Searches for Supersymmetry at the Tevatron

Rencontres de Moriond, QCD
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On behalf of the CDF and DØ Collaborations
Outline

• Brief introduction to SUSY
• SUSY searches at Tevatron
• Some selected analyses in final states:
  • Multi-lepton
  • Jets and Missing Transverse Energy
  • Photons
  • Long-lived
• Summary
Supersymmetry

• A popular extension to the SM
  • Unifies gauge couplings (if $M_{SUSY} < \text{few TeV}$)
  • Incorporate gravity
  • Solve the “fine-tuning” problem (if $M_{SUSY} < \text{few TeV}$)
  • Provide a Dark Matter candidate

• Postulate symmetry between boson and fermion particles
  • Every SM particle has a SUSY partner with same quantum numbers except spin (differ by 1/2)
    
    \[
    e, \nu, u, d, \ldots \text{(spin 1/2)} \Rightarrow \tilde{e}, \tilde{\nu}, \tilde{u}, \tilde{d}, \ldots \text{(spin 0)}
    \]
    
    \[
    \gamma, W^{\pm}, Z^0, g, \ldots \text{(spin 1)} \Rightarrow \tilde{\chi}^0_{1,2,3,4}, \tilde{\chi}^\pm_{1,2}, \tilde{g} \text{ (spin 1/2)}
    \]

• New quantum number: $R$-parity = $(-1)^{3B+L+2S}$
  • Particles: $R=1$, SParticles: $R=-1$
Phenomenology of SUSY

R-parity is conserved:
- SUSY particles are pair produced
- Lightest SUSY Particle (LSP) stable
  - If neutral ⇒
    - escape detection ⇒ Missing Energy (MET) signature!
    - candidate for Cold Dark Matter!
- SUSY is broken ($M_{\text{SUSY}} > M_{\text{SM}}$)
- Some SUSY breaking models

\textbf{mSUGRA}
- SUSY mediated by gravity
- LSP most likely is: $\tilde{\chi}_1^0$
- $M_{\tilde{\chi}_1^\pm} \approx M_{\tilde{\chi}_2^0} \approx 2M_{\tilde{\chi}_1^0}$

\textbf{GMSB}
- SUSY mediated by gauge fields
- LSP: $\tilde{G}$
- Phenomenology mostly determined by the NLSP (slepton or neutralino)

R-parity not conserved:
- SUSY particle can be singly produced
- LSP decays to SM particles, no dark matter candidate
- Process would violate either lepton or baryon quantum numbers
SUSY at the Tevatron

- Predicted rates for SUSY are LOW !!!
- Need to look for distinctive signature to distinguish from SM background

- Present results using data samples: 300 pb\(^{-1}\) to 1 fb\(^{-1}\)
Searches for Chargino/Neutralino in MET+Leptons

- Pair production of chargino/neutralino can produce **multi-lepton and MET in final state** (R-parity conservation)

⇒ Very clean, “Gold Plated” signature, but:
  - Low cross section (x BR)
  - Soft lepton

⇒ Need large integrated luminosity

⇒ Combine various final states

**General search strategy (CDF and DØ):**

- Two isolated leptons (e or $\mu$)
- Additional isolated lepton or track (for Tri-lepton ch.)
- Require some MET
- Veto events where $M_{l+l-}$ in J/$\psi$, $\gamma$, Z peaks

**Main Background:**

- DY, Di-bosons, jets faking leptons, conversions
Searches for Chargino/Neutralino in MET+Leptons

Pre-selection (req. 2 leptons)

After almost all selections

**ee+1**

**eμ+1**
Searches for Chargino/Neutralino in MET+Leptons

<table>
<thead>
<tr>
<th>CDF</th>
<th>$L$ (fb$^{-1}$)</th>
<th>#Predicted Bkg</th>
<th>#Obs. Data</th>
<th>DØ</th>
<th>$L$ (fb$^{-1}$)</th>
<th>#Predicted Bkg</th>
<th>#Obs. Data</th>
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</thead>
<tbody>
<tr>
<td>ee+l (lowpt)</td>
<td>1</td>
<td>0.97±0.28</td>
<td>3</td>
<td>ee+l</td>
<td>1.1</td>
<td>0.76±0.67</td>
<td>0</td>
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<tr>
<td>$\mu\mu+l$ (low pt)</td>
<td>1</td>
<td>0.40±0.12</td>
<td>1</td>
<td>$\mu\mu+l$</td>
<td>1.1</td>
<td>0.32$^{+0.73}_{-0.03}$</td>
<td>2</td>
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<tr>
<td>ell</td>
<td>1</td>
<td>0.75±0.36</td>
<td>0</td>
<td>$e\mu+l$</td>
<td>1.1</td>
<td>0.94$^{+0.40}_{-0.13}$</td>
<td>0</td>
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<tr>
<td>$\mu ll$</td>
<td>0.75</td>
<td>1.26±0.27</td>
<td>1</td>
<td>$\mu\mu$</td>
<td>0.9</td>
<td>1.1±0.4</td>
<td>1</td>
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<tr>
<td>$e^\pm e^\pm, e^\pm \mu^\pm, \mu^\pm \mu^\pm$</td>
<td>1</td>
<td>7.8±1.1</td>
<td>13</td>
<td></td>
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</tr>
</tbody>
</table>

#SUSY signal (per ch) ~ 0.2 – 4 events

Same-sign di-electron

4-5 interactions, electrons from same vertex

$E_T$ (96GeV) e$^+$ (41GeV) e$^+$ (73GeV)
**Searches for Chargino/Neutralino in MET+Leptons**

- Results of various channels are combined
- Present limits in general scenario: mSUGRA like, low tan$\beta$, no slepton mixing

- Obs. limit: $M_{\tilde{\chi}_1^\pm} < 130$ GeV/$c^2$
- Exp. limit: $M_{\tilde{\chi}_1^\pm} < 160$ GeV/$c^2$
- 3l-max ($\mathbf{M}_l \gtrsim M_{\tilde{\chi}_2^0}$, lep. decay max. enhanced)
  - Obs. limit: $M_{\tilde{\chi}_1^\pm} < 141$ GeV/$c^2$
- Exceed LEP’s limit in these scenarios

Slightly different scenarios
Searches for Squarks/Gluinos in MET+Jets

- $\tilde{q}, \tilde{g}$ can be pair produced at Tevatron
- Decays of $\tilde{q}, \tilde{g}$ may produce multiple jets and large MET (Rp conservation)

Main Background:
- QCD multi-jet (fake large MET)
- $Z(\rightarrow \nu\nu)+$jets (irreducible)
- $W(\rightarrow l\nu)+$jets (missed lepton)
- Diboson, ttbar
Searches for Squarks/Gluinos in MET+Jets

- DØ performs separate analyses for each final states (≥2,3,4 jets+MET), to obtain best optimized signal to background separation

- Main selection cuts:
  - Multi-jets + MET
  - Separation of MET direction and jets
  - Lepton veto
  - Large $H_T$ + large MET

<table>
<thead>
<tr>
<th># jets</th>
<th># obs</th>
<th># expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-jets</td>
<td>5</td>
<td>7.5±1.7 -1.5</td>
</tr>
<tr>
<td>3-jets</td>
<td>6</td>
<td>6.1±1.3 -1.2</td>
</tr>
<tr>
<td>4-jets</td>
<td>34</td>
<td>33.4±5.6 -5.0</td>
</tr>
</tbody>
</table>

$L=0.96$ fb$^{-1}$
Searches for Squarks/Gluinos in MET+Jets

- Determine limits in mSUGRA framework
- Red curve: new 95% CL exclusion
- Yellow band: effect from theory cross section uncertainties

\[ M(\tilde{g}) > 309 \text{ GeV}; \ M(\tilde{q}) > 391 \text{ GeV} \]
\[ M(\tilde{g}) > 402 \text{ GeV} \text{ (when } M(\tilde{g}) \sim M(\tilde{q})) \]

- This analysis also constrain the mSUGRA parameters (\(m_0\): universal scalar mass, \(m_{1/2}\): universal gaugino mass)
- Extend limits beyond LEP
- CDF 1fb\(^{-1}\) results coming soon
Search for Third Generation Squarks

- Large mixing between the L- and R-handed weak eigenstates
  - Stop: due to large top quark mass
  - Sbottom: large mixing occurs at high tanβ
  - \( \Rightarrow \) one of the stop and sbottom quarks can be light

Search for Stop/Sbottom Quarks in MET+Jets

- CDF, DØ searched for stop/sbottom quark pair production
- Assume: \( \text{BR}(\tilde{t}_1 \rightarrow c\tilde{\chi}_1^0) = 100\% \)
  \( \text{BR}(\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0) = 100\% \)

**Main Selection:**
- 2,3 jets, with \( \geq 1 \) jet tagged as c/b-jet
- Large MET (>\~50 GeV)
- Separation of MET direction and jets
- Lepton veto

**Main Background**
- \( Z(\rightarrow\nu\nu)+\text{jets}, W(\rightarrow l\nu)+\text{jets} \)
- Di-boson, ttbar
- QCD multi-jet
Search for Stop Quark

Good agreement between Data and SM prediction (after all selection cuts)

Both CDF and DØ exclude $M(\tilde{t}_1) \leq 140$ GeV, for $M(\tilde{\chi}_1^0) = 55$ GeV at 95% CL
• MET distr. after pre-selection cuts

• Data well described by expected SM contributions (low MET dominated by QCD, not simulated)

• After applying all cuts and b-tagging, found no excess in Data above SM prediction

**Exclusion (@ 95% CL):**

DØ : $M(\tilde{b}_1) < 222$ GeV

CDF : $M(\tilde{b}_1) < 195$ GeV
A Sbottom Candidate Event in CDF

Two b-tagged jets

Jet$_1$ $E_T$ = 100.3 GeV
Jet$_2$ $E_T$ = 54.7 GeV

$m_{jj}$ = 82 GeV

Could be ZZ?
Search for SUSY in Delayed Photon Signature

- CDF search for heavy long lived particle decaying (inside detector) into $\gamma$
- Focus on GMSB model where lifetime of $\tilde{\chi}_1^0$ (NLSP) is free parameter

- In GMSB, gravitino $\tilde{G}$ is LSP (escape undetected)
- If $\tilde{\chi}_1^0$ is NLSP, then $\tilde{\chi}_1^0 \rightarrow \gamma + \tilde{G}$
- Final state consists of $\gamma$+Missing $E_T$+X in SUSY production under GMSB

Select events with $\gamma$+MET+jet signature:
- $E_t(\gamma) > 30$ GeV
- $E_t(\text{jet}) > 35$ GeV
- $\text{MET} > 40$ GeV

- Arrival time of $\gamma$ is measured by the timing system of the EM calorimeter

- $\tilde{\chi}_1^0$ is long lived and decays into $\gamma$ and $\tilde{G}$
- $\gamma$ from $\tilde{\chi}_1^0$ decay will arrive at face of detector with time delayed relative to promptly produced $\gamma$
Search for SUSY in Delayed Photon Signature

- $\gamma$ time corrected for TOF assuming coming from interaction point
- Signal window 2-10 ns
- Predict 1.3±0.7 BG events
- Observe 2 events
- Set exclusion in $M(\tilde{\chi}_1^0)$ and $\tilde{\chi}_1^0$ lifetime plane
Search for CHArge Massive Particles (CHAMPs)

- Search for long lived particles:
  - massive, carry charge
  - decay outside detector
- CHAMPs particles: Slow moving, very penetrating (“slow muon”)
- Look for “muon” like particle penetrate through calorimeter to the muon chambers
- Time-of-Flight (TOF) detector to measure $\beta$
- Track momentum and $\beta$ to calculate mass

**Main background:**
- Cosmic
- Instrumental effect:
  - Mis-measurement:
    - Interaction time and arrival time at TOF
  - Track momentum

**Limit:**
- Interpret results in SUSY model w/ one compactified Extra Dimension (R. Barbieri, L.J. Hall, and Y. Nomura, PRD 63, 105007 (2001))
  - LSP: stop quark
- Exclude stable stop quark $M($stop$)<250$ GeV
- No excess in data at high mass
  - $N_{obs}=4$
  - $N_{expect}=4.7\pm0.3$ (mass $>80$ GeV)

No excess in data at high mass:
- $N_{obs}=4$
- $N_{expect}=4.7\pm0.3$ (mass $>80$ GeV)
**CHArge Massive Particles (CHAMPs)**

- Search pair production of Charged Massive stable particles that are slow moving
- Select 2 $\mu$-like high-\(P_T\) candidates
  - Slow: \(S_\beta = \frac{1 - \beta}{\sigma_\beta}\) is large
  - Large di-muon mass
- Est. background from data

Limits:

<table>
<thead>
<tr>
<th>#Exp.</th>
<th>#Obs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.66±0.06</td>
<td>0</td>
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</tbody>
</table>

**GMSB model:**

- Assume CHAMPs = $\tilde{\tau}$ (NLSP)
- Upper limit s : 0.06 pb to 0.62 pb

**Stable Chargino model (small $\Delta M(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$):**

- Assume CHAMPs = $\tilde{\chi}_1^\pm$ (gaugino-like)
- $M(\tilde{\chi}_1^\pm) > 174$ GeV
Summary

• SUSY is a promising venue for New Physics

• CDF and DØ are mounting extensive program to search for it and other physics Beyond the Standard Model

• Just finished analysing 1 fb⁻¹ data, and still have much more in the bag

• New Physics/SUSY may be just hiding in the shadow now … can be observed with brighter “light” !!!

http://www-cdf.fnal.gov/physics/exotic/exotic.html
http://www-d0.fnal.gov/Run2Physics/WWW/results,np.html
Tevatron

\[ \sqrt{s} = 1.96 \text{ TeV} \]
The Tevatron Experiments

Multipurpose detectors:

• Electron, muon, tau identification
• Jet and missing energy measurement

Heavy-flavor tagging through displaced vertices and soft leptons

CDF

DØ
• Tevatron delivered total integrated lumi ~ 2.5 fb$^{-1}$
• CDF/DØ collected ~ 2 fb$^{-1}$ data
Search for SUSY in MET+Di-Photon

• In GMSB, gravitino $\tilde{G}$ is the LSP (escape undetected)

• If $\tilde{\chi}_1^0$ is NLSP, then $\tilde{\chi}_1^0 \rightarrow \gamma + \tilde{G}$

⇒ Thus in SUSY production under GMSB, final state will consist of $\gamma\gamma + \text{Missing } E_T + X$

• DØ searched for GMSB SUSY in $\gamma\gamma + \text{Missing } E_T$ signature

  • 2 photons, $E_T > 25$ GeV
  
  • Missing $E_T > 45$ GeV

\[ 1 \pm 0.7 \] GeV

\[ M(\tilde{\chi}_1^\pm) > 220 \text{ GeV} \]
Non-Collision MET Background

Missed $E_T$

Experimental challenge
Search for SUSY in MET+Di-Photon

- In GMSB, gravitino $\tilde{G}$ is the LSP (escape undetected)
- If $\tilde{\chi}_1^0$ is NLSP, then $\tilde{\chi}_1^0 \rightarrow \gamma + \tilde{G}$

$\Rightarrow$ Thus in SUSY production under GMSB, final state will consist of $\gamma\gamma + \text{Missing Et} + X$

- CDF search for New Physics in $\gamma\gamma + \text{Missing Et}$ signature
- Signature base search, not optimized for any particular model
- Require 2 central photons with $E_T > 13 \text{ GeV}$
- Observe no excess at high MET
- DØ previous search (760 pb$^{-1}$) observe no excess, set limit $M(\tilde{\chi}_1^\pm) > 220 \text{ GeV}$