Searches for Supersymmetry at the Tevatron

Squarks / Gluinos

Charginos / Neutralinos

$B_s \rightarrow \mu^+\mu^-$

R-parity Violation

Gauge Mediated SUSY Breaking

Arnd Meyer

ICHEP, Beijing, August 2004
The Tevatron

- Increased # of bunches:
  6 (3500 ns)
  → 36 (396 ns)

- **New Main Injector**
  storage ring up to 150GeV

- **New “Recycler”**
  (Storage ring for pbar cooling (in commissioning), add e-cooling (installation))

- Run II start March 2001

- Typical peak luminosity
  \[ 0.16 \cdot 10^{32} \text{cm}^{-2}\text{s}^{-1} \] (Run I)
  → \[ 0.8 \cdot 10^{32} \text{cm}^{-2}\text{s}^{-1} \] (“Run IIa”)
  → \[ 2-4 \cdot 10^{32} \text{cm}^{-2}\text{s}^{-1} \] (“Run IIb”)

- Achieved design luminosity for Run II without Recycler this Summer

- \( \int L \, dt \approx 4 - 8 \, \text{fb}^{-1} \) by 2009

pp collisions at \( \sqrt{s} = 1.96 \, \text{TeV} \) (Run I: 1.8 TeV)
Both experiments collected about 500 pb$^{-1}$ so far in Run II. Analyses shown here use up to 250 pb$^{-1}$.
CDF and DØ Experiments

**DØ Strengths:**
Excellent and wide muon coverage, hermetic calorimetry

**CDF Strengths:**
Excellent precision tracking, “deadtimeless” trigger

---

Two general purpose detectors:  

**CDF**  
- Electron Acceptance: $|\eta| < 3.0$  
- Muon Acceptance: $|\eta| < 2.0$  
- Precision Tracking (Silicon): $|\eta| < 2.0$

**DØ**  
- Electron Acceptance: $|\eta| < 3.0$  
- Muon Acceptance: $|\eta| < 2.0$  
- Precision Tracking (Silicon): $|\eta| < 3.0$

---

[Diagram of detector components and acceptance regions]
Supersymmetry at the Tevatron

- **Direct searches for SUSY partners at the Tevatron**
  - **Squarks / Gluinos**
    - Strong production – large cross sections
    - Masses possibly relatively high
  - **Charginos / Neutralinos**
    - Small cross sections
    - Chargino mass limit from direct searches at LEP: “only” 103 GeV
    - Cascade decays can provide clean signatures

- **Signatures vary with model assumptions**
  - **MSSM with R-parity conserved**: Missing $E_T$ (jets + missing $E_T$, trileptons + missing $E_T$)
  - **MSSM with R-parity violation**: Multileptons, leptons + jets
  - **GMSB (with Neutralino NLSP)**: Diphotons
Squarks and Gluinos

- **pp collider**: strong production of squarks / gluinos → large cross section

- **Signature** (squarks lighter than gluinos):
  \[ \tilde{q}\tilde{q} \rightarrow q\tilde{\chi}_1^0 q\tilde{\chi}_1^0 \] (2 jets + \(E_T\))

- Massive background from multijet production, Z + jets (with \(Z \rightarrow \nu\nu\))

- Tight cuts: \(E_T > 175\) GeV, \(H_T > 275\) GeV

- DØ, \(\int L \, dt = 156\) pb\(^{-1}\)
  - 4 events observed, 2.7 ± 1.0 expected
  - Limits improved beyond Run I
Gluino → sbottom bottom

- Sbottom may be light
  - Assume $\text{BR}(\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0) = 100\%$, $R_p$ conserved
  - Assume $m(\tilde{g}) > m(\tilde{b}_1) > m(\tilde{\chi}_1^0)$, $m(t) + m(\tilde{\chi}_1^+) > m(\tilde{b}_1)$
- Exploit b-tagging and kinematics
  - 3 jets $> 15\text{ GeV}$, $E_T' > 80\text{ GeV}$
  - $\Delta \phi (E_T', \text{jets}) > 40^\circ$
  - b-jet secondary vertex tag

$\int L \, dt = 156 \text{ pb}^{-1}$

**Single b-tag:**
- observe 21 events
- expect $16.4 \pm 3.7$

**Double b-tag:**
- observe 4 events
- expect $2.6 \pm 0.7$
Gluino → sbottom bottom

Large region excluded in the $m(\text{sbottom}) - m(\text{gluino})$ plane

Gluino → $\tilde{b}_i b_j$, 95% C.L. Cross Section Limit

CDF Run II Preliminary, 156pb$^{-1}$

- PROSPINO, NLO
- $Q^2$ Scale Uncertainty
- $m(\tilde{q}) = 500$ GeV/$c^2$
- $\Delta m(\tilde{g},\tilde{b}) = 60$ GeV/$c^2$
- $m(\chi_1^0) = 60$ GeV/$c^2$
- Excl. Single B-Tag
- Incl. Double B-Tag

Gluino → $\tilde{b}_i b_j$, 95% C.L. Exclusion Limit, 156pb$^{-1}$

BR($\tilde{g} \rightarrow b \tilde{b}_i$) = 100%
- $m(\chi_1^0) = 60$ GeV/$c^2$
- $m(\tilde{g}) = 500$ GeV/$c^2$

CDF Run II Preliminary

$\tilde{g} \rightarrow b\tilde{b}_i$, kinematically forbidden
(excl. single tag)
(incl. double tag)

CDF Run I excluded

Gluino mass [GeV/$c^2$]
Charginos/Neutralinos

- **Golden channel**: leptonic cascade decays → three leptons + missing $E_T$

- **Challenges**
  - Small event rates ($\sigma \times \text{BR} < 0.5\text{pb}$)
  - Leptons with low transverse momenta

- **DØ**: Four selections, $\int L \, dt = 147 - 249 \, \text{pb}^{-1}$
  - $ee + \text{track}, e\mu + \text{track}, \mu\mu + \text{track}, \mu^\pm\mu^\mp$

- **Backgrounds**: WW, WZ, $W\gamma$
**Selection**: two well identified leptons plus

- Significant missing transverse energy
- Additional isolated track (except for like-sign dimuons)
  - Very low cut on track $p_T$ (3 to 5 GeV), efficient for e, $\mu$ and $\tau$ (including hadronic $\tau$-decays)

<table>
<thead>
<tr>
<th>Selection</th>
<th>Observed</th>
<th>SM Bgrd.</th>
<th>Signal $(m_{\text{chargino}} = 100$ GeV$)$</th>
<th>$\int L , dt$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ee + track</td>
<td>1 event</td>
<td>0.7 ± 0.5</td>
<td>1.83 ± 0.11</td>
<td>249 pb$^{-1}$</td>
</tr>
<tr>
<td>e$\mu$ + track</td>
<td>0 events</td>
<td>0.3 ± 0.3</td>
<td>1.25 ± 0.09</td>
<td>235 pb$^{-1}$</td>
</tr>
<tr>
<td>$\mu\mu$ + track</td>
<td>1 event</td>
<td>1.8 ± 0.5</td>
<td>1.12 ± 0.13</td>
<td>221 pb$^{-1}$</td>
</tr>
<tr>
<td>$\mu^{\pm}\mu^{\pm}$ (LS)</td>
<td>1 event</td>
<td>0.1 ± 0.1</td>
<td>0.36 ± 0.04</td>
<td>147 pb$^{-1}$</td>
</tr>
</tbody>
</table>
Charginos/Neutralinos: Combined

- Take overlaps into account for combination
- Close to reaching sensitivity for mSUGRA beyond LEP limits, significant improvement on Run I limits
- Exclude chargino masses below 97 GeV with comparable chargino, neutralino, and slepton masses

**“mSUGRA”**: maximize leptonic BR ($m(\text{slepton}) \approx m(\chi^0_2) \rightarrow \text{sfermion decays dominate}$)

**“Large $m_0$”**: Decays via $W^*/Z^*$ dominate $\rightarrow$ leptonic BR small

**“Heavy squarks”** (relaxing mass unification): enhanced cross section (destructive interference with squark-exchange suppressed)
Search for $B_s \to \mu^+\mu^-$

- SM prediction: $\text{BR}(B_s \to \mu^+\mu^-) = 3.8 \cdot 10^{-9}$
- Can be enhanced by non-SM contributions
  - SUGRA: $\sim (\tan \beta)^6$ – significant at large $\tan \beta$
  - Complementary to trilepton search
- Tevatron: large production rate for $B_s$
- Selection: two isolated muons, displaced vertex
- Results at 95% CL

CDF (171pb$^{-1}$): $\text{BR}(B_s \to \mu^+\mu^-) < 7.5 \cdot 10^{-7}$
DØ (240pb$^{-1}$): $\text{BR}(B_s \to \mu^+\mu^-) < 4.6 \cdot 10^{-7}$
R-parity Violating SUSY

R-parity: \( R_p = (-1)^{3B+L+2S} \)

\[
W = W_{MSSM} + W_{R_p}
\]

\[
W_{R_p} = \frac{1}{2} \lambda_{ijk} \varepsilon_{ab} L_i^a L_j^b E_k^c + \lambda'_{ijk} \varepsilon_{ab} (L_i^a Q_j^b D_k^c) + \lambda''_{ijk} \varepsilon_{xyz} U_i^c X_j^y D_k^z + \kappa \varepsilon_{ab} L_i^a H_2^b
\]

i,j,k = 1,2,3 generation indices

\( R_p \) violated in decay
\( \rightarrow \) multi lepton final state

Resonant production
\( \rightarrow \) two muon and two jets final state

Chiral superfields:

- \( L \): lepton doublet superfield
- \( E \): lepton singlet superfield
- \( Q \): quark doublet superfield
- \( D \): down-like quark singlet superfield

\( \lambda, \lambda', \lambda'' \): Yukawa couplings

\[ S \text{ is the particle spin,} \]
\[ B \text{ is the baryon number,} \]
\[ L \text{ is the lepton number} \]
RPV Production

- R-parity conserved
- Search for decays via the R-parity violating LLE couplings $\lambda_{121}, \lambda_{122}$
- Final states with 4 leptons or more; analyses ask for at least 3 leptons.

→ R-parity violating $\tilde{\chi}_1^0$ decay ($\lambda'_{211}$)
→ Dimuon and dijet final state

Other modes:
- sneutrino resonance
  → dijet, muon & missing $E_T$ final state
- t-channel slepton exchange
Neutralino Decay

- Only 1 neutralino in resonant channel
  - $\mu^+ \mu^-$ jet jet final state, no missing $E_T$
- Pair produced neutralinos decay via LLE couplings $\lambda_{ijk}$ into 2 charged leptons and 1 neutrino
  - More than one possible final state for each coupling
  - Missing $E_T$

Final state: $e e e e, e e e \mu^-$, $ee \mu^+ \mu^-$, or $ee \mu^+ \mu^-, e \mu \mu, \mu \mu \mu \mu$
RPV: LLE Couplings $\lambda_{121}$

- $\text{D}\bar{O}$, $\int L \, dt = 238 \text{ pb}^{-1}$
- **Selection**: two isolated electrons + additional low-$p_T$ electron or muon, $E_T > 15 \text{ GeV}$
- **Observe 0 events, SM expectation $0.45 \pm 0.43$**
- **Cross section limit as function of $m_{1/2}$ for $m_0 = 250 \text{ GeV}$, tan $\beta = 5$, $A_0 = 0$**

\[ M(\chi_1^{\pm}) > 184 \text{ GeV} \]
\[ M(\chi_1^0) > 95 \text{ GeV} \]

\[ M(\chi_1^{\pm}) > 181 \text{ GeV} \]
\[ M(\chi_1^0) > 98 \text{ GeV} \]
Candidate Event ($\lambda_{121}$)

<table>
<thead>
<tr>
<th>Event #2</th>
<th>Event #2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Runnum</strong></td>
<td>180 116</td>
</tr>
<tr>
<td><strong>Evtnum</strong></td>
<td>4 428 470</td>
</tr>
<tr>
<td><strong>type</strong></td>
<td>eee</td>
</tr>
<tr>
<td><strong>MET</strong></td>
<td>8.3</td>
</tr>
<tr>
<td><strong># of muons</strong></td>
<td>1 (nseg = -2)</td>
</tr>
<tr>
<td><strong>(pt, eta, phi)</strong></td>
<td>(17.4, 1.99, 2.02)</td>
</tr>
<tr>
<td><strong>Mee 1-2, 2-3, 1-3</strong></td>
<td>63.4, 17.7, 31.9</td>
</tr>
<tr>
<td><strong>(M_{123})</strong></td>
<td>(73.1)</td>
</tr>
<tr>
<td><strong>Pt 1, 2, 3</strong></td>
<td>35.6, 28.4, 9.1</td>
</tr>
<tr>
<td><strong>Eta 1, 2, 3</strong></td>
<td>-1.78, -1.83, -1.64</td>
</tr>
<tr>
<td><strong>Phi 1, 2, 3</strong></td>
<td>1.39, 4.36, 5.50</td>
</tr>
<tr>
<td><strong>Charge 1, 2, 3</strong></td>
<td>+1, -1, -1</td>
</tr>
</tbody>
</table>
RPV: LLE Couplings $\lambda_{122}$

- DØ, $\int L \, dt = 160 \text{ pb}^{-1}$
- **Selection**: two isolated muons + additional low-$p_T$ electron or muon (down to 3 GeV)
- Optimized two-dimensional cuts in $E_T$, lepton-$p_T$, invariant mass
- **Observe 2 events, SM expectation $0.63 \pm 1.93$**
- Cross section limit for $m_0 = 250 \text{ GeV}$, $\tan \beta = 5$, $A_0 = 0$

![Graph showing cross section limits for $\mu < 0$ and $\mu > 0$](image)
RPV: LQD Coupling $\lambda'_{211}$

- DØ, $\int L \, dt = 154 \, \text{pb}^{-1}$
- 2 jets above $\sim 20\text{GeV}$, 2 isolated muons above $\sim 20\text{GeV}$ (depending on point under study)
- Reconstruct neutralino and smuon candidate invariant mass

$M_{\tilde{\chi}_1^0} = 75 \, \text{GeV}$

$M_{\tilde{\mu}} = 200 \, \text{GeV}$
Gauge Mediated SUSY Breaking: Gravitino $\tilde{G}$ is LSP

Assuming Neutralino NLSP: $\tilde{\chi}_1^0 \rightarrow \gamma \tilde{G}$

$\rightarrow$ Chargino/Neutralino production leads to final states containing $\gamma\gamma + E_T$

$\rightarrow$ Inclusive search for 2 photons plus $E_T$

Selection: Two central photons with $E_T > 13$ GeV (CDF) / $E_T > 20$ GeV (DØ)

Optimized cut $E'_T > 45$ GeV (CDF) / $E'_T > 40$ GeV (DØ)

Observe 0 / 1 events (CDF / DØ), expect 0.3 / 2.5 events from “fakes”

For $N_5 = 1$, $M_m = 2\Lambda$, $\tan \beta = 5(15)$, $\mu > 0$:

DØ (185 pb$^{-1}$): $m_{\tilde{\chi}_1^0} > 105$ GeV, $m_{\tilde{\chi}^\pm} > 192$ GeV

CDF (202 pb$^{-1}$): $m_{\tilde{\chi}_1^0} > 93$ GeV, $m_{\tilde{\chi}^\pm} > 168$ GeV

Publication with more data under way
Conclusions

- Tevatron collider and experiments are running well
- Experiments recorded about $0.5 \text{ fb}^{-1}$, analyses shown here based on up to $\approx 250 \text{ pb}^{-1}$
- $B_s \rightarrow \mu^+ \mu^-$ results starting to constrain large $\tan \beta$ region
- Searches for supersymmetric particles improve on Run I limits and have entered uncharted territory
  - MSSM with R-parity conserved: Missing $E_T$ (jets + missing $E_T$, trileptons + missing $E_T$)
  - MSSM with R-parity violation: Multileptons, leptons + jets ($\lambda_{121}$, $\lambda_{122}$ and $\lambda'_{211}$)
  - GMSB (with Neutralino NLSP): Diphotons