Discovery Potential of R-hadrons with the ATLAS Detector at the LHC

Berkeley Workshop on Physics Opportunities with Early LHC Data

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on behalf of the ATLAS Collaboration

Stockholm University

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Outline

1 Introduction
   - Motivation
   - R-hadron production and their interactions

2 Analysis
   - MC samples
   - Trigger
   - Final state observables & cuts
   - Results

3 Recent developments

4 Summary & conclusions
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Motivation

- Stable massive particles (SMPs) predicted in a range of SUSY and other BSM scenarios
- Within SUSY: SMPs with different color and electric charges
  - $\tilde{q}$ / $\tilde{g}$ (bound states)
  - $\tilde{\ell}$ or $\tilde{\chi}^+$
- Production processes can have high cross-sections $\Rightarrow$ important early analysis

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In this context, “stable” means decay lengths $\sim$ size of ATLAS

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Table 1

<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 $m</em>{\tilde{\tau}<em>{L,R}}$, $\mu$, $\tan \beta$, and $A</em>{\tau}$) close to $\tilde{\chi}_1^0$ mass.</td>
</tr>
<tr>
<td>$\tilde{G}$</td>
<td>$\tilde{G}$</td>
<td>GMSSB</td>
<td>Large $N$, small $M$, and/or large $\tan \beta$.</td>
</tr>
<tr>
<td>$\tilde{g}$</td>
<td>$\tilde{g}$</td>
<td>jMSB</td>
<td>No detailed phenomenology studies, see [23].</td>
</tr>
<tr>
<td>SUGRA</td>
<td></td>
<td></td>
<td>Supergravity with a gravitino LSP, see [24].</td>
</tr>
<tr>
<td>$\tilde{\tau}_1$</td>
<td>$\tilde{\chi}_1^0$</td>
<td>MSSM</td>
<td>Small $m_{\tilde{\tau}<em>{L,R}}$ and/or large $\tan \beta$ and/or very large $A</em>{\tau}$.</td>
</tr>
<tr>
<td>AMSB</td>
<td>$\tilde{\chi}_1^0$</td>
<td>AMSB</td>
<td>Small $m_0$, large $\tan \beta$.</td>
</tr>
<tr>
<td>$\tilde{\ell}_1$</td>
<td>$\tilde{\ell}_1$</td>
<td>GMSSB</td>
<td>$\tilde{\ell}$ NLSP (see above), $\tilde{\ell}_1$ co-NLSP and also SMP for small $\tan \beta$ and $\mu$.</td>
</tr>
<tr>
<td>$\tilde{\tau}_1$</td>
<td>$\tilde{\chi}_1^0$</td>
<td>jMSB</td>
<td>$\tilde{\ell}_1$ and $\tilde{\mu}_1$ co-LSP and also SMP when stau mixing small.</td>
</tr>
<tr>
<td>$\tilde{\chi}_1^+$</td>
<td>$\tilde{\chi}_1^0$</td>
<td>MSSM</td>
<td>$m_{\tilde{\chi}<em>1^+} - m</em>{\tilde{\chi}<em>1^0} \approx m</em>{\tau}$. Very large $M_{1,2} \gtrsim 2$ TeV $\gg</td>
</tr>
<tr>
<td>AMSB</td>
<td></td>
<td></td>
<td>$M_1 &gt; M_2$ natural. $m_0$ not too small. See MSSM above.</td>
</tr>
<tr>
<td>$\tilde{g}$</td>
<td>$\tilde{g}$</td>
<td>MSSM</td>
<td>Very large $m_3^2 \gg M_1$, e.g. split SUSY.</td>
</tr>
<tr>
<td>$\tilde{G}$</td>
<td>$\tilde{G}$</td>
<td>GMSSB</td>
<td>SUSY GUT extensions [25–27].</td>
</tr>
<tr>
<td>$\tilde{g}$</td>
<td>$\tilde{g}$</td>
<td>MSSM</td>
<td>Very small $M_1 \ll M_{1,2}$, O-II models near $\delta_{GS} = -3$.</td>
</tr>
<tr>
<td>GMSB</td>
<td></td>
<td></td>
<td>SUSY GUT extensions [25–29].</td>
</tr>
<tr>
<td>$\tilde{\ell}_1$</td>
<td>$\tilde{\chi}_1^0$</td>
<td>MSSM</td>
<td>Non-universal squark and gaugino masses. Small $m_{\tilde{q}}^2$ and $M_1$, small $\tan \beta$, large $A_t$.</td>
</tr>
<tr>
<td>$\tilde{b}_1$</td>
<td>$\tilde{\chi}_1^0$</td>
<td>MSSM</td>
<td>Small $m_{\tilde{b}}^2$ and $M_1$, large $\tan \beta$ and/or large $A_b \gg A_t$.</td>
</tr>
</tbody>
</table>

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.

Focus of this analysis: R-hadrons

What are they?
A stable color charged object will hadronize and form R-hadrons

- current mass limits on R-hadrons \( \lesssim 250 \text{ GeV} \)
- R-hadron is a heavy hadron with
  - one heavy sparticle parton that carries most of the hadron’s momentum
  - a light quark system (LQS)

How do they interact?

- heavy parton unlikely to interact (cross-section suppressed by \( \frac{1}{m^2} \))
- LQS interacting with detector material can cause exchange of
  - electric charge
  - baryon number

Focus of this analysis: R-hadrons

Scenarios giving rise to R-hadrons

Split-SUSY

- gaugino and higgsino masses much smaller than scalar masses
- For high $m_{\tilde{q}}$, the $\tilde{g}$ is long-lived enough to fly out through ATLAS

Models with $\tilde{G}$ LSP and $\tilde{t}_1$ NLSP

- $\tilde{t}_1$ will hadronize to R-hadron if $m_{\tilde{t}_1} - m_{\tilde{G}}$ sufficiently small
Focus of this analysis: R-hadrons

R-hadron production

- For a conservative estimate, only $gg$ fusion is considered for $R_{\tilde{g}}$-hadrons ($q\bar{q} \rightarrow \tilde{g}\bar{\tilde{g}}$ also exist, but introduces $m_{\tilde{q}}$ dependence)
- $R_{\tilde{t}}$-hadrons both via $gg$ fusion and $q\bar{q}$ annihilation
- LO diagrams:

![Diagram of R-hadron production processes]
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Analysis overview

This analysis was part of the ATLAS Computing System Commissioning (CSC) exercise and optimized for 1 fb$^{-1}$ of data at 14 TeV. An analysis is currently being developed for 100 pb$^{-1}$ at 10 TeV.

MC signal samples

<table>
<thead>
<tr>
<th>Sparticle</th>
<th>Mass (GeV)</th>
<th>Events/fb$^{-1}$</th>
<th>$\mathcal{L}$ (fb$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{g}$</td>
<td>300</td>
<td>$2.69 \times 10^5$</td>
<td>$3.72 \times 10^{-2}$</td>
</tr>
<tr>
<td>$\tilde{g}$</td>
<td>600</td>
<td>$4.84 \times 10^3$</td>
<td>2.07</td>
</tr>
<tr>
<td>$\tilde{g}$</td>
<td>1000</td>
<td>138</td>
<td>72.5</td>
</tr>
<tr>
<td>$\tilde{g}$</td>
<td>1300</td>
<td>16.4</td>
<td>610</td>
</tr>
<tr>
<td>$\tilde{g}$</td>
<td>1600</td>
<td>2.12</td>
<td>$4.72 \times 10^3$</td>
</tr>
<tr>
<td>$\tilde{g}$</td>
<td>2000</td>
<td>0.230</td>
<td>$4.35 \times 10^4$</td>
</tr>
<tr>
<td>$\tilde{t}$</td>
<td>300</td>
<td>$7.82 \times 10^3$</td>
<td>1.12</td>
</tr>
<tr>
<td>$\tilde{t}$</td>
<td>600</td>
<td>$1.76 \times 10^2$</td>
<td>35.2</td>
</tr>
<tr>
<td>$\tilde{t}$</td>
<td>1000</td>
<td>6.4</td>
<td>$1.5 \times 10^3$</td>
</tr>
</tbody>
</table>
## MC background samples

<table>
<thead>
<tr>
<th>Sample</th>
<th>Gen. Events</th>
<th>Rec. Events</th>
<th>$\mathcal{L}$ (fb$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>QCD: (PYTHIA)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$(140 \text{ GeV} &lt; \hat{p}_T &lt; 280 \text{ GeV})$</td>
<td>$3.125 \times 10^8$</td>
<td>2572</td>
<td>0.98</td>
</tr>
<tr>
<td>$(280 \text{ GeV} &lt; \hat{p}_T &lt; 560 \text{ GeV})$</td>
<td>$2.5 \times 10^7$</td>
<td>4800</td>
<td>1.12</td>
</tr>
<tr>
<td>$(560 \text{ GeV} &lt; \hat{p}_T &lt; 1120 \text{ GeV})$</td>
<td>$3.5 \times 10^5$</td>
<td>738</td>
<td>1.01</td>
</tr>
<tr>
<td>$(1120 \text{ GeV} &lt; \hat{p}_T &lt; 2240 \text{ GeV})$</td>
<td>$5 \times 10^4$</td>
<td>241</td>
<td>9.46</td>
</tr>
<tr>
<td>$(2240 \text{ GeV} &lt; \hat{p}_T$)</td>
<td>$1 \times 10^4$</td>
<td>42</td>
<td>442.29</td>
</tr>
<tr>
<td><strong>Electroweak</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ZZ (HERWIG)</td>
<td>$2.5 \times 10^4$</td>
<td>53</td>
<td>9.82</td>
</tr>
<tr>
<td>WW (HERWIG)</td>
<td>$2 \times 10^4$</td>
<td>50</td>
<td>1.21</td>
</tr>
<tr>
<td>WZ (HERWIG)</td>
<td>$1.5 \times 10^4$</td>
<td>29</td>
<td>2.32</td>
</tr>
<tr>
<td>$Z \rightarrow \mu\mu$ (PYTHIA)</td>
<td>$1.3 \times 10^4$</td>
<td>600</td>
<td>1.29</td>
</tr>
<tr>
<td>$Z \rightarrow \tau\tau$ (PYTHIA)</td>
<td>$3 \times 10^3$</td>
<td>108</td>
<td>9.94</td>
</tr>
<tr>
<td>$W \rightarrow \mu\nu$ (PYTHIA)</td>
<td>$3 \times 10^4$</td>
<td>600</td>
<td>0.94</td>
</tr>
<tr>
<td>$W \rightarrow \tau\nu$ (PYTHIA)</td>
<td>$3 \times 10^4$</td>
<td>120</td>
<td>7.82</td>
</tr>
<tr>
<td><strong>Top</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$t\bar{t}$: (MC@NLO)</td>
<td>$1 \times 10^6$</td>
<td>4065.08</td>
<td>0.98</td>
</tr>
</tbody>
</table>
In this analysis

- Low-$p_T$ muon trigger chain was used
  - Efficient for R-hadrons with charge in the muon spectrometer
  - Matching of muon spectrometer (MS) and inner detector (ID) tracks at Level-2 rejects large fractions of low mass $R_{\tilde{g}}$-hadrons
  - Performance degrades with R-hadron mass due to rapid drop in efficiency for $\beta < 0.6$

- Total trigger efficiencies for R-hadron samples
  - $\tilde{t}$ samples: 20-30%
  - $\tilde{g}$ samples: 10-15%
  - Varies with $m$ which affects $\beta$ spectrum

More refined triggers available now, more on that later...
Final state observables: $p_T$

**Inner detector**

$R_{\tilde{g}}$

$R_{\tilde{t}}$

BG

**Muon spectrometer**

$R_{\tilde{g}}$

$R_{\tilde{t}}$

BG

Gluino masses: (GeV)

$300 \times 10^2$

$600 \times 10^2$

$1000 \times 10^2$

$2000 \times 10^2$

Stop masses: (GeV)

$300 \times 10^2$

$600 \times 10^2$

$1000 \times 10^2$

$2000 \times 10^2$

Backgrounds:

- electroweak
- QCD
- ttbar
Final state observables: Tracking & $\Delta R$

- Left: ATLAS Transition Radiation Tracker gives the number of High Threshold (HT) and Low Threshold (LT) hits indicating the energy loss of the passing particle. The plot shows the fraction $\frac{HT}{LT}$.

- Right: Distance $\Delta R = \sqrt{\eta^2 + \phi^2}$ between a high-$p_T$ “muon” ($> 250 \text{ GeV}$) and the closest jet ($> 100 \text{ GeV}$).
Final state observables: $\cos(\Delta \Phi_{\mu,\mu})$

- R-hadrons produced predominantly in back-to-back configuration
- Electroweak background can give collinear muon pairs (boosted $Z^0$)

$\cos(\Delta \Phi_{\mu,\mu})$: Distance between MS tracks

$\cos(\Delta \Phi_{ID,\mu})$: Distance between tracks in MS and ID
Analysis cuts

- Require muon track with $p_T > 250$ GeV and $\Delta R < 0.36$ (jet veto)
- Use R-hadron topology: require at least one of
  - Two hard back-to-back ID tracks with $\frac{HT}{LT} < 0.05$ in the Transition Radiation Tracker (TRT)
  - At least one MS track with no matching ID track
  - Two hard back-to-back same sign MS tracks\(^1\)
  - MS track with matching ID track with opposite sign\(^1\)

\(^1\)The last two points are only relevant for $R_{\tilde{g}}$-hadrons, but there is obviously no harm in keeping them for the stable $\tilde{t}$ case
Results

- Number of events selected for the given samples (backgrounds not mentioned are completely rejected)
- $R_{\tilde{g}}$-hadrons up to 1 TeV and low-mass $R_{\tilde{t}}$-hadrons should be within reach with 1 fb$^{-1}$

<table>
<thead>
<tr>
<th>Sample</th>
<th>Accepted events</th>
<th>Rate (Events / fb$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>300 GeV $\tilde{g}$</td>
<td>235</td>
<td>$6.44 \times 10^3$</td>
</tr>
<tr>
<td>600 GeV $\tilde{g}$</td>
<td>551</td>
<td>$2.70 \times 10^2$</td>
</tr>
<tr>
<td>1000 GeV $\tilde{g}$</td>
<td>774</td>
<td>10.7</td>
</tr>
<tr>
<td>1300 GeV $\tilde{g}$</td>
<td>732</td>
<td>1.20</td>
</tr>
<tr>
<td>1600 GeV $\tilde{g}$</td>
<td>685</td>
<td>0.147</td>
</tr>
<tr>
<td>2000 GeV $\tilde{g}$</td>
<td>546</td>
<td>$1.26 \times 10^{-2}$</td>
</tr>
<tr>
<td>300 GeV $\tilde{t}$</td>
<td>78</td>
<td>70.0</td>
</tr>
<tr>
<td>600 GeV $\tilde{t}$</td>
<td>134</td>
<td>3.9</td>
</tr>
<tr>
<td>1000 GeV $\tilde{t}$</td>
<td>170</td>
<td>0.1</td>
</tr>
<tr>
<td>J5</td>
<td>1</td>
<td>0.893</td>
</tr>
<tr>
<td>J8</td>
<td>1</td>
<td>$2.26 \times 10^{-3}$</td>
</tr>
<tr>
<td>$Z \rightarrow \mu\mu$</td>
<td>1</td>
<td>0.776</td>
</tr>
</tbody>
</table>
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Trigger strategy & offline reconstruction

Trigger

- With firming of trigger menu definitions, trigger strategy was refined
- Dedicated Level-2/Event Filter trigger for slow particles in the muon spectrometer (using muon trigger chamber timing)

Offline reconstruction

- Offline muon reconstruction for slow particles (plots presented by S. Vallecorsa at PANIC08 in Israel)
Recent developments
Complimentary calorimeter based analysis

- Theoretical results suggest lowest lying $R_{\tilde{g}}$-baryon state neutral
  $\Rightarrow$ R-hadron always neutral in muon spectrometer
  (Farrar et al., PLB153:311, 1985)

- Developing complementary calorimeter-based search:
  - Jet trigger: PYTHIA suggests $\sim 10\%$ of $R_{\tilde{g}}$ events have FSR jet
    ($E \gtrsim 100$ GeV)
  - Exploitation of calorimeter signature
    - Time-of-Flight measurement using the calorimeters
    - $\frac{dE}{dx}$ as discriminant between muons and R-hadrons
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Summary & conclusions

- Stable Massive Particle searches important early analyses
- With the method outlined in this talk, ATLAS is sensitive to $\tilde{g}$ and $\tilde{q}$ masses up to 1 TeV.
- Refined trigger strategies and complementary calorimeter-based search under development and expected to improve sensitivity in low-luminosity (first year) search
Back-up slides

$gg \rightarrow \tilde{g}\tilde{g}$ cross-section @ 14 TeV

- LO cross-section for $gg \rightarrow \tilde{g}\tilde{g}$ at 14 TeV vs. $m_{\tilde{g}}$ according to PYTHIA

- Drops with about $\frac{1}{3}$ for 300 GeV case for $\sqrt{s} = 10$ TeV (bigger drop for higher masses)
The main systematic uncertainties considered in this analysis are

- GEANT4 parameters: 17%
- PDFs + K-factors: 30%
- PYTHIA parameters: 9%
The lifetime of the gluino (in seconds) can be calculated:

$$\tau \simeq 8 \left( \frac{m_S}{10^9 \text{ GeV}} \right)^4 \left( \frac{1 \text{ TeV}}{m_{\tilde{g}}} \right)^5$$  \hspace{1cm} (1)