Minimal Supersymmetric Standard Model

SUSY Breaking

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Super symmetry breaking

- In our body, there electrons but no selectrons!
- Why is electron stable?
- Obviously supersymmetry is broken but we want the breaking to be soft.
- What is the meaning of “soft” breaking?

Hard symmetry breaking

Lagrangian invariant under $\phi \rightarrow e^{i\alpha}\phi$

$$\mathcal{L} = (\partial_\mu \phi)^\dagger \partial^\mu \phi$$

Let us now add: $\mathcal{L}_1 = m^2 \phi^\dagger \phi$ Still invariant

How about this $\frac{\lambda}{3!}\phi^3\phi^\dagger$ $\lambda \ll 1$

Radiative correction: tadpole correction ; correction to mass $\frac{m^2}{2}\phi^2 + \text{H.c.}$

$$m^2 \sim \frac{\lambda^2}{16\pi^2}\Lambda^2$$

Soft symmetry breaking

- Soft breaking

$$\frac{m^2}{2}\phi^2 + \text{H.c.}$$

- Can this term also give a huge radiative correction?
- How about a small one?

Soft supersymmetry breaking terms

$$
\begin{aligned}
\mathcal{L}_{\rm soft}^{\rm MSSM} \;=\; & -\frac{1}{2}\left(M_3\widetilde{g}\widetilde{g} + M_2\widetilde{W}\widetilde{W} + M_1\widetilde{B}\widetilde{B} + {\rm c.c.}\right) \\
& -\left(\widetilde{\overline{u}}\,\mathbf{a_u}\,\widetilde{Q}H_u - \widetilde{\overline{d}}\,\mathbf{a_d}\,\widetilde{Q}H_d - \widetilde{\overline{e}}\,\mathbf{a_e}\,\widetilde{L}H_d + {\rm c.c.}\right) \\
& -\widetilde{Q}^\dagger\,\mathbf{m^2_Q}\,\widetilde{Q} - \widetilde{L}^\dagger\,\mathbf{m^2_L}\,\widetilde{L} - \widetilde{\overline{u}}\,\mathbf{m^2_{\overline{u}}}\,\widetilde{\overline{u}}^\dagger - \widetilde{\overline{d}}\,\mathbf{m^2_{\overline{d}}}\,\widetilde{\overline{d}}^\dagger - \widetilde{\overline{e}}\,\mathbf{m^2_{\overline{e}}}\,\widetilde{\overline{e}}^\dagger \\
& - m^2_{H_u}H_u^*H_u - m^2_{H_d}H_d^*H_d - (bH_uH_d + {\rm c.c.})\,.
\end{aligned}
$$

What are the dimensions of the different terms?

Flavor violation???

R-parity violation???

Non-holomorphic terms

$$\mu' \widetilde{H}_u \widetilde{H}_d + h_t A_{t'} \tilde{t}_R \tilde{Q}_L H_d^\dagger + h_b A_{b'} \tilde{b}_R \tilde{Q}_L H_u^\dagger + h_\tau A'_\tau \tilde{\tau}_R \tilde{L}_L H_u^\dagger + \mathrm{h.c.}$$

Tadpole contribution

How to get soft terms

- Adding by hand??

- Spontaneous symmetry breaking

O'Raifeartaigh model:

$$W = \lambda\phi_0 + m\phi_1\phi_2 + g\phi_0\phi_1^2$$

$$0 = F_0^* = \lambda + g\phi_1^2$$

$$0 = F_1^* = m\phi_2 + 2g\phi_0\phi_1$$

$$0 = F_2^* = m\phi_1$$

No solution! SUSY is broken. Vacuum is degenerate.

Mass spectrum

- For bosons

$$0, 0, \sqrt{m^2 - 2\lambda g}, \sqrt{m^2 + 2\lambda g}, m, m$$

- For fermions

Two massless fermions +

A Dirac fermion with mass m

Sum rule

- For any set conseving a global charge

$$\sum m_f^2 - \sum m_b^2 = 0$$

Tree level

luty's TASI 2004 lectures

Consequence of the Sum rule

- MSSM cannot be complete!
- There should be a hidden sector that breaks SUSY
- The super symmetry breaking shall be transmitted to our world through a messenger .
- (Gravity is most natural candidate)

Messenger scale M

$$m \sim \frac{\langle F \rangle}{M} \sim \frac{\Lambda^2}{M}$$

Supergravity

$$\Lambda \sim 10^{11}\ \mathrm{GeV}.$$

What determines electroweak scale?

- Hidden sector parameter and messenger scale
- Spectrum of SUSY
- Radiative electroweak symmetry breaking
- حالا اینی که گفتم یعنی چه؟ کسی می تونه بگه؟!

Masses for scalars

$$\int d^4\theta\ \Phi^\dagger e^{gV}\Phi \rightarrow m^2\phi^\dagger\phi$$

$$\Phi(x,\theta) = \phi(x) + \sqrt{2}\theta^T c\psi(x) + \theta^T c\theta\, F(x)$$

$$V(x,\theta,\overline{\theta}) = 2\overline{\theta}\sigma^m\theta\ \ A_m + 2\overline{\theta}^2\theta^T c\lambda - 2\theta^2\overline{\theta}^T c\lambda^* + \theta^2\overline{\theta}^2 D$$

D-term

Why not from other terms???

Masses for gaugino

$$\int d^2\theta \ f(\phi) W^T c W \rightarrow m \lambda^T c \lambda$$

$$W_\alpha = \lambda_\alpha + [(i\sigma^{mn} F_{mn} + D)\theta]_\alpha + \theta^2 [\partial_m \lambda^* \ i\overline{\sigma}^m c]_\alpha$$

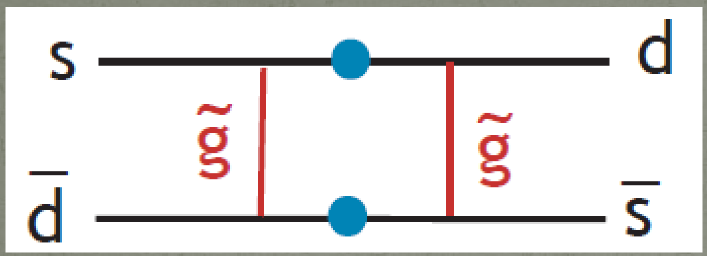
F-term

A- and B-terms

$$\int d^2\theta\ X(\Phi) \to B\phi^2 + A\phi^3$$

$$m\psi^T c\psi\ ,\ C\phi^*\phi^2$$

Flavor violation



$$m^2_{bs}\tilde{b}^\dagger\tilde{s}$$

$$m^2_{\mu e}\tilde{\mu}^\dagger\tilde{e}$$

$$m^2_{\tau e}\tilde{\tau}^\dagger\tilde{e}$$

$$m^2_{\tau\mu}\tilde{\mu}^\dagger\tilde{\tau}$$

$$b \to s\gamma$$

$$\mu \to e\gamma$$

$$\tau \to e\gamma$$

$$\tau \to \mu\gamma$$

Turning off FV terms

From about
100 parameters
To
•22 parameters

Sfermion mass spectra

$$\mathcal{L}_{soft} = -M_f^2 |\widetilde{f}|^2$$

$$V_D = -\frac{g^2}{2} \cdot 2 \cdot (H_d^\dagger \frac{\sigma^3}{2} H_d + H_u^\dagger \frac{\sigma^3}{2} H_u) \cdot (\widetilde{f}^* I^3 \widetilde{f})$$
$$-\frac{g'^2}{2} \cdot 2 \cdot (-\frac{1}{2} H_d^\dagger H_d + \frac{1}{2} H_u^\dagger H_u) \cdot (\widetilde{f}^* Y \widetilde{f})$$

$$\langle H_u \rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \sin\beta \end{pmatrix} \quad \langle H_d \rangle = \begin{pmatrix} \frac{v}{\sqrt{2}} \cos\beta \\ 0 \end{pmatrix}$$

Partners of light fermions

$$V_D = \widetilde{f}^* [\frac{v^2}{4} (\cos^2\beta - \sin^2\beta)(g^2 I^3 - g'^2 Y)] \widetilde{f}$$

$$= \widetilde{f}^* [\frac{(g^2 + g'^2) v^2}{4} \cos 2\beta (I^3 - s_w^2 (I^3 + Y))] \widetilde{f}$$

$$= \widetilde{f}^* [m_Z^2 \cos 2\beta (I^3 - s_w^2 Q)] \widetilde{f}$$

$$\Delta_f = (I^3 - s_w^2 Q) \cos 2\beta \ m_Z^2$$

$$m^2(\widetilde{f}) = M_f^2 + \Delta_f$$

$$m^2(\widetilde{e}) - m^2(\widetilde{\nu}) = |\cos 2\beta| m_Z^2 > 0$$

Partners of heavier fermions

$$|y_b \langle H_d^0 \rangle \tilde{b}|^2 + |y_b \tilde{\bar{b}} \langle H_d^0 \rangle|^2 = m_b^2 (|\tilde{b}|^2 + |\tilde{\bar{b}}|^2)$$

$$\begin{pmatrix} \tilde{b} & \tilde{\bar{b}}^* \end{pmatrix}^* \mathcal{M}_b^2 \begin{pmatrix} \tilde{b} \\ \tilde{\bar{b}}^* \end{pmatrix}$$

$$\mathcal{M}_b^2 = \begin{pmatrix} M_b^2 + \Delta_b + m_b^2 & m_b (A_b - \mu \tan\beta) \\ m_b (A_b - \mu \tan\beta) & M_{\bar{b}}^2 + \Delta_{\bar{b}} + m_b^2 \end{pmatrix}$$

For t, $\tan\beta \to \cot\beta$

Similar for the tau

Danger

- For some parameter space stau can be LSP.
- Charge and Color breaking vacuum

$$A_t^2 \le 3(m_{H_u}^2 + m_{\tilde{Q}_L}^2 + m_{\tilde{t}_R}^2),$$
$$A_b^2 \le 3(m_{H_d}^2 + m_{\tilde{Q}_L}^2 + m_{\tilde{b}_R}^2),$$
$$A_\tau^2 \le 3(m_{H_d}^2 + m_{\tilde{L}_L}^2 + m_{\tilde{\tau}_R}^2).$$

- Notice notation

Alvarez-Guame, Polchinsky, Wise 1983

soft SUSY-breaking: $-\mathcal{L}_{soft} = m_2 \widetilde{w}^{-T} c \widetilde{w}^{+}$

superpotential: $-\mathcal{L}_W = \mu \widetilde{h}_d^{-T} c \widetilde{h}_u^{+}$

kinetic terms: $-\mathcal{L} = \sqrt{2}\frac{g}{\sqrt{2}}(\langle H_d^0 \rangle w^{+T} c \widetilde{h}_d^{-} + \langle H_u^0 \rangle \widetilde{w}^{-T} c \widetilde{h}_u^{+})$

$$\begin{pmatrix} \widetilde{w}^- & \widetilde{h}_d^- \end{pmatrix} m_C \begin{pmatrix} \widetilde{w}^+ \\ \widetilde{h}_u^+ \end{pmatrix}$$

$$m_C = \begin{pmatrix} m_2 & \sqrt{2} m_W \sin\beta \\ \sqrt{2} m_W \cos\beta & \mu \end{pmatrix}$$

$$m_C = V_-^* D_C V_+^\dagger$$

Lower bound

$$\begin{pmatrix} w^+ \\ h_u^+ \end{pmatrix} = V_+ \begin{pmatrix} C_1^+ \\ C_2^+ \end{pmatrix} \qquad \begin{pmatrix} w^- \\ h_d^- \end{pmatrix} = V_- \begin{pmatrix} C_1^- \\ C_2^- \end{pmatrix}$$

Subtle point

$$W^+ = (W^-)^\dagger$$

However

$$C_i^+ \neq (C_i^-)^\dagger$$

$$(\widetilde{b}, \widetilde{w}^0, \widetilde{h}_d^0, \widetilde{h}_u^0)$$

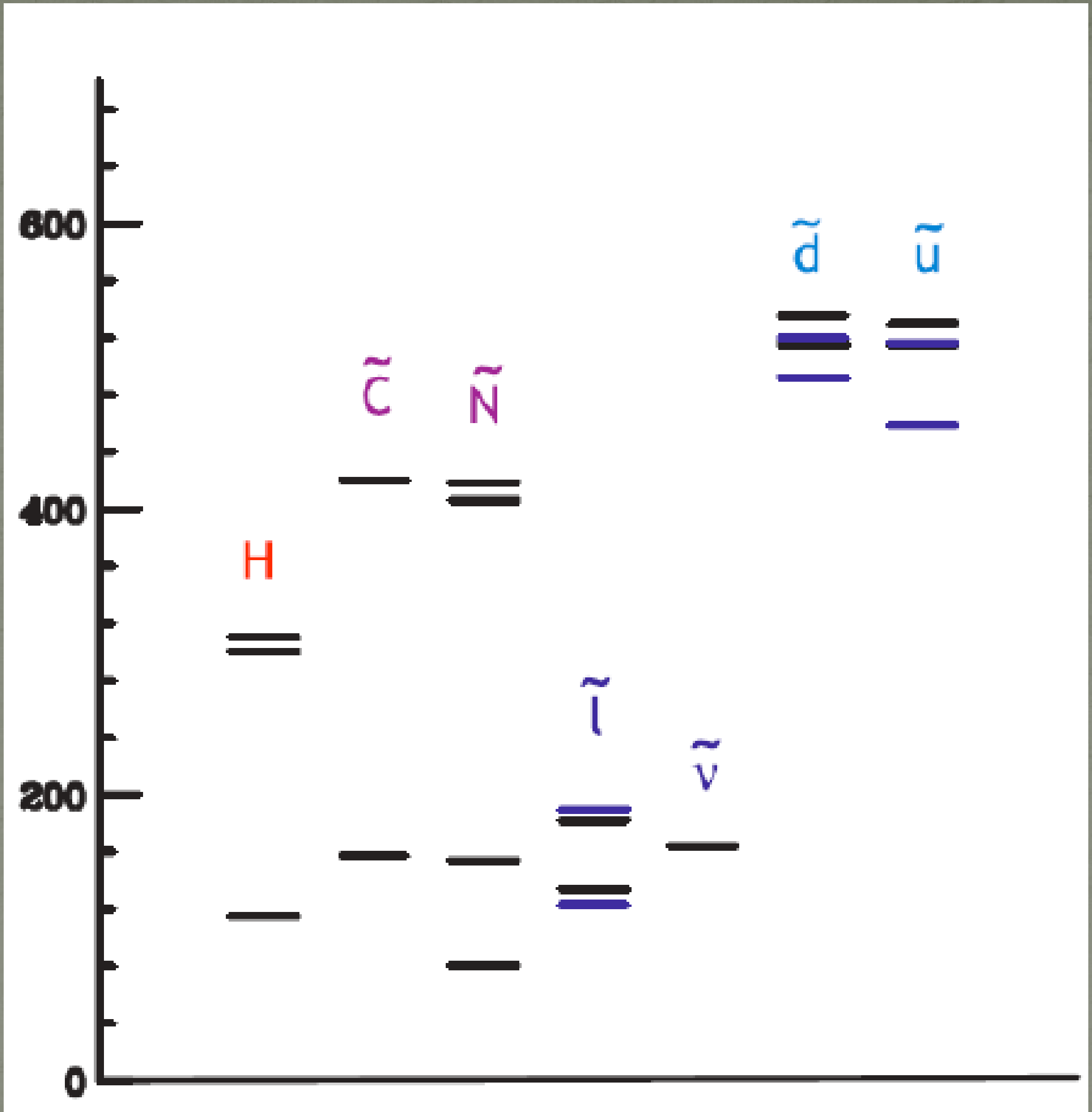
$$m_N = \begin{pmatrix} m_1 & 0 & -m_Z c_\beta s_w & m_Z s_\beta s_w \\ 0 & m_2 & m_Z c_\beta c_w & -m_Z s_\beta c_w \\ -m_Z c_\beta s_w & m_Z c_\beta c_w & 0 & -\mu \\ m_Z s_\beta s_w & -m_Z s_\beta c_w & -\mu & 0 \end{pmatrix}$$

$$m_N = V_0 D_N V_0^T$$

$$\begin{pmatrix} b^0 \\ w^0 \\ h_d^0 \\ h_0^u \end{pmatrix} = V_0 \begin{pmatrix} N_1 \\ N_2 \\ N_3 \\ N_4 \end{pmatrix}$$

gaugino region: $m_1, m_2 < |\mu|$

Higgsino region: $m_1, m_2 > |\mu|$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Running of the gaugino masses

$$\beta_{M_a} \equiv \frac{d}{dt} M_a = \frac{1}{8\pi^2} b_a g_a^2 M_a \quad (b_a = 33/5,\ 1,\ -3)$$

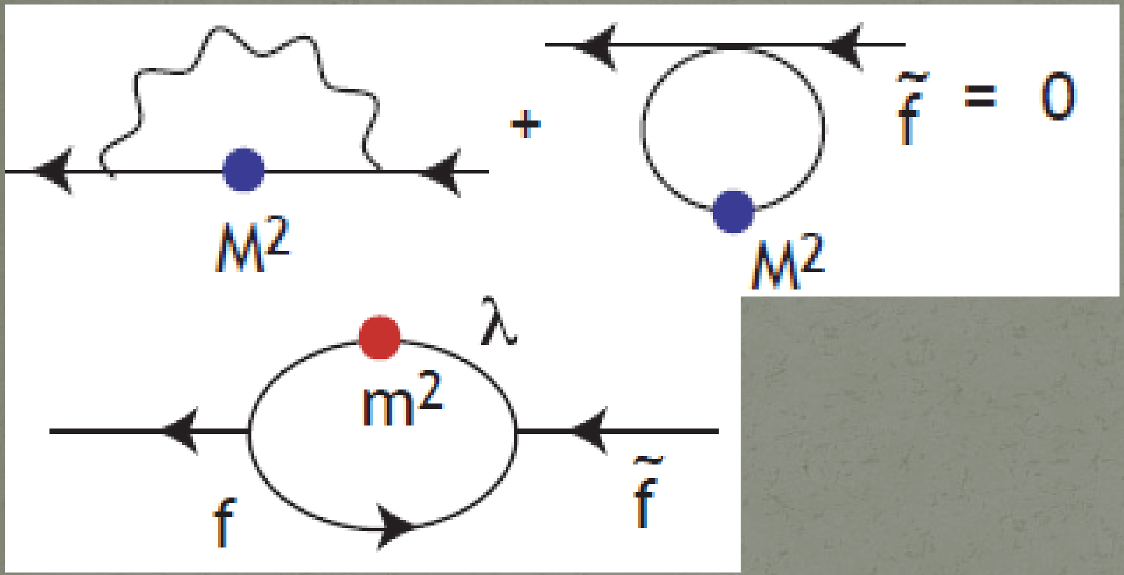
If they unify,

$$\frac{M_1}{g_1^2} = \frac{M_2}{g_2^2} = \frac{M_3}{g_3^2} = \frac{m_{1/2}}{g_U^2}$$

Which one is heavier?

However, at the LHC…

Running of sfermion masses



$$\frac{dM_f^2}{d\log Q} = -\frac{2}{\pi}\sum \alpha_i(Q) C_2(r_i) m_i^2(Q)$$

$$
\begin{aligned}
m_{Q_1}^2 = m_{Q_2}^2 &= m_0^2 + K_3 + K_2 + \frac{1}{36}K_1, \\
m_{\overline{u}_1}^2 = m_{\overline{u}_2}^2 &= m_0^2 + K_3 \qquad\quad + \frac{4}{9}K_1, \\
m_{\overline{d}_1}^2 = m_{\overline{d}_2}^2 &= m_0^2 + K_3 \qquad\quad + \frac{1}{9}K_1, \\
m_{L_1}^2 = m_{L_2}^2 &= m_0^2 \qquad\quad + K_2 + \frac{1}{4}K_1, \\
m_{\overline{e}_1}^2 = m_{\overline{e}_2}^2 &= m_0^2 \qquad\qquad\qquad + K_1.
\end{aligned}
$$

$$
K_a(Q) = \left\{ \begin{array}{c} 3/5 \\ 3/4 \\ 4/3 \end{array} \right\} \times \frac{1}{2\pi^2} \int_{\ln Q}^{\ln Q_0} dt \; g_a^2(t) \, |M_a(t)|^2
$$

$$
K_1 \approx 0.15 m_{1/2}^2, \qquad K_2 \approx 0.5 m_{1/2}^2, \qquad K_3 \approx (4.5 \text{ to } 6.5) m_{1/2}^2.
$$