

# THE MINIMALLY SUPERSYMMETRIC STANDARD MODEL

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# Outline

1. The Standard Model
2. The MSSM

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## ① The Standard Model

- Basics

- The Lagrangian

- Parameter Count

## ② The MSSM

- Basics

- The Lagrangian — SUSY conserving

- The Lagrangian — SUSY breaking

- (Effective) Higgs potential

- Mixing Caveats

- Parameter Count

# Standard Model — The Basics

The gauge group of the Standard Model (SM) is

$$\mathcal{G}_{\text{SM}} = \text{SU}(3)_C \times \text{SU}(2)_T \times \text{U}(1)_Y. \quad (1)$$

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The SM fields transform in representations of this group:

$$s = 0 : \quad (\mathbf{1}, \mathbf{2})_{\frac{1}{2}} \quad (2)$$

$\ni \phi$

$$s = \frac{1}{2} : \quad (\mathbf{3}, \mathbf{2})_{\frac{1}{6}} \oplus (\bar{\mathbf{3}}, \mathbf{1})_{\frac{1}{3}} \oplus (\bar{\mathbf{3}}, \mathbf{1})_{-\frac{2}{3}} \oplus (\mathbf{1}, \mathbf{2})_{-\frac{1}{2}} \oplus (\mathbf{1}, \mathbf{1})_1 \quad (3)$$

$\ni q_L \quad \ni (d_R)^c \quad \ni (u_R)^c \quad \ni \ell_L \quad \ni (e_R)^c$

$$s = 1 : \quad (\mathbf{8}, \mathbf{1})_0 \oplus (\mathbf{1}, \mathbf{3})_0 \oplus (\mathbf{1}, \mathbf{1})_0. \quad (4)$$

$\ni A_\mu^a \quad \ni W_\mu^k \quad \ni B_\mu$

## Standard Model — The Basics

Beware! We only use lefthanded fields  $\psi_L = \begin{pmatrix} \psi_\alpha \\ 0 \end{pmatrix}$ , righthanded fields are included via charge conjugation  $(\psi_R)^c = \begin{pmatrix} 0 \\ \bar{\psi}^{\dot{\alpha}} \end{pmatrix}^c = \begin{pmatrix} \psi_\alpha \\ 0 \end{pmatrix}$ .

The  $SU(2)$ -doublets are written as:

$$\phi = \begin{pmatrix} \phi_+ \\ \phi_0 \end{pmatrix} \quad q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix} \quad \ell_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}.$$

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$\ni A_\mu^a \quad \ni W_\mu^k \quad \ni B_\mu$

# Standard Model — The Lagrangian

The SM Lagrangian contains a variety of terms which roughly fall into three categories:

gauge terms

kinetic terms

Higgs sector

The gauge part is straightforward albeit there being additional gauge configurations:

$$\mathcal{L}_{\text{gauge}} \supset \frac{1}{2g_i^2} \text{tr} \left[ F_{\mu\nu}^{(i)} F^{(i)\mu\nu} \right] \quad (5)$$

$$\supset \frac{\theta_{\text{QCD}}}{16\pi^2 g_s^2} \epsilon^{\mu\nu\rho\sigma} \text{tr} \left[ F_{\mu\nu}^{(3)} F_{\rho\sigma}^{(3)} \right]. \quad (6)$$

Kinetic terms for the fermions are constructed with the covariant derivative

$$\mathcal{L}_{\text{kin}} \supset \bar{\psi}_i i \not{D} \psi_i \quad (7)$$

$$D_\mu = \partial_\mu - iq A_\mu^k \mathcal{R}(T_k) \quad (8)$$



## Standard Model — Higgs sector

The Higgs part is made of a scalar kinetic term, the quartic potential and the Yukawa couplings:

$$\mathcal{L}_{\text{Higgs}} \supset - (D^\mu \phi)^\dagger (D_\mu \phi) + \mu \phi^\dagger \phi - \lambda (\phi^\dagger \phi)^2 - \lambda^\psi [\overline{\psi} \phi \psi]_{\mathbf{1}}. \quad (9)$$

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The fermions gain masses  $m_\psi = v\lambda^\psi$  when the Higgs field acquires its vacuum expectation value (VEV):

$$\langle \phi \rangle = \begin{pmatrix} 0 \\ v \end{pmatrix} \quad (\text{shorthand: } \langle \phi_0 \rangle = v).$$

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For our three types of massive fermions (electron, up-quark, down-quark) the corresponding singlets look like:<sup>1</sup>

$$\lambda^u [\bar{q}_L \tilde{\phi} u_R]_1 \quad \lambda^d [\bar{q}_L \phi d_R]_1 \quad \lambda^e [\bar{\ell}_L \phi e_R]_1. \quad (10)$$

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Furthermore, the SM consists of three generations of fermions thus promoting the  $\lambda^\psi$  to complex 3x3 matrices  $\lambda_{mn}^e$ ,  $\lambda_{mn}^d$  and  $\lambda_{mn}^u$ . The  $\lambda_{mn}^f$  can be diagonalised via bi-unitary transformations:

$$V_f^\dagger \lambda^f U_f \propto \text{diag} \left( m_f^{(1)}, m_f^{(2)}, m_f^{(3)} \right). \quad (11)$$

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# Standard Model — Parameter count

Count parameters and gauge redundancies:

+

- 3 couplings  $g$ ,  $g'$  and  $g_s$ , one vacuum angle  $\theta_{\text{QCD}}$  (4 parameters)
- Higgs parameters  $v$ ,  $\lambda$  (2 parameters)
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- Quark flavour symmetry  $U(3)_{q_L} \times U(3)_{u_R} \times U(3)_{d_R}/U(1)_B$  (3x9-1 parameters)
- Lepton flavour symmetry  $U(3)_{\ell_L} \times U(3)_{e_R}/U(1)_{L_e} \times U(1)_{L_\mu} \times U(1)_{L_\tau}$  (2x9-3 parameters)

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The Standard Model of Particle Physics has 19 free parameters with  $v$  being the only one carrying a physical dimension.<sup>2</sup>

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<sup>2</sup>15 real parameters, 3 mixing angles, 1 CP-violating phase.

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## MSSM — The fields

First of all we promote all our previous fields to real (chiral) superfields resulting in our renewed table:

super field	bosonic field	fermionic field	representation
$\hat{V}_8$	$g$	$\tilde{g}$	$(\mathbf{8}, \mathbf{1})_0$
$\hat{V}$	$W^0, W^\pm$	$\tilde{W}^0, \tilde{W}^\pm$	$(\mathbf{1}, \mathbf{3})_0$
$\hat{V}'$	$B$	$\tilde{B}$	$(\mathbf{1}, \mathbf{1})_0$
$\hat{L}$	$(\tilde{\nu}_e, \tilde{e})$	$(\nu_L, e_L)$	$(\mathbf{1}, \mathbf{2})_{-\frac{1}{2}}$
$\hat{E}^c$	$\tilde{e}_R^c$	$e_R^c$	$(\mathbf{1}, \mathbf{1})_1$
$\hat{Q}$	$(\tilde{u}_L, \tilde{d}_L)$	$(u_L, d_L)$	$(\mathbf{3}, \mathbf{1})_{\frac{1}{6}}$
$\hat{U}^c$	$\tilde{u}_R^c$	$u_R^c$	$(\mathbf{3}, \mathbf{1})_{-\frac{2}{3}}$
$\hat{D}^c$	$\tilde{d}_R^c$	$d_R^c$	$(\mathbf{3}, \mathbf{1})_{\frac{1}{3}}$
$\hat{H}_u$	$(H_u^+, H_u^0)$	$(\tilde{H}_u^+, \tilde{H}_u^0)$	$(\mathbf{1}, \mathbf{2})_{\frac{1}{2}}$
$\hat{H}_d$	$(H_d^0, H_d^-)$	$(\tilde{H}_d^0, \tilde{H}_d^-)$	$(\mathbf{1}, \mathbf{2})_{-\frac{1}{2}}$

## MSSM — SUSY terms

For the gauge part the usual field strength super fields  $\mathcal{W}_{i,\alpha}$  are constructed and included in the Lagrangian:

$$\mathcal{L}_{\text{gauge}}^{\text{MSSM}} \supset \frac{1}{2g_i^2} \text{tr} \left[ \int d^2\theta (\mathcal{W}_i)^\alpha (\mathcal{W}_i)_\alpha + \text{h.c.} \right]. \quad (12)$$

The kinetic terms for the fields read:

$$\mathcal{L}_K^{\text{MSSM}} \supset \int d^2\theta d^2\bar{\theta} \left[ \hat{\Phi}_i^\dagger e^{2V_i} \hat{\Phi}_i \right]_1 \quad (13)$$

$$V_i = \hat{V}_8^a \mathcal{R}_i(T_a) + \hat{V}^k \mathcal{R}_i(T_k) + Y_i \hat{V}'. \quad (14)$$

## MSSM — Superpotential

The superpotential term is simply:

$$\mathcal{L}_W^{\text{MSSM}} = \int d^2\theta W + \text{h.c.} \quad (15)$$

What terms are contained in  $W$ ?

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In general, the superpotential contains a great variety of different terms, under them the Yukawa couplings:

$$\begin{aligned} W = & \lambda_d [H_d Q D]_1 + \lambda_e [H_d L E]_1 - \lambda_u [H_u Q U]_1 + \mu [H_u H_d]_1 \\ & + a [\hat{L} \hat{H}_u]_1 + b [\hat{Q} \hat{L} \hat{D}]_1 + c [\hat{U} \hat{U} \hat{D}]_1 + d [\hat{L} \hat{L} \hat{E}]_1. \end{aligned} \quad (16)$$

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The terms in the last line introduce  $B$ -number violation via proton decay as well as lepton number violation, but by imposing  $R$ -parity

$$R = (-1)^{3(B-L)+2s}, \quad (17)$$

we can get rid of them. Beware! This is not obligatory!

$R$ -conservation implies the existence of a lightest supersymmetric particle (LSP) thus providing us with a dark matter candidate.

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We could use **matter parity**

$$P_m = (-1)^{3(B-L)}, \quad (17)$$

instead and see directly how the lower line gets thrown out.

## MSSM — Soft SUSY breaking terms

Introduce explicitly SUSY breaking terms to generate masses and additional interactions

$$\begin{aligned} -\mathcal{L}_{\text{soft}}^{\text{MSSM}} \supset & \frac{1}{2} M_i \tilde{\lambda}_i \tilde{\lambda}_i + M_{\tilde{F}}^2 \tilde{f}^\dagger \tilde{f} \\ & + m_1^2 H_d^\dagger H_d + m_2^2 H_u^\dagger H_u + m_{12}^2 (H_u H_d + \text{h.c.}) \\ & + T_U H_u \tilde{Q} \tilde{U} + T_D H_d \tilde{Q} \tilde{D} + T_E H_d \tilde{L} \tilde{E} + \text{h.c.} \end{aligned} \quad (18)$$

Often, a parametrisation  $m_{12}^2 = \mu B$  (and  $T_F = \lambda_f A_F$ ) is chosen. Therefore, the corresponding terms are called A and B-terms.

## MSSM — Note on the Higgs sector

Repeat the SM steps: In the MSSM the quartic coupling is generated by the kinetic and soft SUSY breaking terms leading to an effective Higgs potential.

$$\begin{aligned} V_{\text{Higgs}} = & (m_1^2 + |\mu|^2) H_d^\dagger H_d + (m_2^2 + |\mu|^2) H_u^\dagger H_u + m_{12}^2 (H_u \cdot H_d + \text{h.c.}) \\ & + \frac{g^2 + g'^2}{8} (H_d^\dagger H_d - H_u^\dagger H_u) + \frac{1}{2} g^2 |H_d^\dagger H_u|^2, \end{aligned} \quad (19)$$



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The two doublets acquire separate VEVs:

$$\langle H_f^0 \rangle = v_f, \quad (20)$$

related to the previous  $v$  via:

$$\sqrt{v_u^2 + v_d^2} = v, \quad (21)$$

by convention the angle  $\beta$  is defined as

$$\tan \beta = \frac{v_u}{v_d}. \quad (22)$$

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At tree level this implies an upper bound on the mass of the lightest Higgs:

$$m_h \leq m_Z |\cos 2\beta|. \quad (20)$$

# MSSM — Mixing in the particle spectrum

The SM particle spectrum looks like:

$$\begin{array}{cccccc} u & c & t & B & W^0 \\ d & s & b & g & W^\pm \\ & & & & \\ e & \mu & \tau & h^0 & \\ \nu_e & \nu_\mu & \nu_\tau & & \end{array}$$

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$u$	$c$	$t$	$B$	$W^0$
$d$	$s$	$b$	$g$	$W^\pm$
$e$	$\mu$	$\tau$	$H_d^-$	$H_d^0$
$\nu_e$	$\nu_\mu$	$\nu_\tau$	$H_u^0$	$H_u^+$

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$\tilde{u}_L$	$\tilde{u}_R$	$\tilde{c}_L$	$\tilde{c}_R$	$\tilde{t}_L$	$\tilde{t}_R$	$\tilde{B}$	$\tilde{W}^0$
$\tilde{d}_L$	$\tilde{d}_R$	$\tilde{s}_L$	$\tilde{s}_R$	$\tilde{b}_L$	$\tilde{b}_R$	$\tilde{g}$	$\tilde{W}^\pm$
$\tilde{e}_L$	$\tilde{e}_R$	$\tilde{\mu}_L$	$\tilde{\mu}_R$	$\tilde{\tau}_L$	$\tilde{\tau}_R$	$\tilde{H}_d^-$	$\tilde{H}_d^0$
$\tilde{\nu}_e$		$\tilde{\nu}_\mu$		$\tilde{\nu}_\tau$		$\tilde{H}_u^0$	$\tilde{H}_u^+$

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$\nu_e$	$\nu_\mu$	$\nu_\tau$	$A^0$	$H^\pm$

The MSSM particle spectrum<sup>3</sup> looks like:

$\tilde{u}_1$	$\tilde{u}_2$	$\tilde{u}_3$	$\tilde{u}_4$	$\tilde{u}_5$	$\tilde{u}_6$	$\tilde{\chi}_1^\pm$	$\tilde{\chi}_2^\pm$
$\tilde{d}_1$	$\tilde{d}_2$	$\tilde{d}_3$	$\tilde{d}_4$	$\tilde{d}_5$	$\tilde{d}_6$	$\tilde{g}$	
$\tilde{\ell}_1$	$\tilde{\ell}_2$	$\tilde{\ell}_3$	$\tilde{\ell}_4$	$\tilde{\ell}_5$	$\tilde{\ell}_6$	$\tilde{\chi}_1^0$	$\tilde{\chi}_2^0$
$\tilde{\nu}_1$		$\tilde{\nu}_2$		$\tilde{\nu}_3$		$\tilde{\chi}_3^0$	$\tilde{\chi}_4^0$

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<sup>3</sup>Worst case scenario.

# MSSM — Mixing in the particle spectrum

Summary of mixed states:

- The charged bosinos ( $\tilde{W}^\pm$ ,  $\tilde{H}_u^+$ ,  $\tilde{H}_d^-$ ) form the charginos  $\tilde{\chi}_i^\pm$ .
- The neutral bosinos ( $\tilde{B}$ ,  $\tilde{W}^0$ ,  $\tilde{H}_u^0$ ,  $\tilde{H}_d^0$ ) form the neutralinos  $\tilde{\chi}_i^0$ .
- The squarks ( $\tilde{q}_{i,L}$ ,  $\tilde{q}_{i,R}$ ) form mass eigenstates labeled  $\tilde{q}_i$ .
- The sleptons ( $\tilde{e}_{i,L}$ ,  $\tilde{e}_{i,R}$ ) form eigenstates  $\tilde{\ell}_i$ .
- The Higgs bosons ( $H_d^-$ ,  $H_d^0$ ,  $H_u^0$ ,  $H_u^+$ ) form: a charged pair  $H^\pm$ , two CP-even neutral scalars  $h^0$ ,  $H^0$  and a CP-odd  $A^0$ .

Only for certain ranges of the parameters the particle spectrum will resemble a 'double-SM'.



## MSSM — Parameter count

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- 3 couplings  $g_i$ , one vacuum angle  $\theta_{\text{QCD}}$  (4 parameters)
- 3 (complex) gaugino masses  $M_i$  (6 parameters)
- 2 Higgs mass parameters  $v, \beta$  (2 parameters)
- 2 (complex) Higgs/ino mass parameters  $\mu, B$  (4 parameters)
- 5 hermitian scalar mass matrices  $M_{\tilde{F}}^2$  (5x9 parameters)
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The full Minimal Supersymmetric Standard Model has 124 free parameters<sup>3</sup> (MSSM-124).

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<sup>3</sup>Consisting of 3 couplings, 37 real masses, 39 mixing angles and 45 CP-violating phases.

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