Introduction to SUSY

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Why physics beyond the Standard Model?

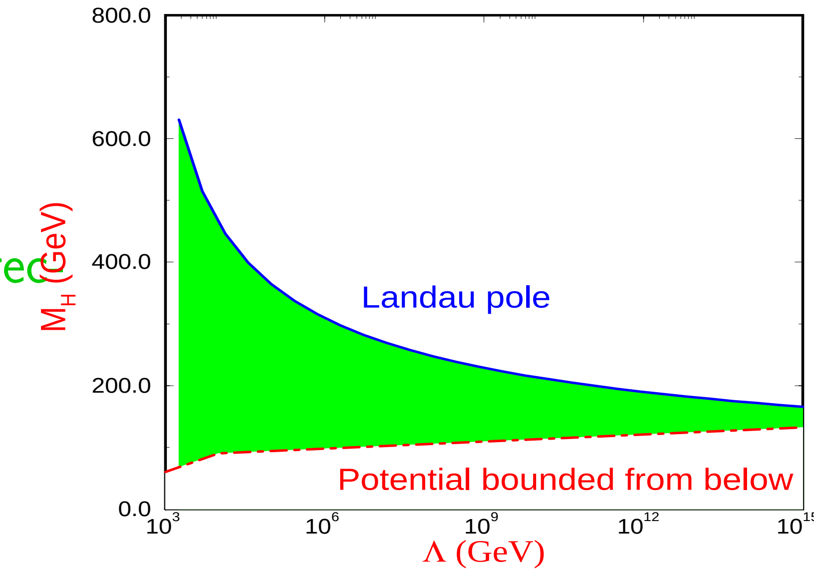
- Gravity is not yet incorporated in the Standard Model
- Hierarchy/Naturalness problem

Standard Model only valid up to scale $\Lambda < M_{pl}$

(ex: M_H =115 GeV $\Rightarrow \Lambda < 10^6$ GeV)

Higgs mass becomes unstable to quantum corrections: from sfermion loops,

$$\delta m_H^2 \propto \lambda_f^2 \Lambda^2$$

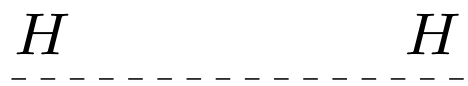


- Additional problems: Unification of couplings, Flavour/family problem

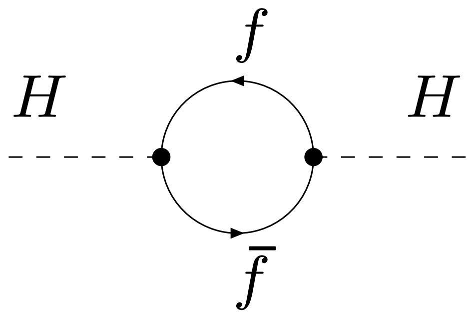
Need a more fundamental theory of which SM is low-E approximation

Hierarchy problem

Mass is what determines the properties of the free propagator of a particle

Free propagation 

inverse propagator: $i(p^2 - M_H^2)$

Loop correction 

inverse propagator: $i(p^2 - M_H^2 + \Delta m_H^2)$

Consider coupling of higgs to fermion f with term -$\lambda_f H \bar{f} f$. Correction is:

$$\Delta m_H^2 \sim \frac{\lambda_f^2}{4\pi^2}(\Lambda^2 + m_f^2) + ...$$

Where Λ is high-energy cutoff to regulate loop integral, energy where new physics alters high-energy behaviour of theory

If $\Lambda \sim M_{Planck} \sim 10^{18}$ GeV , need counterterms fine-tuned to 16 orders of magnitude to regularize higgs mass

Consider now interaction with a scalar $\tilde{f}$, of the form $-\lambda_{\tilde{f}}^2 H^2 \tilde{f}^2$

Quantum correction becomes:

$$\Delta m_H^2 \sim -\frac{\lambda_{\tilde{f}}^2}{4\pi^2}(\Lambda^2 + m_{\tilde{f}}^2) + ...$$

Considering the existence of N_f fermionic degrees of freedom and $N_{\tilde{f}}$ scalar partners, the correction becomes

$$\Delta m_H^2 \sim (N_f \lambda_f^2 - N_{\tilde{f}} \lambda_{\tilde{f}}^2)\Lambda^2 + \sum (m_f^2)_i - \sum (m_{\tilde{f}}^2)_i$$

$\Rightarrow$ quadratic divergences cancel if:

$$N_{\tilde{f}} = N_f$$

$$\lambda_{\tilde{f}}^2 = \lambda_f^2$$

Complete correction vanishes furthermore if for each f $\tilde{f}$ pair

$$m_{\tilde{f}} = m_f$$

Alternative approaches:

- Strong Dynamics
  - New, higher scale QCD: technicolor
  - No Higgs, natural low scale, Resonances predicted in VV scattering
  - Extended TC (Fermion masses), walking TC (avoid FCNC), top-color assisted TC (top mass)
  - Highly contriven, strong constraints from precision EW measurements
- Little Higgs
  - Enlarged symmetry group with gauged subgroup
  - Higgs as Goldstone boson $\Rightarrow$ natural low mass. New fermions, vectors and scalar bosons
  - Strong constaints from precision EW measurements
- Extra-Dimensions
  - Hierarchy generated by geometry of space-time
  - Rich array of models and signatures, studied in detail for the LHC

Supersymmetry

Systematic cancellation of quadratic divergences through a symmetry of lagrangian

Involved symmetry ought to relate fermions and bosons: operator Q generating symmetry must be spinor with:

$$Q|\text{boson}\rangle = |\text{fermion}\rangle \qquad \text{Q}|\text{fermion}\rangle = |\text{boson}\rangle$$

Algebra of such operator highly restricted by general theorems:

$$\{Q, Q^\dagger\} = P^\mu$$

$$\{Q, Q\} = \{Q^\dagger, Q^\dagger\} = 0$$

$$[P^\mu, Q] = [P^\mu, Q^\dagger] = 0$$

Where P^μ is the momentum generator of space-time translations

It can be demonstrated that starting from this algebra the conditions for cancellation of quadratic divergences are achieved:

• Single-particle states of SUSY theory fall into irreducible representations of the SUSY algebra called supermultiplets

• SUSY generator commute with gauge generators: particles in same multiplet have the same gauge numbers: $\lambda^2_{\tilde{f}} = \lambda^2_f$

• It can be demonstrated (see Martin) that each multiplet must contain the same number of bosonic and fermionic degrees of freedom: $n_B = n_F$

Most relevant supermultiplets:

- Chiral supermultiplet: $-\frac{1}{2}$, 0

  Weyl fermion (two helicity states, $n_F = 2$) + two real scalars (each with $N_b = 1$)

- Vector supermultiplet:-1, $-\frac{1}{2}$

  Massless gauge boson (2 helicity states, $n_B = 2$) + Weyl fermion ($N_F = 2$)

- Graviton supermultiplet: -2, $-\frac{3}{2}$

  graviton+gravitino

Write lagrangian invariant under SUSY trasformation

Masses of SUSY particles

Consider fermionic state $|f\rangle$ with mass m

$\Rightarrow$ there is a bosonic state $|b\rangle = Q_\alpha |f\rangle$

$$P^2|f\rangle = m^2|f\rangle$$

$$\Rightarrow P^2|b\rangle = P^2 Q_\alpha |f\rangle = Q_\alpha P^2 |f\rangle = Q_\alpha m^2 |f\rangle = m^2 |b\rangle$$

$\Rightarrow$ for each fermionic state there is a bosonic state with the same mass

This means that for each particle we should have a superparticle with same mass and couplings: this should have been observed since a long time

No possible particle-sparticle pair among the observed particles

$\Rightarrow$ SUSY must be broken

SUSY breaking

From theoretical point of view expect SUSY to be an exact symmetry which is spontaneously broken, but No consensus on how this should be done

Parametrize our ignorance introducing extra terms which break SUSY explicitly

Soft SUSY-breaking terms: do not re-introduce quadratic divergences in the theory

Possible terms:

- Mass terms $M_\lambda \lambda^a \lambda^a$ for each gauge group
- Scalar (mass)^2 $(m^2)^i_j \phi^{j*} \phi_i$ terms
- Bilinear $b^{ij} \phi_i \phi_j$ (scalar)^2 mixing terms
- Trilinear $a^{ijk} \phi_i \phi_j \phi_k$ (scalar)^3 mixing terms

Minimal Supersymmetric Standard Model

SUSY model with soft breaking of SUSY and minimal particle content:

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

- Gaugino mass terms. Parameters: M_1, M_2, M_3
- Trilinear $\tilde{f}\tilde{f}H$ terms. Parameters $\mathbf{a_u}$, $\mathbf{a_d}$, $\mathbf{a_e}$
- Sfermion mass terms. Parameters $\mathbf{m^2_Q}$, $\mathbf{m^2_L}$, $\mathbf{m^2_{\overline{u}}}$, $\mathbf{m^2_{\overline{d}}}$, $\mathbf{m^2_{\overline{e}}}$
- SUSY breaking contributions to Higgs potential. Parameters: $m^2_{H_u}$, $m^2_{H_d}$, b

$\mathbf{a_f}$ and $\mathbf{m^2_f}$ complex 3×3 matrices $\Rightarrow$ model has 105 parameters!

Why two higgs doublets

Consider fermion mass terms in SM case:

$$\mathcal{L}_{SM} = m_d \bar{Q}_L H d_R + m_u \bar{Q}_L \tilde{H} u_R$$

$$Q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L \quad \tilde{H} = i\sigma_2 H^\dagger \quad H \rightarrow \begin{pmatrix} 0 \\ v \end{pmatrix} \quad \tilde{H} \rightarrow \begin{pmatrix} v \\ 0 \end{pmatrix}$$

In SUSY: term $\bar{Q}_L H^\dagger$ not allowed

(For SUSY invariance superpotential must depend only on ϕ_i and not on ϕ_i^*)

No soft SUSY-breaking terms allowed for chiral fermions

$\Rightarrow$ H_u and H_d needed to give masses to down- and up-type fermions

Additional theoretical motivation: two doublets needed for cancellation of triangle gauge anomaly

List of MSSM supermultiplets

Fermions, sfermions:

Left-handed chiral supermultiplets.

Use convention in which all supermultiplets are defined in terms of left-handed Weyl spinors, conjugates of right-handed quarks and leptons appear in supermultiplets

- Q: quark, squark SU(2) doublets
- U: up-type quark, squark singlets
- D: down type quark, squark singlets
- L: lepton, slepton SU(2) doublets
- E: lepton, slepton singlets

Each generation of SM fermions with superpartners described by five chiral supermultiplets

Gauge bosons, gauginos:

Vector supermultiplets:

- gluons g and gluinos $\tilde{g}$
- W bosons and winos $\tilde{W}$
- B boson and bino $\tilde{B}$

Higgs bosons, higgsino

Chiral supermultiplets

In MSSM: two higgs doublets needed: two chiral supermultiplets

Chiral and vector supermultiplets

Names		spin 0	spin 1/2	$SU(3)_C,\ SU(2)_L,\ U(1)_Y$
squarks, quarks	Q	$(\tilde{u}_L\ \ \tilde{d}_L)$	$(u_L\ \ d_L)$	$(\ \mathbf{3},\ \mathbf{2}\ ,\ \frac{1}{6})$
($\times 3$ families)	$\overline{u}$	$\tilde{u}^*_R$	$u^\dagger_R$	$(\ \overline{\mathbf{3}},\ \mathbf{1},\ -\frac{2}{3})$
	$\overline{d}$	$\tilde{d}^*_R$	$d^\dagger_R$	$(\ \overline{\mathbf{3}},\ \mathbf{1},\ \frac{1}{3})$
sleptons, leptons	L	$(\tilde{\nu}\ \ \tilde{e}_L)$	$(\nu\ \ \ e_L)$	$(\ \mathbf{1},\ \mathbf{2}\ ,\ -\frac{1}{2})$
($\times 3$ families)	$\overline{e}$	$\tilde{e}^*_R$	$e^\dagger_R$	$(\ \mathbf{1},\ \mathbf{1},\ 1)$
Higgs, higgsinos	H_u	$(H_u^+\ \ \ H_u^0)$	$(\widetilde{H}_u^+\ \ \ \widetilde{H}_u^0)$	$(\ \mathbf{1},\ \mathbf{2}\ ,\ +\frac{1}{2})$
	H_d	$(H_d^0\ \ \ H_d^-)$	$(\widetilde{H}_d^0\ \ \ \widetilde{H}_d^-)$	$(\ \mathbf{1},\ \mathbf{2}\ ,\ -\frac{1}{2})$

Names	spin 1/2	spin 1	$SU(3)_C,\ SU(2)_L,\ U(1)_Y$
gluino, gluon	$\tilde{g}$	g	$(\ \mathbf{8},\ \mathbf{1}\ ,\ 0)$
winos, W bosons	$\widetilde{W}^\pm\ \ \ \widetilde{W}^0$	$W^\pm\ \ \ W^0$	$(\ \mathbf{1},\ \mathbf{3}\ ,\ 0)$
bino, B boson	$\widetilde{B}^0$	B^0	$(\ \mathbf{1},\ \mathbf{1}\ ,\ 0)$

Additional ingredient:

To guarantee lepton and baryon number conservation require conservation of new quantum number, R-parity:

$$R = (-1)^{3(B-L)+2S}$$

Consequences:

- Lightest Supersymmetric Particle (LSP) is stable
- All sparticle eventually decay to the LSP
- Sparticles produced in pairs

R-parity conservation imposed 'by hand' on the theory

Need to avoid contrast with basic experimental observations such as the suppression of Flavour changing neutral currents $\Rightarrow$ impose constraints on soft SUSY breaking:

- Squark and slepton mass matrices flavour blind (avoid FCNC, LFV): each proportional to 3×3 identity matrix in family space.
- Trilinear couplings proportional to the corresponding Yukawa coupling matrix
- No new complex phases in soft parameters (avoid CP violation effects)

Constraints normally implemented in existing studies

Additional optional constraint in many models: gaugino soft terms are proportional to coupling constants of respective groups:

$$\frac{M_1}{\alpha_1} = \frac{M_2}{\alpha_2} = \frac{M_3}{\alpha_3}$$

After all constraints number of model parameters: $\sim 15 - 20$

The SUSY Zoo

quarks	$\longrightarrow$	squarks	$\tilde{q}_L$, $\tilde{q}_R$	
leptons	$\longrightarrow$	sleptons	$\tilde{\ell}_L$ $\tilde{\ell}_R$	
$W^{\pm}$	$\longrightarrow$	winos	$\tilde{\chi}^{\pm}_{1,2}$	charginos
$H^{\pm}$	$\longrightarrow$	charged higgsinos	$\tilde{\chi}^{\pm}_{1,2}$	charginos
γ	$\longrightarrow$	photino	$\tilde{\chi}^{0}_{1,2,3,4}$	neutralinos
Z	$\longrightarrow$	zino	$\tilde{\chi}^{0}_{1,2,3,4}$	neutralinos
h,H	$\longrightarrow$	higgsinos	$\tilde{\chi}^{0}_{1,2,3,4}$	neutralinos
g	$\longrightarrow$	gluino	$\tilde{g}$	

For each fermion f two partners $\tilde{f}_L$ and $\tilde{f}_R$ corresponding to the two helicity states

The SUSY partners of the W and of the $H^{\pm}$ mix to form 2 charginos

The SUSY partners of the neutral gauge and higgs bosons mix to form 4 neutralinos

Some details useful to understand phenomenology

Neutralino mixing

Gauginos and higgsinos $(\tilde{B}, \tilde{W}^3, \tilde{H}_d^0, \tilde{H}_u^0)$ mix to form mass eigenstates: χ_i^0 (i=1,2,3,4) throug matrix:

$$\mathcal{M} = \begin{pmatrix} M_1 & 0 & -m_Z c_\beta s_W & m_Z s_\beta s_W \\ 0 & M_2 & m_Z c_\beta c_W & -m_Z s_\beta c_W \\ -m_Z c_\beta s_W & m_Z c_\beta c_W & 0 & -\mu \\ m_Z s_\beta s_W & -m_Z s_\beta c_W & -\mu & 0 \end{pmatrix} \quad (1)$$

- Entries M_1 and M_2 come from the soft breaking terms in lagrangian
- Entries μ are supersymmetric higgsino mass terms
- Terms proportional to m_Z arise from EW symmetry breaking

Diagonalize $\mathcal{M}$ by unitary matrix N: $\mathbf{M}_{\widetilde{N}}^{\text{diag}} = \mathbf{N}^* \mathbf{M}_{\widetilde{N}} \mathbf{N}^{-1}$

Each of the neutralino states is a linear combination of gauginos and higgsinos:

$$\tilde{\chi}_i^0 = N_{i1}\tilde{B} + N_{i2}\tilde{W}^3 + N_{i3}\tilde{H}_d^0 + N_{i4}\tilde{H}_u^0$$

With $m(\tilde{\chi}_1^0) > m(\tilde{\chi}_2^0) > m(\tilde{\chi}_3^0) > m(\tilde{\chi}_4^0)$

Special case, realised e.g. in most of mSUGRA parameter space:

$$m_Z \ll |\mu \pm M_1|, |\mu \pm M_2|$$

Putting the EW terms to zero, the characteristic eigenvalue equation

$det(\lambda \mathbf{I} - \mathcal{M}) = 0$ becomes: $(\lambda^2 - \mu^2)(\lambda - M_1)(\lambda - M_2) = 0$

If we have the hierarchy $M_1 < M_2 < \mu$ we obtain:

- $\tilde{\chi}_1^0 \simeq \tilde{B}$, $\tilde{\chi}_2^0 \simeq \tilde{W}^3$ $\tilde{\chi}_3^0 \simeq (\tilde{H}_u - \tilde{H}_d)/\sqrt{2}$, $\tilde{\chi}_4^0 \simeq (\tilde{H}_u + \tilde{H}_d)/\sqrt{2}$
- $m(\tilde{\chi}_1^0) \sim M_1$, $m(\tilde{\chi}_2^0) \sim M_2$, $m(\tilde{\chi}_3^0) \sim m(\tilde{\chi}_4^0) \sim \mu$

Similarly diagonalisation of chargino mixing matrix gives:

- $\tilde{\chi}_1^\pm \simeq \tilde{W}^\pm$, $\tilde{\chi}_2^\pm \simeq \tilde{H}^\pm$
- $m(\tilde{\chi}_1^\pm) \sim M_2$, $m(\tilde{\chi}_2^\pm) \sim \mu$
- $\tilde{\chi}_1^0$ pure bino. If gaugino mass unification $m(\tilde{\chi}_2^0) \sim 2m(\tilde{\chi}_1^0)$
- $\tilde{\chi}_2^0$ and $\tilde{\chi}^\pm$ pure Winos $\sim$ degenerate in mass
- $\tilde{\chi}_3^0, \tilde{\chi}_4^0, \tilde{\chi}_2^\mp$ pure higgsinos, $\sim$ degenerate in mass

Sfermion mixing

(mass)^2 terms in Lagrangian mix the gauge-eigenstates ($\widetilde{f}_L$, $\widetilde{f}_R$) through matrix:

$$\mathbf{m}^2_{\widetilde{\mathbf{F}}} = \begin{pmatrix} m_Q^2 + m_q^2 + L_q & m_q X_q^* \\ m_q X_q & m_{\widetilde{R}}^2 + m_q^2 + R_q \end{pmatrix} \qquad X_q \equiv A_q - \mu^*(\cot\beta)^{2T_{3q}}.$$

L_q, R_q Electroweak correction tems $\sim M_Z^2$

After diagonalization have mass eigenstates $\widetilde{f}_1, \widetilde{f}_2$ with $m^2_{\tilde{f}_1} < m^2_{\tilde{f}_2}$

$$\begin{pmatrix} \widetilde{f}_1 \\ \widetilde{f}_2 \end{pmatrix} = \begin{pmatrix} \cos\theta_{\tilde{f}} & \sin\theta_{\tilde{f}} \\ -\sin\theta_{\tilde{f}} & \cos\theta_{\tilde{f}} \end{pmatrix} \begin{pmatrix} \widetilde{f}_L \\ \widetilde{f}_R \end{pmatrix}$$

All fermion masses $\ll M_z$ except b, τ, t: $\Rightarrow L - R$ mixing only for third generation

- Consider in phenomenology mass autostates $(\tilde{t}_1, \tilde{t}_2)$, $(\tilde{b}_1, \tilde{b}_2)$, $(\tilde{\tau}_1, \tilde{\tau}_2)$
- $\tilde{t}_1, \tilde{b}_1$ lighter than other squarks, $\tilde{\tau}_1$ lighter than other sleptons
- mixing of left and right components changes coupling with gauginos. e.g.:

  $BR(\tilde{\chi}_2^0 \to \tilde{\ell}_R \ell) < BR(\tilde{\chi}_2^0 \to \tilde{\tau}_1 \ell)$

  Because of left component in $\tilde{\tau}_1$

SUSY higgses: basic results

Two higgs doublets, with vacuum expectation values (VEV) at minimum v_u, v_d

Connected to Z mass by:

$$v_u^2 + v_d^2 = v^2 = 2m_Z^2/(g^2 + g'^2) \approx (174\,\text{GeV})^2.$$

Define: $\tan\beta \equiv v_u/v_d$.

After EW symmetry breaking, three of the 8 real degrees of freedom become the longitudinal modes of Z and W bosons.

Five physical higgs states left over:

- CP-odd A^0
- two charged states $H^\pm$
- two scalars: h, H.

All MSSM Higgs phenomenology can be expressed at tree level by two parameters, traditionally take $m(A)$, $\tan\beta$

Higgs masses are given by:

$$m_{A^0}^2 = 2b/\sin 2\beta$$

$$m_{H^\pm}^2 = m_{A^0}^2 + m_W^2$$

$$m_{h^0,H^0}^2 = \frac{1}{2}(m_{A^0}^2 + m_Z^2 \mp \sqrt{(m_{A^0}^2 + m_Z^2)^2 - 4m_Z^2 m_{A^0}^2 \cos^2 2\beta}).$$

- Lower bound on masses of $H, H^\pm$. $A, H, H^\pm \sim$ degenerate for high b
- Upper bound on h mass at tree level:

$$m_{h^0} < |\cos 2\beta| m_Z$$

Phenomenological disaster, h should have been discovered at LEP

One-loop radiative corrections dominated by top-stop loops in scalar potential. In the limit of heavy stops $m_{\tilde{t}_1}$, $m_{\tilde{t}_2} \gg m_t$:

$$\Delta(m_{h^0}^2) = \frac{3}{4\pi^2} v^2 y_t^4 \sin^4\beta \ \ln\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right).$$

Two-loop corrections currently available. Approximate upper limit in MSSM:

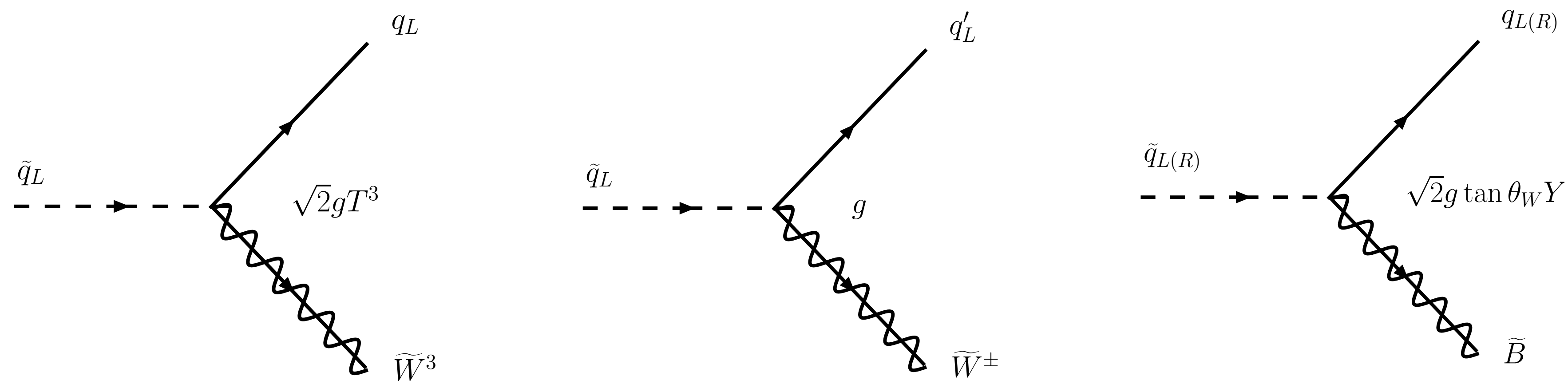
$$m_{h^0} \lesssim 130 \text{ GeV}$$

Sparticle decays

Sfermion decays: two possibilities: gauge interactions and Yukawa interactions

Yukawa interactions proportional to m^2 of corresponding fermions: only relevant for third generation

For gauge interactions same couplings as corresponding SM vertexes:



Cascade decays: decay to $\tilde{\chi}_1^0$ always kinematically favoured, but BR defined by neutralino composition and couplings, decays into heavier gauginos may dominate.

If $\tilde{q} \to \tilde{g}q$ open: dominates beacuse of α_s coupling, otherwise weak decays into gauginos

Case: $m_Z \ll M_1 < M_2 < \mu m_Z$; gaugino composition: $\tilde{\chi}_1^0 \sim \widetilde{B}$, $\tilde{\chi}_1^0 \sim \widetilde{W}^3$, $\tilde{\chi}_1^\pm \sim \widetilde{W}^\pm$

$$BR(\tilde{q}_L \to \tilde{\chi}_2^0 q) = 30\% \quad BR(\tilde{q}_L \to \tilde{\chi}_1^\pm q') = 60\% \quad BR(\tilde{q}_R \to \tilde{\chi}^0 q) = 100\%$$

Cascade decays

Chains can be very long. Extreme example, if

$m_{\tilde{g}} > m_{\tilde{q}} > m_{\tilde{\chi}_4^0} > m_{\tilde{\ell}_L} > m_{\tilde{\chi}_2^0} > m_{\tilde{\ell}_R}$:

$$\tilde{g}$$
$$\hookrightarrow \tilde{q}_L \quad q$$
$$\hookrightarrow \tilde{\chi}_4^0 \quad q$$
$$\hookrightarrow \tilde{\ell}_L^\pm \quad \ell^\mp$$
$$\hookrightarrow \tilde{\chi}_2^0 \quad \ell^\pm$$
$$\hookrightarrow \tilde{\ell}_R^\pm \quad \ell^\mp$$
$$\hookrightarrow \tilde{\chi}_1^0 \quad \ell^\pm$$

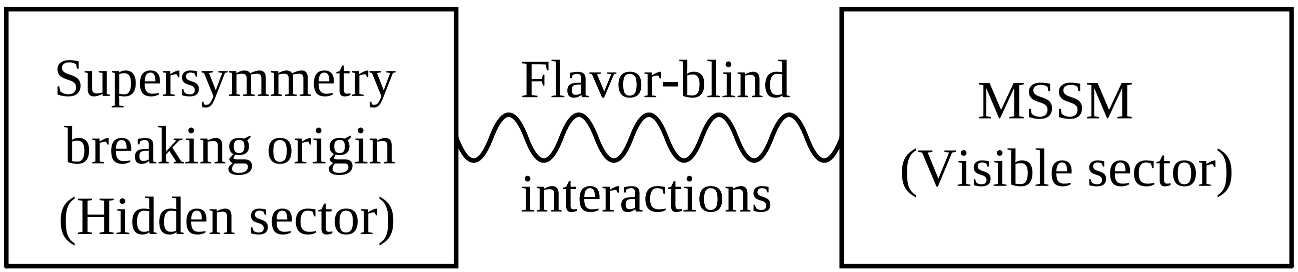
Final state from this leg includes 4 charged leptons, two jets and $\not{E}_T$

More typical case for the same chain would involve 4 successive two-body decays, with four visible particles in final state: 2 jets + two leptons, or four jets + $\not{E}_T$

SUSY breaking models

MSSM agnostic approach, one would like to have a model for SUSY breaking

Spontaneous breaking not possible in MSSM, need to postulate hidden sector.



Phenomenological predictions determined by messenger field:

Three main proposals, sparticle masses and couplings function of few parameters

- Gravity: mSUGRA. Parameters $m_0,\ m_{1/2},\ A_0,\ \tan\beta,$ sgn μ
- Gauge interactions: GMSB. Parameters $\Lambda = F_m/M_m$, M_m, N_5 (number of messenger fields) $\tan\beta$, $sgn(\mu)$, C_{grav}
- Anomalies: AMSB: Parameters: $m_0,\ m_{3/2},\ \tan\beta,\ sign(\mu)$

SUSY breaking structure

SUSY breaking communicated to visible sector at some high scale

$m_0,\ m_{1/2},\ A_0,\ \tan\beta,$ sgn μ (mSUGRA)

Evolve down to EW scale through Renormalization Group Equations (RGE)

$M_1,\ M_2,\ M_3,\ m(\tilde{f}_R),\ m(\tilde{f}_L),\ A_t,\ A_b,\ A_\tau,\ m(A),\ \tan\beta, \mu$

From 'soft' terms derive mass eigenstates and sparticle couplings.

$m(\tilde{\chi}^0_j),\ m(\tilde{\chi}^\pm_j),\ m(\tilde{q}_R),\ m(\tilde{q}_L),\ m(\tilde{b}_1),\ m(\tilde{b}_2),\ m(\tilde{t}_1),\ m(\tilde{t}_2)......$

Structure enshrined in Monte Carlo generators (e.g ISAJET)

Task of experimental SUSY searches is to go up the chain, i.e. to measure enough sparticles and branching ratios to infer information on the SUSY breaking mechanism

Supergravity (SUGRA) inspired model:

Soft SUSY breaking mediated by gravitational interaction at GUT scale.

Gravitation is flavour blind, soft breaking lagrangian at GUT scale like the MSSM lagrangian with the identification:

$$M_3 = M_2 = M_1 = m_{1/2};$$

$$\mathbf{m^2_Q} = \mathbf{m^2_{\overline{u}}} = \mathbf{m^2_{\overline{d}}} = \mathbf{m^2_L} = \mathbf{m^2_{\overline{e}}} = m_0^2\,\mathbf{1}; \quad m^2_{H_u} = m^2_{H_d} = m_0^2;$$

$$\mathbf{a_u} = A_0\mathbf{y_u}; \qquad \mathbf{a_d} = A_0\mathbf{y_d}; \qquad \mathbf{a_e} = A_0\mathbf{y_e};$$

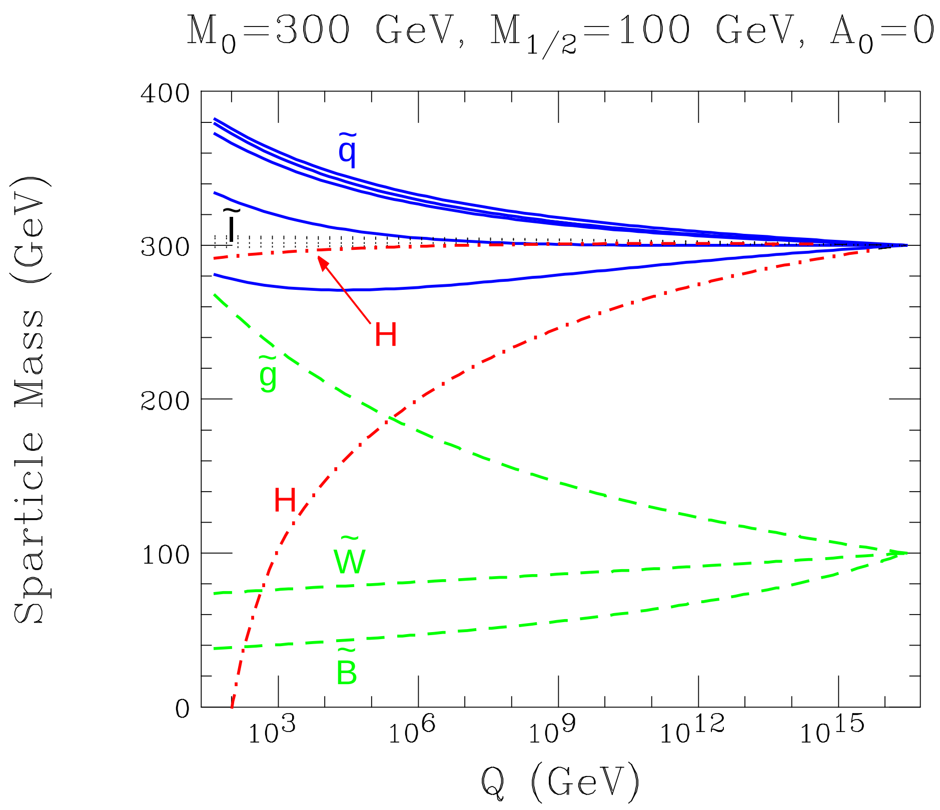
$$b = B_0\mu.$$

This unification is valid at the GUT scale, all parameters are running, need to evolve them down to the electroweak scale

Evolution performed through renormalisation group equations:

Different running of different masses as a function of the gauge quantum numbers of the particles: splitting at the EW scale

Example:



One of the higgs masses driven negative by RGE $\Rightarrow$ radiative EW symmetry breaking

Radiative EW symmetry breaking: require correct value of M_Z at electroweak scale

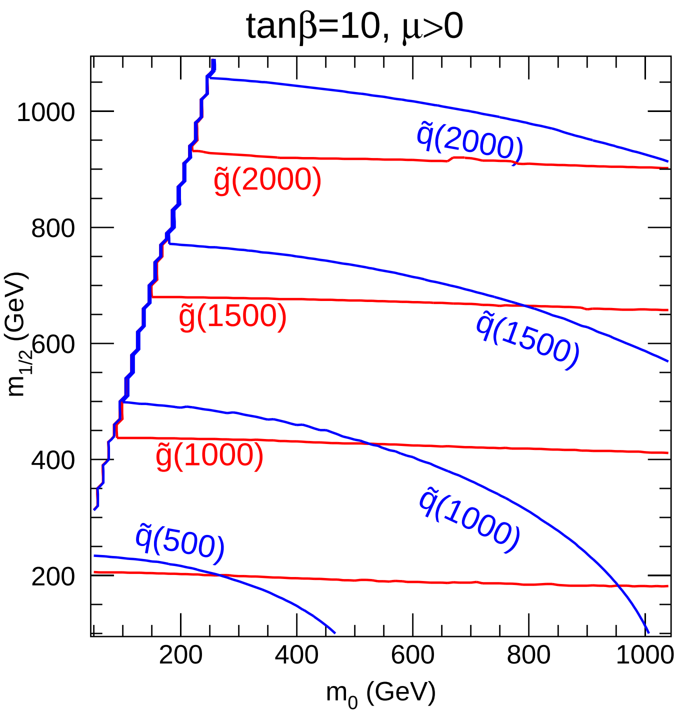
$$\frac{M_Z^2}{2} = \frac{m_{H_d}^2 - m_{H_u}^2 \tan\beta^2}{\tan\beta^2 - 1} - |\mu|^2$$

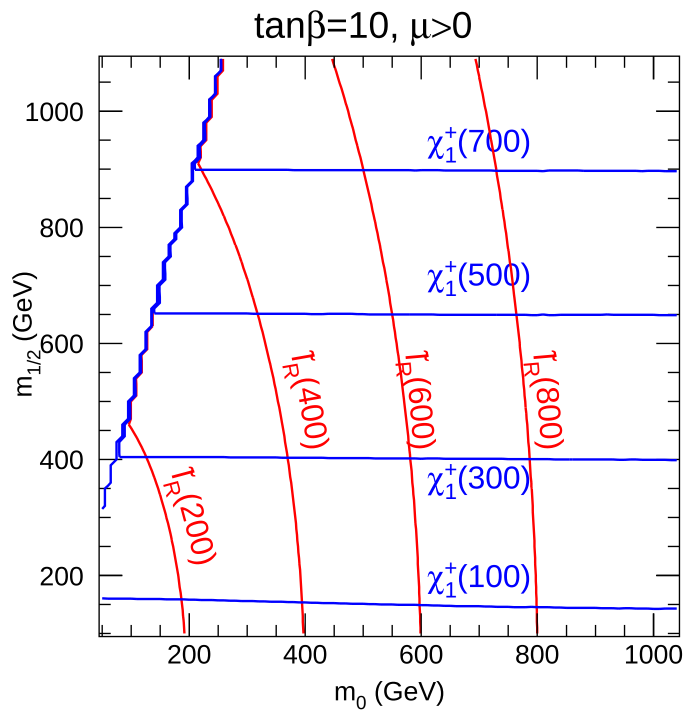
$\Rightarrow |\mu|$, b given in terms of $\tan\beta$, sgn μ. Final set of parameters of model:

- Universal gaugino mass $m_{1/2}$.
- Universal scalar mass m_0.
- Universal A_0 trilinear term.
- $\tan\beta$
- sgn μ

Highly predictive Masses set mainly by m_0, $m_{1/2}$.

Masses in mSUGRA





RGE for $m_{1/2}$ give for soft gaugino terms $M_3 : M_2 : M_1 : m_{1/2} \approx= 7 : 2 : 1 : 2.5$

$m(\tilde{g}) \approx M_3$. In mSUGRA $m(\tilde{\chi}_1^0) \approx M_1$, $m(\tilde{\chi}_2^0) \approx m(\tilde{\chi}_1^\pm) \approx M_2$

Sfermion mass determined by RGE running of m_0 and coupling to gauginos:

$m(\tilde{\ell}_L) \approx \sqrt{m_0^2 + 0.5 m_{1/2}^2}$; $m(\tilde{\ell}_R) \approx \sqrt{m_0^2 + 0.15 m_{1/2}^2}$; $m(\tilde{q}) \approx \sqrt{m_0^2 + 6 m_{1/2}^2}$

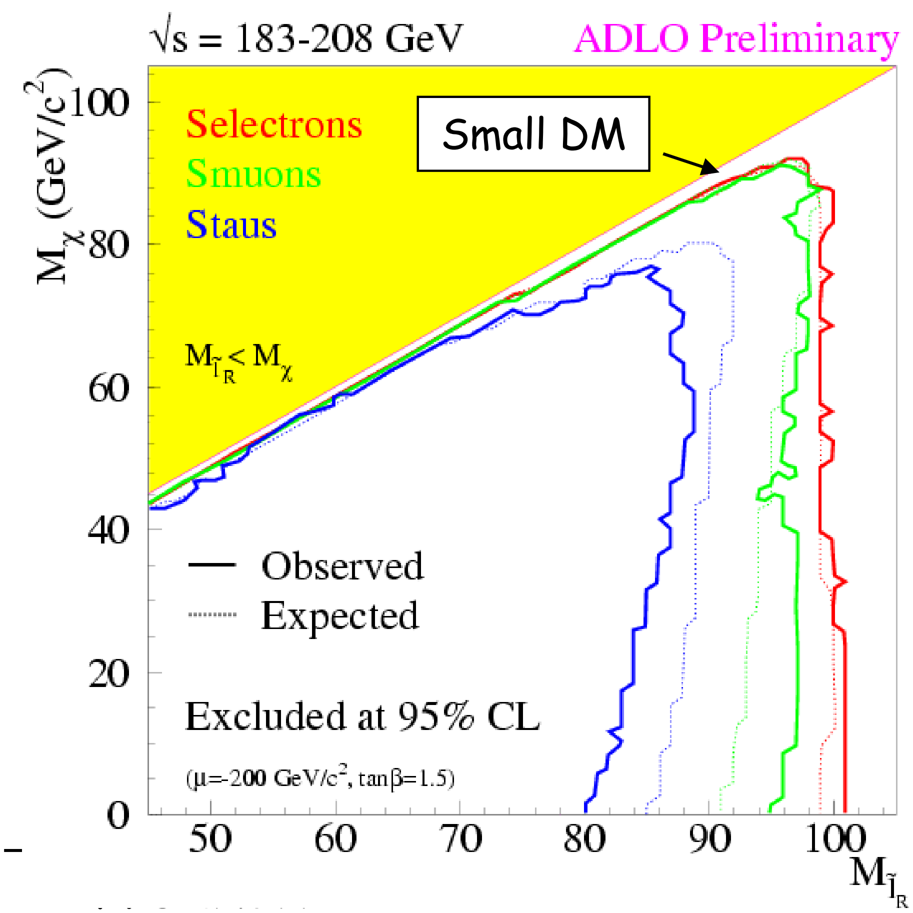
A and $\tan\beta$: significant contribution only to 3^{rd} generation RGE and mixing

Existing limits: LEP

Direct slepton production:

Look for process $e^+e^- \to \tilde{\ell}^+\tilde{\ell}^-$, followed by decay $\tilde{\ell} \to \ell\tilde{\chi}^0_1$ with $\ell = (e, \mu, \tau)$

Signatures: 2 acoplanar leptons + $\not\!\!E_T$

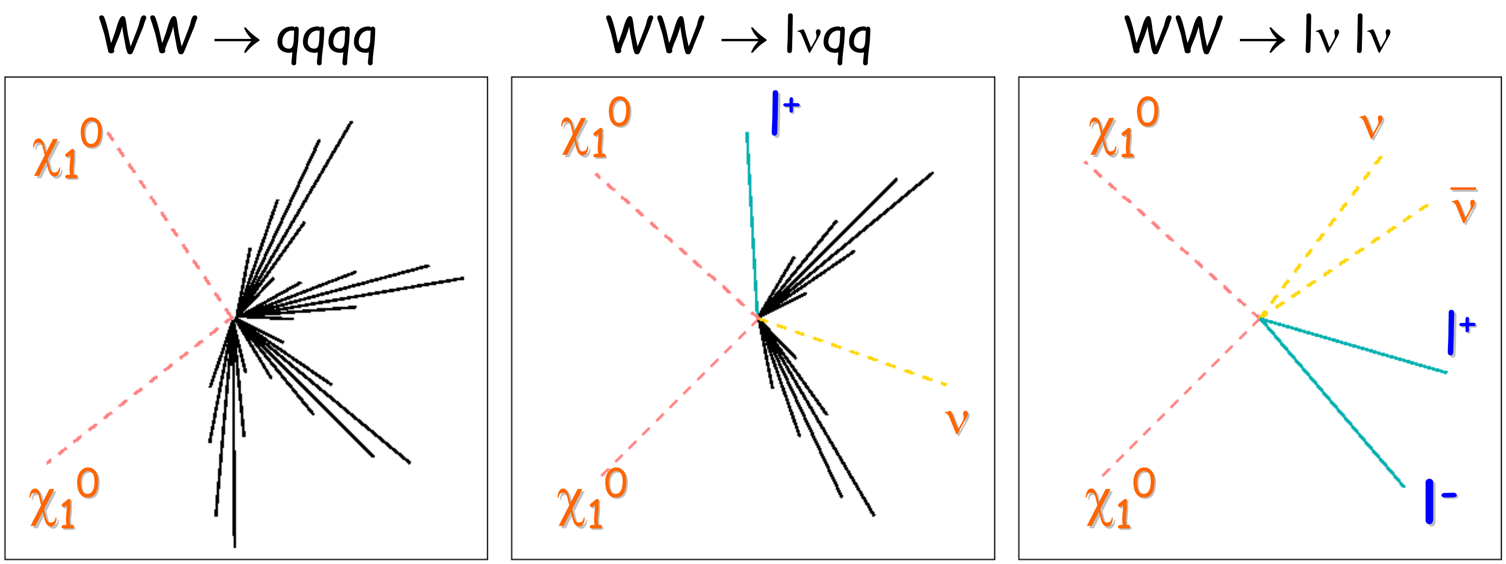


Approximately at the kinematic limit for $\tilde{e}$ and $\tilde{\mu}$

LEP: chargino production

$e^+e^- \longrightarrow \tilde{\chi}_1^+\tilde{\chi}_1^-$, followed by decays:

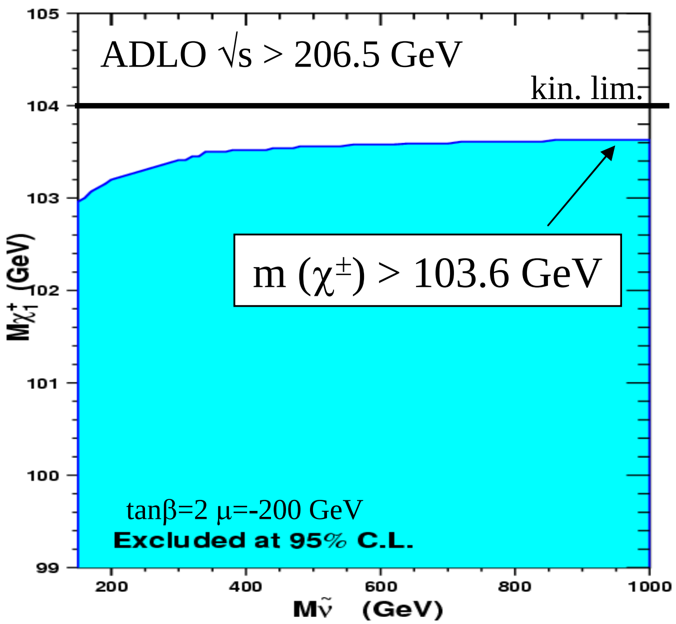
- $\tilde{\chi}_1^+\tilde{\chi}^- \longrightarrow \tilde{\nu}^+\ell^+\tilde{\nu}\ell^- \longrightarrow \nu\nu\tilde{\chi}_1^0\tilde{\chi}_1^0\ell^+\ell^-$ Acoplanar leptons
- $\tilde{\chi}_1^\pm \longrightarrow W^*\tilde{\chi}_1^0$. Final states for this decay:



Main backgronds WW and ZZ can be rejected asking e.g. for large missing mass

LEP chargino limits

"Easy case" : large scalar masses



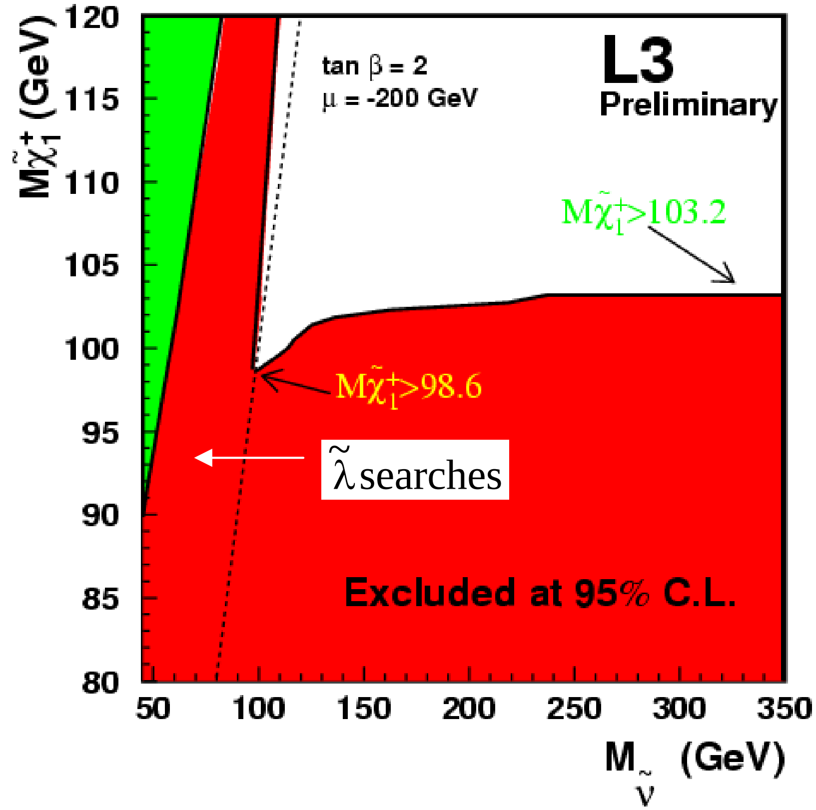
If high scalar masses, three-body decay

$\tilde{\chi}_1^{\pm} \rightarrow W^* \tilde{\chi}_1^0 \rightarrow f f'$ dominates

If $m(\tilde{\chi}_1^{\pm}) \sim 2m(\tilde{\chi}_1^0)$ always visible

Get very near to kimematic limit

If decay to sleptons open, depend on the Δm between chargino and slepton



Existing SUSY limits: Tevatron

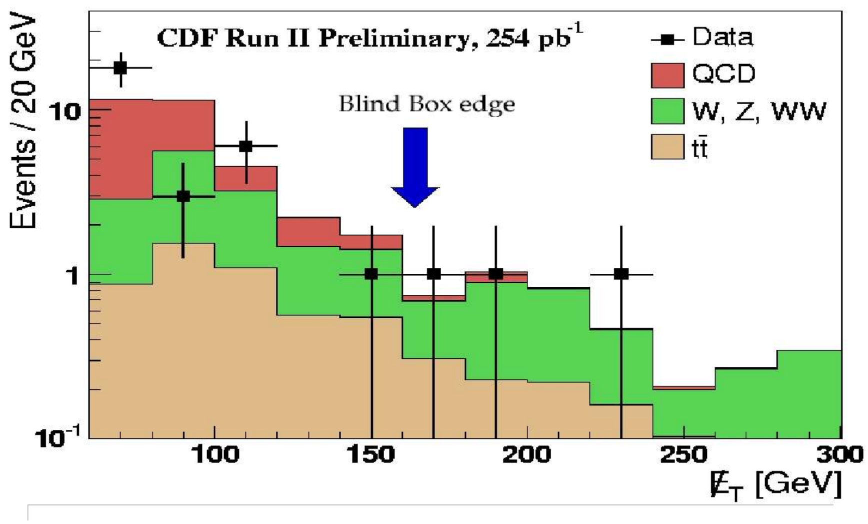
1. $\not{E}_T + jets$ search

Look for production of squarks and gluinos decaying to hadronic jets

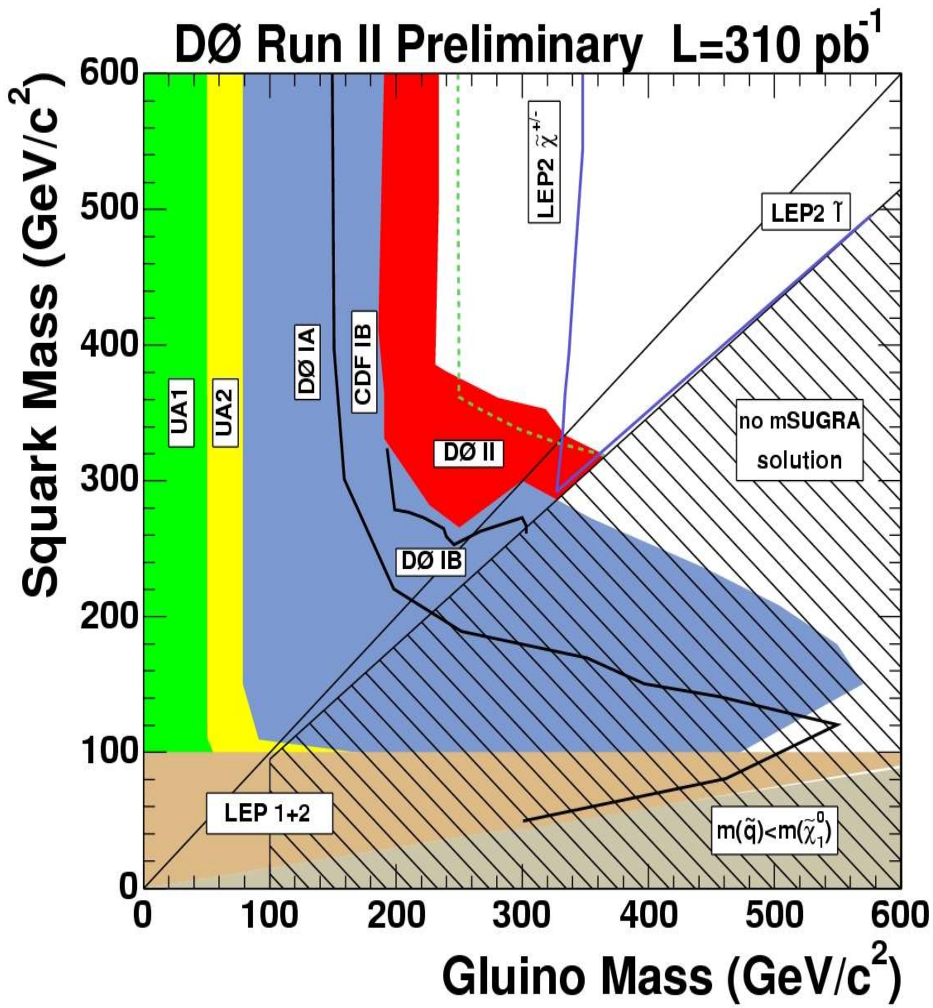
Looking for heavy objects (> 300 GeV): require high energies for jets and high sum of jet energies to reduce SM bakgrounds.

Excess from SUSY in $\not{E}_T$ distribution because of non-interacting LSP in final state

No excess observed with respect to SM. Put limits



Tevatron: $\not\!\!E_T$+jets limit



Production X-section for given squark and gluino mass known

$\not\!\!E_T$+jets signature has no big dependency on details of model

$\Rightarrow$ set limit in $M_{\tilde{g}} - M_{\tilde{q}}$ plane

Tevatron three-lepton search

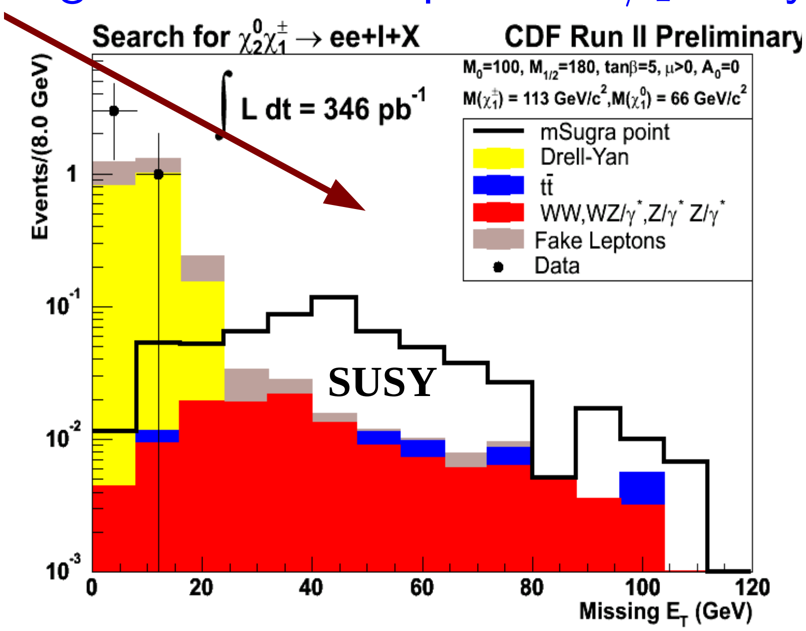
Center of mass energy limits squrk/gluino searches $\Rightarrow$

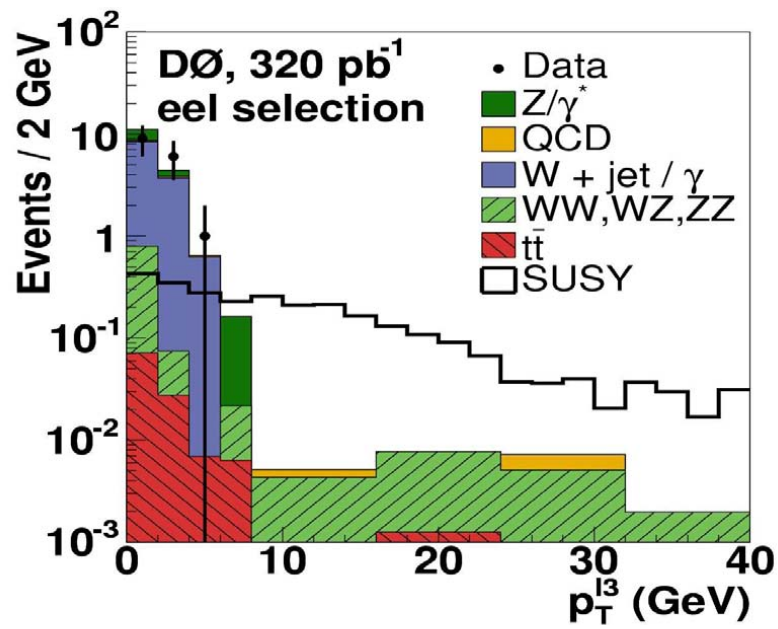
Direct production of gauginos, typically lighter, decay of gauginos to leptons

Best process: $p\bar{p} \longrightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^\pm$ with decays:

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

Signature: three-leptons + $\not\!\!E_T$: very low cross-section, but little SM backgrounds





Tevatron 3-lepton limit

Gaugino production and decay signature very model-dependent

Only place limit on SUSY cross-section as a function of gaugino masses in "standard" assumptions on model