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Center for Fundamental Physics

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ESTABLISHED 2000
INAUGURATED 2011

MSSM in light of recent LHC results. I

Shaaban Khalil

Center for Fundamental Physics
Zewail City of Science and Technology

MSSM Structure

- The MSSM is a straightforward supersymmetrization of the SM with minimal number of new parameters.

- The particle content of MSSM = Two Higgs doublet SM + scalar SUSY partners and fermionic SUSY partners

- Two Higgs doublets are necessary for fermion Yukawa couplings.

  H1: down-type-quark and lepton Yukawa couplings

  H2: up-type-quark Yukawa couplings

- Different assumptions about SUSY breaking are often made. This leads to quite different phenomenological predictions.

- A new symmetry, called R-symmetry is introduced to rule out the terms violate baryon & lepton number explicitly and lead to proton decay at unacceptable rates.

SUSY Particle Spectrum

Supermultiplet	SM	SUSY	$SU(3)_C \times SU(2)_L \times U(1)$
Q_L	quarks $q = (u_L, d_L)^T$ (spin $\frac{1}{2}$)	squarks $\tilde{q} = (\tilde{u}_L, \tilde{d}_L)^T$ (spin 0)	$(3, 2, 1/6)$
U_L^c	quarks u_L^c (spin $\frac{1}{2}$)	squarks $\tilde{u}_L^c$ (spin 0)	$(\bar{3}, 1, -2/3)$
D_L^c	quarks d_L^c (spin $\frac{1}{2}$)	squark $\tilde{d}_L^c$ (spin 0)	$(\bar{3}, 1, 1/3)$
L_L	leptons $l = (\nu_L, e_L)^T$ (spin $\frac{1}{2}$)	sleptons $(\tilde{l}) = (\tilde{\nu}_L, \tilde{e}_L)^T$ (spin 0)	$(1, 2, 1/2)$
E_L^c	leptons e_L^c (spin $\frac{1}{2}$)	sleptons $\tilde{e}_L^c$ (spin 0)	$(1, 1, 1)$
H_u	Higgs $H_u = (H_u^0, H_u^+)^T$ (spin 0)	Higgsino $\tilde{H}_u = (\tilde{H}_u^0, \tilde{H}_u^+)$ (spin $\frac{1}{2}$)	$(1, 2, 1/2)$
H_d	Higgs $H_d = (H_d^-, H_d^0)^T$ (spin 0)	Higgsino $\tilde{H}_d = (\tilde{H}_d^-, \tilde{H}_d^0)^T$ (spin $\frac{1}{2}$)	$(1, 2, 1/2)$

MSSM Lagraganian

- **The MSSM Lagrangian can be written as**

$$\mathcal{L}_{\rm MSSM} = \mathcal{L}_{\rm gauge} + \mathcal{L}_{\rm matter} + W + \mathcal{L}_{\rm soft},$$

- **The gauge Lagrangian is given by**

$$\mathcal{L}_{\rm gauge} = -\frac{1}{4} F_G^{a\,\mu\nu} F^a_{G\,\mu\nu} + i\bar{\lambda}^a_G \bar{\sigma}^\mu D_\mu \lambda^a_G + \frac{1}{2} D^a D_a,$$

- **The matter Lagrangian is given by**

$$\mathcal{L}_{\rm matter} = (D^\mu \phi_i)^\dagger (D_\mu \phi_i) + i\bar{\psi}_i \gamma^\mu D_\mu \psi_i + F_i^* F_i$$
$$+ i g_a \sqrt{2} (\phi^* T^a \lambda^a \psi + \text{h.c.}) - \frac{1}{2} g_a^2 (\phi_i^* T^a \phi_i)^2,$$

- **Where**

$$D_\mu = \partial_\mu + i g' Y B_\mu + i g \frac{\tau^i}{2} W^i_\mu + i g_s \frac{\lambda^a}{2} G^a_\mu.$$

MSSM Superpotential

- **MSSM superpotential describes the interactions between Higgs bosons and matter Superfields**

$$W = Y_u Q_L U_L^c H_u + Y_d Q_L D_L^c H_d + Y_e L_L E_L^c H_d + \mu H_d H_u.$$

- **Need of two Higgs doublets**

$$Y_{Q_i} + Y_{d_R^c} = \frac{1}{6} + \frac{1}{3} = \frac{1}{2} \quad \Rightarrow \quad Y_{H_d} = -\frac{1}{2}$$
$$Y_{Q_i} + Y_{u_R^c} = \frac{1}{6} - \frac{2}{3} = -\frac{1}{2} \quad \Rightarrow \quad Y_{H_u} = \frac{1}{2}$$

in the SM $H_u = H$ *and* $H_d = H^*$. However, a Superpotential containing H^* would be non-supersymmetric.

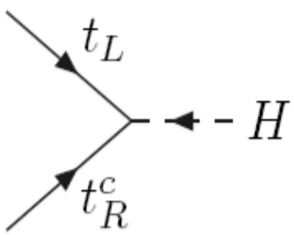
A second doublet also required to cancel the triangle anomaly.

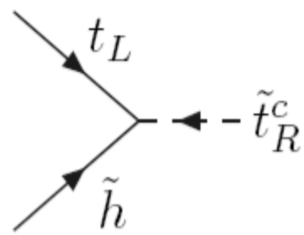
Example: top Yukawa

$$W = h_t \, Q_L H t^c_R$$

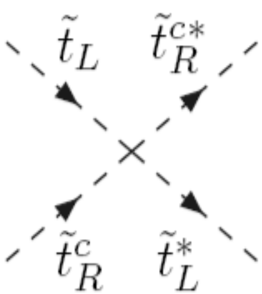
$$L_{int} = -\frac{1}{2} W^{ij} \, \psi_i \psi_j - \frac{1}{2} W^{ij*} \, \bar{\psi}_i \bar{\psi}_j - W^i W^*_i = -\frac{1}{2} \, h_t \left[H \, Q_L t^c_R + \tilde{Q}_L \, \tilde{h} t^c_R + \tilde{t}^c_R \, Q_l \tilde{h} \right] + c.c. - h_t^2 \left(|H \tilde{t}^c_R|^2 + |H \tilde{Q}_L|^2 + |\tilde{Q}_L \tilde{t}^c_R|^2 \right)$$

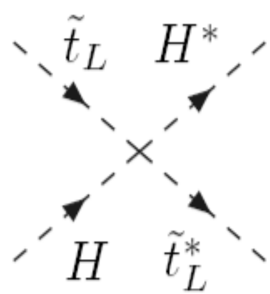
From here the Feynman rules,





$- \, i \, h_t \, L$





$- \, i \, h_t^2$

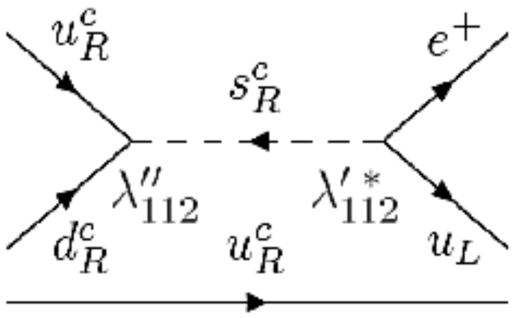
R-Parity

There are other Gauge invariant terms that can appear in W

$$W_{\Delta L=1} = \lambda^{ijk} L_i L_j e^c_{Rk} + \lambda'^{\,ijk} L_i Q_j d^c_{Rk} + \epsilon^i L_i H_2$$

$$W_{\Delta B=1} = \lambda''^{\,ijk}\; u^c_{Ri} d^c_{Rj} d^c_{Rk}$$

violate baryon or lepton number. If λ' and $\lambda'' \neq 0 \Rightarrow$ rapid proton decay!!



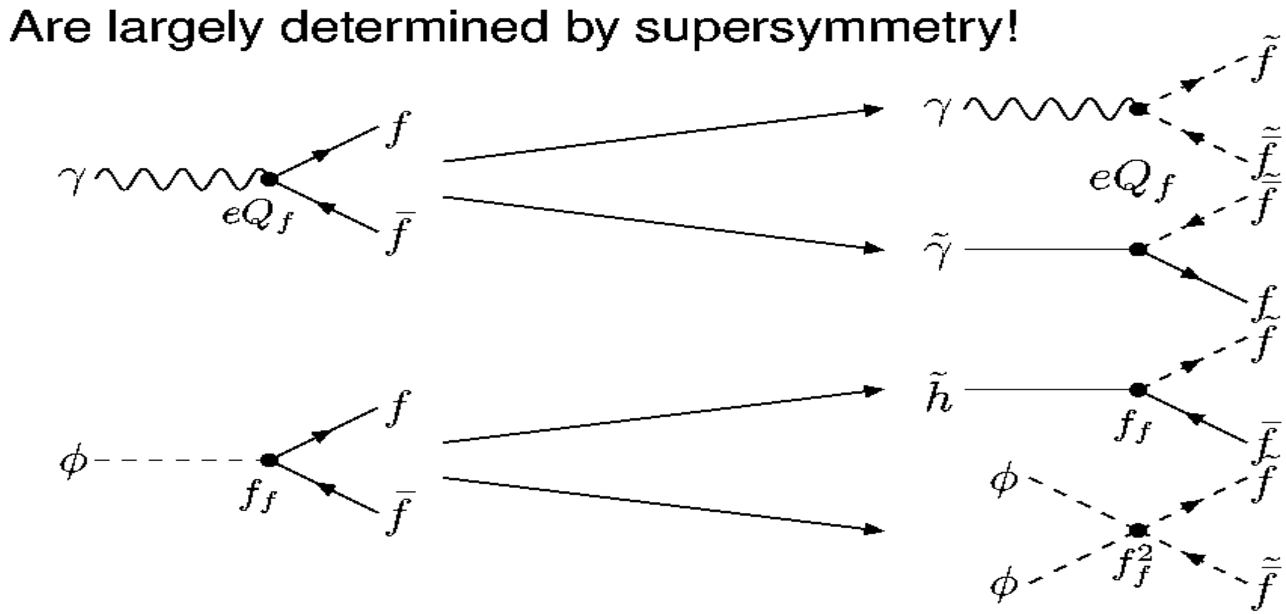
$$p^+ \to e^+ \pi^0 \Rightarrow \lambda'^*_{112} \cdot \lambda''_{112} \leq 2 \times 10^{-27}$$

New discrete symmetry, R-parity, forbid these terms $R_P = (-1)^{3B+L+2S}$.

SM particles and Higgs bosons $R_P = +1$ all superpartners $R_P = -1$

R-parity conservation implies that:

1. SUSY particles are produced or destroyed only in pairs
2. The LSP is absolutely stable and it is a candidate for Dark Matter.



- A major signature for R-parity conserving models is represented by events with missing Energy:

For instance e+ e- → jet + missing energy

Soft SUSY Breaking

- SUSY must be broken, $m_{\tilde{e}} \neq m_e$, $m_{\tilde{g}} \neq 0$.
- Solve hierarchy problem, broken by terms of possitive mass dimension

Soft Supersymmetry Breaking, and $M_{susy} \leq \mathcal{O}(1\text{ TeV})$.

- Gaugino masses

$$L^{(1)}_{soft} = \frac{1}{2}\left(M_1\ \tilde{B}\tilde{B} + M_2\ \tilde{W}\tilde{W} + M_3\ \tilde{g}\tilde{g}\right) + h.c.$$

- Scalar masses

$$L^{(2)}_{soft} = (m^2_{\tilde{Q}})_{ij}\tilde{Q}_i\tilde{Q}^*_j + (m^2_{\tilde{u}})_{ij}\tilde{u}^c_{Ri}\tilde{u}^{c*}_{Rj} + (m^2_{\tilde{d}})_{ij}\tilde{d}^c_{Ri}\tilde{d}^{c*}_{Rj} + (m^2_{\tilde{L}})_{ij}\tilde{L}_i\tilde{L}^*_j + (m^2_{\tilde{e}})_{ij}\tilde{e}^c_{Ri}\tilde{e}^{c*}_{Rj} + (m^2_{H_1})H_1H^*_1 + (m^2_{H_2})H_2H^*_2$$

- Trilinear couplings and B–term

$$L^{(3)}_{soft} = (Y^A_d)^{ij}\tilde{Q}_iH_1\tilde{d}_{Rj} + (Y^A_e)^{ij}\tilde{L}_iH_1\tilde{e}^c_{Rj} + (Y^A_u)^{ij}\tilde{Q}_iH_2\tilde{u}^c_{Rj} + B\mu H_1H_2$$

$m^2_{\tilde{Q}}$, $m^2_{\tilde{u}}$, $m^2_{\tilde{d}}$, $m^2_{\tilde{L}}$ and $m^2_{\tilde{e}}$, hermitian 3×3 matrices in flavour space.
(Y_d^A), (Y_u^A) and (Y_u^A) complex 3×3 matrices

$$\Downarrow$$

Soft SUSY breaking in general MSSM more that 100 parameters !!
Most of the possible flavour structures in soft terms severely constrained by experiment $\Rightarrow$ SUSY flavour and CP problems (lecture 5).

CMSSM (or mSugra)

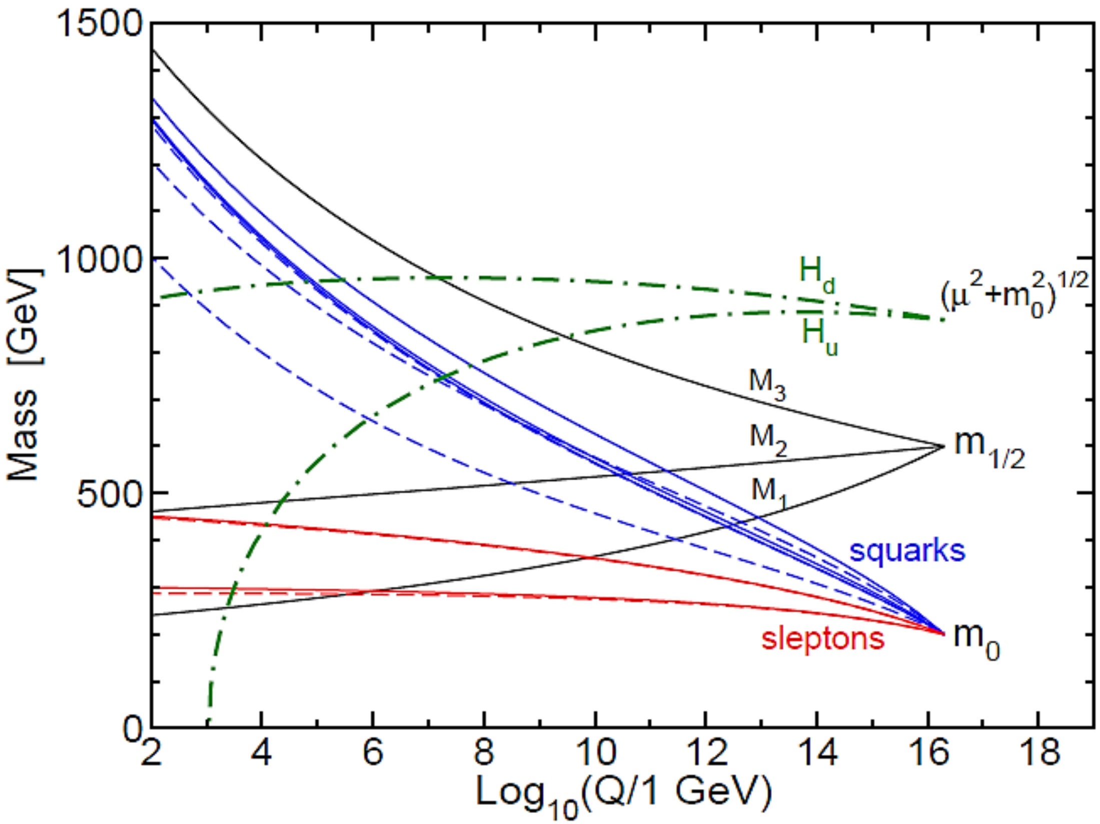
Supersymmetry breaking mediated by gravitational interactions, Minimal Kähler potential and gauge kinetic functions. At the Susy breaking scale :

$$m^2_{\tilde{Q}} = m^2_{\tilde{u}} = m^2_{\tilde{d}} = m^2_{\tilde{L}} = m^2_{\tilde{e}} = m_0^2\, \mathbf{1} \qquad m^2_{H_1} = m^2_{H_2} = m_0^2$$

$$(Y_d^A)_{ij} = A_0 (Y_d)_{ij} \qquad (Y_u^A)_{ij} = A_0 (Y_u)_{ij} \qquad (Y_e^A)_{ij} = A_0 (Y_e)_{ij}$$

- In CMSSM (mSUGRA), universality of soft SUSY breaking terms is assumed at GUT scale.

- The RGE are used to calculate the parameters at the electroweak scale.



Electroweak Symmetry Breaking

- The potential for the neutral Higgs fields

$$V_{Higgs} = (m_{H_1}^2 + \mu^2)|H_1^0|^2 + (m_{H_2}^2 + \mu^2)|H_2^0|^2 + B\mu\, H_1^0 H_2^0 + c.c. + \frac{g^2 + g'^2}{8}(|H_2^0|^2 - |H_1^0|^2)^2$$

- Using gauge invariance to rotate the VEVs from charged components:

$$\langle H_u \rangle = \begin{pmatrix} 0 \\ v_u \end{pmatrix}, \qquad \langle H_d \rangle = \begin{pmatrix} v_d \\ 0 \end{pmatrix}$$

- We minimize the potential with $\tan\beta = v_u / v_d$ and $M_Z^2 = \frac{1}{2}(g^2 + g'^2)(v_u^2 + v_d^2)$,

- Electroweak Breaking Conditions:

$$|\mu|^2 = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} - M_Z^2/2, \qquad \sin 2\beta = \frac{-2B\mu}{m_{H_d}^2 + m_{H_u}^2 + 2|\mu|^2}.$$

- CMSSM is completely determined by m_0, $M_{1/2}$, A_0, and $\tan\beta$ plus sign μ

Higgs mass in SUSY models

- **SUSY models include at least two Higgs doublets.**
- **This means: 8 degrees of freedom, 3 eaten up by the W± and Z → 5 Higgs fields: *h^0,A^0,H^0,$H^\pm$***
- **Connection between Higgs masses and gauge boson masses:**

$$
\begin{aligned}
V_{Higgs} = {} & m_1^2|H_1|^2 + m_2^2|H_2|^2 - m_3^2(H_1 \cdot H_2 + \bar{H}_1 \cdot \bar{H}_2) \\
& + \frac{g_2^2}{8}(\bar{H}_1 \tau^a H_1 + \bar{H}_2 \tau^a H_2)^2 + \frac{g_1^2}{8}(|H_1|^2 - |H_2|^2)^2 \\
& + \Delta V,
\end{aligned}
$$

$$
m_h^2 \leq m_Z^2 \cos^2 2\beta + \frac{6}{(2\pi)^2}\frac{m_t^4}{v^2}\ln\frac{m_{stop}^2}{m_t^2}, \quad \left(\tan\beta = \frac{<H_2^0>}{<H_1^0>}\right)
$$

$$
m_h < 135\text{GeV}
$$

- **Possible vacuum instability is saved by supersymmetry**

Squarks & Sleptons

The squark mass matrices

$$M_{\tilde{u}}^2 = \begin{pmatrix} M_Q^2 + m_u^\dagger m_u + D_{LL}^u & m_u(A_U + \mu \cot\beta) \\ (A_U^\dagger + \mu^* \cot\beta) m_u^\dagger & M_U^2 + m_u m_u^\dagger + D_{RR}^u \end{pmatrix}$$

$$M_{\tilde{d}}^2 = \begin{pmatrix} K^\dagger M_Q^2 K + m_d^\dagger m_d + D_{LL}^d & m_d(A_D + \mu \tan\beta) \\ (A_D^\dagger + \mu^* \tan\beta) m_d^\dagger & M_D^2 + m_d m_d^\dagger + D_{RR}^d \end{pmatrix}$$

Analogous expressions are obtained in the slepton sector, where

$$D_{RR}^f = (m_Z^2 \cos 2\beta \; e_f \sin^2\theta_W)\; 1.$$

Here T_{3f} is the third component of the weak isospin and e_f is the charge.

Charginios

- The mixing of the charged gauginos and charged Higgsinos is described by:

$$M_C = \begin{pmatrix} M_2 & \sqrt{2} M_W \sin\beta \\ \sqrt{2} M_W \cos\beta & -\mu \end{pmatrix}$$

- The chargino masses are given by

$$M_{2,1}^2 = 1/2(M_2^2 + \mu^2 + 2M_W^2 \\ \pm \sqrt{(M_2^2 - \mu^2)^2 + 4M_W^4 \cos^2 2\beta + 4M_W^2 (M_2^2 + \mu^2 - 2M_2\mu \sin 2\beta))}$$

- Within the mSUGRA scenario we have

$$M_{\tilde{\chi}_1^0} \approx 0.45 M_{1/2}$$

$$M_{\tilde{\chi}_2^0} \approx M_{\tilde{\chi}_1^\pm} \approx 2M_{\tilde{\chi}_1^0}$$

$$M_{\tilde{\chi}_2^0} \approx (0.25 - 0.35) M_{\tilde{g}}$$

Neutralinos

- **The neutralinos χ_i (i=1,2,3,4) are the physical (mass) superpositions of fermionic partners of Bino, Wino and Higgsinos.**

$$M_N = \begin{pmatrix} M_1 & 0 & -M_Z \cos\beta \sin\theta_W & M_Z \sin\beta \sin\theta_W \\ 0 & M_1 & M_Z \cos\beta \cos\theta_W & -M_Z \sin\beta \cos\theta_W \\ -M_Z \cos\beta \sin\theta_W & M_Z \cos\beta \cos\theta_W & 0 & \mu \\ M_Z \sin\beta \sin\theta_W & -M_Z \sin\beta \cos\theta_W & \mu & 0 \end{pmatrix}$$

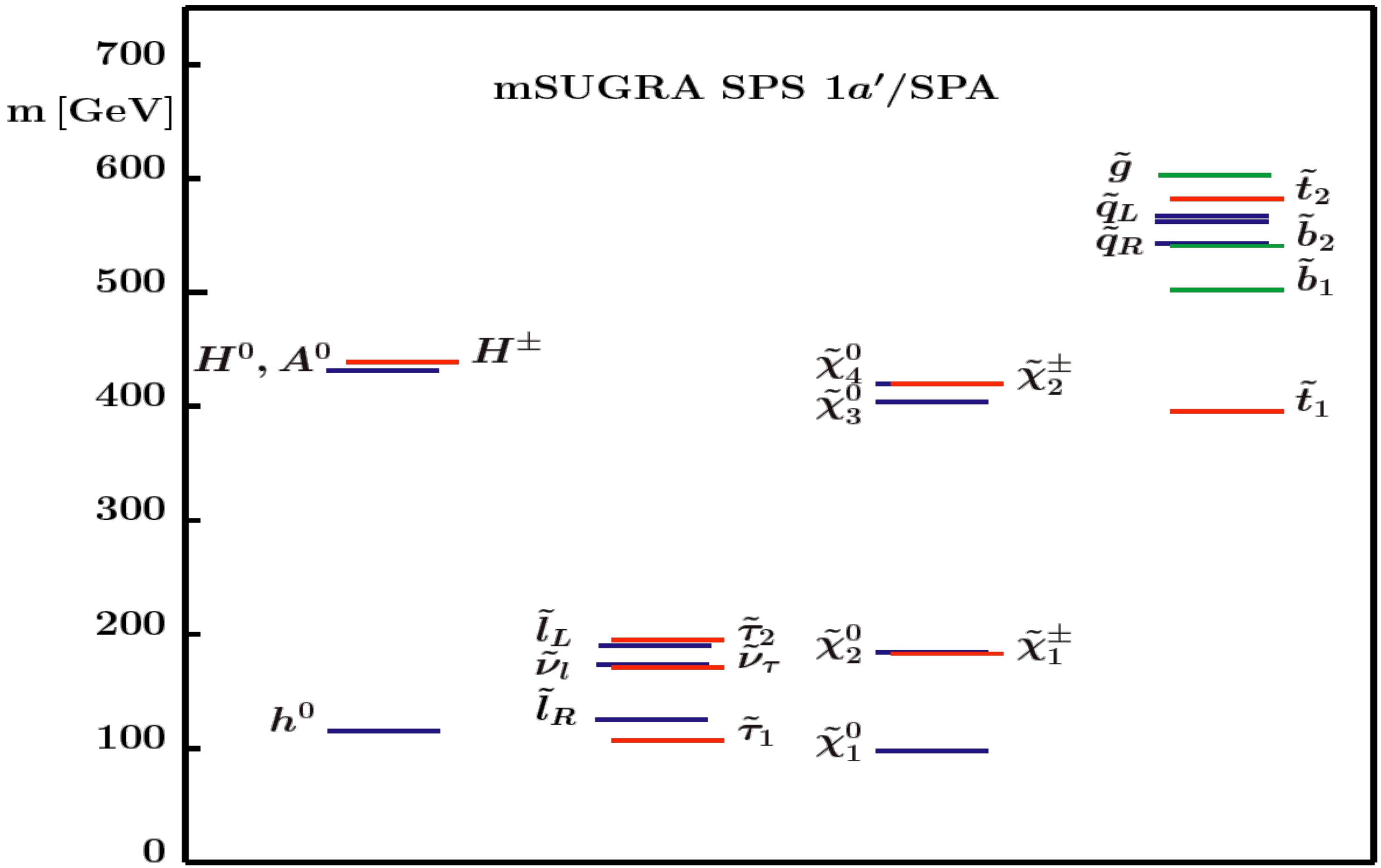
- **The lightest neutralino will be a linear combination of the original fields:**

$$\tilde{\chi}_1^0 = N_{11}\tilde{B}^0 + N_{12}\tilde{W}^0 + N_{13}\tilde{H}_1^0 + U_{14}\tilde{H}_2^0$$

- **The lightest neutralino can be the lightest supersymmetric particle (LSP).**

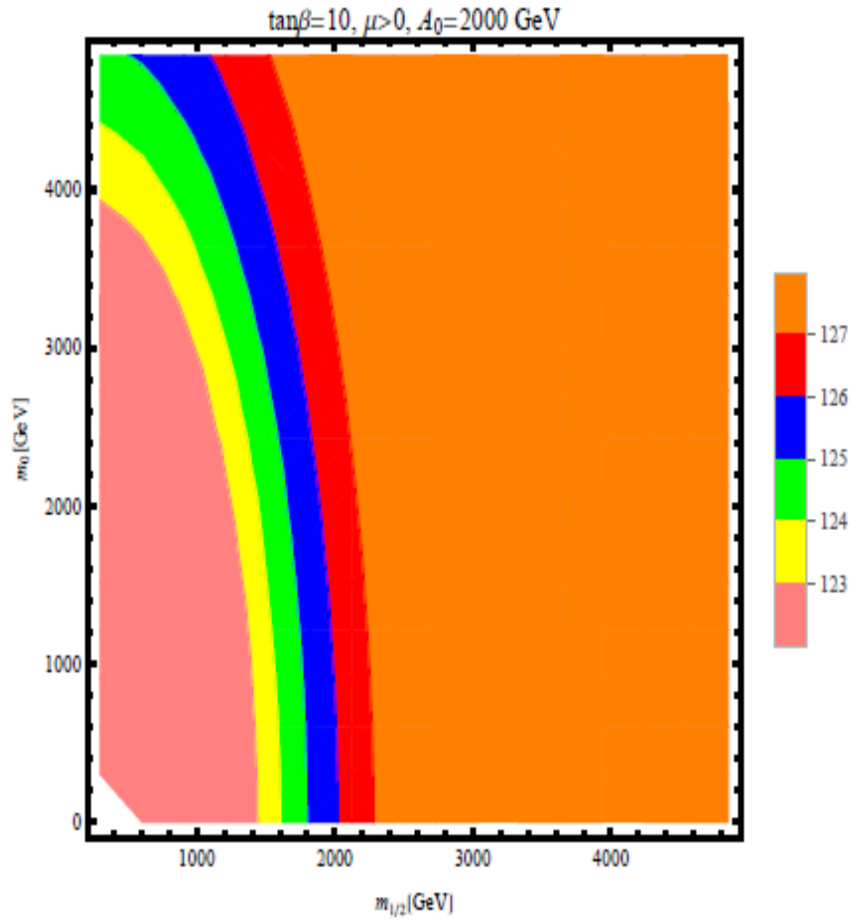
- **Stable Weakly Interacting Massive Particle (WIMP). Interesting candidate for DM.**

mSUGRA Mass Spectrum



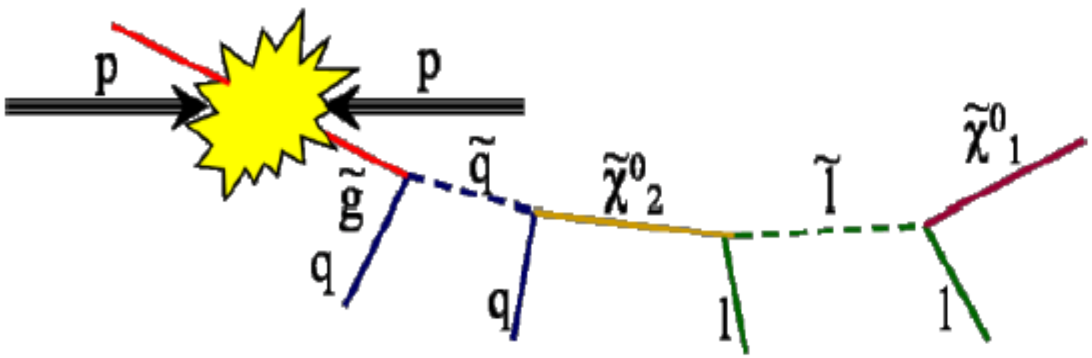
SUSY Higgs Prospects at the LHC

- In July 2012 the ATLAS and CMS collaborations announced the detection of a new particle with 125 GeV mass consistent with a Higgs boson.
- Although a Higgs discovery is not a priori an indication for SUSY, still, the confirmed existence of the lightest Higgs boson is in favor of it
- Higgs mass of order 125 GeV requires a gaugino mass $m_{1/2}$ of order 1.5 TeV.
- The smaller A0 is, the larger $m_{1/2}$ is needed to satisfy this value of Higgs mass.
- It is also remarkable that the scalar mass m_0 remains essentially unconstrained.
- Such large values of $m_{1/2}$ and A_0 seem to imply a heavy SUSY spectrum.



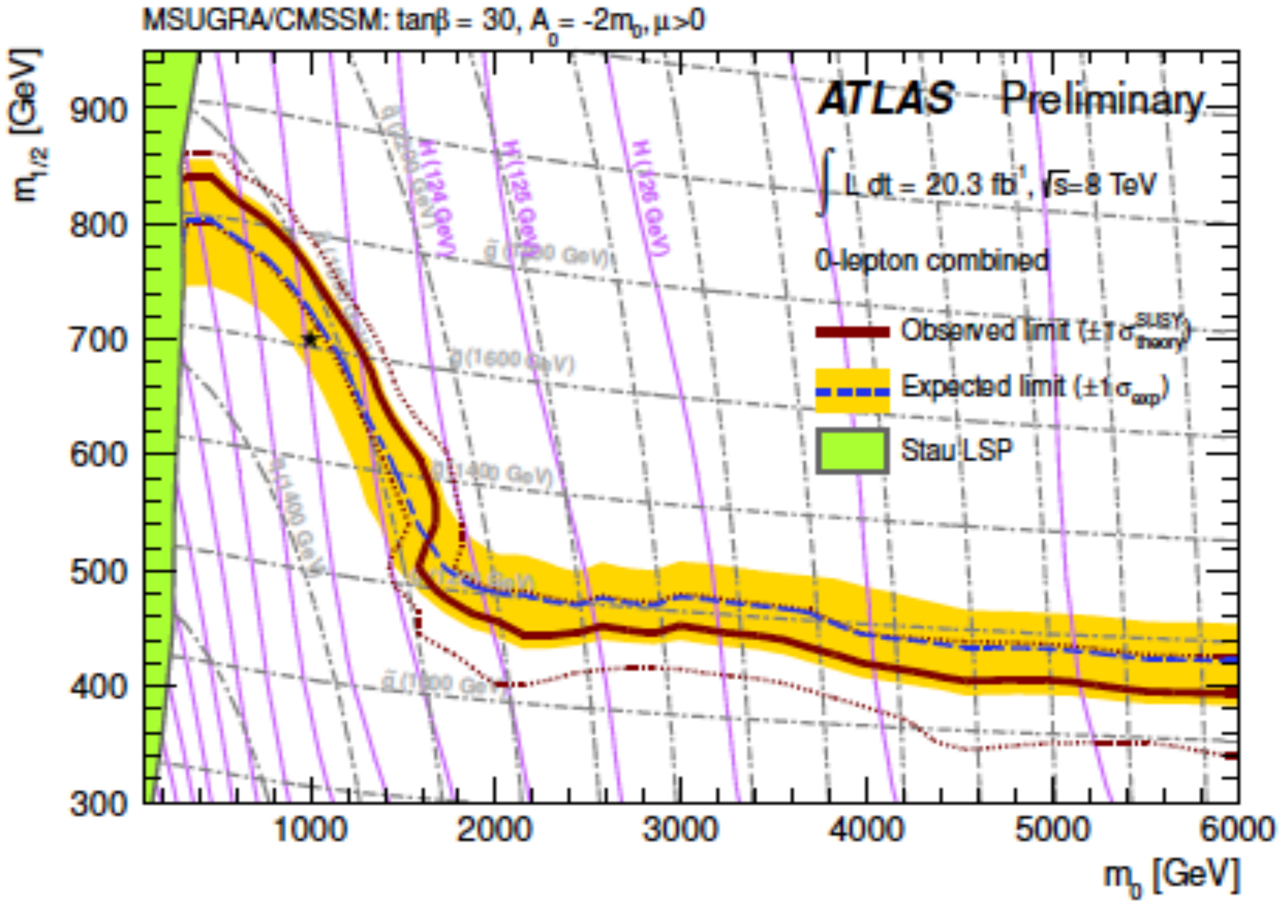
SUSY signature

- At LHC the total SUSY particle production cross section are largely dominated by strongly interacting sparticles.



- Typical high mass SUSY signal has squarks and gluinos which decay through a number of steps to quarks, gluons, charginos, neutralinos, *W*, *Z*, Higgses and finally to a stable χ^0_1.

LHC Constraints on $(m_0 - m_{1/2})$



ATLAS exclusion limits, at 95% C.L. for constrained MSSM model with tanβ = 30, $A_0 = -2m_0$ and $\mu > 0$, on (left) $(m_0 - m_{1/2})$. CMS limits are the same.