The Minimally Supersymmetric Standard Model

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Outline

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Standard Model — The Basics

The gauge group of the Standard Model (SM) is

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

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The SM fields transform in representations of this group:

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

$$s = \frac{1}{2}: \quad \underset{\ni q_L}{(\mathbf{3}, \mathbf{2})_{\frac{1}{6}}} \oplus \underset{\ni (d_R)^c}{(\bar{\mathbf{3}}, \mathbf{1})_{\frac{1}{3}}} \oplus \underset{\ni (u_R)^c}{(\bar{\mathbf{3}}, \mathbf{1})_{-\frac{2}{3}}} \oplus \underset{\ni \ell_L}{(\mathbf{1}, \mathbf{2})_{-\frac{1}{2}}} \oplus \underset{\ni (e_R)^c}{(\mathbf{1}, \mathbf{1})_{1}} \tag{3}$$

$$s = 1: \quad \underset{\ni A^a_\mu}{(\mathbf{8}, \mathbf{1})_0} \oplus \underset{\ni W^k_\mu}{(\mathbf{1}, \mathbf{3})_0} \oplus \underset{\ni B_\mu}{(\mathbf{1}, \mathbf{1})_0}. \tag{4}$$

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 $(\psi_R)^c = \begin{pmatrix} 0 \\ \overline{\psi}^{\dot{\alpha}} \end{pmatrix}^c = \begin{pmatrix} \psi_\alpha \\ 0 \end{pmatrix}$.

The $\mathrm{SU}(2)$-doublets are written as:

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

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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:

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

$$\supset \frac{\theta_{\mathrm{QCD}}}{16\pi^2 g_{\mathrm{s}}^2} \epsilon^{\mu\nu\rho\sigma} \operatorname{tr}\left[F^{(3)}_{\mu\nu} F^{(3)}_{\rho\sigma}\right] . \tag{6}$$

Kinetic terms for the fermions are constructed with the covariant derivative

$$\mathcal{L}_{\text{kin}} \supset \overline{\psi}_i \mathrm{i} \not{D} \psi_i \tag{7}$$

$$D_\mu = \partial_\mu - \mathrm{i} q A^k_\mu \mathcal{R}(T_k) \tag{8}$$

Standard Model — Higgs sector

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

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

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

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

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For our three types of massive fermions (electron, up-quark, down-quark) the corresponding singlets look like:[1]

$$\lambda^{u}\left[\overline{q}_{L}\tilde{\phi}\,u_{R}\right]_{\mathbf{1}} \qquad \lambda^{d}\left[\overline{q}_{L}\phi d_{R}\right]_{\mathbf{1}} \qquad \lambda^{e}\left[\overline{\ell}_{L}\phi e_{R}\right]_{\mathbf{1}}. \tag{10}$$

[1] Careful, since $\tilde{\phi} = \epsilon\phi^{*}$ to account for the u-type quarks.

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Furthermore, the SM consists of three generations of fermions thus promoting the λ^ψ to complex 3x3 matrices λ^e_{mn}, λ^d_{mn} and λ^u_{mn}. The λ^f_{mn} can be diagonalised via bi-unitary transformations:

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

[1] Careful, since $\tilde{\phi} = \epsilon \phi^*$ to account for the u-type quarks.

Standard Model — Parameter count

Count parameters and gauge redundancies:

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

[2] 15 real parameters, 3 mixing angles, 1 CP-violating phase.

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	$\tilde{B}$	$(\mathbf{1},\mathbf{1})_0$
$\hat{L}$	$(\tilde{\nu}_e, \tilde{e})$	(ν_L, e_L)	$(\mathbf{1},\mathbf{2})_{-\frac{1}{2}}$
$\hat{E}^c$	$\tilde{e}^c_R$	e^c_R	$(\mathbf{1},\mathbf{1})_1$
$\hat{Q}$	$\left(\tilde{u}_L, \tilde{d}_L\right)$	(u_L, d_L)	$(\mathbf{3},\mathbf{1})_{\frac{1}{6}}$
$\hat{U}^c$	$\tilde{u}^c_R$	u^c_R	$(\mathbf{3},\mathbf{1})_{-\frac{2}{3}}$
$\hat{D}^c$	$\tilde{d}^c_R$	d^c_R	$(\mathbf{3},\mathbf{1})_{\frac{1}{3}}$
$\hat{H}_u$	(H^+_u, H^0_u)	$\left(\tilde{H}^+_u, \tilde{H}^0_u\right)$	$(\mathbf{1},\mathbf{2})_{\frac{1}{2}}$
$\hat{H}_d$	(H^0_d, H^-_d)	$\left(\tilde{H}^0_d, \tilde{H}^-_d\right)$	$(\mathbf{1},\mathbf{2})_{-\frac{1}{2}}$

MSSM — SUSY terms

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

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

The kinetic terms for the fields read:

$$\mathcal{L}^{\mathrm{MSSM}}_{K} \supset \int \mathrm{d}^2\theta \mathrm{d}^2\bar{\theta}\left[\hat{\Phi}^{\dagger}_{\ i} e^{2V_i}\hat{\Phi}_{\ i}\right]_{\mathbf{1}} \tag{13}$$

$$V_i = \hat{V}^{\ a}_{8}\mathcal{R}_i(T_a) + \hat{V}^{\ k}\mathcal{R}_i(T_k) + Y_i\hat{V}^{\ \prime}. \tag{14}$$

MSSM — Superpotential

The superpotential term is simply:

$$\mathcal{L}_W^{\mathrm{MSSM}} = \int \mathrm{d}^2\theta \, W + \mathrm{h.c.} \tag{15}$$

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:

$$\begin{aligned} W = &\lambda_d \left[H_d Q U\right]_{\mathbf{1}} + \lambda_d \left[H_d L E\right]_{\mathbf{1}} - \lambda_u \left[H_u Q U\right]_{\mathbf{1}} + \mu \left[H_u H_d\right]_{\mathbf{1}} \\ &+ a \left[\hat{L}\, \hat{H}_u\right]_{\mathbf{1}} + b \left[\hat{Q}\, \hat{L}\, \hat{D}\right]_{\mathbf{1}} + c \left[\hat{U}\, \hat{U}\, \hat{D}\right]_{\mathbf{1}} + d \left[\hat{L}\, \hat{L}\, \hat{E}\right]_{\mathbf{1}} . \end{aligned} \tag{16}$$

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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

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

we can get rid of them. Beware! This is not obligatory!
R-conservation implies the existance of a lightest supersymmetric particle (LSP) thus providing us with a dark matter candidate.

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We could use matter parity

$$P_{\mathrm{m}} = (-1)^{3(B-L)}, \tag{17}$$

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

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

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.

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

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The two doublets acquire separate VEVs:

$$\left\langle H_f^0 \right\rangle = v_f, \tag{20}$$

related to the previous v via:

$$\sqrt{v_u^2 + v_d^2} = v, \tag{21}$$

by convention the angle β is defined as

$$\tan\beta = \frac{v_u}{v_d}. \tag{22}$$

MSSM — Mixing in the particle spectrum

The SM particle spectrum looks like:

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

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e & \mu & \tau & H_d^- & H_d^0 \\
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\nu_e & \nu_\mu & \nu_\tau & A^0 & H^\pm
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The MSSM particle spectrum looks like:

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

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\end{array}
$$

The MSSM particle spectrum[3] looks like:

$$
\begin{array}{cccccccc}
\tilde{q}_1 & \tilde{q}_2 & \tilde{q}_3 & \tilde{q}_4 & \tilde{q}_5 & \tilde{q}_6 & \tilde{\chi}^\pm_1 & \tilde{\chi}^\pm_2 \\
\tilde{q}'_1 & \tilde{q}'_2 & \tilde{q}'_3 & \tilde{q}'_4 & \tilde{q}'_5 & \tilde{q}'_6 & \tilde{g} & \\
 & & & & & & & \\
\tilde{\ell}_1 & \tilde{\ell}_2 & \tilde{\ell}_3 & \tilde{\ell}_4 & \tilde{\ell}_5 & \tilde{\ell}_6 & \tilde{\chi}^0_1 & \tilde{\chi}^0_2 \\
\tilde{\nu}_1 & & \tilde{\nu}_2 & & \tilde{\nu}_3 & & \tilde{\chi}^0_3 & \tilde{\chi}^0_4
\end{array}
$$

[3] Worst case scenario.

MSSM — Mixing in the particle spectrum

Summary of mixed states:

- The charged gauginos ($\tilde{W}^{\pm}$, $\tilde{H}_u^{+}$, $\tilde{H}_d^{-}$) form the charginos $\tilde{\chi}_i^{\pm}$.
- The neutral gauginos ($\tilde{B}$, $\tilde{W}^{0}$, $\tilde{H}_u^{0}$, $\tilde{H}_d^{0}$) 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 θ_{QCD} (4 parameters)
- 3 (complex) gaugino masses M_i (6 parameters)
- 2 Higgs mass parameters v, β (2 parameters)
- 2 (complex) Higgs/ino mass parameters μ, B (4 parameters)
- 5 hermitian scalar mass matrices $M^2_{\tilde{F}}$ (5x9 parameters)
- 3 mass matrices λ^f (3x18 parameters)
- 3 trilinear couplings T_F (3x18 parameters)

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The full Minimal Supersymmetric Standard Model has 124 free parameters[3] (MSSM-124).

[3]Consisting of 3 couplings, 37 real masses, 39 mixing angles and 45 CP-violating phases.

References

[1] DJH Chung, LL Everett, GL Kane, SF King, J Lykken, and Lian-Tao Wang.
The soft supersymmetry-breaking Lagrangian: Theory and applications.
Physics Reports 407.1-3 (2005), pp. 1–203.

[2] Patrick Draper and Heidi Rzehak.
A review of Higgs mass calculations in supersymmetric models.
Physics Reports 619 (2016), pp. 1–24.

[3] Howard E Haber.
The status of the minimal supersymmetric standard model and beyond.
Nuclear Physics B-Proceedings Supplements 62.1-3 (1998), pp. 469–484.

[4] Arthur Hebecker.
Lectures on Beyond the Standard Model and the String Theory Landscape.
Heidelberg University, 2020.

[5] Luis E. Ibanez and Angel M. Uranga.
String Theory and Particle Physics: An Introduction to String Phenomenology.
Cambridge University Press, 2012.

[6] Joseph D. Lykken.
Introduction to Supersymmetry.
Theoretical Advanced Study Institute in Elementary Particle Physics (TASI 96): Fields, Strings, and Duality. 1996, pp. 85–153.

[7] Stephen P. Martin.
A Supersymmetry Primer.
Advanced Series on Directions in High Energy Physics (1998), pp. 1–98.

[8] Hans - Peter Nilles.
Supersymmetry, Supergravity and Particle Physics.
Phys. Rept. 110 (1984), pp. 1–162.

[9] Michael E. Peskin.
Supersymmetry in Elementary Particle Physics.
Theoretical Advanced Study Institute in Elementary Particle Physics: Exploring New Frontiers Using Colliders and Neutrinos. 2008, pp. 609–704.

[10] Adrian Signer.
ABC of SUSY.
Journal of Physics G: Nuclear and Particle Physics 36.7 (2009), p. 073002.

[11] Julius Wess and Jonathan A. Bagger.
Supersymmetry and Supergravity.
Princeton University Press, 1992.