Supersymmetry

CERN/Fermilab Hadron Collider Physics Summer School

Fermilab, August 18-20, 2008

Stephen P. Martin

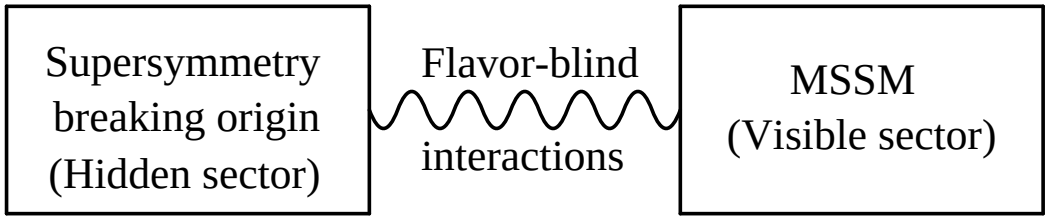
Northern Illinois University

Based in part on "A Supersymmetry Primer", `hep-ph/9709356v4` (revised June 2006).

Lecture 3: Experimental Signatures of Supersymmetry

- Patterns of SUSY breaking
- Sparticle Decays
- LEP2 limits
- Tevatron $p\overline{p}$ collider signals
- LHC pp collider signals
- Special features of Gauge-Mediated SUSY Breaking (GMSB)

Recall that the absence of large SUSY-mediated flavor-violating effects suggests:



In Planck-scale Mediated SUSY Breaking, $m_{\rm soft} \sim \langle F \rangle / M_{\rm Planck}$.

In "mSUGRA", there are only a few parameters:
$m_{1/2}$, m_0^2, A_0, $\tan\beta$, and the phase of μ.

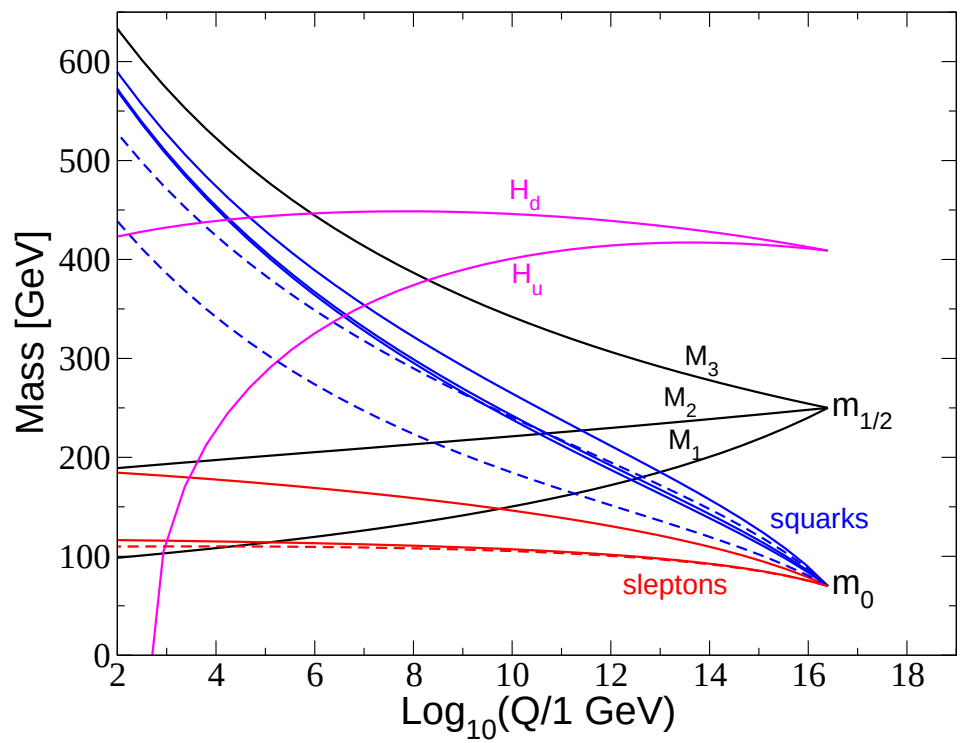
Renormalization Group Running for an mSUGRA model (SPS1A′) with $m_{1/2} =$ 250 GeV, $m_0 =$ 70 GeV, $A_0 = -$300 GeV, $\tan\beta =$ 10, and sign(μ) = +1

Gaugino masses M_1, M_2, M_3

Slepton masses (dashed=stau)

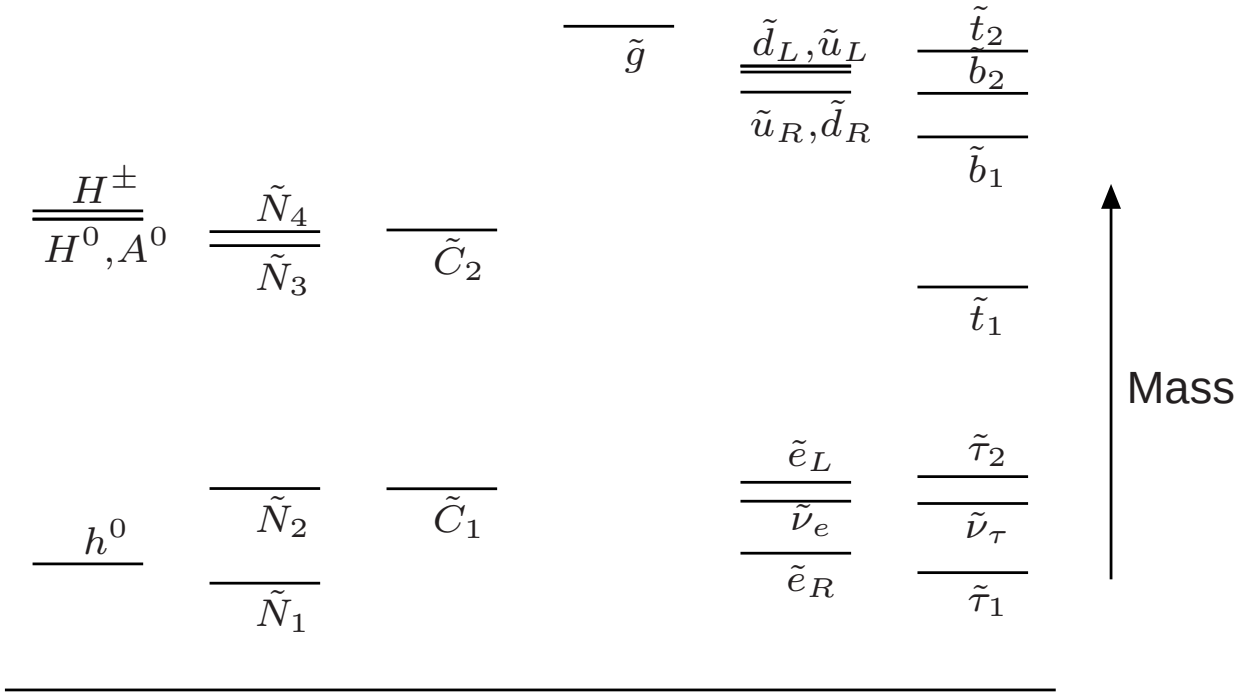
Squark masses (dashed=stop)

Higgs: $(m_{H_u}^2 + \mu^2)^{1/2}$, $(m_{H_d}^2 + \mu^2)^{1/2}$



Electroweak symmetry breaking occurs because $m_{H_u}^2 + \mu^2$ runs negative near the electroweak scale. This is due directly to the large top quark Yukawa coupling.

Here is the resulting sparticle mass spectrum:



This is typical, qualitatively, of mSUGRA models with relatively large $m_{1/2}$.

Notes: The Higgs sector is in the decoupling limit, with h^0 near the LEP2 limit. A neutralino is the LSP. The gluino is the heaviest sparticle. The lightest squark is the top squark. The lightest slepton is the tau slepton.

Gauge-Mediated SUSY Breaking (GMSB) models

The idea: SUSY breaking is transmitted from a hidden sector by the ordinary $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge interactions. This makes them automatically flavor-blind!

To do this, introduce new, heavy, chiral supermultiplets, called **messengers**, which couple to $\langle F \rangle$ and also to the MSSM gauge bosons and gauginos.

If the typical messenger particle masses are $M_{\rm mess}$, the MSSM soft terms are:

$$m_{\rm soft} \sim \frac{\alpha_a}{4\pi} \frac{\langle F \rangle}{M_{\rm mess}}$$

The $\alpha_a/4\pi$ is a one-loop factor for diagrams involving gauge interactions. This follows by dimensional analysis, since $m_{\rm soft}$ must vanish as $\langle F \rangle \to 0$, or as the messengers become very heavy.

Note that $\sqrt{\langle F \rangle}$ can be as low as 10^4 GeV, if $M_{\rm mess}$ is comparable.

This is much lower than in Planck-scale Mediated SUSY Breaking. Therefore, these are also sometimes called “low-scale SUSY breaking” models.

GMSB models typically predict that the gravitino (with mass denoted $m_{3/2}$) is the LSP. This is because, provided that $M_{\rm mess} \ll M_P$,

$$m_{3/2} \sim \frac{\langle F \rangle}{M_P} \quad \ll \quad m_{\rm soft} \sim \frac{\alpha_a}{4\pi} \frac{\langle F \rangle}{M_{\rm mess}}$$

In fact, $m_{3/2}$ can be as low as 0.1 eV, for $\sqrt{\langle F \rangle} \sim 10^4$ GeV.

The lightest of the MSSM superpartner states is then the Next-to-Lightest Supersymmetric Particle (NLSP).

The NLSP need not be neutral, since it can decay into its Standard Model partner and the gravitino.

The gravitino absorbs the Goldstino (the would-be massless Goldstone particle associated with SUSY breaking), so it inherits the Goldstino's couplings, which are weak, but much stronger than gravitational.

Minimal Gauge-Mediated SUSY Breaking model

For a minimal model, take a set of new chiral supermultiplets q, $\overline{q}$, ℓ, $\overline{\ell}$ that transform under $SU(3)_C \times SU(2)_L \times U(1)_Y$ as

$$q \sim (\mathbf{3}, \mathbf{1}, -\frac{1}{3}); \quad \overline{q} \sim (\overline{\mathbf{3}}, \mathbf{1}, \frac{1}{3}); \quad \ell \sim (\mathbf{1}, \mathbf{2}, \frac{1}{2}); \quad \overline{\ell} \sim (\mathbf{1}, \mathbf{2}, -\frac{1}{2}).$$

These supermultiplets contain messenger quarks $\psi_q, \psi_{\overline{q}}$ and scalar quarks $q, \overline{q}$ and messenger leptons $\psi_\ell, \psi_{\overline{\ell}}$ and scalar leptons $\ell, \overline{\ell}$. These particles must get very large masses so as not to have been discovered already. They do so by coupling to a gauge-singlet chiral supermultiplet S through a superpotential:

$$W_{\rm mess} = y_2 S \ell \overline{\ell} + y_3 S q \overline{q}.$$

The scalar component of S and its auxiliary field are both assumed to acquire VEVs, denoted $\langle S \rangle$ and $\langle F_S \rangle$ respectively.

The chiral supermultiplet S might be composite, and $\langle F_S \rangle \neq 0$ might come from an O'Raifeartaigh model, or from some more complicated dynamical mechanism. (We don't need to know!)

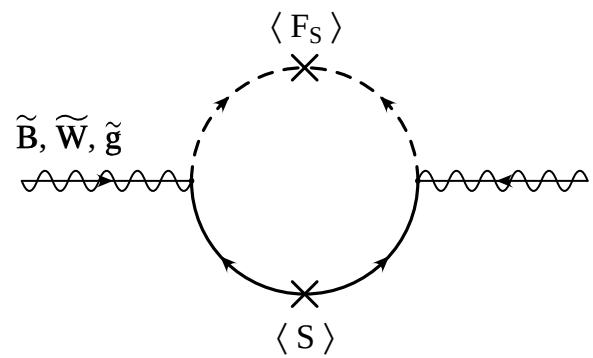
Minimal Gauge-Mediated SUSY Breaking model (continued)

The effect of SUSY breaking is to split the messenger masses:

$$\ell, \overline{\ell}: \qquad m^2_{\text{fermions}} = |y_2 \langle S \rangle|^2 \,, \qquad m^2_{\text{scalars}} = |y_2 \langle S \rangle|^2 \pm |y_2 \langle F_S \rangle| \,;$$

$$q, \overline{q}: \qquad m^2_{\text{fermions}} = |y_3 \langle S \rangle|^2 \,, \qquad m^2_{\text{scalars}} = |y_3 \langle S \rangle|^2 \pm |y_3 \langle F_S \rangle| \,.$$

The SUSY-breaking apparent here is transmitted to the MSSM gauginos through one-loop graphs: The results are

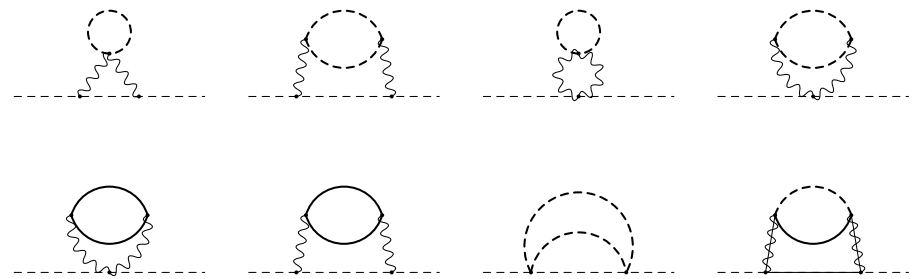


$$M_a = \frac{\alpha_a}{4\pi}\Lambda, \qquad \text{where} \qquad \Lambda \equiv \frac{\langle F_S \rangle}{\langle S \rangle}.$$

The MSSM gauge bosons do not get such a mass shift, since they are protected by gauge invariance. So SUSY breaking has been successfully communicated to the MSSM.

Minimal Gauge-Mediated SUSY Breaking model (continued)

The MSSM scalars do not get any masses at 1-loop order, but do at 2-loops from these Feynman diagrams:



The result for each MSSM scalar ϕ can be written:

$$m_\phi^2 = 2\Lambda^2 \left[\left(\frac{\alpha_3}{4\pi}\right)^2 C_3^\phi + \left(\frac{\alpha_2}{4\pi}\right)^2 C_2^\phi + \left(\frac{\alpha_1}{4\pi}\right)^2 C_1^\phi \right], \qquad \text{where}$$

$$C_3^\phi = \begin{cases} 4/3 & \text{for } \phi = \widetilde{Q}_i, \widetilde{\bar{u}}_i, \widetilde{\bar{d}}_i; \\ 0 & \text{for } \phi = \widetilde{L}_i, \widetilde{\bar{e}}_i, H_u, H_d \end{cases}$$

$$C_2^\phi = \begin{cases} 3/4 & \text{for } \phi = \widetilde{Q}_i, \widetilde{L}_i, H_u, H_d; \\ 0 & \text{for } \phi = \widetilde{\bar{u}}_i, \widetilde{\bar{d}}_i, \widetilde{\bar{e}}_i \end{cases}$$

$$C_1^\phi = 3Y_\phi^2/5 \quad \text{for each } \phi \text{ with weak hypercharge } Y_\phi.$$

These squared masses are positive (fortunately!).

The Minimal GMSB model can be generalized by putting N copies of the messenger sector. The results then become:

$$M_a = \frac{\alpha_a}{4\pi} N\Lambda, \qquad \text{(gauginos)}$$

$$m_\phi^2 = 2N\Lambda^2\left[\left(\frac{\alpha_3}{4\pi}\right)^2 C_3^\phi + \left(\frac{\alpha_2}{4\pi}\right)^2 C_2^\phi + \left(\frac{\alpha_1}{4\pi}\right)^2 C_1^\phi\right], \qquad \text{(scalars)}$$

The parameters of this model framework are just:

- $N =$ number of messengers,
- $M_{\rm mess} =$ typical messenger mass scale,
- $\Lambda =$ effective SUSY-breaking order parameter
- μ, or equivalently $\tan\beta$ and sign(μ)

These models can be further generalized by including more exotic messengers, perhaps with widely varying masses.

GMSB model predictions

The scalar^3 terms $\mathbf{a_u}$, $\mathbf{a_d}$, $\mathbf{a_e}$, arise first at two-loop order, and are suppressed by an additional factor of $\alpha_a/4\pi$ compared to gaugino masses. So it is an excellent approximation to set them $= 0$.

Because gaugino masses arise at one loop, and scalar squared masses arise at two loops, they are roughly comparable:

$$M_a, m_\phi \sim \frac{\alpha}{4\pi}\Lambda.$$

However, the gaugino masses scale like N, while the scalar masses scale like $\sqrt{N}$.

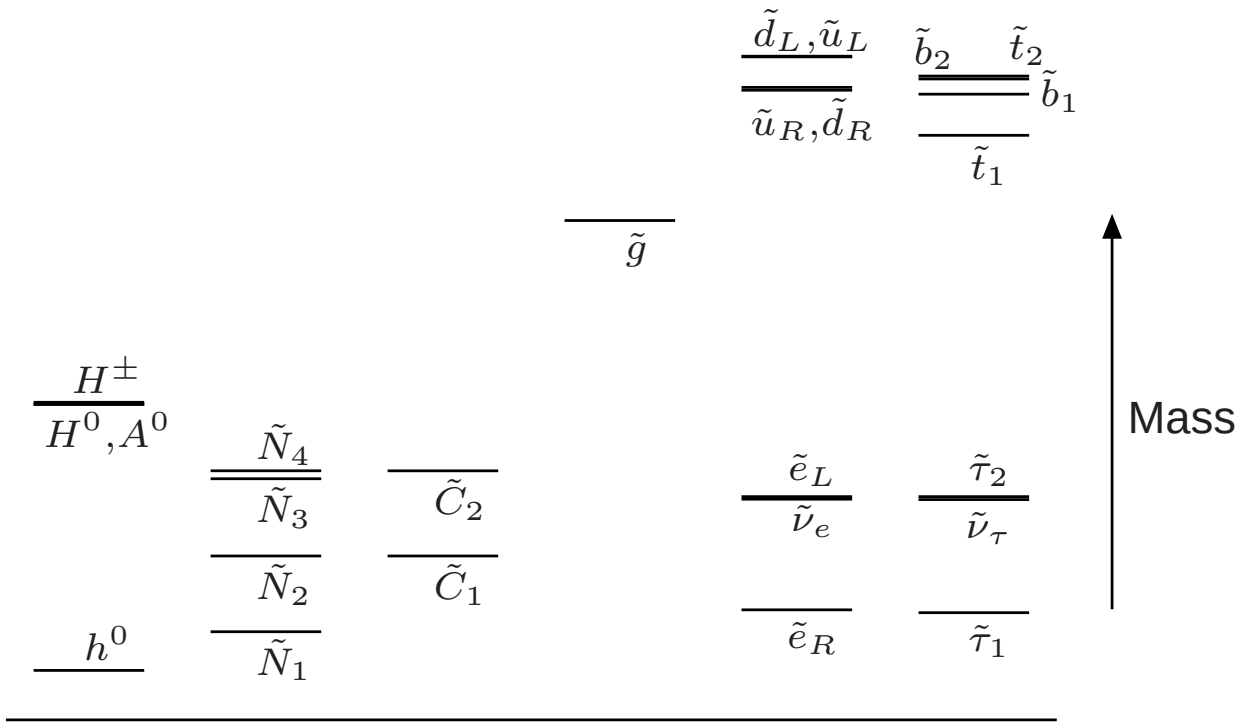
For $N = 1$, a bino-like neutralino will be the NLSP.

For $N \geq 2$, a stau will be the NLSP.

The above predictions for gaugino and scalar masses hold at the renormalization scale $Q_0 = M_{\rm mess}$. They must be run down to the electroweak scale. (This generates non-zero $\mathbf{a_u}$, $\mathbf{a_d}$, $\mathbf{a_e}$, and modifies the other predictions.)

A sample sparticle mass spectrum for Minimal GMSB

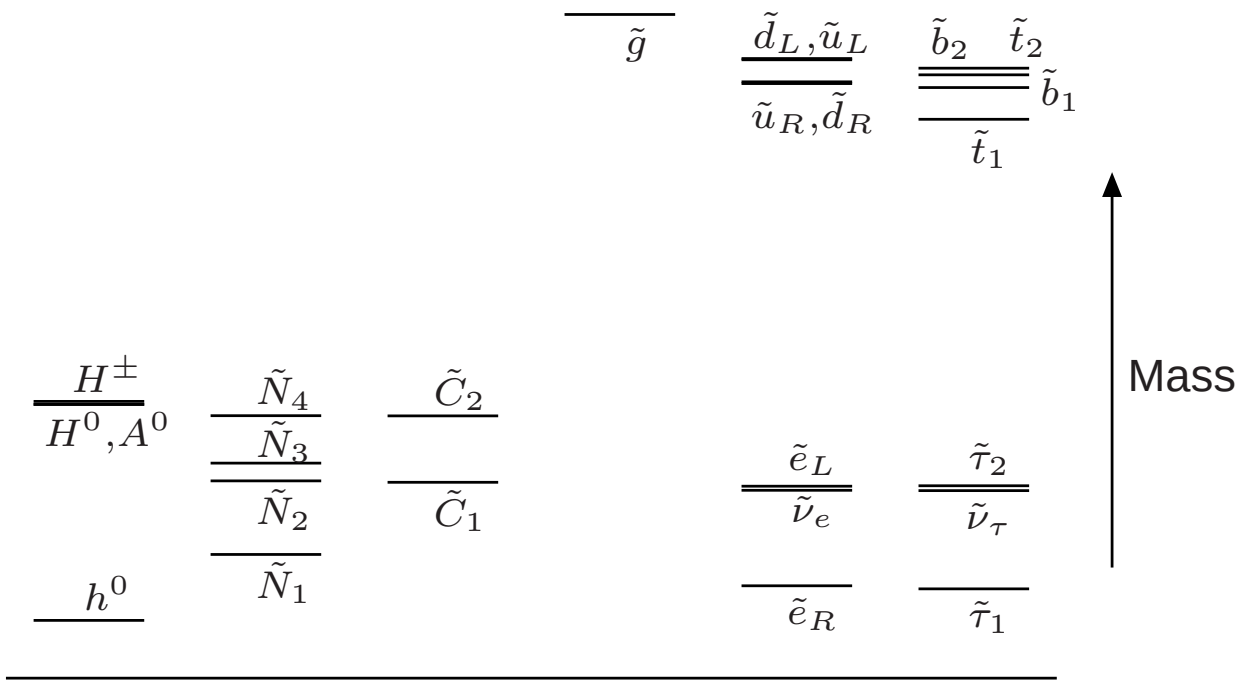
with $N = 1,\ \Lambda = 150$ TeV, $M_{\rm mess} = 300$ TeV, $\tan\beta = 15,$ sign(μ) = +1



The NLSP is a neutralino, which can decay to the nearly massless Goldstino/gravitino by: $\tilde{N}_1 \to \gamma\tilde{G}$. This decay can be prompt, or with a macroscopic decay length.

A sample sparticle mass spectrum for non-minimal GMSB

with $N = 3$, $\Lambda = 60$ TeV, $M_{\rm mess} = 120$ TeV, $\tan\beta = 15$, sign(μ) = +1



The NLSP is a stau ($\tilde{\mu}_R$ and $\tilde{e}_R$ are not much heavier). It can decay to the nearly massless Goldstino/gravitino by: $\tilde{\tau}_1 \to \tau\tilde{G}$. The decay could be prompt, or with a macroscopic length.

Computer programs exist that generate the superpartner mass spectrum for you, given a choice of SUSY-breaking model parameters. Some of the publically available ones:

- `ISASUSY` (Paige, Protopopescu, Baer, Tata)
- `SOFTSUSY` (Allanach)
- `SuSpect` (Djouadi, Kneur, Moultaka)
- `SPheno` (Porod)
- `Supermodel` (Robertson and SPM, to appear)

These can be interfaced, through the SUSY Les Houches Accords (SLHA) to programs that produce cross-sections, decay rates, and Monte Carlo events: `MadGraph/MadEvent`, `Pythia`, `ISAJET`, `HERWIG`, `WHIZARD` `SUSYGEN`, `SDECAY`, `GRACE`, `CompHEP`, `CalcHEP`, `PROSPINO`, ...

The can also be interfaced to programs that compute the abundance of dark matter: `micrOMEGAs`, `DarkSUSY`, `ISAReD`.

SUSY signatures at colliders

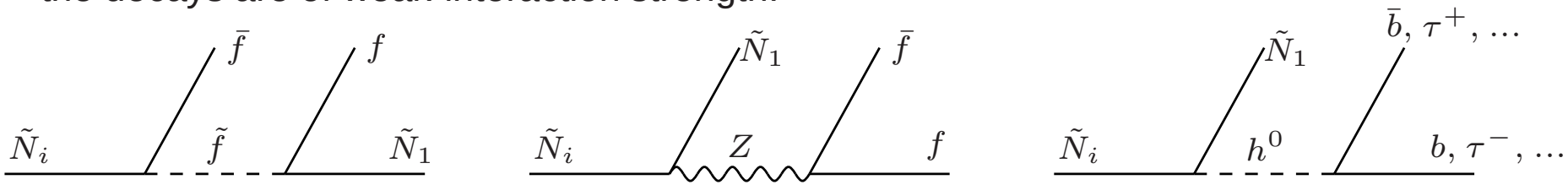
I will concentrate mostly on models with conserved R-parity and a neutralino LSP dark matter candidate $(\tilde{N}_1)$. Recall:

- The most important interactions for producing sparticles are gauge interactions, and interactions related to gauge interactions by SUSY. Their strength is known, up to mixing of sparticles.
- Two sparticles produced in each event, with opposite momenta.
- The LSPs are neutral and extremely weakly interacting, so they carry away energy and momentum.
  - At e^+e^- colliders, the total energy can be accounted for, so one sees missing energy, $\not{E}$.
  - At hadron colliders, the component of the momentum along the beam is unknown on an event-by-event basis, so only the energy component in particles transverse to the beam is observable. So one sees "missing transverse energy", $\not{E}_T$.

Sparticle Decays

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:

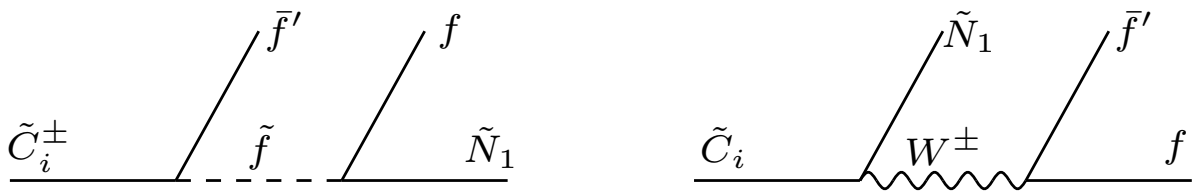
$$\tilde{N}_i \to q\bar{q}\tilde{N}_1 \qquad \text{(seen in detector as } jj + \not{E}\text{)}$$

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

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 a “spoiler” mode, because leptonic final states are rare.

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:

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

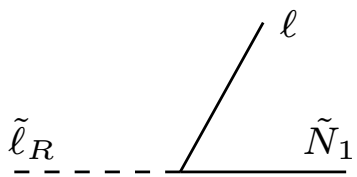
$$\tilde{C}_i^{\pm} \to \ell^{\pm}\nu\tilde{N}_1 \qquad \text{(seen in detector as } \ell^{\pm} + \not{E}\text{)}$$

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.

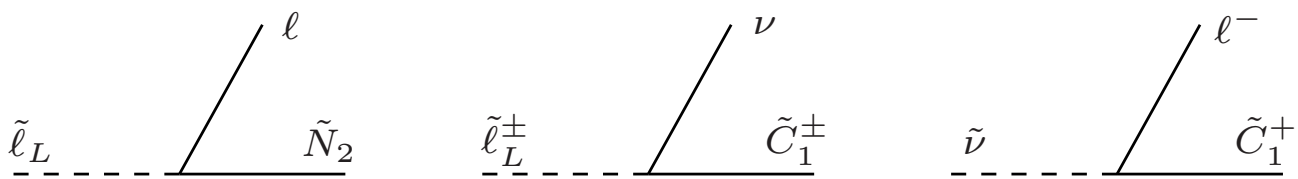
3) Slepton Decays

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 $\ell^\pm + \not{E}$)

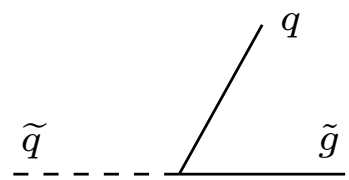
However, the left-handed sleptons $\tilde{e}_L$, $\tilde{\mu}_L$, $\tilde{\nu}$ have no coupling to the bino component of $\tilde{N}_1$, so they often decay preferentially through $\tilde{N}_2$ or $\tilde{C}_1$, which have a large wino content, with strength proportional to g^2:



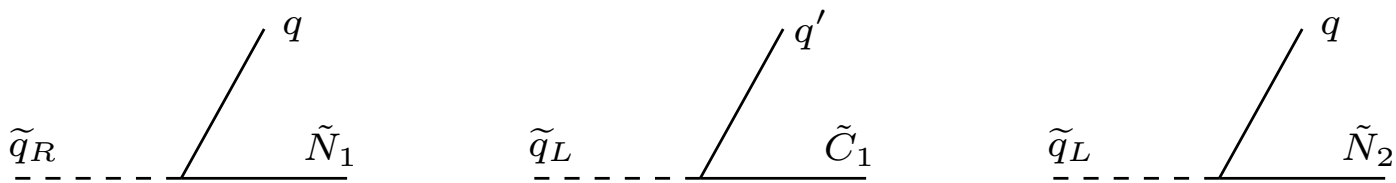
with $\tilde{N}_2$ and $\tilde{C}_1$ decaying as before.

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 $\tilde{N}_2$:

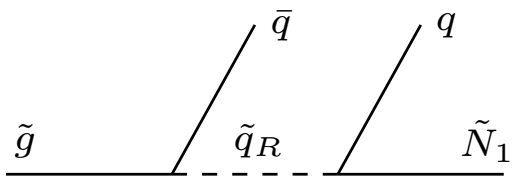


If a top squark is light, then the decays $\tilde{t}_1 \longrightarrow t\tilde{g}$ and $\tilde{t}_1 \longrightarrow t\tilde{N}_1$ may not be kinematically allowed, and it may decay only into charginos: $\tilde{t}_1 \longrightarrow b\tilde{C}_1$. If those decays are also closed, it has $\tilde{t}_1 \longrightarrow bW\tilde{N}_1$. If even that is closed, it has only a suppressed flavor-changing decay $\tilde{t}_1 \longrightarrow c\tilde{N}_1$ or 4-body decay $\tilde{t}_1 \longrightarrow bf\bar{f}'\tilde{N}_1$.

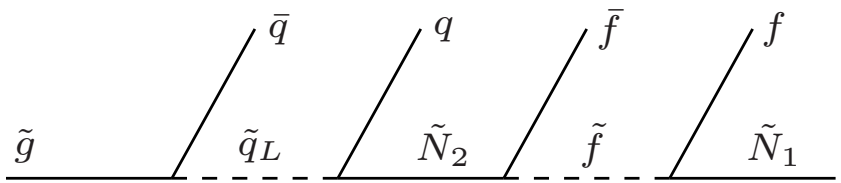
5) Gluino Decays

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

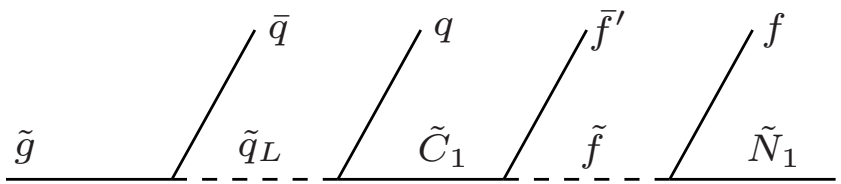
For example:



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



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

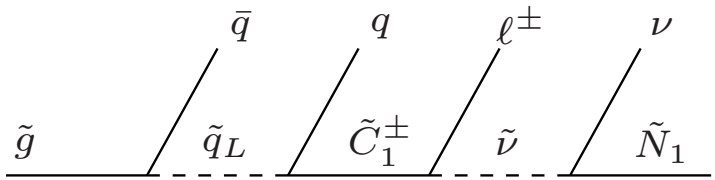


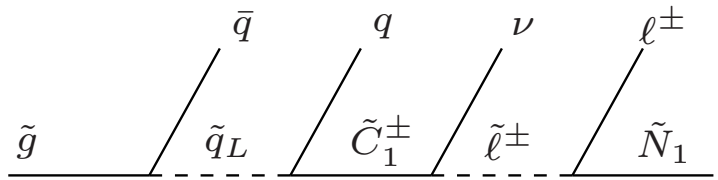
$jjjj + \not{E}$ or $t\bar{t}jj + \not{E}$ or $jj\ell^\pm + \not{E}$

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**.

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.

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

SUSY Limits from LEP2 e^+e^- collisions up to $\sqrt{s} = 208$ GeV

The CERN LEP2 collider had the capability of producing all sparticle-antisparticle pairs, except for the gluino:

$$e^+e^- \to \tilde{\ell}^+\tilde{\ell}^-,\ \tilde{C}_1^+\tilde{C}_1^-,\ \tilde{N}_1\tilde{N}_2,\ \tilde{N}_2\tilde{N}_2,\ \gamma\tilde{N}_1\tilde{N}_1,\ \tilde{q}\tilde{q}^*$$

Exclusions for charged sparticles are typically close to the kinematic limit, except when mass difference are small. For example, at 95% CL:

$m_{\tilde{C}_1} > 103$ GeV (($m_{\tilde{C}_1} - m_{\tilde{N}_1} > 3$ GeV or < 100 MeV)

$m_{\tilde{C}_1} > 92$ GeV (any heavier than $\tilde{N}_1$)

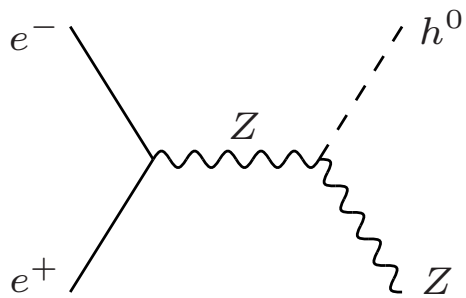
and

$m_{\tilde{e}_R} > 100$ GeV ($m_{\tilde{e}_R} - m_{\tilde{N}_1} > 5$ GeV)

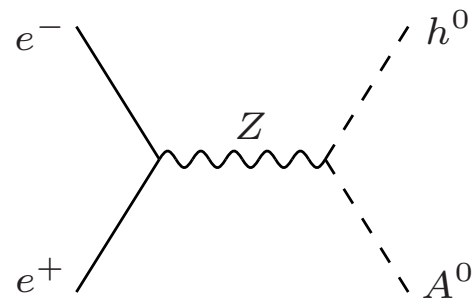
See `http://lepsusy.web.cern.ch/lepsusy/` for detailed results.

LEP2 Searches for Higgs bosons

The most important constraints on SUSY parameter space come from searches for the MSSM Higgs bosons at LEP2. The relevant processes include:



$\propto \sin^2(\beta - \alpha)$



$\propto \cos^2(\beta - \alpha)$

The first diagram is the same as for the Standard Model Higgs search in the decoupling limit, where $\sin^2(\beta - \alpha) \approx 1$. Many SUSY models fall into this category, and the LEP2 bound (nearly) applies:

$$m_{h^0} > 114.4\,\mathrm{GeV} \qquad (95\%\ \mathrm{CL})$$

General bounds in SUSY are much weaker, but “most” of parameter space in the MSSM yields a Standard-Model-like lightest Higgs boson.

Impact of the LEP2 bound on m_{h^0}

Recall that in the decoupling limit:

$$m_{h^0}^2 = m_Z^2 \cos^2(2\beta) + \frac{3}{4\pi^2} y_t^2 m_t^2 \left[\ln\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2} \right) + C_{\tilde{t}\text{-mixing}} \right] + \ldots$$

For $\cos(2\beta) \approx 1$ and $C_{\tilde{t}\text{-mixing}} \approx 0$, we therefore need, roughly:

$$\sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}} \gtrsim 600\,\mathrm{GeV}.$$

This suggests a pessimistic attitude toward discovering squarks at the Tevatron.

However, there are many ways out:

- Top-squark mixing gives positive contributions to m_{h^0}, up to $C_{\tilde{t}\text{-mixing}} = 3$.
- Enlargement of the Higgs sector, for example by adding a singlet Higgs supermultiplet, also gives positive contributions to m_{h^0}.
- The other squarks might be much lighter than the top squarks.
- If the lightest Higgs has non-standard couplings, maybe it is hidden from LEP2. (Dermisek and Gunion)

Tevatron Signals for SUSY in $p\overline{p}$ collisions at $\sqrt{s} = 1.96$ TeV

Trilepton + $\not{E}_T$ Signal at the Tevatron

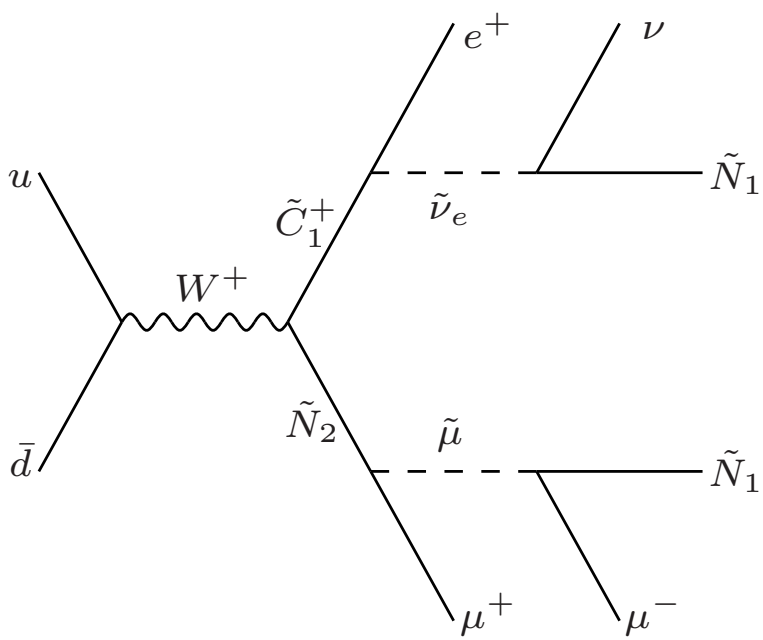
This signal arises if one can produce a pair of wino-like sparticles

$$p\overline{p} \to \tilde{C}_1^{\pm}\tilde{N}_2,$$

which then each decay leptonically with a significant branching fraction,

$$\tilde{N}_2 \to \ell^+\ell^-\tilde{N}_1, \qquad \tilde{C}_1^{\pm} \to \ell^{\pm}\nu\tilde{N}_1$$

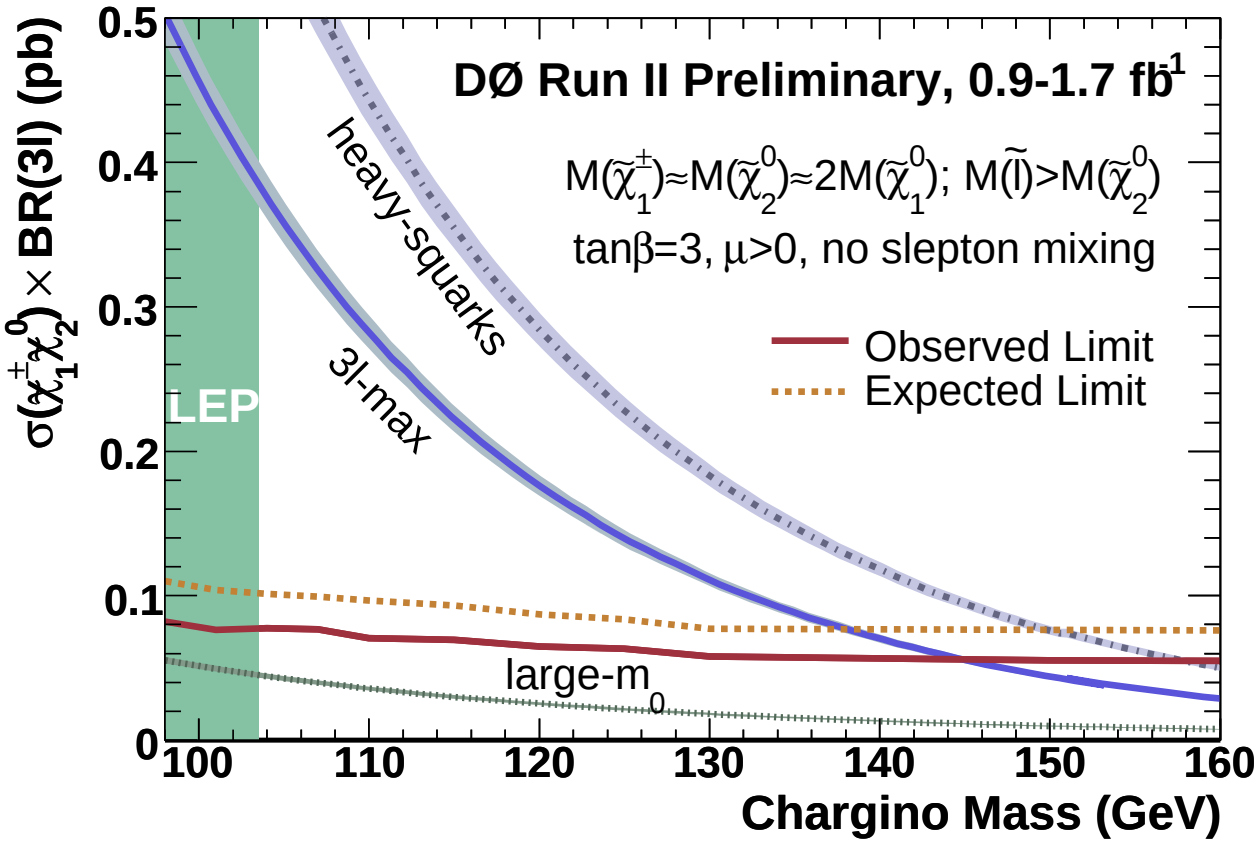
With no hard jets in the event, and three identified leptons, the Standard Model backgrounds are small. Here is a typical Feynman diagram for the whole event:



$$p\overline{p} \to \ell^+\ell^-\ell'^{\pm} + \not{E}_T$$

Decays of $\tilde{C}_1^{\pm}$ and $\tilde{N}_2$ through virtual squarks and/or virtual h^0 kill the signal. Decays through Z, W hurt the signal. Decays through sleptons, as shown, help the signal.

Recent Tevatron trilepton search results (from DØ Conference Note 5464; CDF similar)



This is for an mSUGRA-like model scenario. The greatest sensitivity comes when $0 < m_{\tilde{\ell}} - m_{\tilde{N}_2} \lesssim 20$ GeV, with squarks much heavier.

Multi-Jets + $\not{E}_T$ at Tevatron

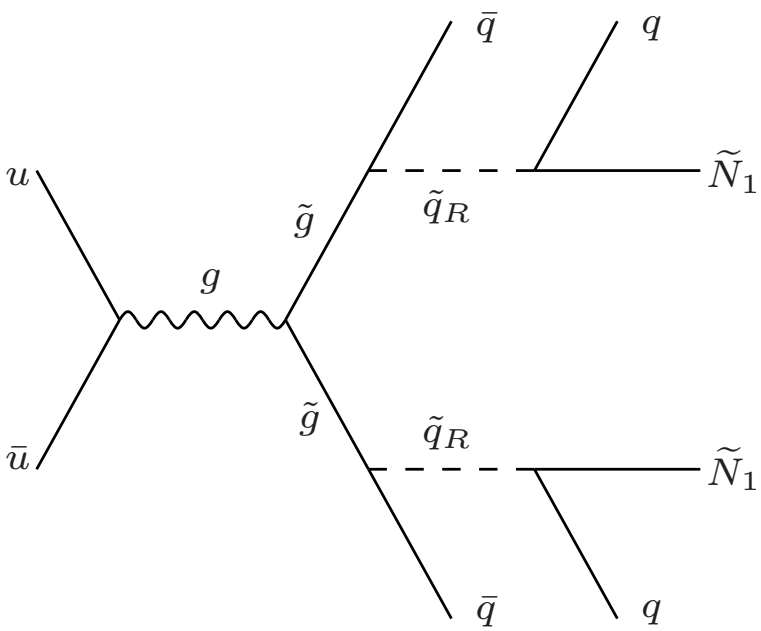
Another strategy: look for events with gluino-gluino, gluino-squark, and squark-squark pair production:

$$p\overline{p} \to \tilde{g}\tilde{g},\ \tilde{g}\tilde{q},\ \tilde{q}\tilde{q}$$

followed by decays **without** leptons:

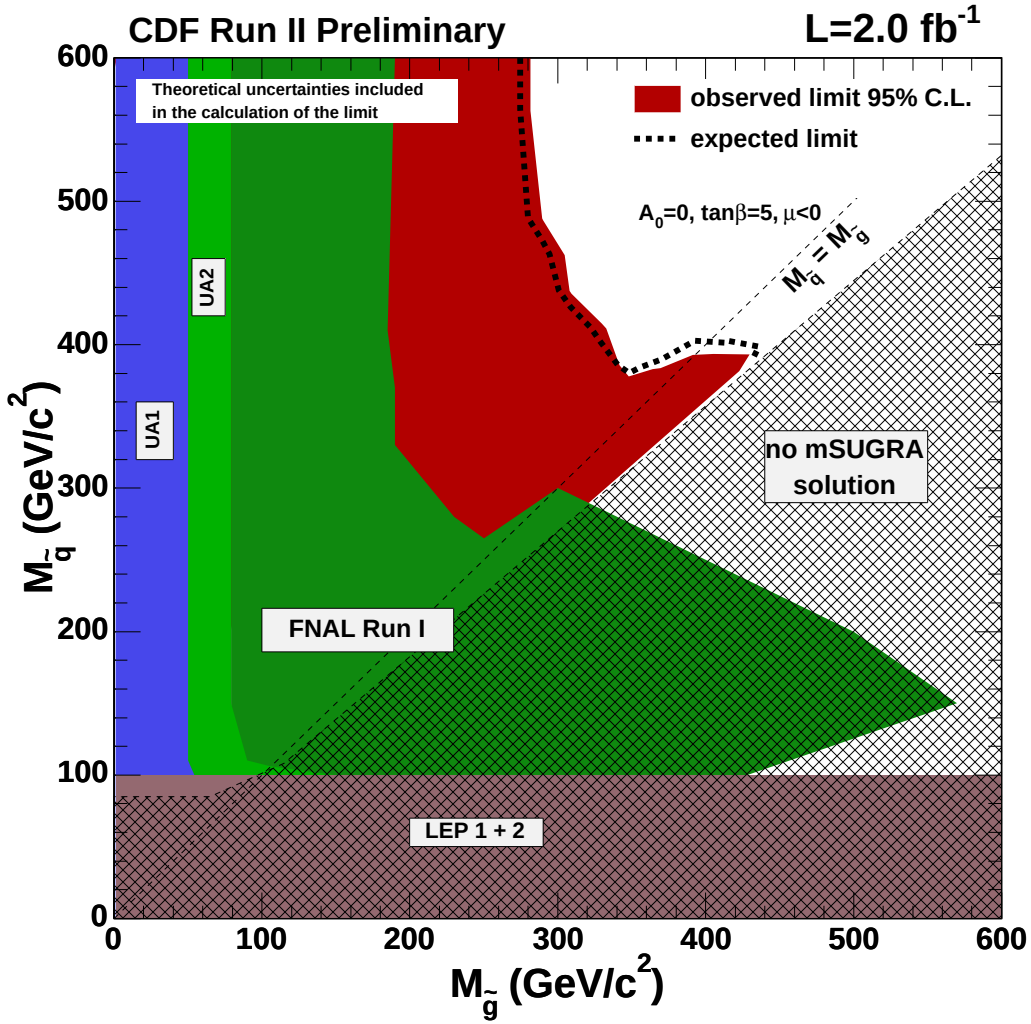
$$\tilde{g} \to q\bar{q}\widetilde{N}_1, \qquad \tilde{q} \to q\widetilde{N}_1$$

A typical Feynman diagram for the whole event:



By vetoing isolated, energetic leptons, the Standard Model backgrounds with $\not{E}_T$ from $W \to \ell\nu$ are reduced.

Tevatron jets$+\not{E}_T$ search (from CDF Note 9229; DØ similar)



Again, this is for an mSUGRA-like model scenario.

Like-Charge Dileptons + $\not{E}_T$ at Tevatron

Exploit the fact mentioned earlier that gluinos decay into leptons of either charge with equal probability:

$$p\overline{p} \to \tilde{g}\tilde{g} \to \text{(jets)} + \ell^{\pm}\ell^{\pm} + \not{E}_T.$$

Multi-b-jets + $\not{E}_T$ at Tevatron

Produce gluons that decay into bottom quark and bottom squark:

$$p\overline{p} \to \tilde{g}\tilde{g} \to (b\tilde{b}_1)(\bar{b}\tilde{b}_1^*) \to (b\bar{b}\tilde{N}_1)(b\bar{b}\tilde{N}_1) \to (b\bar{b})(b\bar{b}) + \not{E}_T.$$

Light Top Squarks at Tevatron

Top squarks with $m_{\tilde{t}_1} <$ Min$[m_{\tilde{N}_1} + m_b + m_W, m_{\tilde{C}_1} + m_b, m_b + m_{\tilde{\nu}}]$ have only suppressed flavor-violating decays to charm:

$$p\overline{p} \to \tilde{t}_1\tilde{t}_1^* \to (c\tilde{N}_1)(\bar{c}\tilde{N}_1) \to jj + \not{E}_T$$

These and other searches are ongoing...

LHC Signals for SUSY in pp collisions at $\sqrt{s} = 14$ TeV

The LHC is a gluon-gluon and gluon-quark collider, to first approximation

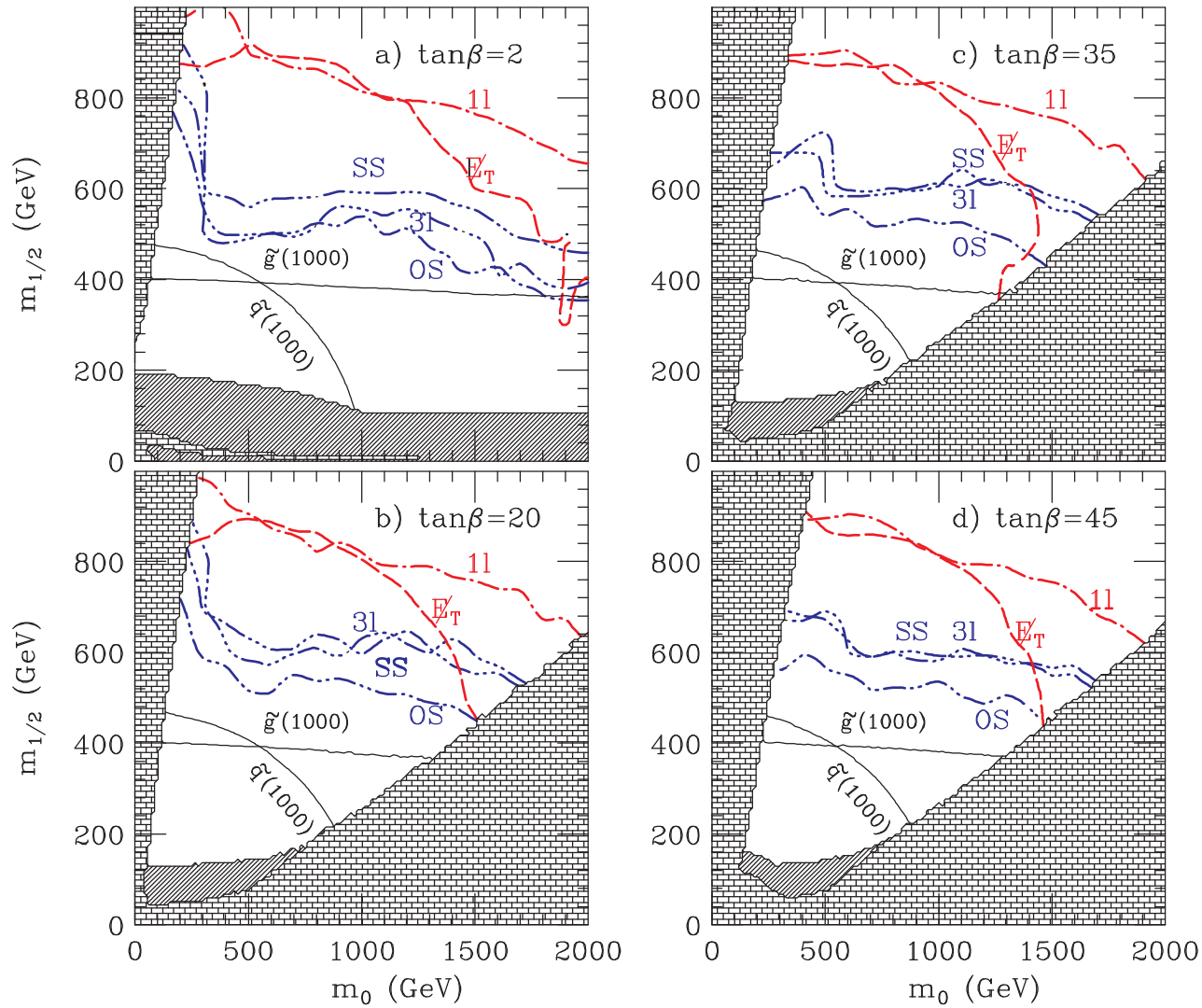
Discovery reach for 10 fb^{-1} extends well beyond 1 TeV in both gluino and squark masses:

The dominant production cross-sections are:

$$pp \to \tilde{g}\tilde{g},\ \tilde{g}\tilde{q},\ \tilde{q}\tilde{q}$$

Discovery signals can be classified by the number of leptons in the event. Event rates are very high.

But $\not{E}_T$ is difficult...



Baer, Chen, Drees, Paige, Tata 1999

$M_{\rm eff} = p_T(j_1) + p_T(j_2) + p_T(j_3) + p_T(j_4) + \not{E}_T$ is a useful discriminant against background, and a rough indicator of $M_{\rm SUSY}$, the cross-section weighted average of gluino and squark masses.

SUSY signals vs. backgrounds for jets+$\not{E}_T$:

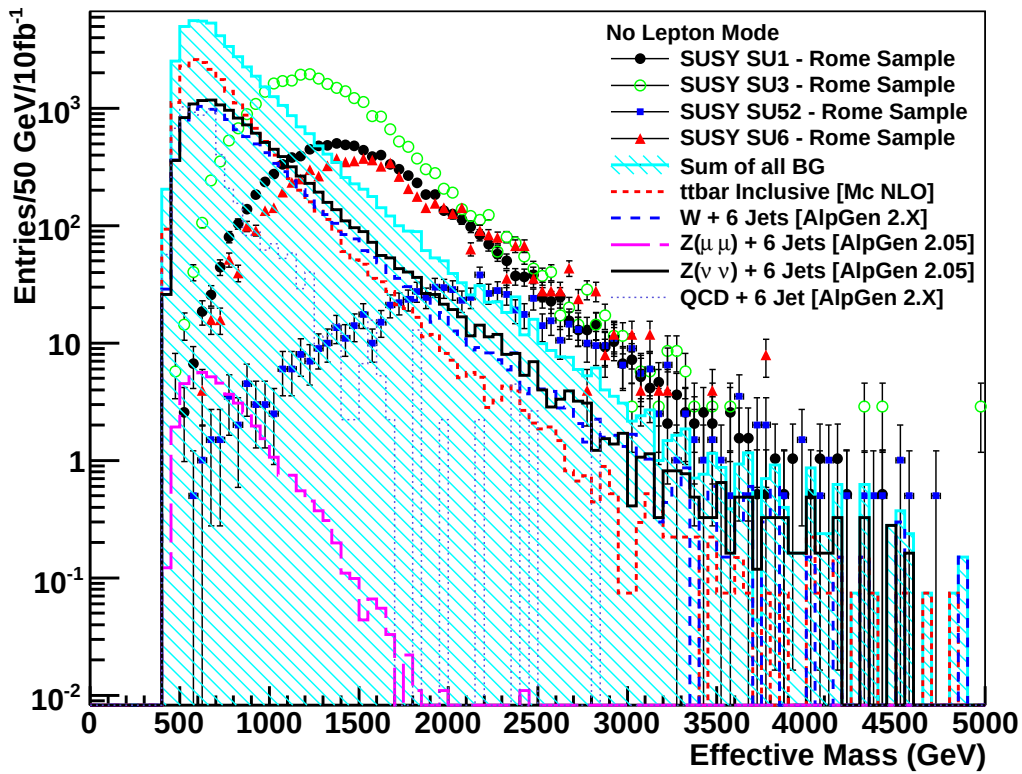
ATLAS Preliminary (PASCOS 2006)
Sanjay Padhi, B. Mellado, Sau Lan Wu

$M_{\rm SUSY} \sim 675$ GeV

$M_{\rm SUSY} \sim 775$ GeV

$M_{\rm SUSY} \sim 875$ GeV

$M_{\rm SUSY} \sim 1300$ GeV



(The 1999 ATLAS TDR had significantly underestimated the backgrounds.)

The single lepton jets$+\not{E}_T$ signal is even better:

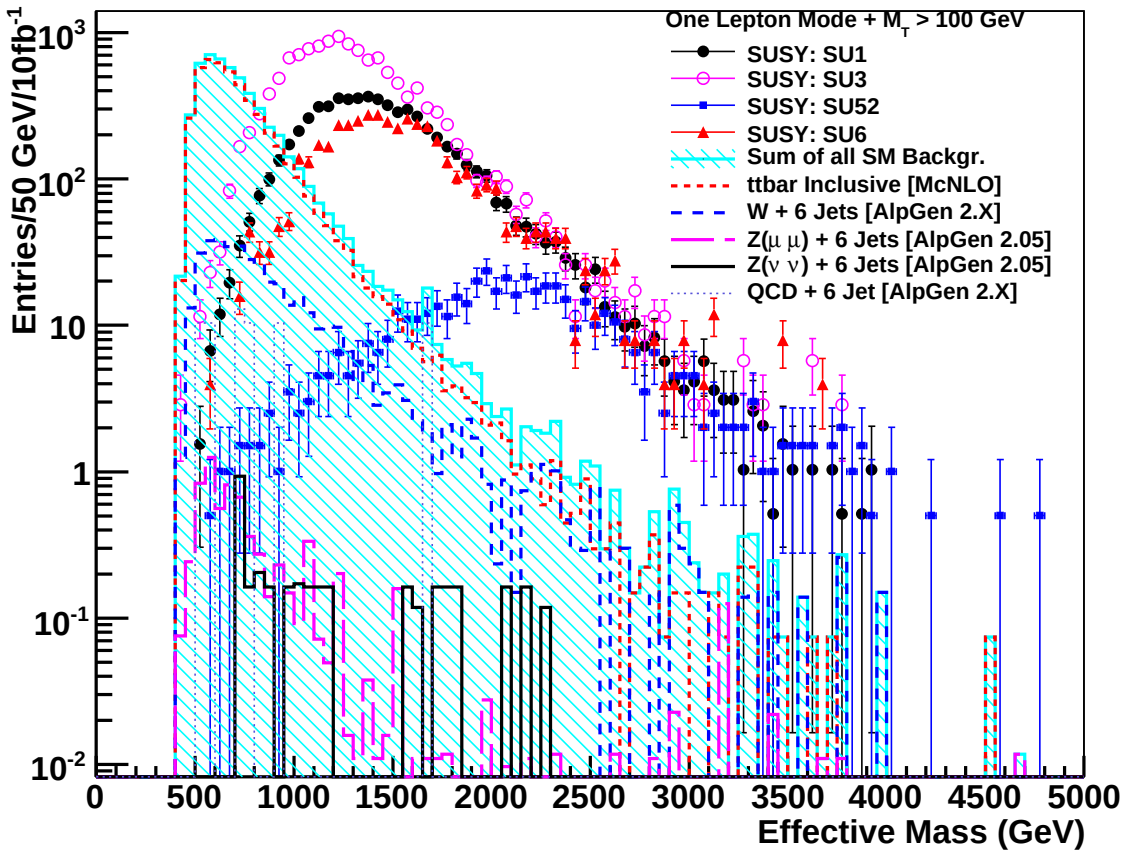
ATLAS Preliminary (PASCOS 2006)
Sanjay Padhi, B. Mellado, Sau Lan Wu

$M_{\rm SUSY} \sim 675$ GeV

$M_{\rm SUSY} \sim 775$ GeV

$M_{\rm SUSY} \sim 875$ GeV

$M_{\rm SUSY} \sim 1300$ GeV

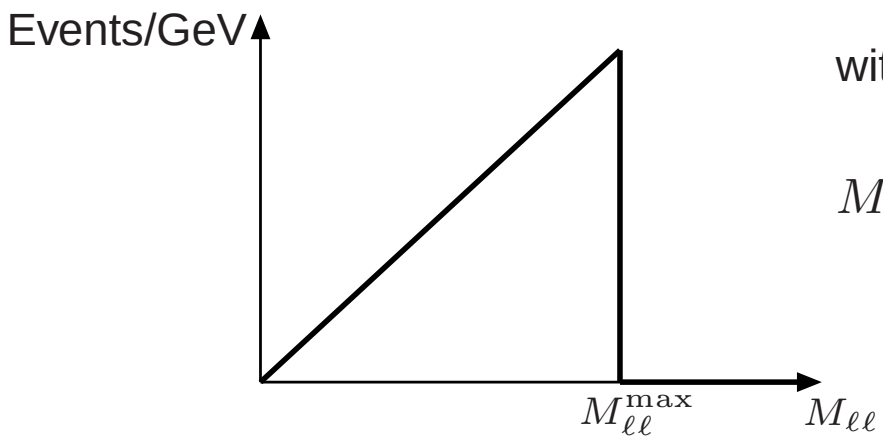


Uses a cut $m_T(\ell) > 100$ GeV to reduce $t\bar{t}$ and $W+$jets backgrounds.

A post-discovery measurement at the LHC: kinematic edge in $\tilde{N}_2$ decay

Combinations of sparticle masses can be measured at the LHC from observing edges in kinematic distributions.

As one of many examples, consider all events leading to $\tilde{N}_2 \to \ell\tilde{\ell} \to \ell^+\ell^-\tilde{N}_1$, from all SUSY production sources. Theoretically, the distribution of the invariant mass for the lepton pair should have this shape (see e.g. Atlas TDR):



with

$$M_{\ell\ell}^{\max} = m_{\tilde{N}_2}\left(1 - \frac{m_{\tilde{\ell}}^2}{m_{\tilde{N}_2}^2}\right)^{1/2}\left(1 - \frac{m_{\tilde{N}_1}^2}{m_{\tilde{\ell}}^2}\right)^{1/2}$$

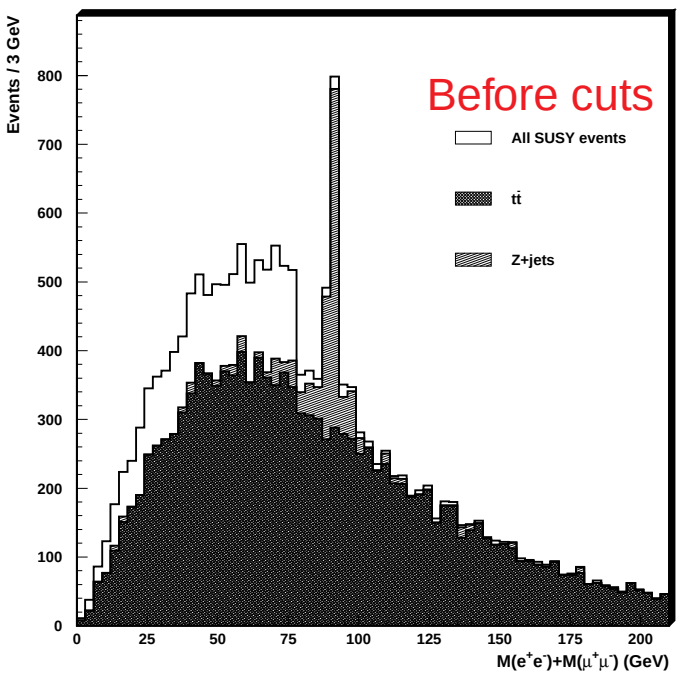
To remove backgrounds, require events to have very large $\not{E}_T$, several hard jets, and two energetic leptons.

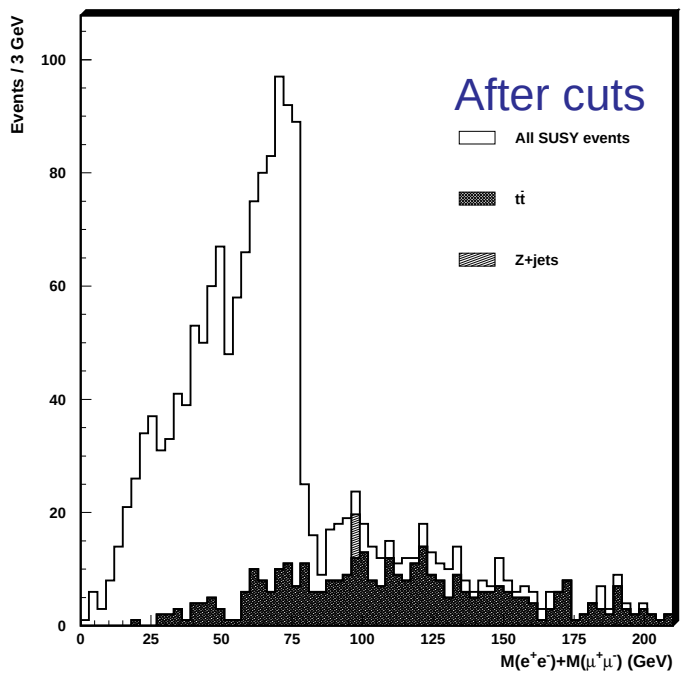
Also, the signal from $\tilde{N}_2$ decay has only same-flavor leptons. Therefore, one can enhance the edge shape by subtracting events that pass the cuts, but with opposite lepton flavors:

$$[e^+e^-] + [\mu^+\mu^-] - [e^+\mu^-] - [\mu^+e^-]$$

Also cuts $\not{E}_T > 150$ GeV and $M(\ell^+\ell^-) > 100$ GeV eliminate the $t\bar{t}$ and Z-peak backgrounds.

CMS study, Chiorboli and Tricomi





Gluino mass reconstruction at the LHC

The gluino mass can be reconstructed once the $\tilde{N}_2$ mass has been found from the dilepton mass edge. For a particularly favorable case, consider decays through $\tilde{b}_1$, so that the gluino decay results in

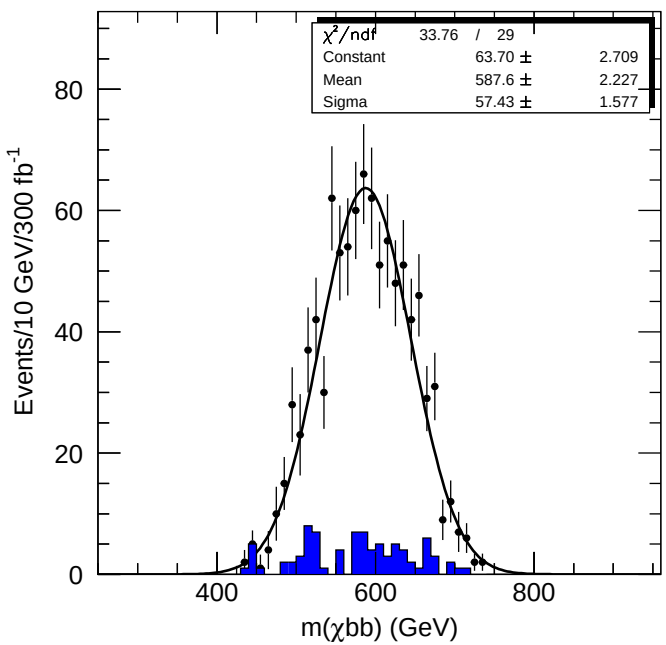
$$\tilde{g} \to \bar{b}\tilde{b}_1 \to b\bar{b}\tilde{N}_2 \to b\bar{b}\ell^+\ell^-\tilde{N}_1$$

By selecting events close to the known dilepton edge, the impact of the unknown $\tilde{N}_1$ momentum can be minimized. Then one reconstructs the invariant mass

$$M(b\bar{b}\tilde{N}_2),$$

and fits the resulting peak to a Monte Carlo generated Gaussian.

(Here $m_{\tilde{g}} = 595$ GeV.)

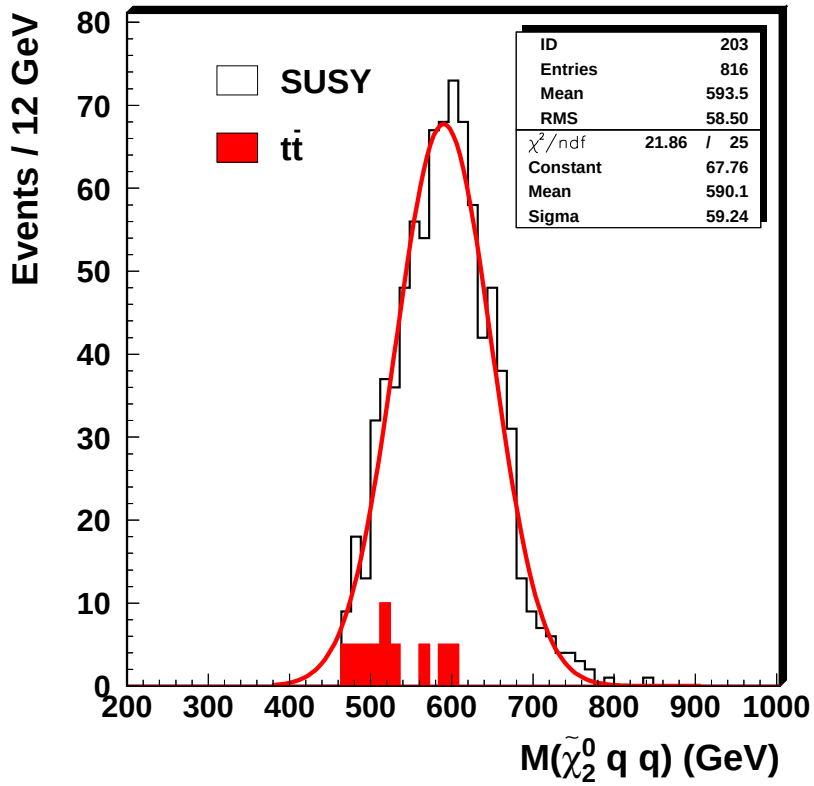


ATLAS study: Gjelsten, Hisano, Kawagoe, Lytken, Miller, Nojiri, Osland, Polesello

Here is another study, this time based on the decay (with no b-tagging):

$$\tilde{g} \to \bar{q}\tilde{q} \to q\bar{q}\tilde{N}_2 \to q\bar{q}\ell^+\ell^-\tilde{N}_1$$

Again, a peak is reconstructed based on the invariant mass $M(jj\tilde{N}_2)$, using the known position of the dilepton edge to minimize the effects of the unknown $\tilde{N}_1$ momentum.



CMS study, Chiorboli and Tricomi

A measurement of the gluino mass is crucial to a quantitative understanding of SUSY breaking. This can only be obtained at the LHC.

However, kinematic measurements at the LHC are essentially determinations of mass **differences**, with the unknown $\tilde{N}_1$ LSP mass used as an input to the fits.

The most accurate determination of absolute masses can be obtained at an International Linear Collider.

Can LHC discover the lightest Higgs boson h^0 and SUSY in the same events?

From the ATLAS TDR:

mSUGRA model with

$m_{\tilde{g}} = 1000$ GeV.

Look for $h^0 \to b\bar{b}$

from the decay $\tilde{N}_2 \to h^0 \tilde{N}_1$

in a sample of SUSY events.

Integrated luminosity = 30 fb^{-1}

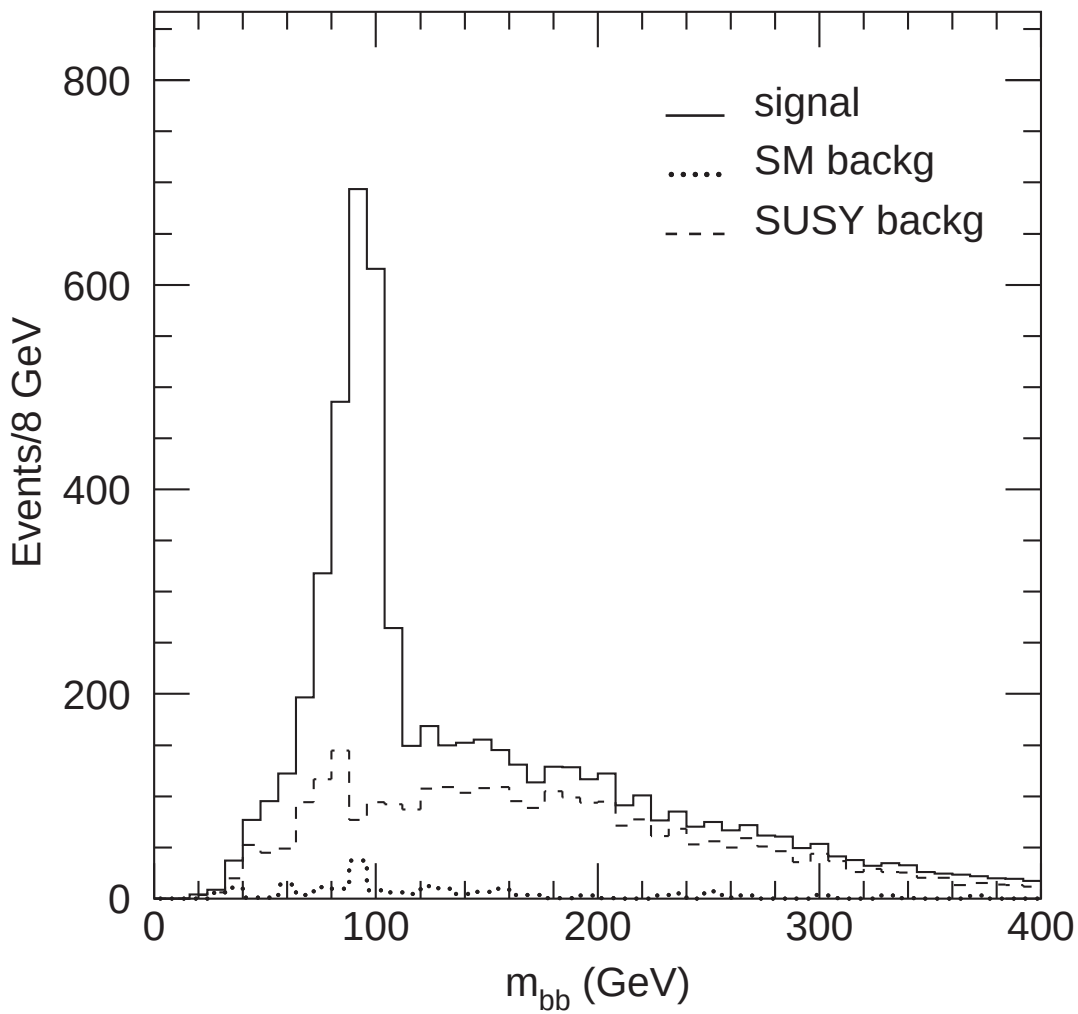
Cuts:

$\not{E}_T > 300$ GeV,

$p_T(b_1, b_2) > 50$ GeV,

$p_T(j_1, j_2) > 100$ GeV,

veto on isolated leptons.



NLSP decay in Gauge-Mediated SUSY Breaking

Recall that GMSB models have the special property that the LSP is a very light Goldstino/gravitino $(\tilde{G})$. The Next-Lightest SUSY Particle (NLSP) can decay into its Standard Model partner and $\tilde{G}$.

This can completely change the SUSY signals at colliders!

In general, the NSLP can have a decay length that is microscopic, comparable to detector elements, or macroscopic:

$$\Gamma(\mathrm{NLSP} \to \mathrm{SM\,particle} + \tilde{\mathrm{G}}) \;=\; 2 \times 10^{-3}\, \kappa \left(\frac{\mathrm{M_{NLSP}}}{100\ \mathrm{GeV}}\right)^{5} \left(\frac{\sqrt{\langle \mathrm{F} \rangle}}{100\ \mathrm{TeV}}\right)^{-4} \mathrm{eV}$$

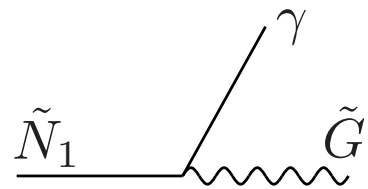
where κ is a mixing matrix factor. If the NLSP has energy E in the lab frame, its decay length will be:

$$d = 9.9 \times 10^{-3}\, \frac{1}{\kappa} \left(\frac{E^2}{M_{\mathrm{NLSP}}^2} - 1\right)^{1/2} \left(\frac{M_{\mathrm{NLSP}}}{100\ \mathrm{GeV}}\right)^{-5} \left(\frac{\sqrt{\langle F \rangle}}{100\ \mathrm{TeV}}\right)^{4} \mathrm{cm}$$

which can be anywhere from sub-micron to kilometers, depending on $\langle F \rangle$.

Neutralino NLSP in Gauge-Mediated SUSY Breaking

If the NLSP is $\tilde{N}_1$, it can have decays:



There are three general possibilities:

1) If the $\tilde{N}_1$ decays are prompt, then every SUSY event will be tagged by two additional **energetic, isolated photons**. There is still missing energy carried away by the $\tilde{G}$. Standard Model backgrounds are very small, so it is relatively easy to discover SUSY with the inclusive signal (X means "anything")

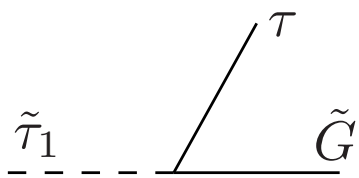
$$X + \gamma\gamma + \not{E}.$$

2) If the $\tilde{N}_1$ decays are delayed, but still occur within the detector, then one can look for photons that do not point back to the interaction vertex. This can be a striking signal, depending on the experimental environment.

3) If the $\tilde{N}_1$ decays occur outside of the detector, then the signals are the same as discussed earlier.

Stau NLSP in Gauge-Mediated SUSY Breaking

If the NLSP is the lightest stau, $\tilde{\tau}_1$, then it can have decays:

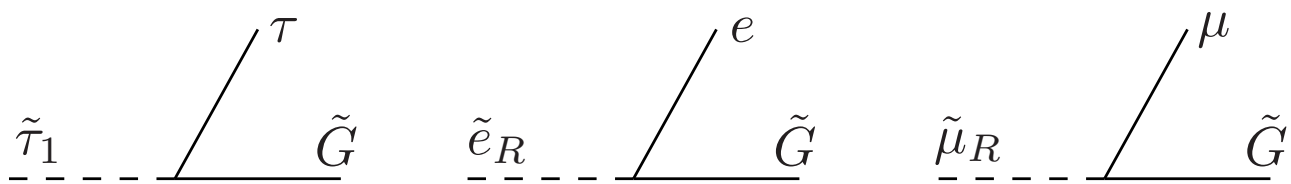


1) If the $\tilde{\tau}_1$ decays are prompt, then every SUSY event will be tagged by two **energetic, isolated τ's**.

2) If the $\tilde{\tau}_1$ decays occur outside of the detector, then one can look for slow, highly ionizing tracks as they move through the detector. These may appear to be slow "muons", or they may be missed if the timing gates do not accommodate them. They can be identified by their anomalously high ionization rate in the detector, or by their long time-of-flight.

Slepton co-NLSP in Gauge-Mediated SUSY Breaking

In GMSB models, $\tilde{\tau}_1$, $\tilde{e}_R$, $\tilde{\mu}_R$ can be nearly degenerate (to within less that $m_\tau = 1.8$ GeV. In that case, SUSY particles will decay to final states involving one of them, and they each act independently as the NLSP, with decays to $\tilde{G}$:



1) If the NLSP decays are prompt, then every SUSY event will be tagged by two **energetic, isolated leptons** (e, μ, τ) with uncorrelated flavors, and often uncorrelated charges.

2) If the NLSP decays occur outside of the detector, then one can look for slow, highly ionizing tracks, just as for the stau NLSP case.

A bold prediction in two parts:

- Supersymmetry will be discovered at the LHC.
- Some feature of it will be completely unexpected by (nearly) everyone.

Expect the unexpected!