Search for SUSY R-Hadrons

Morten Dam Jørgensen (Niels Bohr Institute) on behalf of the ATLAS Collaboration

Overview

- What are R-Hadrons
- Detection methods
- Latest results
What are R-Hadrons

- **Coloured** Massive Particles, i.e. gluinos, squarks
- **Assumed Long-lived** (in our searches)
- Predicted by numerous BSM models including many SUSY scenarios
- **Slow moving** at LHC energies $\beta < 1$
- **Hadronises** with light SM quarks into bound states called $R$-Hadrons
  - Electr**Electrically charged** in specific bound states
  - **Nuclear scattering** of the light quark system with detector causing electrical charge change
- No interaction between detector and primary parton ($\sigma \propto 1/m^2$) assumed

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**SUSY SMP states**

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<table>
<thead>
<tr>
<th>SMP</th>
<th>LSP</th>
<th>Scenario</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{\tau}_1$</td>
<td>$\tilde{\chi}_1^0$</td>
<td>MSSM</td>
<td>$\tilde{\tau}<em>1$ mass (determined by $m</em>{\tilde{\tau}_{L,R}}$, $\mu$, $\tan \beta$, and $A_t$) close to $\tilde{\chi}_1^0$ mass.</td>
</tr>
<tr>
<td>$\tilde{G}$</td>
<td>$\tilde{G}$</td>
<td>GMSB</td>
<td>Large $N$, small $M$, and/or large $\tan \beta$.</td>
</tr>
<tr>
<td>$\tilde{g}$</td>
<td>$\tilde{G}$</td>
<td>GMSB</td>
<td>No detailed phenomenology studies, see [23].</td>
</tr>
<tr>
<td>SUSRA</td>
<td>Supergravity with a gravitino LSP, see [24].</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\tilde{\tau}_1$</td>
<td>$\tilde{\chi}_1^0$</td>
<td>MSSM</td>
<td>Small $m_{\tilde{\tau}_{L,R}}$ and/or large $\tan \beta$ and/or very large $A_t$.</td>
</tr>
<tr>
<td>AMSB</td>
<td>Small $m_0$, large $\tan \beta$.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\tilde{g}$</td>
<td>$\tilde{G}$</td>
<td>MSB</td>
<td>Generic in minimal models.</td>
</tr>
<tr>
<td>$\tilde{\tilde{\tau}}_1$</td>
<td>$\tilde{G}$</td>
<td>GMSB</td>
<td>$\tilde{\tau}_1$ NLSP (see above). $\tilde{e}_1$ and $\tilde{\mu}_1$ co-NLSP and also SMP for small $\tan \beta$ and $\mu$.</td>
</tr>
<tr>
<td>$\tilde{\tau}_1$</td>
<td>$\tilde{G}$</td>
<td>GMSB</td>
<td>$\tilde{e}_1$ and $\tilde{\mu}_1$ co-LSP and also SMP when stau mixing small.</td>
</tr>
<tr>
<td>$\tilde{\chi}_1^+ \tilde{\chi}_1^-</td>
<td>$ MSSM</td>
<td>$m_{\tilde{\chi}<em>1^+} - m</em>{\tilde{\chi}<em>1^-} \ll m</em>{\tilde{\chi}<em>1^0}$. Very large $M</em>{1,2} \gtrsim 2$ TeV, $</td>
<td>\mu</td>
</tr>
<tr>
<td>AMSB</td>
<td>$M_1 &gt; M_2$ natural. $m_0$ not too small. See MSSM above.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\tilde{g}$</td>
<td>$\tilde{\chi}_1^0$</td>
<td>MSSM</td>
<td>Very large $m_0^2 \gg M_2$, e.g. split SUSY.</td>
</tr>
<tr>
<td>$\tilde{G}$</td>
<td>$\tilde{G}$</td>
<td>GMSB</td>
<td>SUSY GUT extensions [25–27].</td>
</tr>
<tr>
<td>$\tilde{g}$</td>
<td>$\tilde{G}$</td>
<td>GMSB</td>
<td>SUSY GUT extensions [25–29].</td>
</tr>
<tr>
<td>$\tilde{\tilde{\tau}}_1$</td>
<td>$\tilde{\chi}_1^0$</td>
<td>MSSM</td>
<td>Non-universal squark and gaugino masses. Small $m_{\tilde{q}}^2$ and $M_3$, small $\tan \beta$, large $A_t$.</td>
</tr>
<tr>
<td>$\tilde{b}_1$</td>
<td>Small $m_{\tilde{b}}^2$ and $M_3$, large $\tan \beta$ and/or $A_t \gg A_\tau$.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1

Brief overview of possible SUSY SMP states considered in the literature. Classified by SMP, LSP, scenario, and typical conditions for this case to materialise in the given scenario.
R-Hadron detection in ATLAS

- Velocity as discriminator
- Time of flight
- Specific Energy Loss
- No physics background, only instrumental effects
- Estimate mass by velocity and momentum
- Can become neutral after hadronic interactions
- Unique charge flipping as signature

Muon spec. ToF
arXiv:1106.4495

Calo ToF
arXiv:1103.1984

TRT “dE/dx”
arXiv:1103.1984

Calo dE/dx
- Charge flipping
cds.cern.ch:1370233 (thesis)

Pixel dE/dx
ATLAS-CONF-2011-016
Inner detector only search

- Most recent result \(2.06 \text{ fb}^{-1}\)
- Pixel \(dE/dx\) Estimator
  - Calibrated on slow SM particles
- Missing Energy Trigger MET > 70 GeV
- Offline MET > 85 GeV
- \(p > 100 \text{ GeV}\)
- Pixel \(dE/dx\) > 1.8 MeV g\(^{-1}\) cm\(^2\)
- Distance to nearest track > 0.25
- Distance to nearest jet > 0.3

ATLAS-CONF-2012-022

**Search for SUSY R-hadrons**

**Inner detector only search**

- **Most recent result** \(2.06 \text{ fb}^{-1}\)
- **Pixel \(dE/dx\) Estimator**
  - Calibrated on slow SM particles
- **Missing Energy Trigger** MET > 70 GeV
- **Offline MET** > 85 GeV
- \(p > 100 \text{ GeV}\)
- **Pixel \(dE/dx\)** > 1.8 MeV g\(^{-1}\) cm\(^2\)
- Distance to nearest track > 0.25
- Distance to nearest jet > 0.3

**2010 Pixel mass (ID+Calo)**

**Proton mass run stability**

**Signal \(dE/dx\) response**

**Signal mass estimates**
Results

- Increased statistics

- No significant deviation from the Standard Model

- Upper limit: <0.1 pb (CLs method 95% CL)

- Gluino mass exclusion up to 810 GeV for Split-SUSY models (ID+Calo 2010 Limit: ~580 GeV)
Conclusion

- Nearly all sub detectors in ATLAS have R-Hadron discrimination capabilities
- New limit from ATLAS on inner detector only searches for R-Hadrons.
- Many other searches ongoing
- We try to avoid heavy model dependence (beyond nuclear scattering) but input from theorists is welcomed!
Backup slides
Pixel counting tables

<table>
<thead>
<tr>
<th>Cut level</th>
<th>Gluino 400 GeV</th>
<th></th>
<th>Gluino 700 GeV</th>
<th></th>
<th>Gluino 1000 GeV</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger</td>
<td>0.205</td>
<td>0.205</td>
<td>0.219</td>
<td>0.219</td>
<td>0.177</td>
<td>0.177</td>
</tr>
<tr>
<td>Offline $E_T^{miss}$</td>
<td>0.976</td>
<td>0.200</td>
<td>0.987</td>
<td>0.216</td>
<td>0.984</td>
<td>0.175</td>
</tr>
<tr>
<td>Primary vtx</td>
<td>0.998</td>
<td>0.200</td>
<td>1.000</td>
<td>0.216</td>
<td>1.000</td>
<td>0.175</td>
</tr>
<tr>
<td>High-$p_T$</td>
<td>0.594</td>
<td>0.120</td>
<td>0.582</td>
<td>0.129</td>
<td>0.592</td>
<td>0.108</td>
</tr>
<tr>
<td>Isolation</td>
<td>0.840</td>
<td>0.100</td>
<td>0.838</td>
<td>0.105</td>
<td>0.879</td>
<td>0.091</td>
</tr>
<tr>
<td>High-$p$</td>
<td>0.993</td>
<td>0.099</td>
<td>0.988</td>
<td>0.104</td>
<td>0.999</td>
<td>0.091</td>
</tr>
<tr>
<td>ionization</td>
<td>0.663</td>
<td>0.067</td>
<td>0.804</td>
<td>0.085</td>
<td>0.923</td>
<td>0.084</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cut level</th>
<th># Events</th>
<th>Cut Eff.</th>
<th>Total Eff.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger</td>
<td>2,413,863</td>
<td>0.589</td>
<td>0.589</td>
</tr>
<tr>
<td>Offline $E_T^{miss}$</td>
<td>1,421,497</td>
<td>0.567</td>
<td></td>
</tr>
<tr>
<td>Primary vtx</td>
<td>1,368,821</td>
<td>0.0133</td>
<td>0.0133</td>
</tr>
<tr>
<td>High-$p_T$</td>
<td>212,464</td>
<td>0.0880</td>
<td></td>
</tr>
<tr>
<td>Isolation</td>
<td>32,188</td>
<td>8.7E-03</td>
<td></td>
</tr>
<tr>
<td>High-$p$</td>
<td>21,040</td>
<td>1.4E-04</td>
<td></td>
</tr>
<tr>
<td>ionization</td>
<td>333</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Search for SUSY R-hadrons

2010

Muon Spectrometer, 2010

\[
\int L dt = 37 \text{ pb}^{-1}
\]

Cross-section [pb]

\[\begin{array}{c}
\text{ATLAS} \\
\text{g production} \\
\text{g-ball fraction} = 0.1 \\
\text{g-ball fraction} = 0.5 \\
\text{g-ball fraction} = 1.0 \\
\text{expected limit} \pm \sigma
\end{array}\]

\[m_\tilde{g} \text{ [GeV]} \]

\[10^2, 10^1, 10^0, 10^{-1} \]

Inner detector & Calorimeter 2010
Detection methods

- Velocity as discriminator
  - Time of flight
  - Specific Energy Loss
- No physics background, only instrumental effects
- Estimate mass by velocity and momentum
- Can become neutral after hadronic interactions
- Unique charge flipping as signature

\[ m = \frac{p}{\beta} \sqrt{1 - \beta^2} \]

\[ m = \frac{p}{\beta \gamma} \]

\[ -\left\langle \frac{dE}{dx} \right\rangle = K Z^2 \frac{1}{A \beta^2} \times \left[ \frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{\text{max}}}{I^2} - \beta^2 - \delta(\beta \gamma) \right] \sim \frac{1}{\beta \gamma^2} \]
Search strategies in ATLAS

- Multiple searches with variation of sub detectors to maximise model coverage

- **General selection**
  - Trigger (MET or Muons)
  - Momentum cut
  - Isolation (from polluting tracks, jets)
  - Data driven background estimation

- **Search specific selection**
  - *Short lifetime, High hadronic interaction probability*
    - **ID only**: Pixel dE/dx
  - *Intermediate lifetimes, moderate hadronic interaction*
    - **ID+Calo**: Pixel dE/dx and Calo ToF
  - *Long lifetime, low mass*
    - **MS only**: Candidates that were neutral in ID but became charged by interactions.

- Inclusive, **maximum detector acceptance**
  - **ID+Calo+MS**: Require a minimum of compatible estimates, “semi-multivariate” methodology
SUSY limits (dec 2011)
Theoretical predictions

- “Split-SUSY”-like predictions
- Cross sections calculated with Prospino 2.1
- Decoupled mass scales, emulating infinite life-time by decay suppression

<table>
<thead>
<tr>
<th>Mass (GeV)</th>
<th>( \sigma ) (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>21200</td>
</tr>
<tr>
<td>200</td>
<td>625</td>
</tr>
<tr>
<td>300</td>
<td>62.1</td>
</tr>
<tr>
<td>400</td>
<td>10.4</td>
</tr>
<tr>
<td>500</td>
<td>2.34</td>
</tr>
<tr>
<td>600</td>
<td>0.634</td>
</tr>
<tr>
<td>700</td>
<td>0.194</td>
</tr>
<tr>
<td>800</td>
<td>0.0651</td>
</tr>
<tr>
<td>900</td>
<td>0.0233</td>
</tr>
<tr>
<td>1000</td>
<td>0.00867</td>
</tr>
</tbody>
</table>

Assumptions
Prospino 2.1 NLO
SUSY Splitting scale 10 TeV
\( \sqrt{s} = 7 \) TeV
CTEQ 6.6 & MSTW 2008
Th. uncertainty represents K-factor variation
Limit

![Plot with mass vs. cross section for ATLAS preliminary results.](https://example.com/atlas_plot.png)
Mass distribution

![Graph showing mass distribution with data points and different mass distributions for different hadron energies.](image)
Pixel dE/dx mass estimator - proton mass stability

Data Period (March - August 2011)

ATLAS Preliminary