Supersymmetry II - MSSM ...

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Outline

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Why study Supersymmetry ?

- Low enegy Supersymmetry is well motivated and has many nice features among them its ability to stabilize the hierarchy.
- Its relevance with very high ($\sim$ Planckian) energies is that $N = 1$ SUSY naturally arises from the String or M - theory in particular compactification schemes !

Widespread optimism that the new discovery will be Supersymmetry, unless ...

" The main goals of collider experiments now are finding superpartners and Higgs bosons, or (if somehow we are on the wrong track in spite of the indirect evidence and strong theoretical arguments) showing that superpartners and Higgs bosons do not exist. "

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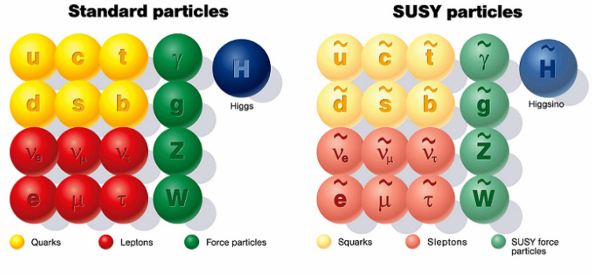
MSSM

- To every **SM** particle a **SUSY** partner is introduced, both members of the same multiplet and the d.o.f. are doubled (at least !).
- The minimal version is the **MSSM**.



- New particles are predicted (sparticles), partners of the known SM particles, and SUSY models are phenomenologically rich.

- **Fermions :**

Each chiral fermion is accomodated along with its scalar partner in a chiral multiplet.

For the electron, for instance, need two chiral multiplets, E , E_c

$$E \sim (e_L, \tilde{e}_L) \quad , \quad E_c \sim (e_L^c, \tilde{e}_L^c)$$

- e_L describes the left handed electron and $\tilde{e}_L$ is its partner, L-handed **selectron**.
- $e_R \equiv \overline{e_L^c}$ describes the right handed electron and $\tilde{e}_R \equiv (\tilde{e}_L^c)^*$ its partner, R-handed **selectron**.

- **Gauge bosons :**

Each gauge boson is accomodated along with its fermion partner in a vector multiplet.

For the U(1) gauge boson B_μ , the vector multiplet contains a **Bino** and so on ...

$$(B_\mu, \tilde{B})$$

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Matter fermions, gauge bosons and their superpartners in the MSSM :

SM world	SUSY world
Quarks and Leptons × 3 families	**Squarks and Sleptons × 3 families**
Quarks : $\begin{pmatrix} u_L \\ d_L \end{pmatrix}$ u_R d_R	Squarks : $\begin{pmatrix} \tilde{u}_L \\ \tilde{d}_L \end{pmatrix}$ $\tilde{u}_R$ $\tilde{d}_R$
Leptons : $\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$ e_R	Sleptons : $\begin{pmatrix} \tilde{\nu}_L \\ \tilde{e}_L \end{pmatrix}$ $\tilde{e}_R$
Gauge bosons	**Gauginos**
$U(1)$: B_μ	$\widetilde{B}$ Bino
$SU(2)$: $W_\mu^{1,2,3}$	$\widetilde{W}^{1,2,3}$ Winos
$SU(3)$: $G_\mu^{1,2...,8}$	$\widetilde{g}^{1,2...,8}$ Gluinos

Higgs bosons :

In the MSSM two scalar Higgs doublets H_1 , H_2 are needed to give masses to "down" $(T_3 = -1/2)$ and "up" $(T_3 = +1/2)$ fermions !

Higgs scalars	Higgsinos
$H_1 = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix}$, $H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix}$	$\tilde{H}_1 = \begin{pmatrix} \tilde{H}_1^0 \\ \tilde{H}_1^- \end{pmatrix}$, $\tilde{H}_2 = \begin{pmatrix} \tilde{H}_2^+ \\ \tilde{H}_2^0 \end{pmatrix}$

Why need two Higgs doublets ?

- In the SM given a doublet H the operation $H \to H' = i\,\sigma_2\, H^*$ produces another doublet, but for a chiral SUSY multiplet this operation produces an **anti-chiral** multiplet !
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- Need couple the chiral multiplets through a proper superpotential to produce Yukawa couplings !
- Need introduce a SUSY breaking sector to lift up sparticle masses. The sparticle spectrum sensitive to SUSY breaking scale !
- SUSY breaking terms and EW breaking cause mixings and Mass eigenstates are not Gauge eigenstates !
- The presence of two Higgs doublets results to five observable Higgs bosons. Higgs phenomenology in the MSSM different from that of the SM.

Superpotential of the MSSM

Quark, Lepton and Higgs chiral multiplets must couple in a gauge invariant manner in the superpotential.

	Multiplets	$SU(3) \times SU(2) \times U(1)$
Quarks - in 3 families	$Q = \begin{pmatrix} U \\ D \end{pmatrix}$	$(3, 2, +\frac{1}{3})$
	U_c	$(\bar{3}, 1, -\frac{4}{3})$
	D_c	$(\bar{3}, 1, +\frac{2}{3})$
Leptons - in 3 families	$L = \begin{pmatrix} N \\ E \end{pmatrix}$	$(1, 2, -1)$
	E_c	$(1, 1, +2)$
Higgses	$H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix}$	$(1, 2, +1)$
$2 =$ up , $1 =$ down	$H_1 = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix}$	$(1, 2, -1)$

- The general form of the superpotential preserving baryon and lepton number is :

$$W = \mathbf{h_U\, Q\, H_2\, U_c} + \mathbf{h_D\, Q\, H_1\, D_c} + \mathbf{h_E\, L\, H_1\, E_c} + \mu\, \mathbf{H_2\, H_1}$$

Yukawa couplings $\mathbf{h_U, h_D, h_L}$ are matrices in family space.

Family and gauge indices indices are suppressed. Doublets coupled in a SU(2) invariant way by $Q\,H_2 \equiv Q_i\,\epsilon_{ij}\;H_{2\,j}$, with $\epsilon_{i\,j}$ antisymmetric, with $\epsilon_{12} = 1$. Same for $Q\,H_1,\ LH_1,\ H_2H_1$.

- Baryon and Lepton number violating superpotentials are allowed by gauge symmetries :

$$W_{\Delta L} = \lambda'\,\mathbf{L\,Q\,D_c} + \lambda\,\mathbf{L\,L\,E_c} + \mu'\,\mathbf{L\,H_2}$$

$$W_{\Delta B} = \lambda''\,\mathbf{D_c\,D_c\,U_c}$$

They lead to fast Baryon and /or Lepton violating processes unless couplings unperceptibly small. Better be vanishing for naturaleness !

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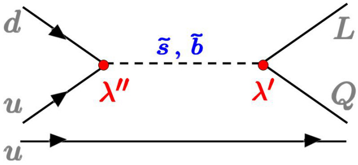
Proton decays fast unless $\lambda' \lambda''$ very small !



- **B, L - violating terms $W_{\Delta L, \Delta B}$ vanish if R - parity is imposed !**

R - parity = Conserved multiplicative quantum number under which each particle carries

$$P = (-1)^{3(B-L)+2S} \quad , \quad s = spin$$

Can arise if a gauge U(1) symmetry is broken at high scale by a vev $\langle \Phi \rangle$ with Φ carrying U(1) charge even integer of $3(B-L)$.

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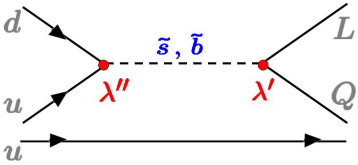

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Under R - Parity :

$$\begin{aligned} \textbf{SM} \quad \textbf{particles :} \quad & P = +1 \\ \textbf{SUSY} \quad \textbf{particles :} \quad & P = -1 \end{aligned}$$

Consequences :

- The LSP is stable since it cannot decay to SM particles ! If neutral it qualifies as a WIMP and is a good candidate for Dark Matter !
- In colliders sparticles are produced in even numbers.
- Heavier than the LSP sparticles eventually decay to odd number of LSPs, which escape detection with missing energy signatures.

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Soft $\not{S}USY$ terms and constraints on them

- No fermion - boson mass degeneracy is observed in nature and thus a SUSY breaking sector should be present !

$$\mathcal{L} = \mathcal{L}^{SUSY} + \Delta\,\mathcal{L}^{\not{S}USY}$$

The part $\Delta\mathcal{L}^{\not{S}USY}$ must not destabilize the hierarchy, **"soft breaking"** . Corrections to scalar masses are logarithmic in the cut - off scale Λ .

$$\delta m^2_{scalar} \sim g^2\, m^2_{susy}\, \log(\Lambda^2 / m^2_{susy})$$

- Sources of soft SUSY breaking can be (only !):

Gaugino masses	M_a
Scalar masses	m_{ij} , b_{ij}
Trilinear couplings	A_{ijk}

- The generic form of the "soft" breaking part :

$$\mathcal{L}_{soft} = -m_{ij}^2 \phi_i^* \phi_j - (b_{ij} \phi_i \phi_j + A_{ijk} \phi_i \phi_j \phi_k + \frac{M_a}{2} \lambda_a \lambda_a + h.c.)$$

  - Parameters depend on the particular scheme employed for the $\not{SUSY}$ and their number is large. The MSSM has 124 parameters !
  - In Supergravity models their values at highier scale, the Planck mass or a unification scale, depend on the gravitino mass $m_{3/2}$ and the way SUSY breaking is transmitted to the visible sector !
  - Their values at EW energies are set by solving the RGEs from this highier scale, to M_W .

- **Several options are available for SUSY breaking !**
- **Numerous terms are present but some of them have undesired features and better be absent !**

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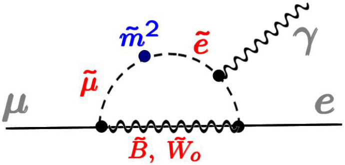
FCNC

FCNC processes restrict soft terms !

- $\mu \longrightarrow e\,\gamma$

A selectron - smuon mass term $\tilde{m}^2\,\tilde{\mu}_L^*\,\tilde{e}_L^*$ leads to $\mu \longrightarrow e\,\gamma$



The decay rate, in MeV :

$$\Gamma = 5 \times 10^{-25} \left(\frac{\tilde{m}^2}{M_{susy}}\right)^2 \left(\frac{1\ TeV}{M_{susy}}\right)^4$$

M_{susy} = maximum of selectrons, bino masses.

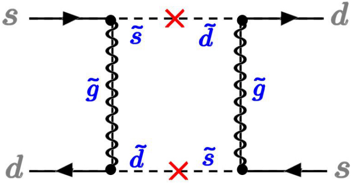
Compared with the experimental bound $\Gamma < 3.6 \times 10^{-27}\, MeV$

$$\tilde{m}^2 < 10^{-1} \left(\frac{M_{susy}}{1\ TeV} \right)^2 M_{susy}{}^2$$

- The flavor changing mass $\tilde{m}$ is bounded if $M_{susy} < 1\, TeV$!
  For $M_{susy} \simeq 0.5\, TeV$ then $\tilde{m} \simeq 80\, GeV$
- Bound weakens if M_{susy} is in the multi - TeV region !

$K_0 \Longleftrightarrow \overline{K}_0$

Mass terms $\tilde{m}_L^2 \tilde{d}_L^* \tilde{s}_L + \tilde{m}_R^2 \tilde{d}_R^* \tilde{s}_R$ generate $K_0 \longleftrightarrow \overline{K}_0$ transitions



Agreement with $\Delta m_{K_0} = 3.490 \pm 0.006 \times 10^{-12}\ MeV$ yields

$$\frac{\sqrt{\tilde{m}_L^2 \tilde{m}_R^2}}{M_{susy}^2} \leq 10^{-3} \left(\frac{M_{susy}}{500\ GeV} \right)$$

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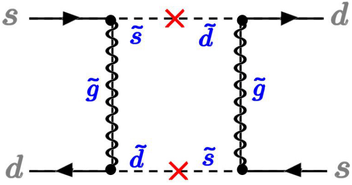

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FCNC processes impose stringent constraints on the $\mathbf{1^{st}}$, $\mathbf{2^{nd}}$ generation squark and slepton masses which can be avoided if :

- Some of the soft masses are in the multi-TeV range so that flavor - violating effects are suppressed. Contrary to the philosophy that SUSY breaking is related to the origin of the EW scale.
- They are naturally suppressed by a super - GIM mechanism !

This is implemented if,

1. **Universality :**
   Squark and Slepton masses are flavor diagonal !
2. **Alignment :**
   Soft $\tilde{q}, \tilde{l}$ masses and trilinear couplings are diagonalized by same rotations diagonalizing Yukawa matrices.

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CP violation

Soft SUSY breaking parameters are in general complex, introducing new CP - violating sources in addition to the CKM phase !

- Important for EW Baryogenesis
- Produce EDMs for elementary fermions and Atoms
- Affect the predictions for LSP relic densities
- Affect the sparticle mass spectrum
- Have large impact on Higgs-boson phenomenology
- Have impact on $B_s \to \mu^+\mu^-$ and $B \to K\phi$
- SUSY $\not{C}P$ phases can be observed in collider physics :
  Through $\tilde{q}, \tilde{g}$ production
  Squark decays ($\tilde{t} \to t + l^+ l^- + \tilde{\chi}$, observable at LHC)
  $e^+e^- \to f\bar{f}$ (observable at ILC)

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Minimal Flavor Violation in MSSM

In MFV models flavor violation resides in the CKM matrix !

- In MSSM the soft SUSY breaking Lagrangian is

$$\Delta \mathcal{L}^{\not{S}USY} =$$
$$- \tilde{Q}^\dagger \mathbf{m}_Q^2 \tilde{Q} - \tilde{U}_c^\dagger \mathbf{m}_U^2 \tilde{U}_c - \tilde{D}_c^\dagger \mathbf{m}_D^2 \tilde{D}_c - \tilde{L}^\dagger \mathbf{m}_L^2 \tilde{L} - \tilde{E}_c^\dagger \mathbf{m}_E^2 \tilde{E}_c$$
$$- m_{H_2}^2 |H_2|^2 - m_{H_1}^2 |H_1|^2 - (m_3^2 H_2 H_2 + h.c.)$$
$$-(\tilde{\mathbf{A}}_U^{ab} \tilde{Q}^a H_2 \tilde{U}_c^b + \tilde{\mathbf{A}}_D^{ab} \tilde{Q}^a H_1 \tilde{D}_c^b + \tilde{\mathbf{A}}_E^{ab} \tilde{L}^a H_1 \tilde{E}_c^b + h.c.)$$
$$-\frac{1}{2} (M_1 \tilde{B} \tilde{B} + M_2 \tilde{W} \tilde{W} + M_3 \tilde{g} \tilde{g} + h.c.)$$

$\mathbf{m}^2_{Q,U,D,L,E}$ and $\tilde{\mathbf{A}}_{U,D,E}$ matrices in family space and $a, b =$ family indices

- To implemented MFV in MSSM requires :
  - Soft squark and slepton masses be diagonal in family space :

$$(\mathbf{m_Q^2})_{ab} = m_Q^2 \, \delta_{ab} \quad \ldots$$

  - Soft trilinear couplings be proportional to Yukawa couplings :

$$(\mathbf{A_U})^{ab} = A_U \, h_U^{ab} \quad \ldots$$

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$$-\,m_{H_2}^2\,|H_2|^2 - m_{H_1}^2\,|H_1|^2 - (\,m_3^2\,H_2\,H_2 + h.c.\,)$$
$$-(\,\tilde{\mathbf{A}}_U^{ab}\,\tilde{Q}^a\,H_2\,\tilde{U}_c^b + \tilde{\mathbf{A}}_D^{ab}\,\tilde{Q}^a\,H_1\,\tilde{D}_c^b + \tilde{\mathbf{A}}_E^{ab}\,\tilde{L}^a\,H_1\,\tilde{E}_c^b + h.c.\,)$$
$$-\tfrac{1}{2}\,(\,M_1\,\tilde{B}\,\tilde{B} + M_2\,\tilde{W}\,\tilde{W} + M_3\,\tilde{g}\,\tilde{g} + h.c.)$$

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&- m^2_{H_2} |H_2|^2 - m^2_{H_1} |H_1|^2 - (m^2_3 H_2 H_2 + h.c.) \\
&- (\tilde{\mathbf{A}}_U^{ab} \tilde{Q}^a H_2 \tilde{U}_c^b + \tilde{\mathbf{A}}_D^{ab} \tilde{Q}^a H_1 \tilde{D}_c^b + \tilde{\mathbf{A}}_E^{ab} \tilde{L}^a H_1 \tilde{E}_c^b + h.c.) \\
&- \frac{1}{2} (M_1 \tilde{B} \tilde{B} + M_2 \tilde{W} \tilde{W} + M_3 \tilde{g} \tilde{g} + h.c.)
\end{aligned}
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In these models the non - SM parameters are :

$m^2_{Q,U,D}$ $m^2_{L,E}$	Squark – slepton soft masses^2
$m^2_{H_1}$ $m^2_{H_2}$	Higgs soft masses^2
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M_1 M_2 M_3	Bino, Wino, Gluino masses
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They are constrained by the EWSB conditions.

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mSUGRA

- Dramatic simplification in minimal Supergravity (mSUGRA):

$$\begin{aligned} m^2_{Q,U,D} = m^2_{L,E} = m^2_{H_1,H_2} &= m_0^2 \\ A_U = A_D = A_E &= A_0 \\ M_1 = M_2 = M_3 &= M_{1/2} \end{aligned}$$

Universal b.c. at M_{GUT} , the energy at which gauge couplings unify.

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Yukawa couplings is the only source of flavor - violation but parameters run ! At lower energies flavor - violation is passed to soft masses through the RGE evolution. The effect is small, since Yukawas of 1^{st} , 2^{nd} generations are small !

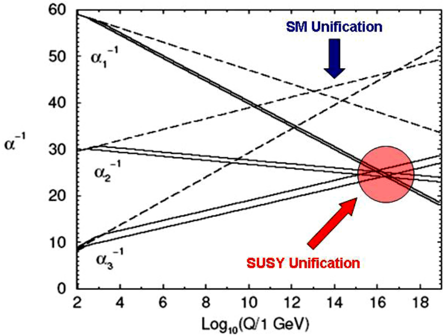
Gauge coupling unification

RGEs for the gauge couplings α_i , $i = 1, 2, 3$,

$$\frac{d\,\alpha_i^{-1}}{d\,\ln Q} = -\frac{b_i}{2\pi} + \text{two} - \text{loop}$$

Beta function coefficients different in SM and MSSM !

$$b_i^{SM} = (41/10\,,\,-19/6\,,\,-7) \quad , \quad b_i^{MSSM} = (33/5\,,1\,,\,-3)$$



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- Low energy SUSY thresholds in α_i are considered in more refined analyses.

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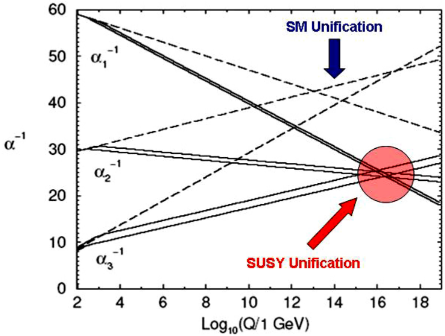

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Evolution of soft masses !

- The soft SUSY breaking parameters run with the energy scale and the complete RGEs are known to 2 - loops
(S. P. Martin & M .T. Vaughn, 1993, Y. Yamada, 1994) .

- Large top Yukawa coupling drives Higgs masses^2 negative towards small energies, signaling Radiative Electroweak Symmetry Breaking !

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Higgs soft masses, 1 - loop RGEs :

$$\frac{d\, m_{H_2}^2}{d \log Q} = \frac{1}{4\pi^2}\left(3\, h_t^2\, (m_{Q_3}^2 + m_{U_3}^2 + m_{H_2}^2 + A_t^2) - (3\, g_2^2\, M_2^2 + \frac{3}{10}\, g_1^2\, M_1^2) \right)$$

$$\frac{d\, m_{H_1}^2}{d \log Q} = \frac{1}{4\pi^2}\left(3\, h_b^2\, (m_{Q_3}^2 + m_{D_3}^2 + m_{H_1}^2 + A_b^2) - (3\, g_2^2\, M_2^2 + \frac{3}{10}\, g_1^2\, M_1^2) \right) + \frac{1}{4\pi^2}\, h_\tau^2\, (m_{L_3}^2 + m_{E_3}^2 + m_{H_1}^2 + A_\tau^2)$$

$$\frac{d\, m_3^2}{d \log Q} = \frac{1}{16\pi^2}\, m_3^2\, (3\, h_t^2 + 3\, h_b^2 + h_\tau^2 - 3\, g_2^2 - \frac{3}{5}\, g_1^2) + \frac{1}{8\pi^2}\, \mu\, (3\, A_t\, h_t^2 + 3\, A_b\, h_b^2 + 3\, A_\tau\, h_\tau^2 - 3\, g_2^2\, M_2 - \frac{3}{5}\, g_1^2\, M_1)$$

Hold in models, like mSUGRA, in which

$$S = m_{H_2}^2 - m_{H_1}^2 + Tr\, (m_Q^2 - m_L^2 - 2\, m_U^2 + m_D^2 + m_E^2) = 0$$

at some - and hence at any ! - scale

The dominant effect to the soft scalar masses stems from the top Yukawa, affecting most the Higgs soft mass $m^2_{H_2}$!

$$\frac{d}{d\log Q}\begin{pmatrix} m^2_{H_2} \\ m^2_{U_3} \\ m^2_{Q_3} \end{pmatrix} = \frac{h_t^2}{8\pi^2}\begin{pmatrix} 3 & 3 & 3 \\ 2 & 2 & 2 \\ 1 & 1 & 1 \end{pmatrix}\begin{pmatrix} m^2_{H_2} \\ m^2_{U_3} \\ m^2_{Q_3} \end{pmatrix} + \frac{h_t^2}{8\pi^2} A_t^2 \begin{pmatrix} 3 \\ 2 \\ 1 \end{pmatrix}$$

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- The Yukawa terms dominate over the negative gaugino contributions on Higgs mass but not in squark masses !
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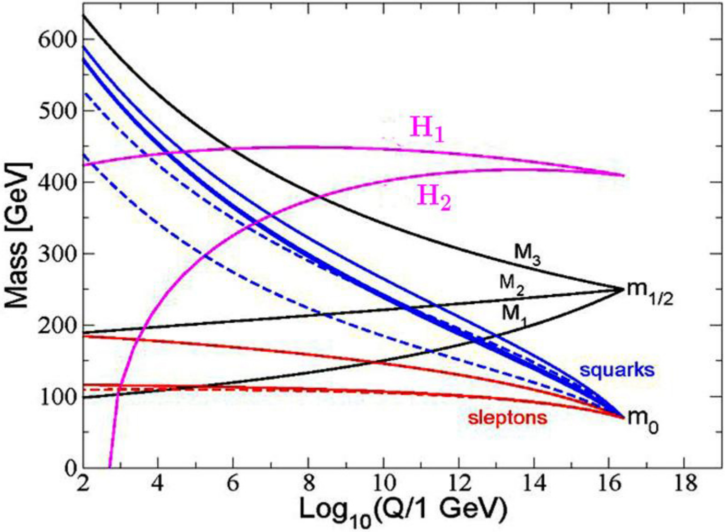

Evolution of soft mass parameters.

Radiative symmetry breaking

Seek minima in the neutral Higgs directions where the potential is :

$$V_0 = m_1^2 |H_1^0|^2 + m_2^2 |H_2^0|^2 + m_3^2 (H_1^0 H_2^0 + h.c.)$$
$$\frac{g^2 + g'^2}{8} \left(|H_1^0|^2 - |H_2^0|^2 \right)^2$$

Higgs mass parameters : $m_1^2 \equiv m_{H_1}^2 + \mu^2$, $m_2^2 \equiv m_{H_2}^2 + \mu^2$.
The condition for EW symmetry breaking is :

$$m_1^2 m_2^2 - m_3^4 < 0$$

The top Yukawa coupling drives $m_2^2 < 0$ and EW breaking occurs !
To ameliorate scale dependences 1-loop corrections should be included

$$\Delta V = \sum_{J=spin} (-1)^{2J} (2J+1) m_J^4(\phi) \left(ln\left(\frac{m_J^2}{Q^2}\right) - \frac{3}{2} \right)$$

- The Higgs vevs can be parametrized by

$$\langle H_1^0 \rangle = \frac{v}{\sqrt{2}} \cos\beta \ , \ \langle H_2^0 \rangle = \frac{v}{\sqrt{2}} \sin\beta$$

  - The value v is set by the Z - boson mass,

$$v^2 = \frac{4}{g^2 + g'^2} \left(M_Z^2 + \Pi_{ZZ}^T(M_Z) \right) \simeq (247\ GeV)^2$$

  - **tan** β sets the relative size of the two vevs,

$$\tan\beta = \langle H_2^0 \rangle / \langle H_1^0 \rangle$$

- The minimization conditions are :

$$\mu^2 = \frac{\overline{m}^2_{H_1} - \overline{m}^2_{H_2} \tan^2\beta}{\tan^2\beta - 1} - \frac{1}{2}\left(M_Z^2 + \Pi_{ZZ}^T(M_Z) \right)$$

$$\sin 2\beta = -\frac{2\, m_3^2}{\overline{m}^2_{H_1} + \overline{m}^2_{H_2} + 2\mu^2}$$

The masses $\overline{m}^2_{H_{1,2}}$ take care of the 1-loop corrections $\overline{m}^2_{H_{1,2}} = m^2_{H_{1,2}} + \frac{\partial^2 \Delta V}{\partial H^2_{1,2}}$

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Higgs masses

Define rotated Higgs fields S_1, S_2

$$S_1 = c_\beta \,(i\,\sigma_2\, H_1^*) + s_\beta\, H_2 \quad , \quad S_2 = - s_\beta \,(i\,\sigma_2\, H_1^*) + c_\beta\, H_2$$

Wth these definitions the Goldstone modes are along the S_1 direction,

$$S_1 = \begin{pmatrix} G_+ \\ (v + \xi_1 + i\, G_0)/\sqrt{2} \end{pmatrix} \quad , \quad S_2 = \begin{pmatrix} H_+ \\ (\xi_2 + i\, A)/\sqrt{2} \end{pmatrix}$$

- G_+ and its congugate are Goldstones eaten by $W^\pm$, and G_0 is the Goldstone eaten by the Z - boson.
- $H_\pm, \xi_1, \xi_2, , A$ are the five Higgs modes surviving the EW symmetry breaking !

ξ_1, ξ_2 are mixed and a rotation is needed to pass to mass eigenstates !

The rotation is parametrized by an angle α (calculable !)

$$\begin{pmatrix} H_0 \\ h_0 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \xi_1 \\ \xi_2 \end{pmatrix}$$

H_0, h_0 are the heavy / light CP - even mass eigenstates.

Higgs mass spectrum (without radiative corrections !)

A CP − odd :

$$m_A^2 = -2m_3^2 / \sin 2\beta$$

$H_\pm$ Charged :

$$m_{H_\pm}^2 = m_A^2 + m_W^2$$

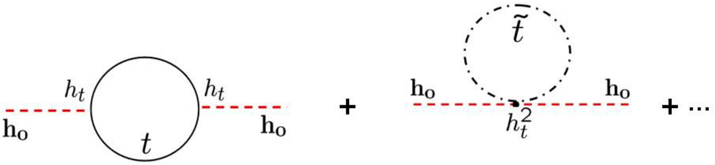
H_0, h_0 CP − even :

$$m_{H_0,\,h_0}^2 = \frac{1}{2}\left[m_A^2 + m_Z^2 \pm \sqrt{(m_A^2 + m_Z^2)^2 - 4\, m_Z^2\, m_A^2 \cos^2 2\beta} \right]$$

- The lightest Higgs is lighter than the Z - boson,

$$m_{h_0} < m_Z \, |\cos 2\beta|$$

top-stops radiative correction are sizable and lift m_{h_0} !



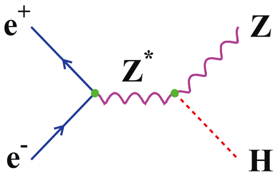
- The dominant corrections are

$$m_{h_0}^2 = m_Z^2 \cos^2 2\beta + \frac{3}{4\pi^2} h_t^2 m_t^2 \ln\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right) + \ldots$$

$\Longrightarrow$ the upper bound is lifted to $m_{h_0} \lesssim 135\ GeV$!

LEP2 Higgs bound

LEP2 did not discover Higgs in the associated Higgs production, at a C.M. energy **208 *GeV*** , putting a bound $m_{Higgs} > 114.5\ GeV$!



This assumes a SM Z - Z - Higgs coupling !

$$\mathcal{L}_{ZZh} = \frac{g\ m_z}{2\ \cos\theta_w}\ Z_\mu Z^\mu\ h_0$$

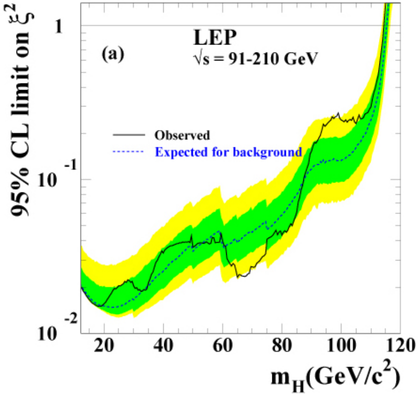
In the MSSM

$$\mathcal{L}_{ZZh} = \frac{g\ m_z}{2\ \cos\theta_w}\ \sin(\beta - \alpha)\ Z_\mu Z^\mu\ h_0$$

MSSM and SM couplings are different and cross sections are related by,

$$\sigma_{MSSM} = \xi^2 \sigma_{SM} \quad (\xi^2 \equiv \sin^2(\beta - \alpha))$$

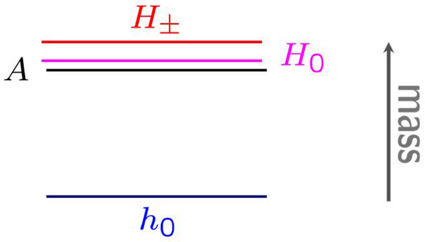
LEP2 data put a mass bound which depends on the ratio ξ^2



- The LEP2 bound $m_h > 114.5\ GeV$ applies when $\xi^2 = 1$
- In models with $\xi^2 < 1$ the bound weakens !

In the decoupling limit $m_A \gg m_Z$:

- $H_\pm$, H_0, A much heavier than h_0



- $\sin(\beta - \alpha) \simeq 1$ and the light Higgs h_0 acts like a SM Higgs, then the LEP2 bound applies !

This limit is realized in mSUGRA - like models

Squark & Slepton masses

3^d generation $\tilde{q}$, $\tilde{l}$ masses :

- The stop mass^2 matrix $\mathcal{M}^2_{\tilde{t}}$ in the $\tilde{t}_L, \tilde{t}_R \equiv \tilde{t}_L^{c\,*}$ basis

$$\begin{pmatrix} m^2_{\tilde{Q}_3} + m_t^2 + m_Z^2 \cos 2\beta\,(\frac{1}{2} - \frac{2}{3}\sin^2\theta_W) & m_t\,(A_t + \mu\cot\beta) \\ m_t\,(A_t + \mu\cot\beta) & m^2_{\tilde{U}_3} + m_t^2 + m_Z^2\cos 2\beta\,(\frac{2}{3}\sin^2\theta_W) \end{pmatrix}$$

Entries are $11 = \tilde{t}_L^* \tilde{t}_L$, $12 = \tilde{t}_L^* \tilde{t}_R$, $21 = \tilde{t}_R^* \tilde{t}_L$, $22 = \tilde{t}_R^* \tilde{t}_R$

- Diagonalize to find mass eigenstates $\tilde{t}_1, \tilde{t}_2$.
  - Off - diagonal terms are large $\sim m_t$ resulting to large Left - Right stop mixings.
  - Large mass splitting of $\tilde{t}_{1,2}$ due to the largeness of the off - diagonal terms in $\mathcal{M}^2_{\tilde{t}}$.

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Mass eigenstates $\tilde{b}_1, \tilde{b}_2$.

- The stau mass^2 matrix $\mathcal{M}^2_{\tilde{\tau}}$ in the $\tilde{\tau}_L, \tilde{\tau}_R \equiv \tilde{\tau}^{c\,*}_L$ basis

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$$\begin{pmatrix} m^2_{Q_3} + m^2_b + m^2_Z \cos 2\beta\,(-\frac{1}{2} + \frac{1}{3}\sin^2\theta_W) & m_b\,(A_b + \mu\tan\beta) \\ m_b\,(A_b + \mu\tan\beta) & m^2_{D_3} + m^2_b + m^2_Z \cos 2\beta\,(-\frac{1}{3}\sin^2\theta_W) \end{pmatrix}$$

Mass eigenstates $\tilde{b}_1, \tilde{b}_2$.

- The stau mass^2 matrix $\mathcal{M}^2_{\tilde{\tau}}$ in the $\tilde{\tau}_L, \tilde{\tau}_R \equiv \tilde{\tau}^{c\,*}_L$ basis

$$\begin{pmatrix} m^2_{L_3} + m^2_\tau + m^2_Z \cos 2\beta\,(-\frac{1}{2} + \sin^2\theta_W) & m_\tau\,(A_\tau + \mu\tan\beta) \\ m_\tau\,(A_\tau + \mu\tan\beta) & m^2_{D_3} + m^2_\tau + m^2_Z \cos 2\beta\,(\sin^2\theta_W) \end{pmatrix}$$

Mass eigenstates $\tilde{\tau}_1, \tilde{\tau}_2$.

- Third generation sneutrino, $\tilde{\nu}_\tau$, with mass (when $m_{\nu_\tau} \simeq 0$)

$$m^2_{\tilde{\nu}_\tau} = m^2_{L_3} + \frac{1}{2} m^2_Z \cos 2\beta$$

1^{st} 2^{nd} generation :

Left and Right-handed squarks and sleptons are almost mass eigenstates since negligible mixing of the Left and Right-handed components, due to the lightness of the fermion masses $\Longrightarrow$ $\tilde{u}_1 \simeq \tilde{u}_R$, $\tilde{u}_2 \simeq \tilde{u}_L$ etc.

Mass	*eigenstates*
$\tilde{u}_L$, $\tilde{u}_R$ $\tilde{d}_L$, $\tilde{d}_R$ $\tilde{e}_L$, $\tilde{e}_R$, $\tilde{\nu}_e$	1^{st} generation
$\tilde{c}_L$, $\tilde{c}_R$ $\tilde{s}_L$, $\tilde{s}_R$ $\tilde{\mu}_L$, $\tilde{\mu}_R$, $\tilde{\nu}_\mu$	2^{nd} generation

$$m^2_{\tilde{u}_L} = m^2_{Q_1} + m^2_u + m^2_Z \cos 2\beta \left(-\frac{1}{2} + \frac{1}{3} \sin^2 \theta_W \right)$$

$$m^2_{\tilde{u}_R} = m^2_{U_1} + m^2_u + m^2_Z \cos 2\beta \left(-\frac{1}{3} \sin^2 \theta_W \right)$$

.....

Charginos

With $\tilde{W}^{\pm} \equiv (\tilde{W}^1 \mp i\,\tilde{W}^2)/\sqrt{2}$ the chargino mass term

$$\mathcal{L} = -(\tilde{W}^-, i\,\tilde{H}_1^-)\,\mathcal{M}_c \begin{pmatrix} \tilde{W}^+ \\ i\,\tilde{H}_2^+ \end{pmatrix} + h.c.$$

Chargino mass matrix

$$\mathcal{M}_c = \begin{pmatrix} M_2 & -g\,\langle H_2^0 \rangle \\ \langle H_1^0 \rangle & \mu \end{pmatrix}$$

Diagonalizing $U\,\mathcal{M}_c\,V^{\dagger}$ = diagonal leads to two "Dirac" mass eigenstates, $\tilde{\chi}_1^+$, $\tilde{\chi}_2^+$, made of $(\tilde{W}^+, \tilde{H}_2^+)$ and $(\tilde{W}^{-\,*}, \tilde{H}_1^{-\,*})$.

Chargino masses :

$$m_{\tilde{\chi}_{1,2}} = \frac{1}{2}\,(M_2{}^2 + \mu^2 + 2\,m_W^2) \mp \frac{1}{2}\sqrt{(M_2{}^2 + \mu^2 + 2\,m_W^2)^2 - 4\,|\,\mu\,M_2 - m_W^2\,\sin 2\,\beta\,|^2\,)}$$

Charginos

- In the limit $|M_2|$, $|\mu| \gg m_W$ the eigenstates are mostly Wino and Higgsino - like

States	Masses	
Wino	$\simeq$	$|M_2|$
Higgsino	$\simeq$	$|\mu|$

Neutralinos

In the basis $\Psi^T \equiv (\tilde{B}, \tilde{W}^3, i\tilde{H}_1^0, i\tilde{H}_2^0)$ the neutralino mass term

$$\mathcal{L} = -\frac{1}{2}\Psi^T \mathcal{M}_N \Psi + h.c.$$

Neutralino mass matrix (symmetric)

$$\mathcal{M}_N = \begin{pmatrix} M_1 & 0 & g'\langle H_1^0\rangle & -g'\langle H_2^0\rangle \\ 0 & M_2 & -g\langle H_1^0\rangle & g\langle H_2^0\rangle \\ g'\langle H_1^0\rangle & -g\langle H_1^0\rangle & 0 & -\mu \\ -g'\langle H_2^0\rangle & g\langle H_2^0\rangle & -\mu & 0 \end{pmatrix}$$

Diagonalization leads to formation of 4 "Majorana" neutral fermions

$$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$$

with masses

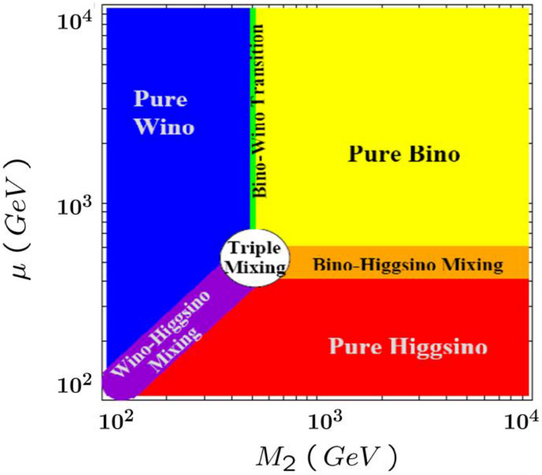
$$m_{\tilde{\chi}_1^0} < m_{\tilde{\chi}_2^0} < m_{\tilde{\chi}_3^0} < m_{\tilde{\chi}_4^0}$$

- When EW breaking efects small, $|M_{1,2}|, |\mu| \gg m_W$,
  the 4 - eigenstates are mostly a Bino a Wino and two Higgsinos,

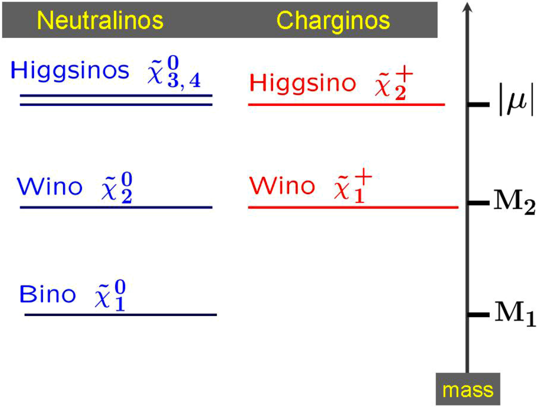
States		Masses
Bino $\tilde{B}$	$\simeq$	$\lvert M_1 \rvert$
Wino $\tilde{W}^3$	$\simeq$	$\lvert M_2 \rvert$
Higgsino $\tilde{H}_1^0 + \tilde{H}_2^0$	$\simeq$	$\lvert \mu \rvert$
Higgsino $\tilde{H}_1^0 - \tilde{H}_2^0$	$\simeq$	$\lvert \mu \rvert$

- The lightest neutralino state may be the LSP and is thus a perfect candidate for **Cold Dark Matter** !
  In the major portion of the parameter space of mSUGRA the LSP is the Bino, but other options are available.

Composition of neutralino LSP in mSUGRA (Masiero, Profumo, Ullio)



- In a typical mSUGRA case $M_1 \simeq 0.5\, M_2 < |\mu|$. Then the bino is the lightest of the neutralinos / charginos. The remaining neutralino states are degenerate in mass with the charginos.



Gluinos

The 8 - gluinos $\tilde{g}$ are colored fermions, not mixed with anything else !
Their masses

$$M_{\tilde{g}} = M_3$$

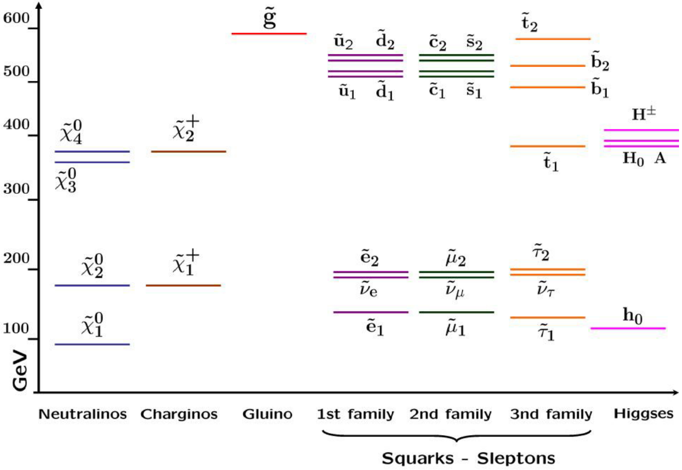
but QCD radiative corrections large !
From the pole of the gluino propagator

$$M_{\tilde{g}} = M_3(Q)\left(1 + \frac{\alpha_s}{4\pi}[15 + 6\ln(Q/M_3)] + S_q\right)$$

- Result independent of the renormalization scale Q .
- S_q = squark - quark loop corrections, can be as large as 20 % !

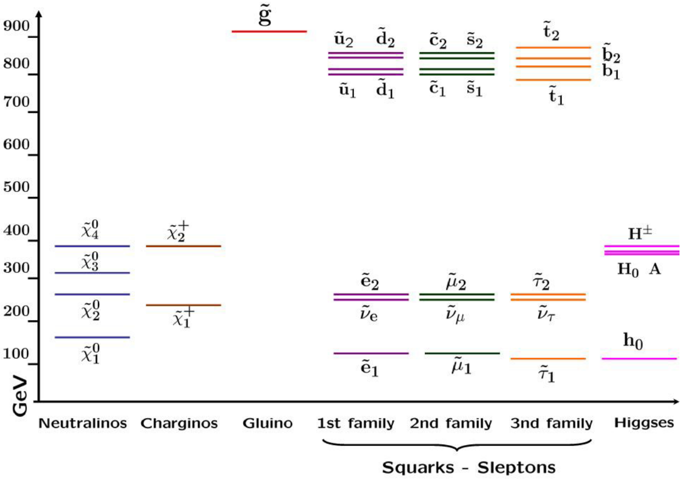
mSUGRA mass spectrum :

$$m_0 = 100 \,,\ M_{1/2} = 100 \,,\ A_0 = -100 \,,\ \tan\beta = 10 \,,\ \mu > 0$$



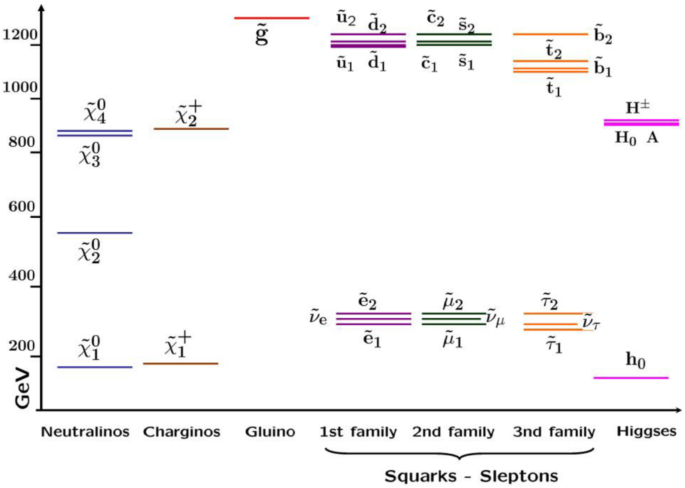
GMSB mass spectrum :

$\Lambda = 40\ TeV\ ,\ M_{mess} = 80\ TeV\ ,\ N_{mess} = 3\ ,\ \tan\beta = 15\ ,\ \mu > 0$



AMSB mass spectrum :

$$m_0 = 400\ GeV\ ,\ m_{3/2} = 60\ TeV\ ,\ \tan\beta = 10\ ,\ \mu > 0$$



From LEP2 to LHC

Citation: C. Amsler et al. (Particle Data Group), PL B667, 1 (2008) and 2009 partial update for the 2010 edition (URL: http://pdg.lbl.gov)

SEARCHES FOR MONOPOLES, SUPERSYMMETRY, TECHNICOLOR, COMPOSITENESS, EXTRA DIMENSIONS, etc.

Magnetic Monopole Searches

Isolated supermassive monopole candidate events have not been confirmed. The most sensitive experiments obtain negative results.

Best cosmic-ray supermassive monopole flux limit:

$< 1.0 \times 10^{-15}$ cm^{-2}sr^{-1}s^{-1} for $1.1 \times 10^{-4} < \beta < 0.1$

Supersymmetric Particle Searches

Limits are based on the Minimal Supersymmetric Standard Model.

Assumptions include: 1) $\tilde{\chi}_1^0$ (or $\tilde{\gamma}$) is lightest supersymmetric particle; 2) R-parity is conserved; 3) With the exception of $\tilde{t}$ and $\tilde{b}$, all scalar quarks are assumed to be degenerate in mass and $m_{\tilde{q}_R} = m_{\tilde{q}_L}$. 4) Limits for sleptons refer to the $\tilde{\ell}_R$ states. 5) Gaugino mass unification at the GUT scale.

See the Particle Listings for a Note giving details of supersymmetry.

$\tilde{\chi}_i^0$ — neutralinos (mixtures of $\tilde{\gamma}$, $\tilde{Z}^0$, and $\tilde{H}_i^0$)

Mass $m_{\tilde{\chi}_1^0} >$ 46 GeV, CL = 95%
[all tanβ, all m_0, all $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$]

Mass $m_{\tilde{\chi}_2^0} >$ 62.4 GeV, CL = 95%
[1<tanβ <40, all m_0, all $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$]

Mass $m_{\tilde{\chi}_3^0} >$ 99.9 GeV, CL = 95%
[1<tanβ <40, all m_0, all $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$]

Mass $m_{\tilde{\chi}_4^0} >$ 116 GeV, CL = 95%
[1<tanβ <40, all m_0, all $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$]

Sparticle mass limits PDG, 2009

Sparticle	Mass limit (in GeV)
$\tilde{\chi}_i^0$	46, 62.4, 99.9, 116
$\tilde{\chi}_1^+$	94
$\tilde{e}_R$	73
$\tilde{\mu}_R$	94
$\tilde{\tau}_R$	82
$\tilde{q}_{RL}$	380 ?
$\tilde{b}_{RL}$	89
$\tilde{t}_{RL}$	96
$\tilde{g}$	308 *

* The lower limit (conservative) is quoted, if more than one is displayed in PDG book !

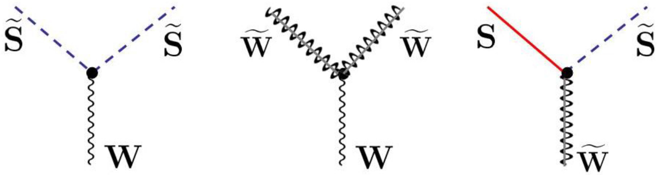
Assumptions :

- MSSM with Neutralino LSP
- R - parity is conserved
- L, R - handed squarks degenerate in mass except stop, sbottom
- Gaugino mass unification is assumed

Supersymmetry in colliders

The dominant interactions to produce sparticles in colliders are gauge interactions or interactions related to these by SUSY

W = gauge boson , $\widetilde{\mathrm{W}}$ = gaugino



S = quark, lepton or Higgs
$\widetilde{\mathrm{S}}$ = squark, slepton or Higgsino

Supersymmetry in colliders

- **Assume that R - parity is conserved and LSP is the neutralino.**
- **2 sparticles produced in each event with opposite momenta.**
- **LSPs are neutral interact weakly and carry away E and $\vec{p}$.**

Supersymmetry in colliders

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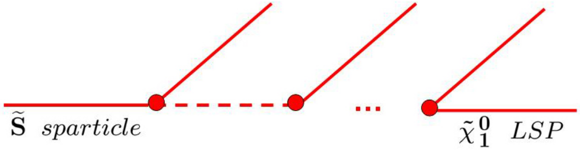
The produced sparticles are observed by their decays.

Sparticles decay to LSP, via multi-step-cascade processes, which escapes detection, identified as missing transverse energy, $\not{E}_T$, in hadron colliders (or missing energy in $e^+ e^-$).

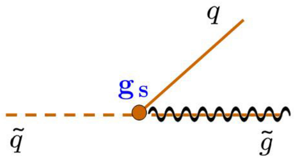


Supersymmetry in colliders

$\tilde{\mathbf{q}}, \tilde{\mathbf{g}}$ are heavy states, strongly interacting, and if not extremely heavy will have large production X-sections with $\tilde{\mathbf{q}}\tilde{\mathbf{q}}$, $\tilde{\mathbf{g}}\tilde{\mathbf{g}}$, $\tilde{\mathbf{q}}\tilde{\mathbf{g}}$ in the final state.

Squark, $\tilde{q}_{L,R}$, decays

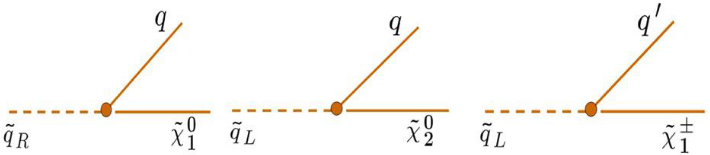
- If the decay $\tilde{q} \rightarrow \tilde{g}\, q$ is kinematically accessible will dominate and the gluino will decay to jets and $\not{E}_T$, or jets + leptons and $\not{E}_T$!



Decay $\tilde{q} \longrightarrow q + \tilde{g}$

The gluino decays to produce jets and $\not{E}_T$,.

- If not kinematically allowed the preferred decays are $\tilde{q}_R \longrightarrow$ Bino-like LSP + quark or $\tilde{q}_L \longrightarrow$ Wino-like chargino or heavy neutralino



Gluino, $\tilde{g}$, decays

- Gluino decays through squarks (virtually or on-shell)

Gluino decay	Signature
$\tilde{g} \longrightarrow q\,\bar{q}\;\; \tilde{\chi}_1^0$	$j\,j + \not{E}_T$
$\tilde{g} \longrightarrow q\,\bar{q} + f\,\bar{f} + \tilde{\chi}_1^0$	$4j + \not{E}_T$, $2j + l^+ l^- + \not{E}_T$
$\tilde{g} \longrightarrow q\,\bar{q}' + f\,\bar{f}' + \tilde{\chi}_1^0$	$4j + \not{E}_T$, $2j + l^{\pm} + \not{E}_T$

- The single lepton signal has same probability for either charge and events

$$l^+ \, l'^+ + jets + \not{E}_T$$

are likely to be seen. The corresponding SM backgrounds are small !

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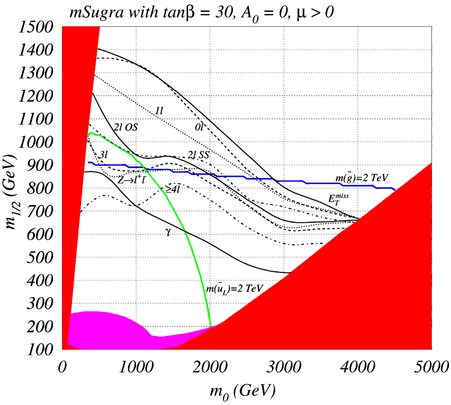
LHC



- In mSUGRA, with 100 fb^{-1} integrated luminosity, the LHC reach for low m_0 extends to $M_{1/2} < 1.4$ *TeV* corresponding to $m_{\tilde{q},\tilde{g}} \simeq 3$ *TeV* .
- For large m_0 , sfermions are too heavy to be produced and the LHC reach comes only from $\tilde{g}$ pair production for $M_{1/2}$ up to ~ 700 *GeV* equivalent to $m_{\tilde{g}} \simeq 2$ *TeV* .

Tevatron at $\sqrt{s} = 1.96\ TeV$

The production

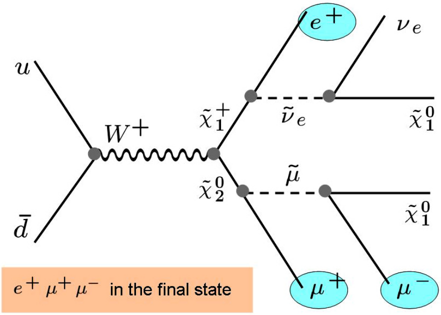
$$p\,\bar{p} \longrightarrow \tilde{\chi}_1^{\pm} + \tilde{\chi}_2^{0} \ldots$$

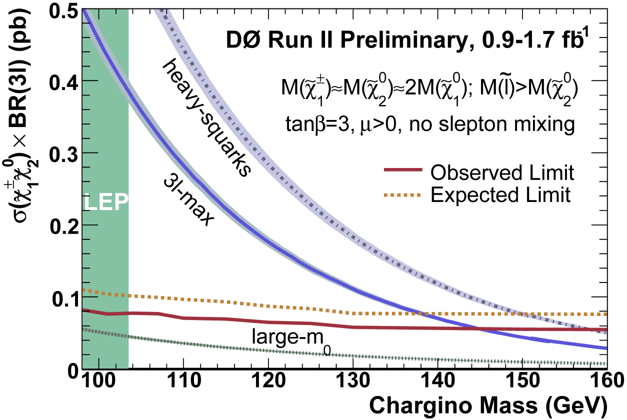
followed by the decays

$$\tilde{\chi}_2^{0} \longrightarrow l^+\,l^- + \tilde{\chi}_1^{0} \quad , \quad \tilde{\chi}_1^{\pm} \longrightarrow l^{\pm}\,\nu + \tilde{\chi}_1^{0}$$

gives a **trilepton signal** with 3 - leptons and missing energy

$$p\,\bar{p} \longrightarrow l'^{\pm}\,l^+\,l^- + \not{E}_T$$





Tevatron trilepton search limits, in the mSUGRA model for specific inputs.

Other signals :

- Gluino and squark pair production

$$p\,\bar{p} \longrightarrow \tilde{g}\,\tilde{g}\,,\tilde{g}\,\tilde{q}\,,\tilde{q}\,\tilde{q}$$

yields events with $4j$, $3j$ or $2j$ and $\not{E}_T$ in the final state.

- Additional signals,

Like charge dilepton	$p\,\bar{p} \longrightarrow \tilde{g}\,\tilde{g}$	$jets + l^{\pm}\,l^{\pm} + \not{E}_T$
Multi b-jet + $\not{E}_T$	$p\,\bar{p} \longrightarrow \tilde{g}\,\tilde{g}$	$b\,\bar{b}\,b\,\bar{b} + \not{E}_T$
Light top squark	$p\,\bar{p} \longrightarrow \tilde{t}_1\,\tilde{t}_1^*$	$jj + \not{E}_T$

.....

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.....

An extra light gravitino ?

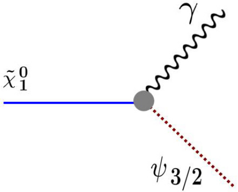
- Some models, like GMSB, predict a very light gravitino $\psi_{3/2}$ which plays the role of the LSP !
- The NLSP decays to it through

$$\mathbf{NLSP \longrightarrow SM - particle + \psi_{3/2}}$$

and its decay length varies from a few microns to a few kilometers !

If the NLSP is $\tilde{\chi}_1^0$:

It decays to a photon and a gravitino

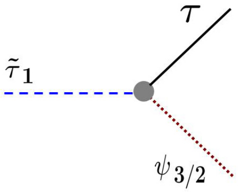


- If decays late, outside the detector, the discovery signals are as discussed !
- If its decay is delayed, but occurs within the detector, we should look for events with photons !
- If $\tilde{\chi}_1^0$ decays are prompt the SUSY event will be tagged by two energetic isolated photons !

$$\gamma\gamma + \textbf{anything} + \not{E}_T$$

If the NLSP is the $\tilde{\tau}$:

It decays to a tau and a gravitino



- If decays late, outside the detector, should look for slow ionizing tracks withn the detector !
- If $\tilde{\tau}$ decays are prompt the SUSY event is tagged by two energetic isolated tau's !

Conclusions

- Models of low energy Supersymmetry predict new particles, SUSY particles or sparticles, with masses in the TeV scale. Supersymmetry is within LHC reach !
- Absence of sparticle discovery so far has put limits on their masses and constrains the parameters of any theoretical model !
- SUSY predicts candidates for CDM and WMAP data, astrophysical data, and other DM searches constrain SUSY theories more than accelerator experiments (at the present stage).
- The hope is that the next generation experiments will not just put limits on sparticle masses but discover SUSY !

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