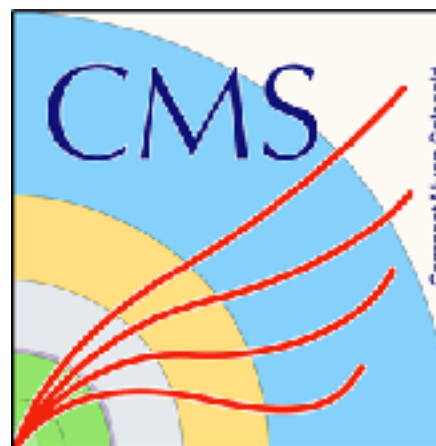


Introduction to Supersymmetry

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LABORATÓRIO DE INSTRUMENTAÇÃO
E FÍSICA EXPERIMENTAL DE PARTÍCULAS



Outline

- Standard Model Refresher
- Supersymmetry Motivations:
 - Hierarchy Problem
 - Dark Matter
 - Coupling Constants
- The Supersymmetry Lagrangian

Standard Model Lagrangian

- The Standard Model construction:
 - Choice of symmetries respected by the model, i.e. specify the gauge group G :

$$U(1) \times SU(2) \times SU(3)$$
 - Bosons are associated to vector fields of the gauge group
 - Matter fields to represent Fermions are chosen
 - Scalar fields are added \rightarrow Give mass to some bosons
 - Write the most general Lagrangian invariant under G which couples all these fields:

$$\mathcal{L} = \mathcal{L}_{\text{free+interaction}} + \mathcal{L}_{\text{Gauge}} + \mathcal{L}_{\text{Higgs}} + \mathcal{L}_{\text{Yukawa}}$$

Further Reading:

- Introduction to the Standard Model and Electroweak Physics - <http://arxiv.org/abs/0901.0241>
- Standard Model: An Introduction - <http://arxiv.org/abs/hep-ph/0001283>

Standard Model Lagrangian

$$\mathcal{L} = \mathcal{L}_{\text{free+interaction}} + \mathcal{L}_{\text{Gauge}} + \mathcal{L}_{\text{Higgs}} + \mathcal{L}_{\text{Yukawa}}$$

- The “free+interaction” term corresponds to the gauge invariant Dirac Lagrangian, it describes the free fermions and their interactions with the gauge fields:

$$\mathcal{L}_{\text{free+interaction}} = \sum_{i=1}^3 \left[\bar{\Psi}_L^i i\gamma^\mu D_\mu \Psi_L^i + \bar{R}_i i\gamma^\mu D_\mu R_i + \bar{Q}_L^i i\gamma^\mu D_\mu Q_L^i + \bar{U}_R^i i\gamma^\mu D_\mu U_R^i + \bar{D}_R^i i\gamma^\mu D_\mu D_R^i \right]$$

- Covariant derivatives are determined from the transformation properties of the fields:

$$\begin{aligned} D_\mu \Psi_L^i &= \left(\partial_\mu - ig_w \frac{\vec{\tau}}{2} \cdot \vec{W}_\mu + i \frac{g'}{2} B_\mu \right) \Psi_L^i \\ D_\mu R_i &= \left(\partial_\mu + ig' B_\mu \right) R_i \\ D_\mu Q_L^i &= \left(\partial_\mu - ig_s \vec{t} \cdot \vec{G}_\mu - ig_w \frac{\vec{\tau}}{2} \cdot \vec{W}_\mu - i \frac{g'}{6} B_\mu \right) Q_L^i \\ D_\mu U_R^i &= \left(\partial_\mu - ig_s \vec{t} \cdot \vec{G}_\mu - i \frac{2}{3} g' B_\mu \right) U_R^i \\ D_\mu D_R^i &= \left(\partial_\mu - ig_s \vec{t} \cdot \vec{G}_\mu + i \frac{g'}{3} B_\mu \right) D_R^i \end{aligned}$$

$g', g_w, g_s \rightarrow$ weak hypercharge, weak isospin and strong couplings

$B_{\mu\nu}, \vec{W}_{\mu\nu}$ and $\vec{G}_{\mu\nu} \rightarrow$ weak hypercharge, weak isospin and strong fields

Dirac spinors:

$\Psi_L^i \rightarrow$ Left-handed lepton and neutrino doublet of SU(2)

$R_i \rightarrow$ Right-handed lepton singlet of SU(2)

$Q_L^i \rightarrow$ Left-handed up and down quark doublet of SU(2)

$U_R^i \rightarrow$ Right-handed up quark singlet of SU(2)

$D_R^i \rightarrow$ Right-handed down quark singlet of SU(2)

Standard Model Lagrangian

$$\mathcal{L} = \mathcal{L}_{\text{free+interaction}} + \mathcal{L}_{\text{Gauge}} + \mathcal{L}_{\text{Higgs}} + \mathcal{L}_{\text{Yukawa}}$$

- The “Gauge” term corresponds to the kinetic energy for the vector fields, i.e. the gauge fields. It describes the free bosons and their self-interactions:

$$\mathcal{L}_{\text{Gauge}} = -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} \vec{W}_{\mu\nu} \cdot \vec{W}^{\mu\nu} - \frac{1}{4} \vec{G}_{\mu\nu} \cdot \vec{G}^{\mu\nu}$$

Weak Hypercharge Field
Weak Isospin Field
Strong Field

- Non-abelian structure of SU(2) and SU(3) groups gives rise to the self-interacting term (the third one in the equations below):

$$B_{\mu\nu}(x) = \partial_\mu B_\nu(x) - \partial_\nu B_\mu(x)$$

$$\vec{W}_{\mu\nu}(x) = \partial_\mu \vec{W}_\nu(x) - \partial_\nu \vec{W}_\mu(x) + ig_w \left(\frac{\vec{W}_\mu(x) \vec{W}_\nu(x) - \vec{W}_\nu(x) \vec{W}_\mu(x)}{2} \right)$$

$$\vec{G}_{\mu\nu}(x) = \partial_\mu \vec{G}_\nu(x) - \partial_\nu \vec{G}_\mu(x) + ig_s \left(\vec{G}_\mu(x) \vec{G}_\nu(x) - \vec{G}_\nu(x) \vec{G}_\mu(x) \right)$$

Standard Model Lagrangian

$$\mathcal{L} = \mathcal{L}_{\text{free+interaction}} + \mathcal{L}_{\text{Gauge}} + \mathcal{L}_{\text{Higgs}} + \mathcal{L}_{\text{Yukawa}}$$

- The “Higgs” term introduces the Higgs potential to the model. It describes the dynamics of the Higgs field and interactions with the gauge bosons:

$$\mathcal{L}_{\text{Higgs}} = |D_{\mu}\Phi|^2 - V(\Phi)$$

$$V(\Phi) = \mu^2\Phi^{\dagger}\Phi + \lambda(\Phi^{\dagger}\Phi)^2$$

- Covariant derivative is determined from the transformation properties of the field:

$$D_{\mu}\Phi = \left(\partial_{\mu} - ig_w \frac{\vec{\tau}}{2} \cdot \vec{W}_{\mu} - i \frac{g'}{2} B_{\mu} \right) \Phi$$

- Three of the four U(1)xSU(2) vector gauge bosons must acquire mass through electroweak symmetry breaking. At least 4 scalar fields are required and are placed in a complex doublet under SU(2):

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

Standard Model Lagrangian

$$\mathcal{L} = \mathcal{L}_{\text{free+interaction}} + \mathcal{L}_{\text{Gauge}} + \mathcal{L}_{\text{Higgs}} + \mathcal{L}_{\text{Yukawa}}$$

- The “Yukawa” term describes the coupling between the scalar field and the fermion fields. Thus, it describes the interactions between the fermions and the scalar bosons:

$$-\mathcal{L}_{\text{Yukawa}} = \sum_{i=1}^3 \left[G_i \left(\bar{\Psi}_L^i R_i \Phi + h.c. \right) \right] + \sum_{i=1}^3 \left[G_u^i \left(\bar{Q}_L^i U_R^i \tilde{\Phi} + h.c. \right) \right] \\ + \sum_{i,j=1}^3 \left[\left(\bar{Q}_L^i G_d^{ij} D_R^j \Phi + h.c. \right) \right]$$

- Note that up and down type quarks can not be simultaneously diagonalised, by convention, the off diagonal terms are attributed to the down type quarks
- After Electroweak symmetry breaking, this term confers mass to the fermions

Standard Model Electroweak Symmetry Breaking

$$\mathcal{L} = \mathcal{L}_{\text{free+interaction}} + \mathcal{L}_{\text{Gauge}} + \mathcal{L}_{\text{Higgs}} + \mathcal{L}_{\text{Yukawa}}$$

- Note that all fields in the SM Lagrangian appear to be massless
- Choosing the μ^2 parameter in the Higgs field to be negative triggers symmetry breaking
- The minimum of the Higgs potential is at a distance v from the origin, defined with: $v^2 = -\mu^2/\lambda$
- The field is translated and the Lagrangian is expanded around the minimum:

$$\Phi \rightarrow \Phi + \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

- New terms appear in the Lagrangian, of particular interest are the mass terms:

$$m_H = \sqrt{-2\mu^2} = \sqrt{2\lambda v^2}$$

$$m_\ell = \frac{1}{\sqrt{2}} G_\ell v \quad \text{with } \ell = e, \mu,$$

$$m_q = G_u^q v \quad \text{with } q = u, c, t$$

Diagonalization of the down-type quark mass terms gives rise to the CKM matrix

$$\longrightarrow m_q = G_d^{ij} v$$

$$\begin{aligned} Z_\mu &= \cos \theta_W B_\mu - \sin \theta_W W_\mu^3 & \text{with } \tan \theta_W &= \frac{g'}{g_w} \\ A_\mu &= \cos \theta_W B_\mu + \sin \theta_W W_\mu^3 \end{aligned}$$

$$m_Z = \frac{v\sqrt{g_w^2 + g'^2}}{2} = \frac{m_W}{\cos \theta_W}$$

$$m_A = 0$$

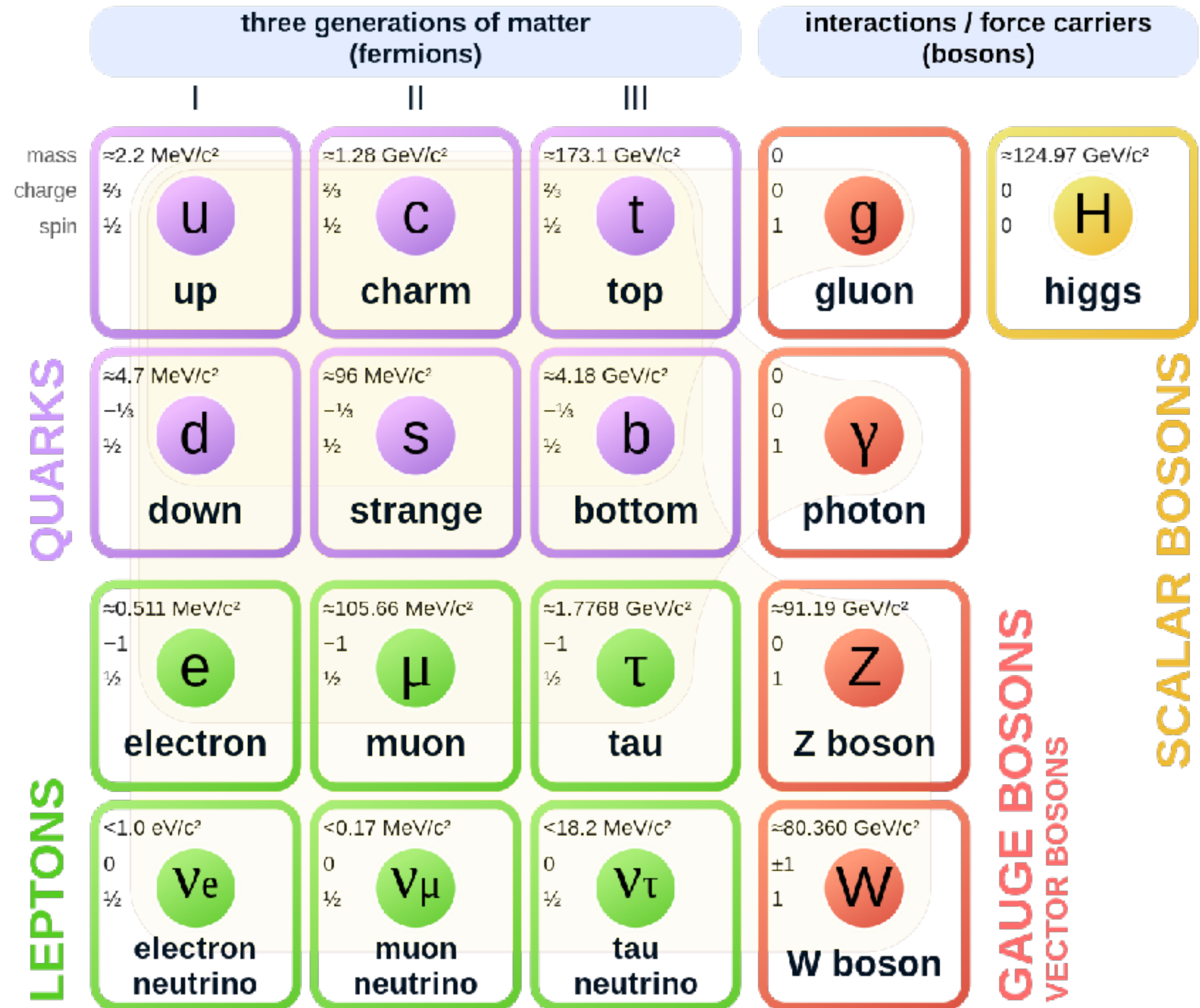
$$m_W = \frac{vg_w}{2}$$

Standard Model Lagrangian

$$\mathcal{L} = \mathcal{L}_{\text{free+interaction}} + \mathcal{L}_{\text{Gauge}} + \mathcal{L}_{\text{Higgs}} + \mathcal{L}_{\text{Yukawa}}$$

- The Classical SM Lagrangian has 19 free parameters:
 - The three gauge coupling constants: g', g_w, g_s
 - The two parameters of the Higgs potential: λ and μ^2
 - Three Yukawa coupling constants for the three lepton families: G_ℓ with $\ell = e, \mu, \tau$
 - Six Yukawa coupling constants for the three quark families: G_u^q with $q = u, c, t$
 G_d^q with $q = d, s, b$
 - Four parameters of the CKM matrix, three angles and a phase
 - QCD theta angle

Particle content of Standard Model



Taken from [Wikipedia](#)

Gauge Fields – Spin 1

Symbol	Associated Charge	Group	Coupling	Representation
B	Weak Hypercharge	$U(1)$	g'	$(1, 1, 0)$
W^i	Weak Isospin	$SU(2)$	g_w	$(1, 3, 0)$
G^i	Colour	$SU(3)$	g_s	$(8, 1, 0)$

Fermion Fields – Spin $\frac{1}{2}$

Symbol	Name	Representation
Q_L^i	Left-handed quark	$(3, 2, \frac{1}{3})$
U_R^{iC}	Left-handed antiquark (up)	$(\bar{3}, 1, -\frac{4}{3})$
D_R^{iC}	Left-handed antiquark (down)	$(\bar{3}, 1, \frac{2}{3})$
Ψ_L^i	Left-handed lepton	$(1, 2, -1)$
R_i^C	Left-handed antilepton	$(1, 1, 2)$

Higgs Fields – Spin 0

Symbol	Name	Representation
Φ	Higgs boson	$(1, 2, 1)$

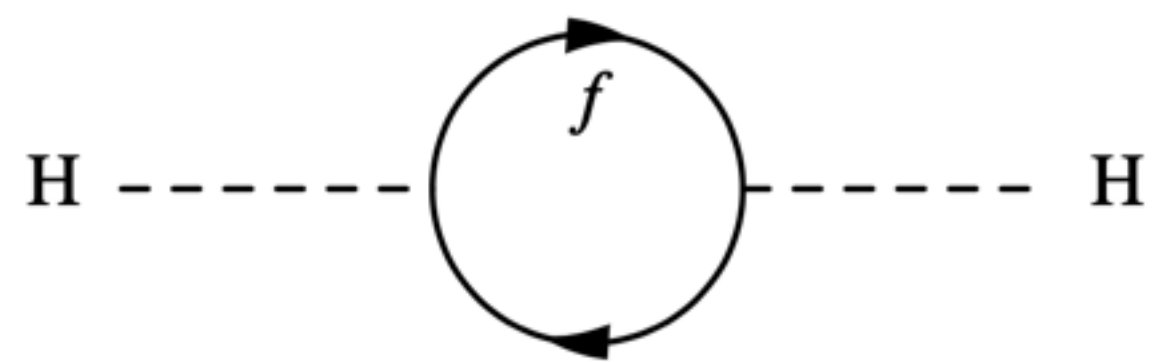
The discovery of the Higgs boson in 2012 completes the picture but...
(All SM parameters are now known)

Shortcomings of the Standard Model

- Even though the SM accurately describes phenomena over several orders of magnitude, it is not a complete theory:
 - Neutrino Oscillations → Neutrinos have mass - Possible in the SM, but the exact mechanism is unknown
 - Matter/Anti-matter asymmetry observed in the universe - Complex CKM phase introduces CP violation, but not enough to explain observations
 - Observed matter only ~5% of the mass-energy content of the universe; Dark Matter ~26% and the rest is Dark Energy
 - Gravity not included

Hierarchy Problem

- The Electroweak scale (~ 250 GeV) is much smaller than the Planck scale. Why such a large difference?
- In an effective theory up to a scale Δ , the one loop corrections to the Higgs mass would be:



(a) Fermion loop



(b) Scalar loop

$$M_h^2 \sim M_{h0}^2 + \frac{g_F^2}{4\pi^2} (\Delta^2 + m_F^2) - \frac{g_S^2}{4\pi^2} (\Delta^2 + m_S^2)$$

- The quadratic contributions diverge with the cutoff scale (Δ) of the effective theory
- At the Planck scale it is expected that gravity will become comparable to the other forces and a quantum theory of gravity would be needed, so the SM can be viewed as an effective theory at the electroweak scale.
- At the Planck scale an incredible fine tuning would be necessary to keep the Higgs mass at 125 GeV
- In other words, why is the Higgs mass unnaturally smaller than its natural theoretical value

Hierarchy Problem

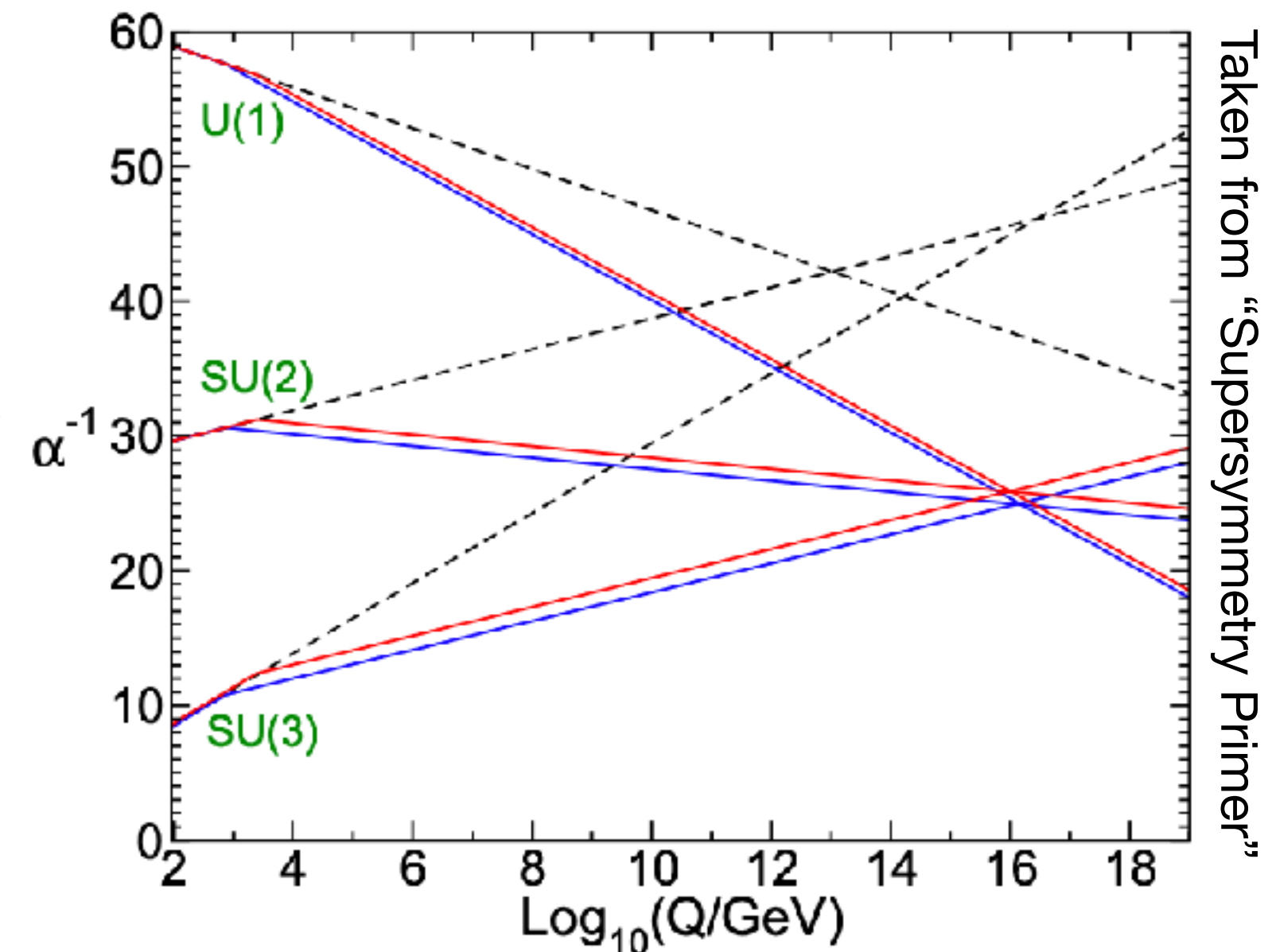
- Formula of the one loop corrections gives a hint to a possible solution:

$$M_h^2 \sim M_{h0}^2 + \frac{g_F^2}{4\pi^2} (\Delta^2 + m_F^2) - \frac{g_S^2}{4\pi^2} (\Delta^2 + m_S^2)$$

- If the fermion and scalar had the same coupling, the components that depend on the cutoff scale would cancel each other due to the opposite sign
→ One of the main motivations for Supersymmetry
- In supersymmetry, there should be a one-to-one correspondence between bosonic fields and fermionic fields
- Known particles are not good candidates for pairings since they do not share quantum numbers, thus do not have the same couplings

Supersymmetry: Other Motivations

- Phenomenology:
 - Dark Matter: In many Supersymmetric Theories, the lightest supersymmetric particle is stable, neutral and a weakly interacting massive particle, thus a good candidate for Dark Matter
- Gauge coupling unification:
 - Coupling constants scale with energy
 - All 3 can meet at a single point in supersymmetry
- Theory:
 - Supersymmetry is the most natural candidate to describe in a unified way not only all known interactions but also all matter and radiation together
 - String theory can only be consistent if it is supersymmetric



Taken from "Supersymmetry Primer"

Supersymmetry

- Construction of the supersymmetric Lagrangian follows same recipe as the SM Lagrangian:

- Choose the gauge group G of the symmetries respected by the model:

$$U(1) \times SU(2) \times SU(3)$$

- Group SM fields into superfields, 2 SM fields can not be grouped in a single superfield since they do not share quantum numbers:

- Bosons are associated to vector superfields of the gauge group
- Chiral superfields to represent fermions
- Additional chiral superfields to add the scalars necessary for electroweak symmetry breaking and generating the masses of the required bosons

- Write the most general Lagrangian invariant under G which couples all these fields:

$$\mathcal{L}_{\text{MSSM}} = \mathcal{L}_{KE} + \mathcal{L}_{\text{interaction}} + \mathcal{L}_W$$

Further reading:

- Lectures on Supersymmetry : <https://web.archive.org/web/20240202053316/https://people.sissa.it/~bertmat/susycourse.pdf>
- Supersymmetry Primer: <https://arxiv.org/abs/hep-ph/9709356>
- Susy and Such: <https://arxiv.org/abs/hep-ph/9612229>

Supersymmetry Field Content

Chiral Superfields		
Superfield	Representation	Field Composition
\widehat{Q}_L^i	$(\mathbf{3}, \mathbf{2}, \frac{1}{3})$	Q_L^i, \widetilde{Q}_L^i
\widehat{U}_R^{iC}	$(\bar{\mathbf{3}}, \mathbf{1}, -\frac{4}{3})$	$U_R^{iC}, \widetilde{U}_R^{iC}$
\widehat{D}_R^{iC}	$(\bar{\mathbf{3}}, \mathbf{1}, \frac{2}{3})$	$D_R^{iC}, \widetilde{D}_R^{iC}$
$\widehat{\Psi}_L^i$	$(\mathbf{1}, \mathbf{2}, -1)$	$\Psi_L^i, \widetilde{\Psi}_L^i$
\widehat{R}_i^C	$(\mathbf{1}, \mathbf{1}, 2)$	R_i^C, \widetilde{R}_i^C
$\widehat{\Phi}_1$	$(\mathbf{1}, \mathbf{2}, 1)$	$\Phi_1, \widetilde{\Phi}_1$
$\widehat{\Phi}_2$	$(\mathbf{1}, \mathbf{2}, -1)$	$\Phi_2, \widetilde{\Phi}_2$
Vector Superfields		
Superfield	Representation	Field Composition
\widehat{B}	$(\mathbf{1}, \mathbf{1}, 0)$	B, \widetilde{B}
\widehat{W}^i	$(\mathbf{1}, \mathbf{3}, 0)$	W^i, \widetilde{W}^i
\widehat{G}^i	$(\mathbf{8}, \mathbf{1}, 0)$	G^i, \widetilde{G}^i

Particle Names

quark, squark

lepton, slepton

higgs, higgsino

B boson, bino

W boson, wino

gluon, gluino

Higgs Superfields

- The Higgs field is the scalar part of a chiral superfield, however there is a fermion superpartner, an $SU(2)$ doublet
- The fermion superpartner contributes to the triangle anomalies, which would be uncancelled
- Easiest way to remove the anomaly is by introducing a second higgs superfield with opposite weak hypercharge
- Gives supersymmetry 2 Higgs superfields and a very rich Higgs sector

Supersymmetry Lagrangian

$$\mathcal{L}_{\text{MSSM}} = \mathcal{L}_{KE} + \mathcal{L}_{\text{interaction}} + \mathcal{L}_W$$

- The “Kinetic Energy” term is summed over all the superfields (chiral and vector) and is analogous to the “free+interaction” term, “Gauge” term and the first part of the “Higgs” term from the SM Lagrangian

$$\begin{aligned} \mathcal{L}_{KE} = & \sum_i \left\{ (D_\mu S_i^*) (D^\mu S_i) + i\bar{\psi}_i \gamma^\mu D_\mu \psi_i \right\} \longleftarrow \text{Chiral Superfields} \\ & + \sum_A \left\{ -\frac{1}{4} F_{\mu\nu}^A F^{\mu\nu A} + \frac{i}{2} \bar{\lambda}_A \gamma^\mu D_\mu \lambda_A \right\} \longleftarrow \text{Vector Superfields} \end{aligned}$$

- Consequently, this term describes all free particles in supersymmetry as well as the interactions with the gauge bosons
- This term contains most of the SM, only missing electroweak symmetry breaking terms from Higgs and the Yukawa terms

Supersymmetry Lagrangian

$$\mathcal{L}_{\text{MSSM}} = \mathcal{L}_{KE} + \mathcal{L}_{\text{interaction}} + \mathcal{L}_W$$

- The “Interaction” term describes the interactions between the chiral superfields and the gauginos as well as the quartic interactions of the scalars:

$$\mathcal{L}_{\text{interaction}} = -\sqrt{2} \sum_{i,A} g_A [S_i^* T^A \bar{\psi}_i \lambda_A + h.c.] - \frac{1}{2} \sum_A \left(\sum_i g_A S_i^* T^A S_i \right)^2$$

Supersymmetry Lagrangian

$$\mathcal{L}_{\text{MSSM}} = \mathcal{L}_{KE} + \mathcal{L}_{\text{interaction}} + \mathcal{L}_W$$

- The “W” term results from the W superpotential. This superpotential is only a function of the chiral superfields and contains terms with 2 and 3 fields. This langrangian term contains the yukawa couplings and scalar field of the SM:

$$\mathcal{L}_W = - \sum_i \left| \frac{\partial W}{\partial z_i} \right|^2 - \frac{1}{2} \sum_{i,j} \left[\bar{\psi}_i \frac{\partial^2 W}{\partial z_i \partial z_j} \psi_j + h.c. \right]$$

- Most general superpotential, for a single family, is (in a more general approach, λ_i could be matrices):

$$W = \epsilon_{ij} \mu \widehat{\Phi}_1^i \widehat{\Phi}_2^j + \epsilon_{ij} \left[\lambda_L \widehat{\Phi}_1^i \widehat{\Psi}_L^j \widehat{R}^C + \lambda_D \widehat{\Phi}_1^i \widehat{Q}_L^j \widehat{D}_R^C + \lambda_U \widehat{\Phi}_2^j \widehat{Q}_L^i \widehat{U}_R^C \right] \\ + \epsilon_{ij} \left[\lambda_1 \widehat{\Psi}_L^i \widehat{\Psi}_L^j \widehat{R}^C + \lambda_2 \widehat{\Psi}_L^i \widehat{Q}_L^j \widehat{D}_R^C \right] + \lambda_3 \widehat{U}_R^C \widehat{D}_R^C \widehat{D}_R^C$$

- The first term, $\mu \widehat{\Phi}_1 \widehat{\Phi}_2$, gives rise to the Higgs mass term and thus electroweak symmetry breaking
- The terms proportional to λ_L , λ_D and λ_U give rise to the Yukawa terms from the SM
- The terms proportional to λ_1 , λ_2 and λ_3 are problematic and give rise to lepton and baryon number violation → One way to handle is by introduction of R-parity

R-Parity

- R-Parity is defined as a multiplicative quantum number where all particles of the SM have $R=+1$ and all their SUSY partners have $R=-1$; it can also be defined as:

$$R \equiv (-1)^{3(B-L)+s}$$

- Consequences:
 - Number of SUSY particles is conserved modulo 2
 - SUSY particles are always pair produced from SM particles (i.e. in colliders)
 - SUSY particle must decay to at least one other SUSY particle
 - There will be a stable lightest supersymmetric particle

Supersymmetry Lagrangian

- The Lagrangian presented so far has all the characteristics necessary for a supersymmetric gauge theory which exhibits spontaneous electroweak symmetry breaking
- However, in the current formulation, the supersymmetric particles exhibit the same mass as their partners → Supersymmetry would have already been discovered
- Observations show this is not the case, in fact no supersymmetric particle has yet been observed → Supersymmetry must be a broken symmetry
 - Breaking mechanism is unknown, but several candidates, such as mSUGRA
 - For now, will use the Minimal Supersymmetric Standard Model (MSSM) approach; use an effective Lagrangian with no assumption on the breaking mechanism itself

MSSM Lagrangian

- Introduce a “Soft” supersymmetry breaking term into the Lagrangian such as with mass terms for the scalar members of the chiral superfields and for the gaugino members of the vector superfields

$$\mathcal{L}_{\text{MSSM}} = \mathcal{L}_{KE} + \mathcal{L}_{\text{interaction}} + \mathcal{L}_W + \mathcal{L}_{\text{soft}}$$

- Termed soft because they break the supersymmetry but not so much as to re-introduce the quadratic divergence which motivated Supersymmetry to start

$$\begin{aligned} -\mathcal{L}_{\text{soft}} = & m_1^2 |H_1|^2 + m_2^2 |H_2|^2 - B\mu\epsilon_{ij} (H_1^i H_2^j + h.c.) + \tilde{M}_Q^2 \tilde{Q}_L^* \tilde{Q}_L \\ & + \tilde{M}_U^2 \tilde{U}_R^* \tilde{U}_R + \tilde{M}_D^2 \tilde{D}_R^* \tilde{D}_R + \tilde{M}_\Psi^2 \tilde{\Psi}_L^* \tilde{\Psi}_L + \tilde{M}_R^2 \tilde{R}^* \tilde{R} \\ & + \frac{1}{2} \left[M_3 \tilde{G}^i \tilde{G}^i + M_2 \tilde{W}^i \tilde{W}^i + M_1 \tilde{B}^C \tilde{B} \right] + \frac{g}{\sqrt{2}M_W} \epsilon_{ij} \left[\frac{M_D}{\cos\beta} A_D H_1^i \tilde{Q}_L^j \tilde{D}_R^* \right. \\ & \left. + \frac{M_U}{\sin\beta} A_U H_2^j \tilde{Q}_L^i \tilde{U}_R^* + \frac{M_R}{\cos\beta} A_E H_1^i \tilde{\Psi}_L^j \tilde{R}^* + h.c. \right] \end{aligned}$$

- Mass terms for scalars, gauginos
- bi-linear and tri-linear mixing terms
- Each factor may be a matrix mixing families

MSSM Lagrangian

- Total of 124 free parameters:
 - 18 analogous to the SM
 - the rest, mostly introduced by the Soft supersymmetry breaking term

MSSM - Higgs Sector

- The second Higgs field in Supersymmetry lends the model a rich phenomenology in the Higgs sector, similar to a “Two Higgs Doublet Model”
- One of the Higgs couples to down-type quark fields and lepton fields and the other one couples to up-type quark fields
- Of the 8 degrees of freedom, 3 are absorbed to give mass to the W and Z bosons, resulting in 5 physical degrees of freedom which produce 5 bosons: 2 CP-even neutral Higgs bosons (h and H), one CP-odd Higgs boson (A) and 2 charged Higgs bosons

- Each Higgs field has its own VEV:

$$\begin{array}{l} \langle H_1^0 \rangle \equiv v_1 \\ \langle H_2^0 \rangle \equiv v_2 \end{array} \xrightarrow[\text{EWK Symmetry Breaking}]{\quad\quad\quad} M_W^2 = \frac{g^2}{2}(v_1^2 + v_2^2)$$

- Ratio of the two VEV is an important MSSM parameter: $\tan \beta \equiv \frac{v_2}{v_1}$

Additional reading:

- Susy and Such: <https://arxiv.org/abs/hep-ph/9612229>
- [http://dx.doi.org/10.1016/0550-3213\(79\)90225-6](http://dx.doi.org/10.1016/0550-3213(79)90225-6)

MSSM - Sfermion Sector

- There is a complex scalar superpartner field for each chiral state of SM field
- Tri-linear soft SUSY terms allow the complex scalar superpartners to mix when forming the mass eigenstates
- Mixing results in a 6x6 matrix (one for lepton SUSY partners, one for up-type SUSY partners and one for down-type SUSY partners)
- Focussing on the top squark sector, the left- and right-handed top squark mixing is given by:

$$M_{\tilde{t}}^2 = \begin{pmatrix} \tilde{M}_Q^2 + M_T^2 + M_Z^2(\frac{1}{2} - \frac{2}{3} \sin^2 \theta_W) \cos 2\beta & M_T(A_T + \mu \cot \beta) \\ M_T(A_T + \mu \cot \beta) & \tilde{M}_U^2 + M_T^2 + \frac{2}{3} M_Z^2 \sin^2 \theta_W \cos 2\beta \end{pmatrix}$$

- The off-diagonal terms, the mixing effect, are proportional to the mass of the particle → lightest stop is often the lightest squark (similar for sbottom and stau)

MSSM - Chargino Sector

- There are 2 charge 1, spin 1/2 sfermions: wino (partner of charged W boson) and higgsino (partner of the charged Higgs boson)
- Physical mass states are formed from a linear combination of these states and are called charginos

$$M_{\tilde{\chi}^{\pm}} = \begin{pmatrix} M_2 & \sqrt{2}M_W \sin \beta \\ \sqrt{2}M_W \cos \beta & -\mu \end{pmatrix}$$

MSSM - Neutralino Sector

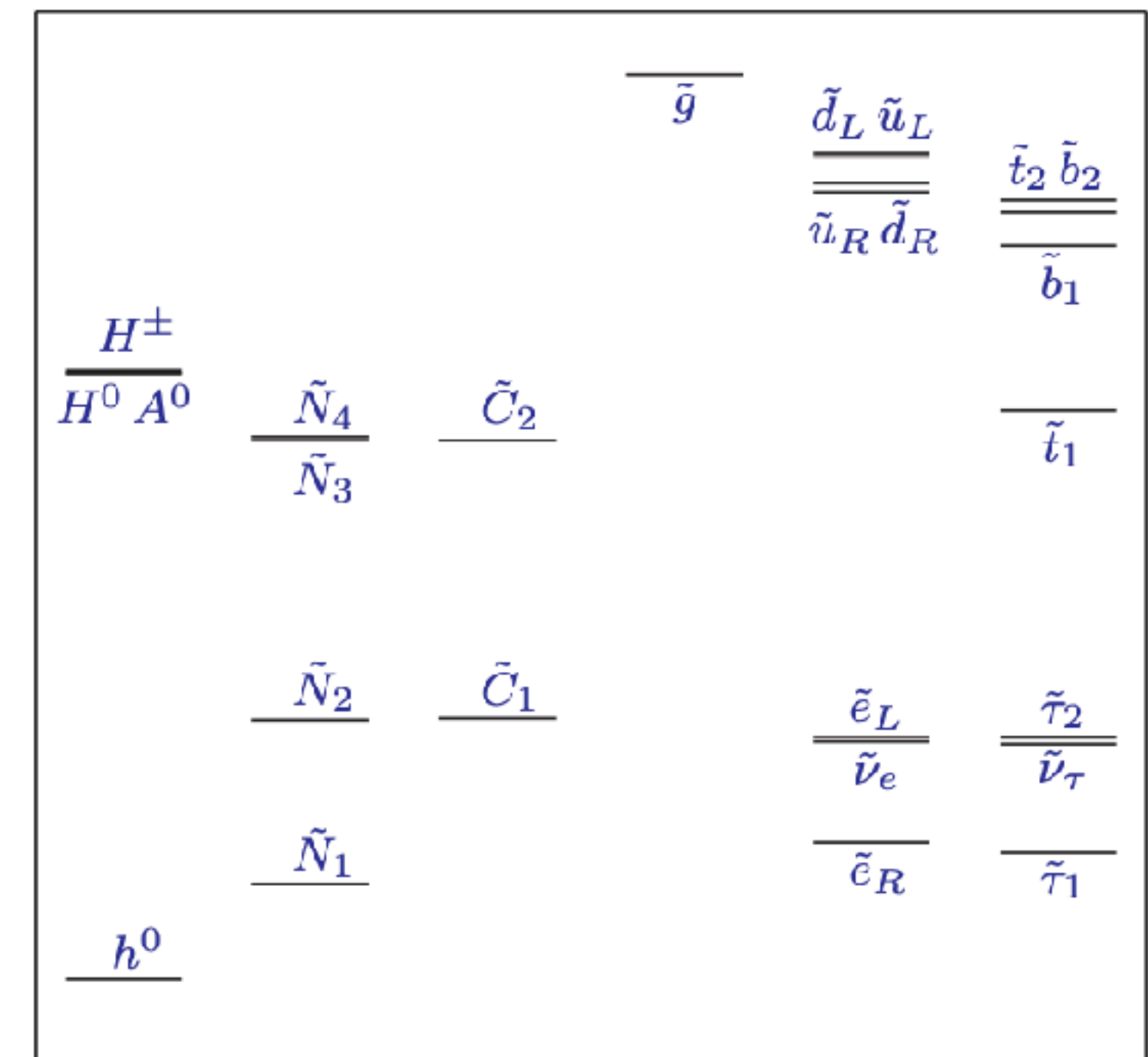
- There are 4 neutral sfermions: Bino (partner of the B boson), wino (partner of the neutral W boson), 2 higgsinos (partners of the neutral higgs bosons)
- Physical mass states are formed from a linear combination of these states and are called neutralinos

$$M_{\tilde{\chi}_i^0} = \begin{pmatrix} M_1 & 0 & -M_Z \cos \beta \sin \theta_W & M_Z \sin \beta \sin \theta_W \\ 0 & M_2 & M_Z \cos \beta \cos \theta_W & -M_Z \sin \beta \cos \theta_W \\ -M_Z \cos \beta \sin \theta_W & M_Z \cos \beta \sin \theta_W & 0 & \mu \\ M_Z \sin \beta \sin \theta_W & -M_Z \sin \beta \cos \theta_W & \mu & 0 \end{pmatrix}$$

- Neutralinos do not necessarily correspond to a photino (partner of the photon) or a zino (partner of the Z boson)
- The lightest neutralino is often assumed to be the lightest supersymmetric particle

Supersymmetry Particle Spectra

- The parameters of the model are chosen, then the supersymmetric particle masses can be computed and the spectra is drawn →
- SuSpect (<http://suspect.in2p3.fr/>) is a tool that can do this process for us
 - User writes an SLHA file describing the Supersymmetry model to use and relevant parameters and provides it to SuSpect
 - SuSpect outputs a more complete SLHA file containing all computed quantities, such as mass states of all the particles
 - SLHA files can be used with MC generators to simulate events, detector responses can be simulated as well. In this way MC samples for a given SUSY scenario can be created



Taken from "Supersymmetry Primer"