Supersymmetry and the LHC: An Introduction

Brent D. Nelson
Northeastern University

8/13/2007
Outline

1. Why do we need to look beyond the Standard Model?

2. What is supersymmetry? What is the MSSM?

3. What are the selling points for supersymmetry?

4. SUSY breaking and superpartner masses

5. Minimal supergravity: the simplest SUSY model

6. Signatures of SUSY at hadron colliders

The Standard Model in One Page!

⇒ The SM gauge symmetry is $SU(3)_c \times SU(2)_L \times U(1)_Y$

$g^{a=1,\ldots,8}_\mu, \ W^{i=1,2,3}_\mu, \ B_\mu \ → \ EWSB \ → \ g^{a=1,\ldots,8}_\mu, \ W^+_\mu \ W^-_\mu \ Z_\mu, \ A_\mu$

⇒ Matter content involves three generations of quarks and leptons

\[
\begin{pmatrix}
  u \\
  d
\end{pmatrix}_L, \ u_R, \ d_R; \ \begin{pmatrix}
  \nu \\
  e
\end{pmatrix}_L, \ e_R, \ \nu_R \ → \ 16 \ of \ SO(10)
\]

⇒ The Higgs sector consists of a single doublet of $SU(2)_L$ which performs two crucial roles: EWSB and fermion mass generation

\[
\phi = \begin{pmatrix}
  \phi^+ \\
  \phi_0
\end{pmatrix}_L; \ \mathcal{L} \ni D_\mu \phi^\dagger D^\mu \phi + Q\phi u_R + Q\phi^\dagger d_R + \ldots
\]

\[
D_\mu = \partial_\mu + gA_\mu + \ldots
\]

⇒ Total SM Lagrangian contains 19 undetermined parameters

⇒ Has (thus far) provided a good-to-excellent description of almost all accelerator/particle physics data ever collected!!
So Why Did we Build the LHC?

⇒ Well...we still haven’t found the Higgs field

⇒ Even if we did, scalars have problems

\[ m_h^2 \simeq m_0^2 + \frac{\lambda^2}{16\pi^2} \Lambda_{uv}^2 + \ldots \]

- Technicolor
- “Little Higgs” Models
- Composite Higgs Models
- Large Extra Dimensions
- Supersymmetry
- ...

⇒ Three things the Standard Model cannot explain

- Baryogenesis
- Dark matter
- Dark energy
⇒ What is meant by a “supermultiplet”?

- Irreducible multiplet of the supersymmetry algebra
- Fields of the same quantum number(s), but different spin
  - Chiral supermultiplet: \( F = \{ \tilde{f}, f, F_f \} \)
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Auxiliary fields $F, D, M, b_\mu$

- NOT dynamical – no kinetic terms in the component Lagrangian
- Required for SUSY algebra to close “off-shell”
- Solve EOM $\partial L / \partial \Phi = 0$ for auxiliary fields to eliminate them (more later)
The Building Blocks of Supersymmetry

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- Solve EOM \( \partial L / \partial \Phi = 0 \) for auxiliary fields to eliminate them (more later)
- But important: vevs trigger SUSY breaking (more later)!
The MSSM I: Field Content

⇒ Fields of the MSSM

<table>
<thead>
<tr>
<th>Names</th>
<th>spin 0</th>
<th>spin 1/2</th>
<th>$SU(3)_C, SU(2)_L, U(1)_Y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>squarks, quarks</td>
<td>$Q$</td>
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</tr>
<tr>
<td>(× 3 families)</td>
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Gauginos: $\tilde{B}$, $\tilde{W}^0$, $\tilde{W}^\pm$, $\tilde{g}$
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⇒ Why two Higgs doublets?

- One Higgs doublet of *scalars* OK for anomalies
- New fermions create triangle anomalies, e.g. $\text{Tr} \ [Y^3] \neq 0$
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Huh?
A supersymmetric Lagrangian is defined by a superpotential $W$.

- A superpotential $W$ must itself be a chiral (holomorphic) object.
- This is ensured by making it a product of chiral supermultiplets only.
- But how to find the component expression? *Tensor calculus*.
From “Superspace” to Real Space

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⇒ To make accounting easier, the superfield was invented

$$u^c_R = \tilde{u}^c_R + \theta u^c_R + \theta^2 F_u$$

$$H_u = \begin{pmatrix} h_u^+ \\ h_u^0 \end{pmatrix} + \theta \begin{pmatrix} \chi_u^+ \\ \chi_u^0 \end{pmatrix} + \theta^2 \begin{pmatrix} F_{H_u}^+ \\ F_{H_u}^0 \end{pmatrix}$$
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- Tensor calculus made simple: every term must have two thetas

$$W \ni \lambda_u Q u^c_R H_u \rightarrow \lambda_u \tilde{u}_L u^+_R \chi^0_u + \lambda_u u_L \tilde{u}^c_R \chi^0_u + \lambda_u u_L u^+_R h_0 + \lambda_u \tilde{d}_L u^+_R \chi^+_u + \cdots$$
⇒ Most general gauge-invariant, renormalizable superpotential

\[ W = W_{\text{MSSM}} + W_R \]

\[ W_{\text{MSSM}} = \lambda_u Q u_R^c H_u + \lambda_d Q d_R^c H_d + \lambda_e L e_R^c H_d + \lambda_{\nu} L \nu_R^c H_u + \mu H_u H_d \]

\[ W_R = \lambda' Q d_R^c L + \lambda'' d_R^c d_R^c u_R^c + \lambda''' L L e_R^c + \mu' L H_u \]

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The MSSM II: Superpotential

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⇒ The second set of terms are allowed, but dangerous!

- Higgs states can mix with leptons
- New contributions to FCNC’s at loop level \( \rightarrow \lambda \sim 0.05 \)
- Products of operators can allow rapid proton decay \( (\tau_p \simeq \tau_n) \)

\[ \text{e.g. } p \rightarrow \ell^+ \pi^0 \text{ via } \tilde{s}_R, \tilde{b}_R \text{ exchange } \rightarrow \lambda' \lambda'' \sim 10^{-30} \]
So we introduce \textit{R-parity}:

\[ R_p = (-1)^{3(B-L)+2s} \]

- Without \(2s\) we have “matter parity”

\[ P_M(Q, u, d, L, e) = -1 \quad P_M(H_u, H_d) = +1 \]

- With spin it instead separates SM from superpartners

\[ R_p(q, \ell; h^0_u, h^0_d; (A_\mu)_a) = +1 \quad R_p(\tilde{q}, \tilde{\ell}; \chi^+, \chi^0_u, \chi^-_d, \chi^0_d; \lambda_a) = -1 \]

⇒ Require each term in component Lagrangian have \( R_p = +1 \)
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Require each term in component Lagrangian have \(R_p = +1\)

- Immediately forbids all of \(W_R\)

- The “two superpartner” rule

- All superpartners must decay into \textit{Lightest Supersymmetric Particle} (LSP)
  - Stable
  - Neutral and weakly-interacting \(\rightarrow\) cold dark matter?
  - Signature implication: \textit{missing energy}
Feynman Diagrams with Superpartners

⇒ Example: scalar field decays

⇒ Example: Top Yukawa (superpotential) interactions
It provides a solution to the so-called “hierarchy problem”

- Consider corrections to SM $m_H^2$ via $\Delta V = -\lambda_S|H|^2|s|^2$

$$\delta m_H^2|_f = \frac{|\lambda_f|^2}{16\pi^2} \left[-2\Lambda_{UV}^2 + 6m_f^2 \ln(\lambda_{UV}/m_f)\right]$$

$$\delta m_H^2|_s = \frac{\lambda_s}{16\pi^2} \left[\Lambda_{UV}^2 - 2m_s^2 \ln(\lambda_{UV}/m_s)\right]$$

- Scalars will diverge like fermions (logarithmically) provided
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  - 2 scalars per every (Weyl) fermion
OK... So Why Supersymmetry? (I)

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$$\delta m_H^2 |_f = \frac{|\lambda_f|^2}{16\pi^2} \left[ -2\Lambda_{UV}^2 + 6m_f^2 \ln(\lambda_{UV}/m_f) \right]$$

$$\delta m_H^2 |_s = \frac{\lambda_s}{16\pi^2} \left[ \Lambda_{UV}^2 - 2m_s^2 \ln(\lambda_{UV}/m_s) \right]$$

- Scalars will diverge like fermions (logarithmically) provided

  ★ 2 scalars per every (Weyl) fermion ✓
  ★ The couplings satisfy $\lambda_S = |\lambda_F|^2$
It provides a solution to the so-called “hierarchy problem”

- Consider corrections to SM $m_H^2$ via $\Delta V = -\lambda_S |H|^2 |s|^2$

$$\delta m_H^2|_f = \frac{|\lambda_f|^2}{16\pi^2} \left[ -2\Lambda_{\text{UV}}^2 + 6m_f^2 \ln(\lambda_{\text{UV}}/m_f) \right]$$

$$\delta m_H^2|_s = \frac{\lambda_s}{16\pi^2} \left[ \Lambda_{\text{UV}}^2 - 2m_s^2 \ln(\lambda_{\text{UV}}/m_s) \right]$$

- Scalars will diverge like fermions (logarithmically) provided
  - 2 scalars per every (Weyl) fermion $\checkmark$
  - The couplings satisfy $\lambda_S = |\lambda_F|^2$ $\checkmark$
  - The scalar and fermion masses are similar

$$\delta m_H^2|_{f+s} \sim \frac{\alpha}{16\pi^2} (m_f^2 - m_s^2) \ln (\Lambda_{\text{UV}}/m)$$

- Hence the desire that $(m_f^2 - m_s^2) \lesssim 1 \text{ TeV}$
• Dark matter
  ✴ LSP is $R_p$-odd $\rightarrow$ nothing to decay into $\rightarrow$ stable!
  ✴ Interacts weakly with itself and with SM $\rightarrow$ perfect CDM candidate!

• Baryogenesis
  ✴ SM has only one (small phase); MSSM has 40 of them!
  ✴ Phase transition for EWSB strongly first-order in MSSM, but not in SM

• Gauge coupling unification
Gaugino Masses I

\[ \mathcal{L}_{\text{soft}} \ni -\frac{1}{2} M_a \lambda_a \lambda_a \]

\[ \Rightarrow \text{Gluinos} \ (M_3) \]

- Only \( s = 1/2 \), \( SU(3) \) adjoint-valued fields \( \rightarrow \) no mixing

- Adjoint irrep.’s \( \rightarrow \) self-conjugate \( \rightarrow \) “LH” and “RH” components identical
Gaugino Masses I

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- Adjoint irrep.'s → self-conjugate → “LH” and “RH” components identical

⇒ Charginos \((M_2\) and \(\mu)\)

- Four 2-component spinors: Higgsinos \((\chi_u^+, \chi_d^-)\) and W-inos \((\tilde{\lambda}_1, \tilde{\lambda}_2)\)

\[ \psi^\pm = \left( \tilde{W}^+, \chi_u^+, \tilde{W}^-, \chi_d^- \right) \]

- Charged → can be grouped into two Dirac spinors \((\tilde{C}_1, \tilde{C}_2)\)

- Mass terms in \(4 \times 4\) notation: \(\mathcal{L} \ni -\frac{1}{2} (\psi^\pm)^T M_{\tilde{C}} (\psi^\pm) + \text{c.c.} \)

\[ M_{\tilde{C}} = \begin{pmatrix} 0 & X^T \\ X & 0 \end{pmatrix} \]

\[ X = \begin{pmatrix} M_2 e^{i\varphi_2} & g_2 v_u \\ g_2 v_d & \mu e^{i\varphi_\mu} \end{pmatrix} \]
Neutralinos ($M_1$, $M_2$ and $\mu$)

- Four 2-comp. spinors: Higgsinos ($\chi_u^0$, $\chi_d^0$), W-ino $\tilde{\lambda}_3 = \tilde{W}^0$ and B-ino $\tilde{B}$
  
$$\psi^0 = \left( \tilde{B}, \tilde{W}^0, \chi_d^0, \chi_u^0 \right)$$

- Neutral → can be organized into four Majorana spinors $\tilde{N}_i$
Neutralinos \((M_1, M_2 \text{ and } \mu)\)
- Four 2-comp. spinors: Higgsinos \((\chi_u^0, \chi_d^0)\), W-ino \(\tilde{\lambda}_3 = \tilde{W}^0\) and B-ino \(\tilde{B}\)

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\]

- Neutral \(\rightarrow\) can be organized into four Majorana spinors \(\tilde{N}_i\)
- Mass terms in \(4 \times 4\) notation: \(\mathcal{L} \ni -\frac{1}{2} (\psi^0)^T M_{\tilde{N}} (\psi^0) + \text{c.c.}\)

\[
M_{\tilde{N}} = \\
\begin{pmatrix}
M_1 e^{i\varphi_1} & 0 & -g' v_d / \sqrt{2} & g' v_u / \sqrt{2} \\
0 & M_2 e^{i\varphi_2} & g' v_d / \sqrt{2} & -g' v_u / \sqrt{2} \\
-g' v_d / \sqrt{2} & g' v_d / \sqrt{2} & 0 & -\mu e^{i\varphi_\mu} \\
g' v_u / \sqrt{2} & -g' v_u / \sqrt{2} & -\mu e^{i\varphi_\mu} & 0
\end{pmatrix}
\]

- Typical eigenstates if \(M_1 \ll M_2 \ll \mu\)

\[
m_{\tilde{N}_1} \approx M_1; \quad m_{\tilde{N}_2} \approx m_{\tilde{C}_1} \approx M_2; \quad m_{\tilde{N}_3} \approx m_{\tilde{N}_4} \approx m_{\tilde{C}_1} \approx \mu \\
\tilde{N}_1 \sim \tilde{B}; \quad \tilde{N}_2 \sim \tilde{W}^0; \quad \tilde{N}_3, \tilde{N}_4 \sim \tilde{H} \\
\tilde{C}_1 \sim \tilde{W}^\pm; \tilde{C}_2 \sim \tilde{H}^\pm
\]
The $\mu$ parameter

⇒ A supersymmetric mass term

\[ W \ni \mu H_u H_d = \mu (H_u)_\alpha (H_d)_\beta \epsilon^{\alpha \beta} \]

\[ \rightarrow \mu (\chi_u^+ \chi_d^- - \chi_u^0 \chi_d^0) + |\mu|^2 (|h_u^0|^2 + |h_d^0|^2 + |h_u^+|^2 + |h_d^-|^2) \]

- Non-vanishing $\mu$ needed to give Higgsinos mass
The $\mu$ parameter

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- But if $V_H \sim m_H^2 |h|^2 + \lambda |h|^4$, need $m_H^2 < 0$ if we want $\langle h \rangle \neq 0$
\( \Rightarrow \) A supersymmetric mass term

\[
W \ni \mu H_u H_d = \mu (H_u)_\alpha (H_d)_\beta \epsilon^{\alpha \beta} \\
\Rightarrow \mu (\chi_u^+ \chi_d^- - \chi_u^0 \chi_d^0) + |\mu|^2 (|h_u^0|^2 + |h_d^0|^2 + |h_u^+|^2 + |h_d^-|^2)
\]

- Non-vanishing \( \mu \) needed to give Higgsinos mass
- But if \( V_H \sim m_H^2 |h|^2 + \lambda |h|^4 \), need \( m_H^2 < 0 \) if we want \( \langle h \rangle \neq 0 \)
- So we need \( |\mu|^2 \lesssim m_f^2 \sim (1 \text{ TeV})^2 \)

\( \Rightarrow \) But not tied to SUSY breaking, so no need to be EW scale!
⇒ Assume that only Higgs fields obtain vevs at minimum

- Minimum can always be found such that \( \langle h_u^+ \rangle = \langle h_d^- \rangle = 0 \)

- Phase rotations on remaining two Higgs states can make potential real and positive

\[
\begin{align*}
V &= \left( |\mu|^2 + m_{H_u}^2 \right) |h_u^0|^2 + \left( |\mu|^2 + m_{H_d}^2 \right) |h_d^0|^2 \\
&\quad - \left( bh_u h_d^0 + \text{c.c.} \right) + \frac{1}{8} \left( g^2 + g'^2 \right) (|h_u^0|^2 - |h_d^0|^2)^2
\end{align*}
\]
Higgs Sector I: EWSB scalar potential

⇒ Assume that only Higgs fields obtain vevs at minimum

• Minimum can always be found such that \( \langle h_u^+ \rangle = \langle h_d^- \rangle = 0 \)

• Phase rotations on remaining two Higgs states can make potential real and positive

\[
V = (|\mu|^2 + m_{H_u}^2) |h_u^0|^2 + (|\mu|^2 + m_{H_d}^2) |h_d^0|^2 - (b h_u^0 h_d^0 + \text{c.c.}) + \frac{1}{8} (g^2 + g'^2) (|h_u^0|^2 - |h_d^0|^2)^2
\]

⇒ Two minimization conditions \( \langle \partial V / \partial h_u^0, h_d^0 \rangle = 0 \)

\[
\mu^2 = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2 \beta}{\tan^2 \beta - 1} - \frac{1}{2} M_z^2; \quad 2b = (m_{H_d}^2 + m_{H_u}^2 + 2\mu^2) \sin 2\beta
\]

• Here we have introduced the parameter \( \tan \beta = v_u / v_d \)

• Note that \( v^2 = v_u^2 + v_d^2 \simeq (174 \text{ GeV})^2 \) and \( M_z^2 = \frac{v^2}{2} \left( \frac{5}{3} (g')^2 + g_2^2 \right) \)
⇒ Two doublets → 8 d.o.f. - 3 d.o.f. (eaten) = 5 Higgs eigenstates

\[ A \sim \sin \beta \text{ Im}(h^0_d) + \cos \beta \text{ Im}(h^0_u) \]
\[ H^+ \sim \cos \beta \, h^+_u + \sin \beta \, (h^-_d)^* \]
\[ \begin{pmatrix} h^0 \\ H^0 \end{pmatrix} \sim \sqrt{2} \begin{pmatrix} \cos \alpha & -\sin \alpha \\ \sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} \text{Re}[h^0_u] - v_u \\ \text{Re}[h^0_d] - v_d \end{pmatrix} \]
Higgs Sector II: Mass Eigenstates

⇒ Two doublets → 8 d.o.f. - 3 d.o.f. (eaten) = 5 Higgs eigenstates

\[ A \sim \sin \beta \text{ Im}(h_d^0) + \cos \beta \text{ Im}(h_u^0) \]
\[ H^+ \sim \cos \beta \ h_u^+ + \sin \beta \ (h_d^-)^* \]
\[ \begin{pmatrix} h^0 \\ H^0 \end{pmatrix} \sim \sqrt{2} \begin{pmatrix} \cos \alpha & -\sin \alpha \\ \sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} \text{Re}[h_u^0] - v_u \\ \text{Re}[h_d^0] - v_d \end{pmatrix} \]

⇒ Masses of these are given by
\[ m_A^2 = \frac{2b}{\sin 2\beta}; \quad m_{H^\pm}^2 = m_A^2 + m_W^2 \]
\[ m_{h^0,H^0}^2 = \frac{1}{2} \left( m_A^2 + M_Z^2 \mp \sqrt{(m_A^2 + M_Z^2)^2 - 4M_Z^2m_A^2 \cos^2 2\beta} \right) \]

⇒ Parameterizing the Higgs sector: minimization conditions allow swap of \( \mu, b \) for \( M_z, \tan \beta \)
What is a *hidden sector*?

- No tree-level (renormalizable) interaction of MSSM fields to SUSY breaking order parameters $\langle F \rangle, \langle D \rangle, \langle M \rangle$

- Thus $\langle D_Y \rangle \neq 0$ and $\langle F_{H_u,H_d} \rangle \neq 0$ can’t be dominant source of SUSY breaking
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• Instead, expect terms like $\langle F_X / M_X \rangle \lambda_a \lambda_a$ or $\langle |F_X|^2 / M_X^2 \rangle k_{i,j} (\phi^i)^* \phi^j$

• That is, SUSY breaking is spontaneous in the hidden sector, but appears explicitly in our sector
Breaking SUSY, Generally

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- Instead, expect terms like $\langle F_X/M_X \rangle \lambda_a \lambda_a$ or $\langle |F_X|^2/M_X^2 \rangle k_{ij}(\phi^i)^*\phi^j$

- That is, SUSY breaking is spontaneous in the hidden sector, but appears explicitly in our sector

Why must we break SUSY in one?

- If no hidden sector, then at least some scalars lighter than fermions!

- Spontaneous breaking in our sector can only be through $\langle D_Y, D_3 \rangle \neq 0$ and $\langle F_{H_u,H_d} \rangle \neq 0$

$$m_t^2 \sim m_t^2 \pm (aD_Y + bD_3)$$
As a result of putting SUSY breaking in a hidden sector that models are classified more by how SUSY breaking is transmitted to our sector than how it was actually broken in the first place.
Gravity Mediation

As a result of putting SUSY breaking in a hidden sector that models are classified more by how SUSY breaking is transmitted to our sector than how it was actually broken in the first place.

⇒ Sterile (gauge-singlet) chiral superfield as spurion

- Imagine soft Lagrangian given by

\[-\frac{F_G}{M_G} \sum_a \lambda_a \lambda_a - \left| \frac{F_S}{M_S} \right|^2 \sum_f k_{ij}^f (\tilde{\phi}_i^f)^* \tilde{\phi}_j^f - \frac{1}{2} \frac{F_B}{M_B} \mu H_u H_d - \frac{F_A}{M_A} \sum_{\alpha} \lambda_{ijk}^\alpha \tilde{\phi}_i \tilde{\phi}_j \tilde{\phi}_k\]

- $M_i$ are the scales of the mediation fields (what’s been integrated out)

- If we take $M_i = M_{PL}$ we have *gravity mediation*
Gravity Mediation

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⇒ Resulting soft terms

\[m_{1/2} = \frac{F_G}{M_G}, \quad m_0^2 = \left| \frac{F_S}{M_S} \right|^2, \quad a_{ijk}^{\alpha} = \lambda_{ijk}^{\alpha} \frac{F_A}{M_A}, \quad b = \mu \frac{F_B}{M_B}\]
Minimal Supergravity (mSUGRA)

Defined by parameter set: \( \{ m_{1/2}, m_0, A_0, \tan \beta, \text{sgn}(\mu) \} \)
mSUGRA Sample Spectrum A
mSUGRA Sample Spectrum B

\[ m \text{ [GeV]} \]

- \( H^0, A^0 \)
- \( H^\pm, \tilde{\ell}, \tilde{\nu} \)
- \( \tilde{\tau} \)
- \( \tilde{\ell}_2 \tilde{b}_1 \)
- \( \tilde{g} \)
- \( \tilde{\chi}_4^0, \tilde{\chi}_2^0, \tilde{\chi}_1^0, \tilde{\chi}_2^0 \)
- \( \tilde{\chi}_2^\pm, \tilde{\chi}_1^\pm \)
One can assume $1 \text{ fb}^{-1} - 10 \text{ fb}^{-1}$ per experiment to tape in first year
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- $W \rightarrow \mu\nu \sim 7 \times 10^7$ events
- $Z \rightarrow \mu\mu \sim 1.1 \times 10^7$ events
- QCD jets with $p_T > 150$ GeV $\sim 10^7$ events
- $t\bar{t} \rightarrow \mu\nu + X \sim 8 \times 10^5$ events
- $g\bar{g}$ ($m_g = 1$ TeV) $\sim 10^3 - 10^4$ events
⇒ One can assume $1 \text{ fb}^{-1} - 10 \text{ fb}^{-1}$ per experiment to tape in first year

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- $\tilde{g}\tilde{g}$ ($m_{\tilde{g}} = 1 \text{ TeV}$) $\sim 10^3 - 10^4$ events

⇒ Recorded to tape: $10^7$ events/3 days [$\sigma_{\text{SUSY}} \sim 100$ events/day ]

⇒ Total: 1Pb of data/year/experiment $\Rightarrow 10^{15}$ bytes
Overview of Classic SUSY Signatures

⇒ Break up into channels by $n$ jets + $m$ leptons + $E_T$

- 0 leptons + $\geq 2$ jets + $E_T$ ("multijet" channel)
- 1 lepton + $\geq 2$ jets + $E_T$
- 2 leptons + $E_T$
  - * Same Sign (SS) vs. Opposite Sign (OS) sub-samples
  - * Can be “clean” (no jets) or with $\geq 2$ jets
- Trilpetons, clean or $\geq 2$ jets, + $E_T$

⇒ Remember: invisible, stable LSP means **no mass peaks**!
Squark, gluino production rate $\sim$ SM jet production at similar $Q^2$

Multijet signal via quark decays

$$\tilde{g} \rightarrow q\bar{q}\tilde{N}_i^0, \quad \tilde{g} \rightarrow \tilde{t}\tilde{t}, \quad \tilde{q}_L \rightarrow q\tilde{C}_i^\pm,$$

etc. [and subsequent cascades]

The ultimate *inclusive signature*

- Just count events – does not matter what the original particles were
- Look for excess over (known) SM rate
Jets plus Missing Energy

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\]

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⇒ Kinematic variable \( M_{\text{eff}} \equiv \not{E}_T + \sum_i (p_{T}^{\text{jet}})_i \) can be useful in SUSY discovery

- Claim: peak in \( M_{\text{eff}} \) distribution proportional to \( M_{\text{SUSY}} \equiv \min(\tilde{M}_g, \tilde{M}_\tilde{q}) \)

- This channel alone can find SUSY for squarks/gluinos up to 1 TeV with 1 fb\(^{-1}\) – 2.5-3 TeV for 300 fb\(^{-1}\)
**$M_{\text{eff}}$** and Kinematic Distributions

- **SM backgrounds**
  - QCD ($gg \rightarrow gg$, etc.) with extra jets from parton showers
  - Heavy flavor production
  - $Z + \text{multijets with } Z \rightarrow \tau\tau$
    or $Z \rightarrow \nu\nu$
  - $W + \text{multijets with } W \rightarrow \tau\nu$
    or $W \rightarrow \ell\nu$

- **A typical set of cuts**
  - $E_T^{\text{jet}} \geq 100, 50, 50, 50$ GeV
  - No isolated lepton with $p_T > 20$ GeV
  - Transverse sphericity $S_T > 0.2$
  - Transverse plane angle $30^\circ < \Delta \phi(E_T,j) < 90^\circ$
  - $E_T > 0.2 \, M_{\text{eff}}$
**Multilepton Events: OS dileptons**

⇒ Multi-lepton signals are comparable in reach/discovery to multijets with $100 \text{ fb}^{-1}$ data

⇒ OS Dilepton events (inclusive)

- Many paths to this signature in SUSY: $\tilde{C}^\pm_1$ pair production, $\tilde{N}^0_2 \rightarrow \tilde{\ell}^\pm \ell^\mp \rightarrow \tilde{N}^0_1 \ell^+ \ell^-$, $\tilde{q}_L \rightarrow \tilde{N}^0_2 q \rightarrow \tilde{N}^0_1 \ell^+ \ell^- q$, etc.

- Main SM background is $t\bar{t}$ production

- Inclusive OS and *same flavor* can be a SUSY discovery mode
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- Many paths to this signature in SUSY: \(\tilde{C}_1^\pm\) pair production, 
  \(\tilde{N}_2^0 \rightarrow \tilde{\ell}^\pm \ell^\mp \rightarrow \tilde{N}_1^0 \ell^+ \ell^-\), \(\tilde{q}_L \rightarrow \tilde{N}_2^0 q \rightarrow \tilde{N}_1^0 \ell^+ \ell^- q\), etc.

- Main SM background is \(t\bar{t}\) production

- Inclusive OS and same flavor can be a SUSY discovery mode

⇒ Reduction of SM background (for clean OS dileptons)

- Use \(e^+e^- + \mu^+\mu^- + e^\pm\mu^\mp\) sample to reduce \(t\bar{t}\)

- Veto \(Z \rightarrow \ell\ell\) via invariant mass cut \(M_{\ell\ell} \neq M_Z \pm 10\) GeV

- Off shell \(\gamma\) and \(Z\) decays to taus reduced by \(\Delta\phi(\ell\ell) \leq 150^\circ\)

⇒ Remaining background includes Drell-Yan \(\ell\ell\) production and \(W^+W^-\) production
Multilepton Events: OS dileptons

![Graphs showing the distribution of events for SUSY, \( \bar{t} \bar{t} \), and \( Z + \text{jet} \) for two different mass distributions.](image)

- **Left Graph**: Events / 3 GeV vs. \( M(e^+e^-) + M(\mu^+\mu^-) \) (GeV)
- **Right Graph**: Events / 2 GeV vs. \( M(e^+e^-) + M(\mu^+\mu^-) \) (GeV)

Key:
- SUSY (White)
- \( \bar{t} \bar{t} \) (Gray)
- \( Z + \text{jet} \) (Light Gray)
SS dilepton events often said to be “truly SUSY” signature

- SS usually seen as gluino-driven; result of Majorana nature

\[ \tilde{g} \rightarrow q\tilde{q} \rightarrow qq'\tilde{C}_1^\pm \rightarrow qq'W^\pm\tilde{N}_1^0 \]

- Signature is $E_T$ + jets + pair of same-sign dileptons
- SM background very low and easy to control for...
Multilepton Events: SS Dileptons & Trileptons

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⇒ “Clean” Trilepton Events: the Gold-Plated Signature

• Lack of jets tends to mean chargino/neutralino production

\[ pp \rightarrow \tilde{C}^\pm_1\tilde{N}^0_2 \rightarrow \tilde{N}^0_1\ell\ell \quad \tilde{N}^0_1\ell\nu \]

• Separation of production mechanism (i.e. isolation of $\tilde{C}^\pm_1\tilde{N}^0_2$ sample) seems possible with cuts

• Various kinematic distributions can be formed $m_{\ell_i\ell_j}$
Information from Lepton Distributions

⇒ Endpoint of effective mass distribution of the two leptons carries information.....but on what?

$$\tilde{N}_2^0 \rightarrow \tilde{N}_1^0 \ell^+ \ell^- \text{ then } M_{\ell\ell}^{\text{max}} = M_{\tilde{N}_2^0} - M_{\tilde{N}_1^0}$$

$$\tilde{N}_2^0 \rightarrow \tilde{\ell}^\pm \ell^\mp \rightarrow \tilde{N}_1^0 \ell^+ \ell^- \text{ then } M_{\ell\ell}^{\text{max}} = \frac{1}{M_\ell} \sqrt{(M_{\tilde{N}_2^0}^2 - M_{\ell}^2)(M_{\tilde{N}_2^0}^2 - M_{\ell}^2)}$$

⇒ Shape of distribution is supposed to tell them apart
Some Words of Caution

Rule of thumb: SUSY “discovery” can be done with **inclusive**, model-independent observations – parameter extraction requires **exclusive**, model-dependent techniques

⇒ *The background to SUSY is more SUSY!*
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Lots of distribution features will be extracted...to what end?

- Example: trilepton + 2 jets allows all sorts of pairings. Do they have information content if you don’t know the spectrum? Can you separate chargino/neutralino sources from squark gluino sources?

- Example: SS dileptons can come from gluinos, but also from

\[
pp \rightarrow \tilde{b}_L \tilde{b}_L X \rightarrow t\tilde{C}^-_1 t\tilde{C}^+_1 X
\]

Endpoint value measures something different here!

⇒ Need to use strict cuts to separate multiple channels leading to same inclusive topology... *reduction in signal and significance*
Concluding Thoughts

⇒ We are passing from theory-rich era of SUSY to data-rich era!
⇒ Analysis Approach and Synthesis Approach will likely both be needed
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• Synthesis direction
  ★ Enlarge the set of inclusive signatures
  ★ Improve SM baseline determination
  ★ Study ability to separate regions with a model's parameter space – and models from one another

• Analysis direction
  ★ Enlarge toolbox using non-SUGRA cases
  ★ Robustness analysis: from points to lines to footprints
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  - Enlarge toolbox using non-SUGRA cases
  - Robustness analysis: from points to lines to footprints

⇒ Towards a decision tree style strategy

1. Organize analysis tools by needed inputs/model dependence
2. Use least dependent tools with global fits to paradigms
3. Cross check promising paradigms against other analysis measurements
4. Organize flow chart as function of integrated luminosity
Supporting Slides
Examples of exclusive analysis: separating contributions to $M_{\text{eff}}$ and $m_{\ell\ell}$

In multijet channel, how do you know what fraction of the sample is from production of gluino pairs and what fraction from squark pairs?
Some Words of Caution: II

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In multijet channel, how do you know what fraction of the sample is from production of gluino pairs and what fraction from squark pairs?

- Jet multiplicity: assume for first/second generation squarks “R” and “L” produced more or less equally
- BR($\tilde{q}_R \rightarrow q\tilde{N}_1^0$) nearly 100% → one jet per decay
- $\tilde{q}_L$ and $\tilde{g}$ have different decays such as $\tilde{g} \rightarrow q\bar{q}\tilde{C}_i^\pm$ and $\tilde{g} \rightarrow q\bar{q}\tilde{N}_i^\pm$ → usually more jets per decay

In SS dilepton + jets sample, how do you separate gluino from squark contributions?
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In SS dilepton + jets sample, how do you separate gluino from squark contributions?

- Charge asymmetry: initial state at LHC is $pp$
- Cascade decays from $\tilde{g}\tilde{q}$ and $\tilde{q}\tilde{q}$ events leads to a larger cross section for positive SS pairs than for negative ones
- This asymmetry is sensitive to $m_{\tilde{g}}/m_{\tilde{q}}$
Some Words of Caution: III

⇒ Many such algorithms known, but all are devised within limited model regimes (all mSUGRA)

- $\text{BR}(\tilde{q}_R \rightarrow q \tilde{N}^0_1)$ nearly 100% artifact of LSP being 99% B-ino
- Obtaining $m_{\tilde{g}}/m_{\tilde{q}}$ from charge asymmetry in SS dileptons really requires outside knowledge of $m_{\tilde{g}}$ to work well
- Gluino mass measurement algorithm based on mSUGRA point where $m^2_{\tilde{\ell}_R} \simeq M_{\tilde{N}^0_2}M_{\tilde{N}^0_1}$ – by no means a general result
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⇒ Even once exclusive samples are prepared, information from distributions may be misleading because of phases

● Can shift peak of $M_{\text{eff}}$ distributions by significant amount

● Can change the shape of kinematic distributions and location of endpoint

● Can effect cross-sections for gaugino production [clean trilepton signal] by 30-40%

● Relation between mass eigenstates and soft Lagrangian parameters becomes more complicated