RPV SUSY searches at HERA

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on behalf of the
ZEUS and H1 Collaborations
Contents

• HERA II e±p collider, now polarized: 25-40%
• R-Parity violation leads to production of Squarks, Gauginos subsequent decay also through other channels
• ZEUS: light stop decaying to chargino
• H1: light stop decaying to sbottom
• H1, ZEUS: GMSB Neutralino decaying to photon + Gravitino
• ZEUS: Neutralino or Chargino with RPV decay
• H1: more general squark search
• Conclusion, outlook
HERA I/II Data ‘on tape’

HERA I and HERA II

H1 integrated luminosity
Summer 2005

unpolarized electrons
left and right–handed positrons
unpolarized positrons
left and right–handed electrons

HERA II
- 2001 upgrade
- 2002+2003 struggling
- 2004+2005 good!
- Polarized $e^\pm$!
- $e^+p$: 0.7/0.35 $\times$ Hera I
- $e^-p$: 4.5 $\times$ HERA I !!!!

Status Analyses:
- HERA I data only..
- H1 published in 2004
- ZEUS preliminary
RPV Production: squark or gaugino

R-parity violation:
\[ \lambda'_{ijk} \cdot \left( -\tilde{e}^i_L u^j_L \tilde{d}^k_R + e^i_L \tilde{u}^j_L \tilde{d}^k_R - (\tilde{e}^i_L)^c u^j_L \tilde{d}^k_R \right) \]

\[ \lambda'_{ijk} L^i_L Q^j_L \tilde{D}^k_R = \]
\[ -\tilde{\nu}^i_L d^j_L \tilde{d}^k_R - v^i_L \tilde{d}^j_L \tilde{d}^k_R - (\tilde{\nu}^i_L)^c u^j_L \tilde{d}^k_R \] + c.c.

• valence \( u, d \) in proton dominate, \( u \geq 2 \cdot d \) at high \( x_{BJ} \)
• s-channel single squark production, like a leptoquark
  \( \sqrt{\lambda'_{11k}} : e^- + u \rightarrow \tilde{d}^k_R \)
  \( \sqrt{\lambda'_{1j1}} : e^+ + d \rightarrow \tilde{u}^j_L \)
• assume only one \( \lambda'_{ijk} > 0 \)

\( \tilde{t} \)-channel slepton exchange
⇒ gaugino production
✓ slepton masses low?
Gauginos decays

- Heavy gaugino cascades down to lighter $\chi_1^0$
  - $\chi^+ \rightarrow W^+ \chi_1^0$
  - $\chi_2^0 \rightarrow e^+ \bar{\tilde{e}}^-, \bar{\tilde{e}}^- \rightarrow e^- \chi_1^0$
  - ... depends strongly on mass spectrum ...

- RPV 3-body decay through virtual slepton or squark
  - $\chi_1^0 \rightarrow e^+ \bar{\tilde{e}}^-, \bar{\tilde{e}}^- \rightarrow \bar{u}d^k$
  - $\chi_1^0 \rightarrow \bar{u}\tilde{u}, \tilde{u} \rightarrow e^+ d^k$
  - ...

- Alternative: Gauge Mediated Susy Breaking with Gravitino LSP, low mass, invisible
  - $\chi_1^0 \rightarrow \tilde{G}\gamma$
  - Signature: photon + missing $P_t$
Squark decays

• Direct RPV decay: like leptoquark
  ✓ B.R. large for massive gaugino and large \( \lambda' \)
  ✓ \( \Rightarrow \) Contribute to limit at highest squark mass
  ✓ Final state like SM NC or CC DIS
  ✓ Invariant mass peak
  ✓ Angular distributions differ

• MSSM Gauge decays
  ✓ 1 or 2-step cascade to ever lighter gluino, chargino, neutralino
    e.g. \( \tilde{u}_L^j \rightarrow \chi_2^0 \tilde{u}_L^j, \chi_2^0 \rightarrow Z \chi_1^0 \)
  ✓ RPV 3-body decay through virtual slepton or squark:
    e.g. \( \chi_1^0 \rightarrow e^+ \tilde{e}^-, \tilde{e}^- \rightarrow \bar{u}d^k \)
  ✓ Final state differs from SM NC or CC DIS:
    1. One or more leptons, neutrinos (missing \( P_t \))
    2. Electron from neutralino can have wrong sign (majorana fermion)
    3. Multiple high-E\( t \) jets, high circularity
    4. Invariant mass peak
ZEUS: light stop decay via chargino

- Heavy $\tilde{b}$ and $\tilde{g}$
- Direct RPV decay $\tilde{t} \rightarrow e^+ d$
- Decay via chargino + beauty
- Ignore $\tilde{t} \rightarrow t\chi_1^0, t\tilde{g}, \tilde{b}W^+$ final states
- Final state like NC or CC DIS, jets

$\chi_1^+$

$W^+$

$f'$

$\nu_e$

$t_1$

$b$

$\tilde{t}_1$

$\tilde{b}$

$e^+$

$d$

$g$

$t \chi_1^0, t \tilde{g}, \tilde{b}W^+$

$100 \text{ GeV} < M_1 < 300 \text{ GeV}$

$-300 \text{ GeV} < \mu < 300 \text{ GeV}$

$tan\beta = 6$

$M_1 = M_2 = M_3$ at GUT scale, sfermion masses free

20 July 2005

Nichol Brümmer, SUSY-2005, Durham
H1: stop decay to sbottom + W

- \( m_{\tilde{b}_1} + m_W < m_{\tilde{t}_1} < m_{\chi^+} + m_b, m_{\chi^0} + m_t \)

- Cannot explain H1 excess events with lepton + \( P_{t,\text{miss}} + \) jet

- Limits given for this decay and direct RPV 'leptoquark'-decay only.

\[
\begin{align*}
\ell^+, \bar{q} & \\
\nu, q' & \\
\bar{\nu}_e & \\
\tilde{b} & \\
\tilde{t} & \\
\chi'_{131} & \\
\chi_{131} & \\
d & \\
d & \\
d & \\
\end{align*}
\]
GMSB Gaugino decay to Gravitino

- Signature: $P_{T,\text{miss}}$ and photon
- Slepton exchange only
- Heavy squarks avoid APV, CCU
  $\Rightarrow \lambda'_{11k}, \lambda'_{1j1}$ as large as 1 for $j,k \neq 1$
- $M_{\gamma\tilde{G}}$ using constraints of $E-P_z$, $P_{T,\text{miss}}$
ZEUS: RPV decay of Gaugino

- Assume squarks heavy, sleptons 100 GeV, $\lambda'_{111} = 1$
- Use 121 pb$^{-1}$ of $e^+p$ collisions from 1996–2000
- Final state has positron or neutrino and 3 jets
- Wrong sign electron too forward to distinguish..
- Define discriminant function of 6 variables
- CC-like final state with neutrino not (quite) done
### H1: comprehensive squark search

<table>
<thead>
<tr>
<th>Channel</th>
<th>$e^+p$ collisions</th>
<th>$e^-p$ collisions</th>
<th>Eff.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DATA</td>
<td>SM exp.</td>
<td>DATA</td>
</tr>
<tr>
<td>$eq$</td>
<td>632</td>
<td>$628\pm46$</td>
<td>204</td>
</tr>
<tr>
<td>$ev$</td>
<td>-</td>
<td>-</td>
<td>261</td>
</tr>
<tr>
<td>$e+ jets$</td>
<td>72</td>
<td>$67.5\pm9.5$</td>
<td>20</td>
</tr>
<tr>
<td>wrong $e+ jets$</td>
<td>0</td>
<td>$0.20\pm0.14$</td>
<td>0</td>
</tr>
<tr>
<td>$ee+ jets$</td>
<td>0</td>
<td>$0.91\pm0.51$</td>
<td>0</td>
</tr>
<tr>
<td>$e\mu+ jets$</td>
<td>0</td>
<td>$0.91\pm0.38$</td>
<td>0</td>
</tr>
<tr>
<td>$ve+ jets$</td>
<td>0</td>
<td>$0.74\pm0.26$</td>
<td>0</td>
</tr>
<tr>
<td>$\nu+ jets$</td>
<td>30</td>
<td>$24.3\pm3.6$</td>
<td>12</td>
</tr>
<tr>
<td>$\nu\mu+ jets$</td>
<td>0</td>
<td>$0.61\pm0.12$</td>
<td>0</td>
</tr>
</tbody>
</table>
H1: important to cover final states!

- For the reaction $e^+ p \rightarrow \tilde{u}_L^{j=1,2}$, the BR is shown for $M_{\text{slepton}} = M_{\text{squark}}$.
- For the reaction $e^- p \rightarrow \tilde{d}_L^{k=1,2}$, the BR is shown for $M_{\text{slepton}} = M_{\text{squark}}$.

B.R. of considered states
Sum to nearly 100% for
Different Model assumptions.
Example here: sleptons with
mass equal to squarks or much lighter, 90 GeV.
Final limit nearly the same!
H1: MSSM with degenerate sfermions

$$\lambda'_{1j1} : e^+ p \rightarrow \tilde{u}^j_{L=1,2}$$

$$\lambda'_{11k} : e^- p \rightarrow \tilde{d}^k_{R=1,2}$$

Unconstrained MSSM, $j=1,2$

Unconstrained MSSM, $k=1,2$

H1

EXCLUDED

$$\lambda'_{121} \quad \text{(APV)}$$

$$\lambda'_{112} \quad \text{(CCU)}$$

$$\tan \beta = 6$$

$$-300 < \mu < 300 \text{ GeV}$$

$$70 < M_2 < 350 \text{ GeV}$$

$$M_{\text{LSP}} > 30 \text{ GeV} \text{ Imposed}$$
\( \lambda'_{1j1} : e^+ p \rightarrow \tilde{u}_L^{j=1,2}, \tilde{t}_L \)

\( \lambda'_{11k} : e^- p \rightarrow \tilde{d}_R^{k=1,2}, \tilde{b}_R \)

**H1: MSSM with degenerate sfermions**

Unconstrained MSSM, \( j=1,2 \)

Unconstrained MSSM, \( k=1,2 \)

\( 10^{-2} \) to \( 10^{-1} \)

\( \tan \beta = 6 \)

-300 \( < \mu < 300 \) GeV

70 \( < M_2 < 350 \) GeV

\( M_{\text{LSP}} > 30 \) GeV Imposed
H1: mSUGRA limits in plane $m_{1/2}$ vs. $m_0$

For $\tan \beta = 2$:

- $\lambda'_{1j1} : e^+ p \rightarrow \tilde{u}, \tilde{c}, \tilde{t}$
- $\lambda'_{11k} : e^- p \rightarrow \tilde{d}, \tilde{s}, \tilde{b}$

For $\tan \beta = 6$:

- $\lambda'_{1j1} : e^+ p \rightarrow \tilde{u}, \tilde{c}$
- $\lambda'_{11k} : e^- p \rightarrow \tilde{d}, \tilde{s}$

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H1: mSUGRA limit on $m_{1/2} = m_0$ vs $\tan \beta$

- Finally constrain to diagonal $m_{1/2} = m_0 = M$
- Mixing of stop sbottom states depends on $\tan \beta$
  - mass of light state decreases at high $\tan \beta$
  - can exclude higher values of $M$ for same squark mass
- For $\tan \beta > 37$ final states with light stau contribute
Conclusion

• HERA results on RPV-SUSY
  - complementary, competitive to LEP, Tevatron, low energy limits
  - ZEUS light stop search beats APV limits when \( m_{\tilde{t}} < 250 \text{GeV} \)
  - H1: light stop \( \rightarrow \) sbottom + W, if \( \lambda'_{131} = 0.3 \), then \( m_{\tilde{t}} > 260 - 275 \text{GeV} \)
  - GMSB neutralino \( \rightarrow \) Gravitino + \( \gamma \), for \( \lambda'_{1jj} = 1 \),
    \( m_{\tilde{\chi}_i^0} > 112 \text{GeV} \) if \( m_{\tilde{\chi}_i^0} \approx m_{\tilde{\chi}_i^0} \) or \( m_{\tilde{\chi}_i^0} > 164 \text{ GeV} \) if \( m_{\tilde{\chi}_i^0} \approx 55 \text{ GeV} \)
  - ZEUS: RPV-decaying gauginos: \( M_2 > 160 \text{ GeV} \) if \( \lambda'_{111} = 1 \), \( m_{\tilde{\chi}_i^0} = 100 \text{GeV} \)
  - H1: combine many channels, MSSM, mSUGRA limits,
    if \( \lambda'_{1jk} = 0.3 \), squark masses up to 280 GeV are excluded,
    with some dependence on the SUSY-parameters.

• HERA II is producing good data
  - Polarized \( e^\pm \) beam: RPV couplings are chiral
  - HERA II total luminosity already equals that of HERA I
  - The HERA II \( e^-p \) sample already \( 4.5 \times \) HERA I !!