Searches for long lived supersymmetric particles with the ATLAS detector

Helen Hayward on behalf of the ATLAS collaboration
Long-lived SUSY particles

R-parity violating:

\[ W_{\text{RPV}} = \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \kappa_i L_i H_2 + \lambda''_{ijk} \bar{D}_i \bar{D}_j \bar{D}_k \]

If \( \lambda, \lambda', \lambda'' \) are small, LSP can have a long lifetime.

\[ \text{lifetime proportional to } \lambda^{-2}, \lambda'^{-2}, \lambda''^{-2} \]

R-parity conserving:

- \( \Delta M(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) \approx 100 \text{ MeV}, \) e.g. AMSB: long lived chargino
- Long-lived gluino due to very heavy squarks mediating its decay: Radhrons
- Weak coupling NLSP-gravitino in GMSB: long-lived sleptons, or neutralino
  - (neutralino can decay to photon or Z-boson)

We are sensitive to a large range in lifetimes!
## Outline

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<td>Preliminary</td>
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<td>non-pointing and delayed photons</td>
<td>8 TeV</td>
<td>20.3 fb⁻¹</td>
<td>Phys. Rev. D. 90, 112005 (2014)</td>
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<td>heavy long-lived particles</td>
<td>8 TeV</td>
<td>19.1 fb⁻¹</td>
<td>JHEP01 (2015) 068</td>
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<td>long-lived stopped R-hadrons</td>
<td>7+8 TeV</td>
<td>5.0 and 22.9 fb⁻¹</td>
<td>Phys. Rev. D 88, 112003 (2013)</td>
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</table>
Displaced Vertices

- Motivated by many theories:
  - R-parity violating SUSY – neutralino decays via $\lambda$, $\lambda'$ or $\lambda''$ couplings (a, b)
  - GGM – Long-lived neutralino decaying to gravitino and $Z$ (c)
  - Split SUSY – Long-lived gluinos (d)
- Search for a displaced vertex (DV) in the region of the inner detector: $z<300$ mm, $r<300$ mm

- Two types of searches:
  - A “multi-track” search: DV+$\mu$, DV+e, DV+jets, DV+MET
  - A “di-lepton” search: $\mu\mu$, ee, $\mu e$ (opposite charges)
Displaced Vertices

- Re-run tracking to find tracks with large $d_0$
  - Default tracking uses $d_0 < 10$ mm
- Veto vertices in material layers (3D material map)
  - Other appropriate selection depending on the channel
- Signal Region
  - DV mass $> 10$ GeV
  - Number of track in DV $> 4$ (for multi-track)

Transverse-plane density of vertices regions that are excluded by the material veto.
Displaced Vertices

- Main source of background:
  - Low mass DV’s that are crossed by an unrelated high-pT track at a large angle, making their reconstructed mass seem high (multi-track)
  - Two unrelated leptons crossing close enough for the vertexing method to combine (di-lepton)
- Data driven methods of estimation

<table>
<thead>
<tr>
<th>Channel</th>
<th>No. of background vertices ($\times 10^{-3}$)</th>
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<tbody>
<tr>
<td>$e^+e^-$</td>
<td>1.0 $\pm$ 0.2 $^{+0.3}_{-0.6}$</td>
</tr>
<tr>
<td>$e^\pm\mu^\mp$</td>
<td>2.4 $\pm$ 0.9 $^{+0.8}_{-1.5}$</td>
</tr>
<tr>
<td>$\mu^+\mu^-$</td>
<td>2.0 $\pm$ 0.5 $^{+0.3}_{-1.4}$</td>
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- Vertex position radius for vertices composed of two non-lepton tracks

![Graph showing data and model comparison for vertex position radius](https://example.com/graph.png)
**New!**

**Displaced Vertices**

With **no events observed in any signal region**, we set upper-limits on the signal yields and production cross-sections as a function of the LLP proper lifetime $\tau$.

- For Split SUSY also limits on the gluino mass vs. $\tau$

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**RPV**

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<th>ATLAS Preliminary</th>
<th>$t\bar{t}$ = 8 TeV, 20.3 fb$^{-1}$</th>
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<tr>
<td>m$<em>{\tilde{g}}$, m$</em>{\tilde{q}}$ (GeV)</td>
<td></td>
</tr>
<tr>
<td>600, 500</td>
<td></td>
</tr>
<tr>
<td>600, 400</td>
<td></td>
</tr>
<tr>
<td>600, 200</td>
<td></td>
</tr>
<tr>
<td>600, 100</td>
<td></td>
</tr>
<tr>
<td>1300, 500</td>
<td></td>
</tr>
<tr>
<td>1300, 1000</td>
<td></td>
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**GGM**

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<tbody>
<tr>
<td>m$<em>{\tilde{g}}$, m$</em>{\tilde{q}}$ (GeV)</td>
<td></td>
</tr>
<tr>
<td>400</td>
<td></td>
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<tr>
<td>1 TeV</td>
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**Split SUSY**

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<tr>
<td>m$<em>{\tilde{g}}$, m$</em>{\tilde{q}}$ (GeV)</td>
<td></td>
</tr>
<tr>
<td>100 GeV</td>
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Helen Hayward 19/03/2015
Displaced Jets

- Search for events with 2 displaced vertices in either InnerDetector, Muon Spectrometer or both
- Displaced jets appear in:
  - **Stealth susy**
  - Scalar boson
  - Hidden Valley Z’

**Trigger**
- Jet/Met (Z’)
- Muon ROI Cluster
  - Designed to select decays of neutral particles in the MS.
  - cluster of muon Rols that are preceded by little or no activity in the ID or calorimeters.

**Selection:**
- Good quality vertex, not consistent with coming from material
- Minimum Ntrack per vertex required : 5 (7 for Z’)
- Vertex close to jet : $\Delta R < 0.4$ (0.6 for Z’)

![Graph showing ID Vertex Reconstruction Efficiency](image)
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Using the pixel detector to search for meta-stable LLP

- Search for heavy muon-like particles with $\beta$$\ll$1
  - high $dE/dx$ measured from pixel detector
- If particle travels at least 45 cm (in $r$) can be studied,
  - Little dependence on interactions in calorimeter, muon spectrometer or on LLP decay mode
- Met Trigger, Met> 100 GeV,
- Rejection of muons from W decays
  - $M_T$> 130 GeV
  - For stable signal region: veto on the track candidate being matched to a reconstructed muon
- Track level (at least one track with):
  - High momentum, isolated track: $p_T$>80 GeV
  - high ionization:
    - $dE/dx > 1.800 - 0.034|\eta| + 0.101|\eta|^2 - 0.029|\eta|^3$ MeV/g cm$^2$
New!

Using the pixel detector to search for meta-stable LLP

- Background is estimated by data driven approach
  - Randomly sampling $p, \eta, \text{dE/dx}$ values from control sample distributions and combining
- No significant deviation from background expectations is observed.
- Exclude:
  - Stable charginos with mass smaller than 549 GeV
  - stable gluino (sbottom, stop) R-hadrons with masses smaller than 1102 (745, 758) GeV respectively.
  - In the metastable case masses exceeding $\approx 1200$ GeV are excluded for R-hadrons of 12 ns

- This is the first measurement of lifetime dependent mass limit for charged R-hadrons in the 1-10 ns range, with little dependence on their decay mode.
Disappearing Track

- If the lowest gauginos are approximately mass-degenerate
  - $\tilde{\chi}_1^\pm$ has lifetime $O(0.1\text{ns}-10\text{ns})$ and decays to $\tilde{\chi}_1^0$ and a $(100\text{ MeV} - \sim 1\text{GeV})\pi^\pm$

- Look for production processes:

$$pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^0 + \text{jet} \quad pp \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^- + \text{jet}$$

- Event Selection:
  - High $p_T$ jet
    - (jet from ISR, needed to trigger on event).
  - Large missing transverse momentum.
  - A track that has less than 5 hits in the TRT

For $\Delta m \sim 160$ MeV (most probable in AMSB), $m(\text{chargino})$ up to $245^{+25}_{-30}$ GeV is excluded
Re-interpretation of prompt jets+MET analyses

- What if gluino is just a little long-lived, about 1 ns? (mini-split SUSY)
- Standard jets+MET SUSY searches should still apply (up to what lifetime?)
  - Leptons vetos may start to fail impact-parameter cuts (when?)
  - Jets will start to be identified as b-jets (when?)
  - Jets may fail cleaning cuts using track pT fraction, EM fraction (when?)
- First explicit re-interpretation of prompt SUSY searches for long-lived gluinos!

\[
\tilde{g} \rightarrow q\bar{q} \chi^0_1 / g \chi^0_1 \quad m(\chi^0_1) = 100 \text{ GeV}
\]

\[
\tilde{g} \rightarrow t\bar{t} \chi^0_1 \quad m(\chi^0_1) = 100 \text{ GeV}
\]
Delayed and Displaced photons

- Delayed and Displaced Photon search performed in the context of GMSB
- This distinct signature arises from finite lifetime (τ) of the NLSP \( \tilde{\chi}^0_1 \)
- 2 SUSY chains with Lightest Neutralino decays to a photon and Gravitino (LSP)
- The photons appears as delayed and may not “point-back” to the PV

Event Selection

- Searching for 2 Loose Photons + Missing Energy
- Signal Region:
  - MET> 75 GeV, \( E_T >50\text{GeV} \)
- Low MET regions used as control regions
- Signal photons may point away from PV and are delayed
- Use Pointing (\( z_{\text{DCA}} \)), and LAr Timing (\( t_{\gamma} \)) to perform a 2D search
Delayed and Displaced photons

- 386 events in our signal region
- No evidence of non-pointing and delayed photons
- Results are interpreted in context of GMSB SPS8 model
  - $\Lambda = 302$ TeV at a lifetime of $\tau = 1.83$ ns.
  - Corresponding to:
    \[
    m(\tilde{\chi}_1^0) = 442\,\text{GeV}, \ m(\tilde{\chi}_\pm) = 841\,\text{GeV}
    \]
Stable Massive Particles (SMPs)

- Several candidate particles, including:
  - Long-lived sleptons in GMSB models.
  - Directly produced charginos, in simplified models where they are nearly degenerate with the lightest neutralino
  - R-hadrons in split-SUSY models
- Common feature: if they are massive, they will be produced with low velocities: $\beta < 1.$

$$m_\beta = \frac{p}{\gamma \beta}$$

- Search for heavy muon-like particles
  - low $\beta$ using muon chambers and Calorimeter timing
  - high $dE/dx$ measured from pixel detector (related to $\gamma \beta$)
- Main background for both slepton and R-hadron searches is high-$p_T$ muons with mis-measured $\beta$. 
Stable Massive Particles

- long-lived staus excluded between 440 and 385 GeV for tan\(\beta\) between 10 and 50

Charginos excluded up to mass 620 GeV

R-hadrons:

<table>
<thead>
<tr>
<th>Containing</th>
<th>Excluded up to mass...</th>
</tr>
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<tbody>
<tr>
<td>gluino</td>
<td>1270 GeV</td>
</tr>
<tr>
<td>sbottom</td>
<td>845 GeV</td>
</tr>
<tr>
<td>stop</td>
<td>900 GeV</td>
</tr>
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</table>
long-lived stopped R-hadrons

- search is for R-hadrons that have come to rest within the ATLAS calorimeter,
  - decay at some later time to hadronic jets and a neutralino
- Not every bunch slot of the LHC is filled.
- Search in “empty-events” when 2 empty bunches cross at ATLAS
- Require:
  - At least 1 high energy jet
  - No muon segments identified in Muon detectors

- BG:
  - Beam halo
  - Cosmic ray
Summary

- With no sign of prompt SUSY decays there has been much speculation that SUSY could be hiding in stable, metastable, displaced decays.
  - We are actively addressing this experimentally challenging regime with a number of analyses.
- **Good coverage of different lifetimes is achieved** by complementary analyses using different detector systems and novel techniques.
- Unfortunately no sign of a signal
- We are looking forward to the increased discovery potential of Run-2