Supersymmetry Searches at the Tevatron

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for the CDF and DØ Collaborations

Hadron Collider Physics Symposium
May 29, 2008
Outline

• SUSY Overview
• “Natural” SUSY
  ➢ squarks and gluinos
    ▪ stop and sbottom
  ➢ charginos and neutralinos
• “Unnatural” SUSY
  ➢ RPV SUSY
  ➢ long-lived SUSY

symmetry = beauty
SUSY for Experimenters

Fermions ⇔ Bosons

Broken symmetry ⇒ hidden symmetry

SUSY masses must be large not to be observed so far

- Solves many questions about Standard Model
  ➢ Introduces some questions of its own

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“Natural” SUSY

• R-parity is conserved

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

- R= +1 normal particles
- R= −1 supersymmetric particles

• Lightest supersymmetric particle (LSP) is stable
  - all other SUSY particles cascade decay to it and non-SUSY particles

• Provides excellent dark matter candidate
  - if cosmological constraints are obeyed
**mSUGRA**
(minimal SUperGravity)

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

**GMSB**
(gauge mediated SUSY breaking)

graviton is LSP

**AMSB**
(anomaly mediated SUSY breaking)

**MSSM**
(minimal SUSY standard model)
Squarks and Gluinos

Strong production → large cross section

$M(q) \ll M(g)$
2 or more jets

$M(q) \approx M(g)$
3 or more jets

$M(q) \gg M(g)$
4 or more jets
Squarks and Gluinos

Distinguish from QCD

2.0 fb⁻¹

Optimize for multiple SUSY points

No data excess observed

2.1 fb⁻¹
Mass Limits

$\mathbf{M > 392 \text{ GeV}}$  \  [M(\tilde{q})=M(\tilde{g})]

$\mathbf{M(\tilde{g}) > 280 \text{ GeV}}$

$\mathbf{M(\tilde{q}) > 392 \text{ GeV}}$

$\mathbf{M(\tilde{g}) > 327 \text{ GeV}}$

PLB 660, 449 (2008)

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...and sbottom
Stop Searches

- Pair production through strong processes
- Numerous search channels
- Depend on dominant decay mode

- dileptons: $e^+ e^-$, $e^+ \mu^-$, $\mu^+ \mu^-$
  +2b+MET

- heavy flavor+MET:
  - $b\bar{b}$+MET
  - $c\bar{c}$+MET

- stable, charged particles
Stop in $e\mu+2b+\text{MET}$

- decay mode stop $\rightarrow b\ell\tilde{\chi}_1^0$
- sneutrino is LSP
- use $e\mu$ channel
  - highest dilepton branching fraction
  - low backgrounds

<table>
<thead>
<tr>
<th>$\Sigma p_T$ (jets) (GeV)</th>
<th>$p_T(\mu) + p_T(e) + \text{MET}$ (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0-70</td>
</tr>
<tr>
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<td>Data</td>
</tr>
<tr>
<td>0-15</td>
<td>1</td>
</tr>
<tr>
<td>15-60</td>
<td>1</td>
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<tr>
<td>60-120</td>
<td>0</td>
</tr>
<tr>
<td>$&gt;120$</td>
<td>0</td>
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</table>
Stop $\rightarrow b\ell\tilde{\chi}_1^0$

- stop mass = 135-155 GeV
- several chargino/neutralino mass points

neutralino is LSP

<table>
<thead>
<tr>
<th></th>
<th>Background</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>ee</td>
<td>10.62±1.49</td>
<td>10</td>
</tr>
<tr>
<td>$\mu\mu$</td>
<td>9.46±1.27</td>
<td>11</td>
</tr>
<tr>
<td>$e\mu$</td>
<td>22.46±2.88</td>
<td>24</td>
</tr>
<tr>
<td>$ll$</td>
<td>42.53±5.56</td>
<td>45</td>
</tr>
</tbody>
</table>

no evidence of stop signal
Stop and Sbottom in cc(bb)+MET

- Pair production of stop or sbottom
  
  \[
  \text{stop} \rightarrow c + \tilde{\chi}_1^0 \quad \text{sbottom} \rightarrow b + \tilde{\chi}_1^0
  \]

- Signature
  
  - two energetic jets + MET
  - one heavy flavor tagged jet

- Optimize selection for each channel in three mass regions

<table>
<thead>
<tr>
<th></th>
<th>stop</th>
<th>bkgd</th>
<th>data</th>
<th>sbottom</th>
<th>bkgd</th>
<th>data</th>
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<tbody>
<tr>
<td></td>
<td>&lt;100</td>
<td>100-120</td>
<td>&gt;120</td>
<td>&lt;140</td>
<td>140-180</td>
<td>&gt;180</td>
</tr>
<tr>
<td>bkgd</td>
<td>137±6.2±14.6</td>
<td>94.9±5.0±9.9</td>
<td>42.7±2.6±4.6</td>
<td>55.0±4.2±5.9</td>
<td>17.8±1.7±1.6</td>
<td>4.7±2.1±0.5</td>
</tr>
<tr>
<td>data</td>
<td>151</td>
<td>108</td>
<td>43</td>
<td>60</td>
<td>18</td>
<td>3</td>
</tr>
</tbody>
</table>

PRD 76, 072010 (2007)

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Stop in $\text{cc+MET}$

- decay mode $\text{stop} \rightarrow c + \tilde{\chi}_1^0$
  - $m_t < m_b + m_{\tilde{\chi}_1^+}$
  - $m_t < m_W + m_b + m_{\tilde{\chi}_1^0}$
- search for acoplanar charm jets

<table>
<thead>
<tr>
<th>stop mass</th>
<th>background</th>
<th>data</th>
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<tbody>
<tr>
<td>95-130 GeV</td>
<td>85.3±1.8</td>
<td>83</td>
</tr>
<tr>
<td>135-145 GeV</td>
<td>59.0±1.6</td>
<td>57</td>
</tr>
<tr>
<td>150-160 GeV</td>
<td>66.6±1.1</td>
<td>66</td>
</tr>
</tbody>
</table>

arXiv:0803.2263

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Sbottom in Gluino Production

- Pair production of gluinos
- Gluino decays to sbottom+bottom
- Sbottom decays to bottom+neutralino

- Search for events with multiple jets (at least one b-tagged) and MET
- Two regions of $\Delta m = M(\tilde{g}) - M(\tilde{b})$

<table>
<thead>
<tr>
<th></th>
<th>Large $\Delta m$</th>
<th>Small $\Delta m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background</td>
<td>22.7 ± 4.6</td>
<td>22.0 ± 3.6</td>
</tr>
<tr>
<td>Data</td>
<td>25</td>
<td>19</td>
</tr>
</tbody>
</table>
**Associated Production of Charginos and Neutralinos**

- **Excellent SUSY signature** ("golden channel")
  - three leptons in final state
    - trileptons
  - very small backgrounds
Trilepton Analyses

- Three search techniques
  - 3 identified leptons (l=e or $\mu$)
  - 2 leptons + isolated track
  - two same sign leptons
- Allows for some additional acceptance
  - taus and low $p_T$ leptons

### CDF

<table>
<thead>
<tr>
<th>CDF</th>
<th>Background</th>
<th>Data</th>
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<tbody>
<tr>
<td>3 tight</td>
<td>0.49±0.04±0.08</td>
<td>1</td>
</tr>
<tr>
<td>2 tight, 1 loose</td>
<td>0.25±0.03±0.03</td>
<td>0</td>
</tr>
<tr>
<td>1 tight, 2 loose</td>
<td>0.14±0.02±0.02</td>
<td>0</td>
</tr>
<tr>
<td>Total trilepton</td>
<td>0.88±0.05±0.13</td>
<td>1</td>
</tr>
<tr>
<td>2 tight, 1 track</td>
<td>3.22±0.48±0.53</td>
<td>4</td>
</tr>
<tr>
<td>1 tight, 1 loose, 1 trk</td>
<td>2.28±0.47±0.42</td>
<td>2</td>
</tr>
<tr>
<td>Total dilepton+track</td>
<td>5.5±0.7±0.9</td>
<td></td>
</tr>
</tbody>
</table>

### DØ

<table>
<thead>
<tr>
<th>DØ</th>
<th>Background</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ee\ell$</td>
<td>1.8±0.8</td>
<td>0</td>
</tr>
<tr>
<td>$\mu\mu\ell$</td>
<td>0.3±1.3-0.3</td>
<td>2</td>
</tr>
<tr>
<td>$e\mu\ell$</td>
<td>0.9±0.4</td>
<td>0</td>
</tr>
<tr>
<td>$\mu^+\mu^+$</td>
<td>1.1±0.4</td>
<td>1</td>
</tr>
</tbody>
</table>

$l$ = lepton or track
M(\tilde{\chi}_1^\pm) > 140 \text{ GeV} \\
\text{mSUGRA} \\
M(\tilde{\chi}_1^\pm) > 145 \text{ GeV} \\
\text{mSUGRA, no slepton mixing}
GMSB in Di-photons

- LSP: gravitino  NLSP: neutralino
- $p\bar{p} \rightarrow \tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 + X \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0 + Y \rightarrow \gamma\tilde{G}\gamma\tilde{G} + Y$
- signature: two photons and MET

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GMSB in Di-photons

\[ M(\tilde{\chi}_1^0) > 125 \text{ GeV} \]
\[ M(\tilde{\chi}_1^\pm) > 229 \text{ GeV} \]

1.1 fb\(^{-1}\)

Previous CDF and DØ combination:
\[ M(\tilde{\chi}_1^0) > 114 \text{ GeV} \]
\[ M(\tilde{\chi}_1^\pm) > 209 \text{ GeV} \]

CDF has analyzed this channel in 2 fb\(^{-1}\)
and is working on a GMSB interpretation

PLB 659, 856 (2008)
“Unnatural” SUSY

No dark matter candidate
or
addition to basic SUSY
“Unnatural” SUSY

• **RPV SUSY**

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

\[ W_{\text{RPV}} = \frac{1}{2} \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \lambda''_{ijk} U_i \bar{D}_j \bar{D}_k \]

- \( \Delta L = 1 \): Lepton number violation
- Gauge symmetry: \( \lambda_{ijk} = -\lambda_{ijk} \)
- \( 9 \) \( \lambda \) couplings
- can create small BR or long lifetimes

• **Long-lived particles**

- suppressed decays (couplings or mass splittings)

• **Different signature** → may miss → dedicated searches
RPV Sneutrinos

- single sneutrino production
- RPV for production and decay
  - different couplings $\lambda'_{311}$ and $\lambda_{132}$
- search for $e\mu$ resonance

Data 68
Bkgd 59.2 ± 5.3

arXiv:0711.3207
Long-lived Stop

• SUSY
  ➢ long-lived stop – escapes detector before decay
• CHAMPS – charged, massive, stable particles
• Signature: slow-moving, muon-like particle
  ➢ measure mass
  ➢ time of flight \rightarrow \text{velocity} + \text{momentum} \rightarrow \text{mass}
• No standard model background
  ➢ use data to estimate background in signal region
• \(m(\text{stop}) > 250 \text{ GeV}\)
Long-lived Neutralinos

- **GMSB SUSY**
  - $\tilde{\chi}_1^0 \rightarrow \tilde{G} \gamma$ (same as diphoton)
  - $\tilde{\chi}_1^0$ is long-lived
  - if heavy $\rightarrow$ slow moving

- Search for $\gamma$+jets+MET events
- Measure arrival time of photon
  - optimize for $\tau = 5$ ns

**Data**

<table>
<thead>
<tr>
<th>Data</th>
<th>Bkgnd</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma + E_T + 1$ jet analysis with EMTiming (570 pb$^{-1}$)</td>
<td></td>
</tr>
<tr>
<td>Predicted exclusion region</td>
<td></td>
</tr>
<tr>
<td>Observed exclusion region</td>
<td></td>
</tr>
<tr>
<td>ALEPH exclusion upper limit</td>
<td></td>
</tr>
</tbody>
</table>

$\chi^0_1$ lifetime (ns)

- $\chi^0_1$ mass (GeV/c$^2$)

- PRL 99, 121801 (2007)

- $2 \pm 1.25$ ± 0.66

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Other SUSY Searches

- Numerous BSM Higgs searches
- $B_s$ and $B_d$ into $\mu\mu$
- Squarks in jets+tau+MET
- Stop in $b$+tau
- Stopped gluinos
- Long-lived neutralinos decaying to dimuons
- 2$^{nd}$ generation slepton resonances
- RPV SUSY in trileptons
- Long-lived charginos and staus

And earlier versions of many analyses presented here
Conclusions

• We have extended the excluded SUSY space to new limits
• More data available/coming
• Well-understood detectors
• New possibilities still under exploration

http://www-cdf.fnal.gov/physics/exotic/exotic.html
http://www-d0.fnal.gov/Run2Physics/WWW/results(np).htm