Introduction to Supersymmetry

Cristóvão B. da Cruz e Silva

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 → Give mass to some bosons
  - Write the most general Lagrangian invariant under G which couples all these fields: $\mathscr{L} = \mathscr{L}_{\text{free+interaction}} + \mathscr{L}_{\text{Gauge}} + \mathscr{L}_{\text{Higgs}} + \mathscr{L}_{\text{Yukawa}}$

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

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

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

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

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

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

$$D_\mu R_i = \left(\partial_\mu + i g' B_\mu \right) R_i$$

$$D_\mu Q_L^i = \left(\partial_\mu - i g_s \vec{t} \cdot \vec{G}_\mu - i g_w \frac{\vec{\tau}}{2} \cdot \vec{W}_\mu - i \frac{g'}{6} B_\mu \right) Q_L^i$$

$$D_\mu U_R^i = \left(\partial_\mu - i g_s \vec{t} \cdot \vec{G}_\mu - i \frac{2}{3} g' B_\mu \right) U_R^i$$

$$D_\mu D_R^i = \left(\partial_\mu - i g_s \vec{t} \cdot \vec{G}_\mu + i \frac{g'}{3} B_\mu \right) D_R^i$$

g', g_w, g_s → weak hypercharge, weak isospin and strong couplings

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

Dirac spinors:

Ψ_L^i → Left-handed lepton and neutrino doublet of SU(2)

R_i → Right-handed lepton singlet of SU(2)

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

U_R^i → Right-handed up quark singlet of SU(2)

D_R^i → Right-handed down quark singlet of SU(2)

Standard Model Lagrangian

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

- 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:

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

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

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

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

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

$$V(\Phi) = \mu^2 \Phi^\dagger \Phi + \lambda \left(\Phi^\dagger \Phi\right)^2$$

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

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

- 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

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

- 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:

$$-\mathscr{L}_{\text{Yukawa}} = \sum_{i=1}^{3}\left[G_i\left(\bar{\Psi}^i_L R_i \Phi + h.c.\right)\right] + \sum_{i=1}^{3}\left[G^i_u\left(\bar{Q}^i_L U^i_R \widetilde{\Phi} + h.c.\right)\right] + \sum_{i,j=1}^{3}\left[\left(\bar{Q}^i_L G^{ij}_d D^j_R \Phi + h.c.\right)\right]$$

- 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

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

- 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:

$$Z_\mu = \cos\theta_W B_\mu - \sin\theta_W {W^3}_\mu \qquad \text{with } \tan\theta_W = \frac{g'}{g_w}$$
$$A_\mu = \cos\theta_W B_\mu + \sin\theta_W {W^3}_\mu$$

$$m_{\text{H}} = \sqrt{-2\mu^2} = \sqrt{2\lambda v^2}$$

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

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

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

$$m_q = G_{\text{d}}^{ij} v$$

$$m_{\text{Z}} = \frac{v\sqrt{{g_w}^2 + {g'}^2}}{2} = \frac{m_{\text{W}}}{\cos\theta_W}$$

$$m_{\text{A}} = 0$$

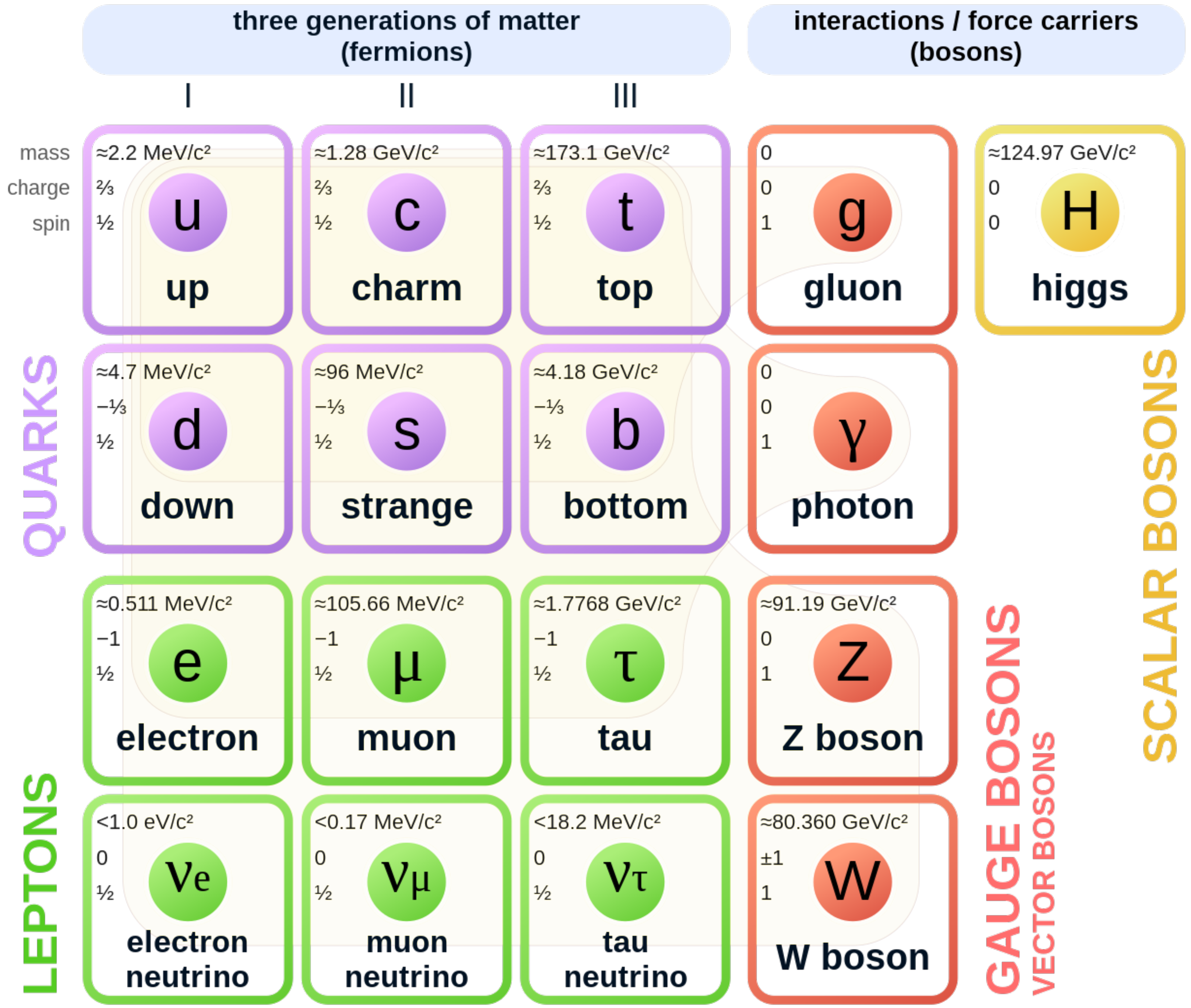
$$m_{\text{W}} = \frac{v g_w}{2}$$

Standard Model Lagrangian

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

- 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 $\ell = \mathrm{e}, \mu, \tau$
  - Six Yukawa coupling constants for the three quark families: G_{u}^q with $q = \mathrm{u, c, t}$; G_{d}^q with $q = \mathrm{d, s, b}$
  - 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'	$(\mathbf{1}, \mathbf{1}, 0)$
W^i	Weak Isospin	$SU(2)$	g_w	$(\mathbf{1}, \mathbf{3}, 0)$
G^i	Colour	$SU(3)$	g_s	$(\mathbf{8}, \mathbf{1}, 0)$

Fermion Fields – Spin $\frac{1}{2}$

Symbol	Name	Representation
Q^i_L	Left-handed quark	$\left(\mathbf{3}, \mathbf{2}, \frac{1}{3}\right)$
$U^{i\ C}_R$	Left-handed antiquark (up)	$\left(\bar{\mathbf{3}}, \mathbf{1}, -\frac{4}{3}\right)$
$D^{i\ C}_R$	Left-handed antiquark (down)	$\left(\bar{\mathbf{3}}, \mathbf{1}, \frac{2}{3}\right)$
Ψ^i_L	Left-handed lepton	$(\mathbf{1}, \mathbf{2}, -1)$
R_i^C	Left-handed antilepton	$(\mathbf{1}, \mathbf{1}, 2)$

Higgs Fields – Spin 0

Symbol	Name	Representation
Φ	Higgs boson	$(\mathbf{1}, \mathbf{2}, 1)$

The discovery of the Higgs boson in 2012 completes the picture but…

(All SM parameters are now known)

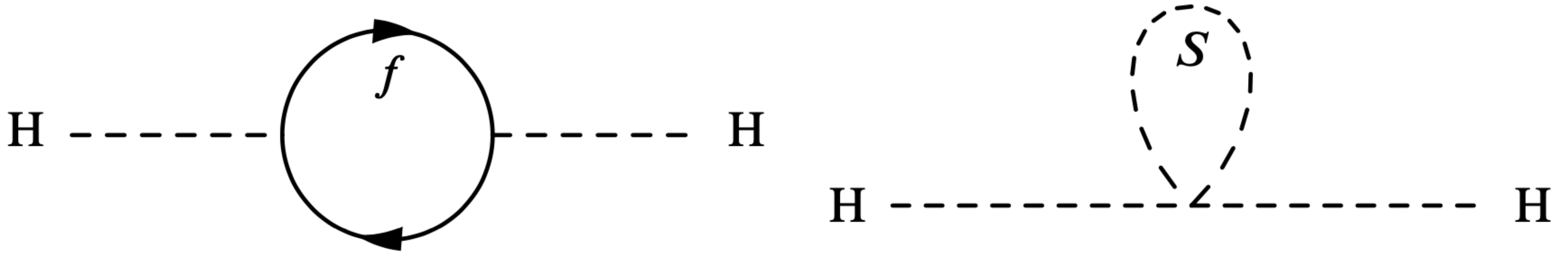
Shortcomings of the Standard Model

- 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

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

- 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:

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

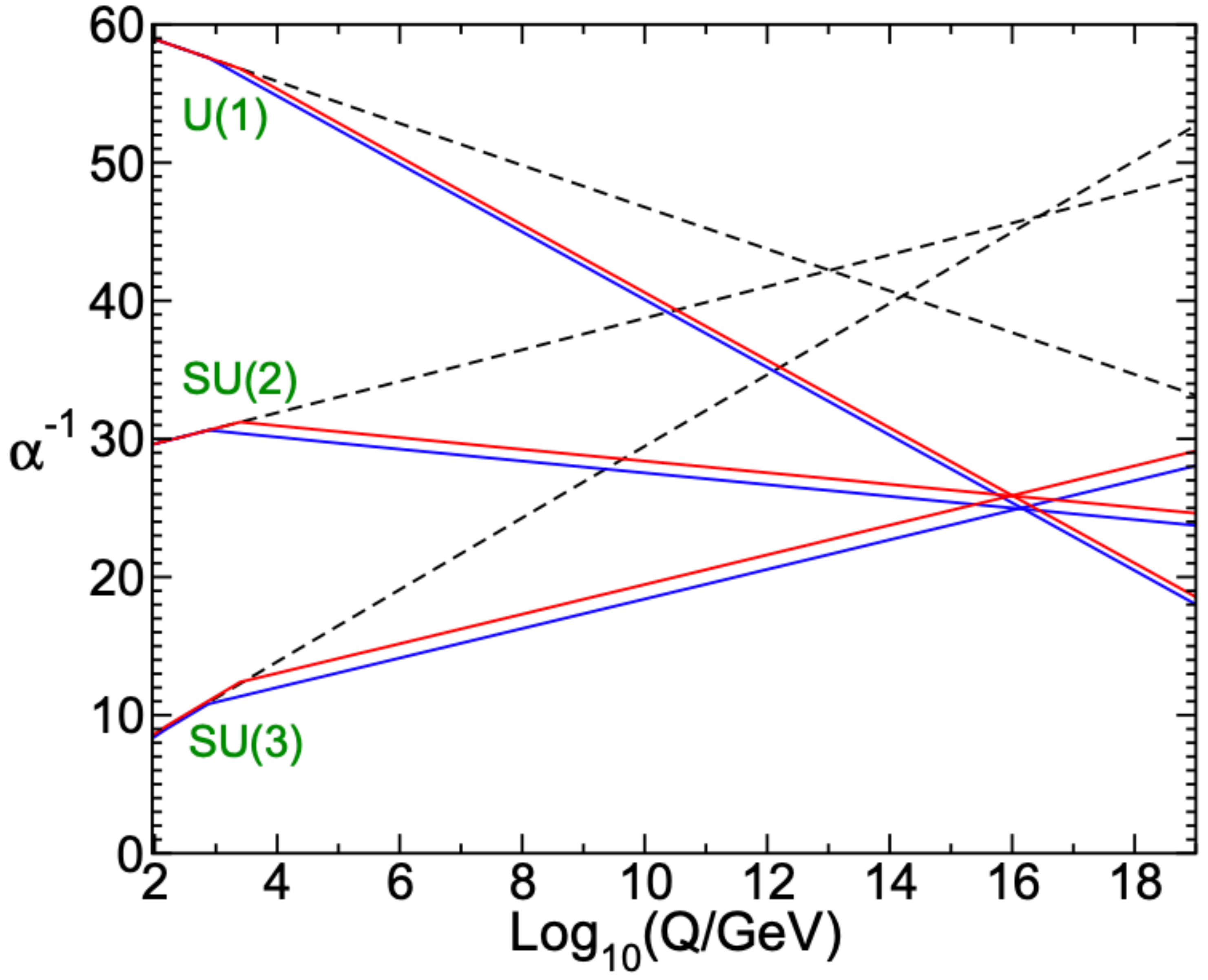
- If the fermion and scaler had the same coupling, the components that depend on the cutoff scale would cancel each other due to the opposite sign → One of the main motivations for Supersymmetry

- 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



Taken from "Supersymmetry Primer"

- 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

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:

    $$\mathscr{L}_{\text{MSSM}} = \mathscr{L}_{KE} + \mathscr{L}_{\text{interaction}} + \mathscr{L}_{W}$$

Further reading:
- Lectures on Supersymmetry : 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	**Particle Names**
$\widehat{Q}^i_L$	$\left(\mathbf{3},\mathbf{2},\frac{1}{3}\right)$	$Q^i_L, \widetilde{Q}^i_L$	
$\widehat{U}^{i\,C}_R$	$\left(\bar{\mathbf{3}},\mathbf{1},-\frac{4}{3}\right)$	$U^{i\,C}_R, \widetilde{U}^{i\,C}_R$	quark, squark
$\widehat{D}^{i\,C}_R$	$\left(\bar{\mathbf{3}},\mathbf{1},\frac{2}{3}\right)$	$D^{i\,C}_R, \widetilde{D}^{i\,C}_R$	
$\widehat{\Psi}^i_L$	$(\mathbf{1},\mathbf{2},-1)$	$\Psi^i_L, \widetilde{\Psi}^i_L$	lepton, slepton
$\widehat{R}^C_i$	$(\mathbf{1},\mathbf{1},2)$	$R^C_i, \widetilde{R}^C_i$	
$\widehat{\Phi}_1$	$(\mathbf{1},\mathbf{2},1)$	$\Phi_1, \widetilde{\Phi}_1$	higgs, higgsino
$\widehat{\Phi}_2$	$(\mathbf{1},\mathbf{2},-1)$	$\Phi_2, \widetilde{\Phi}_2$	

Vector Superfields

Superfield	Representation	Field Composition	
$\widehat{B}$	$(\mathbf{1},\mathbf{1},0)$	$B, \widetilde{B}$	B boson, bino
$\widehat{W}^i$	$(\mathbf{1},\mathbf{3},0)$	$W^i, \widetilde{W}^i$	W boson, wino
$\widehat{G}^i$	$(\mathbf{8},\mathbf{1},0)$	$G^i, \widetilde{G}^i$	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

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

- 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

$$\mathscr{L}_{KE} = \sum_i \left\{ \left(D_\mu S_i^*\right)\left(D^\mu S_i\right) + i\bar{\psi}_i \gamma^\mu D_\mu \psi_i \right\} + \sum_A \left\{ -\frac{1}{4} F_{\mu\nu}{}^A F^{\mu\nu A} + \frac{i}{2} \bar{\lambda}_A \gamma^\mu D_\mu \lambda_A \right\}$$

- 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

$$\mathscr{L}_{\text{MSSM}} = \mathscr{L}_{KE} + \mathscr{L}_{\text{interaction}} + \mathscr{L}_{W}$$

- The "Interaction" term describes the interactions between the chiral superfields and the gauginos as well as the quartic interactions of the scalers:

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

Supersymmetry Lagrangian

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

- 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:

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

- 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

$$\mathscr{L}_{\text{MSSM}} = \mathscr{L}_{KE} + \mathscr{L}_{\text{interaction}} + \mathscr{L}_{W} + \mathscr{L}_{\text{soft}}$$

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

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

- 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:

$$\langle H_1^0 \rangle \equiv v_1 \qquad \langle H_2^0 \rangle \equiv v_2$$

EWK Symmetry Breaking →

$$M_W^2 = \frac{g^2}{2}(v_1^2 + v_2^2)$$

- 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

MSSM - Sfermion Sector

- There is a complex scalar superpartner field for each helicity state of SM field
- Tri-linear soft SUSY terms allow the complex scaler 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

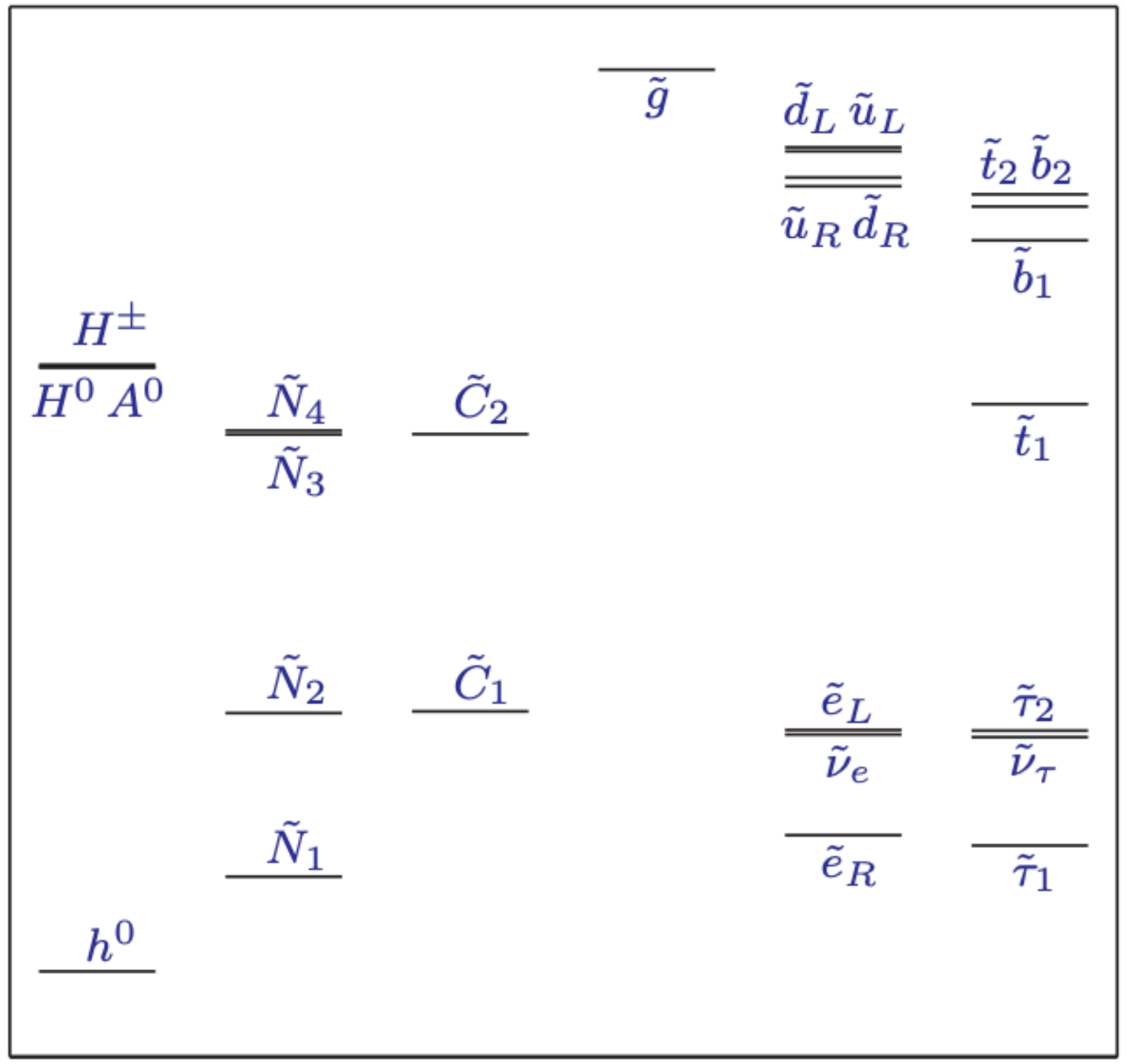
$$M_{\tilde{\chi}_i^0} = \begin{pmatrix} M_1 & 0 & -M_Z \cos\beta \sin\theta_W & M_Z \sin\beta \sin\theta_W \\ 0 & M_2 & M_Z \cos\beta \cos\theta_W & -M_Z \sin\beta \cos\theta_W \\ -M_Z \cos\beta \sin\theta_W & M_Z \cos\beta \sin\theta_W & 0 & \mu \\ M_Z \sin\beta \sin\theta_W & -M_Z \sin\beta \cos\theta_W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

- 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”