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
  - → escapes from detector → missing energy

- **Mass spectrum**
  - Heavier particles decay through a cascade of lighter particles
  - → High multiplicity of objects in SUSY events – multijets, multileptons
  - NLSP affects event content:
    - light stau → events with taus
    - light sbottom → events with bs (also come from cascades to $h^0 \rightarrow b\bar{b}$)
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: $\tilde{B}$, $\tilde{W}^0$, or $\tilde{W}^\pm$
  
  $\tilde{N}_i$ and $\tilde{C}_i$ inherit weak-interaction couplings to scalar+fermion pairs $\tilde{N}_i, \tilde{C}_i \rightarrow$ lepton+slepton or quark+squark [if kinematically allowed]

- Each neutralino and chargino contains at least a small amount of Higgsino $\tilde{N}_i$ and $\tilde{C}_i$ inherit gaugino-higgsino-Higgs and SU(2) gaugino-gaugino-vector boson couplings $\tilde{N}_i, \tilde{C}_i \rightarrow \tilde{N}_j, \tilde{C}_j +$Higgs or $\tilde{N}_j, \tilde{C}_j +$EW gauge boson [if kin. allowed]

Possible 2-body decays:

\begin{align*}
\tilde{N}_i &\rightarrow Z\tilde{N}_j, \ W\tilde{C}_j, \ h^0\tilde{N}_j, \ \ell\bar{\ell}, \ \nu\bar{\nu}, \ \left[A^0\tilde{N}_j, \ H^0\tilde{N}_j, \ H^\pm\tilde{C}_j^\mp, \ q\bar{q}\right] \quad (1) \\
\tilde{C}_i &\rightarrow W\tilde{N}_j, \ Z\tilde{C}_1, \ h^0\tilde{C}_1, \ \ell\bar{\nu}, \ \nu\bar{\ell}, \ \left[A^0\tilde{C}_1, \ H^0\tilde{C}_1, \ H^\pm\tilde{N}_j, \ q\bar{q}\right] \quad (2)
\end{align*}

[modes in brackets less likely to be kinematically allowed]

Typical signatures:

\begin{align*}
p + p(p) &\rightarrow \tilde{C}_1\tilde{N}_2 \rightarrow W\tilde{N}_1 Z\tilde{N}_1 \rightarrow \ell^+\ell^\prime - \ell^+ + \text{MET} \quad \text{(trileptons)} \quad (3) \\
p + p(p) &\rightarrow \tilde{C}_1\tilde{N}_2 \rightarrow W\tilde{N}_1 \tau^+\tilde{\tau}_1^- \rightarrow \ell\tau^+\tau^- + \text{MET} \quad \text{(tau – rich)} \quad (4) \\
p + p(p) &\rightarrow \tilde{C}_1\tilde{N}_2 \rightarrow W\tilde{N}_1 h^0\tilde{N}_1 \rightarrow \ell b\bar{b} + \text{MET} \quad \text{(b – rich)} \quad (5) \\
p + p(p) &\rightarrow \tilde{N}_2\tilde{N}_2 \rightarrow \ell^+\ell^- \ell^+\ell^- \rightarrow \ell^+\ell^+ W^- W^- + \text{MET} \quad \text{(like – sign dileptons)} \quad (6)
\end{align*}

Heavier charginos/neutralinos can have more complicated cascade decays.
For lighter neutralinos/charginos (especially \( \tilde{C}_1 \) and \( \tilde{N}_2 \)), all the 2-body decays may be kinematically forbidden.

Consider 3-body decays.

\[
\tilde{N}_i \rightarrow f \bar{f} \tilde{N}_j \quad \tilde{N}_i \rightarrow f \bar{f} \tilde{C}_j \quad \tilde{C}_i \rightarrow f \bar{f} \tilde{N}_j \quad \tilde{C}_2 \rightarrow f \bar{f} \tilde{C}_1
\]  

(7)

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

\[
\tilde{N}_i \rightarrow Z^* \tilde{N}_j \rightarrow f \bar{f} \tilde{N}_j, \quad \tilde{N}_i \rightarrow \ell\ell^* \rightarrow \ell\ell \tilde{N}_j
\]

(8)

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

\( \tilde{N}_i \rightarrow Z\tilde{N}_j \rightarrow \ell\ell\tilde{N}_j \): dileptons reconstruct \( m_Z \)

\( \tilde{N}_i \rightarrow Z^*\tilde{N}_j \rightarrow \ell\ell\tilde{N}_j \): dilepton invariant mass is a broad distribution

Leptonic decays especially important for phenomenology:

\[
\tilde{C}_1^\pm \rightarrow \ell^\pm \nu \tilde{N}_1 \quad \tilde{N}_2 \rightarrow \ell^+ \ell^- \tilde{N}_1
\]

(9)
Slepton decays

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

\[ \tilde{\ell} \to \ell \tilde{N}_i, \quad \tilde{\ell} \to \nu \tilde{C}_i, \quad \tilde{\nu} \to \nu \tilde{N}_i, \quad \tilde{\nu} \to \ell \tilde{C}_i \]  

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

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

\[ \tilde{\ell} \to \nu \tilde{C}_1, \quad \tilde{\ell} \to \ell \tilde{N}_2, \quad \tilde{\nu} \to \ell \tilde{C}_1 \]  

(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 \textit{quark+gluino} is kinematically allowed, it will always dominate
\[ \tilde{q} \rightarrow q \tilde{g} \]  
\textit{has QCD strength}

Otherwise, squark decays to \textit{quark+neutralino} or \textit{quark+chargino}
- Direct decay \( \tilde{q} \rightarrow q \tilde{N}_1 \) kinematically favored
  
  \textit{Can dominate for right-handed squarks because } \tilde{N}_1 \textit{ is mostly bino}
- Left-handed squarks may strongly prefer decay into heavier neutralinos or charginos, because SU(2) gauge coupling is larger
  
  \textit{Heavier neutralino/chargino subsequently decays } \rightarrow \textit{ cascade!}

- Squark decays to higgsino-like charginos/neutralinos less important, except for stops/sbottoms with large Yukawa couplings
  
  \textit{Higgsino-like neutralino/chargino subsequently decays } \rightarrow \textit{ cascade!}

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

Top squark \( \tilde{t}_1 \) can be special:
  - Typically lighter than the other squarks
    - Top is heavy: decays \( \tilde{t}_1 \rightarrow t \tilde{g} \) and \( \tilde{t}_1 \rightarrow t \tilde{N}_1 \) may be kinematically forbidden!
  
  Can get \( \tilde{t}_1 \) decaying only to charginos: \( \tilde{t}_1 \rightarrow b \tilde{C}^* \)

If this decay is also kinematically forbidden, few options remain:
  - Flavour-changing decay \( \tilde{t}_1 \rightarrow c \tilde{N}_1 \)
  - 3-body decay \( \tilde{t}_1 \rightarrow t^* \tilde{N}_1 \rightarrow W b \tilde{N}_1 \)
  - or even 4-body decay \( \tilde{t}_1 \rightarrow t^* \tilde{N}_1 \rightarrow W^* b \tilde{N}_1 \rightarrow f \bar{f}' b \tilde{N}_1 \)

\( \tilde{t}_1 \) decay could be so slow that it has time to hadronize, or maybe even fly through the detector!  
\textit{Quasi-stable “R-hadrons”}
Gluino decays

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

- If 2-body decays $\tilde{g} \rightarrow \tilde{q}q$ are open, they will dominate
  - Mass spectrum matters!
    - If only $\tilde{g} \rightarrow \tilde{t}_1t$ is open, final state will contain tops.
    - If only $\tilde{g} \rightarrow \tilde{b}_1b$ is open, final state will contain bottoms.
    - If $\tilde{g} \rightarrow \tilde{q}q$ 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 $\tilde{g} \rightarrow \tilde{q}^*q$, with $\tilde{q}^* \rightarrow q\tilde{N}_i$ or $q'\tilde{C}_i$

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? $\tilde{g} \rightarrow \tilde{q}^*q$, but $\tilde{q}$ is very very heavy.
  - 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 → 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 $\tilde{X} \rightarrow X \tilde{G}$:

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

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

Phenomenology depends on what is the NLSP.

• Lightest neutralino:
  Contains an admixture of the photino
  Decays: $\tilde{N}_1 \rightarrow \gamma \tilde{G}$
  Events with two high-energy photons (one for each NLSP decay) plus missing transverse momentum
  (In)famous $ee\gamma\gamma + \text{MET}$ event (CDF Run 1)

Decay length: ($\kappa_{1\gamma}$ is the “photino content” of $\tilde{N}_1$)

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

If $\sqrt{\langle F \rangle}$ is less than a few thousand TeV in gauge-mediated models, then $\tilde{N}_1$ 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:

$\tilde{N}_1$ doesn’t have to be pure photino.

Can also have

\[ \tilde{N}_1 \rightarrow Z\tilde{G}, \quad \tilde{N}_1 \rightarrow h^0\tilde{G}, \quad \tilde{N}_1 \rightarrow A^0\tilde{G}, \quad \tilde{N}_1 \rightarrow H^0\tilde{G} \]  

(13)

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

(for $m_{h^0} = 120$ GeV, $m_{A^0}, m_{H^0} > 400$ GeV)
• Charged slepton:
  RGEs: $\tilde{e}_R, \tilde{\mu}_R, \tilde{\tau}_R$ tend to be lightest “co-NLSPs”
  Yukawa couplings: $\tilde{\tau}_R$ and $\tilde{\tau}_L$ mix $\rightarrow \tilde{\tau}_1, \tilde{\tau}_2$

• If $\tilde{e}_R \rightarrow e\tilde{\tau}_1, \tilde{\mu}_R \rightarrow \mu\tilde{\tau}_1$ are not kinematically allowed, then
  \[
  \tilde{e}_R \rightarrow eG, \quad \tilde{\mu}_R \rightarrow \mu G, \quad \tilde{\tau}_1 \rightarrow \tau G \tag{14}
  \]
end all decay chains: “slepton co-NLSP scenario”

• If $\tilde{e}_R \rightarrow e\tilde{\tau}_1, \tilde{\mu}_R \rightarrow \mu\tilde{\tau}_1$ are allowed, then
  $\tilde{\tau}_1$ is the sole NLSP: $\tilde{\tau}_1 \rightarrow \tau G$ ends all decay chains
  “stau NLSP scenario”

Decay(s) of NLSP(s) to $G$ 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 $\tilde{t}_1$:
  In some weird gauge-mediated models $\tilde{t}_1$ can be quite light.
  This is helped by $\tilde{t}_1$ being driven down by $\tilde{t}_L-\tilde{t}_R$ mixing

Decays:

• $\tilde{t}_1 \rightarrow t\tilde{N}_1 \rightarrow bW\gamma G$
• $\tilde{t}_1 \rightarrow bW\tilde{N}_1 \rightarrow bW\gamma G$
• $\tilde{t}_1 \rightarrow c\tilde{N}_1 \rightarrow c\gamma G$
  Decay mode depends on $\tilde{t}_1-\tilde{N}_1$ mass splitting.

Signals: pair-produce $\tilde{t}_1$; 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-$\sigma$ 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 $Z, \gamma$ exchange

\[
e^+e^- \rightarrow Z^*, \gamma^* \rightarrow \tilde{\ell}\tilde{\ell}, \tilde{q}\tilde{q} \quad e^+e^- \rightarrow Z^* \rightarrow \tilde{\nu}\tilde{\nu}
\] (15)

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

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

- Charginos and neutralinos: pair production via s-channel $Z, \gamma$ exchange

\[
e^+e^- \rightarrow Z^*, \gamma^* \rightarrow \tilde{C}_i^+\tilde{C}_i^- \quad e^+e^- \rightarrow Z^* \rightarrow \tilde{C}_i^+\tilde{C}_j^-, \tilde{N}_i\tilde{N}_j
\] (16)

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

also have production from t-channel exchange of a virtual electron-sneutrino
or electron (respectively)
Superparticle production at hadron colliders

Production via QCD: $\tilde{g}\tilde{g}, \tilde{g}\tilde{q}, \tilde{q}\tilde{q}$. Can be produced in many combinations: e.g.,
- Gluino+squark associated production, $gq \rightarrow \tilde{g}\tilde{q}$
- Production of two squarks and no antisquarks, $qq \rightarrow \tilde{q}\tilde{q}$ (via t-channel $\tilde{g}$ exchange)
- Production of two different-flavour squarks, e.g. $uc \rightarrow \tilde{u}\tilde{c}$

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: $\tilde{C}_i^+\tilde{C}_j^-, \tilde{N}_i\tilde{N}_j, \tilde{N}_i\tilde{C}_j^\pm, \ell\ell^*$

- $\tilde{N}_i\tilde{C}_j^\pm$ 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 $\tilde{N}_i\tilde{q}, \tilde{C}_i^\pm\tilde{q}$ production – EW strength.
Some interesting generic signatures at hadron colliders:

- At least $2m_{\tilde{N}}$ 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 $\tilde{g} \rightarrow \bar{q}\tilde{q} \rightarrow \bar{q}q'\tilde{C}_i$),
  
  and charginos then can decay to charged lepton, neutrino, and $\tilde{N}_1$:
  
  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 $\tilde{q}\tilde{q}$ and $\tilde{q}\tilde{g}$ production if $\tilde{q}$ 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 $\tilde{C}_1\tilde{N}_2$ with decays involving $W+Z$.
  
  Can also come from $\tilde{g}\tilde{g}$, $\tilde{q}\tilde{q}$, or $\tilde{q}\tilde{g}$ when decay chains involve $\tilde{C}_1$ and $\tilde{N}_2$. 