Search for SUSY at the Tevatron

~ 30 papers or notes

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parallel session `Beyond the SM'

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DØ: http://www-d0.fnal.gov/Run2Physics/WWW/results/np.htm
SUSY Models and Signatures

- `usual` mSUGRA
  - $m_0$, $m_{1/2}$, $A_0$
  - $\tan \beta$, $\text{sign}(\mu)$
  - Generic squarks and gluinos
  - sbottom and stop
  - Gauginos $\rightarrow$ leptons

- Split SUSY
  - Gluino metastable
  - Stopping gluinos

- mSUGRA RPV
  - R-parity violated
  - Lepton-lepton couplings
  - Lepton-quark couplings

- GMSB
  - LSP = light gravitino
  - Photons + missing energy

- AMSB
  - Mass degeneracies
  - Long lived heavy charged particles

Limits 95%
`usual` mSUGRA

- generic squarks and gluinos
- sbottom and stop
- gauginos → leptons

$\text{R conserved}$

$LSP = \chi_1^0$

missing energy

Note:

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

stop or sbottom might be light
Squarks and gluinos: jets and missing energy

\[ \tilde{g} \rightarrow q\tilde{\chi}_1^0 \]

\[ \tilde{q} \rightarrow \bar{q}\tilde{\chi}_1^0 \]

\( \sigma \) large!

CDF Run II Preliminary

3 jets

\[ \tan \beta = 5 \]

\[ \mu < 0 \]

\[ H_T > 280 \text{ GeV} \]

\[ \tilde{g} > 241 \text{ GeV} \]

\( \tilde{g}, \tilde{q} > 387 \text{ GeV} \)

for equal masses

Tevatron Run II:

- DØ observed
- DØ expected
- CDF observed
- CDF expected
- mSUGRA solution

no mSUGRA solution

\[ \tan \beta = 5(3) \]

\[ A_0 = 0 \quad \mu < 0 \]

\[ \sigma \text{ direct} \]

310/pb

371/pb

prel.
sbottom can be relatively light if large $\beta \tan$.
$\tilde{t} \rightarrow b l \nu \tilde{\chi}_1^0 \quad l = e, \mu$

$\tilde{t} \rightarrow t \nu \chi^0$

$\chi^- \rightarrow l^- l^+ \nu$

$\mu$ = 225 GeV

$\tan \beta = 20$

$MSSM$

D0 Preliminary

D0 Run II: (e, \mu) 350 pb$^{-1}$

D0 Run I: (e, \mu) 108 pb$^{-1}$

Stop
Charginos/Neutralinos → Leptons

**e.g.:**

- **Electroweak cross section small**
- **Gauginos light**

**Signatures:**
- $ee+l$ + $\mu^+\mu^-$
- $e/\mu+\tau+l$ + ...

**Search for $\chi^0_2\chi^+_1 \rightarrow ee+l+X$**

$$\int L \ dt = 346 \text{ pb}^{-1}$$

- After lepton selection

**CDF Run II Preliminary**

<table>
<thead>
<tr>
<th>Events (8.0 GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^0$</td>
</tr>
</tbody>
</table>

- mSugra point
- Drell-Yan
- WW, WZ, Zjj, Zll
- Fake Leptons
- Data

**DØ Run II Preliminary, 0.3-1.1 fb**

- $M(\chi^+_1)=M(\chi^0_2)=2M(\chi^0_1)$; $M(\tilde{t})>M(\chi^0_2)$
- $\tan\beta=3$, $\mu>0$, no slepton mixing

**Heavy squarks**

**31-max SUSY**

**LEP**

**Large-m$_0$ DØ limit**
Split SUSY

- Gluino metastable
- Stopping gluinos

Split mass scales:
- Heavy sfermions
- Light gauginos

Gluinos $\tilde{g}$ long lived form `R hadrons`
Split SUSY: stopping gluinos

charged R stops in detector isotr. decay $\rightarrow jet + \chi^0_0$ $\tau > 10 \mu s$ = many bunch crossings!

DO monojet event

cross section limits
$\sim 0.5-1.5$ pb for gluinos 200-550 GeV
$\tilde{g} > 270$ GeV

m(gluino)=400GeV m(LSP)=90GeV

Run 164170 Evt 62966279 Sat Feb 4 15:06:30 2006

Triggers:

- 1 MET
- EM
- ICD
- HAD
- CH

D$\Phi$ Preliminary (L=350pb$^{-1}$)

- Background
- Signal (m$_g$=400GeV, xs=0.62pb)
- Data

if LSP light
mSUGRA with R-parity violation

\[ W_{R_P} = \frac{1}{2} \lambda_{ijk} L_i L_j E_k + \lambda'_{ijk} L_i Q_j D_k + \frac{1}{2} \lambda''_{ijk} U_i D_j D_k \]

- **mSUGRA RPV**
  - R-parity violated

- lepton-lepton couplings (LLE)
- lepton-quark couplings (LQD)

- family indices
- lepton number violation
- difficult for hadron colliders

- \( R = (-1)^{3(B-L)+2s} \)

- LSP unstable!
  - ? dark matter?

- assume: only one RPV coupling \( \lambda \neq 0 \)
R-Parity Violation: LLE couplings  $\lambda_{ijk}$

- **production** of SUSY particles in $p \overline{p}$:
  - R conserving, two SUSY particles, e.g. $\chi^\pm_1 \chi^0_2$

- **decay**: R violating, e.g.

  a) $\lambda_{ijk} > O(10^{-2})$
  
  decay prompt, phenomenology independent of coupling

  b) $\lambda_{ijk} < O(10^{-2})$
  
  long lived particle, decay inside detector
Large LLE couplings: prompt decays

\[ \lambda_{121} \rightarrow e e + (e, \mu) \]
\[ \lambda_{122} \rightarrow \mu \mu + (\mu, e) \]
\[ \lambda_{133} \rightarrow \tau \tau + (\tau, e) \]

\[ \geq 4 \text{ charged leptons (require 3)} \]
+ missing energy

<table>
<thead>
<tr>
<th></th>
<th>D0 data</th>
<th>SM backgr.</th>
</tr>
</thead>
<tbody>
<tr>
<td>eel</td>
<td>0</td>
<td>0.9 ± 0.4</td>
</tr>
<tr>
<td>\mu \mu \mu</td>
<td>0</td>
<td>0.4 ± 0.1</td>
</tr>
<tr>
<td>\tau \tau \tau</td>
<td>0</td>
<td>1.3 ± 1.8</td>
</tr>
</tbody>
</table>
Small LLE couplings: long lived (MSSM)

NuTeV: \( pp \) 38 GeV
3 dimuon events
(0.07 expected)

\( \tilde{\chi}_1^0 \) = 5 GeV
MSSM

NuTeV 99% Exclusion
NuTeV 99% Preferred Region

\( \chi_1^0 \) = 5 GeV

\( \sigma(pp \rightarrow N_1^0 N_1^0 \rightarrow \mu^+ \mu^- + X) \) (Pb)

DØ simulation

\( E_T \) scale = 3 GeV

muons

Decay vertex

missing \( E_T \)

\( \tilde{\chi}_1^0 \) \( \tilde{q} \)

\( \tilde{\chi}_1^0 \) \( l^\pm \)

\( l^\pm \) \( \nu \)

\( \nu \) \( l'^{\mp} \)

\( \tilde{q} \)

\( q \)

TRANSLATED TO 1.96 TeV
R-Parity Violation: LQD couplings $\lambda'_{ijk}$ (prompt)

A) stop pairs

$\lambda'_{333}$

CDF Run II Preliminary (322 pb$^{-1}$)

- Observed
- Expected ($\pm\sigma$)

95% C.L. upper limit:

- $\sigma_{\text{NLO}} (pp \rightarrow \tilde{t}_1 \tilde{t}_1) \pm \sqrt{\sigma_{\text{PDF}}^2 + \sigma_{\text{scale}}^2}$
- $\text{Br}(\tilde{t}_1 \rightarrow b\tau) = 100\%$
- $m > 155 \text{ GeV/c}^2$
**R-Parity Violation: LQD couplings $\lambda'_{ijk}$ (prompt)**

### B) resonant slepton production

- **Graphical Representation**:
  - Diagram showing the process $\lambda'_{211}$.
  - Production of two muons ($2\mu$) and two jets ($2\text{jets}$).

- **Absolute slepton mass limits**:
  - $(\tilde{\mu}, \tilde{\nu}_\mu)$ mass limits.

### Table of Excluded slepton mass range and Coupling strength

<table>
<thead>
<tr>
<th>Excluded slepton mass range</th>
<th>Coupling strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m(\tilde{l}) \leq 210$ GeV</td>
<td>for $\lambda'_{211} \geq 0.04$</td>
</tr>
<tr>
<td>$m(\tilde{l}) \leq 340$ GeV</td>
<td>for $\lambda'_{211} \geq 0.06$</td>
</tr>
<tr>
<td>$m(\tilde{l}) \leq 363$ GeV</td>
<td>for $\lambda'_{211} \geq 0.10$</td>
</tr>
</tbody>
</table>

**Notes**:
- $d\bar{u}$ and $\bar{d}u$ indicate the relevant quark states.
- $\chi^0_1$ represents the Lightest Supersymmetric Particle (LSP).
- $A_0 = 0$ indicates a specific point on the exclusion contour graph for $\lambda'_{211}$. 
- $\text{D}0$, $0.38$ fb$^{-1}$ refers to a specific experiment and data point.
Gauge Mediated SUSY Breaking

$LSP = \tilde{G}$

missing energy

here:

$NLSP = \chi_1^0 \rightarrow \gamma \tilde{G}$

GMSB

LSP = light gravitino

photons + missing energy

$M_m$

$\Lambda$

$N_m$

tan $\beta$

sign($\mu$)

c$_{grav}$
GMSB: 2 photons + MET (prompt)

\[ NLSP = \chi_1^0 \]

e.g.: quark-antiquark pair

\[ \tilde{\chi}_1^+ \]
\[ \tilde{\chi}_1^- \]
\[ Z' \] or \( \gamma' \)

\[ \chi_1^0 \]
\[ \chi_1^+ \]
\[ \chi_1^- \]

\[ W^+ \]
\[ W^- \]

\[ \tilde{\chi}_1^0 \]
\[ \tilde{\chi}_1^+ \]
\[ \tilde{\chi}_1^- \]

\[ \gamma \]
\[ \tilde{\gamma} \]

\[ m(\chi_1^0) > 120 \text{ GeV} \]
\[ m(\chi_1^+) > 220 \text{ GeV} \]

Snowmass "Slope" SPS 8
\[ M_m = 2 \Lambda \]
\[ N_m = 1 \]
\[ \tan \beta = 15 \]
\[ \mu > 0 \]

\[ \chi_1^0 \]
\[ \chi_1^0 \]

\[ 4 \text{ events} \]
\[ 2.1 \pm 0.7 \text{ bkg} \]
Anomaly Mediated SUSY Breaking

- hidden sector
- messenger
- visible sector

susy masses through loops

- long lived heavy charged particles

AMS B:
mass degeneracies
Long lived staus or charginos

\textbf{GMSB:} decay $\tilde{\tau} \rightarrow \tau \tilde{G}$ suppressed

\textbf{AMSB:} mass difference $\chi_1^\pm - \chi_1^0$ small

heavy charged particle traversing slowly D0 detector

measured with scintillators in muon system

$$\frac{1 - \text{speed}}{\sigma_{\text{speed}}}$$

charged pair production
Summary and outlook

- Multitude of SUSY corners and signatures explored
- Stringent limits were set
- Significant improvements compared to Tevatron Run I (signal types analyzed and signal sensitivity)
- Tevatron limits often exceed LEP/Hera bounds or are complementary
- 0.2 - 1.1 fb analyzed, much more to come!
SPARE TRANSPARENCIES
Sbottom

A) direct production

B) via gluino decays

CDF Run 2

LEP

D0 310/pb

CDF 295/pb

Gluino → \tilde{b}, b, 95% C.L. Exclusion Limit, 156pb⁻¹
Stop pair production

\[ \tilde{t} \rightarrow c \tilde{\chi}_1^0 \quad \text{(FCNC)} \]

\[ \tilde{t} \rightarrow b l \nu \tilde{\chi}_1^0 \quad l = e, \mu \]

CDF Run II Preliminary (295 pb^{-1})

\[ M(t_1) \quad \text{(GeV/c}^2) \]

D0 Preliminary

\[ M(\tilde{\nu}) = M(\tilde{\chi}_1^0) \]

\[ \tan \beta = 20 \quad \mu = 225 \text{GeV} \]
Muon system
Toroid
Solenoid
PDT's
Liquid Argon Calorimeter
Silicon and
Scintillating Fiber Tracker

D0
Cross Sections at Hadron Colliders
Squark gluino limits
CDF tau sneutrino (RPV)

2 couplings!

CDF Run 2 Preliminary, 344 pb$^{-1}$

$\lambda'_{311}$ $\lambda_{132}$
CDF long lived neutralino, GMSB decay
CDF di-photon event
Charginos/Neutralinos $\rightarrow$ Leptons

e.g.: 

``golden'' trilepton + missing energy signature

electroweak cross section small

gauginos light

signatures:
$ee +e/\mu \quad \mu \mu +e/\mu \quad e^+e^+ / e^-e^-$

CDF Run II Preliminary: $L=310$-750 pb$^{-1}$

MSSM: $\tan\beta=3$, $\mu>0$, $M(\tilde{\chi}^0_2)-M(\tilde{\chi}_1^0)-2M(\tilde{\tau}_1)$

M($\tilde{e}$)=M($\tilde{\mu}$)=M($\tilde{\tau}$)

Search for $\chi_{2}\chi_1 \rightarrow ee + l + X$

CDF Run II Preliminary

$\int L \, dt = 346 \text{ pb}^{-1}$ after lepton selection

Expected Limit $\pm 1\sigma$

95% CL Upper Limit: observed

95% CL Upper Limit: expected

$m$Sugra point

Drell-Yan

$WW, WWZ, WWZ^*$

Fake Leptons

Data

$\sigma_{\text{NLO} \times \text{BR}}$ (3 leptons) (pb)

$\sigma_{\text{NLO} \times \text{BR Uncertainty}}$

Excluded by LEP
Charginos/Neutralinos $\rightarrow$ Leptons

Signatures:
- $ee+l$
- $\mu^-\mu^- / \mu^+\mu^+$
- $e / \mu + \tau + l$ + ...

Diagram showing the decay process:
- $W^*$ decays to $q\chi_1^\pm$
- $\chi_1^0$ -> $l\nu$
- $\chi_2^0$ -> $\tau\nu$

Graph showing $ee+l$ events with MET and $p_T^Z$ as variables.
Chiral supermultiplets

<table>
<thead>
<tr>
<th>Gauge multiplet</th>
<th>Chiral multiplet</th>
</tr>
</thead>
<tbody>
<tr>
<td>J = 1</td>
<td>J = 1/2</td>
</tr>
<tr>
<td>g</td>
<td>$\tilde{g}$</td>
</tr>
<tr>
<td>$W^\pm, W^0$</td>
<td>$\tilde{W}^\pm, \tilde{W}^0$</td>
</tr>
<tr>
<td>$B^0$</td>
<td>$\tilde{B}^0$</td>
</tr>
<tr>
<td>$Q_L, U_L^C, D_L^C$</td>
<td>$\tilde{Q}_L, \tilde{U}_L^C, \tilde{D}_L^C$</td>
</tr>
<tr>
<td>$L_L, E_L^C$</td>
<td>$\tilde{L}_L, \tilde{E}_L^C$</td>
</tr>
</tbody>
</table>

from Luc Pape

<table>
<thead>
<tr>
<th>Charge</th>
<th>Scalar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q</td>
<td>$Q = (\tilde{u}_L, \tilde{d}_L)$</td>
</tr>
<tr>
<td>$U_L^C$</td>
<td>$U_L^C = \tilde{u}_L^c$</td>
</tr>
<tr>
<td>$D_L^C$</td>
<td>$D_L^C = \tilde{d}_L^c$</td>
</tr>
<tr>
<td>L</td>
<td>$L = (\tilde{v}_L, \tilde{e}_L)$</td>
</tr>
<tr>
<td>$E_L^C$</td>
<td>$E_L^C = \tilde{e}_L^c$</td>
</tr>
<tr>
<td>$H_d$</td>
<td>$H_d = (H_d^0, H_d^-)$</td>
</tr>
<tr>
<td>$H_u$</td>
<td>$H_u = (H_u^+, H_u^0)$</td>
</tr>
</tbody>
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