Introduction to SUSY

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Introduction

For 20 years SUSY most popular template for exploration of new physics

SUSY: large class of models with many possible signatures

Canonical model for experimental studies is MSSM with R-parity conservation

Prototype of a generic model with:

- Rich spectrum of new particles
- Complex decay chains
- Two undetected particles in final state (LSP)

I am not a theorist, but I will describe in some detail the features of the model which I found useful to know to understand the detail of the experimental and phenomenological studies on the market

The basic reference, from which I extracted most of the material is:

S.P. Martin: "A Supersymmetry Primer" arXiv:hep-ph/9709356v4

Based on the simple MSSM model, I will address SUSY at the LHC as the development of a program passing through different phases, each posing a different challenge

- Discovery based on challenging and varied signatures, dominated by $\not{E}_T$ from undetected LSP
- Measurement of sparticle masses/couplings requires development of new spectroscopic techniques
- Model discrimination: techniques to differentiate models with similar mass hierarchy
- Connection with low energy and astrophysical data: reconstruction of weak-scale model
- Reconstruction of the high-scale model, understanding of SUSY breaking

Concentrate on measurement techniques on specific exemplary model, as an example of how a complex new physics signal might be treated at the LHC

Why physics beyond the Standard Model?

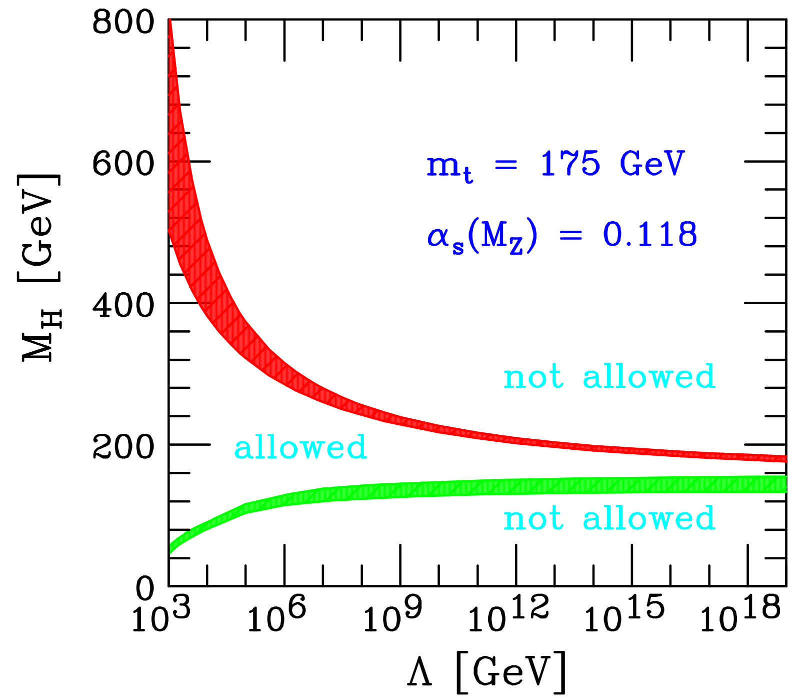
- Gravity is not yet incorporated in the Standard Model
- Hierarchy/Naturalness problem

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

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

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

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



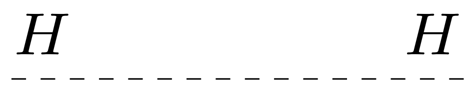
- Additional problems: Unification of couplings, Flavour/family problem

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

Hierarchy problem

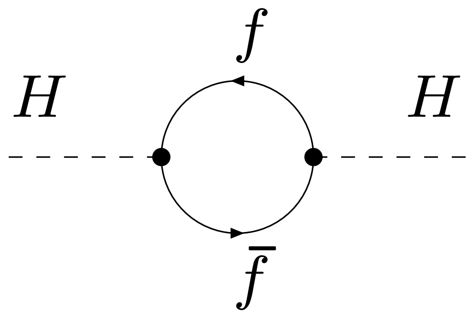
Mass is what determines the properties of the free propagator of a particle

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 contrived, 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 constraints 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 including these matter fields invariant under SUSY transformation

Masses of SUSY particles

Unbroken SUSY is uniquely defined, once the involved supermultiplets are defined.

Evaluate super partner masses in unbroken SUSY

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, but conserve good features for which SUSY was introduced

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

Based on these terms, build a realistic minimal SUSY model: MSSM

Minimal Supersymmetric Standard Model

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

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

- 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!

Chiral and vector supermultiplets of MSSM

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	$(\ \mathbf{1},\ \mathbf{1}\ ,\ 0)$

Why two higgs doublets

Consider fermion mass terms in SM case:

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

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

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

Moreover: two doublets needed for cancellation of triangle gauge anomaly.

The superpotential for the MSSM is thus:

$$W_{\text{MSSM}} = \overline{u}\mathbf{y_u}QH_u - \overline{d}\mathbf{y_d}QH_d - \overline{e}\mathbf{y_e}LH_d + \mu H_u H_d \,. \qquad (1)$$

SUSY higgses: basic structure

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:

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

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

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

Phenomenological consequences:

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

R-parity conservation imposed 'by hand' by omitting from the Lagrangian L or B violating terms:

$$W_{\Delta \mathrm{L}=1} = \frac{1}{2}\lambda^{ijk} L_i L_j \overline{e}_k + \lambda'^{ijk} L_i Q_j \overline{d}_k + \mu'^{i} L_i H_u \quad (2)$$

$$W_{\Delta \mathrm{B}=1} = \frac{1}{2}\lambda''^{ijk} \overline{u}_i \overline{d}_j \overline{d}_k \quad (3)$$

Can build models where some of these terms are present in the Lagrangian compatible with all present constraints: RPV models

Completely different phenomenology, I will not address it here

Low energy constraints on soft parameters

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

Phenomenology determined by the mixing in gaugino sector and by sfermion

left-right mixing

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) through matrix:

$$\mathcal{M} = \begin{pmatrix} M_1 & 0 & -m_Z c_\beta s_W & m_Z s_\beta s_W \\ 0 & M_2 & m_Z c_\beta c_W & -m_Z s_\beta c_W \\ -m_Z c_\beta s_W & m_Z c_\beta c_W & 0 & -\mu \\ m_Z s_\beta s_W & -m_Z s_\beta c_W & -\mu & 0 \end{pmatrix} \tag{4}$$

- 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:

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

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

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.:

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

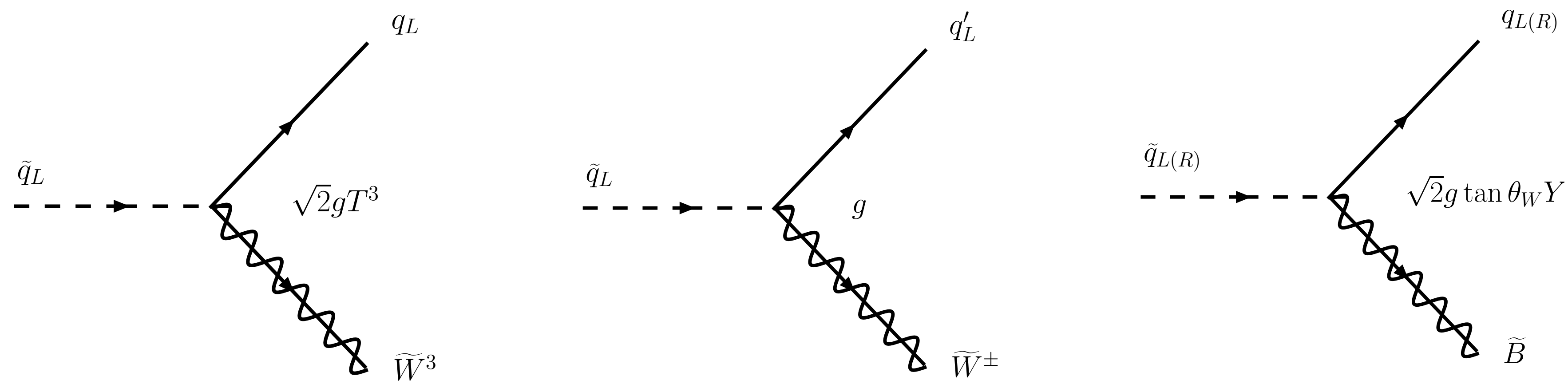
  Because of left component in $\tilde{\tau}_1$

Sparticle decays

Sfermion decays: two possibilities: gauge interactions and Yukawa interactions

Yukawa interactions $\propto$ to m^2 of corresponding fermions: only third generation

For gauge interactions same couplings as corresponding SM vertexes. For squarks:



Decay to $\tilde{\chi}_1^0$ always kinematically favoured, but decays into heavier gauginos may dominate because of the chargino/neutralino composition $\Rightarrow$ Cascade decays

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

Case: $m_Z \ll M_1 < M_2 < \mu m_Z$; gaugino composition is:

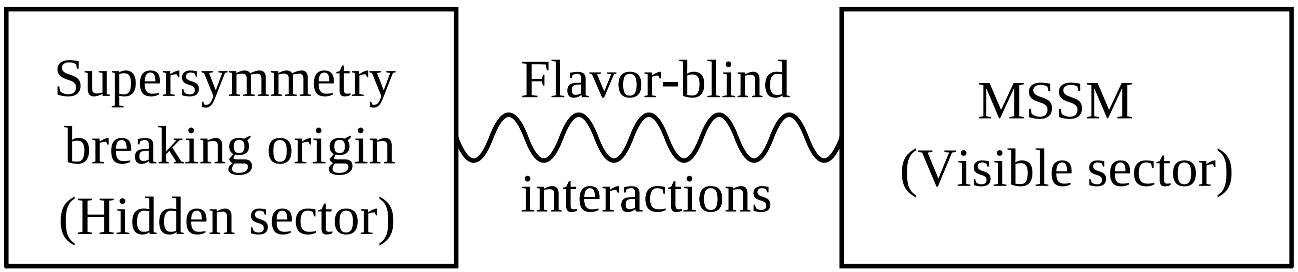
$\tilde{\chi}_1^0 \sim \widetilde{B}$, $\quad \tilde{\chi}_2^0 \sim \widetilde{W}^3$, $\quad \tilde{\chi}_1^\pm \sim \widetilde{W}^\pm$ From the vertexes above one easy sees:

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

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

$m_0, \ m_{1/2}, \ A_0, \ \tan\beta, \ \text{sgn}\,\mu$ (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:

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

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

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

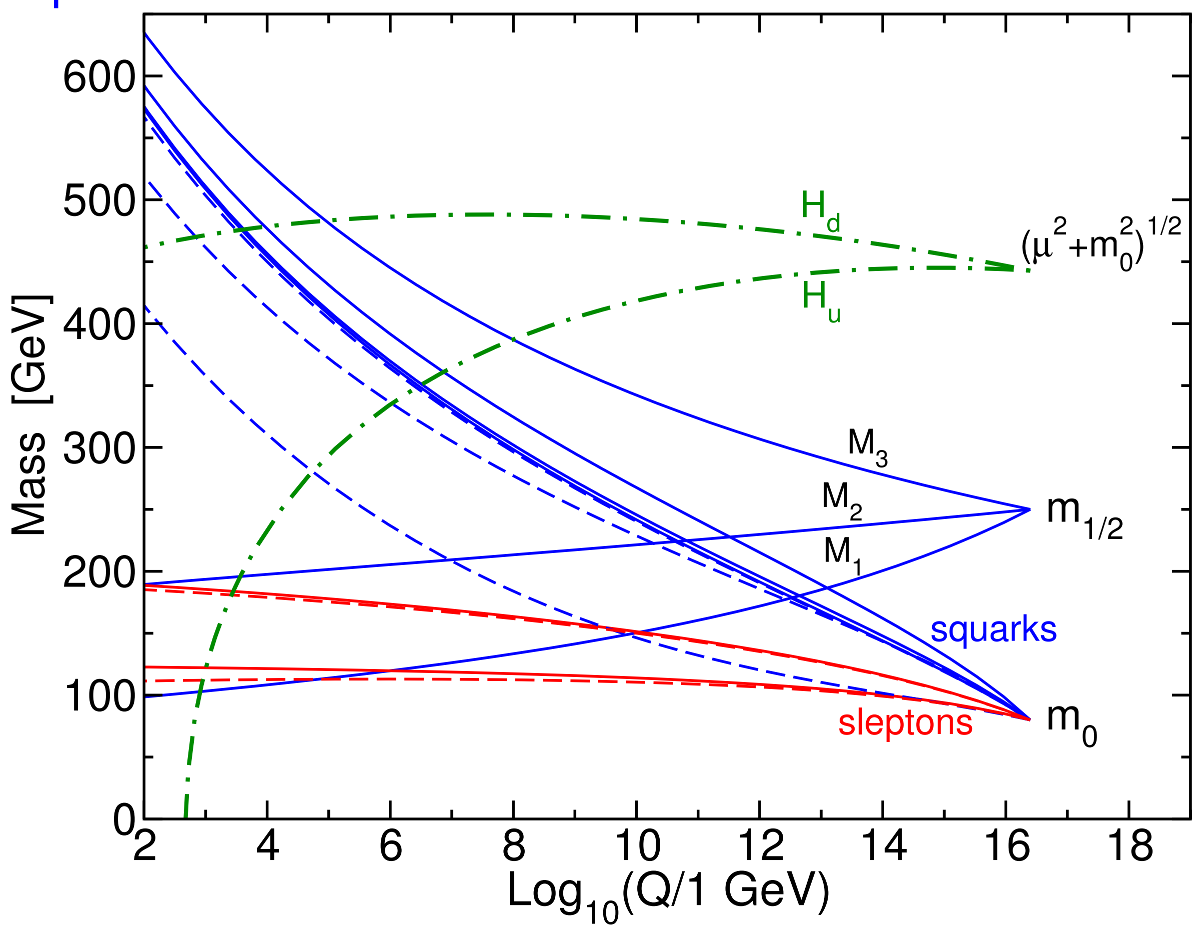
$$b = B_0\mu.$$

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 ⇒ 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.

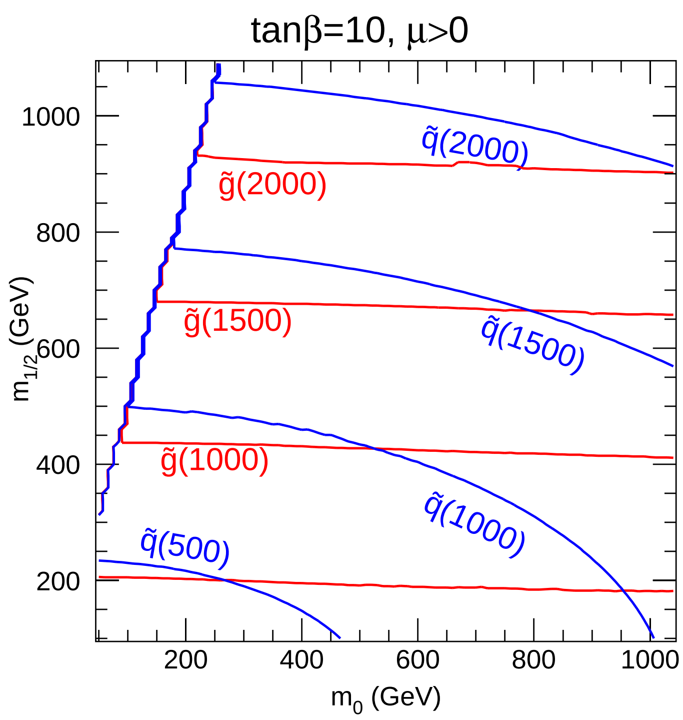
Final set of parameters of model:

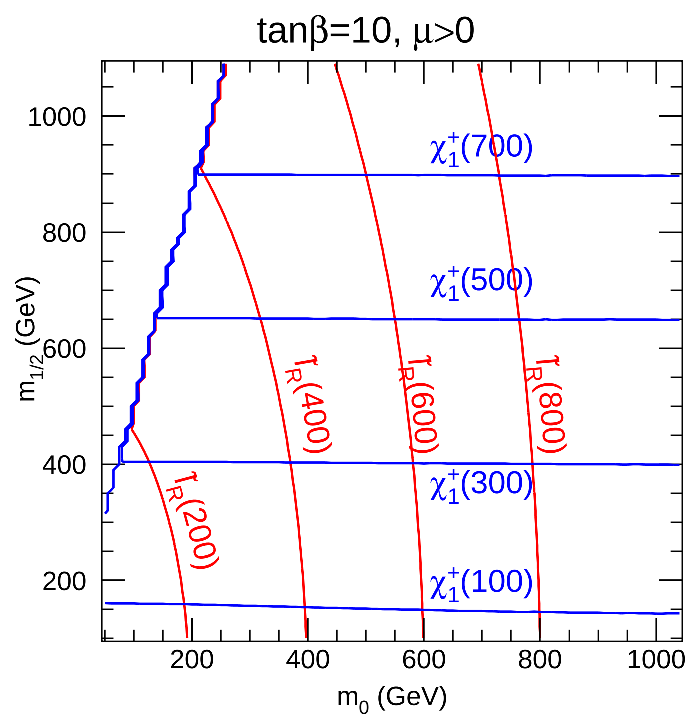
- Universal gaugino mass $m_{1/2}$.
- Universal scalar mass m_0.
- Universal A_0 trilinear term.
- $\tan\beta$
- sgn μ

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

Very simple model, useful testing ground, but very constrained, important to keep in mind that nature may have chosen completely different approach

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:

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

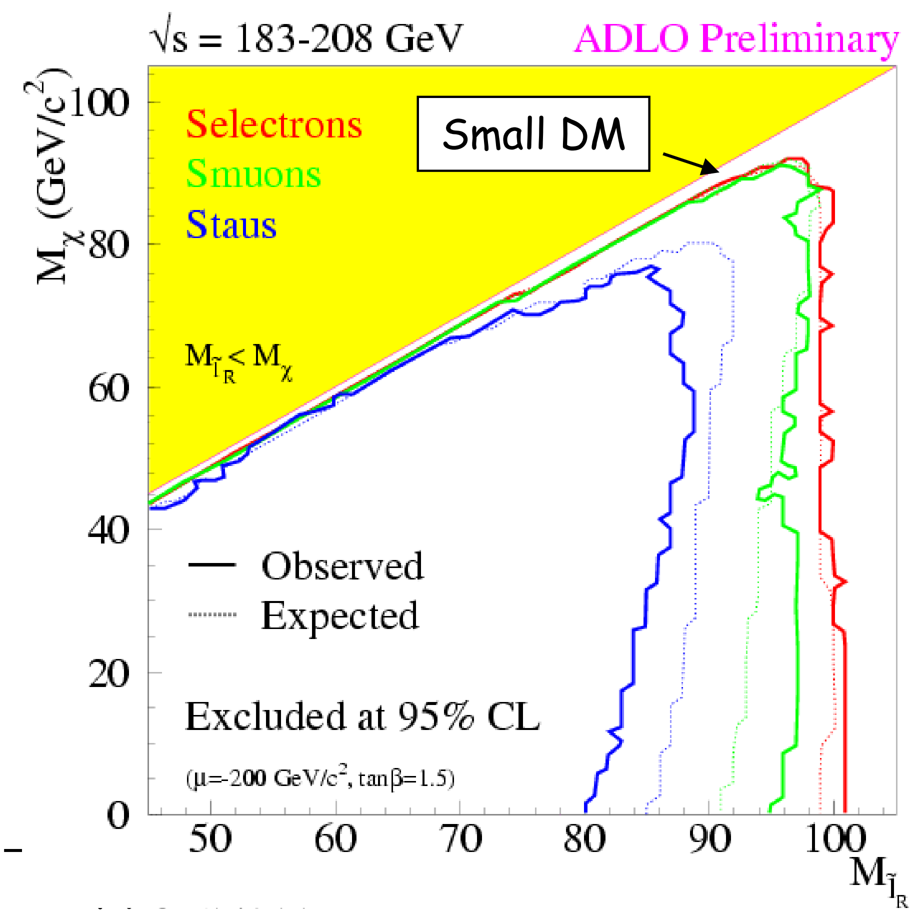
A and $\tan\beta$: significant contribution only to 3^{rd} generation RGE and mixing

Existing limits: LEP

Direct slepton production:

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

Signatures: 2 acoplanar leptons + $\not{E}_T$

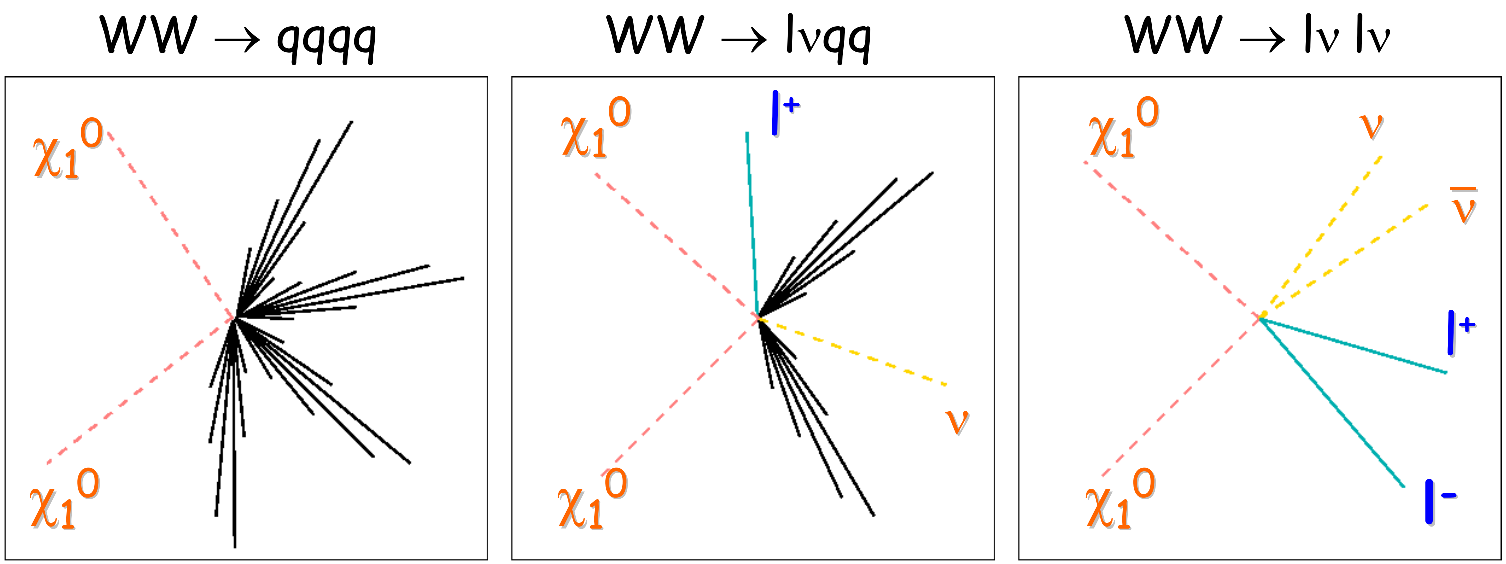


Approximately at the kinematic limit for $\tilde{e}$ and $\tilde{\mu}$

LEP: chargino production

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

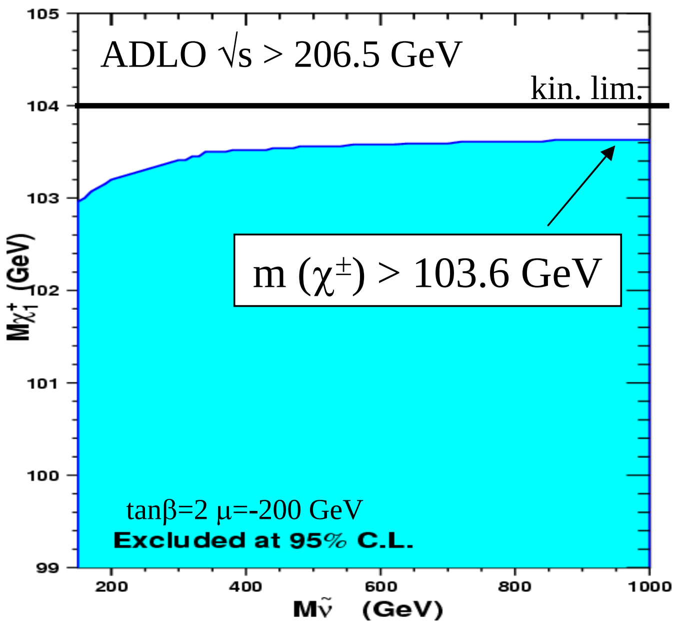
- $\tilde{\chi}_1^+\tilde{\chi}_1^- \longrightarrow \tilde{\nu}^+\ell^+\tilde{\nu}\ell^- \longrightarrow \nu\nu\tilde{\chi}_1^0\tilde{\chi}_1^0\ell^+\ell^-$ Acoplanar leptons
- $\tilde{\chi}_1^\pm \longrightarrow W^*\tilde{\chi}_1^0$. Both hadronic and leptonic final states for this decay:



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

LEP chargino limits

"Easy case" : large scalar masses

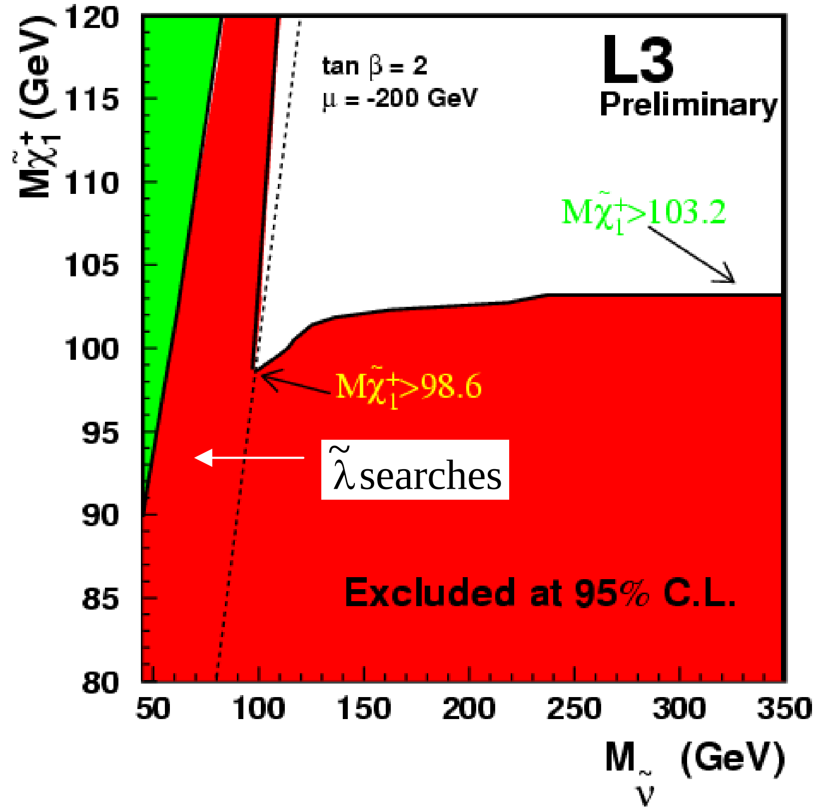


If high scalar masses, three-body decay

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

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

Get very near to kinematic limit



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

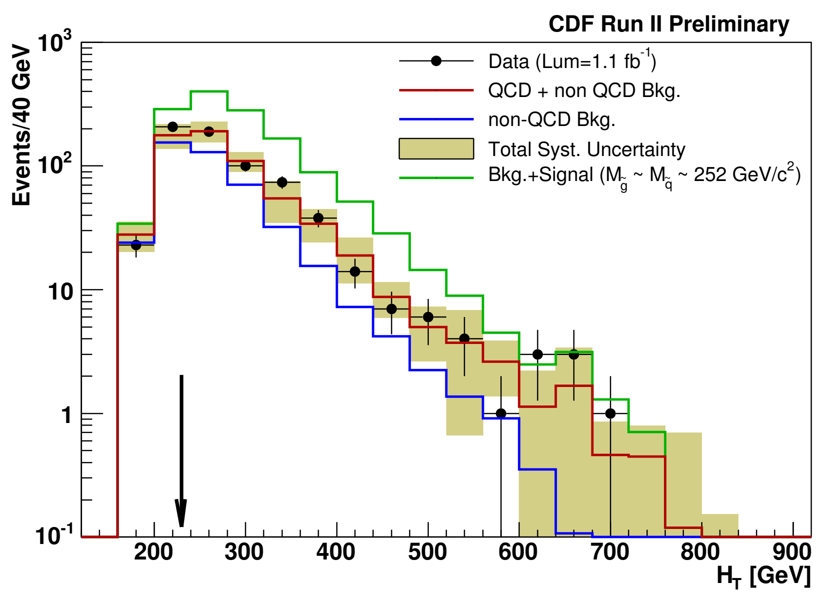
Existing SUSY limits: Tevatron

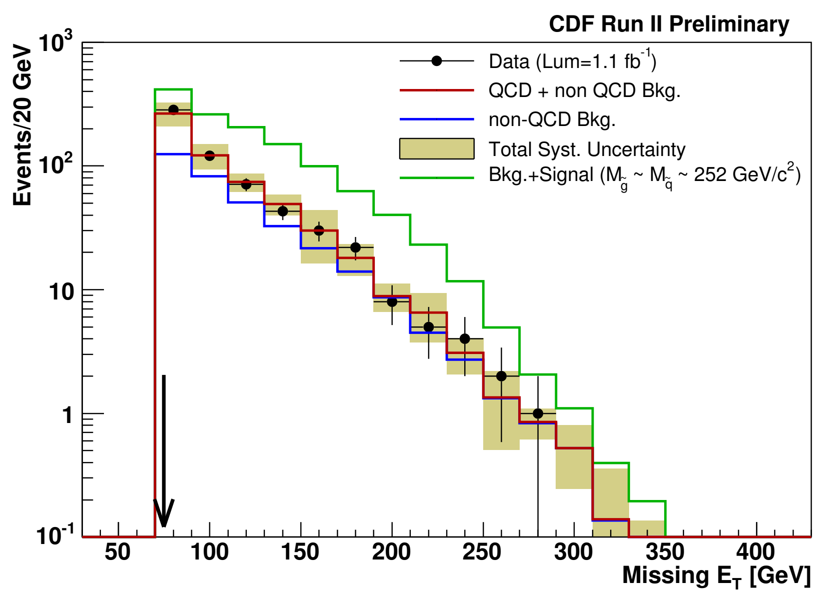
1. $\not\!\!E_T + jets$ search

Look for production of squarks and gluinos decaying to hadronic jets

Looking for heavy objects require high energies for jets and high sum of jet energies (H_T) to reduce SM backgrounds.

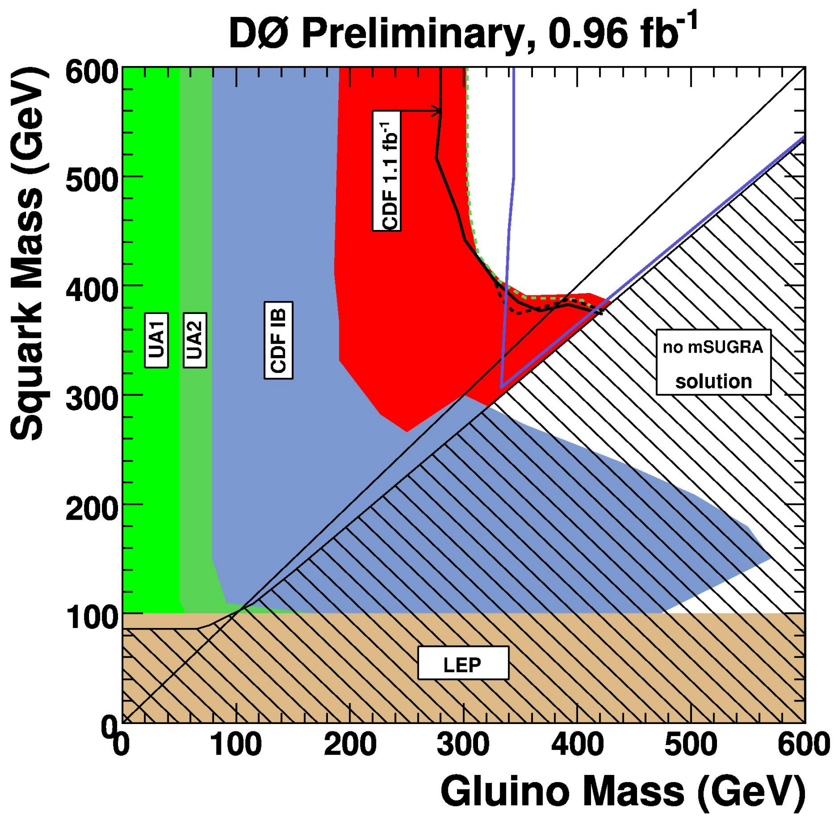
Excess from SUSY in $\not\!\!E_T$ distribution because of non-interacting LSP in final state

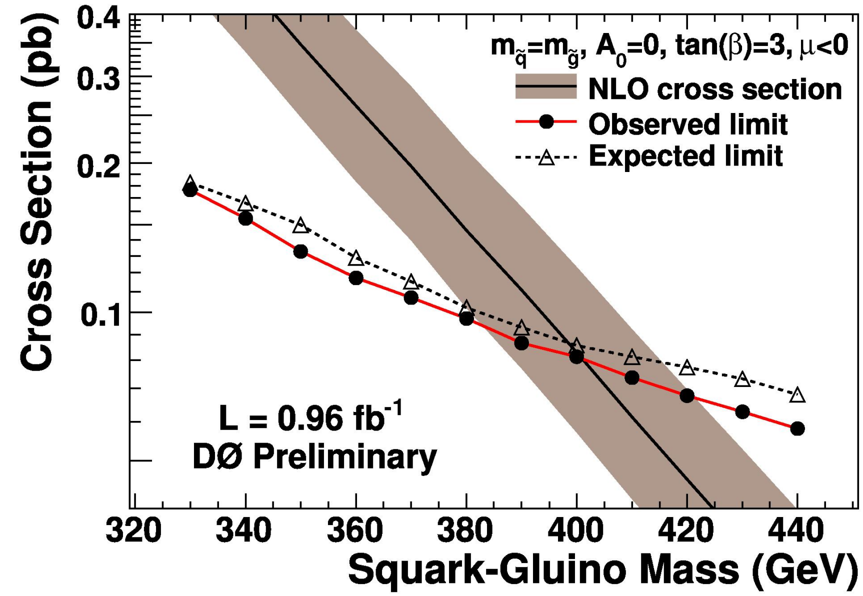




No excess observed with respect to SM. Put limits

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: for $M_{\tilde{g}} \sim M_{\tilde{q}}$ mass limit at ~ 400 GeV

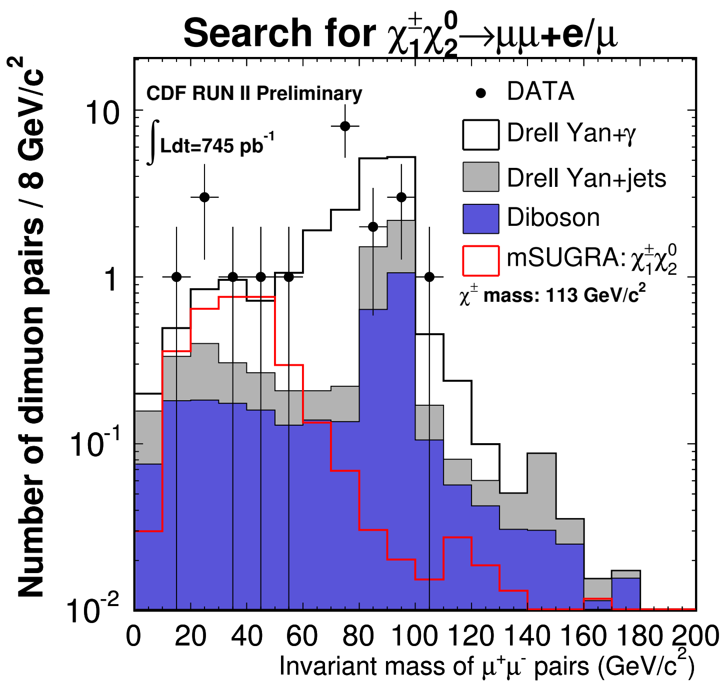
Tevatron three-lepton search

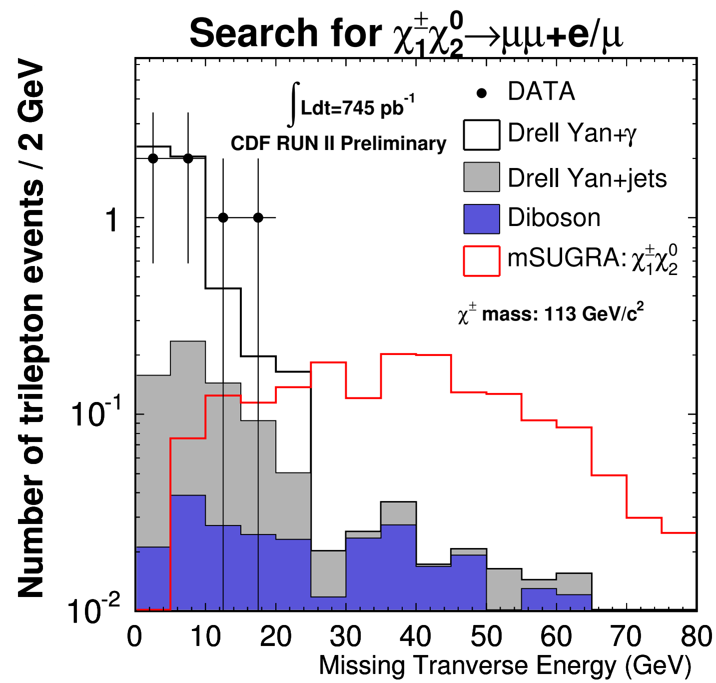
Center of mass energy limits squark/gluino searches $\Rightarrow$

Consider direct production of gauginos, followed by decay of gauginos to leptons

Best process: $p\bar{p} \to \tilde{\chi}_2^0 \tilde{\chi}_1^\pm$ with decays: $\bullet \tilde{\chi}_2^0 \to \ell^+\ell^- \tilde{\chi}_1^0$ $\bullet\ \tilde{\chi}_1^\pm \to \ell\nu\tilde{\chi}_1^0$

Signature: three-leptons + $\not{E}_T$: very low cross-section, but little SM backgrounds





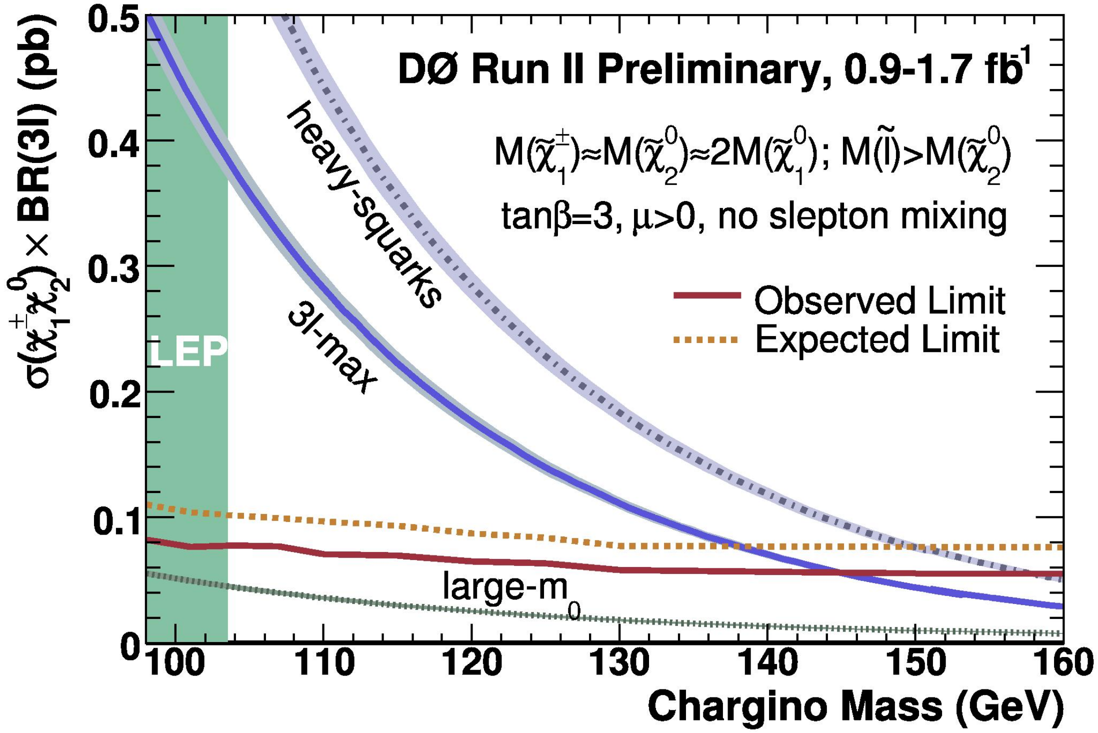
Other approach, to increase signal efficiency: same-sign dileptons

Tevatron 3-lepton limit

No excess observed in any of the many channel considered, can put a limit

Gaugino production and decay signature very model-dependent

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



Limit of $\sim$ 140 GeV in considered scenario.

Indirect constraints: Dark Matter

Existence of Dark Matter in the universe by now well established

Studies of clusters of galaxies suggest $\Omega_{DM} \simeq 0.2$ to 0.3 where $\Omega_X = \rho_X/\rho_{crit}$

From anisotropies in Cosmic Microwave Background (WMAP): $\Omega_{DM} = 0.21 \pm 0.01$

From nucleosynthesis, only 4% of total matter density baryonic

From analyses of structure formation in the universe: most DM must be "cold", non-relativistic at onset of galaxy formation.

DM candidates must be stable on cosmological time scales, interact very weakly with EM radiation, and give the right relic density. Main particle candidates:

- Axions
- Weakly Interacting Massive Particles (WIMP)

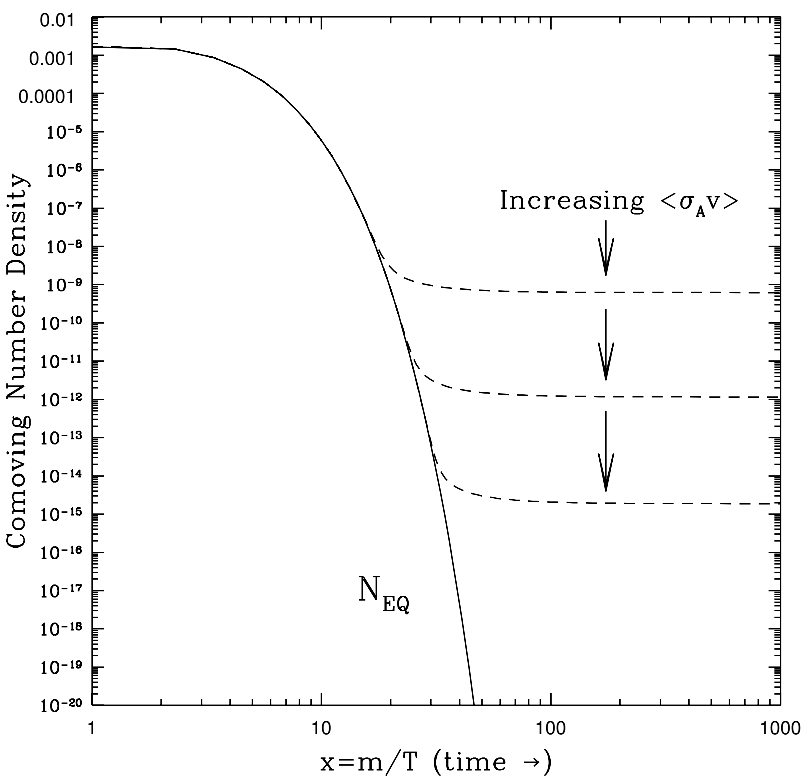
  Mass: 10 GeV – few TeV, and cross section of $\sim$ weak strength

R-parity conserving SUSY provides candidate WIMP: Lightest SUSY Particle (LSP)

Relic Density and LSP annihilation Cross-Section

At first, when $T \gg m_\chi$ all particles in thermal equilibrium. Then universe cools down and expands:

- When $T < m_\chi$ is reached, only annihilation: density becomes exponentially suppressed
- As expansion goes on, particles can not find each other: freeze out and leave a relic density



Master equation for n, number of LSP is:

$$\frac{dn}{dt} = -3Hn - < \sigma_A v > (n^2 - n_{eq}^2) \tag{5}$$

σ_A: LSP annihilation cross-section, v relative speed of LSP, and H Hubble parameter

The relic density $\Omega_{\tilde{\chi}_1^0}$ is defined as:

$$\Omega_{\tilde{\chi}_1^0} = m_{\tilde{\chi}_1^0} n_{\tilde{\chi}_1^0} / \rho_{cri}, \quad \rho_{cri} = h^2 \times 1.91 \times 10^{-29} \mathrm{gcm}^{-3} \tag{6}$$

From solving Boltzmann equation:

$$\Omega_{\tilde{\chi}_1^0} \propto 1 / < \sigma_A v > \tag{7}$$

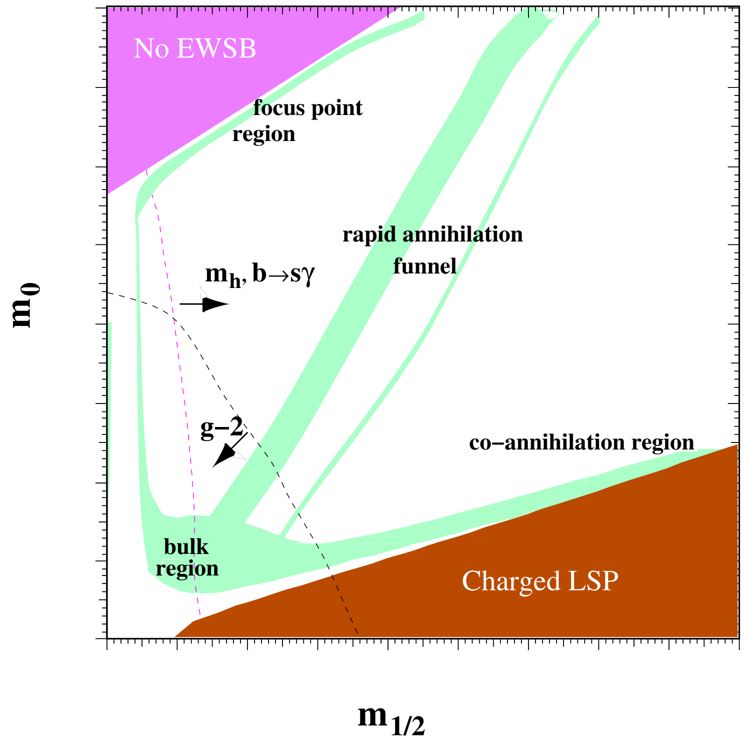
LSP annihilation X-section and thence relic density can be calculated from parameters of SUSY model and compared with WMAP result.

Example: DM constraints in mSUGRA

Large annihilation sross-section required by WMAP data

Boost annihilation via quasi-degeneracy of a sparticle with $\tilde{\chi}_1^0$, or large higgsino content of $\tilde{\chi}_1^0$

Regions in mSUGRA $(m_{1/2}, m_0)$ plane with acceptable $\tilde{\chi}_1^0$ relic density (e.g. Ellis et al.):



- Bulk region: annihilation dominated by slepton exchange, easy LHC signatures fom $\tilde{\chi}_2^0 \to \tilde{\ell}\ell$
- Coannihilation region: small $m(\tilde{\chi}_1^0) - m(\tilde{\tau})$ (1-10 Gev). Dominant processes $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to \tau\tau$, $\tilde{\chi}_1^0\tilde{\tau} \to \tau\gamma$ Similar to bulk, but softer leptons!
- Funnel region: $m(\tilde{\chi}_1^0) \simeq m(H/A)/2$ at high $\tan\beta$ Annihilation through resonant heavy Higgs exchange. Heavy higgs at the LHC observable up to ~800 GeV

- Focus Point: high m_0, large higgsino content $\Rightarrow$ enhanced annihilation through coupling to W/Z Sfermions outside LHC reach, study gluino decays.

Additional low energy constraints

Precision measurements of higher order processes in Standard Model sensitive to loops involving SUSY particles

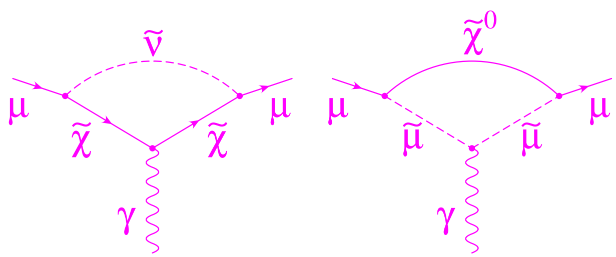
- $g_\mu - 2$

Anomalous gyromagnetic ratio of muon ($\sim 10^{-3}$)

generated by EW radiative corrections

$a_\mu \equiv (g-2)/2$ presently measured to 0.5 ppm

Sensitive to SUSY contributions:



$$\Delta(a_\mu)_{SUSY} \sim 13 \times 10^{-10}[\frac{100\text{GeV}}{M_{SUSY}}]^2 \tan\beta$$