Supersymmetry
Lecture 3

Dr. Jochen Dingfelder und Prof. Markus Schumacher
Universität Freiburg, Sommersemester 2009

Chapter 2: Supersymmetry

2.1 Introduction and Overview
- What is SUSY
- How can we find/measure it?

2.2 SUSY Theory/Phenomenology
- SUSY Lagrangian, MSSM
- SUSY interactions, masses, SUSY breaking

2.3 SUSY searches/measurements at experiments
- past and running experiments
- LHC / future linear collider

2.4 Searches for MSSM Higgs bosons

MSSM Superpotential and B,L Violation

$$W_{\rm MSSM} = \bar{\tilde{u}}\mathbf{y_u}\tilde{Q}H_u - \bar{\tilde{d}}\mathbf{y_d}\tilde{Q}H_d - \bar{\tilde{e}}\mathbf{y_e}\tilde{L}H_d + \mu H_u H_d$$

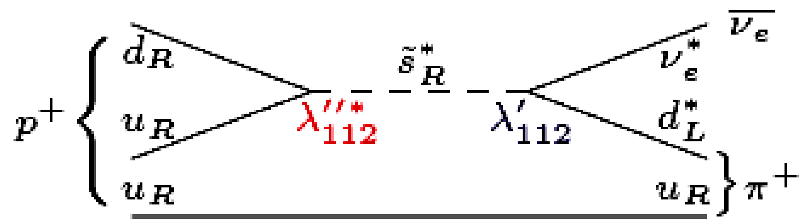
Actually, the most general possible superpotential would also include:

$$W_{\Delta L=1} = \frac{1}{2}\lambda_{ijk}L_iL_j\bar{e}_k + \lambda'_{ijk}L_iQ_j\bar{d}_k + \mu'_iL_iH_u$$

$$W_{\Delta B=1} = \frac{1}{2}\lambda''_{ijk}\bar{u}_i\bar{d}_j\bar{d}_k$$

These violate lepton number ($\Delta L = 1$) or baryon number ($\Delta B = 1$).

If both types of couplings were present, and of order 1, then the proton would decay in a tiny fraction of a second through diagrams like this:



Many other proton decay modes, and other experimental limits on B and L violation, give strong constraints on these terms in the superpotential.

One postulates a new discrete symmetry called **Matter Parity**, also known as **R-parity**.

R-parity is defined for each particle with spin S by: $P_R = (-1)^{3(B-L)+2S}$

Consequences of R-Parity Conservation

The particles with odd R-parity ($P_R = -1$) are the "supersymmetric particles" or "sparticles".

Every interaction vertex in the theory must contain an even number of $P_R = -1$ sparticles. Three extremely important consequences:

- The lightest sparticle with $P_R = -1$, called the "Lightest Supersymmetric Particle" or LSP, must be absolutely stable. If the LSP is electrically neutral, it interacts only weakly with ordinary matter, and so can make an attractive candidate for the non-baryonic dark matter required by cosmology.
- In collider experiments, sparticles can only be produced in even numbers (usually two-at-a-time).
- Each sparticle other than the LSP must eventually decay into a state that contains an odd number of LSPs (usually just one). The LSP escapes the detector, with a missing momentum signature.

SUSY Breaking

Reminder: Soft SUSY-Breaking in the MSSM

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

The first line gives masses to the MSSM gauginos (gluino $\widetilde{g}$, winos $\widetilde{W}$, bino $\widetilde{B}$).

The second line consists of (scalar)^3 interactions.

The third line is (mass)^2 terms for the squarks and sleptons.

The last line is Higgs (mass)^2 terms.

If SUSY is to solve the Hierarchy Problem, we expect:

$$M_1,\ M_2,\ M_3,\ \mathbf{a_u},\ \mathbf{a_d},\ \mathbf{a_e}\ \sim\ m_{\text{soft}};$$

$$\mathbf{m^2_Q},\ \mathbf{m^2_L},\ \mathbf{m^2_{\overline{u}}},\ \mathbf{m^2_{\overline{d}}},\ \mathbf{m^2_{\overline{e}}},\ m^2_{H_u},\ m^2_{H_d},\ b\ \sim\ m^2_{\text{soft}}$$

where $m_{\text{soft}} \lesssim 1$ TeV.

The squark and slepton squared masses and (scalar)^3 couplings are 3×3 matrices in family space. The soft SUSY-breaking Lagrangian of the MSSM contains 105 new parameters not found in the Standard Model.

Most of what we do not already know about SUSY is expressed by the question: "How is supersymmetry broken?"

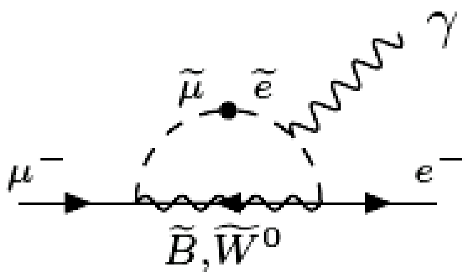
Many proposals exist. None are completely convincing.

The question can be answered experimentally by discovering the pattern of Higgs and squark and slepton and gaugino masses, because they are the main terms in the SUSY-breaking Lagrangian.

Experimental Constraints on Soft Terms

Fortunately, we already know that the MSSM soft terms cannot be arbitrary, because of experimental constraints on flavor violation.

For example, if there is a smuon-selectron mixing (mass)^2 term $\mathcal{L} = -m^2_{\tilde{\mu}_L \tilde{e}_L} \tilde{e}_L \tilde{\mu}^*_L$, and $\tilde{M} =$ Max$[m_{\tilde{e}_L}, m_{\tilde{e}_R}, M_2]$, then by calculating this one-loop diagram, one finds the decay width:



$\mu^- \to e^- \gamma$

$$\Gamma(\mu^- \to e^- \gamma) = 5 \times 10^{-21} \text{ MeV} \left(\frac{m^2_{\tilde{\mu}_L \tilde{e}_L}}{\tilde{M}^2} \right)^2 \left(\frac{100 \text{ GeV}}{\tilde{M}} \right)^4$$

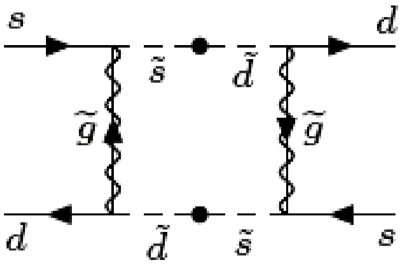
For comparison, the experimental limit is (from MEGA at LAMPF):

$$\Gamma(\mu^- \to e^- \gamma) < 3.6 \times 10^{-27} \text{ MeV}.$$

So the amount of smuon-selectron mixing in the soft Lagrangian is limited by:

$$\boxed{\left(\frac{m^2_{\tilde{\mu}_L \tilde{e}_L}}{\tilde{M}^2} \right) < 10^{-3} \left(\frac{\tilde{M}}{100 \text{ GeV}} \right)^2}$$

Experimental Constraints on Soft Terms



Another example: $K^0 \leftrightarrow \overline{K^0}$ mixing.

Let $\mathcal{L} = -m^2_{\tilde{d}_L \tilde{s}_L} \tilde{d}_L \tilde{s}^*_L$ be the flavor-violating term, and $\tilde{M} = \text{Max}[m_{\tilde{d}_L}, m_{\tilde{s}_L}, m_{\tilde{g}}]$.

Comparing this diagram with Δm_{K^0} gives:

$$\boxed{\frac{m^2_{\tilde{d}_L \tilde{s}_L}}{\tilde{M}^2} < 0.04 \left(\frac{\tilde{M}}{500\ \text{GeV}} \right)}$$

The experimental values of ϵ and ϵ'/ϵ in the effective Hamiltonian for the $K^0, \overline{K^0}$ system also give strong constraints on the amount of $\tilde{d}_L, \tilde{s}_L$ and $\tilde{d}_R, \tilde{s}_R$ mixing and CP violation in the soft terms.

Similarly:

The $D^0, \overline{D^0}$ system constrains $\tilde{u}_L, \tilde{c}_L$ and $\tilde{u}_R, \tilde{c}_R$ soft SUSY-breaking mixing.

The $B^0_d, \overline{B^0_d}$ system constrains $\tilde{d}_L, \tilde{b}_L$ and $\tilde{d}_R, \tilde{b}_R$ soft SUSY-breaking mixing.

In general, the soft-SUSY breaking terms must be either very heavy, or nearly flavor-blind, to avoid flavor-changing violating experimental limits.

The Flavor-Preserving MSSM

Take an idealized limit in which in which the squark and slepton (mass)^2 matrices are flavor-blind, each proportional to the 3×3 identity matrix in family space:

$$\boxed{\mathbf{m^2_{\tilde{Q}}} = m^2_{\tilde{Q}}\mathbf{1}; \quad \mathbf{m^2_{\bar{\tilde{u}}}} = m^2_{\bar{\tilde{u}}}\mathbf{1}; \quad \mathbf{m^2_{\bar{\tilde{d}}}} = m^2_{\bar{\tilde{d}}}\mathbf{1}; \quad \mathbf{m^2_{\tilde{L}}} = m^2_{\tilde{L}}\mathbf{1}; \quad \mathbf{m^2_{\bar{\tilde{e}}}} = m^2_{\bar{\tilde{e}}}\mathbf{1}.}$$

Then all squark and slepton mixing angles are rendered trivial, because squarks

Also assume:

$$\boxed{\mathbf{a_u} = A_{u0}\,\mathbf{y_u}; \qquad \mathbf{a_d} = A_{d0}\,\mathbf{y_d}; \qquad \mathbf{a_e} = A_{e0}\,\mathbf{y_e}.}$$

Also, assume no new CP-violating phases:

$$\boxed{M_1,\, M_2,\, M_3,\, A_{u0},\, A_{d0},\, A_{e0} = \text{real}}$$

→ “soft SUSY-breaking universality“

The Flavor-Preserving MSSM

The new parameters, besides those already found in the Standard Model, are:

- M_1, M_2, M_3 (3 real gaugino)
- $m^2_{\tilde{Q}}, m^2_{\tilde{\bar{u}}}, m^2_{\tilde{\bar{d}}}, m^2_{\tilde{L}}, m^2_{\tilde{\bar{e}}}$ (5 squark and slepton mass^2 parameters)
- A_{u0}, A_{d0}, A_{e0} (3 real scalar^3 couplings)
- $m^2_{H_u}, m^2_{H_d}, b, \mu$ (4 real parameters)

So there are 15 real parameters

The parameters μ and $b \equiv B\mu$ are often traded for the known Higgs VEV $v = 175$ GeV, $\tan\beta$, and sign(μ).

Most viable SUSY breaking models are special cases of this.

However, these are Lagrangian parameters that run with the renormalization scale, Q. Therefore, one must also choose an "input scale" Q_0 where the flavor-independence holds.

The Flavor-Preserving MSSM

What is the input scale Q_0 ?

Perhaps:

- $Q_0 = M_{\mathrm{Planck}}$, or
- $Q_0 = M_{\mathrm{string}}$, or
- $Q_0 = M_{\mathrm{GUT}}$, or
- Q_0 is some other scale associated with the type of SUSY breaking.

In any case, one can pick the SUSY-breaking parameters at Q_0 as boundary conditions, then run them down to the weak scale using their renormalization group (RG) equations. Flavor violation will remain small, because the Yukawa couplings of the first two families are small.

At the weak scale, use the renormalized parameters to predict physical masses, decay rates, cross-sections, dark matter relic density, etc.

Origins of SUSY Breaking

Up to now, we have simply put SUSY breaking into the MSSM explicitly.

To gain deeper understanding, let us consider how SUSY could be spontaneously broken. This means that the Lagrangian is invariant under SUSY transformations, but the ground state is not:

$$\boxed{Q_\alpha|0\rangle \neq 0, \qquad\qquad Q^\dagger_{\dot\alpha}|0\rangle \neq 0.}$$

The SUSY algebra tells us that the Hamiltonian is related to the SUSY charges by:

$$H = P^0 = \tfrac{1}{4}(Q_1Q_1^\dagger + Q_1^\dagger Q_1 + Q_2Q_2^\dagger + Q_2^\dagger Q_2).$$

Therefore, if SUSY is unbroken in the ground state, then $H|0\rangle = 0$, so the ground state energy is 0. Conversely, if SUSY is spontaneously broken, then the ground state must have positive energy, since

$$\boxed{\langle 0|H|0\rangle = \tfrac{1}{4}\left(||Q_1^\dagger|0\rangle||^2 + ||Q_1|0\rangle||^2 + ||Q_2^\dagger|0\rangle||^2 + ||Q_2|0\rangle||^2\right) > 0}$$

To achieve spontaneous SUSY breaking, we need a theory in which the prospective ground state $|0\rangle$ has positive energy.

Recall that in SUSY, the potential energy

$$V = \sum_i F^{*i} F_i + \tfrac{1}{2} \sum_a D^a D^a$$

is a sum of squared of auxiliary fields. So, for spontaneous SUSY breaking, one must arrange that **no** state (or field configuration, classically) has all $F_i = 0$ and all $D^a = 0$.

Models of SUSY breaking where

- $F_i \neq 0$ are called "O'Raifeartaigh models" or "F-term Breaking models"
- $D^a \neq 0$ are called "Fayet-Iliopoulis models" or "D-term breaking models"

Spontaneous Breaking of SUSY requires us to extend the MSSM

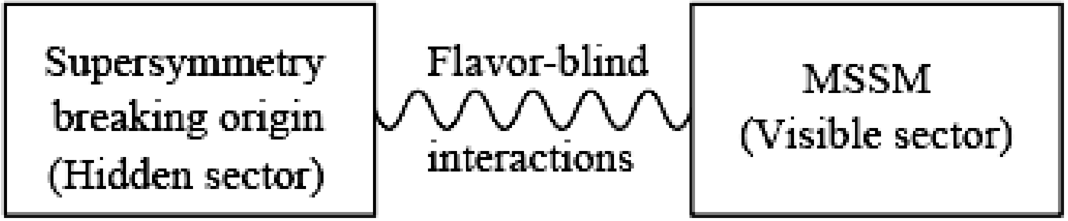
- D-term breaking can't work **(→ wrong phenomenology)**
- There is no gauge-singlet chiral supermultiplet in the MSSM that could get a non-zero F-term VEV.

Even if there were such an $\langle F \rangle$, there is another general obstacle. Gaugino masses cannot arise in a renormalizable SUSY theory at tree-level. This is because SUSY does not contain any (gaugino)-(gaugino)-(scalar) coupling that could turn into a gaugino mass term when the scalar gets a VEV.

We also have the clue that SUSY breaking must be essentially flavor-blind in order to not conflict with experiment.

This leads to the following general schematic picture of SUSY breaking. . .

The MSSM soft SUSY-breaking terms arise indirectly or radiatively, not from tree-level renormalizable couplings directly to the SUSY-breaking sector.



Spontaneous SUSY breaking occurs in a "hidden sector" of particles with no (or tiny) direct couplings to the "visible sector" chiral supermultiplets of the MSSM. However, the two sectors do share some mediating interactions that transmit SUSY-breaking effects indirectly. As a bonus, if the mediating interactions are flavor-blind, then the soft SUSY-breaking terms of the MSSM will be also.

There are two obvious guesses for the flavor-blind interactions: gravitational and the ordinary gauge interactions.

Common Models for SUSY Breaking

- mSUGRA: Minimal Supergravity

  At GUT scale:
  - Unify all scalar and all spin-1/2 masses
  - Unify all trilinear couplings $A_t = A_b = A_\tau = A_0$

  $m_{1/2}$, m_0, $\tan\beta$, $\mathrm{sign}(\mu)$, A_0

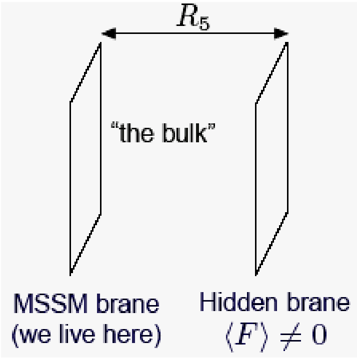
  LSP = lightest neutralino

- GMSB: Gauge mediated SUSY breaking

  M, Λ, N, $\tan\beta$, $\mathrm{sign}(\mu)$

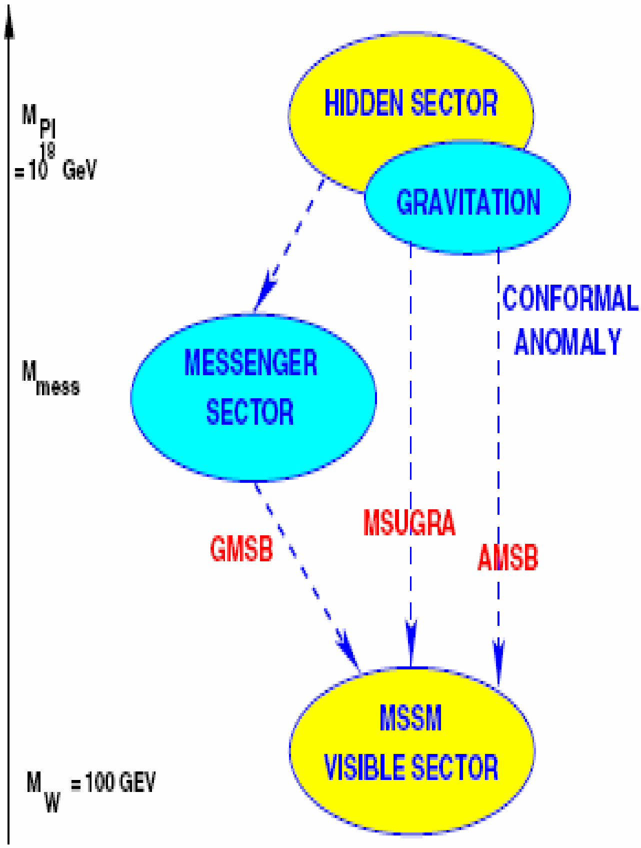
  LSP = Gravitino

- AMSB: Anomaly-mediated SUSY breaking



  $m_{3/2}$, m_0, $\tan\beta$, $\mathrm{sign}(\mu)$

  LSP = lightest neutralino



Sparticle Masses and Mixing

Reminder: Renormalization Group Equations

Evolution of SUSY masses: "Renormalization Group Equations (RGE)"

- Gaugino masses:

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

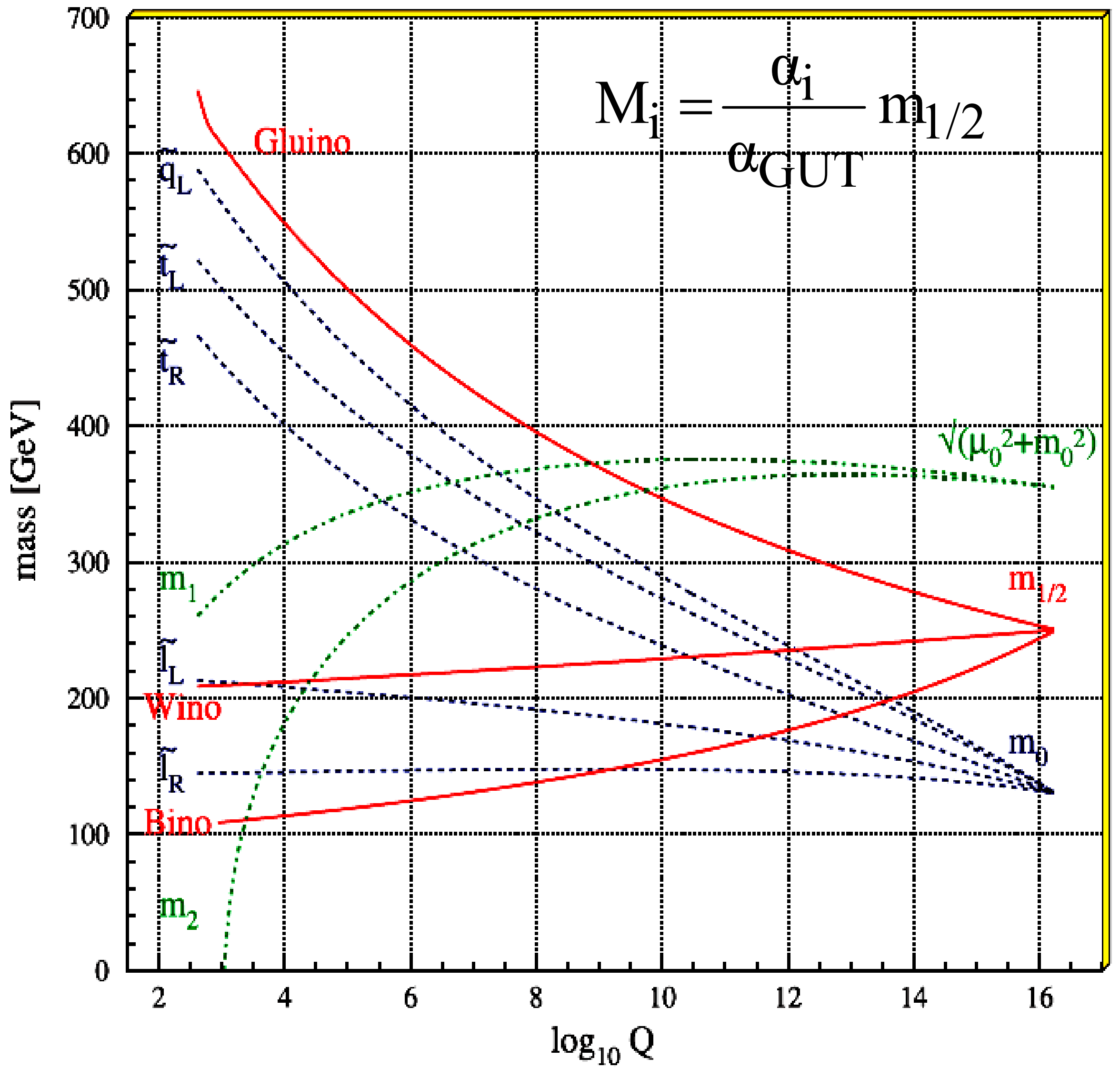
$M_3 \equiv M_{\tilde{g}} \simeq 2.7 m_{1/2}$, **gluino**

$M_2(M_Z) \simeq 0.8 m_{1/2}$, **wino**

$M_1(M_Z) \simeq 0.4 m_{1/2}$. **bino**

- Sfermion masses:

$$\boxed{m_{\tilde{l}} < m_{\tilde{q}} \simeq M_{\tilde{g}}}$$



Chargino and Neutralino Mixing

- Physical charginos/neutralinos are mixtures of Bino, Winos and higgsinos (due to electroweak symmetry breaking)

- The mass eigenstates depend on:
  - EWSB parameters (mixing $B^0, W^0 \rightarrow Z, \gamma$) : m_Z, $\sin^2\theta_W$
  - SUSY masses and breaking parameters : M_1, M_2, $\tan\beta$, μ

M_1, M_2: Bino and wino mass terms in $\mathcal{L}_{soft}$

$$\mathcal{L}_{\rm soft}^{\rm MSSM} = -\tfrac{1}{2}\left(M_3\widetilde{g}\widetilde{g} + M_2\widetilde{W}\widetilde{W} + M_1\widetilde{B}\widetilde{B}\right) + \text{c.c.} + \ldots$$

μ: Higgsino mass term in MSSM superpotential

$$W_{\rm MSSM} = \tilde{\bar{u}}\mathbf{y_u}\tilde{Q}H_u - \tilde{\bar{d}}\mathbf{y_d}\tilde{Q}H_d - \tilde{\bar{e}}\mathbf{y_e}\tilde{L}H_d + \mu H_u H_d$$

$\tan\beta$: ratio of H_u and H_d vacuum expectation values, $\tan\beta = v_u/v_d$

Chargino Mixing and Masses

$$\mathcal{L}_{\text{chargino mass}} = -\tfrac{1}{2}(\psi^{\pm})^T \mathbf{M}_{\tilde{C}} \psi^{\pm} + \text{c.c.}$$

$$\begin{pmatrix} \chi_1^+ \\ \chi_2^+ \end{pmatrix} = \begin{pmatrix} M_2 & \sqrt{2} m_W \sin\beta \\ \sqrt{2} m_W \cos\beta & \mu \end{pmatrix} \begin{pmatrix} \tilde{W}^+ \\ \tilde{H}^+ \end{pmatrix}$$

- Diagonalization of the matrix (to get eigenvalues) gives the chargino mass values
- In the limit $m_W, m_Z << |\mu \pm M_2|$ ("not unlikely"):

$$\begin{aligned} m_{\tilde{C}_1} &= M_2 - \frac{m_W^2 (M_2 + \mu \sin 2\beta)}{\mu^2 - M_2^2} + \ldots \\ m_{\tilde{C}_2} &= |\mu| + \frac{m_W^2 I(\mu + M_2 \sin 2\beta)}{\mu^2 - M_2^2} + \ldots . \end{aligned}$$

→ $\chi_{1\pm}$ is mostly wino with mass ≈ M_2

→ $\chi_2^{\pm}$ is mostly higgsino with mass ≈ $|\mu|$

Neutralino Mixing and Masses

$$\mathcal{L}_{\text{neutralino mass}} = -\tfrac{1}{2}(\psi^0)^T \mathbf{M}_{\tilde{N}} \psi^0$$

$$\begin{pmatrix} \chi_1^0 \\ \chi_2^0 \\ \chi_3^0 \\ \chi_4^0 \end{pmatrix} = \begin{pmatrix} M_1 & 0 & -m_Z c_\beta s_W & m_Z s_\beta s_W \\ 0 & M_2 & m_Z c_\beta c_W & -m_Z s_\beta c_W \\ -m_Z c_\beta s_W & m_Z c_\beta c_W & 0 & -\mu \\ m_Z s_\beta s_W & -m_Z s_\beta c_W & -\mu & 0 \end{pmatrix} \begin{pmatrix} \tilde{B} \\ \tilde{W}^3 \\ \tilde{H}_1^0 \\ \tilde{H}_2^0 \end{pmatrix}$$

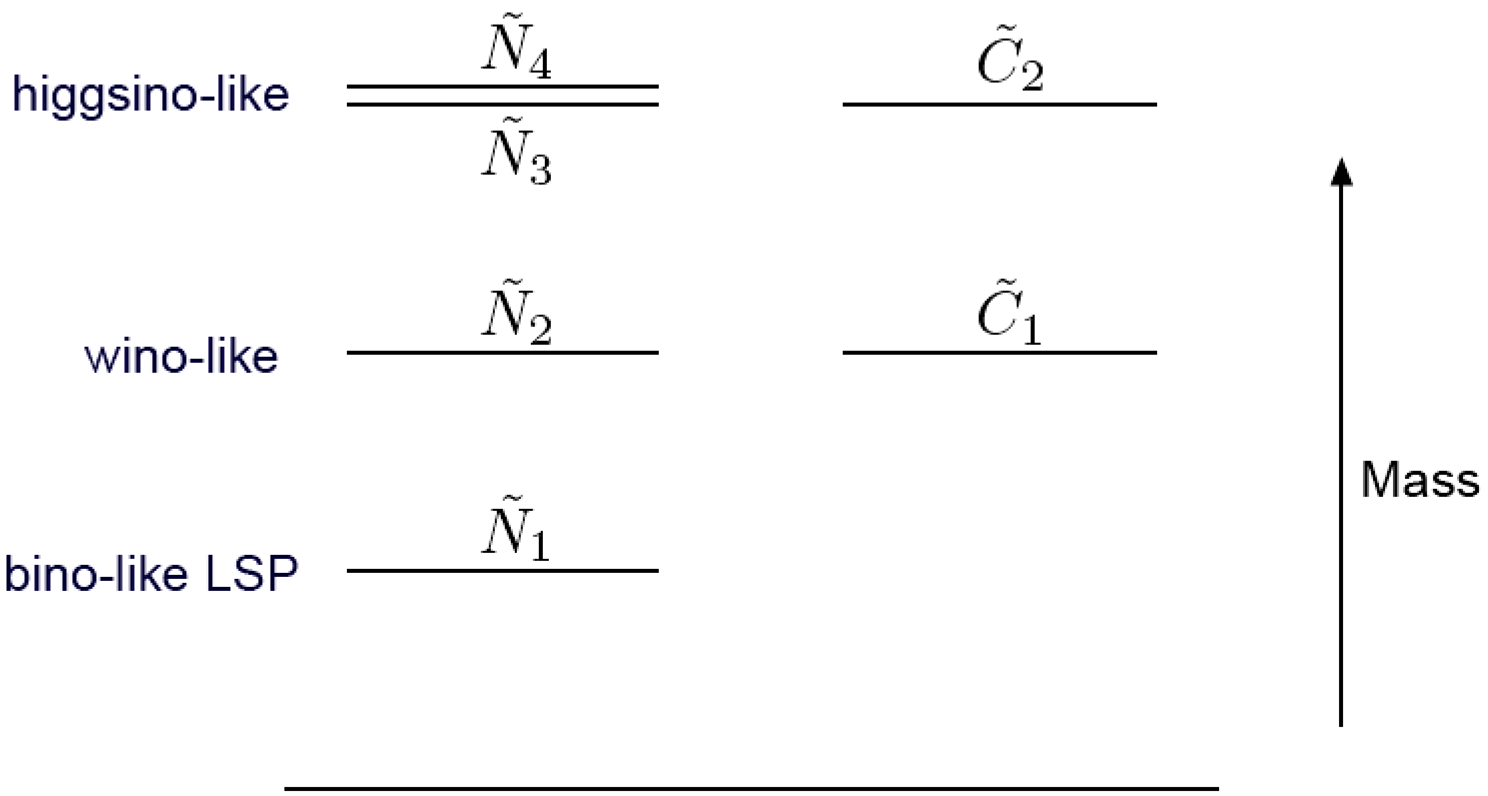
- In the limit m_W, m_Z << $|\mu \pm M_1|$, $|\mu \pm M_2|$:

$$\begin{aligned} m_{\tilde{N}_1} &= M_1 - \frac{m_Z^2 s_W^2 (M_1 + \mu \sin 2\beta)}{\mu^2 - M_1^2} + \ldots \\ m_{\tilde{N}_2} &= M_2 - \frac{m_W^2 (M_2 + \mu \sin 2\beta)}{\mu^2 - M_2^2} + \ldots \\ m_{\tilde{N}_3}, m_{\tilde{N}_4} &= |\mu| + \frac{m_Z^2 (I - \sin 2\beta)(\mu + M_1 c_W^2 + M_2 s_W^2)}{2(\mu + M_1)(\mu + M_2)} + \ldots, \\ & \quad |\mu| + \frac{m_Z^2 (I + \sin 2\beta)(\mu - M_1 c_W^2 - M_2 s_W^2)}{2(\mu - M_1)(\mu - M_2)} + \ldots \end{aligned}$$

→ Bino-like χ_1^0 with mass ~ M_1, wino-like χ_2^0 with mass ~ M_2

→ Higgsino-like χ_3^0, χ_4^0 with masses ~ $|\mu|$

Neutralino and Chargino Masses



This is a plausibel and popular mass spectrum,
but it is not guaranteed!

Gluino Mass

- Gluinos do not have the right quantum numbers to mix with any other states ($SU(3)_C$ color-octet fermions)

  → at tree level the gluino mass is:

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

- But quantum corrections (e.g. from squarks) to the gluino mass are large! They increase the gluino mass by 5 – 25% compared to tree level, depending on the squark masses.

Squark and Slepton Mixing and Masses

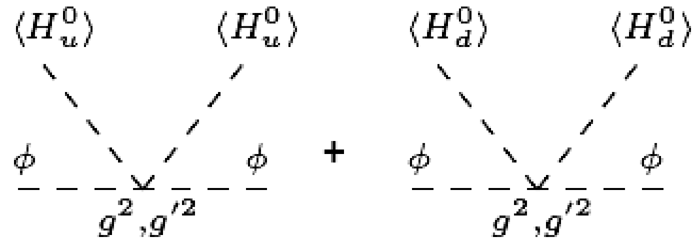
To treat these in complete generality, we would have to take into account arbitrary mixing. So the mass eigenstates would be obtained by diagonalizing:

- a 6×6 (mass)^2 matrix for up-type squarks $(\widetilde{u}_L, \widetilde{c}_L, \widetilde{t}_L, \widetilde{u}_R, \widetilde{c}_R, \widetilde{t}_R)$,
- a 6×6 (mass)^2 matrix for down-type squarks $(\widetilde{d}_L, \widetilde{s}_L, \widetilde{b}_L, \widetilde{d}_R, \widetilde{s}_R, \widetilde{b}_R)$,
- a 6×6 (mass)^2 matrix for charged sleptons $(\widetilde{e}_L, \widetilde{\mu}_L, \widetilde{\tau}_L, \widetilde{e}_R, \widetilde{\mu}_R, \widetilde{\tau}_R)$,
- a 3×3 matrix for sneutrinos $(\widetilde{\nu}_e, \widetilde{\nu}_\mu, \widetilde{\nu}_\tau)$

Fortunately, the general hypothesis of flavor-blind soft parameters predicts that most of these mixing angles are very small.

The first- and second-family squarks and sleptons have negligible Yukawa couplings, so they end up in 7 very nearly degenerate, unmixed pairs $(\widetilde{e}_R, \widetilde{\mu}_R)$, $(\widetilde{\nu}_e, \widetilde{\nu}_\mu)$, $(\widetilde{e}_L, \widetilde{\mu}_L)$, $(\widetilde{u}_R, \widetilde{c}_R)$, $(\widetilde{d}_R, \widetilde{s}_R)$, $(\widetilde{u}_L, \widetilde{c}_L)$, $(\widetilde{d}_L, \widetilde{s}_L)$.

Squark and Slepton Mixing and Masses

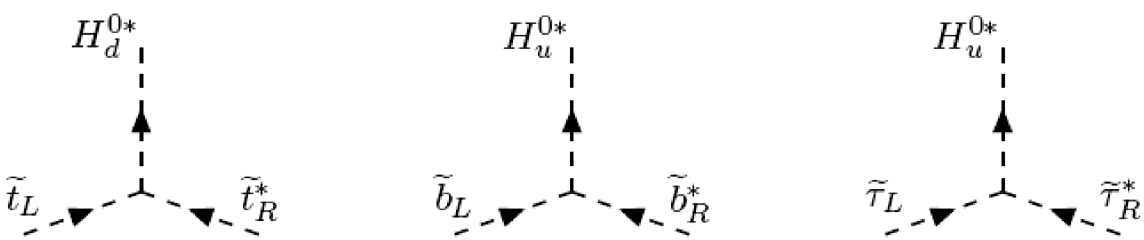


This leads to model-independent sum rules

$$m^2_{\tilde{e}_L} - m^2_{\tilde{\nu}_e} = m^2_{\tilde{d}_L} - m^2_{\tilde{u}_L} = g^2(v_u^2 - v_d^2)/2 = -\cos 2\beta\, m_W^2 .$$

Since $\cos 2\beta < 0$ in the allowed range $\tan\beta > 1$, it follows that $m_{\tilde{e}_L} > m_{\tilde{\nu}_e}$ and $m_{\tilde{d}_L} > m_{\tilde{u}_L}$, with the magnitude of the splittings constrained by electroweak symmetry breaking.

- **For the 3rd generation, also (scalar)³ Yukawa couplings are important:**



→ This leads to left-right mixing!

Squark and Slepton Mixing: 3rd Generation

- Due to the large Yukawa couplings of the 3rd generation, there is non-trivial mixing in the tau sector:

$$\begin{pmatrix} \tilde\tau_1 \\ \tilde\tau_2 \end{pmatrix} = \underbrace{\begin{pmatrix} c_{\tilde\tau} & -s^*_{\tilde\tau} \\ s_{\tilde\tau} & c_{\tilde\tau} \end{pmatrix}}_{M_{\tilde\tau}} \begin{pmatrix} \tilde\tau_L \\ \tilde\tau_R \end{pmatrix}$$

$$M_{\tilde\tau} = \begin{pmatrix} M^2_{\tilde\tau_L} + m^2_\tau + M^2_Z \cos 2\beta \left(-\frac{1}{2} + \sin^2\theta_W\right) & m_\tau \left(A_\tau - \mu \tan\beta\right) \\ m_\tau \left(A_\tau - \mu \tan\beta\right) & M^2_{\tilde\tau_R} + m^2_\tau - M^2_Z \cos 2\beta \sin^2\theta_W \end{pmatrix}$$

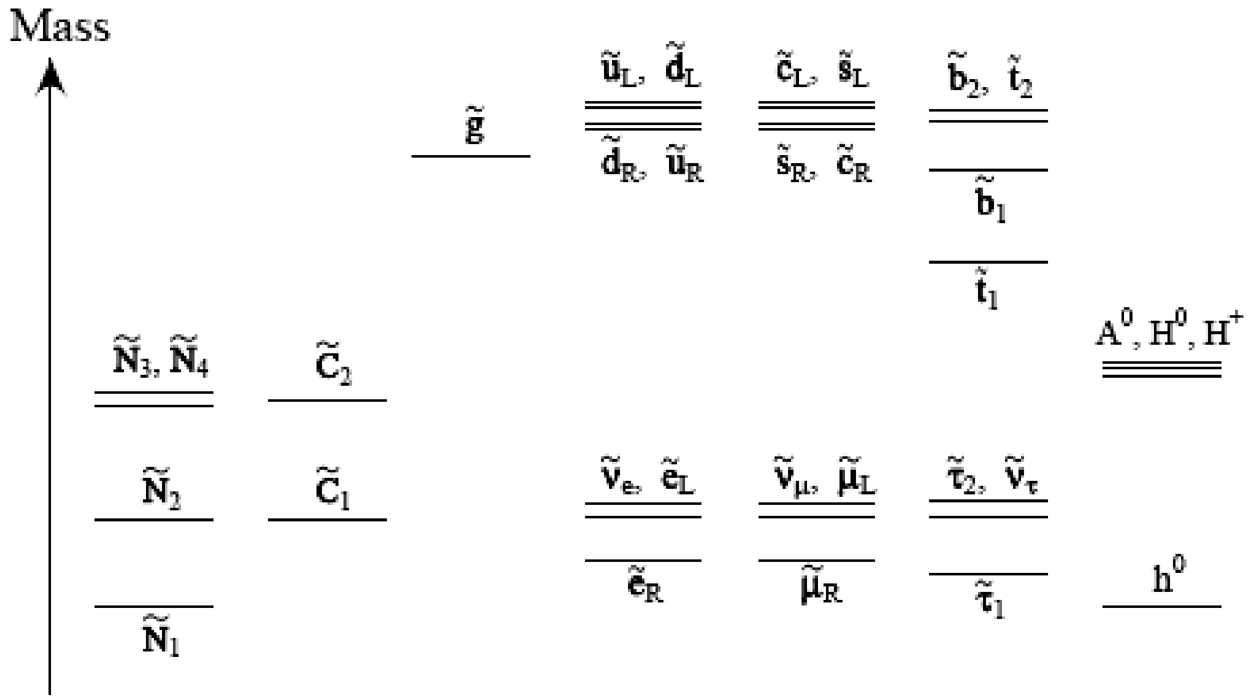
and analogously in the top and bottom sectors:

$$\begin{pmatrix} \tilde t_1 \\ \tilde t_2 \end{pmatrix} = \begin{pmatrix} c_{\tilde t} & -s^*_{\tilde t} \\ s_{\tilde t} & c_{\tilde t} \end{pmatrix} \begin{pmatrix} \tilde t_L \\ \tilde t_R \end{pmatrix} \qquad \begin{pmatrix} \tilde b_1 \\ \tilde b_2 \end{pmatrix} = \begin{pmatrix} c_{\tilde b} & -s^*_{\tilde b} \\ s_{\tilde b} & c_{\tilde b} \end{pmatrix} \begin{pmatrix} \tilde b_L \\ \tilde b_R \end{pmatrix}$$

MSSM Mass and Gauge Eigenstates

Names	Spin	P_R	Mass Eigenstates	Gauge Eigenstates
Higgs bosons	0	$+1$	$h^0 \;\; H^0 \;\; A^0 \;\; H^\pm$	$H_u^0 \;\; H_d^0 \;\; H_u^+ \;\; H_d^-$
squarks	0	-1	$\widetilde{u}_L \;\; \widetilde{u}_R \;\; \widetilde{d}_L \;\; \widetilde{d}_R$	" "
			$\widetilde{s}_L \;\; \widetilde{s}_R \;\; \widetilde{c}_L \;\; \widetilde{c}_R$	" "
			$\widetilde{t}_1 \;\; \widetilde{t}_2 \;\; \widetilde{b}_1 \;\; \widetilde{b}_2$	$\widetilde{t}_L \;\; \widetilde{t}_R \;\; \widetilde{b}_L \;\; \widetilde{b}_R$
sleptons	0	-1	$\widetilde{e}_L \;\; \widetilde{e}_R \;\; \widetilde{\nu}_e$	" "
			$\widetilde{\mu}_L \;\; \widetilde{\mu}_R \;\; \widetilde{\nu}_\mu$	" "
			$\widetilde{\tau}_1 \;\; \widetilde{\tau}_2 \;\; \widetilde{\nu}_\tau$	$\widetilde{\tau}_L \;\; \widetilde{\tau}_R \;\; \widetilde{\nu}_\tau$
neutralinos	$1/2$	-1	$\widetilde{N}_1 \;\; \widetilde{N}_2 \;\; \widetilde{N}_3 \;\; \widetilde{N}_4$	$\widetilde{B}^0 \;\; \widetilde{W}^0 \;\; \widetilde{H}_u^0 \;\; \widetilde{H}_d^0$
charginos	$1/2$	-1	$\widetilde{C}_1^\pm \;\; \widetilde{C}_2^\pm$	$\widetilde{W}^\pm \;\; \widetilde{H}_u^+ \;\; \widetilde{H}_d^-$
gluino	$1/2$	-1	$\widetilde{g}$	" "

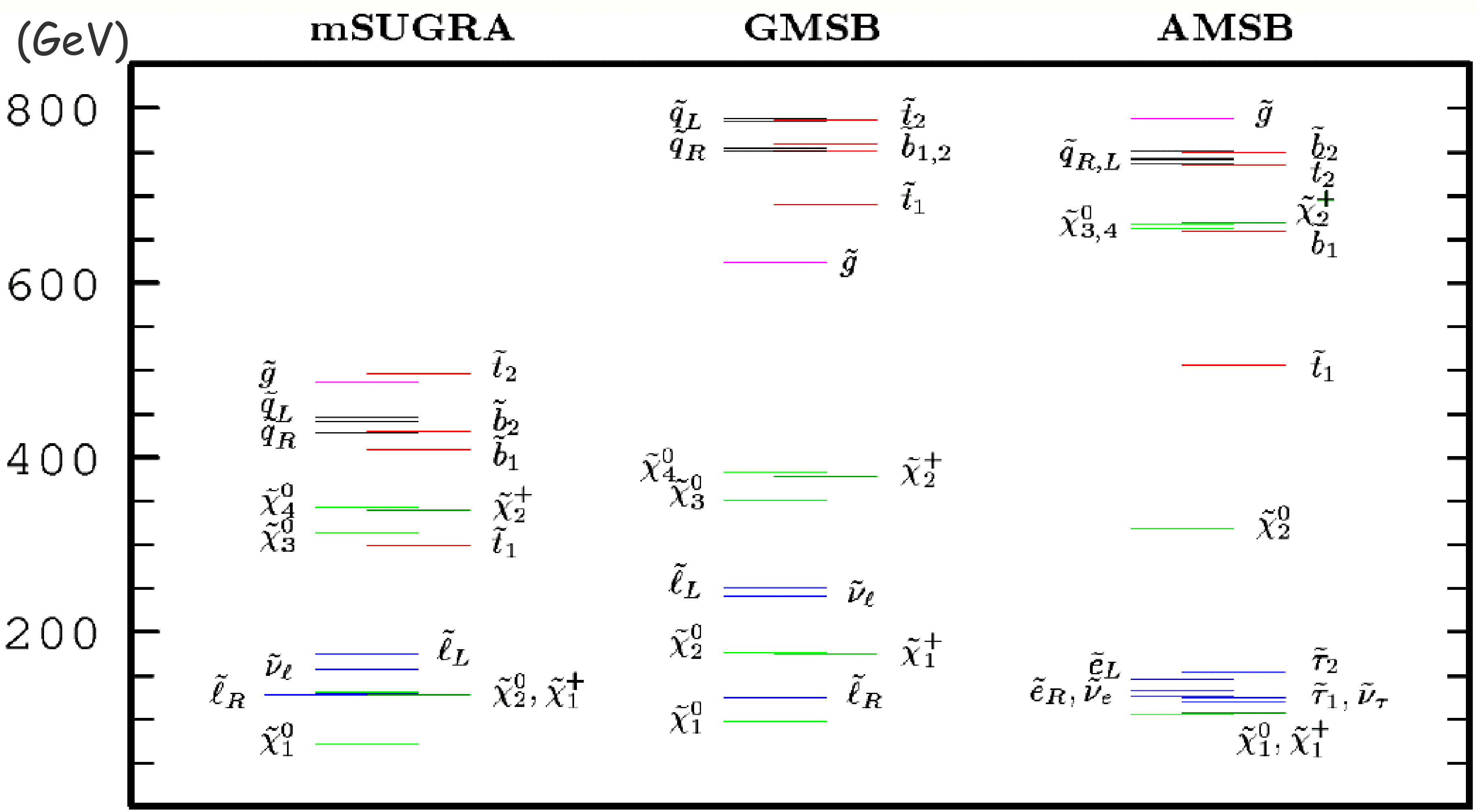
A sample mass spectrum for the MSSM



This may or may not look anything like the Real World. It incorporates, qualitatively, some theoretical prejudices that are common to many different models.

In the next lecture, we will explore various candidate ideas for how SUSY is broken, and relate them to features of the SUSY spectrum.

Comparison of Typical Mass Spectra

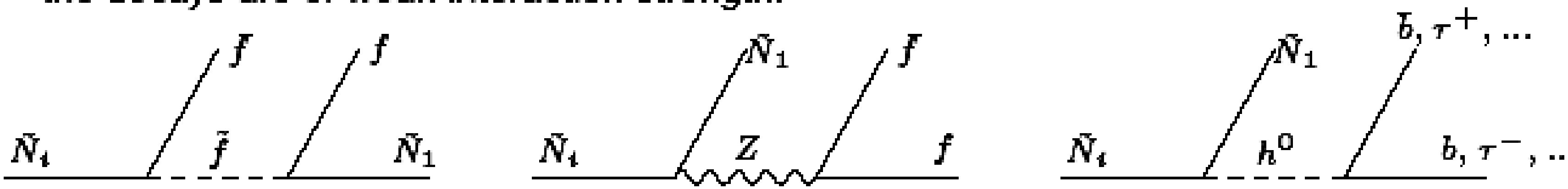


Sparticle Decays

Sparticle Decays: Neutralinos

1) Neutralino Decays

If R-parity is conserved and $\tilde{N}_1$ is the LSP, then it cannot decay. For the others, the decays are of weak-interaction strength:



In each case, the intermediate boson (squark or slepton $\tilde{f}$, Z boson, or Higgs boson h^0) might be on-shell, if that two-body decay is kinematically allowed.

In general, the visible decays are either:

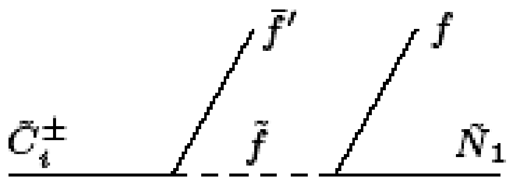
$$\tilde{N}_i \to q\bar{q}\tilde{N}_1 \qquad \text{(seen in detector as } jj + \not{E}\text{)}$$
$$\tilde{N}_i \to \ell^+\ell^-\tilde{N}_1 \qquad \text{(seen in detector as } \ell^+\ell^- + \not{E}\text{)}$$

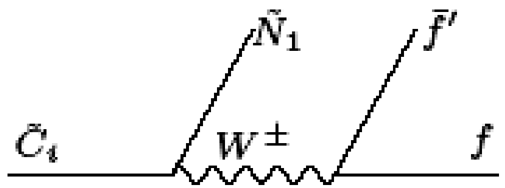
Some SUSY signals rely on leptons in the final state. This is more likely if sleptons are relatively light. If $\tilde{N}_i \to \tilde{N}_1 h^0$ is kinematically open, then it often dominates. This is called the “spoiler mode”, because leptonic final states are rare.

Sparticle Decays: Charginos

2) Chargino Decays

Charginos $\tilde{C}_i$ have decays of weak-interaction strength:





In each case, the intermediate boson (squark or slepton $\tilde{f}$, or W boson) might be on-shell, if that two-body decay is kinematically allowed.

In general, the decays are either:

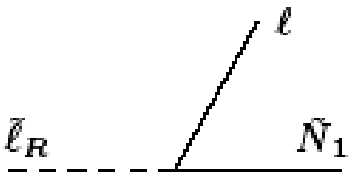
$$\boxed{\begin{array}{ll} \tilde{C}_i^\pm \to q\bar{q}'\tilde{N}_1 & \text{(seen in detector as } jj + \not{E}) \\ \tilde{C}_i^\pm \to \ell^\pm \nu \tilde{N}_1 & \text{(seen in detector as } \ell^\pm + \not{E}) \end{array}}$$

Again, leptons in final state are more likely if sleptons are relatively light.

For both neutralinos and charginos, a relatively light, mixed $\tilde{\tau}_1$ can lead to enhanced τ's in the final state. This is increasingly important for larger $\tan\beta$. Tau identification may be a crucial limiting factor for experimental SUSY.

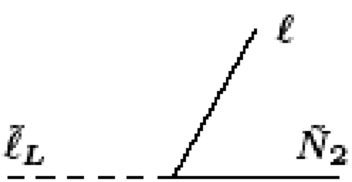
3) Slepton Decays

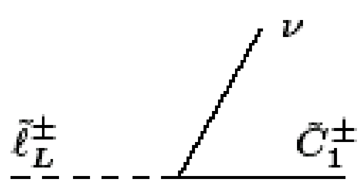
When $\tilde{N}_1$ is the LSP and has a large bino content, the sleptons $\tilde{e}_R$, $\tilde{\mu}_R$ (and often $\tilde{\tau}_1$ and $\tilde{\tau}_2$) prefer the direct two-body decays with strength proportional to g'^2:

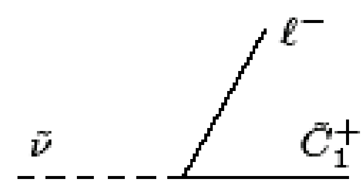


(seen in detector as $\ell^\pm + \not{E}$)

However, the left-handed sleptons $\tilde{e}_L$, $\tilde{\mu}_L$, $\tilde{\nu}$ have no coupling to the bino component of $\tilde{N}_1$, so they often decay preferentially through $\tilde{N}_2$ or $\tilde{C}_1$, which have a large wino content, with strength proportional to g^2:



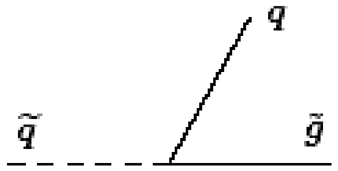




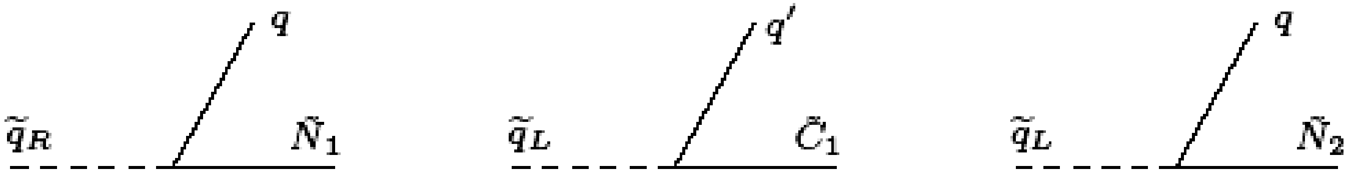
with $\tilde{N}_2$ and $\tilde{C}_1$ decaying as before.

4) Squark Decays

If the decay $\tilde{q} \longrightarrow q\tilde{g}$ is kinematically allowed, it will always dominate, because the squark-quark-gluino vertex has QCD strength:



Otherwise, right-handed squarks prefer to decay directly to a bino-like LSP, while left-handed squarks prefer to decay to a wino-like $\tilde{C}_1$ or $\tilde{N}_2$:

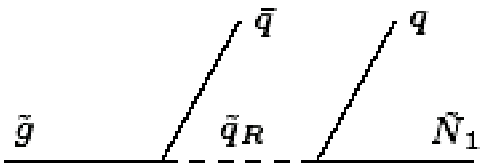


If a top squark is light, then the decays $\tilde{t}_1 \longrightarrow t\tilde{g}$ and $\tilde{t}_1 \longrightarrow t\tilde{N}_1$ may not be kinematically allowed, and it may decay only into charginos: $\tilde{t}_1 \longrightarrow b\tilde{C}_1$. If even that is not allowed, it has only a suppressed flavor-changing decay: $\tilde{t}_1 \longrightarrow c\tilde{N}_1$.

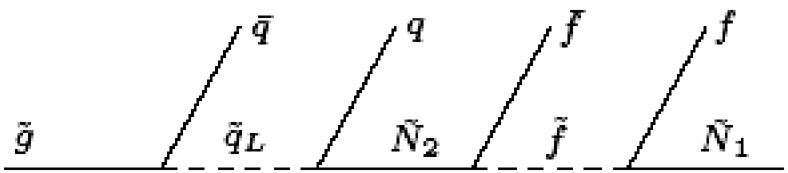
5) Gluino Decays

The gluino can only decay through squarks, either on-shell (if allowed) or virtual.

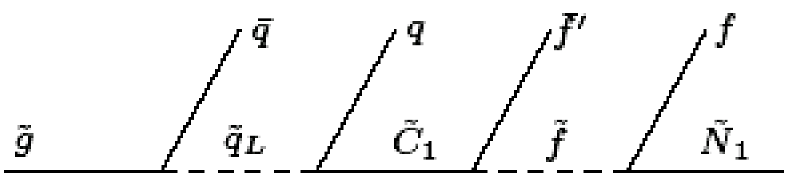
For example:



$$jj + \not{E} \quad \text{or} \quad t\bar{t} + \not{E}$$



$$jjjj + \not{E} \quad \text{or} \quad t\bar{t}jj + \not{E} \quad \text{or}$$
$$jj\ell^+\ell^- + \not{E}$$



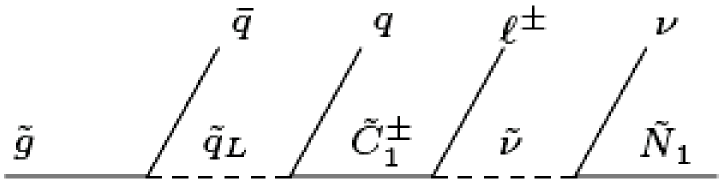
$$jjjj + \not{E} \quad \text{or} \quad t\bar{t}jj + \not{E} \quad \text{or}$$
$$jj\ell^\pm + \not{E}$$

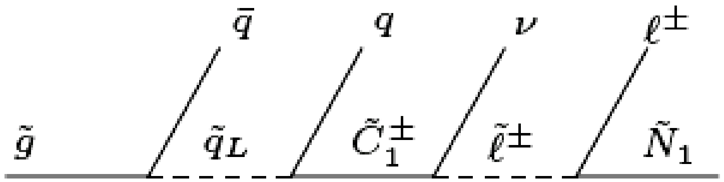
Because $m_{\tilde{t}_1} \ll$ other squark masses, top quarks can appear in these decays.

The possible signatures of gluinos and squarks are typically numerous and complicated because of these and other **cascade decays**.

Sparticle Decays

An important feature of gluino decays with one lepton:





In each case, $\tilde{g} \to jj\ell^\pm + \not{E}$, and the lepton has either charge with equal probability. (The gluino does not “know” about electric charge.)

So, events with at least one gluino, and exactly one charged lepton in the final state from each sparticle that was produced, will have probability 0.5 to have **same-charge leptons**, and probability 0.5 to have opposite-charge leptons.

This is important at hadron collider, where Standard Model backgrounds with same-charge leptons are much smaller.

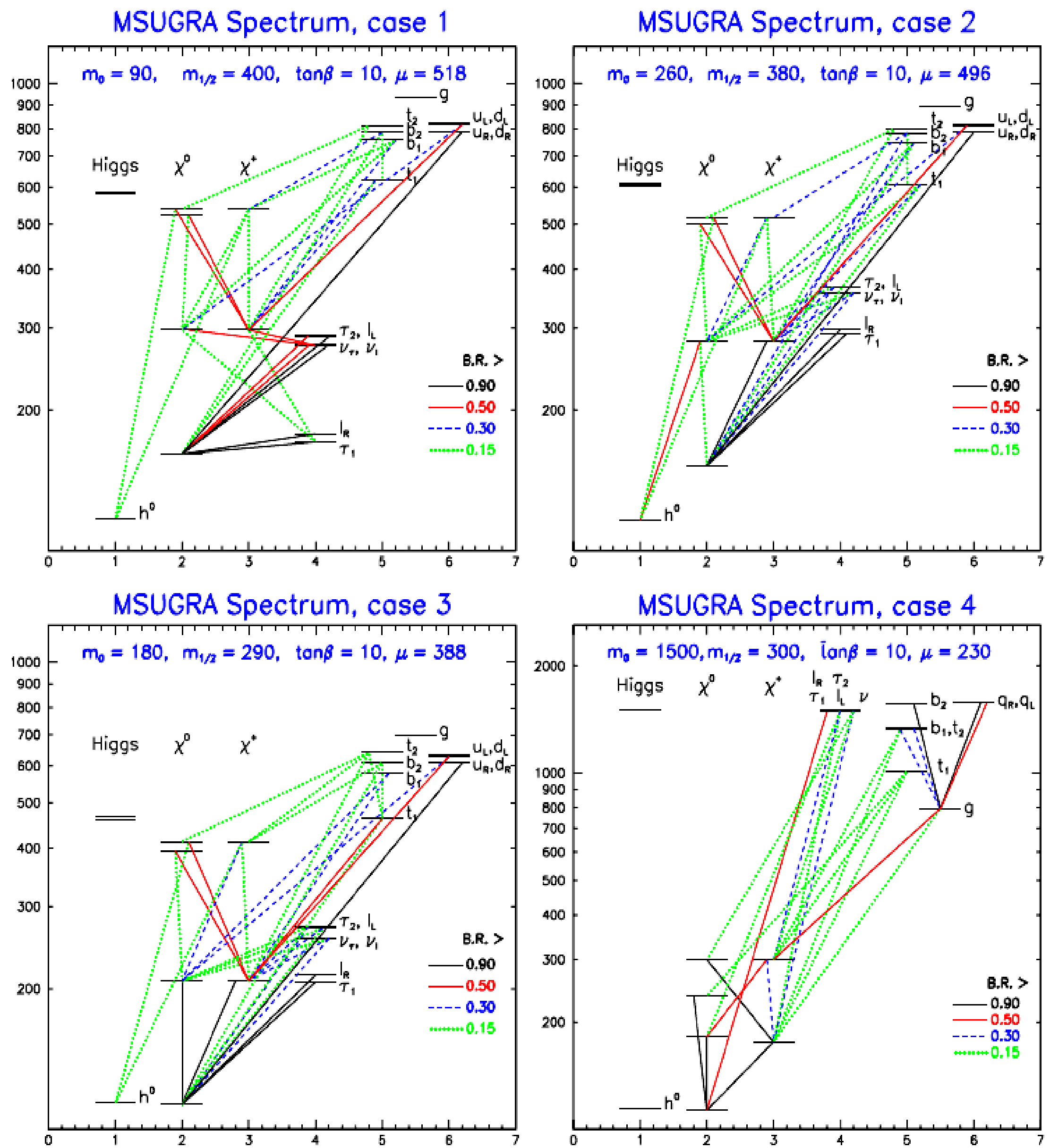
$$\text{(SUSY)} \to \ell^+\ell'^+ + \text{ jets } + \not{E}_T$$

Example mSUGRA Mass Spectra and Decays

<u>General considerations for SUSY searches:</u>

- Mass differences
  - $M_{squark} >> M_{LSP}$
    → Large E_T
    → model-independent
  - $M_{slepton}$ close to M_{LSP}
    → leptons with low E_T
    → model-dependent

- Decay patterns
  - parameter-dependent
  - Often long decay chains
  - Missing LSP



Previous and Current SUSY searches - some examples -

Two Ways to Search for Supersymmetry

- Indirect Search:
  - SUSY particles in loops
    M_{SUSY} large → small contribution to cross section
  - Need precise experiments of processes with small cross sections
    $\mu \to e\gamma$, $b \to s\gamma$, ...
  - Advantage: Limit for observable M_{SUSY} given by data statistics
  - Disadvantage: If deviation from SM is found, what is it?

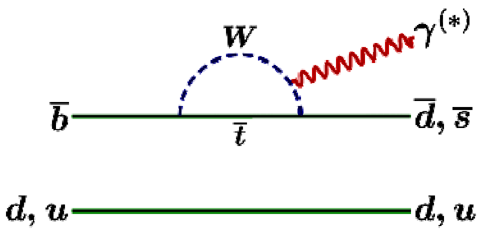
- Direct Search:
  - Production of SUSY particles at colliders
    → Pair production, cross section known as function of mass
    → Life time of heavy SUSY particles ~ 10^{-23} s → cannot be measured (exception: LSP = gravition → NLSP long-lived
    → Look for peaks in invariant mass distributions of final-state Standard-Model particles
  - Upper limit on MSUSY from center-of-mass energy

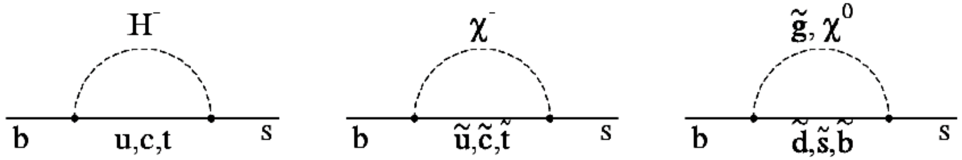
Indirect SUSY Searches: Rare Decays

- Search for forbidden decays or measure rare decays
- Branching fractions potentially enhanced by sparticles "in loops"

Example 1: $\mu \rightarrow e\,\gamma$ (already discussed)

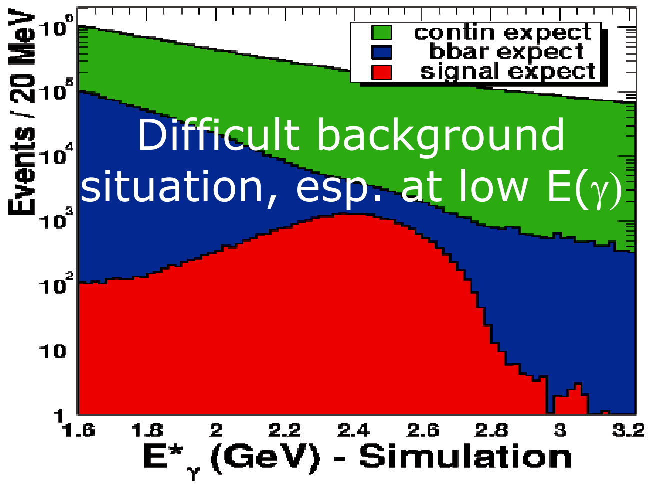
Example 2: $b \rightarrow s\,\gamma$ ("radiative penguin", flavor-changing neutral current FCNC)

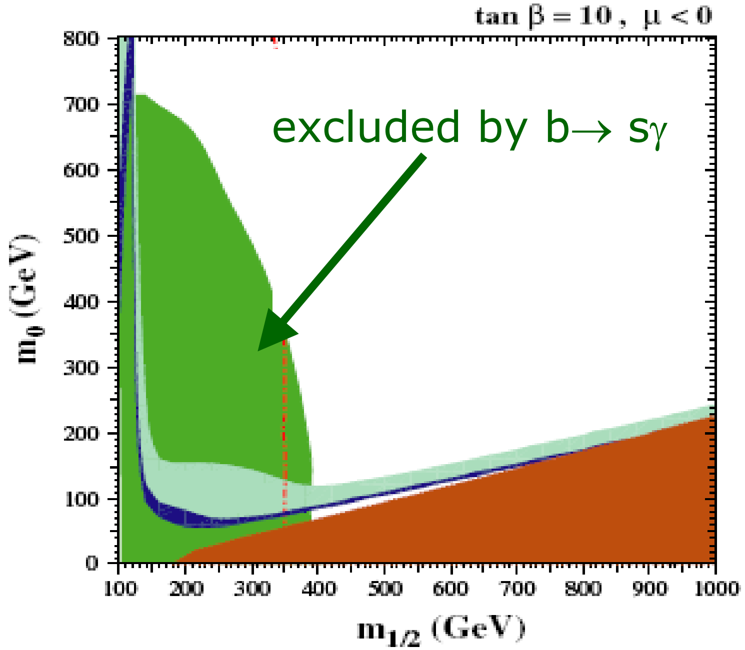




SUSY contributions

Branching fraction in SM ~ 3×10^{-4}
Measured at B Factories (BaBar, Belle)





"The Origin of Penguins"

from Symmetry Magazin, Jan./Feb. 2007

The origin of penguins

Told by John Ellis:

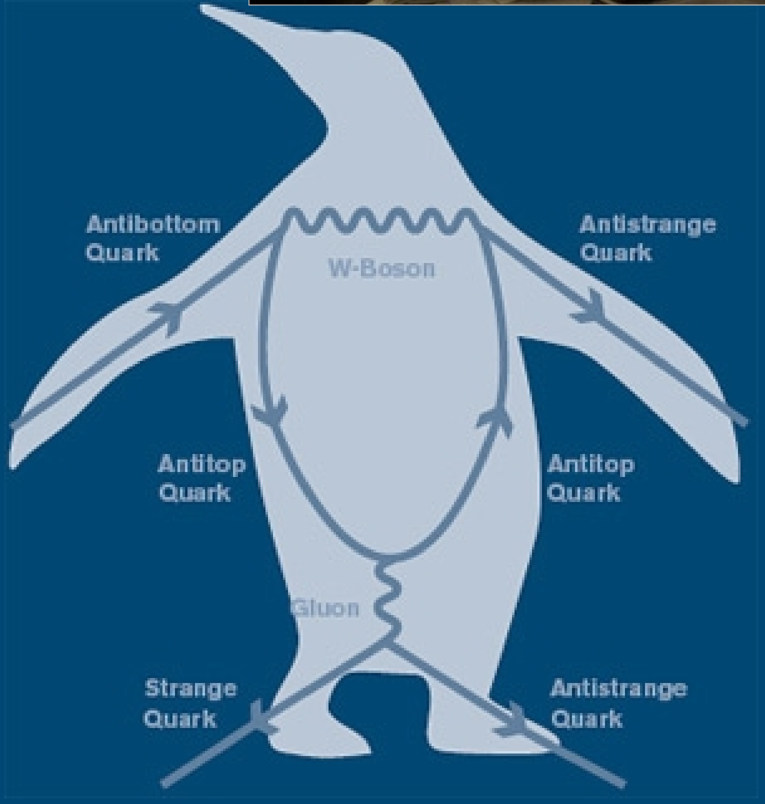
"Mary K. [Gaillard], Dimitri [Nanopoulos], and I first got interested in what are now called penguin diagrams while we were studying CP violation in the Standard Model in 1976... The penguin name came in 1977, as follows.

In the spring of 1977, Mike Chanowitz, Mary K. and I wrote a paper on GUTs [Grand Unified Theories] predicting the *b* quark mass before it was found. When it was found a few weeks later, Mary K., Dimitri, Serge Rudaz and I immediately started working on its phenomenology.

That summer, there was a student at CERN, Melissa Franklin, who is now an experimentalist at Harvard. One evening, she, I, and Serge went to a pub, and she and I started a game of darts. We made a bet that if I lost I had to put the word penguin into my next paper. She actually left the darts game before the end, and was replaced by Serge, who beat me. Nevertheless, I felt obligated to carry out the conditions of the bet.

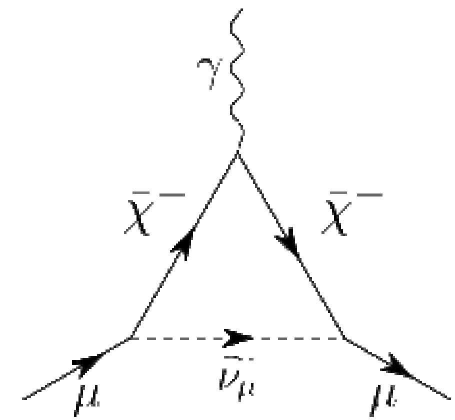
For some time, it was not clear to me how to get the word into this *b* quark paper that we were writing at the time.... Later...I had a sudden flash that the famous diagrams look like penguins. So we put the name into our paper, and the rest, as they say, is history."

John Ellis in Mikhail Shifman's "ITEP Lectures in Particle Physics and Field Theory", *hep-ph/9510397*



- Anomalous magnetic moment in Dirac theory

$$\boxed{\mu = g\mu_B s} \qquad g = 2, s = 1/2 \qquad \mu_B = \frac{eh}{2mc}$$



- Measurement (Brookhaven):

$$\alpha_\mu(exp) = \frac{g-2}{g} = 11659203(15) \times 10^{-10}$$

- <u>Prediction Standard Model:</u>

$$\begin{aligned}
\alpha_\mu(SM) = &= 0.5(\alpha/\pi) - 0.32848(\alpha/pi)^2 + ... \\
&= (11659159.6 \pm 6.7)10^{-10} \\
\alpha_\mu(QED) &= 11658470.56(0.29) \times 10^{-10} \\
\alpha_\mu(schwach) &= 15.1(0.4) \times 10^{-10} \\
\alpha_\mu(hadronisch) &= 673.9(6.7) \times 10^{-10}
\end{aligned}$$

<u>PredictionSUSY:</u>

$$\alpha_\mu(SUSY) \simeq 140 \times 10^{-11} (\frac{100GeV}{m_S})^2 \tan\beta$$

→ Restriction of SUSY mass scale
(m_S=120-400 GeV for tanβ=4…40)

- Observed deviation from Standard Model: ~ 2.6 Sigma

$$\boxed{\alpha_\mu(exp) - \alpha_\mu(SM) = 43(16) \times 10^{-10}}$$

… problem with the hadronic corrections?!