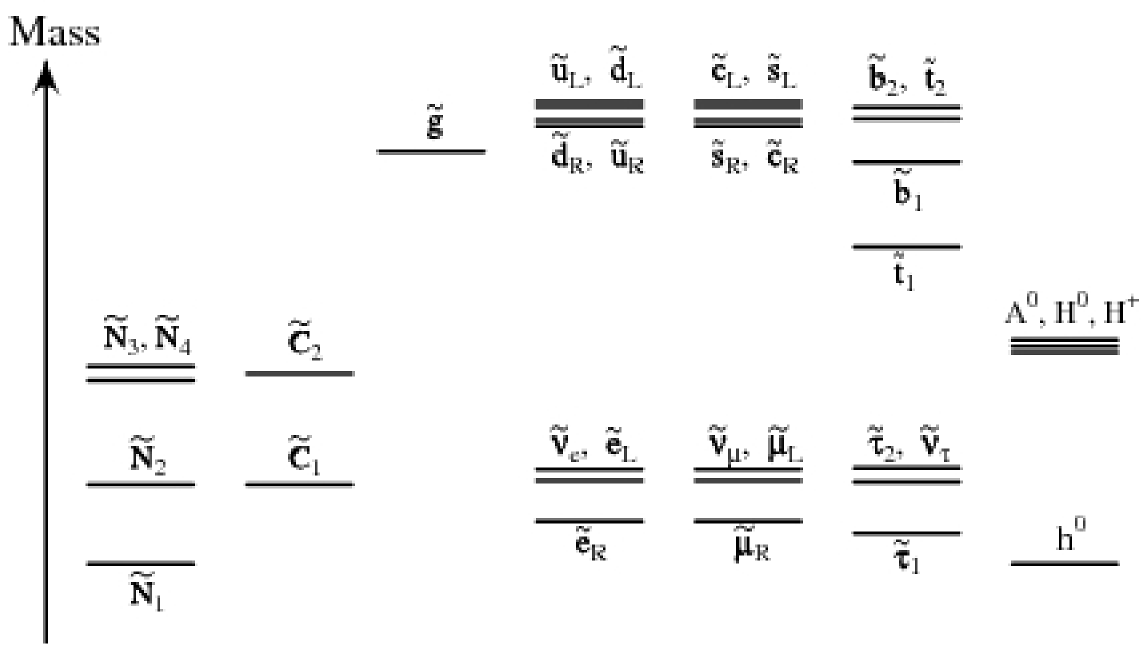
Sparticle Decays

The general features of SUSY particle decays are controlled by:

- R-parity conservation
  Lightest R-odd particle (LSP) is stable
  Decay chains of R-odd (SUSY) particles must end in LSP
  LSP as dark matter: require LSP to be neutral and uncoloured
  $\longrightarrow$ escapes from detector $\longrightarrow$ missing energy
- Mass spectrum
  Heavier particles decay through a cascade of lighter particles
  $\longrightarrow$ High multiplicity of objects in SUSY events – multijets, multileptons
  NLSP affects event content:
  – light stau $\longrightarrow$ events with taus
  – light sbottom $\longrightarrow$ events with bs (also come from cascades to $h^0 \to b\bar{b}$)



sample spectrum

Decays of neutralinos and charginos

Let's think first about 2-body decays.

- Each neutralino and chargino contains at least a small amount of electroweak gaugino: $\widetilde{B}$, $\widetilde{W}^0$, or $\widetilde{W}^\pm$

  $\widetilde{N}_i$ and $\widetilde{C}_i$ inherit weak-interaction couplings to scalar+fermion pairs

  $\widetilde{N}_i, \widetilde{C}_i \to$ lepton+slepton or quark+squark [if kinematically allowed]

- Each neutralino and chargino contains at least a small amount of Higgsino

  $\widetilde{N}_i$ and $\widetilde{C}_i$ inherit gaugino-higgsino-Higgs and SU(2) gaugino-gaugino-vector boson couplings

  $\widetilde{N}_i, \widetilde{C}_i \to \widetilde{N}_j, \widetilde{C}_j$+Higgs or $\widetilde{N}_j, \widetilde{C}_j$+EW gauge boson [if kin. allowed]

Possible 2-body decays:

$$\widetilde{N}_i \to Z\widetilde{N}_j, \quad W\widetilde{C}_j, \quad h^0\widetilde{N}_j, \quad \ell\widetilde{\ell}, \quad \nu\widetilde{\nu}, \quad [A^0\widetilde{N}_j, \quad H^0\widetilde{N}_j, \quad H^\pm\widetilde{C}_j^\mp, \quad q\widetilde{q}] \tag{1}$$

$$\widetilde{C}_i \to W\widetilde{N}_j, \quad Z\widetilde{C}_1, \quad h^0\widetilde{C}_1, \quad \ell\widetilde{\nu}, \quad \nu\widetilde{\ell}, \quad [A^0\widetilde{C}_1, \quad H^0\widetilde{C}_1, \quad H^\pm\widetilde{N}_j, \quad q\widetilde{q}'] \tag{2}$$

[modes in brackets less likely to be kinematically allowed]

Typical signatures:

$$p + p(\bar{p}) \to \widetilde{C}_1\widetilde{N}_2 \to W\widetilde{N}_1 Z\widetilde{N}_1 \to \ell^+\ell^-\ell' + \text{MET} \qquad \text{(trileptons)} \tag{3}$$

$$p + p(\bar{p}) \to \widetilde{C}_1\widetilde{N}_2 \to W\widetilde{N}_1 \tau^+\widetilde{\tau}_1^- \to \ell\tau^+\tau^- + \text{MET} \qquad \text{(tau-rich)} \tag{4}$$

$$p + p(\bar{p}) \to \widetilde{C}_1\widetilde{N}_2 \to W\widetilde{N}_1 h^0\widetilde{N}_1 \to \ell b\bar{b} + \text{MET} \qquad \text{(b-rich)} \tag{5}$$

$$p + p(\bar{p}) \to \widetilde{N}_2\widetilde{N}_2 \to \ell^+\widetilde{\ell}^-\ell^+\widetilde{\ell}^- \to \ell^+\ell^+W^-W^- + \text{MET} \qquad \text{(like-sign dileptons)} \tag{6}$$

Heavier charginos/neutralinos can have more complicated cascade decays.

For lighter neutralinos/charginos (especially $\widetilde{C}_1$ and $\widetilde{N}_2$), all the 2-body decays may be kinematically forbidden.
Consider 3-body decays.

$$\widetilde{N}_i \to f\bar{f}\widetilde{N}_j \qquad \widetilde{N}_i \to f\bar{f}'\widetilde{C}_j \qquad \widetilde{C}_i \to f\bar{f}'\widetilde{N}_j \qquad \widetilde{C}_2 \to f\bar{f}\widetilde{C}_1 \tag{7}$$

via off-shell gauge bosons, Higgs scalars, sleptons, and/or squarks, e.g.

$$\widetilde{N}_i \to Z^*\widetilde{N}_j \to f\bar{f}\widetilde{N}_j, \qquad \widetilde{N}_i \to \ell\widetilde{\ell}^* \to \ell\ell\widetilde{N}_j \tag{8}$$

Different from 2-body cascade decays because final-state particles do not reconstruct definite invariant mass of (virtual) parent.

$\widetilde{N}_i \to Z\widetilde{N}_j \to \ell\ell\widetilde{N}_j$: dileptons reconstruct m_Z

$\widetilde{N}_i \to Z^*\widetilde{N}_j \to \ell\ell\widetilde{N}_j$: dilepton invariant mass is a broad distribution

Leptonic decays especially important for phenomenology:

$$\widetilde{C}_1^{\pm} \to \ell^{\pm}\nu\widetilde{N}_1 \qquad \widetilde{N}_2 \to \ell^+\ell^-\widetilde{N}_1 \tag{9}$$

Slepton decays

Sleptons have 2-body decays to lepton+chargino or lepton+neutralino :

$$\tilde{\ell} \to \ell \tilde{N}_i, \qquad \tilde{\ell} \to \nu \tilde{C}_i, \qquad \tilde{\nu} \to \nu \tilde{N}_i, \qquad \tilde{\nu} \to \ell \tilde{C}_i \tag{10}$$

If $\tilde{N}_1$ is the LSP, then $\tilde{\ell} \to \ell \tilde{N}_1$ and $\tilde{\nu} \to \nu \tilde{N}_1$ are always allowed

(unless $m_{\tilde{\tau}_1} - m_{\tilde{N}_1} < m_\tau$)

For sufficiently heavy sleptons, decays to charginos and heavier neutralinos are important:

$$\tilde{\ell} \to \nu \tilde{C}_1, \qquad \tilde{\ell} \to \ell \tilde{N}_2, \qquad \tilde{\nu} \to \ell \tilde{C}_1 \tag{11}$$

- These are followed by decays of $\tilde{C}_1$, $\tilde{N}_2$.
- Left-handed sleptons may prefer these decays, since $\tilde{C}_1$, $\tilde{N}_2$ are often mostly wino: larger gauge charge than bino-like $\tilde{N}_1$.

Right-handed sleptons are not charged under SU(2):

$\tilde{\ell}_R \to \ell \tilde{N}_1$ preferred if $\tilde{N}_1$ is bino-like

Squark decays

If the squark decay to quark+gluino is kinematically allowed, it will always dominate

$\widetilde{q} \to q\widetilde{g}$ has QCD strength

Otherwise, squark decays to quark+neutralino or quark+chargino

- Direct decay $\widetilde{q} \to q\widetilde{N}_1$ kinematically favored

  Can dominate for right-handed squarks because $\widetilde{N}_1$ is mostly bino

- Left-handed squarks may strongly prefer decay into heavier neutralinos or charginos, because SU(2) gauge coupling is larger

  Heavier neutralino/chargino subsequently decays $\to$ cascade!

- Squark decays to higgsino-like charginos/neutralinos less important, except for stops/sbottoms with large Yukawa couplings

  Higgsino-like neutralino/chargino subsequently decays $\to$ cascade!

Cascade decays: can have large numbers of jets/leptons/etc in the final state.

Top squark $\widetilde{t}_1$ can be special:

Typically lighter than the other squarks

Top is heavy: decays $\widetilde{t}_1 \to t\widetilde{g}$ and $\widetilde{t}_1 \to t\widetilde{N}_1$ may be kinematically forbidden!

Can get $\widetilde{t}_1$ decaying only to charginos: $\widetilde{t}_1 \to b\widetilde{C}_1$

If this decay is also kinematically forbidden, few options remain:

Flavour-changing decay $\widetilde{t}_1 \to c\widetilde{N}_1$

3-body decay $\widetilde{t}_1 \to t^*\widetilde{N}_1 \to Wb\widetilde{N}_1$

or even 4-body decay $\widetilde{t}_1 \to t^*\widetilde{N}_1 \to W^*b\widetilde{N}_1 \to f\bar{f}'b\widetilde{N}_1$

$\widetilde{t}_1$ decay could be so slow that it has time to hadronize,
or maybe even fly through the detector! Quasi-stable "R-hadrons"

Gluino decays

The gluino can only decay to quark+squark
(squark can be on-shell or virtual)

- If 2-body decays $\widetilde{g} \to \widetilde{q}q$ are open, they will dominate
  - Mass spectrum matters!
    - If only $\widetilde{g} \to \widetilde{t}_1 t$ is open, final state will contain tops.
    - If only $\widetilde{g} \to \widetilde{b}_1 b$ is open, final state will contain bottoms.
    - If $\widetilde{g} \to \widetilde{q}q$ is open, final state will contain more generic looking jets.
  - These are followed by decay chain of the squark.
- If no 2-body decays are open, gluino will decay via an off-shell squark
  $\widetilde{g} \to \widetilde{q}^* q$, with $\widetilde{q}^* \to q\widetilde{N}_i$ or $q'\widetilde{C}_i$

A (perhaps crazy) possibility: Split Supersymmetry

The gluino, gauginos, Higgsinos, and h^0 are at the EW/TeV scale

All the other scalars (squarks, sleptons, heavier Higgses) are VERY heavy, like 10^{11} GeV

How will the gluino decay? $\widetilde{g} \to \widetilde{q}^* q$, but $\widetilde{q}$ is very very heavy.

$\to$ Long-lived gluino!

Colliders: can get displaced vertices and/or R-hadron

Cosmic rays: can get gluino-sourced air showers

Early universe: gluinos decaying at the wrong time can screw up Big Bang Nucleosynthesis $\to$ constraints on gluino lifetime!

Charginos and neutralinos can decay in ways that don't involve squarks or sleptons: will be short-lived like normal.

Decays to the gravitino/goldstino

In some models the LSP is the gravitino (the superpartner of the graviton!)

Typically happens in gauge-mediated models

Gravitino itself couples with gravity-strength couplings: basically irrelevant

However, once local SUSY is broken, gravitino gets goldstino as its longitudinal components

Goldstino has non-gravitational coupling to all sparticle-particle pairs: can be relevant for collider phenomenology

Decay $\widetilde{X} \to X\widetilde{G}$:

Typically too slow to compete with other decays of sparticle $\widetilde{X}$,
UNLESS $\widetilde{X}$ is the NLSP (LSP is $\widetilde{G}$)

$\to$ NLSP will always decay to its superpartner and $\widetilde{G}$.

Phenomenology depends on what is the NLSP.

- Lightest neutralino:

  Contains an admixture of the photino

  Decays: $\widetilde{N}_1 \to \gamma\widetilde{G}$

  Events with two high-energy photons (one for each NLSP decay) plus missing transverse momentum

  (In)famous $ee\gamma\gamma$+MET event (CDF Run 1)

Decay length: ($\kappa_{1\gamma}$ is the "photino content" of $\widetilde{N}_1$)

$$d = 9.9 \times 10^{-3} \frac{1}{\kappa_{1\gamma}} \left(\frac{E^2}{m^2_{\widetilde{N}_1}} - 1 \right)^{1/2} \left(\frac{m_{\widetilde{N}_1}}{100 \text{ GeV}} \right)^5 \left(\frac{\sqrt{\langle F \rangle}}{100 \text{ TeV}} \right)^{-4} \text{cm} \qquad (12)$$

If $\sqrt{\langle F \rangle}$ is less than a few thousand TeV in gauge-mediated models, then $\widetilde{N}_1$ can decay before leaving a collider detector.

Decay length can be from sub-micron to multi-kilometer

"Non-pointing photons" – very distinctive signature

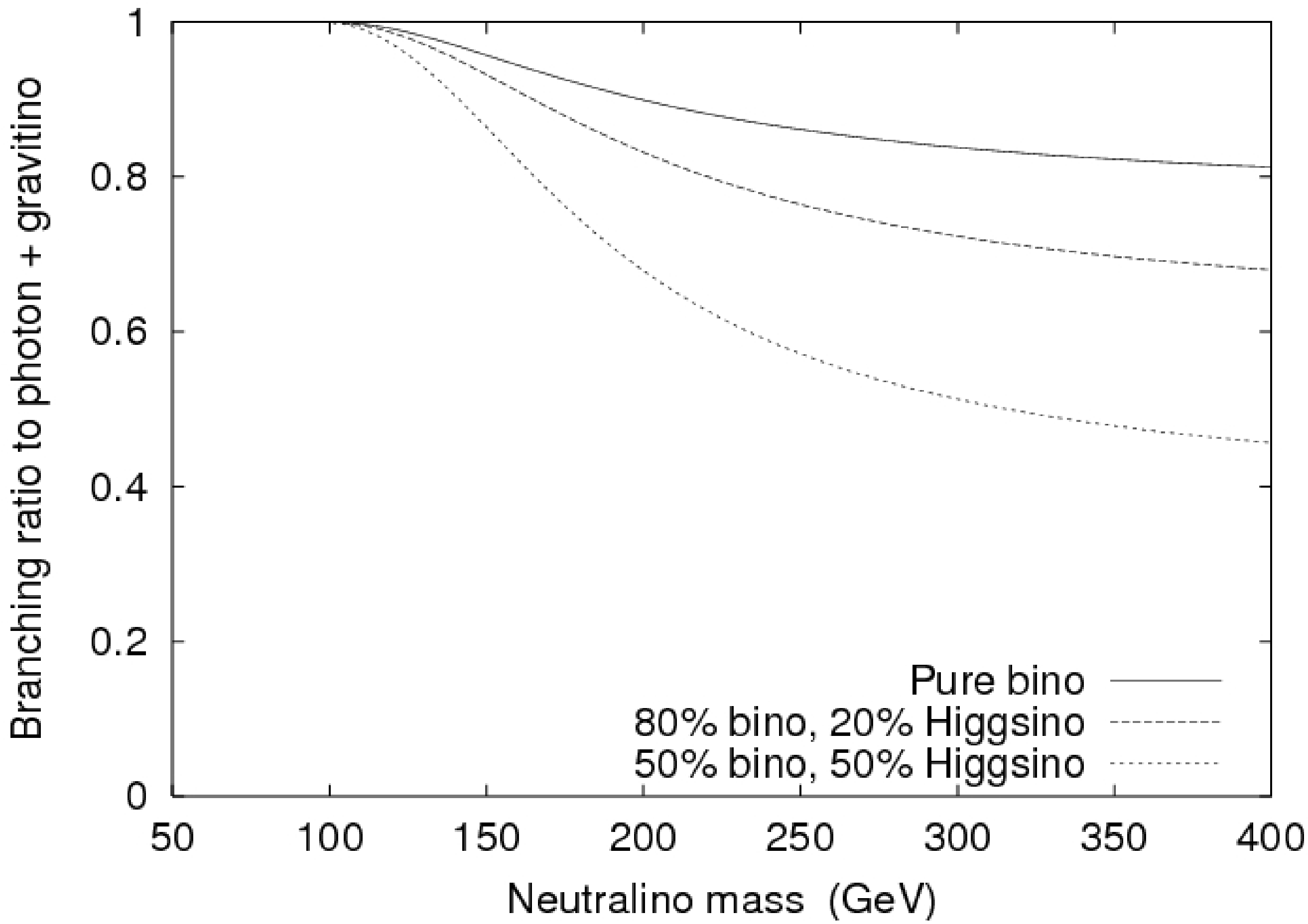
Lightest neutralino, continued:

$\widetilde{N}_1$ doesn't have to be pure photino.

Can also have

$$\widetilde{N}_1 \to Z\widetilde{G}, \qquad \widetilde{N}_1 \to h^0\widetilde{G}, \qquad \widetilde{N}_1 \to A^0\widetilde{G}, \qquad \widetilde{N}_1 \to H^0\widetilde{G} \tag{13}$$

These tend to be kinematically suppressed compared to $\widetilde{N}_1 \to \gamma\widetilde{G}$.



(for $m_{h^0} = 120$ GeV, $m_{A^0}, m_{H^0} > 400$ GeV)

- Charged slepton:

RGEs: $\widetilde{e}_R$, $\widetilde{\mu}_R$, $\widetilde{\tau}_R$ tend to be lightest "co-NLSPs"
Yukawa couplings: $\widetilde{\tau}_R$ and $\widetilde{\tau}_L$ mix $\rightarrow \widetilde{\tau}_1$, $\widetilde{\tau}_2$

- If $\widetilde{e}_R \rightarrow e\tau\widetilde{\tau}_1$, $\widetilde{\mu}_R \rightarrow \mu\tau\widetilde{\tau}_1$ are not kinematically allowed, then

$$\widetilde{e}_R \rightarrow e\widetilde{G}, \qquad \widetilde{\mu}_R \rightarrow \mu\widetilde{G}, \qquad \widetilde{\tau}_1 \rightarrow \tau\widetilde{G} \tag{14}$$

end all decay chains: "slepton co-NLSP scenario"

- If $\widetilde{e}_R \rightarrow e\tau\widetilde{\tau}_1$, $\widetilde{\mu}_R \rightarrow \mu\tau\widetilde{\tau}_1$ are allowed, then

$\widetilde{\tau}_1$ is the sole NLSP: $\widetilde{\tau}_1 \rightarrow \tau\widetilde{G}$ ends all decay chains
"stau NLSP scenario"

Decay(s) of NLSP(s) to $\widetilde{G}$ can be fast or very slow, depending on $\sqrt{\langle F \rangle}$.
Slepton NLSP(s): could see tracks of slepton and decay kinks inside detector!
Tracks of slepton: anomalously high ionization rate; time-of-flight

- Lighter stop $\widetilde{t}_1$:

In some weird gauge-mediated models $\widetilde{t}_1$ can be quite light.
This is helped by $\widetilde{t}_1$ being driven down by $\widetilde{t}_L$-$\widetilde{t}_R$ mixing
Decays:

- $\widetilde{t}_1 \rightarrow t\widetilde{N}_1 \rightarrow bW\gamma\widetilde{G}$
- $\widetilde{t}_1 \rightarrow bW\widetilde{N}_1 \rightarrow bW\gamma\widetilde{G}$
- $\widetilde{t}_1 \rightarrow c\widetilde{N}_1 \rightarrow c\gamma\widetilde{G}$

Decay mode depends on $\widetilde{t}_1$-$\widetilde{N}_1$ mass splitting.
Signals: pair-produce $\widetilde{t}_1$; decays contain 2 photons and MET
Tagging the photons cuts down QCD background significantly!

Experimental signals for supersymmetry

The plan:
• First I'll give a general overview of SUSY particle production at e^+e^- colliders (ILC) and hadron colliders (LHC/ATLAS) (following the Primer).
• Then I'll go into more detail on the physics behind various SUSY measurement techniques.
E.g., kinematic endpoints, spin correlations, use of polarized e^+e^- beams.

Indirect signals of SUSY could show up from virtual sparticle effects in SM processes (i.e., sparticles in the loop):
Z-pole observables from LEP, $b \to s\gamma$, neutral meson mixing (K^0-$\bar{K}^0$, B^0-$\bar{B}^0$, D^0-$\bar{D}^0$), muon $g-2$, $\mu \to e\gamma$, electric dipole moments of neutron and electron
All have placed bounds on SUSY (with the occasional 2-σ hint...)
A positive signal in any these could have *many* New-Physics interpretations
Direct detection of SUSY particles is essential to establish their existence

Superparticle production at e^+e^- colliders

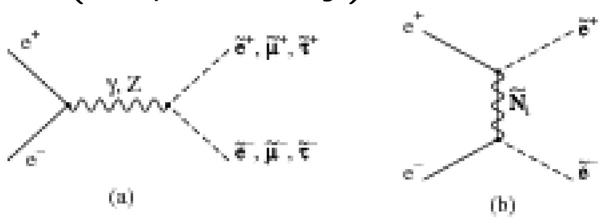
All (kinematically accessible) sparticles can be pair produced in e^+e^-
The gluino can't be produced at tree level, but it can be produced via a loop

- Squarks, sleptons: pair production via s-channel Z, γ exchange

$$e^+e^- \to Z^*, \gamma^* \to \widetilde{\ell}\widetilde{\ell}, \widetilde{q}\widetilde{q} \qquad e^+e^- \to Z^* \to \widetilde{\nu}\widetilde{\nu} \tag{15}$$

- Selectrons $\widetilde{e}_L\widetilde{e}_L$, $\widetilde{e}_R\widetilde{e}_R$ and electron-sneutrinos $\widetilde{\nu}_e\widetilde{\nu}_e$:

also have production from t-channel exchange of a virtual neutralino or chargino (respectively)



$\bar{e}_L e_L \to \widetilde{e}_L\widetilde{e}_L$: t-channel $\widetilde{B}$, $\widetilde{W}^0$
$\bar{e}_L e_L \to \widetilde{\nu}_e\widetilde{\nu}_e$: t-channel $\widetilde{W}^\pm$
$\bar{e}_R e_R \to \widetilde{e}_R\widetilde{e}_R$: t-channel $\widetilde{B}$
e^-e^- collisions isolate t-channel $\widetilde{e}^-\widetilde{e}^-$ production

- Charginos and neutralinos: pair production via s-channel Z, γ exchange

$$e^+e^- \to Z^*, \gamma^* \to \widetilde{C}_i^+\widetilde{C}_i^- \qquad e^+e^- \to Z^* \to \widetilde{C}_i^+\widetilde{C}_j^-, \widetilde{N}_i\widetilde{N}_j \tag{16}$$

- Charginos $\widetilde{C}_i^+\widetilde{C}_j^-$ and neutralinos $\widetilde{N}_i\widetilde{N}_j$:

also have production from t-channel exchange of a virtual electron-sneutrino or selectron (respectively)

Superparticle production at hadron colliders

Production via QCD: $\widetilde{g}\widetilde{g}, \widetilde{g}\widetilde{q}, \widetilde{q}\widetilde{q}$. Can be produced in many combinations: e.g.,

- Gluino+squark associated production, $gq \to \widetilde{g}\widetilde{q}$
- Production of two squarks and no antisquarks, $qq \to \widetilde{q}\widetilde{q}$ (via t-channel $\widetilde{g}$ exchange)
- Production of two different-flavour squarks, e.g. $uc \to \widetilde{u}\widetilde{c}$

LHC reach for gluinos, squarks typically out to about 1 to 2 TeV.

Rule of thumb: QCD production typically gets large ($\mathcal{O}(1)$) radiative corrections. NLO squark/gluino production codes exist; e.g. PROSPINO.

Although coloured particles are typically heavier than colour-neutral particles (due to RGE running), large QCD production cross sections make them typically easier to see at LHC.

Production via EW: $\widetilde{C}_i^+\widetilde{C}_j^-, \widetilde{N}_i\widetilde{N}_j, \widetilde{N}_i\widetilde{C}_j^\pm, \widetilde{\ell}\widetilde{\ell}^*$

$\widetilde{N}_i\widetilde{C}_j^\pm$ is through $W^\pm$ exchange.

Slepton pair production tends to be harder to see.

Rates are smaller than for coloured particles because production cross sections involve EW couplings.

Can also have associated $\widetilde{N}_i\widetilde{q}$, $\widetilde{C}_i^\pm\widetilde{q}$ production – EW strength.

Some interesting generic signatures at hadron colliders:

- At least $2m_{\widetilde{N}}$ of missing energy from the two LSPs.

Hadron collider: Can only measure transverse component of missing energy!

Don't know the momentum of the centre-of-mass in beam direction

Typical signature is jets+missing E_T.

Backgrounds:

genuine missing E_T from leptonic W decays $\rightarrow$ veto events with leptons

mismeasurement of jet energies $\rightarrow$ fake missing E_T

- If gluinos decay to hadrons+chargino (via chain $\widetilde{g} \rightarrow \bar{q}\widetilde{q} \rightarrow \bar{q}q'\widetilde{C}_i$),

and charginos then can decay to charged lepton, neutrino, and $\widetilde{N}_1$:

Gluino doesn't know anything about electric charge: charged lepton can have either sign from each gluino decay.

Can get events with two leptons of the same charge ("like-sign dileptons") and possibly different flavours, plus jets and missing E_T.

Can also get like-sign dileptons from $\widetilde{q}\widetilde{q}$ and $\widetilde{q}\widetilde{g}$ production if $\widetilde{q}$ decays to a gluino.

Like-sign dileptons $\rightarrow$ smaller SM background:

main SM backgrounds with leptons are W^+W^-, Drell-Yan, and $t\bar{t}$, which only give opposite-sign dileptons.

- Trilepton signal from $\widetilde{C}_1\widetilde{N}_2$ with decays involving $W + Z$.

Can also come from $\widetilde{g}\widetilde{g}$, $\widetilde{q}\widetilde{g}$, or $\widetilde{q}\widetilde{g}$ when decay chains involve $\widetilde{C}_1$ and $\widetilde{N}_2$.