SUSY searches @ the TeVatron

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For the CDF and DØ collaborations

Overview

• Introduction
• charginos/neutralinos
• stop
• RPV
• GMSB
• CHAMPS
More than 5 fb$^{-1}$ (data collection efficiency is about 90%).
In this talk, analysis use 1 to 3 fb$^{-1}$

Best peak lumi: 350e30 cm$^{-2}$s$^{-1}$
• Standard Model very successful but not complete. Supersymmetry (SUSY) is a very popular extension:

✓ extension of Poincare group: fermions ↔ bosons
✓ solves the hierarchy problem
✓ Unification of the gauge couplings
✓ Lightest SUSY Particle
    (possible Dark matter candidate)
✓ ....

• On the other hand:
✓ full set of new particles ("s"-particles)
✓ broken symmetry
✓ sparticles masses must not be too high: TeV scale

\[ \Delta M_H^2 = \frac{\lambda_f^2}{8\pi^2} \times (m_f^2 - m_S^2) \log \left( \frac{\Lambda}{m_S} \right) + ... \]
MSSM features

- Minimal Susy Standard Model sparticles spectrum

<table>
<thead>
<tr>
<th>Names</th>
<th>spin</th>
<th>$R_P$</th>
<th>Gauge eigenstates</th>
<th>Mass eigenstates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Higgs bosons</td>
<td>0</td>
<td>+1</td>
<td>$H^0_u \ H^0_d \ H^+_u \ H^-_d$</td>
<td>$h^0 \ H^0 \ A^0 \ H^\pm$</td>
</tr>
<tr>
<td>squarks</td>
<td>0</td>
<td>-1</td>
<td>$\tilde{u}_L \ \tilde{u}_R \ d_L \ d_R$</td>
<td>same</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\tilde{c}_L \ \tilde{c}_R \ \tilde{s}_L \ \tilde{s}_R$</td>
<td>same</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\tilde{t}_L \ \tilde{t}_R \ b_L \ b_R$</td>
<td>$\tilde{t}_1 \ \tilde{t}_2 \ b_1 \ b_2$</td>
</tr>
<tr>
<td>sleptons</td>
<td>0</td>
<td>-1</td>
<td>$\tilde{e}_L \ \tilde{e}_R \ \tilde{\nu}_e$</td>
<td>same</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\tilde{\mu}_L \ \tilde{\mu}<em>R \ \tilde{\nu}</em>\mu$</td>
<td>same</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\tilde{\tau}_L \ \tilde{\tau}<em>R \ \tilde{\nu}</em>\tau$</td>
<td>$\tilde{\tau}_1 \ \tilde{\tau}<em>2 \ \tilde{\nu}</em>\tau$</td>
</tr>
<tr>
<td>neutralinos</td>
<td>1/2</td>
<td>-1</td>
<td>$\tilde{B}^0 \ W^0 \ H^0_u \ H^0_d$</td>
<td>$\chi^0_1 \ \chi^0_2 \ \chi^0_3 \ \chi^0_4$</td>
</tr>
<tr>
<td>charginos</td>
<td>1/2</td>
<td>-1</td>
<td>$\tilde{W}^\pm \ \tilde{H}^+_u \ \tilde{H}^-_d$</td>
<td>$\chi^+_1 \ \chi^+_2$</td>
</tr>
<tr>
<td>gluino</td>
<td>1/2</td>
<td>-1</td>
<td>$\tilde{g}$</td>
<td>same</td>
</tr>
<tr>
<td>goldstino</td>
<td>1/2</td>
<td>-1</td>
<td>$\tilde{G}$</td>
<td>same</td>
</tr>
</tbody>
</table>

- $R$-parity: $R_P = (-1)^{2S} (-1)^3 (B-L)$

  - **$R$-parity conservation**: prevents B and L numbers violations, stable LSP... sparticles are pair produced
  - **$R$-parity violation**: automatic generation of neutrino masses and mixing... single sparticle can be produced

$$W = \frac{1}{2} \lambda_{ijk} L^i L^j e^k + \frac{1}{2} \lambda'_{ijk} L^i Q^j d^k + \frac{1}{2} \lambda''_{ijk} u^i d^j d^k$$

$\lambda, \ \lambda': \ \Delta L = 1$
$\lambda'': \ \Delta B = 1$
A golden mode for SUSY searches at TeVatron

Very clean signature:
- 3 isolated leptons
- $E_T$ due to undetected $\tilde{\chi}_1^0$ and $\nu$

Challenge:
- low cross section: $\sigma \times B r < 0.5 \text{ pb}$
- very soft 3rd lepton $p_T$

Search Strategies
- **CDF:**
  - 3 identified leptons (e, $\mu$)
  - 2 identified leptons + track ($\ell$)
  - 2.0 fb$^{-1}$

- **DØ:**
  - 2 identified leptons (e, $\mu$) + $\ell$
  - $\mu\tau + \ell$ and $\mu\tau + \tau$ (T had decay)
  - "low"-pT vs "high"-pT search
  - 2.3 fb$^{-1}$
Background is reduced with several set of kinematical cuts: inv-mass cut, lepton (track) $p_T$ cut, $E_T$, $M_T$, $\Delta\Phi$ between leptons, number of jets...

<table>
<thead>
<tr>
<th></th>
<th>DØ $\int L dt = 2.3$ fb$^{-1}$</th>
<th>CDF $\int L dt = 2.0$ fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background</td>
<td>Data 5.4±0.6 9</td>
<td>Data 0.88±0.14 1</td>
</tr>
<tr>
<td>low $p_T$</td>
<td>Trilepton 3.3±0.4 4</td>
<td>Lepton+track 5.5±1.1 6</td>
</tr>
</tbody>
</table>

Main backgrounds:
- diboson (WW, WZ)
- Drell-Yan $W \rightarrow l\nu$, $t\bar{t}$

Data compatible with SM
Set limits in the mSUGRA model
mSUGRA: only 5 parameters 
$m_0$, $m_{1/2}$, $\tan\beta$, $A^0$, sign($\mu$)

Benchmark scenario: 
$A^0=0$, $\tan\beta=3$, $\mu > 0$

Constrain the 2D parameter space $m_0$-$m_{1/2}$

Signal efficiencies vary from 1% to 5% depending in each channel

CDF, 2.0 fb$^{-1}$

Search for $\tilde{\chi}_{1/2}^{\pm}$

CDF Run II Preliminary 

Excluded Region in mSUGRA

CDF $2.0$ fb$^{-1}$

mSUGRA $\tan\beta=3$, $A_0=0$, $\mu > 0$

$m(\tilde{e}_L)$, $m(\tilde{e}_R)$, $m(\tilde{\nu}_L)$, $m(\tilde{\nu}_R)$

$M(\tilde{e}_L) > M(\tilde{\nu}_L)$

$M(\tilde{e}_R) > M(\tilde{\nu}_R)$

CDF observed limit

LEP direct limit

LEP Slepton Limit

LEP Chargino Limit

Search for $\tilde{\chi}_1^{\pm} \tilde{\chi}_1^{0}$

DØ observed limit

DØ expected limit

$M(\tilde{\chi}_1^0) = M(\tilde{\chi}_1^\pm)$

$M(\tilde{e}_L) = M(\tilde{\nu}_L)$

$M(\tilde{e}_R) = M(\tilde{\nu}_R)$

$DØ, 2.3$ fb$^{-1}$

$\tilde{\chi}_2 \tilde{\chi}_1^0$ prod: "trileptons"
Some examples of excluded charginos

CDF: $m_0 = 60$ GeV  
$m_{\tilde{\chi}_1^\pm} > 145.4$ GeV

CDF: $m_0 = 100$ GeV  
$m_{\tilde{\chi}_1^\pm} > 127.0$ GeV

DØ: "3l-max"  
$m_{\tilde{\chi}_1^\pm} > 138$ GeV

Dependence with other parameters: eg tan\(\beta\)

DØ: Exclude chargino of 130 GeV up to tan\(\beta\)=9.6

DØ: arXiv: 0901.0646 (sub. to PLB)
If stop light enough, $m[\tilde{t}] < m[t]$, several interesting decays, depending on the sparticles spectrum:

1. $\tilde{t} \rightarrow b \tilde{\chi}_1^+ \rightarrow b l \nu \tilde{\chi}_1^0$ \quad ($m_{\tilde{\chi}_1^+} < m_{\tilde{t}}$)
2. $\tilde{t} \rightarrow b \tilde{\nu} l$ \quad ($m_{\tilde{\chi}_1^+} > m_{\tilde{t}}$)
3. $\tilde{t} \rightarrow c \tilde{\chi}_1^0$

1. **CDF 2.7 fb$^{-1}$**: dileptons (e/μ) with one isolated lepton, $E_T$, high $p_T$ jets, b-tagging. reconstruct the stop mass with a kinematic fit.

$$\tilde{t}_1 \tilde{t}_1 \rightarrow b b l l' \nu \bar{\nu} \tilde{\chi}_1^0 \tilde{\chi}_1^0$$

<table>
<thead>
<tr>
<th></th>
<th>ee</th>
<th>μμ</th>
<th>eμ</th>
<th>Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal</td>
<td>1.1</td>
<td>1.4</td>
<td>3.0</td>
<td>5.5</td>
</tr>
<tr>
<td>Background</td>
<td>14.2</td>
<td>12.4</td>
<td>29.4</td>
<td>56.0</td>
</tr>
<tr>
<td>Data</td>
<td>15</td>
<td>12</td>
<td>30</td>
<td>57</td>
</tr>
</tbody>
</table>

**Observed 95% CL**

CDF Run II Preliminary (2.7 fb$^{-1}$)

$M(\tilde{\chi}_1^0) = 105.8 \text{ GeV/c}^2$

BR($\tilde{t} \rightarrow \tilde{\chi}_1^0 b$) = 1

BR($\tilde{\chi}_1^0 \rightarrow \tilde{\chi}_1^0 l l$) = 0.50

BR($\tilde{\chi}_1^0 \rightarrow \tilde{\chi}_1^0 \nu \bar{\nu}$) = 0.25

CDF Run II Preliminary (2.7 fb$^{-1}$)

$M(\tilde{\chi}_1^0) = 125.8 \text{ GeV/c}^2$

BR($\tilde{t} \rightarrow \tilde{\chi}_1^0 b$) = 1

BR($\tilde{\chi}_1^0 \rightarrow \tilde{\chi}_1^0 l l$) = 0.50

BR($\tilde{\chi}_1^0 \rightarrow \tilde{\chi}_1^0 \nu \bar{\nu}$) = 0.25

Excluded by LEP
2. **DØ 1.0 fb⁻¹:** ee, eµ.

require high p_T isolated leptons, E_L, use kinematics and b-tagging (for ee) to disentangle signal from background.

Signal efficiency ranges from 0.1 to 10% depending on $\Delta m = m_{\tilde{t}_1} - m_{\tilde{\nu}}$

Good agreement with SM exp. background.

<table>
<thead>
<tr>
<th>channel</th>
<th>Data</th>
<th>Exp. Bkg.</th>
<th>Sig. A</th>
<th>Sig. B</th>
</tr>
</thead>
<tbody>
<tr>
<td>ee</td>
<td>12</td>
<td>12.2 ± 0.4</td>
<td>0.6</td>
<td>4.6</td>
</tr>
<tr>
<td>eµ</td>
<td>61</td>
<td>65 ± 4</td>
<td>6.0</td>
<td>16.1</td>
</tr>
</tbody>
</table>

For large $\Delta m$: $m_{\tilde{t}_1} < 175$ GeV

arXiv: 0811.0459 (sub. to PLB)
Hypotheses: all RPV couplings are null but $\lambda'_{311}$ and $\lambda_{321} = \lambda_{312}$

Indirect constraints:

$\lambda'_{311} \leq 0.12$, $\lambda_{321} \leq 0.07$ for $M_{\tilde{\nu}_\tau} \geq 100 \text{ GeV}$

Very clean signature:

• 2 hard isolated leptons
• typical signal acceptance: 5 to 15%

Search Strategies

CDF: • 1.0 fb$^{-1}$
• 3 channels: $e\mu$, $\mu\tau$, $e\tau$

DØ: • 4.1 fb$^{-1}$, brand new result!
• only one channel: $e\mu$
\[ \tilde{\nu}_\tau : \text{RPV} \]

**DØ, 4.1 fb\(^{-1}\) preliminary**

- **Observed Limit**
- **Expected Limit**

\[
\text{95\% CL } \sigma \times \text{BR}(\text{e}\mu)(\text{fb})
\]

**CDF Run II Preliminary, 1 fb\(^{-1}\)**

- **Observed**
- **Expected**

\[
\text{95\% CL } \lambda \times \text{BR}(\text{e}\mu)(\text{pb})
\]

**CDF** places limits on \( \lambda'_{311} \) for several values of \( \lambda'_{321} \) depending on the stau mass. **Updated limits underway (using more accurate theo. predictions).**
In Gauge Mediated Supersymmetry Breaking models, Susy is broken in an hidden sector. The breaking is communicated to (s)quarks, (s)leptons and Higgs(inos) by messengers via gauge bosons and gauginos interactions. Special features:
- gravitino is the LSP
- NLSP is a neutralino or a slepton
- NLSP can be fast enough to occur within the detector volume
- If NLSP = neutralino, one has: $\tilde{\chi}_1^0 \rightarrow \tilde{G} \gamma$

CDF: 2.0 fb$^{-1}$

<table>
<thead>
<tr>
<th>Background Source</th>
<th>Expected Rate±Stat±Sys</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electroweak</td>
<td>0.39±0.14±0.11</td>
</tr>
<tr>
<td>QCD</td>
<td>0.10±0.10±0.00</td>
</tr>
<tr>
<td>Non-Collision</td>
<td>0.049±0.042±0.028</td>
</tr>
<tr>
<td>Tri-Photon</td>
<td>0.00±0.180±0.035</td>
</tr>
<tr>
<td>Wrong Vertex</td>
<td>0.081±0.081±0.008</td>
</tr>
<tr>
<td>Total</td>
<td>0.62±0.26±0.12</td>
</tr>
</tbody>
</table>

1 event observed.
Charge massive stable particles (CHAMPS) are predicted by several extensions of the Standard Model. It could be the case of the stau and the chargino in some SUSY models (GMSB, AMSB).

**DØ: 1.1 fb⁻¹**

CHAMPS may appear as "slow" moving muons. Striking signature:
- isolated high pT muons
- use timing in muon system to measure the speed
- the di-muon mass also provides discrimination

**Limits:**
- \( \tilde{\tau} \): no sensitivity
- \( \tilde{\chi}_1^\pm, \tilde{h} \)-like
  \[ m_{\tilde{\chi}_1^\pm} > 171 \text{ GeV} \]
- \( \tilde{\chi}_1^\pm \), gaugino-like
  \[ m_{\tilde{\chi}_1^\pm} > 206 \text{ GeV} \]

**also: CHAMPS search by CDF**
\[ m_{\tilde{\tau}} > 249 \text{ GeV} \]

DØ: arXiv:0809.0472 (sub. to PRL)
CDF: arXiv:0902.1266 (sub. to PRL)
Conclusions

• TeVatron, CDF and DØ are doing better than ever:
  ▶ 6 fb$^{-1}$ delivered by the TeVatron
  ▶ 5 fb$^{-1}$ already recorded by DØ and CDF, ie about 2 times more than what was presented here
  ▶ One search analysed 4 fb$^{-1}$!
  ▶ And still more to come!

• squarks/gluinos: combination DØ/CDF underway...

• No hint of SUSY yet

• Probe new regions

• Additional details and many over searches:

DØ : http://www-d0.fnal.gov/Run2Physics/WWW/results.htm
CDF and $D\emptyset$ detectors

Multi purpose detectors: $\mu$ id, EM id, jets, taus, $E_T$

CDF:
excellent tracking

$D\emptyset$:
excellent calorimetry, muon
Search for $\tilde{\nu}_\tau$: RPV

• Hypotheses: No RPV couplings but $\lambda'_{311}$ and $\lambda_{321} = \lambda_{312}$

\[
\begin{align*}
\text{d}(p_1) & \to \tilde{\nu} \\
& \to e^-(p_3) \\
\text{d}(p_2) & \to \mu^+(p_4)
\end{align*}
\]

Indirect constraints:

$\lambda'_{311} \leq 0.12, \lambda_{321} \leq 0.07$ for $M_{\tilde{\nu}_\tau} \geq 100$ GeV

Very clean signature:

• 2 hard isolated leptons

Selection ($D\phi$):

• veto on jet
• veto on high $E_T$
• high $p_T$ leptons ($p_T > 25/30$ GeV)
• typical signal acceptance: 5 to 15%

Search Strategies

CDF:

• 1.0 fb$^{-1}$
• 3 channels: $e\mu; \mu\tau; e\tau$

D$\phi$:

• 4.1 fb$^{-1}$
• only 1 channel: $e\mu$
• brand new result!
SM backgrounds:
- mostly $Z \rightarrow \tau\tau$
- diboson

<table>
<thead>
<tr>
<th>Process</th>
<th>events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z/\gamma^*$</td>
<td>83 ± 3</td>
</tr>
<tr>
<td>diboson</td>
<td>46 ± 2</td>
</tr>
<tr>
<td>$tt$ incl.</td>
<td>3 ± 0</td>
</tr>
<tr>
<td>$W + jet/\gamma^*$</td>
<td>13 ± 2</td>
</tr>
<tr>
<td>total background</td>
<td>145 ± 4</td>
</tr>
<tr>
<td>data</td>
<td>143</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CDF $m_{e\mu}, m_{\nu_{vis}}$</th>
<th>$e+\mu$</th>
<th>$e+\tau$</th>
<th>$\mu+\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background</td>
<td>0.1</td>
<td>1.4</td>
<td>1.0</td>
</tr>
<tr>
<td>Data</td>
<td>0</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>
If $\tilde{b}$ light enough, they can be produced via $\tilde{g}$ decay. $\tilde{g}\tilde{g}$ has high cross section at hadron collider.

**Signature:** 4 b-jets + missing energy

Use $E_T$, b-tagging and 2 Neural Network to reject backgrounds

<table>
<thead>
<tr>
<th></th>
<th>Large $\Delta m$</th>
<th>Small $\Delta m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exp.</td>
<td>4.5 ± 1.4</td>
<td>2.3 ± 0.8</td>
</tr>
<tr>
<td>Obs.</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>Sig ($m_{\tilde{g}} = 335$, $m_{\tilde{b}} = 260$)</td>
<td>14.9 ± 5.0</td>
<td>-</td>
</tr>
<tr>
<td>Sig ($m_{\tilde{g}} = 335$, $m_{\tilde{b}} = 315$)</td>
<td>-</td>
<td>8.5 ± 2.8</td>
</tr>
</tbody>
</table>

**Bkg:**
- QCD
- W/Z + jets
- $t\bar{t}$

CDF: 2.5 fb$^{-1}$
mSUGRA: only 5 parameters

\[ m_0, \ m_{1/2}, \ \tan \beta, \ A^0, \ \text{sign}(\mu) \]
One golden mode to search for SUSY at TeVatron

- Neutralino LSP, all squarks but the stop are mass degenerated.
- Very well Motivated in mSUGRA models:
  - low \(m_0\): \(\tilde{q}\tilde{q} \rightarrow q q \tilde{\chi}_1^0 \tilde{\chi}_1^0\)
  - intermediate \(m_0\): \(\tilde{q}\tilde{g} \rightarrow q q q \tilde{\chi}_1^0 \tilde{\chi}_1^0\)
  - high \(m_0\): \(\tilde{g}\tilde{g} \rightarrow q q q q \tilde{\chi}_1^0 \tilde{\chi}_1^0\)

"dijet" optimisation
"3-jet" optimisation
"gluino" optimisation

**Signature:**
- large \(E_T\)
- large \(H_T = \sum_{\text{jets}} p_T[\text{jets}]\)

**Background:**
- QCD
- W+jets , Z+jets

2 jets
3 jets
gluinos
GMSB backup

CDF Run II Preliminary, 2 fb⁻¹

γγ → E_L analysis in GMSB

CDF Run II Preliminary, 2 fb⁻¹

Data
QCD with fake E_T
SM with real E_T
Non-collision
GMSB signal
χ₁⁻⁻⁰ mass=140 GeV, lifetime=0 ns

Events per 10 GeV

χ₁⁻⁻⁰ lifetime (ns)
χ₁⁻⁻⁰ mass (GeV/c²)

Data
QCD with fake E_T
SM with real E_T
Non-collision
GMSB signal

χ₁⁻⁻⁰ mass=140 GeV, lifetime=0 ns

Events per 10 GeV

χ₁⁻⁻⁰ lifetime (ns)
χ₁⁻⁻⁰ mass (GeV/c²)
CHAMPS appears slowly moving, highly ionizing and penetrating particle, ie slow muon.

CDF uses the Time-Of-Flight detector and the tracking system to get the mass of the charged particle.

Set limits for weakly and strongly interacting CHAMPS.

eg, a stop CHAMPS in susy models with extra-dimensions.
Systematics (@ DØ)

<table>
<thead>
<tr>
<th>Main sources</th>
<th>Background</th>
<th>Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>trigger, lepton identification, reconstruction efficiencies</td>
<td>4%</td>
<td>4%</td>
</tr>
<tr>
<td>Jet and tau energy Scale</td>
<td>2–9%</td>
<td>2–6%</td>
</tr>
<tr>
<td>Track momentum</td>
<td>1%</td>
<td>1%</td>
</tr>
<tr>
<td>Track reconstruction</td>
<td>1%</td>
<td>1%</td>
</tr>
<tr>
<td>PDF/scale errors on the cross section</td>
<td>4.5%</td>
<td>4.5%</td>
</tr>
<tr>
<td>Luminosity</td>
<td>6%</td>
<td>6%</td>
</tr>
</tbody>
</table>

3l-max scenario: maximizes the branching to 3l
RPV: emu channel

- Systematics

<table>
<thead>
<tr>
<th>source</th>
<th>syst(%)</th>
<th>signal</th>
<th>$Z/\gamma^* \rightarrow \tau\tau$</th>
<th>$WW$ incl.</th>
<th>$WZ$ incl.</th>
<th>$\bar{t}\bar{t}$ incl.</th>
<th>$W + jet/\gamma^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>luminosity</td>
<td>6.1</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>trigger</td>
<td>0.1</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>cross section</td>
<td>8.0</td>
<td>3.5</td>
<td>6.6</td>
<td>2.7</td>
<td>14.8</td>
<td>8.1</td>
<td></td>
</tr>
<tr>
<td>PDF for signal acceptance</td>
<td>0.4-0.6</td>
<td>√</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>electron ID</td>
<td>2.3</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>muon local ID</td>
<td>2.3</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
</tr>
</tbody>
</table>

- Invariant mass

CDF places limits on the stau mass assuming $\lambda'_{311}=0.10$ and $\lambda_{321}=\lambda_{133}=0.05$