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• Signatures of supersymmetry
• What can we do in Run IIa (500 pb$^{-1}$)
• Thoughts & Outlook

DØ Workshop, Seattle, Washington
June 28, 1999
Supersymmetry?

Standard Model Particles

\( W^\pm, H^\pm, \gamma, Z, h, H, A, u, d, e, \nu \) .......

\[ \downarrow \] \[ \downarrow \] \[ \downarrow \]

\[ \tilde{\chi}_2, \tilde{\chi}_1, \tilde{\chi}_4, \tilde{\chi}_3, \tilde{\chi}_2, \tilde{\chi}_1 \]

\[ \tilde{u}_L \tilde{d}_L \tilde{e}_L \tilde{\nu}_L \]

\[ \tilde{u}_R \tilde{d}_R \tilde{e}_R \tilde{\nu}_R \]

Supersymmetric Particles

Supersymmetry must be broken

\( \text{SUSY is assumed to occur in a hidden sector} \)

Phenomenology depends on

- the way \( \text{SUSY} \) is transmitted
- whether R-parity is conserved
- the lightest supersymmetric particle

No evidence against supersymmetry
Gravity-Inspired Models

Supersymmetry breaking is transmitted by gravity-like interactions
breaking scale $\Rightarrow \Lambda \sim 10^9$ TeV

Lightest neutralino ($\tilde{\chi}_1^0$) is often assumed to be the LSP

\[
\begin{align*}
\tilde{\chi}_i^0 (\tilde{\chi}_j^\pm) & \quad \tilde{\chi}_1^0 \\
\tilde{\chi}_i^0 & \rightarrow Z \tilde{\chi}_1^0 \\
\tilde{\chi}_j^\pm & \rightarrow W \tilde{\chi}_1^0 \\
\tilde{q} & \rightarrow q \tilde{\chi}_1^0 \\
\tilde{g} & \rightarrow q \tilde{\chi}_1^0
\end{align*}
\]

Signatures:
\[
p\bar{p} \rightarrow SUSY \Rightarrow E_T + \ell^n + j^m
\]
Supersymmetry breaking is transmitted through gauge-like interactions $\Rightarrow \Lambda \sim 100$ TeV

$$\Rightarrow m_{\tilde{G}} \sim 6 \times 10^{-5} \left( \frac{\Lambda}{500 \text{ GeV}} \right)^2 \text{ eV}$$

$\tilde{G}$ is naturally the LSP (GMSB models)

Signatures depend on the next-lightest supersymmetric particle (NLSP)

$$\tilde{\chi}_1^0 \rightarrow \gamma \tilde{G}, \ Z\tilde{G}, \ h\tilde{G}$$

$$\tilde{\ell} \rightarrow \ell \tilde{G}$$

Depending on their lifetimes, NLSPs can decay at the production vertex, inside and outside detector

- displaced photons
- hot cells
- slow moving particles
- kinked tracks

Signatures:

$\gamma\gamma E_T$, $\ell\ell E_T$, $\gamma b\bar{b} E_T$, ...
In addition to the SM interactions, following interactions are allowed

Resulting lepton and baryon number violations as well as the R-parity violation

B-violating $\lambda''_{ijk}$ couplings will lead to multijet events without $E_T$

The L-violating $\lambda_{ijk}$ and $\lambda'_{ijk}$ couplings will give rise to multilepton events

$$\tilde{\chi}_1^0 \rightarrow \nu \tilde{\nu}^* \Rightarrow \nu \ell \ell \ (\lambda_{ijk})$$

$$\tilde{\chi}_1^0 \rightarrow \ell \tilde{\ell}^* \Rightarrow \ell q q \ (\lambda'_{ijk})$$

Frequent assumptions:
1) R-parity violating LSP decay
2) couplings are not too week or too strong
3) terms with similar event topology dominate

**Signatures:**

$$p\bar{p} \rightarrow SUSY \Rightarrow \ell^n + j^m (+E_T)$$
In many supersymmetry models, stop (and sbottom) can be significantly lighter than other squarks.

Assuming pair production of $\tilde{t}_1$ will yield the decay:

$$\tilde{t}_1 \rightarrow \tilde{\chi}_1^+ + b \rightarrow \tilde{\chi}_1^0 + Wb$$

and

$$\tilde{t}_1 \rightarrow \tilde{\chi}_1^0 + c$$

Signatures:
1) two acoplanar c-jets with $E_T$
2) excess of SM top events

Assuming $Br(\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0) = 100\%$

pair production of $\tilde{b}_1$ will yield two acoplanar b - jets

Signatures:
- two acoplanar b-jets with $E_T$
The minimal supersymmetric extension of the standard model has more than 100 additional parameters

### Minimal SuperGravity Model (mSUGRA)

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_0$</td>
<td>common scalar mass parameter</td>
</tr>
<tr>
<td>$m_{1/2}$</td>
<td>common gaugino mass parameter</td>
</tr>
<tr>
<td>$A_0$</td>
<td>common trilinear coupling</td>
</tr>
<tr>
<td>$\tan \beta$</td>
<td>ratio of the v.e.v of the two higgs doublets</td>
</tr>
<tr>
<td>$\text{sign}(\mu)$</td>
<td>sign of the higgs mass parameter</td>
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</tbody>
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### Minimal Gauge Mediation Model (MGM)

<table>
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<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda$</td>
<td>supersymmetry breaking scale</td>
</tr>
<tr>
<td>$M_m$</td>
<td>messenger sector scale</td>
</tr>
<tr>
<td>$N$</td>
<td>number of messengers</td>
</tr>
<tr>
<td>$\tan \beta$</td>
<td>ratio of the v.e.v. of the two higgs doublets</td>
</tr>
<tr>
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</table>
Most supersymmetry signatures can be grouped into three broad categories

**Leptonic Signatures**
- Single-lepton ✓
- Di-lepton
  - opposite-sign di-lepton ✓
  - like-sign di-lepton
  - massive stable charged particles
- Tri-lepton
  - chargino-neutralino ✓
  - R-parity violating ✓
- τ events

**Photonic Signatures**
- Single-photon ✓
- Di-photon ✓

**Jet Signatures**
- b-quark jets ✓
- c-quark jets
- jets ✓

**Run I Analyses:**
1) mSUGRA motivated searches
   \[ \ell\ell jj \cancel{E}_T \text{jets} + \cancel{E}_T \]
2) GMSB motivated searches
   \[ \gamma\gamma \cancel{E}_T \]
3) \(R_p\) searches
   \[ ee jj jj jj \ell\ell\ell \cancel{E}_T \]
4) Others
   \[ \ell\ell\ell \cancel{E}_T \gamma jj \cancel{E}_T jj \cancel{E}_T \]

**New opportunities in Run II**
1) like-sign di-leptons
2) massive stable charged particles
3) heavy-flavor jets
4) more efficient τ identification
The year long workshop was organized to improve our understanding on what future Tevatron runs can do in the areas of Higgs and Supersymmetry.

**Five Working Groups:**
- Higgs physics
- Supergravity models
- Gauge mediated models
- Beyond the MSSM
- Event generators

**Workshop Product:**
A published report summarizing the workshop results

**When?**
First deadline: December 1998, final deadline: April 15, 1999
and we still don’t have the report...
For $M_H = 120$ GeV, about 500 Higgs events are expected for in Run IIA

Most of those are $b\bar{b}$ events, buried by QCD $b\bar{b}$ events

There is no sensitivity for $\int L dt = 0.5$ fb$^{-1}$

[Run II Higgs Working Group]
If $H^\pm$ are sufficiently light, they can be produced in top quark decays $t \rightarrow Hb$

Therefore $t \rightarrow Hb$ will compete with the standard model $t \rightarrow Wb$ decay

Since $H^+ \rightarrow c\bar{s}, \tau\nu, Wb\bar{b}$

signature for H production in $t\bar{t}$ events

• disappearance of standard $WWbb$ signature
• anomalous $\tau$ lepton production

Sensitive only to the parameter regions with large $\text{Br}(t \rightarrow Hb)$

Disappearance search is only sensitive to $H \rightarrow c\bar{s}$ and $\tau\nu$ decays
Charginos and Neutralinos

Production of $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ will lead to trilepton events with $E_T$, one of the cleanest signature for supersymmetry.

Backgrounds:
$WZ, ZZ, Zb, Wb\bar{b}, t\bar{t}, ...$

Run II improvements:
1) identification of soft-leptons (efficiency)
2) lepton charge measurement (background)
Long-lived Neutralino

\[ \tilde{\chi}_1^0 \rightarrow \gamma \tilde{G} \]

Central Region

\[ \sigma_{r\tilde{z}} = 2.2 \text{ cm} \]

\[ \sigma_{r\phi} = 1.4 \text{ cm} \]

Similar resolutions in forward region

\[ \sigma_{r\phi} = 1.2 \text{ cm} \quad \sigma_{r\tilde{z}} = 2.8 \text{ cm} \]

[D. Cutts & G. Landsberg hep-ph/9904396]
Tools for massive stable charged particles (MSP)

dE/dx information from
1) Silicon
2) Fiber tracker
3) Preshowers
4) Calorimeter

An efficiency of 68% for MSP and a rejection factor of 10 for MIP are assumed.
\[ p\bar{p} \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp, \tilde{\chi}_1^\pm \tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 + X \]
\[ \Rightarrow \gamma\gamma E_T + X \text{ (prompt } \tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}) \]
\[ \Rightarrow \gamma j j E_T + X \text{ (delayed } \tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}) \]

\[ \gamma\gamma E_T + X \]

- Cuts: \( \geq 2\gamma, E_T > 20 \text{ GeV, } E_T > 50 \text{ GeV} \)
- Backgrounds:
  - 0.4 fb (QCD)
  - 0.2 fb (Fakes)
- Efficiency: 15–30%
- 5\sigma reach: \( M_{\tilde{\chi}_1^\pm} < 260 \text{ GeV} \)

\[ \gamma j j E_T + X \]

- Cuts: \( \geq 1\gamma', E_T > 20 \text{ GeV, } E_T > 50 \text{ GeV} \)
- Backgrounds: 0.3 fb
- Efficiencies: varies

[JQ: hep-ph/9903548]
MGM with a Stau NLSP

Quasi-stable $\tilde{\tau}_1$

$\ell\ell + dE/dx$

Cuts: $p_T^\ell > 50$ GeV, $M_{\ell\ell} > 150$ GeV, $dE/dx$

Background: 0.5 fb
Efficiency: 35–55%

[JQ: hep-ph/9903548]
**Slepton and Higgsino NLSPs**

$\tilde{\ell} \rightarrow \ell \tilde{G}$

Prompt: $\ell \ell \ell j E_T + X$
Efficiency: 1-15%
5$\sigma$ reach: $M_{\tilde{\chi}_1^\pm} < 250$ GeV

Quasi-stable: $\ell \ell + dE/dx$
Efficiency: 30 - 50%
5$\sigma$ reach: $M_{\tilde{\chi}_1^\pm} < 330$ GeV

$\tilde{\chi}_1^0 \rightarrow \gamma \tilde{G}$
Prompt decay
$\Rightarrow \gamma b j E_T + X$ events

$\tilde{\chi}_1^0 \rightarrow h \tilde{G}$
$\geq 1\gamma$ with $E_T > 20$ GeV
$\geq 2j$ with $E_T > 20$ GeV
$\geq 1$ tagged $b$-jet
$E_T > 50$ GeV

Backgrounds: 0.4 fb
using $P(j \rightarrow b) = 10^{-3}$

For $\int L dt = 0.5$ fb$^{-1}$ and $m_h = 105$ GeV
Expect 5 signal events with
less than 1 background events
R-parity Violation

\[ p\bar{p} \rightarrow \text{SUSY} \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 + X \]
\[ \Rightarrow (\ell\bar{\ell})(\ell\bar{\ell}) + X \Rightarrow (\ell q\bar{q}')(\ell q\bar{q}') + X \]

\[ p\bar{p} \Rightarrow \ell\ell + \geq 4 \text{ jets} \quad (\ell = e, \mu) \]
Sensitive to couplings \( \lambda'_{1jk} \) and \( \lambda'_{2jk} \)

Extrapolating from Run I \( eejjjj \) analysis:
Selection:
\[ \geq 2\ell \text{ with } E_T > 15,10 \text{ GeV} \]
\[ \geq 4\text{jets with } E_T > 15 \text{ GeV} \]
\[ Z \rightarrow \ell\ell \text{ veto} \]

Backgrounds:
DY + 4 jets
\( t\bar{t} \rightarrow \ell\ell + \text{jets} \)
Fakes


Using mSUGRA framework as a measure of sensitivity
\( \tan\beta = 2, A_0 = 0, \mu < 0 \)

Obviously we have much to gain from like-sign di-lepton events
Thoughts for Drink

• Focus on data, less on limits – keep our hope alive

• Orient analyses towards event topologies, not models
  models are mostly wrong
  models confuse people
  better use resources, minimize duplication
  fast response to theoretical fashions

• Uniform particle identifications – EB for particle IDs?
  better documentation
  reduce duplication
  coherent publications

• Establish working groups with CDF
We cannot exclude supersymmetry
then
Can we make discovery ?

Yes, we can
with an effective effort
and a little help from God