_u + i\frac{1}{\sqrt{2}}\sigma_u \tag{14.80}$$

$$S = \frac{1}{\sqrt{2}}\phi_s + \frac{1}{\sqrt{2}}v_s + i\frac{1}{\sqrt{2}}\sigma_s \tag{14.81}$$

14.5 Tadpole Equations

$$\begin{aligned}\frac{\partial V}{\partial v_d} = \frac{1}{8}\Big(&8m^2_{H_d}v_d + g_1^2 v_d^3 + g_2^2 v_d^3 - g_1^2 v_d v_u^2 - g_2^2 v_d v_u^2 + 4v_d v_s^2|\lambda|^2 + 4v_d v_u^2|\lambda|^2\\ &+ 8v_d|\mu|^2 - 4v_u\lambda L_1^* - 2\sqrt{2}v_s v_u\lambda M_S^* - 2v_s^2 v_u\lambda\kappa^* - 4L_1 v_u\lambda^* - 2\sqrt{2}M_S v_s v_u\lambda^*\\ &- 2v_s^2 v_u\kappa\lambda^* + 4\sqrt{2}v_d v_s\mu\lambda^* + 4\sqrt{2}v_d v_s\lambda\mu^* - 2\sqrt{2}v_s v_u T_\lambda^* - 8v_u\Re\Big(B_\mu\Big) - 2\sqrt{2}v_s v_u T_\lambda\Big)\end{aligned} \tag{14.82}$$

$$\begin{aligned}\frac{\partial V}{\partial v_u} = \frac{1}{8}\Big(&8m^2_{H_u}v_u - g_1^2 v_d^2 v_u - g_2^2 v_d^2 v_u + g_1^2 v_u^3 + g_2^2 v_u^3 + 4v_d^2 v_u|\lambda|^2 + 4v_s^2 v_u|\lambda|^2\\ &+ 8v_u|\mu|^2 - 4v_d\lambda L_1^* - 2\sqrt{2}v_d v_s\lambda M_S^* - 2v_d v_s^2\lambda\kappa^* - 4L_1 v_d\lambda^* - 2\sqrt{2}M_S v_d v_s\lambda^*\end{aligned}$$

$$- 2 v_d v_s^2 \kappa \lambda^* + 4\sqrt{2} v_s v_u \mu \lambda^* + 4\sqrt{2} v_s v_u \lambda \mu^* - 2\sqrt{2} v_d v_s T_\lambda^* - 8 v_d \Re\Big(B_\mu\Big) - 2\sqrt{2} v_d v_s T_\lambda\Big) \tag{14.83}$$

$$\begin{aligned}\frac{\partial V}{\partial v_s} &= \frac{1}{4}\Big(4 m_S^2 v_s + 4 v_s^3 |\kappa|^2 + 2 v_d^2 v_s |\lambda|^2 + 2 v_s v_u^2 |\lambda|^2 + 2\Big(2 v_s \kappa + \sqrt{2} M_S\Big) L_1^* \\ &+ \Big(2\sqrt{2} L_1 + 4 M_S v_s + \sqrt{2}\Big(3 v_s^2 \kappa - v_d v_u \lambda\Big)\Big) M_S^* + 4 L_1 v_s \kappa^* + 3\sqrt{2} M_S v_s^2 \kappa^* - 2 v_d v_s v_u \lambda \kappa^* \\ &- \sqrt{2} M_S v_d v_u \lambda^* - 2 v_d v_s v_u \kappa \lambda^* + \sqrt{2} v_d^2 \mu \lambda^* + \sqrt{2} v_u^2 \mu \lambda^* + \sqrt{2} v_d^2 \lambda \mu^* + \sqrt{2} v_u^2 \lambda \mu^* \\ &+ 2\sqrt{2} \xi_1^* + \sqrt{2} v_s^2 T_\kappa^* - \sqrt{2} v_d v_u T_\lambda^* + 2\sqrt{2} \xi_1 + 4 v_s \Re\Big(B_S\Big) + \sqrt{2} v_s^2 T_\kappa - \sqrt{2} v_d v_u T_\lambda\Big)\end{aligned} \tag{14.84}$$

14.6 Particle content for eigenstates 'EWSB'

Name	Type	complex/real	Generations	Indices
$\tilde{d}$	Scalar	complex	6	generation, color
$\tilde{\nu}$	Scalar	complex	3	generation
$\tilde{u}$	Scalar	complex	6	generation, color
$\tilde{e}$	Scalar	complex	6	generation
h	Scalar	real	3	generation
A^0	Scalar	real	3	generation
H^-	Scalar	complex	2	generation
ν	Fermion	Dirac	3	generation
$\tilde{g}$	Fermion	Majorana	8	generation
$\tilde{\chi}^0$	Fermion	Majorana	5	generation
$\tilde{\chi}^-$	Fermion	Dirac	2	generation
e	Fermion	Dirac	3	generation
d	Fermion	Dirac	3	generation, color
u	Fermion	Dirac	3	generation, color
g	Vector	real	8	generation, lorentz
W^-	Vector	complex	1	lorentz
γ	Vector	real	1	lorentz
Z	Vector	real	1	lorentz
η^G	Ghost	real	8	generation
η^-	Ghost	complex	1	
η^+	Ghost	complex	1	
η^γ	Ghost	real	1	
η^Z	Ghost	real	1	

14.7 Modelfile for SARAH

```
Off[General::spell]
Print["Model file for the SMSSM loaded"];

ModelNameLaTeX ="SMSSM";


(*-------------------------------------------*)
(*   Particle Content*)
(*-------------------------------------------*)

(* Gauge Superfields *)

Gauge[[1]]={B,   U[1], hypercharge, g1,False};
Gauge[[2]]={WB, SU[2], left,        g2,True};
Gauge[[3]]={G,  SU[3], color,       g3,False};


(* Chiral Superfields *)

Fields[[1]] = {{uL,  dL},  3, q,   1/6, 2, 3};
Fields[[2]] = {{vL,  eL},  3, l,  -1/2, 2, 1};
Fields[[3]] = {{Hd0, Hdm}, 1, Hd, -1/2, 2, 1};
Fields[[4]] = {{Hup, Hu0}, 1, Hu,  1/2, 2, 1};

Fields[[5]] = {conj[dR], 3, d,  1/3, 1, -3};
Fields[[6]] = {conj[uR], 3, u, -2/3, 1, -3};
Fields[[7]] = {conj[eR], 3, e,    1, 1,  1};
Fields[[8]] = {sR, 1, s,    0, 1,  1};


(*-----------------------------------------------------*)
(* Superpotential *)
(*-----------------------------------------------------*)

SuperPotential = { {{1, Yu},{q,Hu,u}}, {{-1,Yd},{q,Hd,d}},
                   {{-1,Ye},{l,Hd,e}},
                   {{1,\[Lambda]},{Hu,Hd,s}},
                   {{1/3,\[Kappa]},{s,s,s}},
   {{1,L1},{s}},{{1/2,MS},{s,s}},{{1,\[Mu]},{Hu,Hd}}};


(*-------------------------------------------*)
(* Integrate Out or Delete Particles         *)
(*-------------------------------------------*)
```

```
IntegrateOut={};
DeleteParticles={};


(*-----------------------------------------------*)
(*   DEFINITION                                  *)
(*-----------------------------------------------*)

NameOfStates={GaugeES, EWSB};

(* ----- Before EWSB ----- *)


DEFINITION[GaugeES][GaugeFixing]=
{ {Der[VWB],  -1/(2 RXi[W])},
     {Der[VG],   -1/(2 RXi[G]) }};

(* ----- After EWSB ----- *)

DEFINITION[EWSB][GaugeSector]=
{{VWB,{1,{VWm,1/Sqrt[2]},{conj[VWm],1/Sqrt[2]}},
      {2,{VWm,-\[ImaginaryI]/Sqrt[2]},{conj[VWm],\[ImaginaryI]/Sqrt[2]}},
      {3,{VP,Sin[ThetaW]},{VZ,Cos[ThetaW]}}},
 {VB, {1,{VP,Cos[ThetaW]},{VZ,-Sin[ThetaW]}}},
 {fWB,{1,{fWm,1/Sqrt[2]},{fWp,1/Sqrt[2]}},
      {2,{fWm,-\[ImaginaryI]/Sqrt[2]},{fWp,\[ImaginaryI]/Sqrt[2]}},
      {3,{fW0,1}}}};



DEFINITION[EWSB][VEVs]=
{    {SHd0, {vd, 1/Sqrt[2]}, {sigmad, \[ImaginaryI]/Sqrt[2]},{phid, \
\
1/Sqrt[2]}},
     {SHu0, {vu, 1/Sqrt[2]}, {sigmau, \[ImaginaryI]/Sqrt[2]},{phiu, \
\
1/Sqrt[2]}},
     {SsR, {vS, 1/Sqrt[2]}, {sigmaS, \[ImaginaryI]/Sqrt[2]},{phiS, \
\
1/Sqrt[2]}}     };



DEFINITION[EWSB][MatterSector]=

{    {{SdL, SdR}, {Sd, ZD}},
     {{SvL}, {Sv, ZV}},
```

```
     {{SuL, SuR}, {Su, ZU}},
     {{SeL, SeR}, {Se, ZE}},
     {{phid, phiu, phiS}, {hh, ZH}},
     {{sigmad, sigmau,sigmaS}, {Ah, ZA}},
     {{SHdm,conj[SHup]},{Hpm,ZP}},
     {{fB, fW0, FHd0, FHu0,FsR}, {L0, ZN}},
     {{{fWm, FHdm}, {fWp, FHup}}, {{Lm,UM}, {Lp,UP}}},
     {{{FeL},{conj[FeR]}},{{FEL,ZEL},{FER,ZER}}},
     {{{FdL},{conj[FdR]}},{{FDL,ZDL},{FDR,ZDR}}},
     {{{FuL},{conj[FuR]}},{{FUL,ZUL},{FUR,ZUR}}}
   };

DEFINITION[EWSB][Phases]=
{    {fG, PhaseGlu}
    };

DEFINITION[EWSB][GaugeFixing]=
  { {Der[VP],                                          - 1/(2 RXi[P])},
{Der[VWm]+\[ImaginaryI] Mass[VWm] RXi[W] Hpm[{1}],   - 1/(RXi[W])},
{Der[VZ] - Mass[VZ] RXi[Z] Ah[{1}],                  - 1/(2 RXi[Z])},
{Der[VG],                                            - 1/(2 RXi[G])}};

(*-------------------------------------------------------*)
(* Dirac-Spinors *)
(*-------------------------------------------------------*)

dirac[[1]] = {Fd,  FDL, conj[FDR]};
dirac[[2]] = {Fe,  FEL, conj[FER]};
dirac[[3]] = {Fu,  FUL, conj[FUR]};
dirac[[4]] = {Fv,  FvL, 0};
dirac[[5]] = {Chi, L0, conj[L0]};
dirac[[6]] = {Cha, Lm, conj[Lp]};
dirac[[7]] = {Glu, fG, conj[fG]};
dirac[[8]] = {Bino, fB, conj[fB]};
dirac[[9]] = {Wino, fWB, conj[fWB]};
dirac[[10]] = {H0, FHu0, conj[FHd0]};
dirac[[11]] = {HC, FHup, conj[FHdm]};
dirac[[12]] = {S, FsR, conj[FsR]};


(* Unbroken EW *)

dirac[[13]] = {Fd1, FdL, 0};
dirac[[14]] = {Fd2, 0, FdR};
dirac[[15]] = {Fu1, FuL, 0};
dirac[[16]] = {Fu2, 0, FuR};
dirac[[17]] = {Fe1, FeL, 0};
dirac[[18]] = {Fe2, 0, FeR};
```

```
(*------------------------------------------------------*)
(* Automatized Output        *)
(*------------------------------------------------------*)

(*
makeOutput = {
                   {EWSB, {TeX, FeynArts}}
             };

            *)

SpectrumFile= None;
```

14.8 Implementation in SARAH

Model directory: `SMSSM`

14.8.1 Particles for eigenstates 'GaugeES'

- Fermions

$\tilde{B} = \begin{pmatrix} \lambda_{\tilde{B}} \\ \lambda^*_{\tilde{B}} \end{pmatrix}$	$\texttt{Bino} = \begin{pmatrix} \texttt{fB} \\ \texttt{conj[fB]} \end{pmatrix}$
$d^1_{i\alpha} = \begin{pmatrix} d_{L,i\alpha} \\ 0 \end{pmatrix}$	$\texttt{Fd1[\{generation, color\}]} = \begin{pmatrix} \texttt{FdL[\{generation, color\}]} \\ 0 \end{pmatrix}$
$d^2_{i\alpha} = \begin{pmatrix} 0 \\ d_{R,i\alpha} \end{pmatrix}$	$\texttt{Fd2[\{generation, color\}]} = \begin{pmatrix} 0 \\ \texttt{FdR[\{generation, color\}]} \end{pmatrix}$
$e^1_{i} = \begin{pmatrix} e_{L,i} \\ 0 \end{pmatrix}$	$\texttt{Fe1[\{generation\}]} = \begin{pmatrix} \texttt{FeL[\{generation\}]} \\ 0 \end{pmatrix}$
$e^2_{i} = \begin{pmatrix} 0 \\ e_{R,i} \end{pmatrix}$	$\texttt{Fe2[\{generation\}]} = \begin{pmatrix} 0 \\ \texttt{FeR[\{generation\}]} \end{pmatrix}$
$u^1_{i\alpha} = \begin{pmatrix} u_{L,i\alpha} \\ 0 \end{pmatrix}$	$\texttt{Fu1[\{generation, color\}]} = \begin{pmatrix} \texttt{FuL[\{generation, color\}]} \\ 0 \end{pmatrix}$
$u^2_{i\alpha} = \begin{pmatrix} 0 \\ u_{R,i\alpha} \end{pmatrix}$	$\texttt{Fu2[\{generation, color\}]} = \begin{pmatrix} 0 \\ \texttt{FuR[\{generation, color\}]} \end{pmatrix}$

$\nu_i = \begin{pmatrix} \text{FvL}\Big(\{\text{gt1}\}\Big) \\ 0 \end{pmatrix}$	`Fv[{generation}]` $= \begin{pmatrix} \texttt{FvL[\{generation\}]} \\ \texttt{0} \end{pmatrix}$
$\tilde{g}_i = \begin{pmatrix} \lambda_{\tilde{g},i} \\ \lambda^*_{\tilde{g},i} \end{pmatrix}$	`Glu[{generation}]` $= \begin{pmatrix} \texttt{fG[\{generation\}]} \\ \texttt{conj[fG[\{generation\}]]} \end{pmatrix}$
$\tilde{H}^0 = \begin{pmatrix} \tilde{H}^0_u \\ \tilde{H}^{0,*}_d \end{pmatrix}$	`H0` $= \begin{pmatrix} \texttt{FHu0} \\ \texttt{conj[FHd0]} \end{pmatrix}$
$\tilde{H}^- = \begin{pmatrix} \tilde{H}^+_u \\ \tilde{H}^{-,*}_d \end{pmatrix}$	`HC` $= \begin{pmatrix} \texttt{FHup} \\ \texttt{conj[FHdm]} \end{pmatrix}$
$\tilde{S} = \begin{pmatrix} \tilde{S} \\ \tilde{S}^* \end{pmatrix}$	`S` $= \begin{pmatrix} \texttt{FsR} \\ \texttt{conj[FsR]} \end{pmatrix}$
$\tilde{W}_i = \begin{pmatrix} \lambda_{\tilde{W},i} \\ \lambda^*_{\tilde{W},i} \end{pmatrix}$	`Wino[{generation}]` $= \begin{pmatrix} \texttt{fWB[\{generation\}]} \\ \texttt{conj[fWB[\{generation\}]]} \end{pmatrix}$

- Scalars

$\tilde{d}_{L,i\alpha}$	`SdL[{generation, color}]`	$\tilde{u}_{L,i\alpha}$	`SuL[{generation, color}]`
$\tilde{e}_{L,i}$	`SeL[{generation}]`	$\tilde{\nu}_{L,i}$	`SvL[{generation}]`
H^0_d	`SHd0`	H^-_d	`SHdm`
H^0_u	`SHu0`	H^+_u	`SHup`
$\tilde{d}_{R,i\alpha}$	`SdR[{generation, color}]`	$\tilde{u}_{R,i\alpha}$	`SuR[{generation, color}]`
$\tilde{e}_{R,i}$	`SeR[{generation}]`	S	`SsR`

- Vector Bosons

B_ρ	`VB[{lorentz}]`	$W^-_{i\rho}$	`VWB[{generation, lorentz}]`
$g_{i\rho}$	`VG[{generation, lorentz}]`		

- Ghosts

η^B	gB	$\text{gWB}\Big(\{\text{gt1}\}\Big)$	gWB[{generation}]
η^G_i	gG[{generation}]		

14.8.2 Particles for eigenstates 'EWSB'

- Fermions

$\tilde{\chi}^-_i = \begin{pmatrix} \lambda^-_i \\ \lambda^{+,*}_i \end{pmatrix}$	$\texttt{Cha[\{generation\}]} = \begin{pmatrix} \texttt{Lm[\{generation\}]} \\ \texttt{conj[Lp[\{generation\}]]} \end{pmatrix}$
$\tilde{\chi}^0_i = \begin{pmatrix} \lambda^0_i \\ \lambda^{0,*}_i \end{pmatrix}$	$\texttt{Chi[\{generation\}]} = \begin{pmatrix} \texttt{L0[\{generation\}]} \\ \texttt{conj[L0[\{generation\}]]} \end{pmatrix}$
$d_{i\alpha} = \begin{pmatrix} D_{L,i\alpha} \\ D^*_{R,i\alpha} \end{pmatrix}$	$\texttt{Fd[\{generation, color\}]} = \begin{pmatrix} \texttt{FDL[\{generation, color\}]} \\ \texttt{conj[FDR[\{generation, color\}]]} \end{pmatrix}$
$e_i = \begin{pmatrix} E_{L,i} \\ E^*_{R,i} \end{pmatrix}$	$\texttt{Fe[\{generation\}]} = \begin{pmatrix} \texttt{FEL[\{generation\}]} \\ \texttt{conj[FER[\{generation\}]]} \end{pmatrix}$
$u_{i\alpha} = \begin{pmatrix} U_{L,i\alpha} \\ U^*_{R,i\alpha} \end{pmatrix}$	$\texttt{Fu[\{generation, color\}]} = \begin{pmatrix} \texttt{FUL[\{generation, color\}]} \\ \texttt{conj[FUR[\{generation, color\}]]} \end{pmatrix}$
$\nu_i = \begin{pmatrix} \text{FvL}\Big(\{\text{gt1}\}\Big) \\ 0 \end{pmatrix}$	$\texttt{Fv[\{generation\}]} = \begin{pmatrix} \texttt{FvL[\{generation\}]} \\ 0 \end{pmatrix}$
$\tilde{g}_i = \begin{pmatrix} \lambda_{\tilde{g},i} \\ \lambda^*_{\tilde{g},i} \end{pmatrix}$	$\texttt{Glu[\{generation\}]} = \begin{pmatrix} \texttt{fG[\{generation\}]} \\ \texttt{conj[fG[\{generation\}]]} \end{pmatrix}$

- Scalars

$\tilde{d}_{i\alpha}$	Sd[{generation, color}]	$\tilde{\nu}_i$	Sv[{generation}]
$\tilde{u}_{i\alpha}$	Su[{generation, color}]	$\tilde{e}_i$	Se[{generation}]
h_i	hh[{generation}]	A^0_i	Ah[{generation}]
H^-_i	Hpm[{generation}]		

- Vector Bosons

$g_{i\rho}$	`VG[{generation, lorentz}]`	W^-_ρ	`VWm[{lorentz}]`
γ_ρ	`VP[{lorentz}]`	Z_ρ	`VZ[{lorentz}]`

- Ghosts

η^G_i	`gG[{generation}]`	η^-	`gWm`
η^+	`gWmC`	η^γ	`gP`
η^Z	`gZ`		

14.8.3 Parameters

g_1	`g1`	g_2	`g2`	g_3	`g3`
Y_u	`Yu`	T_u	`T[Yu]`	Y_d	`Yd`
T_d	`T[Yd]`	Y_e	`Ye`	T_e	`T[Ye]`
λ	`\[Lambda]`	T_λ	`T[\[Lambda]]`	κ	`\[Kappa]`
T_κ	`T[\[Kappa]]`	L_1	`L1`	ξ_1	`L[L1]`
M_S	`MS`	B_S	`B[MS]`	μ	`\[Mu]`
B_μ	`B[\[Mu]]`	m_q^2	`mq2`	m_l^2	`ml2`
$m_{H_d}^2$	`mHd2`	$m_{H_u}^2$	`mHu2`	m_d^2	`md2`
m_u^2	`mu2`	m_e^2	`me2`	m_S^2	`ms2`
M_1	`MassB`	M_2	`MassWB`	M_3	`MassG`
v_d	`vd`	v_u	`vu`	v_s	`vS`
Θ_W	`ThetaW`	$\phi_{\tilde{g}}$	`PhaseGlu`	Z^D	`ZD`
Z^V	`ZV`	Z^U	`ZU`	Z^E	`ZE`
Z^H	`ZH`	Z^A	`ZA`	Z^+	`ZP`
N	`ZN`	U	`UM`	V	`UP`
U^e_L	`ZEL`	U^e_R	`ZER`	U^d_L	`ZDL`
U^d_R	`ZDR`	U^u_L	`ZUL`	U^u_R	`ZUR`
β	`\[Beta]`				

Chapter 15

The $U(1)$-Extended Minimal Supersymmetric Standard Model

15.1 Superfields

15.1.1 Vector Superfields

SF	Spin $\frac{1}{2}$	Spin 1	$SU(N)$	Coupling	Name
$\hat{B}$	$\lambda_{\tilde{B}}$	B	$U(1)$	g_1	hypercharge
$\hat{W}$	$\lambda_{\tilde{W}}$	W^-	SU(2)	g_2	left
$\hat{g}$	$\lambda_{\tilde{g}}$	g	SU(3)	g_3	color
$\hat{U}$	λ_U	U	$U(1)$	g_p	additional

15.1.2 Chiral Superfields

SF	Spin 0	Spin $\frac{1}{2}$	Generations	$(U(1)\otimes \text{SU}(2)\otimes \text{SU}(3)\otimes U(1))$
$\hat{q}$	$\tilde{q}$	q	3	$(\frac{1}{6},\mathbf{2},\mathbf{3},Q_q)$
$\hat{l}$	$\tilde{l}$	l	3	$(-\frac{1}{2},\mathbf{2},\mathbf{1},Q_q)$
$\hat{H}_d$	H_d	$\tilde{H}_d$	1	$(-\frac{1}{2},\mathbf{2},\mathbf{1},Q_{H_d})$
$\hat{H}_u$	H_u	$\tilde{H}_u$	1	$(\frac{1}{2},\mathbf{2},\mathbf{1},Q_{H_u})$
$\hat{d}$	$\tilde{d}_R^*$	d_R^*	3	$(\frac{1}{3},\mathbf{1},\overline{\mathbf{3}},Q_d)$
$\hat{u}$	$\tilde{u}_R^*$	u_R^*	3	$(-\frac{2}{3},\mathbf{1},\overline{\mathbf{3}},Q_u)$
$\hat{e}$	$\tilde{e}_R^*$	e_R^*	3	$(1,\mathbf{1},\mathbf{1},Q_e)$
$\hat{s}$	S	$\tilde{S}$	1	$(0,\mathbf{1},\mathbf{1},Q_s)$

15.2 Superpotential and Lagrangian

15.2.1 Superpotential

$$W = Y_u\, \hat{q}\, \hat{H}_u\, \hat{u}\, - Y_d\, \hat{q}\, \hat{H}_d\, \hat{d}\, - Y_e\, \hat{l}\, \hat{H}_d\, \hat{e}\, + \lambda\, \hat{H}_u\, \hat{H}_d\, \hat{s} \tag{15.1}$$

15.2.2 Softbreaking terms

$$\begin{aligned} L_{SB,W} = & - H_d^0 H_u^0 S T_\lambda + H_d^- H_u^+ S T_\lambda + H_d^0 \tilde{d}^*_{R,k\gamma} \delta_{\alpha\gamma} \tilde{d}_{L,i\alpha} T_{d,ik} - H_d^- \tilde{d}^*_{R,k\gamma} \delta_{\alpha\gamma} \tilde{u}_{L,i\alpha} T_{d,ik} \\ & + H_d^0 \tilde{e}^*_{R,k} \tilde{e}_{L,i} T_{e,ik} - H_d^- \tilde{e}^*_{R,k} \tilde{\nu}_{L,i} T_{e,ik} - H_u^+ \tilde{u}^*_{R,k\gamma} \delta_{\alpha\gamma} \tilde{d}_{L,i\alpha} T_{u,ik} + H_u^0 \tilde{u}^*_{R,k\gamma} \delta_{\alpha\gamma} \tilde{u}_{L,i\alpha} T_{u,ik} + \text{h.c.} \end{aligned} \tag{15.2}$$

$$\begin{aligned} L_{SB,\phi} = & - m_{H_d}^2 |H_d^0|^2 - m_{H_d}^2 |H_d^-|^2 - m_{H_u}^2 |H_u^0|^2 - m_{H_u}^2 |H_u^+|^2 - m_S^2 |S|^2 \\ & - \tilde{d}^*_{L,j\beta} \delta_{\alpha\beta} m^2_{q,ij} \tilde{d}_{L,i\alpha} - \tilde{d}^*_{R,i\alpha} \delta_{\alpha\beta} m^2_{d,ij} \tilde{d}_{R,j\beta} - \tilde{e}^*_{L,j} m^2_{l,ij} \tilde{e}_{L,i} - \tilde{e}^*_{R,i} m^2_{e,ij} \tilde{e}_{R,j} \\ & - \tilde{u}^*_{L,j\beta} \delta_{\alpha\beta} m^2_{q,ij} \tilde{u}_{L,i\alpha} - \tilde{u}^*_{R,i\alpha} \delta_{\alpha\beta} m^2_{u,ij} \tilde{u}_{R,j\beta} - \tilde{\nu}^*_{L,j} m^2_{l,ij} \tilde{\nu}_{L,i} \end{aligned} \tag{15.3}$$

$$L_{SB,\lambda} = \frac{1}{2} \left(-\lambda_{\tilde{B}}^2 M_1 - \lambda_{\tilde{U}}^2 M_Z - M_2 \lambda^2_{\tilde{W},i} - M_3 \lambda^2_{\tilde{g},i} + \text{h.c.} \right) \tag{15.4}$$

15.2.3 Gauge fixing terms

Gauge fixing terms for eigenstates 'GaugeES'

$$L_{GF} = -\frac{1}{2} \partial_\mu g \xi_G^{-1} - \frac{1}{2} \partial_\mu W^- \xi_W^{-1} \tag{15.5}$$

Gauge fixing terms for eigenstates 'TEMP'

$$L_{GF} = -\frac{1}{2} \partial_\mu \gamma \xi_P^{-1} - \frac{1}{2} \partial_\mu g \xi_G^{-1} - \frac{1}{2} \xi_Z^{-1} \Big(- A_1^0 m_Z \xi_Z + \partial_\mu Z \Big) - \xi_W^{-1} \Big(i H_1^- m_{W^-} \xi_W + \partial_\mu W^- \Big) \tag{15.6}$$

Gauge fixing terms for eigenstates 'EWSB'

$$L_{GF} = -\frac{1}{2} \partial_\mu \gamma \xi_P^{-1} - \frac{1}{2} \partial_\mu g \xi_G^{-1} - \frac{1}{2} \xi_{Z1}^{-1} \Big(- A_1^0 m_{Z_1} \xi_{Z1} + \partial_\mu Z_1 \Big) - \xi_W^{-1} \Big(i H_1^- m_{W^-} \xi_W + \partial_\mu W^- \Big) \tag{15.7}$$

15.2.4 Fields integrated out

None

15.3 Field Rotations

15.3.1 Rotations in gauge sector for eigenstates 'EWSB'

$$Z_\rho = \cos\Theta_Z Z_{2,\rho} + \sin\Theta_Z Z_{1,\rho} \tag{15.8}$$

$$U_\rho = \cos\Theta_Z Z_{1,\rho} - \sin\Theta_W Z_{2,\rho} \tag{15.9}$$

$$\lambda_{\tilde{W},1} = \frac{1}{\sqrt{2}} \tilde{W}^- + \frac{1}{\sqrt{2}} \tilde{W}^+ \tag{15.10}$$

$$\lambda_{\tilde{W},2} = -i\frac{1}{\sqrt{2}}\tilde{W}^- + i\frac{1}{\sqrt{2}}\tilde{W}^+ \tag{15.11}$$

$$\lambda_{\tilde{W},3} = \tilde{W}^0 \tag{15.12}$$

15.3.2 Rotations in Mass sector for eigenstates 'EWSB'

Mass Matrices for Scalars

- **Mass matrix for Down-Squarks**, Basis: $\Big(\tilde{d}_{L,o_1\alpha_1}, \tilde{d}_{R,o_2\alpha_2}\Big), \Big(\tilde{d}^*_{L,p_1\beta_1}, \tilde{d}^*_{R,p_2\beta_2}\Big)$

$$m^2_{\tilde{d}} = \begin{pmatrix} m_{11} & \frac{1}{2}\delta_{\alpha_1\beta_2}\Big(\sqrt{2}v_d T_{d,o_1p_2} - v_s v_u \lambda^* Y_{d,o_1p_2}\Big) \\ \frac{1}{2}\Big(\sqrt{2}v_d T^*_{d,p_1o_2} - v_s v_u \lambda Y^*_{d,p_1o_2}\Big)\delta_{\alpha_2\beta_1} & m_{22} \end{pmatrix} \tag{15.13}$$

$$\begin{aligned} m_{11} = &\frac{1}{24}\delta_{\alpha_1\beta_1}\Big(\Big(3\Big(4g_p^2 Q_q\Big(Q_{H_d}v_d^2 + Q_{H_u}v_u^2 + Q_s v_s^2\Big) + g_2^2\Big(-v_d^2 + v_u^2\Big)\Big) + g_1^2\Big(-v_d^2 + v_u^2\Big)\Big)\delta_{o_1p_1} \\ &+ 12\Big(2m^2_{q,o_1p_1} + v_d^2\sum_{a=1}^{3}Y^*_{d,p_1a}Y_{d,o_1a}\Big)\Big) \end{aligned} \tag{15.14}$$

$$m_{22} = \frac{1}{12}\delta_{\alpha_2\beta_2}\Big(6\Big(2m^2_{d,p_2o_2} + v_d^2\sum_{a=1}^{3}Y^*_{d,ao_2}Y_{d,ap_2}\Big) + \Big(6g_p^2 Q_d\Big(Q_{H_d}v_d^2 + Q_{H_u}v_u^2 + Q_s v_s^2\Big) + g_1^2\Big(-v_d^2 + v_u^2\Big)\Big)\delta_{o_2p_2}\Big) \tag{15.15}$$

This matrix is diagonalized by Z^D:

$$Z^D m^2_{\tilde{d}} Z^{D,\dagger} = m^{dia}_{2,\tilde{d}} \tag{15.16}$$

with

$$\tilde{d}_{L,i\alpha} = \sum_{t_2} Z^{D,*}_{ji}\tilde{d}_{j\alpha}, \qquad \tilde{d}_{R,i\alpha} = \sum_{t_2} Z^{D,*}_{ji}\tilde{d}_{j\alpha} \tag{15.17}$$

- **Mass matrix for Sneutrinos**, Basis: $\left(\tilde{\nu}_{L,o_1}\right), \left(\tilde{\nu}^*_{L,p_1}\right)$

$$m^2_{\tilde{\nu}} = \begin{pmatrix} m_{11} \end{pmatrix} \tag{15.18}$$

$$m_{11} = \frac{1}{8}\Big(\Big(4g_p^2 Q_q\Big(Q_{H_d}v_d^2 + Q_{H_u}v_u^2 + Q_s v_s^2\Big) + g_1^2\Big(-v_u^2 + v_d^2\Big) + g_2^2\Big(-v_u^2 + v_d^2\Big)\Big)\delta_{o_1p_1} + 8m^2_{l,o_1p_1}\Big) \tag{15.19}$$

This matrix is diagonalized by Z^V:

$$Z^V m^2_{\tilde{\nu}} Z^{V,\dagger} = m^{dia}_{2,\tilde{\nu}} \tag{15.20}$$

with

$$\tilde{\nu}_{L,i} = \sum_{t_2} Z^{V,*}_{ji}\tilde{\nu}_j \tag{15.21}$$

- **Mass matrix for Up-Squarks**, Basis: $\left(\tilde{u}_{L,o_1\alpha_1}, \tilde{u}_{R,o_2\alpha_2}\right), \left(\tilde{u}^*_{L,p_1\beta_1}, \tilde{u}^*_{R,p_2\beta_2}\right)$

$$m^2_{\tilde{u}} = \left(\begin{array}{cc} m_{11} & \frac{1}{2}\delta_{\alpha_1\beta_2}\Big(\sqrt{2}v_u T_{u,o_1p_2} - v_d v_s \lambda^* Y_{u,o_1p_2}\Big) \\ \frac{1}{2}\Big(\sqrt{2}v_u T^*_{u,p_1o_2} - v_d v_s \lambda Y^*_{u,p_1o_2}\Big)\delta_{\alpha_2\beta_1} & m_{22} \end{array} \right) \tag{15.22}$$

$$\begin{aligned} m_{11} &= \frac{1}{24}\delta_{\alpha_1\beta_1}\Big(\Big(3\Big(4g_p^2 Q_q\Big(Q_{H_d}v_d^2 + Q_{H_u}v_u^2 + Q_s v_s^2\Big) + g_2^2\Big(-v_u^2 + v_d^2\Big)\Big) + g_1^2\Big(-v_d^2 + v_u^2\Big)\Big)\delta_{o_1p_1} \\ &+ 12\Big(2m^2_{q,o_1p_1} + v_u^2\sum_{a=1}^{3} Y^*_{u,p_1a}Y_{u,o_1a}\Big)\Big) \end{aligned} \tag{15.23}$$

$$m_{22} = \frac{1}{6}\delta_{\alpha_2\beta_2}\Big(\Big(3g_p^2 Q_u\Big(Q_{H_d}v_d^2 + Q_{H_u}v_u^2 + Q_s v_s^2\Big) + g_1^2\Big(-v_u^2 + v_d^2\Big)\Big)\delta_{o_2p_2} + 3v_u^2\sum_{a=1}^{3} Y^*_{u,ao_2}Y_{u,ap_2} + 6m^2_{u,p_2o_2}\Big) \tag{15.24}$$

This matrix is diagonalized by Z^U:

$$Z^U m^2_{\tilde{u}} Z^{U,\dagger} = m^{dia}_{2,\tilde{u}} \tag{15.25}$$

with

$$\tilde{u}_{L,i\alpha} = \sum_{t_2} Z^{U,*}_{ji}\tilde{u}_{j\alpha}\,, \qquad \tilde{u}_{R,i\alpha} = \sum_{t_2} Z^{U,*}_{ji}\tilde{u}_{j\alpha} \tag{15.26}$$

- **Mass matrix for Sleptons**, Basis: $\left(\tilde{e}_{L,o_1}, \tilde{e}_{R,o_2}\right), \left(\tilde{e}^*_{L,p_1}, \tilde{e}^*_{R,p_2}\right)$

$$m^2_{\tilde{e}} = \left(\begin{array}{cc} m_{11} & -\frac{1}{2}v_s v_u \lambda^* Y_{e,o_1p_2} + \frac{1}{\sqrt{2}}v_d T_{e,o_1p_2} \\ -\frac{1}{2}v_s v_u \lambda Y^*_{e,p_1o_2} + \frac{1}{\sqrt{2}}v_d T^*_{e,p_1o_2} & m_{22} \end{array} \right) \tag{15.27}$$

$$\begin{aligned} m_{11} &= \frac{1}{8}\Big(\Big(4g_p^2 Q_q\Big(Q_{H_d}v_d^2 + Q_{H_u}v_u^2 + Q_s v_s^2\Big) + g_1^2\Big(-v_u^2 + v_d^2\Big) + g_2^2\Big(-v_d^2 + v_u^2\Big)\Big)\delta_{o_1p_1} + 8m^2_{l,o_1p_1} \\ &+ 4v_d^2\sum_{a=1}^{3} Y^*_{e,p_1a}Y_{e,o_1a}\Big) \end{aligned} \tag{15.28}$$

$$m_{22} = \frac{1}{4}\Big(\Big(2g_p^2 Q_e\Big(Q_{H_d}v_d^2 + Q_{H_u}v_u^2 + Q_s v_s^2\Big) + g_1^2\Big(-v_d^2 + v_u^2\Big)\Big)\delta_{o_2p_2} + 2v_d^2\sum_{a=1}^{3} Y^*_{e,ao_2}Y_{e,ap_2} + 4m^2_{e,p_2o_2}\Big) \tag{15.29}$$

This matrix is diagonalized by Z^E:

$$Z^E m^2_{\tilde{e}} Z^{E,\dagger} = m^{dia}_{2,\tilde{e}} \tag{15.30}$$

with

$$\tilde{e}_{L,i} = \sum_{t_2} Z^{E,*}_{ji}\tilde{e}_j\,, \qquad \tilde{e}_{R,i} = \sum_{t_2} Z^{E,*}_{ji}\tilde{e}_j \tag{15.31}$$

- **Mass matrix for Higgs**, Basis: $\left(\phi_d, \phi_u, \phi_s\right), \left(\phi_d, \phi_u, \phi_s\right)$

$$m_h^2 = \begin{pmatrix} m_{11} & m^*_{21} & m^*_{31} \\ m_{21} & m_{22} & m^*_{32} \\ m_{31} & m_{32} & m_{33} \end{pmatrix} \tag{15.32}$$

$$\begin{aligned} m_{11} &= \frac{1}{8}\Big(8m_{H_d}^2 + 3g_1^2 v_d^2 + 3g_2^2 v_d^2 + 12g_p^2 Q_{H_d}^2 v_d^2 + 4g_p^2 Q_{H_d} Q_s v_s^2 - g_1^2 v_u^2 - g_2^2 v_u^2 \\ &\quad + 4g_p^2 Q_{H_d} Q_{H_u} v_u^2 + 4\Big(v_s^2 + v_u^2\Big)|\lambda|^2\Big) \end{aligned} \tag{15.33}$$

$$m_{21} = \frac{1}{4}\Big(- 2\sqrt{2} v_s \Re\Big(T_\lambda\Big) - \Big(- 4g_p^2 Q_{H_d} Q_{H_u} + g_1^2 + g_2^2\Big) v_d v_u\Big) + v_d v_u |\lambda|^2 \tag{15.34}$$

$$\begin{aligned} m_{22} &= \frac{1}{8}\Big(8m_{H_u}^2 - g_1^2 v_d^2 - g_2^2 v_d^2 + 4g_p^2 Q_{H_d} Q_{H_u} v_d^2 + 4g_p^2 Q_{H_u} Q_s v_s^2 + 3g_1^2 v_u^2 + 3g_2^2 v_u^2 \\ &\quad + 12g_p^2 Q_{H_u}^2 v_u^2 + 4\Big(v_d^2 + v_s^2\Big)|\lambda|^2\Big) \end{aligned} \tag{15.35}$$

$$m_{31} = -\frac{1}{\sqrt{2}} v_u \Re\Big(T_\lambda\Big) + g_p^2 Q_{H_d} Q_s v_d v_s + v_d v_s |\lambda|^2 \tag{15.36}$$

$$m_{32} = -\frac{1}{\sqrt{2}} v_d \Re\Big(T_\lambda\Big) + g_p^2 Q_{H_u} Q_s v_s v_u + v_s v_u |\lambda|^2 \tag{15.37}$$

$$m_{33} = \frac{1}{2}\Big(2m_S^2 + g_p^2 Q_s\Big(3Q_s v_s^2 + Q_{H_d} v_d^2 + Q_{H_u} v_u^2\Big) + \Big(v_d^2 + v_u^2\Big)|\lambda|^2\Big) \tag{15.38}$$

This matrix is diagonalized by Z^H:

$$Z^H m_h^2 Z^{H,\dagger} = m_{2,h}^{dia} \tag{15.39}$$

with

$$\phi_d = \sum_{t_2} Z_{j1}^{H,*} h_j\,, \qquad \phi_u = \sum_{t_2} Z_{j2}^{H,*} h_j\,, \qquad \phi_s = \sum_{t_2} Z_{j3}^{H,*} h_j \tag{15.40}$$

- **Mass matrix for Pseudo-Scalar Higgs**, Basis: $\left(\sigma_d, \sigma_u, \sigma_s\right), \left(\sigma_d, \sigma_u, \sigma_s\right)$

$$m_{A^0}^2 = \begin{pmatrix} m_{11} & \frac{1}{\sqrt{2}} v_s \Re\Big(T_\lambda\Big) & \frac{1}{\sqrt{2}} v_u \Re\Big(T_\lambda\Big) \\ \frac{1}{\sqrt{2}} v_s \Re\Big(T_\lambda\Big) & m_{22} & \frac{1}{\sqrt{2}} v_d \Re\Big(T_\lambda\Big) \\ \frac{1}{\sqrt{2}} v_u \Re\Big(T_\lambda\Big) & \frac{1}{\sqrt{2}} v_d \Re\Big(T_\lambda\Big) & m_{33} \end{pmatrix} \tag{15.41}$$

$$\begin{aligned} m_{11} &= \frac{1}{8}\Big(8m_{H_d}^2 + g_1^2 v_d^2 + g_2^2 v_d^2 + 4g_p^2 Q_{H_d}^2 v_d^2 + 4g_p^2 Q_{H_d} Q_s v_s^2 - g_1^2 v_u^2 - g_2^2 v_u^2 \\ &\quad + 4g_p^2 Q_{H_d} Q_{H_u} v_u^2 + 4\Big(v_s^2 + v_u^2\Big)|\lambda|^2\Big) \end{aligned} \tag{15.42}$$

$$m_{22} = \frac{1}{8}\Big(8m_{H_u}^2 - g_1^2 v_d^2 - g_2^2 v_d^2 + 4g_p^2 Q_{H_d} Q_{H_u} v_d^2 + 4g_p^2 Q_{H_u} Q_s v_s^2 + g_1^2 v_u^2 + g_2^2 v_u^2$$

$$+ 4g_p^2 Q_{H_u}^2 v_u^2 + 4\Big(v_d^2 + v_s^2\Big)|\lambda|^2\Big) \tag{15.43}$$

$$m_{33} = \frac{1}{2}\Big(2m_S^2 + g_p^2 Q_s\Big(Q_{H_d} v_d^2 + Q_{H_u} v_u^2 + Q_s v_s^2\Big) + \Big(v_d^2 + v_u^2\Big)|\lambda|^2\Big) \tag{15.44}$$

This matrix is diagonalized by Z^A:

$$Z^A m_{A^0}^2 Z^{A,\dagger} = m_{2,A^0}^{dia} \tag{15.45}$$

with

$$\sigma_d = \sum_{t_2} Z_{j1}^{A,*} A_j^0\,, \qquad \sigma_u = \sum_{t_2} Z_{j2}^{A,*} A_j^0\,, \qquad \sigma_s = \sum_{t_2} Z_{j3}^{A,*} A_j^0 \tag{15.46}$$

- **Mass matrix for Charged Higgs**, Basis: $\left(H_d^-, H_u^{+,*}\right), \left(H_d^{-,*}, H_u^+\right)$

$$m_{H^-}^2 = \begin{pmatrix} m_{11} & \frac{1}{4}\Big(2\sqrt{2} v_s T_\lambda - 2v_d v_u |\lambda|^2 + g_2^2 v_d v_u\Big) \\ \frac{1}{4}\Big(2\sqrt{2} v_s T_\lambda^* - 2v_d v_u |\lambda|^2 + g_2^2 v_d v_u\Big) & m_{22} \end{pmatrix} \tag{15.47}$$

$$m_{11} = \frac{1}{8}\Big(8m_{H_d}^2 + g_1^2 v_d^2 + g_2^2 v_d^2 + 4g_p^2 Q_{H_d}^2 v_d^2 + 4g_p^2 Q_{H_d} Q_s v_s^2 - g_1^2 v_u^2 + g_2^2 v_u^2$$
$$+ 4g_p^2 Q_{H_d} Q_{H_u} v_u^2 + 4v_s^2|\lambda|^2\Big) \tag{15.48}$$

$$m_{22} = \frac{1}{8}\Big(8m_{H_u}^2 - g_1^2 v_d^2 + g_2^2 v_d^2 + 4g_p^2 Q_{H_d} Q_{H_u} v_d^2 + 4g_p^2 Q_{H_u} Q_s v_s^2 + g_1^2 v_u^2 + g_2^2 v_u^2$$
$$+ 4g_p^2 Q_{H_u}^2 v_u^2 + 4v_s^2|\lambda|^2\Big) \tag{15.49}$$

This matrix is diagonalized by Z^+:

$$Z^+ m_{H^-}^2 Z^{+,\dagger} = m_{2,H^-}^{dia} \tag{15.50}$$

with

$$H_d^- = \sum_{t_2} Z_{j1}^{+,*} H_j^-\,, \qquad H_u^+ = \sum_{t_2} Z_{j2}^{+} H_j^+ \tag{15.51}$$

The mixing matrix can be parametrized by

$$Z^+ = \begin{pmatrix} -\cos\beta & \sin\beta \\ \sin\beta & \cos\beta \end{pmatrix} \tag{15.52}$$

Mass Matrices for Fermions

- **Mass matrix for Neutralinos**, Basis: $\Big(\lambda_U, \lambda_{\tilde{B}}, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0, \tilde{S}\Big), \Big(\lambda_U, \lambda_{\tilde{B}}, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0, \tilde{S}\Big)$

$$m_{\tilde{\chi}^0} = \begin{pmatrix} M_Z & 0 & 0 & g_p Q_{H_d} v_d & g_p Q_{H_u} v_u & g_p Q_s v_s \\ 0 & M_1 & 0 & -\frac{1}{2} g_1 v_d & \frac{1}{2} g_1 v_u & 0 \\ 0 & 0 & M_2 & \frac{1}{2} g_2 v_d & -\frac{1}{2} g_2 v_u & 0 \\ g_p Q_{H_d} v_d & -\frac{1}{2} g_1 v_d & \frac{1}{2} g_2 v_d & 0 & -\frac{1}{\sqrt{2}} v_s \lambda & -\frac{1}{\sqrt{2}} v_u \lambda \\ g_p Q_{H_u} v_u & \frac{1}{2} g_1 v_u & -\frac{1}{2} g_2 v_u & -\frac{1}{\sqrt{2}} v_s \lambda & 0 & -\frac{1}{\sqrt{2}} v_d \lambda \\ g_p Q_s v_s & 0 & 0 & -\frac{1}{\sqrt{2}} v_u \lambda & -\frac{1}{\sqrt{2}} v_d \lambda & 0 \end{pmatrix} \tag{15.53}$$

This matrix is diagonalized by N:

$$N m_{\tilde{\chi}^0} N^\dagger = m^{dia}_{\tilde{\chi}^0} \tag{15.54}$$

with

$$\lambda_U = \sum_{t_2} N^*_{j1}\lambda^0_j\,, \qquad \lambda_{\tilde{B}} = \sum_{t_2} N^*_{j2}\lambda^0_j\,, \qquad \tilde{W}^0 = \sum_{t_2} N^*_{j3}\lambda^0_j \tag{15.55}$$

$$\tilde{H}^0_d = \sum_{t_2} N^*_{j4}\lambda^0_j\,, \qquad \tilde{H}^0_u = \sum_{t_2} N^*_{j5}\lambda^0_j\,, \qquad \tilde{S} = \sum_{t_2} N^*_{j6}\lambda^0_j \tag{15.56}$$

- **Mass matrix for Charginos**, Basis: $\left(\tilde{W}^-, \tilde{H}^-_d\right), \left(\tilde{W}^+, \tilde{H}^+_u\right)$

$$m_{\tilde{\chi}^-} = \begin{pmatrix} M_2 & \frac{1}{\sqrt{2}} g_2 v_u \\ \frac{1}{\sqrt{2}} g_2 v_d & \frac{1}{\sqrt{2}} v_s \lambda \end{pmatrix} \tag{15.57}$$

This matrix is diagonalized by U and V

$$U^* m_{\tilde{\chi}^-} V^\dagger = m^{dia}_{\tilde{\chi}^-} \tag{15.58}$$

with

$$\tilde{W}^- = \sum_{t_2} U^*_{j1}\lambda^-_j\,, \qquad \tilde{H}^-_d = \sum_{t_2} U^*_{j2}\lambda^-_j \tag{15.59}$$

$$\tilde{W}^+ = \sum_{t_2} V^*_{1j}\lambda^+_j\,, \qquad \tilde{H}^+_u = \sum_{t_2} V^*_{2j}\lambda^+_j \tag{15.60}$$

- **Mass matrix for Leptons**, Basis: $\left(e_{L,o_1}\right), \left(e^*_{R,p_1}\right)$

$$m_e = \begin{pmatrix} \frac{1}{\sqrt{2}} v_d Y_{e,o_1 p_1} \end{pmatrix} \tag{15.61}$$

This matrix is diagonalized by U^e_L and U^e_R

$$U^{e,*}_L m_e U^{e,\dagger}_R = m^{dia}_e \tag{15.62}$$

with

$$e_{L,i} = \sum_{t_2} U^{e,*}_{L,ji} E_{L,j} \tag{15.63}$$

$$e_{R,i} = \sum_{t_2} U^e_{R,ij} E^*_{R,j} \tag{15.64}$$

- **Mass matrix for Down-Quarks**, Basis: $\left(d_{L,o_1\alpha_1}\right), \left(d^*_{R,p_1\beta_1}\right)$

$$m_d = \begin{pmatrix} \frac{1}{\sqrt{2}} v_d \delta_{\alpha_1\beta_1} Y_{d,o_1 p_1} \end{pmatrix} \tag{15.65}$$

This matrix is diagonalized by U^d_L and U^d_R

$$U^{d,*}_L m_d U^{d,\dagger}_R = m^{dia}_d \tag{15.66}$$

with

$$d_{L,i\alpha} = \sum_{t_2} U^{d,*}_{L,ji} D_{L,j\alpha} \tag{15.67}$$

$$d_{R,i\alpha} = \sum_{t_2} U^{d}_{R,ij} D^*_{R,j\alpha} \tag{15.68}$$

- **Mass matrix for Up-Quarks**, Basis: $\left(u_{L,o_1\alpha_1}\right), \left(u^*_{R,p_1\beta_1}\right)$

$$m_u = \left(\begin{array}{c} \frac{1}{\sqrt{2}} v_u \delta_{\alpha_1\beta_1} Y_{u,o_1p_1} \end{array} \right) \tag{15.69}$$

This matrix is diagonalized by U^u_L and U^u_R

$$U^{u,*}_L m_u U^{u,\dagger}_R = m^{dia}_u \tag{15.70}$$

with

$$u_{L,i\alpha} = \sum_{t_2} U^{u,*}_{L,ji} U_{L,j\alpha} \tag{15.71}$$

$$u_{R,i\alpha} = \sum_{t_2} U^{u}_{R,ij} U^*_{R,j\alpha} \tag{15.72}$$

15.4 Vacuum Expectation Values

15.4.1 VEVs for eigenstates 'EWSB'

$$H^0_d = \frac{1}{\sqrt{2}}\phi_d + \frac{1}{\sqrt{2}}v_d + i\frac{1}{\sqrt{2}}\sigma_d \tag{15.73}$$

$$H^0_u = \frac{1}{\sqrt{2}}\phi_u + \frac{1}{\sqrt{2}}v_u + i\frac{1}{\sqrt{2}}\sigma_u \tag{15.74}$$

$$S = \frac{1}{\sqrt{2}}\phi_s + \frac{1}{\sqrt{2}}v_s + i\frac{1}{\sqrt{2}}\sigma_s \tag{15.75}$$

15.5 Tadpole Equations

15.5.1 Tadpole Equations for eigenstates 'TEMP'

$$\begin{aligned}\frac{\partial V}{\partial v_d} = {} & \frac{1}{8}\Big(\Big(4g_p^2 Q_{H_d}^2 + g_1^2 + g_2^2\Big)v_d^3 \\ & + v_d\Big(4v_s^2\Big(g_p^2 Q_{H_d} Q_s + |\lambda|^2\Big) + 8m^2_{H_d} - v_u^2\Big(- 4g_p^2 Q_{H_d} Q_{H_u} - 4|\lambda|^2 + g_1^2 + g_2^2\Big)\Big) - 2\sqrt{2}v_s v_u\Big(T^*_\lambda + T_\lambda\Big)\Big)\end{aligned} \tag{15.76}$$

$$\frac{\partial V}{\partial v_u} = \frac{1}{8}\Big(v_u\Big(8m_{H_u}^2 + g_1^2 v_u^2 + g_2^2 v_u^2 + 4g_p^2 Q_{H_u}^2 v_u^2 - v_d^2\Big(-4g_p^2 Q_{H_d} Q_{H_u} - 4|\lambda|^2 + g_1^2 + g_2^2\Big) \\ + 4v_s^2\Big(g_p^2 Q_{H_u} Q_s + |\lambda|^2\Big)\Big) \\ - 4\sqrt{2} v_d v_s \Re\Big(T_\lambda\Big)\Big) \tag{15.77}$$

$$\frac{\partial V}{\partial v_s} = \frac{1}{4}\Big(2g_p^2 Q_s^2 v_s^3 + 2v_s\Big(2m_S^2 + g_p^2 Q_s\Big(Q_{H_d} v_d^2 + Q_{H_u} v_u^2\Big) + \Big(v_d^2 + v_u^2\Big)|\lambda|^2\Big) - \sqrt{2} v_d v_u\Big(T_\lambda^* + T_\lambda\Big)\Big) \tag{15.78}$$

15.5.2 Tadpole Equations for eigenstates 'EWSB'

$$\frac{\partial V}{\partial v_d} = \frac{1}{8}\Big(v_d\Big(8m_{H_d}^2 + g_2^2 v_d^2 + 4g_p^2 Q_{H_d}^2 v_d^2 + 4g_p^2 Q_{H_d} Q_s v_s^2 - g_2^2 v_u^2 + 4g_p^2 Q_{H_d} Q_{H_u} v_u^2 \\ + g_1^2\Big(-v_u^2 + v_d^2\Big)\Big) \\ + 4v_d\Big(v_s^2 + v_u^2\Big)|\lambda|^2 - 4\sqrt{2} v_s v_u \Re\Big(T_\lambda\Big)\Big) \tag{15.79}$$

$$\frac{\partial V}{\partial v_u} = \frac{1}{8}\Big(v_u\Big(8m_{H_u}^2 - g_2^2 v_d^2 + 4g_p^2 Q_{H_d} Q_{H_u} v_d^2 + 4g_p^2 Q_{H_u} Q_s v_s^2 + g_2^2 v_u^2 + 4g_p^2 Q_{H_u}^2 v_u^2 \\ + g_1^2\Big(-v_d^2 + v_u^2\Big)\Big) \\ + 4\Big(v_d^2 + v_s^2\Big)v_u|\lambda|^2 - 4\sqrt{2} v_d v_s \Re\Big(T_\lambda\Big)\Big) \tag{15.80}$$

$$\frac{\partial V}{\partial v_s} = \frac{1}{2}\Big(-\sqrt{2} v_d v_u \Re\Big(T_\lambda\Big) + v_s\Big(2m_S^2 + g_p^2 Q_s\Big(Q_{H_d} v_d^2 + Q_{H_u} v_u^2 + Q_s v_s^2\Big)\Big) + v_s\Big(v_d^2 + v_u^2\Big)|\lambda|^2\Big) \tag{15.81}$$

15.6 Particle content for eigenstates 'EWSB'

Name	Type	complex/real	Generations	Indices
$\tilde{d}$	Scalar	complex	6	generation, color
$\tilde{\nu}$	Scalar	complex	3	generation
$\tilde{u}$	Scalar	complex	6	generation, color
$\tilde{e}$	Scalar	complex	6	generation
h	Scalar	real	3	generation
A^0	Scalar	real	3	generation
H^-	Scalar	complex	2	generation
ν	Fermion	Dirac	3	generation
$\tilde{g}$	Fermion	Majorana	8	generation
$\tilde{\chi}^0$	Fermion	Majorana	6	generation
$\tilde{\chi}^-$	Fermion	Dirac	2	generation
e	Fermion	Dirac	3	generation
d	Fermion	Dirac	3	generation, color
u	Fermion	Dirac	3	generation, color

g	Vector	real	8	generation, lorentz
W^-	Vector	complex	1	lorentz
γ	Vector	real	1	lorentz
Z_1	Vector	real	1	lorentz
Z_2	Vector	real	1	lorentz
η^G	Ghost	real	8	generation
η^-	Ghost	complex	1	
η^+	Ghost	complex	1	
η^γ	Ghost	real	1	
η^{Z_1}	Ghost	real	1	
η^{Z_2}	Ghost	real	1	

15.7 Modelfile for SARAH

```
Off[General::spell]
Print["Model file for the UMSSM loaded"];

ModelNameLaTeX ="UMSSM";


(*-------------------------------------------*)
(*   Particle Content*)
(*-------------------------------------------*)

(* Gauge Superfields *)

Gauge[[1]]={B,   U[1], hypercharge, g1,False};
Gauge[[2]]={WB, SU[2], left,        g2,True};
Gauge[[3]]={G,  SU[3], color,       g3,False};
Gauge[[4]]={U,   U[1], additional,  gp,False};


(* Chiral Superfields *)

Fields[[1]] = {{uL,  dL},  3, q,   1/6, 2, 3, Qq};
Fields[[2]] = {{vL,  eL},  3, l,  -1/2, 2, 1, Ql};
Fields[[3]] = {{Hd0, Hdm}, 1, Hd, -1/2, 2, 1, QHd};
Fields[[4]] = {{Hup, Hu0}, 1, Hu,  1/2, 2, 1, QHu};

Fields[[5]] = {conj[dR], 3, d,  1/3, 1, -3, Qd};
Fields[[6]] = {conj[uR], 3, u, -2/3, 1, -3, Qu};
Fields[[7]] = {conj[eR], 3, e,    1, 1,  1, Qe};
Fields[[8]] = {sR, 1, s,    0, 1,  1, Qs};


(*-----------------------------------------------------*)
(* Superpotential *)
(*-----------------------------------------------------*)

SuperPotential = { {{1, Yu},{q,Hu,u}}, {{-1,Yd},{q,Hd,d}},
                   {{-1,Ye},{l,Hd,e}},
                   {{1,\[Lambda]},{Hu,Hd,s}}};


(*-------------------------------------------*)
(* Integrate Out or Delete Particles         *)
(*-------------------------------------------*)
```

```
IntegrateOut={};
DeleteParticles={};


(*----------------------------------------------*)
(*   DEFINITION                                 *)
(*----------------------------------------------*)

NameOfStates={GaugeES,TEMP, EWSB};

(* ----- Before EWSB ----- *)


DEFINITION[GaugeES][GaugeFixing]=
{ {Der[VWB],  -1/(2 RXi[W])},
     {Der[VG],   -1/(2 RXi[G]) }};

(* ----- After EWSB ----- *)

DEFINITION[TEMP][GaugeSector]=
{{VWB,{1,{VWm,1/Sqrt[2]},{conj[VWm],1/Sqrt[2]}},
      {2,{VWm,-\[ImaginaryI]/Sqrt[2]},{conj[VWm],\[ImaginaryI]/Sqrt[2]}},
      {3,{VP,Sin[ThetaW]},{VZ,Cos[ThetaW]}}},
 {VB, {1,{VP,Cos[ThetaW]},{VZ,-Sin[ThetaW]}}}};

DEFINITION[EWSB][GaugeSector]=
{{VZ, {1,{VZ1,Sin[ThetaZ]},{VZ2,Cos[ThetaZ]}}},
 {VU, {1,{VZ1,Cos[ThetaZ]},{VZ2,-Sin[ThetaW]}}},
 {fWB,{1,{fWm,1/Sqrt[2]},{fWp,1/Sqrt[2]}},
      {2,{fWm,-\[ImaginaryI]/Sqrt[2]},{fWp,\[ImaginaryI]/Sqrt[2]}},
      {3,{fW0,1}}}};



DEFINITION[EWSB][VEVs]=
{    {SHd0, {vd, 1/Sqrt[2]}, {sigmad, \[ImaginaryI]/Sqrt[2]},{phid, \
\
1/Sqrt[2]}},
     {SHu0, {vu, 1/Sqrt[2]}, {sigmau, \[ImaginaryI]/Sqrt[2]},{phiu, \
\
1/Sqrt[2]}},
     {SsR, {vS, 1/Sqrt[2]}, {sigmaS, \[ImaginaryI]/Sqrt[2]},{phiS, \
\
1/Sqrt[2]}}     };



DEFINITION[EWSB][MatterSector]=
```

```
{    {{SdL, SdR}, {Sd, ZD}},
     {{SvL}, {Sv, ZV}},
     {{SuL, SuR}, {Su, ZU}},
     {{SeL, SeR}, {Se, ZE}},
     {{phid, phiu, phiS}, {hh, ZH}},
     {{sigmad, sigmau,sigmaS}, {Ah, ZA}},
     {{SHdm,conj[SHup]},{Hpm,ZP}},
     {{fU,fB, fW0, FHd0, FHu0,FsR}, {L0, ZN}},
     {{{fWm, FHdm}, {fWp, FHup}}, {{Lm,UM}, {Lp,UP}}},
     {{{FeL},{conj[FeR]}},{{FEL,ZEL},{FER,ZER}}},
     {{{FdL},{conj[FdR]}},{{FDL,ZDL},{FDR,ZDR}}},
     {{{FuL},{conj[FuR]}},{{FUL,ZUL},{FUR,ZUR}}}
   };

DEFINITION[EWSB][Phases]=
{    {fG, PhaseGlu}
    };

DEFINITION[TEMP][GaugeFixing]=
  { {Der[VP],                                       - 1/(2 RXi[P])},
{Der[VWm]+\[ImaginaryI] Mass[VWm] RXi[W] Hpm[{1}], - 1/(RXi[W])},
{Der[VZ] - Mass[VZ] RXi[Z] Ah[{1}],                 - 1/(2 RXi[Z])},
{Der[VG],                                       - 1/(2 RXi[G])}    };

DEFINITION[EWSB][GaugeFixing]=
  { {Der[VP],                                       - 1/(2 RXi[P])},
{Der[VWm]+\[ImaginaryI] Mass[VWm] RXi[W] Hpm[{1}], - 1/(RXi[W])},
{Der[VZ1] - Mass[VZ1] RXi[Z1] Ah[{1}],                - 1/(2 RXi[Z1])},
{Der[VG],                                       - 1/(2 RXi[G])}    };

(*-----------------------------------------------------*)
(* Dirac-Spinors *)
(*-----------------------------------------------------*)

dirac[[1]] = {Fd,  FDL, conj[FDR]};
dirac[[2]] = {Fe,  FEL, conj[FER]};
dirac[[3]] = {Fu,  FUL, conj[FUR]};
dirac[[4]] = {Fv,  FvL, 0};
dirac[[5]] = {Chi, L0, conj[L0]};
dirac[[6]] = {Cha, Lm, conj[Lp]};
dirac[[7]] = {Glu, fG, conj[fG]};
dirac[[8]] = {Bino, fB, conj[fB]};
dirac[[9]] = {Wino, fWB, conj[fWB]};
dirac[[10]] = {H0, FHu0, conj[FHd0]};
dirac[[11]] = {HC, FHup, conj[FHdm]};
dirac[[12]] = {S, FsR, conj[FsR]};
```

```
(* Unbroken EW *)

dirac[[13]] = {Fd1, FdL, 0};
dirac[[14]] = {Fd2, 0, FdR};
dirac[[15]] = {Fu1, FuL, 0};
dirac[[16]] = {Fu2, 0, FuR};
dirac[[17]] = {Fe1, FeL, 0};
dirac[[18]] = {Fe2, 0, FeR};
dirac[[19]] = {FU, fU, conj[fU]};

(*------------------------------------------------------*)
(* Automatized Output        *)
(*------------------------------------------------------*)

(*
makeOutput = {
                   {EWSB, {TeX, FeynArts}}
             };

            *)

SpectrumFile= None;
```

15.8 Implementation in SARAH

Model directory: UMSSM

15.8.1 Particles for eigenstates 'GaugeES'

- Fermions

$\tilde{B} = \begin{pmatrix} \lambda_{\tilde{B}} \\ \lambda^*_{\tilde{B}} \end{pmatrix}$	Bino = (fB , conj[fB])
$d^1_{i\alpha} = \begin{pmatrix} d_{L,i\alpha} \\ 0 \end{pmatrix}$	Fd1[{generation, color}] = (FdL[{generation, color}] , 0)
$d^2_{i\alpha} = \begin{pmatrix} 0 \\ d_{R,i\alpha} \end{pmatrix}$	Fd2[{generation, color}] = (0 , FdR[{generation, color}])
$e^1_{i} = \begin{pmatrix} e_{L,i} \\ 0 \end{pmatrix}$	Fe1[{generation}] = (FeL[{generation}] , 0)

$e^2_i = \begin{pmatrix} 0 \\ e_{R,i} \end{pmatrix}$	$\texttt{Fe2[\{generation\}]} = \begin{pmatrix} \texttt{0} \\ \texttt{FeR[\{generation\}]} \end{pmatrix}$
$\tilde{U} = \begin{pmatrix} \lambda_U \\ \lambda^*_U \end{pmatrix}$	$\texttt{FU} = \begin{pmatrix} \texttt{fU} \\ \texttt{conj[fU]} \end{pmatrix}$
$u^1_{i\alpha} = \begin{pmatrix} u_{L,i\alpha} \\ 0 \end{pmatrix}$	$\texttt{Fu1[\{generation, color\}]} = \begin{pmatrix} \texttt{FuL[\{generation, color\}]} \\ \texttt{0} \end{pmatrix}$
$u^2_{i\alpha} = \begin{pmatrix} 0 \\ u_{R,i\alpha} \end{pmatrix}$	$\texttt{Fu2[\{generation, color\}]} = \begin{pmatrix} \texttt{0} \\ \texttt{FuR[\{generation, color\}]} \end{pmatrix}$
$\nu_i = \begin{pmatrix} \nu_{L,i} \\ 0 \end{pmatrix}$	$\texttt{Fv[\{generation\}]} = \begin{pmatrix} \texttt{FvL[\{generation\}]} \\ \texttt{0} \end{pmatrix}$
$\tilde{g}_i = \begin{pmatrix} \lambda_{\tilde{g},i} \\ \lambda^*_{\tilde{g},i} \end{pmatrix}$	$\texttt{Glu[\{generation\}]} = \begin{pmatrix} \texttt{fG[\{generation\}]} \\ \texttt{conj[fG[\{generation\}]]} \end{pmatrix}$
$\tilde{H}^0 = \begin{pmatrix} \tilde{H}^0_u \\ \tilde{H}^{0,*}_d \end{pmatrix}$	$\texttt{H0} = \begin{pmatrix} \texttt{FHu0} \\ \texttt{conj[FHd0]} \end{pmatrix}$
$\tilde{H}^- = \begin{pmatrix} \tilde{H}^+_u \\ \tilde{H}^{-,*}_d \end{pmatrix}$	$\texttt{HC} = \begin{pmatrix} \texttt{FHup} \\ \texttt{conj[FHdm]} \end{pmatrix}$
$\tilde{S} = \begin{pmatrix} \tilde{S} \\ \tilde{S}^* \end{pmatrix}$	$\texttt{S} = \begin{pmatrix} \texttt{FsR} \\ \texttt{conj[FsR]} \end{pmatrix}$
$\tilde{W}_i = \begin{pmatrix} \lambda_{\tilde{W},i} \\ \lambda^*_{\tilde{W},i} \end{pmatrix}$	$\texttt{Wino[\{generation\}]} = \begin{pmatrix} \texttt{fWB[\{generation\}]} \\ \texttt{conj[fWB[\{generation\}]]} \end{pmatrix}$

- Scalars

$\tilde{d}_{L,i\alpha}$	SdL[{generation, color}]	$\tilde{u}_{L,i\alpha}$	SuL[{generation, color}]
$\tilde{e}_{L,i}$	SeL[{generation}]	$\tilde{\nu}_{L,i}$	SvL[{generation}]
H^0_d	SHd0	H^-_d	SHdm
H^0_u	SHu0	H^+_u	SHup
$\tilde{d}_{R,i\alpha}$	SdR[{generation, color}]	$\tilde{u}_{R,i\alpha}$	SuR[{generation, color}]
$\tilde{e}_{R,i}$	SeR[{generation}]	S	SsR

- Vector Bosons

B_ρ	`VB[{lorentz}]`	$W^-_{i\rho}$	`VWB[{generation, lorentz}]`
$g_{i\rho}$	`VG[{generation, lorentz}]`	U_ρ	`VU[{lorentz}]`

- Ghosts

η^B	`gB`	gWB$\Big(\{$gt1$\}\Big)$	`gWB[{generation}]`
η^G_i	`gG[{generation}]`	gU	`gU`

15.8.2 Particles for eigenstates `'TEMP'`

- Fermions

$\tilde{B} = \begin{pmatrix} \lambda_{\tilde{B}} \\ \lambda^*_{\tilde{B}} \end{pmatrix}$	`Bino` $= \begin{pmatrix} \texttt{fB} \\ \texttt{conj[fB]} \end{pmatrix}$
$d^1_{i\alpha} = \begin{pmatrix} d_{L,i\alpha} \\ 0 \end{pmatrix}$	`Fd1[{generation, color}]` $= \begin{pmatrix} \texttt{FdL[\{generation, color\}]} \\ 0 \end{pmatrix}$
$d^2_{i\alpha} = \begin{pmatrix} 0 \\ d_{R,i\alpha} \end{pmatrix}$	`Fd2[{generation, color}]` $= \begin{pmatrix} 0 \\ \texttt{FdR[\{generation, color\}]} \end{pmatrix}$
$e^1_i = \begin{pmatrix} e_{L,i} \\ 0 \end{pmatrix}$	`Fe1[{generation}]` $= \begin{pmatrix} \texttt{FeL[\{generation\}]} \\ 0 \end{pmatrix}$
$e^2_i = \begin{pmatrix} 0 \\ e_{R,i} \end{pmatrix}$	`Fe2[{generation}]` $= \begin{pmatrix} 0 \\ \texttt{FeR[\{generation\}]} \end{pmatrix}$
$\tilde{U} = \begin{pmatrix} \lambda_U \\ \lambda^*_U \end{pmatrix}$	`FU` $= \begin{pmatrix} \texttt{fU} \\ \texttt{conj[fU]} \end{pmatrix}$
$u^1_{i\alpha} = \begin{pmatrix} u_{L,i\alpha} \\ 0 \end{pmatrix}$	`Fu1[{generation, color}]` $= \begin{pmatrix} \texttt{FuL[\{generation, color\}]} \\ 0 \end{pmatrix}$
$u^2_{i\alpha} = \begin{pmatrix} 0 \\ u_{R,i\alpha} \end{pmatrix}$	`Fu2[{generation, color}]` $= \begin{pmatrix} 0 \\ \texttt{FuR[\{generation, color\}]} \end{pmatrix}$
$\nu_i = \begin{pmatrix} \nu_{L,i} \\ 0 \end{pmatrix}$	`Fv[{generation}]` $= \begin{pmatrix} \texttt{FvL[\{generation\}]} \\ 0 \end{pmatrix}$
$\tilde{g}_i = \begin{pmatrix} \lambda_{\tilde{g},i} \\ \lambda^*_{\tilde{g},i} \end{pmatrix}$	`Glu[{generation}]` $= \begin{pmatrix} \texttt{fG[\{generation\}]} \\ \texttt{conj[fG[\{generation\}]]} \end{pmatrix}$

$\tilde{H}^0 = \begin{pmatrix} \tilde{H}_u^0 \\ \tilde{H}_d^{0,*} \end{pmatrix}$	$\texttt{H0} = \begin{pmatrix} \texttt{FHu0} \\ \texttt{conj[FHd0]} \end{pmatrix}$
$\tilde{H}^- = \begin{pmatrix} \tilde{H}_u^+ \\ \tilde{H}_d^{-,*} \end{pmatrix}$	$\texttt{HC} = \begin{pmatrix} \texttt{FHup} \\ \texttt{conj[FHdm]} \end{pmatrix}$
$\tilde{S} = \begin{pmatrix} \tilde{S} \\ \tilde{S}^* \end{pmatrix}$	$\texttt{S} = \begin{pmatrix} \texttt{FsR} \\ \texttt{conj[FsR]} \end{pmatrix}$
$\tilde{W}_i = \begin{pmatrix} \lambda_{\tilde{W},i} \\ \lambda^*_{\tilde{W},i} \end{pmatrix}$	$\texttt{Wino[\{generation\]}} = \begin{pmatrix} \texttt{fWB[\{generation\}]} \\ \texttt{conj[fWB[\{generation\}]]} \end{pmatrix}$

- Scalars

$\tilde{d}_{L,i\alpha}$	SdL[{generation, color}]	$\tilde{u}_{L,i\alpha}$	SuL[{generation, color}]
$\tilde{e}_{L,i}$	SeL[{generation}]	$\tilde{\nu}_{L,i}$	SvL[{generation}]
H_d^0	SHd0	H_d^-	SHdm
H_u^0	SHu0	H_u^+	SHup
$\tilde{d}_{R,i\alpha}$	SdR[{generation, color}]	$\tilde{u}_{R,i\alpha}$	SuR[{generation, color}]
$\tilde{e}_{R,i}$	SeR[{generation}]	S	SsR

- Vector Bosons

$g_{i\rho}$	VG[{generation, lorentz}]	U_ρ	VU[{lorentz}]
W_ρ^-	VWm[{lorentz}]	γ_ρ	VP[{lorentz}]
Z_ρ	VZ[{lorentz}]		

- Ghosts

η_i^G	gG[{generation}]	gU	gU
η^-	gWm	η^+	gWmC
η^γ	gP	η^Z	gZ

15.8.3 Particles for eigenstates 'EWSB'

- Fermions

$\tilde{\chi}^-_i = \begin{pmatrix} \lambda^-_i \\ \lambda^{+,*}_i \end{pmatrix}$	`Cha[{generation}]` $= \begin{pmatrix} \texttt{Lm[\{generation\}]} \\ \texttt{conj[Lp[\{generation\}]]} \end{pmatrix}$
$\tilde{\chi}^0_i = \begin{pmatrix} \lambda^0_i \\ \lambda^{0,*}_i \end{pmatrix}$	`Chi[{generation}]` $= \begin{pmatrix} \texttt{L0[\{generation\}]} \\ \texttt{conj[L0[\{generation\}]]} \end{pmatrix}$
$d_{i\alpha} = \begin{pmatrix} D_{L,i\alpha} \\ D^*_{R,i\alpha} \end{pmatrix}$	`Fd[{generation, color}]` $= \begin{pmatrix} \texttt{FDL[\{generation, color\}]} \\ \texttt{conj[FDR[\{generation, color\}]]} \end{pmatrix}$
$e_i = \begin{pmatrix} E_{L,i} \\ E^*_{R,i} \end{pmatrix}$	`Fe[{generation}]` $= \begin{pmatrix} \texttt{FEL[\{generation\}]} \\ \texttt{conj[FER[\{generation\}]]} \end{pmatrix}$
$u_{i\alpha} = \begin{pmatrix} U_{L,i\alpha} \\ U^*_{R,i\alpha} \end{pmatrix}$	`Fu[{generation, color}]` $= \begin{pmatrix} \texttt{FUL[\{generation, color\}]} \\ \texttt{conj[FUR[\{generation, color\}]]} \end{pmatrix}$
$\nu_i = \begin{pmatrix} \nu_{L,i} \\ 0 \end{pmatrix}$	`Fv[{generation}]` $= \begin{pmatrix} \texttt{FvL[\{generation\}]} \\ 0 \end{pmatrix}$
$\tilde{g}_i = \begin{pmatrix} \lambda_{\tilde{g},i} \\ \lambda^*_{\tilde{g},i} \end{pmatrix}$	`Glu[{generation}]` $= \begin{pmatrix} \texttt{fG[\{generation\}]} \\ \texttt{conj[fG[\{generation\}]]} \end{pmatrix}$

- Scalars

$\tilde{d}_{i\alpha}$	`Sd[{generation, color}]`	$\tilde{\nu}_i$	`Sv[{generation}]`
$\tilde{u}_{i\alpha}$	`Su[{generation, color}]`	$\tilde{e}_i$	`Se[{generation}]`
h_i	`hh[{generation}]`	A^0_i	`Ah[{generation}]`
H^-_i	`Hpm[{generation}]`		

- Vector Bosons

$g_{i\rho}$	`VG[{generation, lorentz}]`	W^-_ρ	`VWm[{lorentz}]`
γ_ρ	`VP[{lorentz}]`	$Z_{1,\rho}$	`VZ1[{lorentz}]`
$Z_{2,\rho}$	`VZ2[{lorentz}]`		

- Ghosts

η_i^G	gG[{generation}]	η^-	gWm
η^+	gWmC	η^γ	gP
η^{Z_1}	gZ1	η^{Z_2}	gZ2

15.8.4 Parameters

Q_q	Qq	Q_q	Ql	Q_{H_d}	QHd
Q_{H_u}	QHu	Q_d	Qd	Q_u	Qu
Q_e	Qe	Q_s	Qs	g_1	g1
g_2	g2	g_3	g3	g_p	gp
Y_u	Yu	T_u	T[Yu]	Y_d	Yd
T_d	T[Yd]	Y_e	Ye	T_e	T[Ye]
λ	\[Lambda]	T_λ	T[\[Lambda]]	m_q^2	mq2
m_l^2	ml2	$m_{H_d}^2$	mHd2	$m_{H_u}^2$	mHu2
m_d^2	md2	m_u^2	mu2	m_e^2	me2
m_S^2	ms2	M_1	MassB	M_2	MassWB
M_3	MassG	M_Z	MassU	Θ_W	ThetaW
v_d	vd	v_u	vu	v_s	vS
Θ_Z	ThetaZ	$\phi_{\tilde{g}}$	PhaseGlu	Z^D	ZD
Z^V	ZV	Z^U	ZU	Z^E	ZE
Z^H	ZH	Z^A	ZA	Z^+	ZP
N	ZN	U	UM	V	UP
U_L^e	ZEL	U_R^e	ZER	U_L^d	ZDL
U_R^d	ZDR	U_L^u	ZUL	U_R^u	ZUR
β	\[Beta]				

Chapter 16

The Secluded $U(1)$-Extended Minimal Supersymmetric Standard Model

16.1 Superfields

16.1.1 Vector Superfields

SF	Spin $\frac{1}{2}$	Spin 1	$SU(N)$	Coupling	Name
$\hat{B}$	$\lambda_{\tilde{B}}$	B	$U(1)$	g_1	hypercharge
$\hat{W}$	$\lambda_{\tilde{W}}$	W^-	SU(2)	g_2	left
$\hat{g}$	$\lambda_{\tilde{g}}$	g	SU(3)	g_3	color
$\hat{U}$	$\tilde{U}$	U	$U(1)$	g_p	additional

16.1.2 Chiral Superfields

SF	Spin 0	Spin $\frac{1}{2}$	Generations	$(U(1)\otimes \mathrm{SU}(2)\otimes \mathrm{SU}(3)\otimes U(1))$
$\hat{q}$	$\tilde{q}$	q	3	$(\frac{1}{6},\mathbf{2},\mathbf{3},Q_q)$
$\hat{l}$	$\tilde{l}$	l	3	$(-\frac{1}{2},\mathbf{2},\mathbf{1},Q_q)$
$\hat{H}_d$	H_d	$\tilde{H}_d$	1	$(-\frac{1}{2},\mathbf{2},\mathbf{1},Q_{H_d})$
$\hat{H}_u$	H_u	$\tilde{H}_u$	1	$(\frac{1}{2},\mathbf{2},\mathbf{1},Q_{H_u})$
$\hat{d}$	$\tilde{d}_R^*$	d_R^*	3	$(\frac{1}{3},\mathbf{1},\overline{\mathbf{3}},Q_d)$
$\hat{u}$	$\tilde{u}_R^*$	u_R^*	3	$(-\frac{2}{3},\mathbf{1},\overline{\mathbf{3}},Q_u)$
$\hat{e}$	$\tilde{e}_R^*$	e_R^*	3	$(1,\mathbf{1},\mathbf{1},Q_e)$
$\hat{s}$	S	$\tilde{S}$	1	$(0,\mathbf{1},\mathbf{1},Q_s)$
$\hat{s}_1$	S_1	$\tilde{s}_1$	1	$(0,\mathbf{1},\mathbf{1},Q_1)$
$\hat{s}_2$	S_2	$\tilde{s}_2$	1	$(0,\mathbf{1},\mathbf{1},Q_2)$
$\hat{s}_3$	S_3	$\tilde{s}_3$	1	$(0,\mathbf{1},\mathbf{1},Q_3)$

16.2 Superpotential and Lagrangian

16.2.1 Superpotential

$$W = Y_u\,\hat{q}\,\hat{H}_u\,\hat{u}\,-Y_d\,\hat{q}\,\hat{H}_d\,\hat{d}\,-Y_e\,\hat{l}\,\hat{H}_d\,\hat{e}\,+\lambda\,\hat{H}_u\,\hat{H}_d\,\hat{s}\,+\kappa\,\hat{s}_1\,\hat{s}_2\,\hat{s}_3 \tag{16.1}$$

16.2.2 Softbreaking terms

$$\begin{aligned} L_{SB,W} = &+S_1 S_2 S_3 T_\kappa - H_d^0 H_u^0 S T_\lambda + H_d^- H_u^+ S T_\lambda + H_d^0 \tilde{d}^*_{R,k\gamma}\delta_{\alpha\gamma}\tilde{d}_{L,i\alpha}T_{d,ik}\\ &- H_d^- \tilde{d}^*_{R,k\gamma}\delta_{\alpha\gamma}\tilde{u}_{L,i\alpha}T_{d,ik} + H_d^0\tilde{e}^*_{R,k}\tilde{e}_{L,i}T_{e,ik} - H_d^-\tilde{e}^*_{R,k}\tilde{\nu}_{L,i}T_{e,ik} - H_u^+\tilde{u}^*_{R,k\gamma}\delta_{\alpha\gamma}\tilde{d}_{L,i\alpha}T_{u,ik}\\ &+ H_u^0\tilde{u}^*_{R,k\gamma}\delta_{\alpha\gamma}\tilde{u}_{L,i\alpha}T_{u,ik} + \text{h.c.} \end{aligned} \tag{16.2}$$

$$\begin{aligned} L_{SB,\phi} = &- m_{H_d}^2|H_d^0|^2 - m_{H_d}^2|H_d^-|^2 - m_{H_u}^2|H_u^0|^2 - m_{H_u}^2|H_u^+|^2 - ms12|S_1|^2 - ms22|S_2|^2 - ms32|S_3|^2\\ &- m_S^2|S|^2 - \tilde{d}^*_{L,j\beta}\delta_{\alpha\beta}m^2_{q,ij}\tilde{d}_{L,i\alpha} - \tilde{d}^*_{R,i\alpha}\delta_{\alpha\beta}m^2_{d,ij}\tilde{d}_{R,j\beta} - \tilde{e}^*_{L,j}m^2_{l,ij}\tilde{e}_{L,i}\\ &- \tilde{e}^*_{R,i}m^2_{e,ij}\tilde{e}_{R,j} - \tilde{u}^*_{L,j\beta}\delta_{\alpha\beta}m^2_{q,ij}\tilde{u}_{L,i\alpha} - \tilde{u}^*_{R,i\alpha}\delta_{\alpha\beta}m^2_{u,ij}\tilde{u}_{R,j\beta} - \tilde{\nu}^*_{L,j}m^2_{l,ij}\tilde{\nu}_{L,i} \end{aligned} \tag{16.3}$$

$$L_{SB,\lambda} = \frac{1}{2}\Big(-\lambda^2_{\tilde{B}}M_1 - M_2\lambda^2_{\tilde{W},i} - M_3\lambda^2_{\tilde{g},i} - \tilde{U}^2 M_U + \text{h.c.}\Big) \tag{16.4}$$

16.2.3 Gauge fixing terms

Gauge fixing terms for eigenstates 'GaugeES'

$$L_{GF} = -\frac{1}{2}\partial_\mu g\xi_G^{-1} - \frac{1}{2}\partial_\mu W^-\xi_W^{-1} \tag{16.5}$$

Gauge fixing terms for eigenstates 'TEMP'

$$L_{GF} = -\frac{1}{2}\partial_\mu\gamma\xi_P^{-1} - \frac{1}{2}\partial_\mu g\xi_G^{-1} - \frac{1}{2}\xi_Z^{-1}\Big(-A_1^0 m_Z\xi_Z + \partial_\mu Z\Big) - \xi_W^{-1}\Big(iH_1^- m_{W^-}\xi_W + \partial_\mu W^-\Big) \tag{16.6}$$

Gauge fixing terms for eigenstates 'EWSB'

$$L_{GF} = -\frac{1}{2}\partial_\mu\gamma\xi_P^{-1} - \frac{1}{2}\partial_\mu g\xi_G^{-1} - \frac{1}{2}\xi_{Z1}^{-1}\Big(-A_1^0 m_{Z_1}\xi_{Z1} + \partial_\mu Z_1\Big) - \xi_W^{-1}\Big(iH_1^- m_{W^-}\xi_W + \partial_\mu W^-\Big) \tag{16.7}$$

16.2.4 Fields integrated out

None

16.3 Field Rotations

16.3.1 Rotations in gauge sector for eigenstates 'EWSB'

$$Z_\rho = \cos\Theta_Z Z_{2,\rho} + \sin\Theta_Z Z_{1,\rho} \tag{16.8}$$

$$U_\rho = \cos\Theta_Z Z_{1,\rho} - \sin\Theta_W Z_{2,\rho} \tag{16.9}$$

$$\lambda_{\tilde{W},1} = \frac{1}{\sqrt{2}}\tilde{W}^{-} + \frac{1}{\sqrt{2}}\tilde{W}^{+} \tag{16.10}$$

$$\lambda_{\tilde{W},2} = -i\frac{1}{\sqrt{2}}\tilde{W}^{-} + i\frac{1}{\sqrt{2}}\tilde{W}^{+} \tag{16.11}$$

$$\lambda_{\tilde{W},3} = \tilde{W}^{0} \tag{16.12}$$

16.3.2 Rotations in Mass sector for eigenstates 'EWSB'

Mass Matrices for Scalars

- **Mass matrix for Down-Squarks**, Basis: $\left(\tilde{d}_{L,o_1\alpha_1}, \tilde{d}_{R,o_2\alpha_2}\right), \left(\tilde{d}^*_{L,p_1\beta_1}, \tilde{d}^*_{R,p_2\beta_2}\right)$

$$m^2_{\tilde{d}} = \begin{pmatrix} m_{11} & \frac{1}{2}\delta_{\alpha_1\beta_2}\Big(\sqrt{2}v_d T_{d,o_1p_2} - v_s v_u \lambda^* Y_{d,o_1p_2}\Big) \\ \frac{1}{2}\Big(\sqrt{2}v_d T^*_{d,p_1o_2} - v_s v_u \lambda Y^*_{d,p_1o_2}\Big)\delta_{\alpha_2\beta_1} & m_{22} \end{pmatrix} \tag{16.13}$$

$$m_{11} = \frac{1}{24}\delta_{\alpha_1\beta_1}\Big(\Big(12g_p^2 Q_q\Big(Q_1 v1^2 + Q_2 v2^2 + Q_3 v3^2 + Q_{H_d}v_d^2 + Q_{H_u}v_u^2 + Q_s v_s^2\Big) - \Big(3g_2^2 + g_1^2\Big)\Big(-v_u^2 + v_d^2\Big)\Big)\delta_{o_1p_1}$$
$$+ 12\Big(2m^2_{q,o_1p_1} + v_d^2\sum_{a=1}^{3} Y^*_{d,p_1a}Y_{d,o_1a}\Big)\Big) \tag{16.14}$$

$$m_{22} = \frac{1}{12}\delta_{\alpha_2\beta_2}\Big(\Big(6g_p^2 Q_d\Big(Q_1 v1^2 + Q_2 v2^2 + Q_3 v3^2 + Q_{H_d}v_d^2 + Q_{H_u}v_u^2 + Q_s v_s^2\Big) + g_1^2\Big(-v_d^2 + v_u^2\Big)\Big)\delta_{o_2p_2}$$
$$+ 6\Big(2m^2_{d,p_2o_2} + v_d^2\sum_{a=1}^{3} Y^*_{d,ao_2}Y_{d,ap_2}\Big)\Big) \tag{16.15}$$

This matrix is diagonalized by Z^D:

$$Z^D m^2_{\tilde{d}} Z^{D,\dagger} = m^{dia}_{2,\tilde{d}} \tag{16.16}$$

with

$$\tilde{d}_{L,i\alpha} = \sum_{t_2} Z^{D,*}_{ji}\tilde{d}_{j\alpha}\,, \qquad \tilde{d}_{R,i\alpha} = \sum_{t_2} Z^{D,*}_{ji}\tilde{d}_{j\alpha} \tag{16.17}$$

- **Mass matrix for Sneutrinos**, Basis: $\left(\tilde{\nu}_{L,o_1}\right), \left(\tilde{\nu}^*_{L,p_1}\right)$

$$m^2_{\tilde{\nu}} = \begin{pmatrix} m_{11} \end{pmatrix} \tag{16.18}$$

$$m_{11} = \frac{1}{8}\Big(\Big(4g_p^2 Q_q\Big(Q_1 v1^2 + Q_2 v2^2 + Q_3 v3^2 + Q_{H_d}v_d^2 + Q_{H_u}v_u^2 + Q_s v_s^2\Big) + \Big(g_1^2 + g_2^2\Big)\Big(-v_u^2 + v_d^2\Big)\Big)\delta_{o_1p_1} + 8m^2_{l,o_1p_1}\Big) \tag{16.19}$$

This matrix is diagonalized by Z^V:

$$Z^V m^2_{\tilde{\nu}} Z^{V,\dagger} = m^{dia}_{2,\tilde{\nu}} \tag{16.20}$$

with

$$\tilde{\nu}_{L,i} = \sum_{t_2} Z^{V,*}_{ji}\tilde{\nu}_j \tag{16.21}$$

- **Mass matrix for Up-Squarks**, Basis: $(\tilde{u}_{L,o_1\alpha_1}, \tilde{u}_{R,o_2\alpha_2}), \Big(\tilde{u}^*_{L,p_1\beta_1}, \tilde{u}^*_{R,p_2\beta_2}\Big)$

$$m^2_{\tilde{u}} = \left(\begin{array}{cc} m_{11} & \frac{1}{2}\delta_{\alpha_1\beta_2}\Big(\sqrt{2}v_u T_{u,o_1p_2} - v_d v_s \lambda^* Y_{u,o_1p_2}\Big) \\ \frac{1}{2}\Big(\sqrt{2}v_u T^*_{u,p_1o_2} - v_d v_s \lambda Y^*_{u,p_1o_2}\Big)\delta_{\alpha_2\beta_1} & m_{22} \end{array}\right) \tag{16.22}$$

$$m_{11} = \frac{1}{24}\delta_{\alpha_1\beta_1}\Big(\Big(12g_p^2 Q_q\Big(Q_1 v1^2 + Q_2 v2^2 + Q_3 v3^2 + Q_{H_d}v_d^2 + Q_{H_u}v_u^2 + Q_s v_s^2\Big) - \Big(-3g_2^2 + g_1^2\Big)\Big(-v_u^2 + v_d^2\Big)\Big)\delta_{o_1p_1}$$
$$+ 12\Big(2m^2_{q,o_1p_1} + v_u^2\sum_{a=1}^{3} Y^*_{u,p_1a}Y_{u,o_1a}\Big)\Big) \tag{16.23}$$

$$m_{22} = \frac{1}{6}\delta_{\alpha_2\beta_2}\Big(\Big(3g_p^2 Q_u\Big(Q_1 v1^2 + Q_2 v2^2 + Q_3 v3^2 + Q_{H_d}v_d^2 + Q_{H_u}v_u^2 + Q_s v_s^2\Big) + g_1^2\Big(-v_u^2 + v_d^2\Big)\Big)\delta_{o_2p_2} + 6m^2_{u,p_2o_2}$$
$$+ 3v_u^2\sum_{a=1}^{3} Y^*_{u,ao_2}Y_{u,ap_2}\Big) \tag{16.24}$$

This matrix is diagonalized by Z^U:

$$Z^U m^2_{\tilde{u}} Z^{U,\dagger} = m^{dia}_{2,\tilde{u}} \tag{16.25}$$

with

$$\tilde{u}_{L,i\alpha} = \sum_{t_2} Z^{U,*}_{ji}\tilde{u}_{j\alpha}\,, \qquad \tilde{u}_{R,i\alpha} = \sum_{t_2} Z^{U,*}_{ji}\tilde{u}_{j\alpha} \tag{16.26}$$

- **Mass matrix for Sleptons**, Basis: $(\tilde{e}_{L,o_1}, \tilde{e}_{R,o_2}), (\tilde{e}^*_{L,p_1}, \tilde{e}^*_{R,p_2})$

$$m^2_{\tilde{e}} = \left(\begin{array}{cc} m_{11} & -\frac{1}{2}v_s v_u \lambda^* Y_{e,o_1p_2} + \frac{1}{\sqrt{2}}v_d T_{e,o_1p_2} \\ -\frac{1}{2}v_s v_u \lambda Y^*_{e,p_1o_2} + \frac{1}{\sqrt{2}}v_d T^*_{e,p_1o_2} & m_{22} \end{array}\right) \tag{16.27}$$

$$m_{11} = \frac{1}{8}\Big(\Big(4g_p^2 Q_q\Big(Q_1 v1^2 + Q_2 v2^2 + Q_3 v3^2 + Q_{H_d}v_d^2 + Q_{H_u}v_u^2 + Q_s v_s^2\Big) + \Big(-g_2^2 + g_1^2\Big)\Big(-v_u^2 + v_d^2\Big)\Big)\delta_{o_1p_1} + 8m^2_{l,o_1p_1}$$
$$+ 4v_d^2\sum_{a=1}^{3} Y^*_{e,p_1a}Y_{e,o_1a}\Big) \tag{16.28}$$

$$m_{22} = \frac{1}{4}\Big(\Big(2g_p^2 Q_e\Big(Q_1 v1^2 + Q_2 v2^2 + Q_3 v3^2 + Q_{H_d}v_d^2 + Q_{H_u}v_u^2 + Q_s v_s^2\Big) + g_1^2\Big(-v_d^2 + v_u^2\Big)\Big)\delta_{o_2p_2} + 4m^2_{e,p_2o_2}$$
$$+ 2v_d^2\sum_{a=1}^{3} Y^*_{e,ao_2}Y_{e,ap_2}\Big) \tag{16.29}$$

This matrix is diagonalized by Z^E:

$$Z^E m^2_{\tilde{e}} Z^{E,\dagger} = m^{dia}_{2,\tilde{e}} \tag{16.30}$$

with

$$\tilde{e}_{L,i} = \sum_{t_2} Z^{E,*}_{ji}\tilde{e}_j\,, \qquad \tilde{e}_{R,i} = \sum_{t_2} Z^{E,*}_{ji}\tilde{e}_j \tag{16.31}$$

- **Mass matrix for Higgs**, Basis: $\left(\phi_d, \phi_u, \phi_s, \phi_1, \phi_2, \phi_3\right), \left(\phi_d, \phi_u, \phi_s, \phi_1, \phi_2, \phi_3\right)$

$$m_h^2 = \begin{pmatrix} m_{11} & m^*_{21} & m^*_{31} & m^*_{41} & m^*_{51} & m^*_{61} \\ m_{21} & m_{22} & m^*_{32} & m^*_{42} & m^*_{52} & m^*_{62} \\ m_{31} & m_{32} & m_{33} & m^*_{43} & m^*_{53} & m^*_{63} \\ m_{41} & m_{42} & m_{43} & m_{44} & m^*_{54} & m^*_{64} \\ m_{51} & m_{52} & m_{53} & m_{54} & m_{55} & m^*_{65} \\ m_{61} & m_{62} & m_{63} & m_{64} & m_{65} & m_{66} \end{pmatrix} \tag{16.32}$$

$$\begin{aligned} m_{11} = &\frac{1}{8}\Big(8 m_{H_d}^2 + 4 g_p^2 Q_{H_d} Q_1 v1^2 + 4 g_p^2 Q_{H_d} Q_2 v2^2 + 4 g_p^2 Q_{H_d} Q_3 v3^2 + 3 g_1^2 v_d^2 + 3 g_2^2 v_d^2 + 12 g_p^2 Q_{H_d}^2 v_d^2 \\ &+ 4 g_p^2 Q_{H_d} Q_s v_s^2 - g_1^2 v_u^2 - g_2^2 v_u^2 + 4 g_p^2 Q_{H_d} Q_{H_u} v_u^2 + 4\Big(v_s^2 + v_u^2\Big)|\lambda|^2\Big) \end{aligned} \tag{16.33}$$

$$m_{21} = \frac{1}{4}\Big(- 2\sqrt{2} v_s \Re\Big(T_\lambda\Big) - \Big(- 4 g_p^2 Q_{H_d} Q_{H_u} + g_1^2 + g_2^2\Big) v_d v_u\Big) + v_d v_u |\lambda|^2 \tag{16.34}$$

$$\begin{aligned} m_{22} = &\frac{1}{8}\Big(8 m_{H_u}^2 + 4 g_p^2 Q_{H_u} Q_1 v1^2 + 4 g_p^2 Q_{H_u} Q_2 v2^2 + 4 g_p^2 Q_{H_u} Q_3 v3^2 - g_1^2 v_d^2 - g_2^2 v_d^2 \\ &+ 4 g_p^2 Q_{H_d} Q_{H_u} v_d^2 + 4 g_p^2 Q_{H_u} Q_s v_s^2 + 3 g_1^2 v_u^2 + 3 g_2^2 v_u^2 + 12 g_p^2 Q_{H_u}^2 v_u^2 + 4\Big(v_d^2 + v_s^2\Big)|\lambda|^2\Big) \end{aligned} \tag{16.35}$$

$$m_{31} = -\frac{1}{\sqrt{2}} v_u \Re\Big(T_\lambda\Big) + g_p^2 Q_{H_d} Q_s v_d v_s + v_d v_s |\lambda|^2 \tag{16.36}$$

$$m_{32} = -\frac{1}{\sqrt{2}} v_d \Re\Big(T_\lambda\Big) + g_p^2 Q_{H_u} Q_s v_s v_u + v_s v_u |\lambda|^2 \tag{16.37}$$

$$m_{33} = \frac{1}{2}\Big(2 m_S^2 + g_p^2 Q_s\Big(3 Q_s v_s^2 + Q_1 v1^2 + Q_2 v2^2 + Q_3 v3^2 + Q_{H_d} v_d^2 + Q_{H_u} v_u^2\Big) + \Big(v_d^2 + v_u^2\Big)|\lambda|^2\Big) \tag{16.38}$$

$$m_{41} = g_p^2 Q_{H_d} Q_1 v1 v_d \tag{16.39}$$

$$m_{42} = g_p^2 Q_{H_u} Q_1 v1 v_u \tag{16.40}$$

$$m_{43} = g_p^2 Q_s Q_1 v1 v_s \tag{16.41}$$

$$m_{44} = \frac{1}{2}\Big(2 ms12 + g_p^2 Q_1\Big(3 Q_1 v1^2 + Q_2 v2^2 + Q_3 v3^2 + Q_{H_d} v_d^2 + Q_{H_u} v_u^2 + Q_s v_s^2\Big) + \Big(v2^2 + v3^2\Big)|\kappa|^2\Big) \tag{16.42}$$

$$m_{51} = g_p^2 Q_{H_d} Q_2 v2 v_d \tag{16.43}$$

$$m_{52} = g_p^2 Q_{H_u} Q_2 v2 v_u \tag{16.44}$$

$$m_{53} = g_p^2 Q_s Q_2 v2 v_s \tag{16.45}$$

$$m_{54} = \frac{1}{\sqrt{2}} v3 \Re\Big(T_\kappa\Big) + g_p^2 Q_1 Q_2 v1 v2 + v1 v2 |\kappa|^2 \tag{16.46}$$

$$m_{55} = \frac{1}{2}\Big(2 ms22 + g_p^2 Q_2\Big(3 Q_2 v2^2 + Q_1 v1^2 + Q_3 v3^2 + Q_{H_d} v_d^2 + Q_{H_u} v_u^2 + Q_s v_s^2\Big) + \Big(v1^2 + v3^2\Big)|\kappa|^2\Big) \tag{16.47}$$

$$m_{61} = g_p^2 Q_{H_d} Q_3 v3 v_d \tag{16.48}$$

$$m_{62} = g_p^2 Q_{H_u} Q_3 v3 v_u \tag{16.49}$$

$$m_{63} = g_p^2 Q_s Q_3 v3 v_s \tag{16.50}$$

$$m_{64} = \frac{1}{\sqrt{2}} v2 \Re\Big(T_\kappa\Big) + g_p^2 Q_1 Q_3 v1 v3 + v1 v3 |\kappa|^2 \tag{16.51}$$

$$m_{65} = \frac{1}{\sqrt{2}} v1 \Re\Big(T_\kappa\Big) + g_p^2 Q_2 Q_3 v2 v3 + v2 v3 |\kappa|^2 \tag{16.52}$$

$$m_{66} = \frac{1}{2}\Big(2ms32 + g_p^2 Q_3 \Big(3Q_3 v3^2 + Q_1 v1^2 + Q_2 v2^2 + Q_{H_d} v_d^2 + Q_{H_u} v_u^2 + Q_s v_s^2\Big) + \Big(v1^2 + v2^2\Big)|\kappa|^2\Big) \tag{16.53}$$

This matrix is diagonalized by Z^H:

$$Z^H m_h^2 Z^{H,\dagger} = m_{2,h}^{dia} \tag{16.54}$$

with

$$\phi_d = \sum_{t_2} Z_{j1}^{H,*} h_j\,, \qquad \phi_u = \sum_{t_2} Z_{j2}^{H,*} h_j\,, \qquad \phi_s = \sum_{t_2} Z_{j3}^{H,*} h_j \tag{16.55}$$

$$\phi_1 = \sum_{t_2} Z_{j4}^{H,*} h_j\,, \qquad \phi_2 = \sum_{t_2} Z_{j5}^{H,*} h_j\,, \qquad \phi_3 = \sum_{t_2} Z_{j6}^{H,*} h_j \tag{16.56}$$

- **Mass matrix for Pseudo-Scalar Higgs**, Basis: $(\sigma_d, \sigma_u, \sigma_s, \sigma_1, \sigma_2, \sigma_3), (\sigma_d, \sigma_u, \sigma_s, \sigma_1, \sigma_2, \sigma_3)$

$$m_{A^0}^2 = \begin{pmatrix} m_{11} & \frac{1}{\sqrt{2}} v_s \Re\Big(T_\lambda\Big) & \frac{1}{\sqrt{2}} v_u \Re\Big(T_\lambda\Big) & 0 & 0 & 0 \\ \frac{1}{\sqrt{2}} v_s \Re\Big(T_\lambda\Big) & m_{22} & \frac{1}{\sqrt{2}} v_d \Re\Big(T_\lambda\Big) & 0 & 0 & 0 \\ \frac{1}{\sqrt{2}} v_u \Re\Big(T_\lambda\Big) & \frac{1}{\sqrt{2}} v_d \Re\Big(T_\lambda\Big) & m_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & m_{44} & -\frac{1}{\sqrt{2}} v3 \Re\Big(T_\kappa\Big) & -\frac{1}{\sqrt{2}} v2 \Re\Big(T_\kappa\Big) \\ 0 & 0 & 0 & -\frac{1}{\sqrt{2}} v3 \Re\Big(T_\kappa\Big) & m_{55} & -\frac{1}{\sqrt{2}} v1 \Re\Big(T_\kappa\Big) \\ 0 & 0 & 0 & -\frac{1}{\sqrt{2}} v2 \Re\Big(T_\kappa\Big) & -\frac{1}{\sqrt{2}} v1 \Re\Big(T_\kappa\Big) & m_{66} \end{pmatrix} \tag{16.57}$$

$$\begin{aligned} m_{11} = \frac{1}{8}\Big(&8m_{H_d}^2 + 4g_p^2 Q_{H_d} Q_1 v1^2 + 4g_p^2 Q_{H_d} Q_2 v2^2 + 4g_p^2 Q_{H_d} Q_3 v3^2 + g_1^2 v_d^2 + g_2^2 v_d^2 + 4g_p^2 Q_{H_d}^2 v_d^2 \\ &+ 4g_p^2 Q_{H_d} Q_s v_s^2 - g_1^2 v_u^2 - g_2^2 v_u^2 + 4g_p^2 Q_{H_d} Q_{H_u} v_u^2 + 4\Big(v_s^2 + v_u^2\Big)|\lambda|^2\Big) \end{aligned} \tag{16.58}$$

$$\begin{aligned} m_{22} = \frac{1}{8}\Big(&8m_{H_u}^2 + 4g_p^2 Q_{H_u} Q_1 v1^2 + 4g_p^2 Q_{H_u} Q_2 v2^2 + 4g_p^2 Q_{H_u} Q_3 v3^2 - g_1^2 v_d^2 - g_2^2 v_d^2 \\ &+ 4g_p^2 Q_{H_d} Q_{H_u} v_d^2 + 4g_p^2 Q_{H_u} Q_s v_s^2 + g_1^2 v_u^2 + g_2^2 v_u^2 + 4g_p^2 Q_{H_u}^2 v_u^2 + 4\Big(v_d^2 + v_s^2\Big)|\lambda|^2\Big) \end{aligned} \tag{16.59}$$

$$m_{33} = \frac{1}{2}\Big(2m_S^2 + g_p^2 Q_s \Big(Q_1 v1^2 + Q_2 v2^2 + Q_3 v3^2 + Q_{H_d} v_d^2 + Q_{H_u} v_u^2 + Q_s v_s^2\Big) + \Big(v_d^2 + v_u^2\Big)|\lambda|^2\Big) \tag{16.60}$$

$$m_{44} = \frac{1}{2}\Big(2ms12 + g_p^2 Q_1 \Big(Q_1 v1^2 + Q_2 v2^2 + Q_3 v3^2 + Q_{H_d} v_d^2 + Q_{H_u} v_u^2 + Q_s v_s^2\Big) + \Big(v2^2 + v3^2\Big)|\kappa|^2\Big) \tag{16.61}$$

$$m_{55} = \frac{1}{2}\Big(2ms22 + g_p^2 Q_2 \Big(Q_1 v1^2 + Q_2 v2^2 + Q_3 v3^2 + Q_{H_d} v_d^2 + Q_{H_u} v_u^2 + Q_s v_s^2\Big) + \Big(v1^2 + v3^2\Big)|\kappa|^2\Big) \tag{16.62}$$

$$m_{66} = \frac{1}{2}\Big(2ms32 + g_p^2 Q_3 \Big(Q_1 v1^2 + Q_2 v2^2 + Q_3 v3^2 + Q_{H_d} v_d^2 + Q_{H_u} v_u^2 + Q_s v_s^2\Big) + \Big(v1^2 + v2^2\Big)|\kappa|^2\Big) \tag{16.63}$$

This matrix is diagonalized by Z^A:

$$Z^A m^2_{A^0} Z^{A,\dagger} = m^{dia}_{2,A^0} \tag{16.64}$$

with

$$\sigma_d = \sum_{t_2} Z^{A,*}_{j1} A^0_j\,, \qquad \sigma_u = \sum_{t_2} Z^{A,*}_{j2} A^0_j\,, \qquad \sigma_s = \sum_{t_2} Z^{A,*}_{j3} A^0_j \tag{16.65}$$

$$\sigma_1 = \sum_{t_2} Z^{A,*}_{j4} A^0_j\,, \qquad \sigma_2 = \sum_{t_2} Z^{A,*}_{j5} A^0_j\,, \qquad \sigma_3 = \sum_{t_2} Z^{A,*}_{j6} A^0_j \tag{16.66}$$

- **Mass matrix for Charged Higgs**, Basis: $\left(H_d^-, H_u^{+,*}\right), \left(H_d^{-,*}, H_u^+\right)$

$$m^2_{H^-} = \begin{pmatrix} m_{11} & \frac{1}{4}\Big(2\sqrt{2} v_s T_\lambda - 2 v_d v_u |\lambda|^2 + g_2^2 v_d v_u\Big) \\ \frac{1}{4}\Big(2\sqrt{2} v_s T^*_\lambda - 2 v_d v_u |\lambda|^2 + g_2^2 v_d v_u\Big) & m_{22} \end{pmatrix} \tag{16.67}$$

$$m_{11} = \frac{1}{8}\Big(8 m^2_{H_d} + 4 g_p^2 Q_{H_d} Q_1 v1^2 + 4 g_p^2 Q_{H_d} Q_2 v2^2 + 4 g_p^2 Q_{H_d} Q_3 v3^2 + g_1^2 v_d^2 + g_2^2 v_d^2 + 4 g_p^2 Q^2_{H_d} v_d^2 + 4 g_p^2 Q_{H_d} Q_s v_s^2 - g_1^2 v_u^2 + g_2^2 v_u^2 + 4 g_p^2 Q_{H_d} Q_{H_u} v_u^2 + 4 v_s^2 |\lambda|^2\Big) \tag{16.68}$$

$$m_{22} = \frac{1}{8}\Big(8 m^2_{H_u} + 4 g_p^2 Q_{H_u} Q_1 v1^2 + 4 g_p^2 Q_{H_u} Q_2 v2^2 + 4 g_p^2 Q_{H_u} Q_3 v3^2 - g_1^2 v_d^2 + g_2^2 v_d^2 + 4 g_p^2 Q_{H_d} Q_{H_u} v_d^2 + 4 g_p^2 Q_{H_u} Q_s v_s^2 + g_1^2 v_u^2 + g_2^2 v_u^2 + 4 g_p^2 Q^2_{H_u} v_u^2 + 4 v_s^2 |\lambda|^2\Big) \tag{16.69}$$

This matrix is diagonalized by Z^+:

$$Z^+ m^2_{H^-} Z^{+,\dagger} = m^{dia}_{2,H^-} \tag{16.70}$$

with

$$H_d^- = \sum_{t_2} Z^{+,*}_{j1} H_j^-\,, \qquad H_u^+ = \sum_{t_2} Z^+_{j2} H_j^+ \tag{16.71}$$

The mixing matrix can be parametrized by

$$Z^+ = \begin{pmatrix} -\cos\beta & \sin\beta \\ \sin\beta & \cos\beta \end{pmatrix} \tag{16.72}$$

Mass Matrices for Fermions

- **Mass matrix for Neutralinos**, Basis: $\left(\tilde{U},\lambda_{\tilde{B}},\tilde{W}^0,\tilde{H}_d^0,\tilde{H}_u^0,\tilde{S},\tilde{s}_1,\tilde{s}_2,\tilde{s}_3\right),\left(\tilde{U},\lambda_{\tilde{B}},\tilde{W}^0,\tilde{H}_d^0,\tilde{H}_u^0,\tilde{S},\tilde{s}_1,\tilde{s}_2,\tilde{s}_3\right)$

$$m_{\tilde{\chi}^0} = \begin{pmatrix} M_U & 0 & 0 & m_{41} & m_{51} & m_{61} & g_p Q_1 v1 & g_p Q_2 v2 & g_p Q_3 v3 \\ 0 & M_1 & 0 & -\frac{1}{2}g_1 v_d & \frac{1}{2}g_1 v_u & 0 & 0 & 0 & 0 \\ 0 & 0 & M_2 & \frac{1}{2}g_2 v_d & -\frac{1}{2}g_2 v_u & 0 & 0 & 0 & 0 \\ m_{41} & -\frac{1}{2}g_1 v_d & \frac{1}{2}g_2 v_d & 0 & m_{54} & m_{64} & 0 & 0 & 0 \\ m_{51} & \frac{1}{2}g_1 v_u & -\frac{1}{2}g_2 v_u & m_{54} & 0 & m_{65} & 0 & 0 & 0 \\ m_{61} & 0 & 0 & m_{64} & m_{65} & 0 & 0 & 0 & 0 \\ g_p Q_1 v1 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{\sqrt{2}}v3\kappa & \frac{1}{\sqrt{2}}v2\kappa \\ g_p Q_2 v2 & 0 & 0 & 0 & 0 & 0 & \frac{1}{\sqrt{2}}v3\kappa & 0 & \frac{1}{\sqrt{2}}v1\kappa \\ g_p Q_3 v3 & 0 & 0 & 0 & 0 & 0 & \frac{1}{\sqrt{2}}v2\kappa & \frac{1}{\sqrt{2}}v1\kappa & 0 \end{pmatrix} \tag{16.73}$$

$$m_{41} = g_p Q_{H_d} v_d \tag{16.74}$$
$$m_{51} = g_p Q_{H_u} v_u \tag{16.75}$$
$$m_{54} = -\frac{1}{\sqrt{2}} v_s \lambda \tag{16.76}$$
$$m_{61} = g_p Q_s v_s \tag{16.77}$$
$$m_{64} = -\frac{1}{\sqrt{2}} v_u \lambda \tag{16.78}$$
$$m_{65} = -\frac{1}{\sqrt{2}} v_d \lambda \tag{16.79}$$

This matrix is diagonalized by N:

$$N m_{\tilde{\chi}^0} N^\dagger = m^{dia}_{\tilde{\chi}^0} \tag{16.80}$$

with

$$\tilde{U} = \sum_{t_2} N^*_{j1}\lambda^0_j\,, \qquad \lambda_{\tilde{B}} = \sum_{t_2} N^*_{j2}\lambda^0_j\,, \qquad \tilde{W}^0 = \sum_{t_2} N^*_{j3}\lambda^0_j \tag{16.81}$$
$$\tilde{H}^0_d = \sum_{t_2} N^*_{j4}\lambda^0_j\,, \qquad \tilde{H}^0_u = \sum_{t_2} N^*_{j5}\lambda^0_j\,, \qquad \tilde{S} = \sum_{t_2} N^*_{j6}\lambda^0_j \tag{16.82}$$
$$\tilde{s}_1 = \sum_{t_2} N^*_{j7}\lambda^0_j\,, \qquad \tilde{s}_2 = \sum_{t_2} N^*_{j8}\lambda^0_j\,, \qquad \tilde{s}_3 = \sum_{t_2} N^*_{j9}\lambda^0_j \tag{16.83}$$

- **Mass matrix for Charginos**, Basis: $\left(\tilde{W}^-,\tilde{H}_d^-\right),\left(\tilde{W}^+,\tilde{H}_u^+\right)$

$$m_{\tilde{\chi}^-} = \begin{pmatrix} M_2 & \frac{1}{\sqrt{2}}g_2 v_u \\ \frac{1}{\sqrt{2}}g_2 v_d & \frac{1}{\sqrt{2}}v_s\lambda \end{pmatrix} \tag{16.84}$$

This matrix is diagonalized by U and V

$$U^* m_{\tilde{\chi}^-} V^\dagger = m^{dia}_{\tilde{\chi}^-} \tag{16.85}$$

with

$$\tilde{W}^- = \sum_{t_2} U^*_{j1}\lambda^-_j \,, \qquad \tilde{H}^-_d = \sum_{t_2} U^*_{j2}\lambda^-_j \tag{16.86}$$

$$\tilde{W}^+ = \sum_{t_2} V^*_{1j}\lambda^+_j \,, \qquad \tilde{H}^+_u = \sum_{t_2} V^*_{2j}\lambda^+_j \tag{16.87}$$

- **Mass matrix for Leptons**, Basis: $\left(e_{L,o_1}\right), \left(e^*_{R,p_1}\right)$

$$m_e = \left(\begin{array}{c} \frac{1}{\sqrt{2}} v_d Y_{e,o_1 p_1} \end{array} \right) \tag{16.88}$$

This matrix is diagonalized by U^e_L and U^e_R

$$U^{e,*}_L m_e U^{e,\dagger}_R = m^{dia}_e \tag{16.89}$$

with

$$e_{L,i} = \sum_{t_2} U^{e,*}_{L,ji} E_{L,j} \tag{16.90}$$

$$e_{R,i} = \sum_{t_2} U^{e}_{R,ij} E^*_{R,j} \tag{16.91}$$

- **Mass matrix for Down-Quarks**, Basis: $\left(d_{L,o_1\alpha_1}\right), \left(d^*_{R,p_1\beta_1}\right)$

$$m_d = \left(\begin{array}{c} \frac{1}{\sqrt{2}} v_d \delta_{\alpha_1\beta_1} Y_{d,o_1 p_1} \end{array} \right) \tag{16.92}$$

This matrix is diagonalized by U^d_L and U^d_R

$$U^{d,*}_L m_d U^{d,\dagger}_R = m^{dia}_d \tag{16.93}$$

with

$$d_{L,i\alpha} = \sum_{t_2} U^{d,*}_{L,ji} D_{L,j\alpha} \tag{16.94}$$

$$d_{R,i\alpha} = \sum_{t_2} U^{d}_{R,ij} D^*_{R,j\alpha} \tag{16.95}$$

- **Mass matrix for Up-Quarks**, Basis: $\left(u_{L,o_1\alpha_1}\right), \left(u^*_{R,p_1\beta_1}\right)$

$$m_u = \left(\begin{array}{c} \frac{1}{\sqrt{2}} v_u \delta_{\alpha_1\beta_1} Y_{u,o_1 p_1} \end{array} \right) \tag{16.96}$$

This matrix is diagonalized by U^u_L and U^u_R

$$U^{u,*}_L m_u U^{u,\dagger}_R = m^{dia}_u \tag{16.97}$$

with

$$u_{L,i\alpha} = \sum_{t_2} U^{u,*}_{L,ji} U_{L,j\alpha} \tag{16.98}$$

$$u_{R,i\alpha} = \sum_{t_2} U^{u}_{R,ij} U^*_{R,j\alpha} \tag{16.99}$$

16.4 Vacuum Expectation Values

16.4.1 VEVs for eigenstates 'EWSB'

$$H^0_d = \frac{1}{\sqrt{2}}\phi_d + \frac{1}{\sqrt{2}}v_d + i\frac{1}{\sqrt{2}}\sigma_d \tag{16.100}$$

$$H^0_u = \frac{1}{\sqrt{2}}\phi_u + \frac{1}{\sqrt{2}}v_u + i\frac{1}{\sqrt{2}}\sigma_u \tag{16.101}$$

$$S = \frac{1}{\sqrt{2}}\phi_s + \frac{1}{\sqrt{2}}v_s + i\frac{1}{\sqrt{2}}\sigma_s \tag{16.102}$$

$$S_1 = \frac{1}{\sqrt{2}}\phi_1 + \frac{1}{\sqrt{2}}v1 + i\frac{1}{\sqrt{2}}\sigma_1 \tag{16.103}$$

$$S_2 = \frac{1}{\sqrt{2}}\phi_2 + \frac{1}{\sqrt{2}}v2 + i\frac{1}{\sqrt{2}}\sigma_2 \tag{16.104}$$

$$S_3 = \frac{1}{\sqrt{2}}\phi_3 + \frac{1}{\sqrt{2}}v3 + i\frac{1}{\sqrt{2}}\sigma_3 \tag{16.105}$$

16.5 Tadpole Equations

16.5.1 Tadpole Equations for eigenstates 'TEMP'

$$\begin{aligned}\frac{\partial V}{\partial v_d} = &\frac{1}{8}\Big(\Big(4g_p^2 Q_{H_d}^2 + g_1^2 + g_2^2\Big)v_d^3\\ &+ v_d\Big(8m^2_{H_d} + 4g_p^2 Q_{H_d} Q_1 v1^2 + 4g_p^2 Q_{H_d} Q_2 v2^2 + 4g_p^2 Q_{H_d} Q_3 v3^2 + 4g_p^2 Q_{H_d} Q_s v_s^2 - g_1^2 v_u^2\\ &- g_2^2 v_u^2 + 4g_p^2 Q_{H_d} Q_{H_u} v_u^2 + 4\Big(v_s^2 + v_u^2\Big)|\lambda|^2\Big)\\ &- 2\sqrt{2}v_s v_u\Big(T^*_\lambda + T_\lambda\Big)\Big)\end{aligned} \tag{16.106}$$

$$\begin{aligned}\frac{\partial V}{\partial v_u} = &\frac{1}{8}\Big(v_u\Big(4g_p^2 Q_{H_u}\Big(Q_1 v1^2 + Q_2 v2^2 + Q_3 v3^2 + Q_{H_d} v_d^2 + Q_{H_u} v_u^2 + Q_s v_s^2\Big) + 8m^2_{H_u} - \Big(g_1^2 + g_2^2\Big)\Big(-v_u^2 + v_d^2\Big)\Big)\\ &+ 4\Big(v_d^2 + v_s^2\Big)v_u|\lambda|^2 - 4\sqrt{2}v_d v_s \Re\Big(T_\lambda\Big)\Big)\end{aligned} \tag{16.107}$$

$$\begin{aligned}\frac{\partial V}{\partial v_s} = &\frac{1}{4}\Big(2g_p^2 Q_s^2 v_s^3 + 2v_s\Big(2m_S^2 + g_p^2 Q_s\Big(Q_1 v1^2 + Q_2 v2^2 + Q_3 v3^2 + Q_{H_d} v_d^2 + Q_{H_u} v_u^2\Big) + \Big(v_d^2 + v_u^2\Big)|\lambda|^2\Big)\\ &- \sqrt{2}v_d v_u\Big(T^*_\lambda + T_\lambda\Big)\Big)\end{aligned} \tag{16.108}$$

$$\frac{\partial V}{\partial v1} = \frac{1}{4}\Big(2g_p^2 Q_1^2 v1^3 + 2v1\Big(2ms12 + g_p^2 Q_1\Big(Q_2 v2^2 + Q_3 v3^2 + Q_{H_d} v_d^2 + Q_{H_u} v_u^2 + Q_s v_s^2\Big) + \Big(v2^2 + v3^2\Big)|\kappa|^2\Big) + \sqrt{2} v2 v3\Big(T_\kappa^* \tag{16.109}$$

$$\frac{\partial V}{\partial v2} = \frac{1}{4}\Big(2g_p^2 Q_2^2 v2^3 + 2v2\Big(2ms22 + g_p^2 Q_2\Big(Q_1 v1^2 + Q_3 v3^2 + Q_{H_d} v_d^2 + Q_{H_u} v_u^2 + Q_s v_s^2\Big) + \Big(v1^2 + v3^2\Big)|\kappa|^2\Big) + \sqrt{2} v1 v3\Big(T_\kappa^* \tag{16.110}$$

$$\frac{\partial V}{\partial v3} = \frac{1}{2}\Big(\sqrt{2} v1 v2 \Re\Big(T_\kappa\Big) + \Big(v1^2 + v2^2\Big) v3 |\kappa|^2 + v3\Big(2ms32 + g_p^2 Q_3\Big(Q_1 v1^2 + Q_2 v2^2 + Q_3 v3^2 + Q_{H_d} v_d^2 + Q_{H_u} v_u^2 + Q_s v_s^2\Big)\Big) \tag{16.111}$$

16.5.2 Tadpole Equations for eigenstates 'EWSB'

$$\begin{aligned}\frac{\partial V}{\partial v_d} = &\frac{1}{8}\Big(v_d\Big(4g_p^2 Q_{H_d}\Big(Q_1 v1^2 + Q_2 v2^2 + Q_3 v3^2 + Q_{H_d} v_d^2 + Q_{H_u} v_u^2 + Q_s v_s^2\Big) + 8m_{H_d}^2 + \Big(g_1^2 + g_2^2\Big)\Big(-v_u^2 + v_d^2\Big)\Big)\\ &+ 4v_d\Big(v_s^2 + v_u^2\Big)|\lambda|^2 - 4\sqrt{2} v_s v_u \Re\Big(T_\lambda\Big)\Big)\end{aligned} \tag{16.112}$$

$$\begin{aligned}\frac{\partial V}{\partial v_u} = &\frac{1}{8}\Big(v_u\Big(4g_p^2 Q_{H_u}\Big(Q_1 v1^2 + Q_2 v2^2 + Q_3 v3^2 + Q_{H_d} v_d^2 + Q_{H_u} v_u^2 + Q_s v_s^2\Big) + 8m_{H_u}^2 - \Big(g_1^2 + g_2^2\Big)\Big(-v_u^2 + v_d^2\Big)\Big)\\ &+ 4\Big(v_d^2 + v_s^2\Big)v_u|\lambda|^2 - 4\sqrt{2} v_d v_s \Re\Big(T_\lambda\Big)\Big)\end{aligned} \tag{16.113}$$

$$\begin{aligned}\frac{\partial V}{\partial v_s} = &\frac{1}{2}\Big(v_s\Big(2m_S^2 + g_p^2 Q_s\Big(Q_1 v1^2 + Q_2 v2^2 + Q_3 v3^2 + Q_{H_d} v_d^2 + Q_{H_u} v_u^2 + Q_s v_s^2\Big)\Big) + v_s\Big(v_d^2 + v_u^2\Big)|\lambda|^2\\ &- \sqrt{2} v_d v_u \Re\Big(T_\lambda\Big)\Big)\end{aligned} \tag{16.114}$$

$$\frac{\partial V}{\partial v1} = \frac{1}{2}\Big(\sqrt{2} v2 v3 \Re\Big(T_\kappa\Big) + v1\Big(2ms12 + g_p^2 Q_1\Big(Q_1 v1^2 + Q_2 v2^2 + Q_3 v3^2 + Q_{H_d} v_d^2 + Q_{H_u} v_u^2 + Q_s v_s^2\Big)\Big) + v1\Big(v2^2 + v3^2\Big)|\kappa|^2 \tag{16.115}$$

$$\frac{\partial V}{\partial v2} = \frac{1}{2}\Big(\sqrt{2} v1 v3 \Re\Big(T_\kappa\Big) + v2\Big(2ms22 + g_p^2 Q_2\Big(Q_1 v1^2 + Q_2 v2^2 + Q_3 v3^2 + Q_{H_d} v_d^2 + Q_{H_u} v_u^2 + Q_s v_s^2\Big)\Big) + v2\Big(v1^2 + v3^2\Big)|\kappa|^2 \tag{16.116}$$

$$\frac{\partial V}{\partial v3} = \frac{1}{2}\Big(\sqrt{2} v1 v2 \Re\Big(T_\kappa\Big) + \Big(v1^2 + v2^2\Big) v3 |\kappa|^2 + v3\Big(2ms32 + g_p^2 Q_3\Big(Q_1 v1^2 + Q_2 v2^2 + Q_3 v3^2 + Q_{H_d} v_d^2 + Q_{H_u} v_u^2 + Q_s v_s^2\Big)\Big) \tag{16.117}$$

16.6 Particle content for eigenstates 'EWSB'

Name	Type	complex/real	Generations	Indices
$\tilde{d}$	Scalar	complex	6	generation, color
$\tilde{\nu}$	Scalar	complex	3	generation
$\tilde{u}$	Scalar	complex	6	generation, color
$\tilde{e}$	Scalar	complex	6	generation
h	Scalar	real	6	generation
A^0	Scalar	real	6	generation
H^-	Scalar	complex	2	generation

ν	Fermion	Dirac	3	generation
$\tilde{g}$	Fermion	Majorana	8	generation
$\tilde{\chi}^0$	Fermion	Majorana	9	generation
$\tilde{\chi}^-$	Fermion	Dirac	2	generation
e	Fermion	Dirac	3	generation
d	Fermion	Dirac	3	generation, color
u	Fermion	Dirac	3	generation, color
g	Vector	real	8	generation, lorentz
W^-	Vector	complex	1	lorentz
γ	Vector	real	1	lorentz
Z_1	Vector	real	1	lorentz
Z_2	Vector	real	1	lorentz
η^G	Ghost	real	8	generation
η^-	Ghost	complex	1	
η^+	Ghost	complex	1	
η^γ	Ghost	real	1	
η^{Z_1}	Ghost	real	1	
η^{Z_2}	Ghost	real	1	

16.7 Modelfile for SARAH

```
Off[General::spell]
Print["Model file for the secluded MSSM loaded"];

ModelNameLaTeX ="secluded MSSM";


(*-------------------------------------------*)
(*   Particle Content*)
(*-------------------------------------------*)

(* Gauge Superfields *)

Gauge[[1]]={B,   U[1], hypercharge, g1,False};
Gauge[[2]]={WB, SU[2], left,        g2,True};
Gauge[[3]]={G,  SU[3], color,       g3,False};
Gauge[[4]]={U,   U[1], additional,  gp,False};


(* Chiral Superfields *)

Fields[[1]] = {{uL,  dL},  3, q,   1/6, 2, 3, Qq};
Fields[[2]] = {{vL,  eL},  3, l,  -1/2, 2, 1, Ql};
Fields[[3]] = {{Hd0, Hdm}, 1, Hd, -1/2, 2, 1, QHd};
Fields[[4]] = {{Hup, Hu0}, 1, Hu,  1/2, 2, 1, QHu};

Fields[[5]] = {conj[dR], 3, d,  1/3, 1, -3, Qd};
Fields[[6]] = {conj[uR], 3, u, -2/3, 1, -3, Qu};
Fields[[7]] = {conj[eR], 3, e,    1, 1,  1, Qe};
Fields[[8]] = {sR, 1, s,    0, 1,  1, Qs};
Fields[[9]] = {S1, 1, s1,    0, 1,  1, Qs1};
Fields[[10]] = {S2, 1, s2,    0, 1,  1, Qs2};
Fields[[11]] = {S3, 1, s3,    0, 1,  1, Qs3};


(*-----------------------------------------------------*)
(* Superpotential *)
(*-----------------------------------------------------*)

SuperPotential = { {{1, Yu},{q,Hu,u}}, {{-1,Yd},{q,Hd,d}},
                   {{-1,Ye},{l,Hd,e}},
                   {{1,\[Lambda]},{Hu,Hd,s}},
                   {{1,\[Kappa]},{s1,s2,s3}} };
```

```
(*-------------------------------------------*)
(* Integrate Out or Delete Particles         *)
(*-------------------------------------------*)

IntegrateOut={};
DeleteParticles={};


(*----------------------------------------------*)
(*   DEFINITION                                 *)
(*----------------------------------------------*)

NameOfStates={GaugeES,TEMP, EWSB};

(* ----- Before EWSB ----- *)


DEFINITION[GaugeES][GaugeFixing]=
{ {Der[VWB],  -1/(2 RXi[W])},
     {Der[VG],   -1/(2 RXi[G]) }};

(* ----- After EWSB ----- *)

DEFINITION[TEMP][GaugeSector]=
{{VWB,{1,{VWm,1/Sqrt[2]},{conj[VWm],1/Sqrt[2]}},
      {2,{VWm,-\[ImaginaryI]/Sqrt[2]},{conj[VWm],\[ImaginaryI]/Sqrt[2]}},
      {3,{VP,Sin[ThetaW]},{VZ,Cos[ThetaW]}}},
 {VB, {1,{VP,Cos[ThetaW]},{VZ,-Sin[ThetaW]}}}};

DEFINITION[EWSB][GaugeSector]=
{{VZ, {1,{VZ1,Sin[ThetaZ]},{VZ2,Cos[ThetaZ]}}},
 {VU, {1,{VZ1,Cos[ThetaZ]},{VZ2,-Sin[ThetaW]}}},
 {fWB,{1,{fWm,1/Sqrt[2]},{fWp,1/Sqrt[2]}},
      {2,{fWm,-\[ImaginaryI]/Sqrt[2]},{fWp,\[ImaginaryI]/Sqrt[2]}},
      {3,{fW0,1}}}};



DEFINITION[EWSB][VEVs]=
{{SHd0, {vd, 1/Sqrt[2]}, {sigmad, \[ImaginaryI]/Sqrt[2]},{phid,1/Sqrt[2]}},
 {SHu0, {vu, 1/Sqrt[2]}, {sigmau, \[ImaginaryI]/Sqrt[2]},{phiu,1/Sqrt[2]}},
 {SsR, {vS, 1/Sqrt[2]}, {sigmaS, \[ImaginaryI]/Sqrt[2]},{phiS,1/Sqrt[2]}},
 {SS1, {v1, 1/Sqrt[2]}, {sigma1, \[ImaginaryI]/Sqrt[2]},{phi1,1/Sqrt[2]}},
 {SS2, {v2, 1/Sqrt[2]}, {sigma2, \[ImaginaryI]/Sqrt[2]},{phi2,1/Sqrt[2]}},
 {SS3, {v3, 1/Sqrt[2]}, {sigma3, \[ImaginaryI]/Sqrt[2]},{phi3,1/Sqrt[2]}}
        };
```

```
DEFINITION[EWSB][MatterSector]=

{    {{SdL, SdR}, {Sd, ZD}},
     {{SvL}, {Sv, ZV}},
     {{SuL, SuR}, {Su, ZU}},
     {{SeL, SeR}, {Se, ZE}},
     {{phid, phiu, phiS,phi1,phi2,phi3}, {hh, ZH}},
     {{sigmad, sigmau,sigmaS,sigma1,sigma2,sigma3}, {Ah, ZA}},
     {{SHdm,conj[SHup]},{Hpm,ZP}},
     {{fU,fB, fW0, FHd0, FHu0,FsR,FS1,FS2,FS3}, {L0, ZN}},
     {{{fWm, FHdm}, {fWp, FHup}}, {{Lm,UM}, {Lp,UP}}},
     {{{FeL},{conj[FeR]}},{{FEL,ZEL},{FER,ZER}}},
     {{{FdL},{conj[FdR]}},{{FDL,ZDL},{FDR,ZDR}}},
     {{{FuL},{conj[FuR]}},{{FUL,ZUL},{FUR,ZUR}}}
   };

DEFINITION[EWSB][Phases]=
{    {fG, PhaseGlu}
    };

DEFINITION[TEMP][GaugeFixing]=
  {     {Der[VP],                                     - 1/(2 RXi[P])},
{Der[VWm]+\[ImaginaryI] Mass[VWm] RXi[W] Hpm[{1}], - 1/(RXi[W])},
{Der[VZ] - Mass[VZ] RXi[Z] Ah[{1}],               - 1/(2 RXi[Z])},
{Der[VG],                                    - 1/(2 RXi[G])}    };

DEFINITION[EWSB][GaugeFixing]=
  { {Der[VP],                                     - 1/(2 RXi[P])},
{Der[VWm]+\[ImaginaryI] Mass[VWm] RXi[W] Hpm[{1}], - 1/(RXi[W])},
{Der[VZ1] - Mass[VZ1] RXi[Z1] Ah[{1}],               - 1/(2 RXi[Z1])},
{Der[VG],                                    - 1/(2 RXi[G])}    };

(*------------------------------------------------------*)
(* Dirac-Spinors *)
(*------------------------------------------------------*)

dirac[[1]] = {Fd,  FDL, conj[FDR]};
dirac[[2]] = {Fe,  FEL, conj[FER]};
dirac[[3]] = {Fu,  FUL, conj[FUR]};
dirac[[4]] = {Fv,  FvL, 0};
dirac[[5]] = {Chi, L0, conj[L0]};
dirac[[6]] = {Cha, Lm, conj[Lp]};
dirac[[7]] = {Glu, fG, conj[fG]};
dirac[[8]] = {Bino, fB, conj[fB]};
dirac[[9]] = {Wino, fWB, conj[fWB]};
dirac[[10]] = {H0, FHu0, conj[FHd0]};
dirac[[11]] = {HC, FHup, conj[FHdm]};
```

```
dirac[[12]] = {S, FsR, conj[FsR]};

(* Unbroken EW *)

dirac[[13]] = {Fd1, FdL, 0};
dirac[[14]] = {Fd2, 0, FdR};
dirac[[15]] = {Fu1, FuL, 0};
dirac[[16]] = {Fu2, 0, FuR};
dirac[[17]] = {Fe1, FeL, 0};
dirac[[18]] = {Fe2, 0, FeR};
dirac[[19]] = {Fs1, FS1, conj[FS1]};
dirac[[20]] = {Fs2, FS2, conj[FS2]};
dirac[[21]] = {Fs3, FS3, conj[FS3]};
dirac[[22]] = {FU, fU, conj[fU]};



(*-------------------------------------------------------*)
(* Automatized Output        *)
(*-------------------------------------------------------*)

(*
makeOutput = {
                   {EWSB, {TeX, FeynArts}}
             };

            *)

SpectrumFile= None;
```

16.8 Implementation in SARAH

Model directory: `secluded-MSSM`

16.8.1 Particles for eigenstates 'GaugeES'

- Fermions

$\tilde{B} = \begin{pmatrix} \lambda_{\tilde{B}} \\ \lambda^*_{\tilde{B}} \end{pmatrix}$	$\texttt{Bino} = \begin{pmatrix} \texttt{fB} \\ \texttt{conj[fB]} \end{pmatrix}$

$d^1_{i\alpha} = \begin{pmatrix} d_{L,i\alpha} \\ 0 \end{pmatrix}$	`Fd1[{generation, color}]` $= \begin{pmatrix} \texttt{FdL[\{generation, color\}]} \\ 0 \end{pmatrix}$
$d^2_{i\alpha} = \begin{pmatrix} 0 \\ d_{R,i\alpha} \end{pmatrix}$	`Fd2[{generation, color}]` $= \begin{pmatrix} 0 \\ \texttt{FdR[\{generation, color\}]} \end{pmatrix}$
$e^1_{i} = \begin{pmatrix} e_{L,i} \\ 0 \end{pmatrix}$	`Fe1[{generation}]` $= \begin{pmatrix} \texttt{FeL[\{generation\}]} \\ 0 \end{pmatrix}$
$e^2_{i} = \begin{pmatrix} 0 \\ e_{R,i} \end{pmatrix}$	`Fe2[{generation}]` $= \begin{pmatrix} 0 \\ \texttt{FeR[\{generation\}]} \end{pmatrix}$
$\tilde{S}_1 = \begin{pmatrix} \tilde{s}_1 \\ \tilde{s}^*_1 \end{pmatrix}$	`Fs1` $= \begin{pmatrix} \texttt{FS1} \\ \texttt{conj[FS1]} \end{pmatrix}$
$\tilde{S}_2 = \begin{pmatrix} \tilde{s}_2 \\ \tilde{s}^*_2 \end{pmatrix}$	`Fs2` $= \begin{pmatrix} \texttt{FS2} \\ \texttt{conj[FS2]} \end{pmatrix}$
$\tilde{S}_3 = \begin{pmatrix} \tilde{s}_3 \\ \tilde{s}^*_3 \end{pmatrix}$	`Fs3` $= \begin{pmatrix} \texttt{FS3} \\ \texttt{conj[FS3]} \end{pmatrix}$
$\mathrm{FU} = \begin{pmatrix} \tilde{U} \\ \tilde{U}^* \end{pmatrix}$	`FU` $= \begin{pmatrix} \texttt{fU} \\ \texttt{conj[fU]} \end{pmatrix}$
$u^1_{i\alpha} = \begin{pmatrix} u_{L,i\alpha} \\ 0 \end{pmatrix}$	`Fu1[{generation, color}]` $= \begin{pmatrix} \texttt{FuL[\{generation, color\}]} \\ 0 \end{pmatrix}$
$u^2_{i\alpha} = \begin{pmatrix} 0 \\ u_{R,i\alpha} \end{pmatrix}$	`Fu2[{generation, color}]` $= \begin{pmatrix} 0 \\ \texttt{FuR[\{generation, color\}]} \end{pmatrix}$
$\nu_{i} = \begin{pmatrix} \nu_{L,i} \\ 0 \end{pmatrix}$	`Fv[{generation}]` $= \begin{pmatrix} \texttt{FvL[\{generation\}]} \\ 0 \end{pmatrix}$
$\tilde{g}_{i} = \begin{pmatrix} \lambda_{\tilde{g},i} \\ \lambda^*_{\tilde{g},i} \end{pmatrix}$	`Glu[{generation}]` $= \begin{pmatrix} \texttt{fG[\{generation\}]} \\ \texttt{conj[fG[\{generation\}]]} \end{pmatrix}$
$\tilde{H}^0 = \begin{pmatrix} \tilde{H}^0_u \\ \tilde{H}^{0,*}_d \end{pmatrix}$	`H0` $= \begin{pmatrix} \texttt{FHu0} \\ \texttt{conj[FHd0]} \end{pmatrix}$
$\tilde{H}^- = \begin{pmatrix} \tilde{H}^+_u \\ \tilde{H}^{-,*}_d \end{pmatrix}$	`HC` $= \begin{pmatrix} \texttt{FHup} \\ \texttt{conj[FHdm]} \end{pmatrix}$
$\tilde{S} = \begin{pmatrix} \tilde{S} \\ \tilde{S}^* \end{pmatrix}$	`S` $= \begin{pmatrix} \texttt{FsR} \\ \texttt{conj[FsR]} \end{pmatrix}$
$\tilde{W}_{i} = \begin{pmatrix} \lambda_{\tilde{W},i} \\ \lambda^*_{\tilde{W},i} \end{pmatrix}$	`Wino[{generation}]` $= \begin{pmatrix} \texttt{fWB[\{generation\}]} \\ \texttt{conj[fWB[\{generation\}]]} \end{pmatrix}$

- Scalars

$\tilde{d}_{L,i\alpha}$	SdL[{generation, color}]	$\tilde{u}_{L,i\alpha}$	SuL[{generation, color}]
$\tilde{e}_{L,i}$	SeL[{generation}]	$\tilde{\nu}_{L,i}$	SvL[{generation}]
H_d^0	SHd0	H_d^-	SHdm
H_u^0	SHu0	H_u^+	SHup
$\tilde{d}_{R,i\alpha}$	SdR[{generation, color}]	$\tilde{u}_{R,i\alpha}$	SuR[{generation, color}]
$\tilde{e}_{R,i}$	SeR[{generation}]	S	SsR
S_1	SS1	S_2	SS2
S_3	SS3		

- Vector Bosons

B_ρ	VB[{lorentz}]	$W_{i\rho}^-$	VWB[{generation, lorentz}]
$g_{i\rho}$	VG[{generation, lorentz}]	U_ρ	VU[{lorentz}]

- Ghosts

η^B	gB	$\mathrm{gWB}\Big(\{\mathrm{gt1}\}\Big)$	gWB[{generation}]
η_i^G	gG[{generation}]	gU	gU

16.8.2 Particles for eigenstates 'TEMP'

- Fermions

$\tilde{B} = \begin{pmatrix} \lambda_{\tilde{B}} \\ \lambda^*_{\tilde{B}} \end{pmatrix}$	$\texttt{Bino} = \begin{pmatrix} \texttt{fB} \\ \texttt{conj[fB]} \end{pmatrix}$
$d^1_{i\alpha} = \begin{pmatrix} d_{L,i\alpha} \\ 0 \end{pmatrix}$	$\texttt{Fd1[\{generation, color\}]} = \begin{pmatrix} \texttt{FdL[\{generation, color\}]} \\ 0 \end{pmatrix}$
$d^2_{i\alpha} = \begin{pmatrix} 0 \\ d_{R,i\alpha} \end{pmatrix}$	$\texttt{Fd2[\{generation, color\}]} = \begin{pmatrix} 0 \\ \texttt{FdR[\{generation, color\}]} \end{pmatrix}$
$e^1_i = \begin{pmatrix} e_{L,i} \\ 0 \end{pmatrix}$	$\texttt{Fe1[\{generation\}]} = \begin{pmatrix} \texttt{FeL[\{generation\}]} \\ 0 \end{pmatrix}$

$e_i^2 = \begin{pmatrix} 0 \\ e_{R,i} \end{pmatrix}$	`Fe2[{generation}]` $= \begin{pmatrix} \texttt{0} \\ \texttt{FeR[\{generation\}]} \end{pmatrix}$
$\tilde{S}_1 = \begin{pmatrix} \tilde{s}_1 \\ \tilde{s}_1^* \end{pmatrix}$	`Fs1` $= \begin{pmatrix} \texttt{FS1} \\ \texttt{conj[FS1]} \end{pmatrix}$
$\tilde{S}_2 = \begin{pmatrix} \tilde{s}_2 \\ \tilde{s}_2^* \end{pmatrix}$	`Fs2` $= \begin{pmatrix} \texttt{FS2} \\ \texttt{conj[FS2]} \end{pmatrix}$
$\tilde{S}_3 = \begin{pmatrix} \tilde{s}_3 \\ \tilde{s}_3^* \end{pmatrix}$	`Fs3` $= \begin{pmatrix} \texttt{FS3} \\ \texttt{conj[FS3]} \end{pmatrix}$
$\mathrm{FU} = \begin{pmatrix} \tilde{U} \\ \tilde{U}^* \end{pmatrix}$	`FU` $= \begin{pmatrix} \texttt{fU} \\ \texttt{conj[fU]} \end{pmatrix}$
$u_{i\alpha}^1 = \begin{pmatrix} u_{L,i\alpha} \\ 0 \end{pmatrix}$	`Fu1[{generation, color}]` $= \begin{pmatrix} \texttt{FuL[\{generation, color\}]} \\ \texttt{0} \end{pmatrix}$
$u_{i\alpha}^2 = \begin{pmatrix} 0 \\ u_{R,i\alpha} \end{pmatrix}$	`Fu2[{generation, color}]` $= \begin{pmatrix} \texttt{0} \\ \texttt{FuR[\{generation, color\}]} \end{pmatrix}$
$\nu_i = \begin{pmatrix} \nu_{L,i} \\ 0 \end{pmatrix}$	`Fv[{generation}]` $= \begin{pmatrix} \texttt{FvL[\{generation\}]} \\ \texttt{0} \end{pmatrix}$
$\tilde{g}_i = \begin{pmatrix} \lambda_{\tilde{g},i} \\ \lambda_{\tilde{g},i}^* \end{pmatrix}$	`Glu[{generation}]` $= \begin{pmatrix} \texttt{fG[\{generation\}]} \\ \texttt{conj[fG[\{generation\}]]} \end{pmatrix}$
$\tilde{H}^0 = \begin{pmatrix} \tilde{H}_u^0 \\ \tilde{H}_d^{0,*} \end{pmatrix}$	`H0` $= \begin{pmatrix} \texttt{FHu0} \\ \texttt{conj[FHd0]} \end{pmatrix}$
$\tilde{H}^- = \begin{pmatrix} \tilde{H}_u^+ \\ \tilde{H}_d^{-,*} \end{pmatrix}$	`HC` $= \begin{pmatrix} \texttt{FHup} \\ \texttt{conj[FHdm]} \end{pmatrix}$
$\tilde{S} = \begin{pmatrix} \tilde{S} \\ \tilde{S}^* \end{pmatrix}$	`S` $= \begin{pmatrix} \texttt{FsR} \\ \texttt{conj[FsR]} \end{pmatrix}$
$\tilde{W}_i = \begin{pmatrix} \lambda_{\tilde{W},i} \\ \lambda_{\tilde{W},i}^* \end{pmatrix}$	`Wino[{generation}]` $= \begin{pmatrix} \texttt{fWB[\{generation\}]} \\ \texttt{conj[fWB[\{generation\}]]} \end{pmatrix}$

- Scalars

$\tilde{d}_{L,i\alpha}$	`SdL[{generation, color}]`	$\tilde{u}_{L,i\alpha}$	`SuL[{generation, color}]`
$\tilde{e}_{L,i}$	`SeL[{generation}]`	$\tilde{\nu}_{L,i}$	`SvL[{generation}]`
H_d^0	`SHd0`	H_d^-	`SHdm`
H_u^0	`SHu0`	H_u^+	`SHup`
$\tilde{d}_{R,i\alpha}$	`SdR[{generation, color}]`	$\tilde{u}_{R,i\alpha}$	`SuR[{generation, color}]`
$\tilde{e}_{R,i}$	`SeR[{generation}]`	S	`SsR`

S_1	`SS1`	S_2	`SS2`
S_3	`SS3`		

- Vector Bosons

$g_{i\rho}$	`VG[{generation, lorentz}]`	U_ρ	`VU[{lorentz}]`
W^-_ρ	`VWm[{lorentz}]`	γ_ρ	`VP[{lorentz}]`
Z_ρ	`VZ[{lorentz}]`		

- Ghosts

η^G_i	`gG[{generation}]`	gU	`gU`
η^-	`gWm`	η^+	`gWmC`
η^γ	`gP`	η^Z	`gZ`

16.8.3 Particles for eigenstates 'EWSB'

- Fermions

$\tilde{\chi}^-_i = \begin{pmatrix} \lambda^-_i \\ \lambda^{+,*}_i \end{pmatrix}$	$\texttt{Cha[\{generation\}]} = \begin{pmatrix} \texttt{Lm[\{generation\}]} \\ \texttt{conj[Lp[\{generation\}]]} \end{pmatrix}$
$\tilde{\chi}^0_i = \begin{pmatrix} \lambda^0_i \\ \lambda^{0,*}_i \end{pmatrix}$	$\texttt{Chi[\{generation\}]} = \begin{pmatrix} \texttt{L0[\{generation\}]} \\ \texttt{conj[L0[\{generation\}]]} \end{pmatrix}$
$d_{i\alpha} = \begin{pmatrix} D_{L,i\alpha} \\ D^*_{R,i\alpha} \end{pmatrix}$	$\texttt{Fd[\{generation, color\}]} = \begin{pmatrix} \texttt{FDL[\{generation, color\}]} \\ \texttt{conj[FDR[\{generation, color\}]]} \end{pmatrix}$
$e_i = \begin{pmatrix} E_{L,i} \\ E^*_{R,i} \end{pmatrix}$	$\texttt{Fe[\{generation\}]} = \begin{pmatrix} \texttt{FEL[\{generation\}]} \\ \texttt{conj[FER[\{generation\}]]} \end{pmatrix}$
$u_{i\alpha} = \begin{pmatrix} U_{L,i\alpha} \\ U^*_{R,i\alpha} \end{pmatrix}$	$\texttt{Fu[\{generation, color\}]} = \begin{pmatrix} \texttt{FUL[\{generation, color\}]} \\ \texttt{conj[FUR[\{generation, color\}]]} \end{pmatrix}$
$\nu_i = \begin{pmatrix} \nu_{L,i} \\ 0 \end{pmatrix}$	$\texttt{Fv[\{generation\}]} = \begin{pmatrix} \texttt{FvL[\{generation\}]} \\ 0 \end{pmatrix}$

$\tilde{g}_i = \begin{pmatrix} \lambda_{\tilde{g},i} \\ \lambda^*_{\tilde{g},i} \end{pmatrix}$	Glu[{generation}] $= \begin{pmatrix} \texttt{fG[\{generation\}]} \\ \texttt{conj[fG[\{generation\}]]} \end{pmatrix}$

- Scalars

$\tilde{d}_{i\alpha}$	Sd[{generation, color}]	$\tilde{\nu}_i$	Sv[{generation}]
$\tilde{u}_{i\alpha}$	Su[{generation, color}]	$\tilde{e}_i$	Se[{generation}]
h_i	hh[{generation}]	A^0_i	Ah[{generation}]
H^-_i	Hpm[{generation}]		

- Vector Bosons

$g_{i\rho}$	VG[{generation, lorentz}]	W^-_ρ	VWm[{lorentz}]
γ_ρ	VP[{lorentz}]	$Z_{1,\rho}$	VZ1[{lorentz}]
$Z_{2,\rho}$	VZ2[{lorentz}]		

- Ghosts

η^G_i	gG[{generation}]	η^-	gWm
η^+	gWmC	η^γ	gP
η^{Z_1}	gZ1	η^{Z_2}	gZ2

16.8.4 Parameters

Q_q	Qq	Q_q	Ql	Q_{H_d}	QHd
Q_{H_u}	QHu	Q_d	Qd	Q_u	Qu
Q_e	Qe	Q_s	Qs	Q_1	Qs1
Q_2	Qs2	Q_3	Qs3	g_1	g1

g_2	g2	g_3	g3	g_p	gp
Y_u	Yu	T_u	T[Yu]	Y_d	Yd
T_d	T[Yd]	Y_e	Ye	T_e	T[Ye]
λ	\[Lambda]	T_λ	T[\[Lambda]]	κ	\[Kappa]
T_κ	T[\[Kappa]]	m_q^2	mq2	m_l^2	ml2
$m_{H_d}^2$	mHd2	$m_{H_u}^2$	mHu2	m_d^2	md2
m_u^2	mu2	m_e^2	me2	m_S^2	ms2
$ms12$	ms12	$ms22$	ms22	$ms32$	ms32
M_1	MassB	M_2	MassWB	M_3	MassG
M_U	MassU	Θ_W	ThetaW	v_d	vd
v_u	vu	v_s	vS	$v1$	v1
$v2$	v2	$v3$	v3	Θ_Z	ThetaZ
$\phi_{\tilde{g}}$	PhaseGlu	Z^D	ZD	Z^V	ZV
Z^U	ZU	Z^E	ZE	Z^H	ZH
Z^A	ZA	Z^+	ZP	N	ZN
U	UM	V	UP	U_L^e	ZEL
U_R^e	ZER	U_L^d	ZDL	U_R^d	ZDR
U_L^u	ZUL	U_R^u	ZUR	β	\[Beta]

Chapter 17

The $\mu\nu$ Supersymmetric Standard Model

17.1 Superfields

17.1.1 Vector Superfields

SF	Spin $\frac{1}{2}$	Spin 1	$SU(N)$	Coupling	Name
$\hat{B}$	$\lambda_{\tilde{B}}$	B	$U(1)$	g_1	hypercharge
$\hat{W}$	$\lambda_{\tilde{W}}$	W^-	SU(2)	g_2	left
$\hat{g}$	$\lambda_{\tilde{g}}$	g	SU(3)	g_3	color

17.1.2 Chiral Superfields

SF	Spin 0	Spin $\frac{1}{2}$	Generations	$(U(1) \otimes \text{SU}(2) \otimes \text{SU}(3))$
$\hat{q}$	$\tilde{q}$	q	3	$(\frac{1}{6}, \mathbf{2}, \mathbf{3})$
$\hat{l}$	$\tilde{l}$	l	3	$(-\frac{1}{2}, \mathbf{2}, \mathbf{1})$
$\hat{H}_d$	H_d	$\tilde{H}_d$	1	$(-\frac{1}{2}, \mathbf{2}, \mathbf{1})$
$\hat{H}_u$	H_u	$\tilde{H}_u$	1	$(\frac{1}{2}, \mathbf{2}, \mathbf{1})$
$\hat{d}$	$\tilde{d}_R^*$	d_R^*	3	$(\frac{1}{3}, \mathbf{1}, \overline{\mathbf{3}})$
$\hat{u}$	$\tilde{u}_R^*$	u_R^*	3	$(-\frac{2}{3}, \mathbf{1}, \overline{\mathbf{3}})$
$\hat{e}$	$\tilde{e}_R^*$	e_R^*	3	$(1, \mathbf{1}, \mathbf{1})$
$\hat{\nu}$	$\tilde{\nu}_R$	ν_R	1	$(0, \mathbf{1}, \mathbf{1})$

17.2 Superpotential and Lagrangian

17.2.1 Superpotential

$$W = Y_u\, \hat{q}\, \hat{H}_u\, \hat{u}\, - Y_d\, \hat{q}\, \hat{H}_d\, \hat{d}\, - Y_e\, \hat{l}\, \hat{H}_d\, \hat{e}\, + Y_v\, \hat{l}\, \hat{H}_u\, \hat{\nu}\, + \lambda\, \hat{H}_u\, \hat{H}_d\, \hat{\nu}\, + \frac{1}{3}\kappa\, \hat{\nu}\, \hat{\nu}\, \hat{\nu} \tag{17.1}$$

17.2.2 Softbreaking terms

$$
\begin{aligned}
L_{SB,W} = &+ \frac{1}{3}\tilde{\nu}_R^3 T_\kappa - H_d^0 H_u^0 \tilde{\nu}_R T_\lambda + H_d^- H_u^+ \tilde{\nu}_R T_\lambda + H_d^0 \tilde{d}^*_{R,k\gamma}\delta_{\alpha\gamma}\tilde{d}_{L,i\alpha} T_{d,ik} - H_d^- \tilde{d}^*_{R,k\gamma}\delta_{\alpha\gamma}\tilde{u}_{L,i\alpha} T_{d,ik} \\
&+ H_d^0 \tilde{e}^*_{R,k}\tilde{e}_{L,i} T_{e,ik} - H_d^- \tilde{e}^*_{R,k}\tilde{\nu}_{L,i} T_{e,ik} - H_u^+ \tilde{u}^*_{R,k\gamma}\delta_{\alpha\gamma}\tilde{d}_{L,i\alpha} T_{u,ik} + H_u^0 \tilde{u}^*_{R,k\gamma}\delta_{\alpha\gamma}\tilde{u}_{L,i\alpha} T_{u,ik} \\
&- H_u^+ \tilde{\nu}_R \tilde{e}_{L,i} T_{v,i} + H_u^0 \tilde{\nu}_R \tilde{\nu}_{L,i} T_{v,i} + \text{h.c.}
\end{aligned} \tag{17.2}
$$

$$
\begin{aligned}
L_{SB,\phi} = &- m_{H_d}^2 |H_d^0|^2 - m_{H_d}^2 |H_d^-|^2 - m_{H_u}^2 |H_u^0|^2 - m_{H_u}^2 |H_u^+|^2 - m_v^2 |\tilde{\nu}_R|^2 \\
&- \tilde{d}^*_{L,j\beta}\delta_{\alpha\beta} m^2_{q,ij}\tilde{d}_{L,i\alpha} - \tilde{d}^*_{R,i\alpha}\delta_{\alpha\beta} m^2_{d,ij}\tilde{d}_{R,j\beta} - \tilde{e}^*_{L,j} m^2_{l,ij}\tilde{e}_{L,i} - \tilde{e}^*_{R,i} m^2_{e,ij}\tilde{e}_{R,j} \\
&- \tilde{u}^*_{L,j\beta}\delta_{\alpha\beta} m^2_{q,ij}\tilde{u}_{L,i\alpha} - \tilde{u}^*_{R,i\alpha}\delta_{\alpha\beta} m^2_{u,ij}\tilde{u}_{R,j\beta} - \tilde{\nu}^*_{L,j} m^2_{l,ij}\tilde{\nu}_{L,i}
\end{aligned} \tag{17.3}
$$

$$
L_{SB,\lambda} = \frac{1}{2}\left(-\lambda_{\tilde{B}}^2 M_1 - M_2 \lambda_{\tilde{W},i}^2 - M_3 \lambda_{\tilde{g},i}^2 + \text{h.c.}\right) \tag{17.4}
$$

17.2.3 Gauge fixing terms

Gauge fixing terms for eigenstates 'GaugeES'

$$
L_{GF} = -\frac{1}{2}\partial_\mu g \xi_G^{-1} - \frac{1}{2}\partial_\mu W^- \xi_W^{-1} \tag{17.5}
$$

Gauge fixing terms for eigenstates 'EWSB'

$$
L_{GF} = -\frac{1}{2}\partial_\mu \gamma \xi_P^{-1} - \frac{1}{2}\partial_\mu g \xi_G^{-1} - \frac{1}{2}\xi_Z^{-1}\Big(-A_1^0 m_Z \xi_Z + \partial_\mu Z\Big) - \xi_W^{-1}\Big(iH_1^- m_{W^-}\xi_W + \partial_\mu W^-\Big) \tag{17.6}
$$

17.2.4 Fields integrated out

None

17.3 Field Rotations

17.3.1 Rotations in gauge sector for eigenstates 'EWSB'

$$
W_{1\rho}^- = \frac{1}{\sqrt{2}}W_\rho^- + \frac{1}{\sqrt{2}}W_\rho^+ \tag{17.7}
$$

$$
W_{2\rho}^- = -i\frac{1}{\sqrt{2}}W_\rho^- + i\frac{1}{\sqrt{2}}W_\rho^+ \tag{17.8}
$$

$$
W_{3\rho}^- = \cos\Theta_W Z_\rho + \sin\Theta_W \gamma_\rho \tag{17.9}
$$

$$
B_\rho = \cos\Theta_W \gamma_\rho - \sin\Theta_W Z_\rho \tag{17.10}
$$

$$
\lambda_{\tilde{W},1} = \frac{1}{\sqrt{2}}\tilde{W}^- + \frac{1}{\sqrt{2}}\tilde{W}^+ \tag{17.11}
$$

$$
\lambda_{\tilde{W},2} = -i\frac{1}{\sqrt{2}}\tilde{W}^- + i\frac{1}{\sqrt{2}}\tilde{W}^+ \tag{17.12}
$$

$$
\lambda_{\tilde{W},3} = \tilde{W}^0 \tag{17.13}
$$

17.3.2 Rotations in Mass sector for eigenstates 'EWSB'

Mass Matrices for Scalars

- **Mass matrix for Down-Squarks**, Basis: $\left(\tilde{d}_{L,o_1\alpha_1}, \tilde{d}_{R,o_2\alpha_2}\right), \left(\tilde{d}^*_{L,p_1\beta_1}, \tilde{d}^*_{R,p_2\beta_2}\right)$

$$m^2_{\tilde{d}} = \begin{pmatrix} m_{11} & \frac{1}{2}\delta_{\alpha_1\beta_2}\Big(\sqrt{2}v_d T_{d,o_1p_2} - v_R v_u \lambda^* Y_{d,o_1p_2}\Big) \\ \frac{1}{2}\Big(\sqrt{2}v_d T^*_{d,p_1o_2} - v_R v_u \lambda Y^*_{d,p_1o_2}\Big)\delta_{\alpha_2\beta_1} & m_{22} \end{pmatrix} \tag{17.14}$$

$$m_{11} = \frac{1}{24}\delta_{\alpha_1\beta_1}\Big(12\Big(2m^2_{q,o_1p_1} + v_d^2\sum_{a=1}^{3} Y^*_{d,p_1a}Y_{d,o_1a}\Big) - \Big(3g_2^2 + g_1^2\Big)\delta_{o_1p_1}\Big(-v_u^2 + v_d^2 + \sum_{a=1}^{3} v^2_{L,a}\Big)\Big) \tag{17.15}$$

$$m_{22} = \frac{1}{12}\delta_{\alpha_2\beta_2}\Big(6\Big(2m^2_{d,p_2o_2} + v_d^2\sum_{a=1}^{3} Y^*_{d,ao_2}Y_{d,ap_2}\Big) - g_1^2\delta_{o_2p_2}\Big(-v_u^2 + v_d^2 + \sum_{a=1}^{3} v^2_{L,a}\Big)\Big) \tag{17.16}$$

This matrix is diagonalized by Z^D:

$$Z^D m^2_{\tilde{d}} Z^{D,\dagger} = m^{dia}_{2,\tilde{d}} \tag{17.17}$$

with

$$\tilde{d}_{L,i\alpha} = \sum_{t_2} Z^{D,*}_{ji}\tilde{d}_{j\alpha}\,, \qquad \tilde{d}_{R,i\alpha} = \sum_{t_2} Z^{D,*}_{ji}\tilde{d}_{j\alpha} \tag{17.18}$$

- **Mass matrix for Up-Squarks**, Basis: $\left(\tilde{u}_{L,o_1\alpha_1}, \tilde{u}_{R,o_2\alpha_2}\right), \left(\tilde{u}^*_{L,p_1\beta_1}, \tilde{u}^*_{R,p_2\beta_2}\right)$

$$m^2_{\tilde{u}} = \begin{pmatrix} m_{11} & m^*_{21} \\ m_{21} & m_{22} \end{pmatrix} \tag{17.19}$$

$$m_{11} = \frac{1}{24}\delta_{\alpha_1\beta_1}\Big(12\Big(2m^2_{q,o_1p_1} + v_u^2\sum_{a=1}^{3} Y^*_{u,p_1a}Y_{u,o_1a}\Big) - \Big(-3g_2^2 + g_1^2\Big)\delta_{o_1p_1}\Big(-v_u^2 + v_d^2 + \sum_{a=1}^{3} v^2_{L,a}\Big)\Big) \tag{17.20}$$

$$m_{21} = \frac{1}{2}\delta_{\alpha_2\beta_1}\Big(\sqrt{2}v_u T^*_{u,p_1o_2} + v_R Y^*_{u,p_1o_2}\Big(-v_d\lambda + \sum_{a=1}^{3} v_{L,a}Y_{v,a}\Big)\Big) \tag{17.21}$$

$$m_{22} = \frac{1}{6}\delta_{\alpha_2\beta_2}\Big(3v_u^2\sum_{a=1}^{3} Y^*_{u,ao_2}Y_{u,ap_2} + 6m^2_{u,p_2o_2} + g_1^2\delta_{o_2p_2}\Big(-v_u^2 + v_d^2 + \sum_{a=1}^{3} v^2_{L,a}\Big)\Big) \tag{17.22}$$

This matrix is diagonalized by Z^U:

$$Z^U m^2_{\tilde{u}} Z^{U,\dagger} = m^{dia}_{2,\tilde{u}} \tag{17.23}$$

with

$$\tilde{u}_{L,i\alpha} = \sum_{t_2} Z^{U,*}_{ji}\tilde{u}_{j\alpha}\,, \qquad \tilde{u}_{R,i\alpha} = \sum_{t_2} Z^{U,*}_{ji}\tilde{u}_{j\alpha} \tag{17.24}$$

- **Mass matrix for Higgs**, Basis: $(\phi_d, \phi_u, \phi_R, \phi_{L,o_4}), (\phi_d, \phi_u, \phi_R, \phi_{L,p_4})$

$$m_h^2 = \begin{pmatrix} m_{11} & m_{21}^* & m_{31}^* & m_{41}^* \\ m_{21} & m_{22} & m_{32}^* & m_{42}^* \\ m_{31} & m_{32} & m_{33} & m_{43}^* \\ m_{41} & m_{42} & m_{43} & m_{44} \end{pmatrix} \tag{17.25}$$

$$m_{11} = \frac{1}{8}\Big(3g_1^2 v_d^2 + 3g_2^2 v_d^2 + 4\Big(v_R^2 + v_u^2\Big)|\lambda|^2 + 8m_{H_d}^2 + \Big(g_1^2 + g_2^2\Big)\sum_{a=1}^{3} v_{L,a}^2 - g_1^2 v_u^2 - g_2^2 v_u^2\Big) \tag{17.26}$$

$$\begin{aligned} m_{21} = \frac{1}{4}\Big(&- g_1^2 v_d v_u - g_2^2 v_d v_u - v_R^2 \lambda \kappa^* - 2\sqrt{2} v_R \Re\Big(T_\lambda\Big) - 2 v_u \lambda \sum_{a=1}^{3} Y_{v,a}^* v_{L,a} \\ &- \lambda^*\Big(2 v_u \sum_{a=1}^{3} v_{L,a} Y_{v,a} - 4 v_d v_u \lambda + v_R^2 \kappa\Big)\Big) \end{aligned} \tag{17.27}$$

$$\begin{aligned} m_{22} = \frac{1}{8}\Big(&8m_{H_u}^2 - g_1^2 v_d^2 - g_2^2 v_d^2 + 3g_1^2 v_u^2 + 3g_2^2 v_u^2 + 4v_R^2 \sum_{a=1}^{3} |Y_{v,a}|^2 - 4 v_d \lambda \sum_{a=1}^{3} Y_{v,a}^* v_{L,a} \\ &- g_1^2 \sum_{a=1}^{3} v_{L,a}^2 - g_2^2 \sum_{a=1}^{3} v_{L,a}^2 + 4\lambda^*\Big(\Big(v_d^2 + v_R^2\Big)\lambda - v_d \sum_{a=1}^{3} v_{L,a} Y_{v,a}\Big) + 4\sum_{a=1}^{3} v_{L,a} Y_{v,a} \sum_{b=1}^{3} Y_{v,b}^* v_{L,b}\Big) \end{aligned} \tag{17.28}$$

$$m_{31} = \frac{1}{2}\Big(-\sqrt{2} v_u \Re\Big(T_\lambda\Big) - v_R \lambda^*\Big(-2 v_d \lambda + v_u \kappa + \sum_{a=1}^{3} v_{L,a} Y_{v,a}\Big) - v_R \lambda \sum_{a=1}^{3} Y_{v,a}^* v_{L,a} - v_R v_u \lambda \kappa^*\Big) \tag{17.29}$$

$$\begin{aligned} m_{32} = \frac{1}{4}\Big(&\Big(-2 v_d v_R \kappa + 4 v_R v_u \lambda\Big)\lambda^* - 2\sqrt{2} v_d \Re\Big(T_\lambda\Big) + 4 v_R v_u \sum_{a=1}^{3} |Y_{v,a}|^2 + 2 v_R \kappa \sum_{a=1}^{3} Y_{v,a}^* v_{L,a} + \sqrt{2}\sum_{a=1}^{3} T_{v,a}^* v_{L,a} \\ &+ 2 v_R \kappa^*\Big(-v_d \lambda + \sum_{a=1}^{3} v_{L,a} Y_{v,a}\Big) + \sqrt{2}\sum_{a=1}^{3} v_{L,a} T_{v,a}\Big) \end{aligned} \tag{17.30}$$

$$\begin{aligned} m_{33} = \frac{1}{2}\Big(&2m_v^2 + 2\sqrt{2} v_R \Re\Big(T_\kappa\Big) + v_u^2 \sum_{a=1}^{3} |Y_{v,a}|^2 + v_u \kappa \sum_{a=1}^{3} Y_{v,a}^* v_{L,a} - v_d \lambda \sum_{a=1}^{3} Y_{v,a}^* v_{L,a} \\ &+ \lambda^*\Big(v_d^2 \lambda - v_d \sum_{a=1}^{3} v_{L,a} Y_{v,a} - v_d v_u \kappa + v_u^2 \lambda\Big) + \kappa^*\Big(6 v_R^2 \kappa - v_d v_u \lambda + v_u \sum_{a=1}^{3} v_{L,a} Y_{v,a}\Big) \\ &+ \sum_{a=1}^{3} v_{L,a} Y_{v,a} \sum_{b=1}^{3} Y_{v,b}^* v_{L,b}\Big) \end{aligned} \tag{17.31}$$

$$m_{41} = \frac{1}{4}\Big(\Big(g_1^2 + g_2^2\Big) v_d \sum_{a=1}^{3} v_{L,a} - \Big(v_R^2 + v_u^2\Big)\lambda^* Y_{v,o_4} - \Big(v_R^2 + v_u^2\Big)\lambda Y_{v,o_4}^*\Big) \tag{17.32}$$

$$\begin{aligned} m_{42} = \frac{1}{4}\Big(&2\sqrt{2} v_R \Re\Big(T_{v,o_4}\Big) - g_1^2 v_u \sum_{a=1}^{3} v_{L,a} - g_2^2 v_u \sum_{a=1}^{3} v_{L,a} + Y_{v,o_4}^*\Big(-2 v_d v_u \lambda + 2 v_u \sum_{a=1}^{3} v_{L,a} Y_{v,a} + v_R^2 \kappa\Big) \\ &+ v_R^2 \kappa^* Y_{v,o_4} - 2 v_d v_u \lambda^* Y_{v,o_4} + 2 v_u \sum_{a=1}^{3} Y_{v,a}^* v_{L,a} Y_{v,o_4}\Big) \end{aligned} \tag{17.33}$$

$$m_{43} = \frac{1}{2}\Big(\sqrt{2}v_u\Re\Big(T_{v,o_4}\Big) + v_R\Big(-v_d\lambda^* + v_u\kappa^* + \sum_{a=1}^{3}Y^*_{v,a}v_{L,a}\Big)Y_{v,o_4} + v_R Y^*_{v,o_4}\Big(-v_d\lambda + v_u\kappa + \sum_{a=1}^{3}v_{L,a}Y_{v,a}\Big)\Big) \tag{17.34}$$

$$m_{44} = \frac{1}{8}\Big(\Big(g_1^2 + g_2^2\Big)\delta_{o_4p_4}\Big(-v_u^2 + v_d^2 + \sum_{a=1}^{3}v_{L,a}^2\Big) + 2\Big(2m^2_{l,o_4p_4} + 2m^2_{l,p_4o_4} + g_1^2\sum_{a=1}^{3}v_{L,a}\sum_{b=1}^{3}v_{L,b} + g_2^2\sum_{a=1}^{3}v_{L,a}\sum_{b=1}^{3}v_{L,b} + v_R^2Y^*_{v,p_4}Y_{v,o_4} + v_u^2Y^*_{v,p_4}Y_{v,o_4} + v_R^2Y^*_{v,o_4}Y_{v,p_4} + v_u^2Y^*_{v,o_4}Y_{v,p_4}\Big)\Big) \tag{17.35}$$

This matrix is diagonalized by Z^H:

$$Z^H m_h^2 Z^{H,\dagger} = m^{dia}_{2,h} \tag{17.36}$$

with

$$\phi_d = \sum_{t_2} Z^H_{j1}h_j\,, \qquad \phi_u = \sum_{t_2} Z^H_{j2}h_j\,, \qquad \phi_R = \sum_{t_2} Z^H_{j3}h_j \tag{17.37}$$

$$\phi_{L,i} = \sum_{t_2} Z^H_{ji}h_j \tag{17.38}$$

- **Mass matrix for Pseudo-Scalar Higgs**, Basis: $(\sigma_d, \sigma_u, \sigma_R, \sigma_{L,o_4}), (\sigma_d, \sigma_u, \sigma_R, \sigma_{L,p_4})$

$$m^2_{A^0} = \begin{pmatrix} m_{11} & m^*_{21} & m^*_{31} & m^*_{41} \\ m_{21} & m_{22} & m^*_{32} & m^*_{42} \\ m_{31} & m_{32} & m_{33} & m^*_{43} \\ m_{41} & m_{42} & m_{43} & m_{44} \end{pmatrix} \tag{17.39}$$

$$m_{11} = \frac{1}{8}\Big(4\Big(v_R^2 + v_u^2\Big)|\lambda|^2 + 8m^2_{H_d} + \Big(g_1^2 + g_2^2\Big)\sum_{a=1}^{3}v_{L,a}^2 + g_1^2v_d^2 - g_1^2v_u^2 + g_2^2v_d^2 - g_2^2v_u^2\Big) \tag{17.40}$$

$$m_{21} = \frac{1}{4}v_R\Big(2\sqrt{2}\Re\Big(T_\lambda\Big) + v_R\kappa\lambda^* + v_R\lambda\kappa^*\Big) \tag{17.41}$$

$$m_{22} = \frac{1}{8}\Big(8m^2_{H_u} - g_1^2v_d^2 - g_2^2v_d^2 + g_1^2v_u^2 + g_2^2v_u^2 + 4v_R^2\sum_{a=1}^{3}|Y_{v,a}|^2 - 4v_d\lambda\sum_{a=1}^{3}Y^*_{v,a}v_{L,a} - g_1^2\sum_{a=1}^{3}v_{L,a}^2 - g_2^2\sum_{a=1}^{3}v_{L,a}^2 + 4\lambda^*\Big(\Big(v_d^2 + v_R^2\Big)\lambda - v_d\sum_{a=1}^{3}v_{L,a}Y_{v,a}\Big) + 4\sum_{a=1}^{3}v_{L,a}Y_{v,a}\sum_{b=1}^{3}Y^*_{v,b}v_{L,b}\Big) \tag{17.42}$$

$$m_{31} = -\frac{1}{2}v_u\Big(-\sqrt{2}\Re\Big(T_\lambda\Big) + v_R\kappa\lambda^* + v_R\lambda\kappa^*\Big) \tag{17.43}$$

$$m_{32} = \frac{1}{4}\Big(-2v_dv_R\kappa\lambda^* + 2\sqrt{2}v_d\Re\Big(T_\lambda\Big) + 2v_R\kappa\sum_{a=1}^{3}Y^*_{v,a}v_{L,a} - \sqrt{2}\sum_{a=1}^{3}T^*_{v,a}v_{L,a} + 2v_R\kappa^*\Big(-v_d\lambda + \sum_{a=1}^{3}v_{L,a}Y_{v,a}\Big)$$

$$- \sqrt{2}\sum_{a=1}^{3} v_{L,a} T_{v,a}\Big) \tag{17.44}$$

$$m_{33} = \frac{1}{2}\Big(2m_v^2 - 2\sqrt{2}v_R \Re\Big(T_\kappa\Big) + v_u^2 \sum_{a=1}^{3} |Y_{v,a}|^2 - v_u\kappa \sum_{a=1}^{3} Y^*_{v,a} v_{L,a} - v_d\lambda \sum_{a=1}^{3} Y^*_{v,a} v_{L,a}$$
$$+ \lambda^*\Big(v_d^2\lambda - v_d \sum_{a=1}^{3} v_{L,a} Y_{v,a} + v_d v_u \kappa + v_u^2 \lambda\Big) + \kappa^*\Big(2v_R^2\kappa + v_d v_u \lambda - v_u \sum_{a=1}^{3} v_{L,a} Y_{v,a}\Big)$$
$$+ \sum_{a=1}^{3} v_{L,a} Y_{v,a} \sum_{b=1}^{3} Y^*_{v,b} v_{L,b}\Big) \tag{17.45}$$

$$m_{41} = -\frac{1}{4}\Big(v_R^2 + v_u^2\Big)\Big(\lambda^* Y_{v,o_4} + \lambda Y^*_{v,o_4}\Big) \tag{17.46}$$

$$m_{42} = -\frac{1}{4} v_R \Big(2\sqrt{2}\Re\Big(T_{v,o_4}\Big) + v_R\kappa^* Y_{v,o_4} + v_R \kappa Y^*_{v,o_4}\Big) \tag{17.47}$$

$$m_{43} = \frac{1}{2} v_u \Big(- \sqrt{2}\Re\Big(T_{v,o_4}\Big) + v_R\kappa^* Y_{v,o_4} + v_R\kappa Y^*_{v,o_4}\Big) \tag{17.48}$$

$$m_{44} = \frac{1}{8}\Big(2\Big(2m^2_{l,o_4 p_4} + 2m^2_{l,p_4 o_4} + \Big(v_R^2 + v_u^2\Big)\Big(Y^*_{v,o_4} Y_{v,p_4} + Y^*_{v,p_4} Y_{v,o_4}\Big)\Big) + \Big(g_1^2 + g_2^2\Big)\delta_{o_4 p_4}\Big(- v_u^2 + v_d^2 + \sum_{a=1}^{3} v^2_{L,a}\Big)\Big) \tag{17.49}$$

This matrix is diagonalized by Z^A:

$$Z^A m^2_{A^0} Z^{A,\dagger} = m^{dia}_{2,A^0} \tag{17.50}$$

with

$$\sigma_d = \sum_{t_2} Z^A_{j1} A^0_j\,, \qquad \sigma_u = \sum_{t_2} Z^A_{j2} A^0_j\,, \qquad \sigma_R = \sum_{t_2} Z^A_{j3} A^0_j \tag{17.51}$$

$$\sigma_{L,i} = \sum_{t_2} Z^A_{ji} A^0_j \tag{17.52}$$

- **Mass matrix for Charged Higgs**, Basis: $\Big(H_d^-, H_u^{+,*}, \tilde{e}_{L,o_3}, \tilde{e}_{R,o_4}\Big)$, $\Big(H_d^{-,*}, H_u^+, \tilde{e}^*_{L,p_3}, \tilde{e}^*_{R,p_4}\Big)$

$$m^2_{H^-} = \begin{pmatrix} m_{11} & m^*_{21} & m^*_{31} & m^*_{41} \\ m_{21} & m_{22} & m^*_{32} & m^*_{42} \\ m_{31} & m_{32} & m_{33} & m^*_{43} \\ m_{41} & m_{42} & m_{43} & m_{44} \end{pmatrix} \tag{17.53}$$

$$m_{11} = \frac{1}{8}\Big(8m^2_{H_d} + g_1^2 v_d^2 + g_2^2 v_d^2 - g_1^2 v_u^2 + g_2^2 v_u^2 + 4v_R^2|\lambda|^2 + \Big(- g_2^2 + g_1^2\Big) \sum_{a=1}^{3} v^2_{L,a}$$
$$+ 4\sum_{c=1}^{3}\sum_{b=1}^{3}\sum_{a=1}^{3} Y^*_{e,ca} Y_{e,ba} v_{L,b} v_{L,c}\Big) \tag{17.54}$$

$$m_{21} = \frac{1}{4}\Big(2\lambda^* \Big(- v_d v_u \lambda + v_R^2 \kappa + v_u \sum_{a=1}^{3} v_{L,a} Y_{v,a}\Big) + 2\sqrt{2} v_R T_{\lambda}^* + g_2^2 v_d v_u \Big) \tag{17.55}$$

$$m_{22} = \frac{1}{8}\Big(8 m_{H_u}^2 - g_1^2 v_d^2 + g_2^2 v_d^2 + g_1^2 v_u^2 + g_2^2 v_u^2 + 4 v_R^2 |\lambda|^2 + 4 v_R^2 \sum_{a=1}^{3} |Y_{v,a}|^2 \\ + \Big(- g_1^2 + g_2^2\Big) \sum_{a=1}^{3} v_{L,a}^2 \Big) \tag{17.56}$$

$$m_{31} = \frac{1}{4}\Big(- 2 \Big(v_d \sum_{b=1}^{3} \sum_{a=1}^{3} Y^*_{e,ba} Y_{e,o_3 a} v_{L,b} + v_R^2 \lambda^* Y_{v,o_3}\Big) + g_2^2 v_d \sum_{a=1}^{3} v_{L,a} \Big) \tag{17.57}$$

$$m_{32} = \frac{1}{4}\Big(- 2 \Big(\sqrt{2} v_R T_{v,o_3} - v_d v_u \lambda^* Y_{v,o_3} + v_R^2 \kappa^* Y_{v,o_3} + v_u \sum_{a=1}^{3} Y_{v,a}^* v_{L,a} Y_{v,o_3}\Big) + g_2^2 v_u \sum_{a=1}^{3} v_{L,a} \Big) \tag{17.58}$$

$$m_{33} = \frac{1}{8}\Big(8 m_{l,o_3 p_3}^2 + \Big(- g_2^2 + g_1^2\Big)\delta_{o_3 p_3} \Big(- v_u^2 + v_d^2 + \sum_{a=1}^{3} v_{L,a}^2 \Big) + 4 v_d^2 \sum_{a=1}^{3} Y^*_{e,p_3 a} Y_{e,o_3 a} + 2 g_2^2 \sum_{a=1}^{3} v_{L,a} \sum_{b=1}^{3} v_{L,b} \\ + 4 v_R^2 Y_{v,p_3}^* Y_{v,o_3} \Big) \tag{17.59}$$

$$m_{41} = -\frac{1}{2} v_R v_u \sum_{a=1}^{3} Y^*_{e,a o_4} Y_{v,a} - \frac{1}{\sqrt{2}} \sum_{a=1}^{3} T^*_{e,a o_4} v_{L,a} \tag{17.60}$$

$$m_{42} = -\frac{1}{2} v_R \Big(\lambda \sum_{a=1}^{3} Y^*_{e,a o_4} v_{L,a} + v_d \sum_{a=1}^{3} Y^*_{e,a o_4} Y_{v,a} \Big) \tag{17.61}$$

$$m_{43} = -\frac{1}{2} v_R v_u \lambda Y^*_{e,p_3 o_4} + \frac{1}{\sqrt{2}} v_d T^*_{e,p_3 o_4} \tag{17.62}$$

$$m_{44} = \frac{1}{4}\Big(2\Big(2 m_{e,p_4 o_4}^2 + \sum_{a=1}^{3} v_{L,a} Y_{e,a p_4} \sum_{b=1}^{3} Y^*_{e,b o_4} v_{L,b} + v_d^2 \sum_{a=1}^{3} Y^*_{e,a o_4} Y_{e,a p_4}\Big) - g_1^2 \delta_{o_4 p_4} \Big(- v_u^2 + v_d^2 + \sum_{a=1}^{3} v_{L,a}^2 \Big)\Big) \tag{17.63}$$

This matrix is diagonalized by Z^+:

$$Z^+ m^2_{H^-} Z^{+,\dagger} = m^{dia}_{2,H^-} \tag{17.64}$$

with

$$H_d^- = \sum_{t_2} Z^{+,*}_{j1} H_j^- \,, \qquad H_u^+ = \sum_{t_2} Z^+_{j2} H_j^+ \,, \qquad \tilde{e}_{L,i} = \sum_{t_2} Z^{+,*}_{ji} H_j^- \tag{17.65}$$

$$\tilde{e}_{R,i} = \sum_{t_2} Z^{+,*}_{ji} H_j^- \tag{17.66}$$

Mass Matrices for Fermions

- **Mass matrix for Neutralinos**, Basis: $\left(\lambda_{\tilde{B}}, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0, \nu_R, \nu_{L,o_6}\right), \left(\lambda_{\tilde{B}}, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0, \nu_R, \nu_{L,p_6}\right)$

$$m_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -\frac{1}{2} g_1 v_d & \frac{1}{2} g_1 v_u & 0 & -\frac{1}{2} g_1 \sum_{a=1}^{3} v_{L,a} \\ 0 & M_2 & \frac{1}{2} g_2 v_d & -\frac{1}{2} g_2 v_u & 0 & \frac{1}{2} g_2 \sum_{a=1}^{3} v_{L,a} \\ -\frac{1}{2} g_1 v_d & \frac{1}{2} g_2 v_d & 0 & -\frac{1}{\sqrt{2}} v_R \lambda & -\frac{1}{\sqrt{2}} v_u \lambda & 0 \\ \frac{1}{2} g_1 v_u & -\frac{1}{2} g_2 v_u & -\frac{1}{\sqrt{2}} v_R \lambda & 0 & m_{54} & \frac{1}{\sqrt{2}} v_R Y_{v,p_6} \\ 0 & 0 & -\frac{1}{\sqrt{2}} v_u \lambda & m_{54} & \sqrt{2} v_R \kappa & \frac{1}{\sqrt{2}} v_u Y_{v,p_6} \\ -\frac{1}{2} g_1 \sum_{a=1}^{3} v_{L,a} & \frac{1}{2} g_2 \sum_{a=1}^{3} v_{L,a} & 0 & \frac{1}{\sqrt{2}} v_R Y_{v,o_6} & \frac{1}{\sqrt{2}} v_u Y_{v,o_6} & 0 \end{pmatrix} \tag{17.67}$$

$$m_{54} = \frac{1}{\sqrt{2}} \Big(- v_d \lambda + \sum_{a=1}^{3} v_{L,a} Y_{v,a} \Big) \tag{17.68}$$

This matrix is diagonalized by N:

$$N m_{\tilde{\chi}^0} N^\dagger = m^{dia}_{\tilde{\chi}^0} \tag{17.69}$$

with

$$\lambda_{\tilde{B}} = \sum_{t_2} N^*_{j1} \lambda^0_j\,, \qquad \tilde{W}^0 = \sum_{t_2} N^*_{j2} \lambda^0_j\,, \qquad \tilde{H}^0_d = \sum_{t_2} N^*_{j3} \lambda^0_j \tag{17.70}$$

$$\tilde{H}^0_u = \sum_{t_2} N^*_{j4} \lambda^0_j\,, \qquad \nu_R = \sum_{t_2} N^*_{j5} \lambda^0_j\,, \qquad \nu_{L,i} = \sum_{t_2} N^*_{ji} \lambda^0_j \tag{17.71}$$

- **Mass matrix for Charginos**, Basis: $\left(\tilde{W}^-, \tilde{H}_d^-, e_{L,o_3}\right), \left(\tilde{W}^+, \tilde{H}_u^+, e^*_{R,p_3}\right)$

$$m_{\tilde{\chi}^-} = \begin{pmatrix} M_2 & \frac{1}{\sqrt{2}} g_2 v_u & 0 \\ \frac{1}{\sqrt{2}} g_2 v_d & \frac{1}{\sqrt{2}} v_R \lambda & -\frac{1}{\sqrt{2}} \sum_{a=1}^{3} v_{L,a} Y_{e,a p_3} \\ \frac{1}{\sqrt{2}} g_2 \sum_{a=1}^{3} v_{L,a} & -\frac{1}{\sqrt{2}} v_R Y_{v,o_3} & \frac{1}{\sqrt{2}} v_d Y_{e,o_3 p_3} \end{pmatrix} \tag{17.72}$$

This matrix is diagonalized by U and V

$$U^* m_{\tilde{\chi}^-} V^\dagger = m^{dia}_{\tilde{\chi}^-} \tag{17.73}$$

with

$$\tilde{W}^- = \sum_{t_2} U^*_{j1} \lambda^-_j\,, \qquad \tilde{H}^-_d = \sum_{t_2} U^*_{j2} \lambda^-_j\,, \qquad e_{L,i} = \sum_{t_2} U^*_{ji} \lambda^-_j \tag{17.74}$$

$$\tilde{W}^+ = \sum_{t_2} V^*_{1j} \lambda^+_j\,, \qquad \tilde{H}^+_u = \sum_{t_2} V^*_{2j} \lambda^+_j\,, \qquad e_{R,i} = \sum_{t_2} V_{ij} \lambda^{+,*}_j \tag{17.75}$$

- **Mass matrix for Down-Quarks**, Basis: $\left(d_{L,o_1\alpha_1}\right), \left(d^*_{R,p_1\beta_1}\right)$

$$m_d = \left(\begin{array}{c} \frac{1}{\sqrt{2}} v_d \delta_{\alpha_1\beta_1} Y_{d,o_1p_1} \end{array} \right) \tag{17.76}$$

This matrix is diagonalized by U^d_L and U^d_R

$$U^{d,*}_L m_d U^{d,\dagger}_R = m^{dia}_d \tag{17.77}$$

with

$$d_{L,i\alpha} = \sum_{t_2} U^{d,*}_{L,ji} D_{L,j\alpha} \tag{17.78}$$

$$d_{R,i\alpha} = \sum_{t_2} U^{d}_{R,ij} D^*_{R,j\alpha} \tag{17.79}$$

- **Mass matrix for Up-Quarks**, Basis: $\left(u_{L,o_1\alpha_1}\right), \left(u^*_{R,p_1\beta_1}\right)$

$$m_u = \left(\begin{array}{c} \frac{1}{\sqrt{2}} v_u \delta_{\alpha_1\beta_1} Y_{u,o_1p_1} \end{array} \right) \tag{17.80}$$

This matrix is diagonalized by U^u_L and U^u_R

$$U^{u,*}_L m_u U^{u,\dagger}_R = m^{dia}_u \tag{17.81}$$

with

$$u_{L,i\alpha} = \sum_{t_2} U^{u,*}_{L,ji} U_{L,j\alpha} \tag{17.82}$$

$$u_{R,i\alpha} = \sum_{t_2} U^{u}_{R,ij} U^*_{R,j\alpha} \tag{17.83}$$

17.4 Vacuum Expectation Values

$$H^0_d = \frac{1}{\sqrt{2}}\phi_d + \frac{1}{\sqrt{2}}v_d + i\frac{1}{\sqrt{2}}\sigma_d \tag{17.84}$$

$$H^0_u = \frac{1}{\sqrt{2}}\phi_u + \frac{1}{\sqrt{2}}v_u + i\frac{1}{\sqrt{2}}\sigma_u \tag{17.85}$$

$$\tilde{\nu}_L = \frac{1}{\sqrt{2}}\phi_L + \frac{1}{\sqrt{2}}v_L + i\frac{1}{\sqrt{2}}\sigma_L \tag{17.86}$$

$$\tilde{\nu}_R = \frac{1}{\sqrt{2}}\phi_R + \frac{1}{\sqrt{2}}v_R + i\frac{1}{\sqrt{2}}\sigma_R \tag{17.87}$$

17.5 Tadpole Equations

$$\frac{\partial V}{\partial v_d} = \frac{1}{8}\Big(8m_{H_d}^2 v_d + g_1^2 v_d^3 + g_2^2 v_d^3 - g_1^2 v_d v_u^2 - g_2^2 v_d v_u^2 - 2v_R^2 v_u \lambda \kappa^* - 4\sqrt{2} v_R v_u \Re\Big(T_\lambda\Big)$$

$$- 2v_R^2 \lambda \sum_{a=1}^{3} Y_{v,a}^* v_{L,a} - 2v_u^2 \lambda \sum_{a=1}^{3} Y_{v,a}^* v_{L,a} + g_1^2 v_d \sum_{a=1}^{3} v_{L,a}^2 + g_2^2 v_d \sum_{a=1}^{3} v_{L,a}^2$$

$$- 2\lambda^* \Big(- 2v_d v_u^2 \lambda + v_R^2 \Big(- 2v_d \lambda + v_u \kappa\Big) + \Big(v_R^2 + v_u^2\Big) \sum_{a=1}^{3} v_{L,a} Y_{v,a}\Big)\Big) \tag{17.88}$$

$$\frac{\partial V}{\partial v_u} = \frac{1}{8}\Big(8m_{H_u}^2 v_u - g_1^2 v_d^2 v_u - g_2^2 v_d^2 v_u + g_1^2 v_u^3 + g_2^2 v_u^3 - 4\sqrt{2} v_d v_R \Re\Big(T_\lambda\Big)$$

$$+ 4v_R^2 v_u \sum_{a=1}^{3} |Y_{v,a}|^2 + 2v_R^2 \kappa \sum_{a=1}^{3} Y_{v,a}^* v_{L,a} - 4v_d v_u \lambda \sum_{a=1}^{3} Y_{v,a}^* v_{L,a} + 2\sqrt{2} v_R \sum_{a=1}^{3} T_{v,a}^* v_{L,a}$$

$$- g_1^2 v_u \sum_{a=1}^{3} v_{L,a}^2 - g_2^2 v_u \sum_{a=1}^{3} v_{L,a}^2 + 2v_R^2 \kappa^* \Big(- v_d \lambda + \sum_{a=1}^{3} v_{L,a} Y_{v,a}\Big)$$

$$+ \lambda^* \Big(- 2v_d v_R^2 \kappa + 4v_d^2 v_u \lambda - 4v_d v_u \sum_{a=1}^{3} v_{L,a} Y_{v,a} + 4v_R^2 v_u \lambda\Big) + 2\sqrt{2} v_R \sum_{a=1}^{3} v_{L,a} T_{v,a}$$

$$+ 4v_u \sum_{a=1}^{3} v_{L,a} Y_{v,a} \sum_{b=1}^{3} Y_{v,b}^* v_{L,b}\Big) \tag{17.89}$$

$$\frac{\partial V}{\partial v_L} = \frac{1}{8}\Big(4\sqrt{2} v_R v_u \Re\Big(T_{v,i}\Big) + 4\sum_{a=1}^{3} m_{l,ia}^2 v_{L,a} + 4\sum_{a=1}^{3} m_{l,ai}^2 v_{L,a}$$

$$+ 2Y_{v,i}^* \Big(- v_d v_u^2 \lambda + v_R^2 \Big(- v_d \lambda + v_u \kappa\Big) + \Big(v_R^2 + v_u^2\Big) \sum_{a=1}^{3} v_{L,a} Y_{v,a}\Big) + g_1^2 v_d^2 v_{L,i} + g_2^2 v_d^2 v_{L,i}$$

$$- g_1^2 v_u^2 v_{L,i} - g_2^2 v_u^2 v_{L,i} + g_1^2 \sum_{a=1}^{3} v_{L,a}^2 v_{L,i} + g_2^2 \sum_{a=1}^{3} v_{L,a}^2 v_{L,i} + 2v_R^2 v_u \kappa^* Y_{v,i}$$

$$- 2v_d v_R^2 \lambda^* Y_{v,i} - 2v_d v_u^2 \lambda^* Y_{v,i} + 2v_R^2 \sum_{a=1}^{3} Y_{v,a}^* v_{L,a} Y_{v,i} + 2v_u^2 \sum_{a=1}^{3} Y_{v,a}^* v_{L,a} Y_{v,i}\Big) \tag{17.90}$$

$$\frac{\partial V}{\partial v_R} = \frac{1}{4}\Big(4m_v^2 v_R - \sqrt{2} v_d v_u T_\lambda^* + 2\sqrt{2} v_R^2 \Re\Big(T_\kappa\Big) + 2v_R v_u^2 \sum_{a=1}^{3} |Y_{v,a}|^2 + 2v_R v_u \kappa \sum_{a=1}^{3} Y_{v,a}^* v_{L,a}$$

$$- 2v_d v_R \lambda \sum_{a=1}^{3} Y_{v,a}^* v_{L,a} + \sqrt{2} v_u \sum_{a=1}^{3} T_{v,a}^* v_{L,a}$$

$$+ 2v_R \lambda^* \Big(v_d^2 \lambda - v_d \sum_{a=1}^{3} v_{L,a} Y_{v,a} - v_d v_u \kappa + v_u^2 \lambda\Big)$$

$$+ 2v_R \kappa^* \Big(2v_R^2 \kappa - v_d v_u \lambda + v_u \sum_{a=1}^{3} v_{L,a} Y_{v,a}\Big) + \sqrt{2} v_u \sum_{a=1}^{3} v_{L,a} T_{v,a} + 2v_R \sum_{a=1}^{3} v_{L,a} Y_{v,a} \sum_{b=1}^{3} Y_{v,b}^* v_{L,b}$$

$$- \sqrt{2} v_d v_u T_\lambda\Big) \tag{17.91}$$

17.6 Particle content for eigenstates 'EWSB'

Name	Type	complex/real	Generations	Indices
$\tilde{d}$	Scalar	complex	6	generation, color
$\tilde{u}$	Scalar	complex	6	generation, color
h	Scalar	real	6	generation
A^0	Scalar	real	6	generation
H^-	Scalar	complex	8	generation
$\tilde{g}$	Fermion	Majorana	8	generation
$\tilde{\chi}^0$	Fermion	Majorana	8	generation
$\tilde{\chi}^-$	Fermion	Dirac	5	generation
d	Fermion	Dirac	3	generation, color
u	Fermion	Dirac	3	generation, color
g	Vector	real	8	generation, lorentz
W^-	Vector	complex	1	lorentz
γ	Vector	real	1	lorentz
Z	Vector	real	1	lorentz
η^G	Ghost	real	8	generation
η^-	Ghost	complex	1	
η^+	Ghost	complex	1	
η^γ	Ghost	real	1	
η^Z	Ghost	real	1	

17.7 Modelfile for SARAH

```
(* ::Package:: *)

Off[General::spell]
Print["Model file for the munuMSSM loaded"];

ModelNameLaTeX ="$\\mu\\nu$SSM";


(*-------------------------------------------*)
(*   Particle Content*)
(*-------------------------------------------*)

(* Gauge Superfields *)

Gauge[[1]]={B,   U[1], hypercharge, g1,False};
Gauge[[2]]={WB, SU[2], left,        g2,True};
Gauge[[3]]={G,  SU[3], color,       g3,False};


(* Chiral Superfields *)

Fields[[1]] = {{uL,  dL},  3, q,   1/6, 2, 3};
Fields[[2]] = {{vL,  eL},  3, l,  -1/2, 2, 1};
Fields[[3]] = {{Hd0, Hdm}, 1, Hd, -1/2, 2, 1};
Fields[[4]] = {{Hup, Hu0}, 1, Hu,  1/2, 2, 1};

Fields[[5]] = {conj[dR], 3, d,  1/3, 1, -3};
Fields[[6]] = {conj[uR], 3, u, -2/3, 1, -3};
Fields[[7]] = {conj[eR], 3, e,    1, 1,  1};
Fields[[8]] = {vR, 1, v,    0, 1,  1};




(*-----------------------------------------------------*)
(* Superpotential *)
(*-----------------------------------------------------*)

SuperPotential = { {{1, Yu},{q,Hu,u}}, {{-1,Yd},{q,Hd,d}},
                   {{-1,Ye},{l,Hd,e}}, {{1,Yv},{l,Hu,v}},
                   {{1,\[Lambda]},{Hu,Hd,v}},
                   {{1/3,\[Kappa]},{v,v,v}}  };
```

```
(*-------------------------------------------*)
(* Integrate Out or Delete Particles         *)
(*-------------------------------------------*)

IntegrateOut={};
DeleteParticles={};

(*----------------------------------------------*)
(*   DEFINITION                                 *)
(*----------------------------------------------*)

NameOfStates={GaugeES, EWSB};

(* ----- Before EWSB ----- *)


DEFINITION[GaugeES][GaugeFixing]=
{ {Der[VWB],  -1/(2 RXi[W])},
     {Der[VG],   -1/(2 RXi[G]) }};

(* Gauge Sector *)

DEFINITION[EWSB][GaugeSector]=
{ {VWB, {1,{VWm,1/Sqrt[2]},{conj[VWm],1/Sqrt[2]}},
        {2,{VWm,-I/Sqrt[2]},{conj[VWm],I/Sqrt[2]}},
        {3,{VP, Sin[ThetaW]},{VZ, Cos[ThetaW]}}},
  {VB,  {1,{VP, Cos[ThetaW]},{VZ,-Sin[ThetaW]}}},
  {fWB, {1,{fWm,1/Sqrt[2]}, {fWp,1/Sqrt[2]}},
        {2,{fWm,-I/Sqrt[2]},{fWp,I/Sqrt[2]}},
        {3,{fW0,1}}}                                                   \
      };




(* ----- VEVs ---- *)

DEFINITION[EWSB][VEVs]=
{    {SHd0, {vd, 1/Sqrt[2]}, {sigmad, I/Sqrt[2]},{phid, \
1/Sqrt[2]}},
     {SHu0, {vu, 1/Sqrt[2]}, {sigmau, I/Sqrt[2]},{phiu, \
1/Sqrt[2]}},
      {SvL, {vL, 1/Sqrt[2]}, {sigmaL, I/Sqrt[2]},{phiL, \
1/Sqrt[2]}},
      {SvR, {vR, 1/Sqrt[2]}, {sigmaR, I/Sqrt[2]},{phiR, \
1/Sqrt[2]}}     };
```

```
(* ---- Mixings ---- *)

DEFINITION[EWSB][MatterSector]=
{    {{SdL, SdR}, {Sd, ZD}},
     {{SuL, SuR}, {Su, ZU}},
     {{phid, phiu, phiR, phiL}, {hh, ZH}},
     {{sigmad, sigmau,sigmaR,sigmaL}, {Ah, ZA}},
     {{SHdm,conj[SHup], SeL, SeR},{Hpm,ZP}},
     {{fB, fW0, FHd0, FHu0, FvR, FvL}, {L0, ZN}},
     {{{fWm, FHdm, FeL}, {fWp, FHup, conj[FeR]}}, {{Lm,UM}, {Lp,UP}}},
     {{{FdL},{conj[FdR]}},{{FDL,ZDL},{FDR,ZDR}}},
     {{{FuL},{conj[FuR]}},{{FUL,ZUL},{FUR,ZUR}}}                     \
       };


(*--- Gauge Fixing ---- *)

DEFINITION[EWSB][GaugeFixing]=
  { {Der[VP],                                               - 1/(2 RXi[P])},
{Der[VWm]+\[ImaginaryI] Mass[VWm] RXi[W] Hpm[{1}],   - 1/(RXi[W])},
{Der[VZ] - Mass[VZ] RXi[Z] Ah[{1}],                 - 1/(2 RXi[Z])},
{Der[VG],                                           - 1/(2 RXi[G])}};


DEFINITION[EWSB][Phases]=
{    {fG, PhaseGlu}
    };


(*------------------------------------------------------*)
(* Dirac-Spinors *)
(*------------------------------------------------------*)

dirac[[1]] = {Fd,  FDL, conj[FDR]};
dirac[[2]] = {Fu,  FUL, conj[FUR]};
dirac[[3]] = {Chi, L0, conj[L0]};
dirac[[4]] = {Cha, Lm, conj[Lp]};
dirac[[5]] = {Glu, fG, conj[fG]};


(* Unbroken EW *)

dirac[[6]] = {Bino, fB, conj[fB]};
dirac[[7]] = {Wino, fWB, conj[fWB]};
dirac[[8]] = {H0, FHd0, conj[FHu0]};
dirac[[9]] = {HC, FHdm, conj[FHup]};
dirac[[10]] = {Fd1, FdL, 0};
```

```
dirac[[11]] = {Fd2, 0, FdR};
dirac[[12]] = {Fu1, FuL, 0};
dirac[[13]] = {Fu2, 0, FuR};
dirac[[14]] = {Fe1, FeL, 0};
dirac[[15]] = {Fe2, 0, FeR};
dirac[[16]] = {Fv1, FvL, 0};
dirac[[17]] = {Fv2, 0, FvR};



(*------------------------------------------------------*)
(* Automatized Output        *)
(*------------------------------------------------------*)

(*
makeOutput = {
                    {EWSB, {TeX, FeynArts}}
             };
            *)

ReadSpectrum=None;
```

17.8 Implementation in SARAH

Model directory: `munuSSM`

17.8.1 Particles for eigenstates 'GaugeES'

- Fermions

$\tilde{B} = \begin{pmatrix} \lambda_{\tilde{B}} \\ \lambda^*_{\tilde{B}} \end{pmatrix}$	$\texttt{Bino} = \begin{pmatrix} \texttt{fB} \\ \texttt{conj[fB]} \end{pmatrix}$
$d^1_{i\alpha} = \begin{pmatrix} d_{L,i\alpha} \\ 0 \end{pmatrix}$	$\texttt{Fd1[\{generation, color\}]} = \begin{pmatrix} \texttt{FdL[\{generation, color\}]} \\ 0 \end{pmatrix}$
$d^2_{i\alpha} = \begin{pmatrix} 0 \\ d_{R,i\alpha} \end{pmatrix}$	$\texttt{Fd2[\{generation, color\}]} = \begin{pmatrix} 0 \\ \texttt{FdR[\{generation, color\}]} \end{pmatrix}$
$e^1_{i} = \begin{pmatrix} e_{L,i} \\ 0 \end{pmatrix}$	$\texttt{Fe1[\{generation\}]} = \begin{pmatrix} \texttt{FeL[\{generation\}]} \\ 0 \end{pmatrix}$
$e^2_{i} = \begin{pmatrix} 0 \\ e_{R,i} \end{pmatrix}$	$\texttt{Fe2[\{generation\}]} = \begin{pmatrix} 0 \\ \texttt{FeR[\{generation\}]} \end{pmatrix}$
$u^1_{i\alpha} = \begin{pmatrix} u_{L,i\alpha} \\ 0 \end{pmatrix}$	$\texttt{Fu1[\{generation, color\}]} = \begin{pmatrix} \texttt{FuL[\{generation, color\}]} \\ 0 \end{pmatrix}$

$u^2_{i\alpha} = \begin{pmatrix} 0 \\ u_{R,i\alpha} \end{pmatrix}$	$\texttt{Fu2[\{generation, color\}]} = \begin{pmatrix} \texttt{0} \\ \texttt{FuR[\{generation, color\}]} \end{pmatrix}$
$\mathrm{Fv1}\Big(\{\mathrm{gt1}\}\Big) = \begin{pmatrix} \nu_{L,i} \\ 0 \end{pmatrix}$	$\texttt{Fv1[\{generation\}]} = \begin{pmatrix} \texttt{FvL[\{generation\}]} \\ \texttt{0} \end{pmatrix}$
$\mathrm{Fv2} = \begin{pmatrix} 0 \\ \nu_R \end{pmatrix}$	$\mathrm{Fv2} = \begin{pmatrix} \texttt{0} \\ \texttt{FvR} \end{pmatrix}$
$\tilde{g}_i = \begin{pmatrix} \lambda_{\tilde{g},i} \\ \lambda^*_{\tilde{g},i} \end{pmatrix}$	$\texttt{Glu[\{generation\}]} = \begin{pmatrix} \texttt{fG[\{generation\}]} \\ \texttt{conj[fG[\{generation\}]]} \end{pmatrix}$
$\tilde{H}^0 = \begin{pmatrix} \tilde{H}^0_d \\ \tilde{H}^{0,*}_u \end{pmatrix}$	$\texttt{H0} = \begin{pmatrix} \texttt{FHd0} \\ \texttt{conj[FHu0]} \end{pmatrix}$
$\tilde{H}^- = \begin{pmatrix} \tilde{H}^-_d \\ \tilde{H}^{+,*}_u \end{pmatrix}$	$\texttt{HC} = \begin{pmatrix} \texttt{FHdm} \\ \texttt{conj[FHup]} \end{pmatrix}$
$\tilde{W}_i = \begin{pmatrix} \lambda_{\tilde{W},i} \\ \lambda^*_{\tilde{W},i} \end{pmatrix}$	$\texttt{Wino[\{generation\}]} = \begin{pmatrix} \texttt{fWB[\{generation\}]} \\ \texttt{conj[fWB[\{generation\}]]} \end{pmatrix}$

- Scalars

$\tilde{d}_{L,i\alpha}$	`SdL[{generation, color}]`	$\tilde{u}_{L,i\alpha}$	`SuL[{generation, color}]`
$\tilde{e}_{L,i}$	`SeL[{generation}]`	$\tilde{\nu}_{L,i}$	`SvL[{generation}]`
H^0_d	`SHd0`	H^-_d	`SHdm`
H^0_u	`SHu0`	H^+_u	`SHup`
$\tilde{d}_{R,i\alpha}$	`SdR[{generation, color}]`	$\tilde{u}_{R,i\alpha}$	`SuR[{generation, color}]`
$\tilde{e}_{R,i}$	`SeR[{generation}]`	$\tilde{\nu}_R$	`SvR`

- Vector Bosons

B_ρ	`VB[{lorentz}]`	$W^-_{i\rho}$	`VWB[{generation, lorentz}]`
$g_{i\rho}$	`VG[{generation, lorentz}]`		

- Ghosts

η^B	gB	gWB$\Big(\{gt1\}\Big)$	gWB[{generation}]
η^G_i	gG[{generation}]		

17.8.2 Particles for eigenstates 'EWSB'

- Fermions

$\tilde{\chi}^-_i = \begin{pmatrix} \lambda^-_i \\ \lambda^{+,*}_i \end{pmatrix}$	Cha[{generation}] = (Lm[{generation}] , conj[Lp[{generation}]])
$\tilde{\chi}^0_i = \begin{pmatrix} \lambda^0_i \\ \lambda^{0,*}_i \end{pmatrix}$	Chi[{generation}] = (L0[{generation}] , conj[L0[{generation}]])
$d_{i\alpha} = \begin{pmatrix} D_{L,i\alpha} \\ D^*_{R,i\alpha} \end{pmatrix}$	Fd[{generation, color}] = (FDL[{generation, color}] , conj[FDR[{generation, color}]])
$u_{i\alpha} = \begin{pmatrix} U_{L,i\alpha} \\ U^*_{R,i\alpha} \end{pmatrix}$	Fu[{generation, color}] = (FUL[{generation, color}] , conj[FUR[{generation, color}]])
$\tilde{g}_i = \begin{pmatrix} \lambda_{\tilde{g},i} \\ \lambda^*_{\tilde{g},i} \end{pmatrix}$	Glu[{generation}] = (fG[{generation}] , conj[fG[{generation}]])

- Scalars

$\tilde{d}_{i\alpha}$	Sd[{generation, color}]	$\tilde{u}_{i\alpha}$	Su[{generation, color}]
h_i	hh[{generation}]	A^0_i	Ah[{generation}]
H^-_i	Hpm[{generation}]		

- Vector Bosons

$g_{i\rho}$	VG[{generation, lorentz}]	W^-_ρ	VWm[{lorentz}]
γ_ρ	VP[{lorentz}]	Z_ρ	VZ[{lorentz}]

- Ghosts

η_i^G	gG[{generation}]	η^-	gWm
η^+	gWmC	η^γ	gP
η^Z	gZ		

17.8.3 Parameters

g_1	g1	g_2	g2	g_3	g3
Y_u	Yu	T_u	T[Yu]	Y_d	Yd
T_d	T[Yd]	Y_e	Ye	T_e	T[Ye]
Y_v	Yv	T_v	T[Yv]	λ	\[Lambda]
T_λ	T[\[Lambda]]	κ	\[Kappa]	T_κ	T[\[Kappa]]
m_q^2	mq2	m_l^2	ml2	$m_{H_d}^2$	mHd2
$m_{H_u}^2$	mHu2	m_d^2	md2	m_u^2	mu2
m_e^2	me2	m_v^2	mv2	M_1	MassB
M_2	MassWB	M_3	MassG	v_d	vd
v_u	vu	v_L	vL	v_R	vR
Θ_W	ThetaW	$\phi_{\tilde{g}}$	PhaseGlu	Z^D	ZD
Z^U	ZU	Z^H	ZH	Z^A	ZA
Z^+	ZP	N	ZN	U	UM
V	UP	U_L^d	ZDL	U_R^d	ZDR
U_L^u	ZUL	U_R^u	ZUR		

Chapter 18

Seesaw I

18.1 Superfields

18.1.1 Vector Superfields

SF	Spin $\frac{1}{2}$	Spin 1	$SU(N)$	Coupling	Name
$\hat{B}$	$\lambda_{\tilde{B}}$	B	$U(1)$	g_1	hypercharge
$\hat{W}$	$\lambda_{\tilde{W}}$	W^-	SU(2)	g_2	left
$\hat{g}$	$\lambda_{\tilde{g}}$	g	SU(3)	g_3	color

18.1.2 Chiral Superfields

SF	Spin 0	Spin $\frac{1}{2}$	Generations	$(U(1) \otimes \text{SU}(2) \otimes \text{SU}(3))$
$\hat{q}$	$\tilde{q}$	q	3	$(\frac{1}{6}, \mathbf{2}, \mathbf{3})$
$\hat{l}$	$\tilde{l}$	l	3	$(-\frac{1}{2}, \mathbf{2}, \mathbf{1})$
$\hat{H}_d$	H_d	$\tilde{H}_d$	1	$(-\frac{1}{2}, \mathbf{2}, \mathbf{1})$
$\hat{H}_u$	H_u	$\tilde{H}_u$	1	$(\frac{1}{2}, \mathbf{2}, \mathbf{1})$
$\hat{d}$	$\tilde{d}_R^*$	d_R^*	3	$(\frac{1}{3}, \mathbf{1}, \overline{\mathbf{3}})$
$\hat{u}$	$\tilde{u}_R^*$	u_R^*	3	$(-\frac{2}{3}, \mathbf{1}, \overline{\mathbf{3}})$
$\hat{e}$	$\tilde{e}_R^*$	e_R^*	3	$(1, \mathbf{1}, \mathbf{1})$
$\hat{\nu}$	$\tilde{\nu}_R$	ν_R	3	$(0, \mathbf{1}, \mathbf{1})$

18.2 Superpotential and Lagrangian

18.2.1 Superpotential

$$W = Y_u\, \hat{u}\, \hat{q}\, \hat{H}_u\, - Y_d\, \hat{d}\, \hat{q}\, \hat{H}_d\, - Y_e\, \hat{e}\, \hat{l}\, \hat{H}_d\, + \mu\, \hat{H}_u\, \hat{H}_d\, + Y_v\, \hat{\nu}\, \hat{l}\, \hat{H}_u\, + \frac{1}{2} M_v\, \hat{\nu}\, \hat{\nu} \tag{18.1}$$

18.2.2 Softbreaking terms

$$
\begin{aligned}
L_{SB,W} = & - H_d^0 H_u^0 B_\mu + H_d^- H_u^+ B_\mu + \frac{1}{2}\tilde{\nu}_{R,i}\tilde{\nu}_{R,j} B_{v,ij} + H_d^0 \tilde{d}^*_{R,i\alpha}\delta_{\alpha\beta}\tilde{d}_{L,j\beta}T_{d,ij} - H_d^- \tilde{d}^*_{R,i\alpha}\delta_{\alpha\beta}\tilde{u}_{L,j\beta}T_{d,ij} \\
& + H_d^0 \tilde{e}^*_{R,i}\tilde{e}_{L,j}T_{e,ij} - H_d^- \tilde{e}^*_{R,i}\tilde{\nu}_{L,j}T_{e,ij} - H_u^+ \tilde{u}^*_{R,i\alpha}\delta_{\alpha\beta}\tilde{d}_{L,j\beta}T_{u,ij} + H_u^0 \tilde{u}^*_{R,i\alpha}\delta_{\alpha\beta}\tilde{u}_{L,j\beta}T_{u,ij} \\
& - H_u^+ \tilde{e}_{L,j}\tilde{\nu}_{R,i}T_{v,ij} + H_u^0 \tilde{\nu}_{L,j}\tilde{\nu}_{R,i}T_{v,ij} + \text{h.c.}
\end{aligned} \tag{18.2}
$$

$$
\begin{aligned}
L_{SB,\phi} = & - m^2_{H_d}|H_d^0|^2 - m^2_{H_d}|H_d^-|^2 - m^2_{H_u}|H_u^0|^2 - m^2_{H_u}|H_u^+|^2 - \tilde{d}^*_{L,j\beta}\delta_{\alpha\beta}m^2_{q,ij}\tilde{d}_{L,i\alpha} \\
& - \tilde{d}^*_{R,i\alpha}\delta_{\alpha\beta}m^2_{d,ij}\tilde{d}_{R,j\beta} - \tilde{e}^*_{L,j}m^2_{l,ij}\tilde{e}_{L,i} - \tilde{e}^*_{R,i}m^2_{e,ij}\tilde{e}_{R,j} - \tilde{u}^*_{L,j\beta}\delta_{\alpha\beta}m^2_{q,ij}\tilde{u}_{L,i\alpha} \\
& - \tilde{u}^*_{R,i\alpha}\delta_{\alpha\beta}m^2_{u,ij}\tilde{u}_{R,j\beta} - \tilde{\nu}^*_{L,j}m^2_{l,ij}\tilde{\nu}_{L,i} - \tilde{\nu}^*_{R,j}m^2_{v,ij}\tilde{\nu}_{R,i}
\end{aligned} \tag{18.3}
$$

$$
L_{SB,\lambda} = \frac{1}{2}\Big(-\lambda^2_{\tilde{B}}M_1 - M_2\lambda^2_{\tilde{W},i} - M_3\lambda^2_{\tilde{g},i} + \text{h.c.}\Big) \tag{18.4}
$$

18.2.3 Gauge fixing terms

Gauge fixing terms for eigenstates 'GaugeES'

$$
L_{GF} = -\frac{1}{2}\partial_\mu g \xi_G^{-1} - \frac{1}{2}\partial_\mu W^- \xi_W^{-1} \tag{18.5}
$$

Gauge fixing terms for eigenstates 'EWSB'

$$
L_{GF} = -\frac{1}{2}\partial_\mu \gamma \xi_P^{-1} - \frac{1}{2}\partial_\mu g \xi_G^{-1} - \frac{1}{2}\xi_Z^{-1}\Big(-A_1^0 m_Z \xi_Z + \partial_\mu Z\Big) - \xi_W^{-1}\Big(iH_1^- m_{W^-}\xi_W + \partial_\mu W^-\Big) \tag{18.6}
$$

18.2.4 Fields integrated out

a) $\hat{\nu}$

Chapter 19

Seesaw II

19.1 Superfields

19.1.1 Vector Superfields

SF	Spin $\frac{1}{2}$	Spin 1	$SU(N)$	Coupling	Name
$\hat{B}$	$\lambda_{\tilde{B}}$	B	$U(1)$	g_1	hypercharge
$\hat{W}$	$\lambda_{\tilde{W}}$	W^-	SU(2)	g_2	left
$\hat{g}$	$\lambda_{\tilde{g}}$	g	SU(3)	g_3	color

19.1.2 Chiral Superfields

SF	Spin 0	Spin $\frac{1}{2}$	Generations	$(U(1) \otimes \text{SU}(2) \otimes \text{SU}(3))$
$\hat{q}$	$\tilde{q}$	q	3	$(\frac{1}{6}, \mathbf{2}, \mathbf{3})$
$\hat{l}$	$\tilde{l}$	l	3	$(-\frac{1}{2}, \mathbf{2}, \mathbf{1})$
$\hat{H}_d$	H_d	$\tilde{H}_d$	1	$(-\frac{1}{2}, \mathbf{2}, \mathbf{1})$
$\hat{H}_u$	H_u	$\tilde{H}_u$	1	$(\frac{1}{2}, \mathbf{2}, \mathbf{1})$
$\hat{d}$	$\tilde{d}_R^*$	d_R^*	3	$(\frac{1}{3}, \mathbf{1}, \overline{\mathbf{3}})$
$\hat{u}$	$\tilde{u}_R^*$	u_R^*	3	$(-\frac{2}{3}, \mathbf{1}, \overline{\mathbf{3}})$
$\hat{e}$	$\tilde{e}_R^*$	e_R^*	3	$(1, \mathbf{1}, \mathbf{1})$
$\hat{T}$	$\tilde{T}$	T	1	$(1, \mathbf{3}, \mathbf{1})$
$\hat{\bar{T}}$	$\tilde{\bar{T}}$	$\bar{T}$	1	$(-1, \mathbf{3}, \mathbf{1})$
$\hat{S}$	$\tilde{S}$	S	1	$(-\frac{2}{3}, \mathbf{1}, \mathbf{6})$
$\hat{\bar{S}}$	$\tilde{\bar{S}}^*$	$\bar{S}^*$	1	$(\frac{2}{3}, \mathbf{1}, \overline{\mathbf{6}})$
$\hat{Z}$	$\tilde{Z}$	Z	1	$(\frac{1}{6}, \mathbf{2}, \mathbf{3})$
$\hat{\bar{Z}}$	$\tilde{\bar{Z}}$	$\bar{Z}$	1	$(-\frac{1}{6}, \mathbf{2}, \overline{\mathbf{3}})$

19.2 Superpotential and Lagrangian

19.2.1 Superpotential

$$
\begin{aligned}
W = & Y_u\,\hat{u}\,\hat{q}\,\hat{H}_u\,-Y_d\,\hat{d}\,\hat{q}\,\hat{H}_d\,-Y_e\,\hat{e}\,\hat{l}\,\hat{H}_d\,+\mu\,\hat{H}_u\,\hat{H}_d\,+\frac{1}{\sqrt{2}}Y_t\,\hat{l}\,\hat{T}\,\hat{l}\,+\frac{1}{\sqrt{2}}Y_s\,\hat{d}\,\hat{S}\,\hat{d}\,+Y_z\,\hat{d}\,\hat{Z}\,\hat{l}\\
& +\frac{1}{\sqrt{2}}\lambda_1\,\hat{H}_d\,\hat{T}\,\hat{H}_d\,+\frac{1}{\sqrt{2}}\lambda_2\,\hat{H}_u\,\hat{\bar{T}}\,\hat{H}_u\,+M_T\,\hat{T}\,\hat{\bar{T}}\,+M_Z\,\hat{Z}\,\hat{\bar{Z}}\,+M_S\,\hat{S}\,\hat{\bar{S}}
\end{aligned}
\tag{19.1}
$$

19.2.2 Softbreaking terms

$$
\begin{aligned}
L_{SB,W} = & +\tilde{T}^0\tilde{T}^{--}B_T+\tilde{T}^-\tilde{T}^+B_T+\tilde{\bar{T}}^0\tilde{T}^{++}B_T-H_d^0H_u^0B_\mu+H_d^-H_u^+B_\mu+B_S\tilde{\bar{S}}^*_{\beta\mathrm{ct2b}}\delta_{\alpha\mathrm{ct2b}}\delta_{\mathrm{ct1b}\beta}\tilde{S}_{\alpha\mathrm{ct1b}}\\
& -B_Z\delta_{\alpha\beta}\tilde{\bar{Z}}_{1,\beta}\tilde{Z}_{2,\alpha}+B_Z\delta_{\alpha\beta}\tilde{Z}_{1,\alpha}\tilde{\bar{Z}}_{2,\beta}\\
& +\frac{1}{\sqrt{2}}\Big(-\frac{1}{\sqrt{2}}H_d^{0,2}\tilde{T}^+T_{\lambda_1}+\frac{1}{\sqrt{2}}H_d^{-,2}\tilde{T}^+T_{\lambda_1}-H_d^0H_d^-\tilde{T}^0T_{\lambda_1}-H_d^0H_d^-\tilde{T}^{++}T_{\lambda_1}\Big)\\
& +\frac{1}{\sqrt{2}}\Big(\frac{1}{\sqrt{2}}H_u^{0,2}\tilde{T}^-T_{\lambda_2}-\frac{1}{\sqrt{2}}H_u^{+,2}\tilde{T}^-T_{\lambda_2}-H_u^0H_u^+\tilde{\bar{T}}^0T_{\lambda_2}-H_u^0H_u^+\tilde{T}^{--}T_{\lambda_2}\Big)\\
& +H_d^0\tilde{d}^*_{R,i\alpha}\delta_{\alpha\beta}\tilde{d}_{L,j\beta}T_{d,ij}-H_d^-\tilde{d}^*_{R,i\alpha}\delta_{\alpha\beta}\tilde{u}_{L,j\beta}T_{d,ij}+H_d^0\tilde{e}^*_{R,i}\tilde{e}_{L,j}T_{e,ij}-H_d^-\tilde{e}^*_{R,i}\tilde{\nu}_{L,j}T_{e,ij}\\
& +\frac{1}{\sqrt{2}}\tilde{d}^*_{R,i\alpha}\tilde{d}^*_{R,k\gamma}\delta_{\alpha\beta}\delta_{\mathrm{ct2b}\gamma}\tilde{S}_{\beta\mathrm{ct2b}}T_{s,ik}\\
& +\frac{1}{\sqrt{2}}\Big(\frac{1}{\sqrt{2}}\tilde{T}^+\tilde{e}_{L,i}\tilde{e}_{L,k}T_{t,ik}-\frac{1}{\sqrt{2}}\tilde{T}^+\tilde{\nu}_{L,i}\tilde{\nu}_{L,k}T_{t,ik}-\tilde{T}^0\tilde{e}_{L,i}\tilde{\nu}_{L,k}T_{t,ik}-\tilde{T}^{++}\tilde{e}_{L,k}\tilde{\nu}_{L,i}T_{t,ik}\Big)\\
& -H_u^+\tilde{u}^*_{R,i\alpha}\delta_{\alpha\beta}\tilde{d}_{L,j\beta}T_{u,ij}+H_u^0\tilde{u}^*_{R,i\alpha}\delta_{\alpha\beta}\tilde{u}_{L,j\beta}T_{u,ij}+\tilde{d}^*_{R,i\alpha}\delta_{\alpha\beta}\tilde{e}_{L,k}\tilde{Z}_{1,\beta}T_{z,ik}\\
& -\tilde{d}^*_{R,i\alpha}\delta_{\alpha\beta}\tilde{\nu}_{L,k}\tilde{Z}_{2,\beta}T_{z,ik}+\text{h.c.}
\end{aligned}
\tag{19.2}
$$

$$
\begin{aligned}
L_{SB,\phi} = & -m_{H_d}^2|H_d^0|^2-m_{H_d}^2|H_d^-|^2-m_{H_u}^2|H_u^0|^2-m_{H_u}^2|H_u^+|^2-m_t^2|\tilde{T}^0|^2-m_{\bar{t}}^2|\tilde{\bar{T}}^0|^2\\
& -m_{\bar{t}}^2|\tilde{T}^-|^2-m_{\bar{t}}^2|\tilde{T}^{--}|^2-m_t^2|\tilde{T}^+|^2-m_t^2|\tilde{T}^{++}|^2-\tilde{d}^*_{L,j\beta}\delta_{\alpha\beta}m^2_{q,ij}\tilde{d}_{L,i\alpha}\\
& -\tilde{d}^*_{R,i\alpha}\delta_{\alpha\beta}m^2_{d,ij}\tilde{d}_{R,j\beta}-\tilde{e}^*_{L,j}m^2_{l,ij}\tilde{e}_{L,i}-\tilde{e}^*_{R,i}m^2_{e,ij}\tilde{e}_{R,j}-m_s^2\tilde{S}^*_{\beta\mathrm{ct2b}}\delta_{\alpha\beta}\delta_{\mathrm{ct1bct2b}}\tilde{S}_{\alpha\mathrm{ct1b}}\\
& -m_{\bar{s}}^2\tilde{\bar{S}}^*_{\alpha\mathrm{ct1b}}\delta_{\alpha\beta}\delta_{\mathrm{ct1bct2b}}\tilde{\bar{S}}_{\beta\mathrm{ct2b}}-\tilde{u}^*_{L,j\beta}\delta_{\alpha\beta}m^2_{q,ij}\tilde{u}_{L,i\alpha}-\tilde{u}^*_{R,i\alpha}\delta_{\alpha\beta}m^2_{u,ij}\tilde{u}_{R,j\beta}-\tilde{\nu}^*_{L,j}m^2_{l,ij}\tilde{\nu}_{L,i}\\
& -m_z^2\tilde{Z}^*_{1,\beta}\delta_{\alpha\beta}\tilde{Z}_{1,\alpha}-m_{\bar{z}}^2\tilde{\bar{Z}}^*_{1,\beta}\delta_{\alpha\beta}\tilde{\bar{Z}}_{1,\alpha}-m_z^2\tilde{Z}^*_{2,\beta}\delta_{\alpha\beta}\tilde{Z}_{2,\alpha}-m_{\bar{z}}^2\tilde{\bar{Z}}^*_{2,\beta}\delta_{\alpha\beta}\tilde{\bar{Z}}_{2,\alpha}
\end{aligned}
\tag{19.3}
$$

$$
L_{SB,\lambda} = \frac{1}{2}\left(-\lambda_{\tilde{B}}^2M_1-M_2\lambda^2_{\tilde{W},i}-M_3\lambda^2_{\tilde{g},i}+\text{h.c.}\right)
\tag{19.4}
$$

19.2.3 Gauge fixing terms

Gauge fixing terms for eigenstates 'GaugeES'

$$
L_{GF} = -\frac{1}{2}\partial_\mu g\xi_G^{-1}-\frac{1}{2}\partial_\mu W^-\xi_W^{-1}
\tag{19.5}
$$

Gauge fixing terms for eigenstates 'EWSB'

$$
L_{GF} = -\frac{1}{2}\partial_\mu\gamma\xi_P^{-1}-\frac{1}{2}\partial_\mu g\xi_G^{-1}-\frac{1}{2}\xi_Z^{-1}\Big(-A_1^0m_Z\xi_Z+\partial_\mu Z\Big)-\xi_W^{-1}\Big(iH_1^-m_{W^-}\xi_W+\partial_\mu W^-\Big)
\tag{19.6}
$$

19.2.4 Fields integrated out

a) $\hat{T}$

b) $\hat{\hat{T}}$

c) $\hat{S}$

d) $\hat{\hat{S}}$

e) $\hat{Z}$

f) $\hat{\hat{Z}}$

Chapter 20

Seesaw III

20.1 Superfields

20.1.1 Vector Superfields

SF	Spin $\frac{1}{2}$	Spin 1	$SU(N)$	Coupling	Name
$\hat{B}$	$\lambda_{\tilde{B}}$	B	$U(1)$	g_1	hypercharge
$\hat{W}$	$\lambda_{\tilde{W}}$	W^-	SU(2)	g_2	left
$\hat{g}$	$\lambda_{\tilde{g}}$	g	SU(3)	g_3	color

20.1.2 Chiral Superfields

SF	Spin 0	Spin $\frac{1}{2}$	Generations	$(U(1)\otimes \mathrm{SU}(2)\otimes \mathrm{SU}(3))$
$\hat{q}$	$\tilde{q}$	q	3	$(\frac{1}{6},\mathbf{2},\mathbf{3})$
$\hat{l}$	$\tilde{l}$	l	3	$(-\frac{1}{2},\mathbf{2},\mathbf{1})$
$\hat{H}_d$	H_d	$\tilde{H}_d$	1	$(-\frac{1}{2},\mathbf{2},\mathbf{1})$
$\hat{H}_u$	H_u	$\tilde{H}_u$	1	$(\frac{1}{2},\mathbf{2},\mathbf{1})$
$\hat{d}$	$\tilde{d}_R^*$	d_R^*	3	$(\frac{1}{3},\mathbf{1},\overline{\mathbf{3}})$
$\hat{u}$	$\tilde{u}_R^*$	u_R^*	3	$(-\frac{2}{3},\mathbf{1},\overline{\mathbf{3}})$
$\hat{e}$	$\tilde{e}_R^*$	e_R^*	3	$(1,\mathbf{1},\mathbf{1})$
$\hat{W}_M$	$\tilde{W}_M$	W_M	3	$(0,\mathbf{3},\mathbf{1})$
$\hat{G}_M$	$\tilde{G}_M$	G_M	3	$(0,\mathbf{1},\mathbf{8})$
$\hat{B}_M$	$\tilde{B}_M$	B_M	3	$(0,\mathbf{1},\mathbf{1})$
$\hat{X}_M$	$\tilde{X}_M$	X_M	3	$(\frac{5}{6},\mathbf{2},\overline{\mathbf{3}})$
$\hat{\bar{X}}_M$	$\tilde{\bar{X}}_M$	$\bar{X}_M$	3	$(-\frac{5}{6},\mathbf{2},\mathbf{3})$

20.2 Superpotential and Lagrangian

20.2.1 Superpotential

$$\begin{aligned}
W = & Y_u\, \hat{u}\, \hat{q}\, \hat{H}_u\, - Y_d\, \hat{d}\, \hat{q}\, \hat{H}_d\, - Y_e\, \hat{e}\, \hat{l}\, \hat{H}_d\, + \mu\, \hat{H}_u\, \hat{H}_d\, + \sqrt{\frac{3}{10}} Y_b\, \hat{H}_u\, \hat{B}_M\, \hat{l}\, + Y_w\, \hat{H}_u\, \hat{W}_M\, \hat{l}\, + Y_x\, \hat{H}_u\, \hat{\bar{X}}_M\, \hat{d} \\
& + M_X\, \hat{X}_M\, \hat{\bar{X}}_M\, + \frac{1}{2} M_W\, \hat{W}_M\, \hat{W}_M\, + \frac{1}{2} M_G\, \hat{G}_M\, \hat{G}_M\, + \frac{1}{2} M_B\, \hat{B}_M\, \hat{B}_M\, + MNuL\, \hat{l}\, \hat{H}_u\, \hat{l}\, \hat{H}_u
\end{aligned} \tag{20.1}$$

20.2.2 Softbreaking terms

$$\begin{aligned}
L_{SB,W} = & - H_d^0 H_u^0 B_\mu + H_d^- H_u^+ B_\mu + \frac{1}{2} \tilde{B}_{M,i} \tilde{B}_{M,j} B_{B,ij} + \frac{1}{2} \delta_{\alpha \mathrm{ct2b}} \delta_{\mathrm{ct1b}\beta} \tilde{G}_{M,i\alpha\mathrm{ct1b}} \tilde{G}_{M,j\beta\mathrm{ct2b}} B_{G,ij} \\
& + \frac{1}{2}\Big(\tilde{W}^0_{M,i} \tilde{W}^0_{M,j} B_{W,ij} + \tilde{W}^-_{M,i} \tilde{W}^+_{M,j} B_{W,ij} + \tilde{W}^-_{M,j} \tilde{W}^+_{M,i} B_{W,ij} \Big) + \delta_{\alpha\beta} \tilde{\bar{X}}^d_{M,j\beta} \tilde{X}^u_{M,i\alpha} B_{X,ij} \\
& - \delta_{\alpha\beta} \tilde{X}^d_{M,i\alpha} \tilde{\bar{X}}^u_{M,j\beta} B_{X,ij} + \sqrt{\frac{3}{10}} \Big(- H_u^0 \tilde{B}_{M,j} \tilde{\nu}_{L,k} T_{b,jk} + H_u^+ \tilde{e}_{L,k} \tilde{B}_{M,j} T_{b,jk} \Big) + H_d^0 \tilde{d}^*_{R,i\alpha} \delta_{\alpha\beta} \tilde{d}_{L,j\beta} T_{d,ij} \\
& - H_d^- \tilde{d}^*_{R,i\alpha} \delta_{\alpha\beta} \tilde{u}_{L,j\beta} T_{d,ij} + H_d^0 \tilde{e}^*_{R,i} \tilde{e}_{L,j} T_{e,ij} - H_d^- \tilde{e}^*_{R,i} \tilde{\nu}_{L,j} T_{e,ij} - H_u^+ \tilde{u}^*_{R,i\alpha} \delta_{\alpha\beta} \tilde{d}_{L,j\beta} T_{u,ij} \\
& + H_u^0 \tilde{u}^*_{R,i\alpha} \delta_{\alpha\beta} \tilde{u}_{L,j\beta} T_{u,ij} + \frac{1}{\sqrt{2}} H_u^+ \tilde{e}_{L,k} \tilde{W}^0_{M,j} T_{w,jk} - H_u^0 \tilde{e}_{L,k} \tilde{W}^+_{M,j} T_{w,jk} - \frac{1}{\sqrt{2}} H_u^0 \tilde{W}^0_{M,j} \tilde{\nu}_{L,k} T_{w,jk} \\
& + H_u^+ \tilde{W}^-_{M,j} \tilde{\nu}_{L,k} T_{w,jk} + H_u^+ \tilde{d}^*_{R,k\gamma} \delta_{\beta\gamma} \tilde{\bar{X}}^d_{M,j\beta} T_{x,jk} - H_u^0 \tilde{d}^*_{R,k\gamma} \delta_{\beta\gamma} \tilde{\bar{X}}^u_{M,j\beta} T_{x,jk} + \mathrm{h.c.}
\end{aligned} \tag{20.2}$$

$$\begin{aligned}
L_{SB,\phi} = & - m^2_{H_d} |H_d^0|^2 - m^2_{H_d} |H_d^-|^2 - m^2_{H_u} |H_u^0|^2 - m^2_{H_u} |H_u^+|^2 - \tilde{d}^*_{L,j\beta} \delta_{\alpha\beta} m^2_{q,ij} \tilde{d}_{L,i\alpha} \\
& - \tilde{d}^*_{R,i\alpha} \delta_{\alpha\beta} m^2_{d,ij} \tilde{d}_{R,j\beta} - \tilde{e}^*_{L,j} m^2_{l,ij} \tilde{e}_{L,i} - \tilde{e}^*_{R,i} m^2_{e,ij} \tilde{e}_{R,j} - \tilde{B}^*_{M,j} m^2_{B,ij} \tilde{B}_{M,i} \\
& - \mathrm{conj}\Big(\mathrm{SHG}\Big(\{\mathrm{gt2}, \mathrm{ct2}, \mathrm{ct2b}\}\Big)\Big) \delta_{\alpha\beta} \delta_{\mathrm{ct1bct2b}} m^2_{G,ij} \tilde{G}_{M,i\alpha\mathrm{ct1b}} - \tilde{W}^{0,*}_{M,j} m^2_{W,ij} \tilde{W}^0_{M,i} - \tilde{W}^{-,*}_{M,j} m^2_{W,ij} \tilde{W}^-_{M,i} - \tilde{W}^{+,*}_{M,j} m^2_{W,ij} \\
& - \tilde{X}^{d,*}_{M,j\beta} \delta_{\alpha\beta} m^2_{X,ij} \tilde{X}^d_{M,i\alpha} - \tilde{\bar{X}}^{d,*}_{M,j\beta} \delta_{\alpha\beta} m^2_{\bar{X},ij} \tilde{\bar{X}}^d_{M,i\alpha} - \tilde{X}^{u,*}_{M,j\beta} \delta_{\alpha\beta} m^2_{X,ij} \tilde{X}^u_{M,i\alpha} \\
& - \tilde{\bar{X}}^{u,*}_{M,j\beta} \delta_{\alpha\beta} m^2_{\bar{X},ij} \tilde{\bar{X}}^u_{M,i\alpha} - \tilde{u}^*_{L,j\beta} \delta_{\alpha\beta} m^2_{q,ij} \tilde{u}_{L,i\alpha} - \tilde{u}^*_{R,i\alpha} \delta_{\alpha\beta} m^2_{u,ij} \tilde{u}_{R,j\beta} - \tilde{\nu}^*_{L,j} m^2_{l,ij} \tilde{\nu}_{L,i}
\end{aligned} \tag{20.3}$$

$$L_{SB,\lambda} = \frac{1}{2} \left(-\lambda^2_{\tilde{B}} M_1 - M_2 \lambda^2_{\tilde{W},i} - M_3 \lambda^2_{\tilde{g},i} + \mathrm{h.c.} \right) \tag{20.4}$$

20.2.3 Gauge fixing terms

Gauge fixing terms for eigenstates 'GaugeES'

$$L_{GF} = -\frac{1}{2} \partial_\mu g \xi_G^{-1} - \frac{1}{2} \partial_\mu W^- \xi_W^{-1} \tag{20.5}$$

Gauge fixing terms for eigenstates 'EWSB'

$$L_{GF} = -\frac{1}{2} \partial_\mu \gamma \xi_P^{-1} - \frac{1}{2} \partial_\mu g \xi_G^{-1} - \frac{1}{2} \xi_Z^{-1} \Big(- A_1^0 m_Z \xi_Z + \partial_\mu Z \Big) - \xi_W^{-1} \Big(i H_1^- m_{W^-} \xi_W + \partial_\mu W^- \Big) \tag{20.6}$$

20.2.4 Fields integrated out

a) $\hat{W}_M$

b) $\hat{G}_M$

c) $\hat{B}_M$

d) $\hat{X}_M$

e) $\hat{\bar{X}}_M$