Search for long-lived massive particles with the ATLAS detector

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On behalf of the ATLAS collaboration
Standard Model object IDs

- electrons
- photons
- muons
- jets
- b-jets
- $E_T^{\text{miss}}$
- ...
New particle searches

- New particle searches typically search for rare combinations of Standard Model objects:

  - **New long-lived particles**
    - Neutral
      - Displaced vertices/jets
    - Massive charged
      - Slow $\rightarrow$ highly ionizing
      - Really slow $\rightarrow$ stop (decay out-of-time)
      - Decay $\rightarrow$ kinked or disappearing track

  - Multiple jets
  - High $p_T$ leptons
  - $E_T^{\text{miss}}$

- Need new object IDs!

* SUSY models (GMSB, AMSB, Split, RPV, Stealth, SUGRA...)

Exotic models (Hidden Valleys, Univ. extra dimensions...)

5/25/12
Long-lived particle ATLAS Analyses

- Neutral massive particles
  - Hidden Valley: displaced vertex
  - RPV LSP decay: displaced vertex
- Charged massive particles
  - R-hadrons: dE/dx, β
  - Stable stau: β
  - HIP: high-threshold TRT hits
- Stopped R-hadron
  - Jets in empty/unpaired bunch crossings
- Anomaly-Mediated SUSY-breaking
  - Truncated tracks: missing TRT hits
This talk: recent ATLAS analyses

- Neutral massive particles
  - Hidden Valley: displaced vertex
  - RPV LSP decay: displaced vertex
- Charged massive particles
  - R-hadrons: dE/dx, β
  - Stable stau: β
  - HIP: high-threshold TRT hits
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Neutral massive: hidden valley

4 models: $m_h = 120,140 \text{ GeV}$, $m(\pi^0) = 20,40 \text{ GeV}$

Chose $\pi^0$ proper lifetime ($c\tau$) to give decays throughout the detector

Different techniques are required for each section of the detector.
3 triggers

trackless jet trigger
Jet $E_T > 35$ GeV
No tracks with $p_T > 1$ GeV near jet
Muon spectrometer activity
Low efficiency

Log($E_{had}/E_{EM}$)
Jet $E_T > 35$ GeV
No tracks with $p_T > 1$ GeV near jet
Log($E_{had}/E_{EM}$) > 1.0
Very good efficiency

muon spectromter cluster trigger
three muon clusters all close by
no jets
no tracks
Very good efficiency
muon spectrometer vertex

The ATLAS muon spectrometer is designed to reconstruct muon tracks stand alone.

It can do more than particle ID!

Efficiency x-checked with punch-thru jets.
Analysis Strategy

Muon Cluster Trigger
2 back-to-back vertices in the muon spectrometer
No Jet or Track activity near the vertex

0 events seen in 1.94 fb⁻¹

Expected Backgrounds:

1 Trigger 1 Vertex
(15543)  

P(2nd Vertex|No Trigger)
(9.7±6.9) \times 10⁻⁷

2 Trigger 1 Vertex
(1)

P(2nd Vertex|Trigger)
(1.11±0.01) \times 10⁻²

Expected signal in 1.94 fb⁻¹
equal systematic error contributions from theory and efficiency verification for our signals.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Systematic uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Higgs cross section</td>
<td>+18.8% -14.9%</td>
</tr>
<tr>
<td>$m_{h}$ = 140 GeV</td>
<td>+19.7% -15.1%</td>
</tr>
<tr>
<td>$m_{h}$ = 120 GeV</td>
<td></td>
</tr>
<tr>
<td>RoI cluster trigger</td>
<td>14%</td>
</tr>
<tr>
<td>MS vertex (per vertex)</td>
<td>16%</td>
</tr>
<tr>
<td>Luminosity</td>
<td>3.7%</td>
</tr>
</tbody>
</table>

List of the systematic uncertainties.

\[
\int L d\tau = 1.94 \text{ fb}^{-1} \quad \sqrt{s} = 7 \text{ TeV}
\]

<table>
<thead>
<tr>
<th>$m_{h}$ (GeV)</th>
<th>$m_{\pi}$ (GeV)</th>
<th>Excluded Region</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>20</td>
<td>$0.50 &lt; c\tau &lt; 20.65 \text{ m}$</td>
</tr>
<tr>
<td>120</td>
<td>40</td>
<td>$1.60 &lt; c\tau &lt; 24.65 \text{ m}$</td>
</tr>
<tr>
<td>140</td>
<td>20</td>
<td>$0.45 &lt; c\tau &lt; 15.8 \text{ m}$</td>
</tr>
<tr>
<td>140</td>
<td>40</td>
<td>$1.10 &lt; c\tau &lt; 26.75 \text{ m}$</td>
</tr>
</tbody>
</table>
Charged massive: decaying

anomaly-mediated SUSY breaking

compressed mass spectra

$\chi_1^+ \rightarrow \chi_1^0 \pi^\pm$

LSP escapes detector: $E_T^{\text{miss}}$

Small $p_T$, perhaps 100 MeV

Mass difference between $\chi_1^\pm$ and $\chi_1^0$ so small it has a long lifetime

analysis is sensitive to decays occurring somewhere in ATLAS inner tracker

Chargino leaves hits in tracker until it decays!

Looked at mass $\chi_1^\pm = 90.2, 117.8, 147.7$ GeV, $\text{BR}(\chi_1^\pm \rightarrow \chi_1^0 \pi^\pm) = 1.0$

the analysis

Transition Radiation Tracker

- \(0.5 \text{m} < r < 1.1 \text{m}\)
- average of 15 hits for a charged track in the outer TRT (\(N_{\text{TRT}}^{\text{outer}}\))

**trigger**

1 jet, \(p_T > 75 \text{ GeV}\)

\(E_T^{\text{miss}} > 55 \text{ GeV}\)

**offline**

3 jets, \(p_T > 130, 60, 60 \text{ GeV}\)

\(E_T^{\text{miss}} > 130 \text{ GeV}\)

lepton veto

track: \(p_T > 10 \text{ GeV}\)

isolated

less than 5 hits in the TRT

304 events remain in 4.7 fb\(^{-1}\) of data

the shape of the track \(p_T\) spectra differentiates signal and backgrounds
Background track $p_T$ shapes

shape for high $p_T$ tracks that interact
Sample is signal-free:
$N_{\text{TRT outer}} > 10$.

shape for mismeasured low $p_T$ tracks
Sample is signal-free:
$E_T^{\text{miss}} < 100$ GeV
no pixel hits
Fit track $p_T$ shape

The 3 templates are fit to data:
- The two background templates are fit for $p_T > 10$ GeV
- The signal template is included in the fit for $p_T > 50$ GeV

data and background fit best fit has zero contribution from signal template

Fit prefers zero signal contribution!
limits

Limit for the mass
Previous LEP2 limit: $\chi^\pm_1 > 92$ GeV (for any lifetime)

primary uncertainty is the theoretical cross section (27%)
backgrounds are data driven and so have very small uncertainty
Charged massive: R-hadrons

SUSY LSP is gluino (colored)

Hadronizes \( \tilde{g}, \tilde{g}q, \tilde{g}qq \ldots \)

“R-Hadron”: unlike a normal neutral LSP, can interact with the ATLAS detector!

Travels slowly through detector  
\( \Rightarrow \text{large } dE/dx \)

Mass(\( p, dE/dx \))

Pixel detector fires if > 3100e\(^{-}\) deposited

Measures time-above-threshold  
\( \Rightarrow dE/dx \)

Bethe-Bloch to infer mass
analysis

trigger
No dE/dx information available
MIP in Calorimeter + ISR means $E_T^{\text{miss}}$
$E_T^{\text{miss}} > 70 \text{ GeV}$
20% efficient

offline
$E_T^{\text{miss}} > 85 \text{ GeV}$
isolated track, $p_T > 50 \text{ GeV}$, $p > 100 \text{ GeV}$
$\Delta R(\text{track}, p_T > 5 \text{ GeV track}) > 0.25$
dE/dx cut depends on $\eta$. 333 events left over in 2.1 fb$^{-1}$ data
data driven background

apply all cuts except require small $dE/dx$

expected background $\eta$ and $p$ distributions

randomly sample $p, \eta, dE/dx$ from these distributions

all tracks with $p<100$ GeV

expected background $dE/dx$ distributions

normalize to data in low mass region before $dE/dx$ cut

Expected : 332 events
(333 observed)
results

Gluino R-hadron mass < 810 GeV
conclusions

• three analyses presented
  – Hidden Valley search, AMSB search, R-hadron search
  – New limits on masses/lifetimes
  – More analyses and updates are ongoing

• non standard object ID
  – late appearance of jets, truncated tracks, high dE/dx, out-of-time energy, displaced vertices

• lots of information from the these detectors!!
  – how else can we combine this information to search for new things!!?
backup
analyses on 2010 data

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>stopped gluinos</td>
<td>Particles come to rest in the ATLAS detector volume, and decay out-of-time. (1201.5595, submitted to EPJC)</td>
</tr>
<tr>
<td>displaced vertices</td>
<td>R-parity violating SUSY. Displaced vertices with r&gt;4mm (1109.2242, PLB 707 (2012) 478-496)</td>
</tr>
<tr>
<td>R-Hadron</td>
<td>Neutral R-hadron becomes charged in calorimeter and leaves track in muon system (1103.1984, PLB 701 (2011) 1 )</td>
</tr>
<tr>
<td>HIP search</td>
<td>Massive long lived highly ionizing particles with large electric charge (q-balls, stable micro black holes, etc.). Energy loss in calorimeter and tracker used (arxiv:1102.0459; PLB698:353-370,2011)</td>
</tr>
</tbody>
</table>
Hidden valley backup: the models

$m_h=120$ GeV, 140 GeV
$m(\pi^0_v)=20$ GeV, 40 GeV

allow proper lifetime ($c\tau$) to vary to give
decays through out the detector

$m_h=120$ GeV, $m(\pi^0_v)=20$ GeV

For a particular lifetime
Backup: hidden valley long-lived particle triggers

- ATLAS has only so much bandwidth, drive space, cpu
  → Triggering means throwing away “less important” data
- Single-objects unprescaled @ end of 2011
  - 1e@22, 1μ@18, 1j@250...
  → single medium-p_T objects not an option
- b-tagging triggers
  - good for a decay a few millimeters from primary vertex
  - huge backgrounds from QCD b\bar{b} production
- Specially designed triggers
  - L1 is hardware-based (nothing can be done)
  - Room for innovation at L2/HLT
- Long-lived neutral particle triggers
  - neutral particle decays mid-detector
  - run for full 2011 dataset (5 fb-1)
Hidden Valley backup

Muon RoI trigger efficiency

![Graph showing Muon RoI trigger efficiency with various lines representing different scenarios.](image)
backup: AMSB model parameters

Table 1: Parameters of AMSB signal points, chargino masses and their NLO+NLL cross sections. The parameters $\tan \beta$ and $sgn(\mu)$ are set to 5 and +1. The cross sections only include $\tilde{g}\tilde{g}$, $\tilde{q}\tilde{q}$ and $\tilde{q}\tilde{q}$ production processes.

<table>
<thead>
<tr>
<th>Sample</th>
<th>$m_0$[TeV]</th>
<th>$m_{3/2}$[TeV]</th>
<th>$m_{\tilde{\chi}^\pm}$[GeV]</th>
<th>Cross section[pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LL01</td>
<td>1.5</td>
<td>32</td>
<td>90.2</td>
<td>$6.79 \times 10^{-2}$</td>
</tr>
<tr>
<td>LL02</td>
<td>1.8</td>
<td>41</td>
<td>117.8</td>
<td>$8.66 \times 10^{-3}$</td>
</tr>
<tr>
<td>LL03</td>
<td>2.0</td>
<td>51</td>
<td>147.7</td>
<td>$1.16 \times 10^{-3}$</td>
</tr>
</tbody>
</table>
backup: AMSB cut flow

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Observed events</th>
<th>Signal efficiency (purity) [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger selection and non-collision rejection</td>
<td>7141026</td>
<td>LL01: 87.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LL02: 89.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LL03: 90.1</td>
</tr>
<tr>
<td>Lepton veto</td>
<td>6644394</td>
<td>LL01: 72.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LL02: 72.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LL03: 72.6</td>
</tr>
<tr>
<td>$E_{T}^{\text{miss}} &gt; 130$ GeV</td>
<td>321412</td>
<td>LL01: 66.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LL02: 68.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LL03: 69.6</td>
</tr>
<tr>
<td>Jet requirements</td>
<td>73433</td>
<td>LL01: 64.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LL02: 67.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LL03: 69.0</td>
</tr>
<tr>
<td>High-$p_T$ isolated track selection</td>
<td>8458</td>
<td>LL01: 24.8 (67.6)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LL02: 26.2 (66.8)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LL03: 27.2 (66.7)</td>
</tr>
<tr>
<td>Disappearing track selection</td>
<td>304</td>
<td>LL01: 6.1 (94.6)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LL02: 6.6 (94.5)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LL03: 7.3 (94.7)</td>
</tr>
</tbody>
</table>

Note: purity is only for tracks in the signal sample – it is not S/B!
Backup: R-Hadron models

SUSY, but the LSP is colored

hadronizes into colored hadrons

\[ \tilde{g}g, \tilde{g}qq, \tilde{q}q, \tilde{g}qqq, \tilde{qq}, \text{etc}... \]

“they carry one unit of R-Parity”

the R-Hadron will, unlike a normal neutral LSP, have interactions in the ATLAS detector!

three models are used (regge, generic, and “intermediate”)
the generic is used for limits, the other models are taken as a systematic error

backup: R-hadron model details

The first model assumes that $R$-hadrons containing gluinos are simulated according to [19]. This model employs a triple-Regge formalism to describe hadronic scattering, and will henceforth be referred to as Regge.

The second physics model described in [30, 31] and hereafter referred to as generic has been used in other publications [32–34] and it imposes few constraints on allowed stable states. Doubly charged $R$-hadrons and a wide variety of ”charge reversal” signatures in the detector are possible. Hadronic scattering is described through a purely phase space driven approach.

More recent models for the hadronic scattering of gluino $R$-hadrons predict that the majority of all produced $R$-hadrons will be electrically neutral after just a few hadronic interactions. The third model belongs to this family, is based on the bag-model calculations presented in [35] and is referred to as intermediate.
Backup: r-hadron mass resolution

![Graph showing calculated proton mass against data period and mass distribution.](image)
backup: R-hadron cut flow

Table 1: Observed event yields at different steps of the selection procedure. The total efficiency is computed with respect to the events that passed the trigger and the data quality decision. Trigger selects only those events which satisfy the calorimetric ($E_T^{miss} > 70$ GeV) online trigger. Offline $E_T^{miss}$ should exceed 85 GeV. Primary vtx requires a primary vertex with at least five tracks. Next cuts require in the event at least one track with: High-$p_T$ corresponds to the request on high $p_T$, cuts on the impact parameters and Pixel/SCT clusters; Isolation refers to the requirement that the track satisfies $\Delta R_{track,othertrack} > 0.25$ from any other track with $p_T > 5$ GeV; High-$p$ corresponds to the request on $p > 100$ GeV, ionization is the request on the Pixel $dE/dx$ as explained in the text.

<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>0.567</td>
</tr>
<tr>
<td>Primary vtx</td>
<td>1,368,821</td>
<td>0.0880</td>
<td>0.0880</td>
</tr>
<tr>
<td>High-$p_T$</td>
<td>212,464</td>
<td>0.0133</td>
<td>0.0133</td>
</tr>
<tr>
<td>Isolation</td>
<td>32,188</td>
<td>0.016</td>
<td>0.016</td>
</tr>
<tr>
<td>High-$p$</td>
<td>21,040</td>
<td>8.7E-03</td>
<td>8.7E-03</td>
</tr>
<tr>
<td>ionization</td>
<td>333</td>
<td>1.4E-04</td>
<td>1.4E-04</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger</td>
<td>0.205 ± 0.013</td>
<td>0.205 ± 0.013</td>
<td>0.219 ± 0.009</td>
<td>0.219 ± 0.009</td>
<td>0.177 ± 0.009</td>
<td>0.177 ± 0.009</td>
</tr>
<tr>
<td>Offline $E_T^{miss}$</td>
<td>0.98 ± 0.08</td>
<td>0.200 ± 0.013</td>
<td>0.99 ± 0.05</td>
<td>0.216 ± 0.009</td>
<td>0.98 ± 0.07</td>
<td>0.175 ± 0.009</td>
</tr>
<tr>
<td>Primary vtx</td>
<td>1.00 ± 0.09</td>
<td>0.120 ± 0.010</td>
<td>1.00 ± 0.05</td>
<td>0.216 ± 0.009</td>
<td>1.00 ± 0.07</td>
<td>0.175 ± 0.009</td>
</tr>
<tr>
<td>High-$p_T$</td>
<td>0.59 ± 0.06</td>
<td>0.58 ± 0.04</td>
<td>0.59 ± 0.05</td>
<td>0.129 ± 0.007</td>
<td>0.59 ± 0.05</td>
<td>0.108 ± 0.008</td>
</tr>
<tr>
<td>Isolation</td>
<td>0.84 ± 0.10</td>
<td>0.84 ± 0.06</td>
<td>0.84 ± 0.06</td>
<td>0.105 ± 0.006</td>
<td>0.88 ± 0.09</td>
<td>0.091 ± 0.007</td>
</tr>
<tr>
<td>High-$p$</td>
<td>0.99 ± 0.12</td>
<td>0.99 ± 0.08</td>
<td>0.99 ± 0.08</td>
<td>0.104 ± 0.006</td>
<td>1.00 ± 0.10</td>
<td>0.091 ± 0.007</td>
</tr>
<tr>
<td>Ionization</td>
<td>0.66 ± 0.09</td>
<td>0.80 ± 0.07</td>
<td>0.80 ± 0.07</td>
<td>0.085 ± 0.005</td>
<td>0.92 ± 0.09</td>
<td>0.084 ± 0.006</td>
</tr>
</tbody>
</table>
stopped particles

- Long-lived particles produced with low $\beta$ can stop in detector material and decay much later.
- Most likely to stop in densest part of ATLAS $\Rightarrow$ calorimeters.
- Look for events with large energy deposits in calorimeter in “empty” bunches.

backgrounds: calorimeter noise, cosmics, beam-halo
stopped particles
stopped particles

ATLAS
Leading Jet Energy > 100 GeV
$N_{\text{jets}} = 1$

95% CL $\sigma(pp \rightarrow \tilde{g})$ (pb)

$\sqrt{s} = 7$ TeV
$\int L dt = 31$ pb$^{-1}$

$M_\tilde{g}$ (GeV)
Long-lived charged particles (LLPs) are allowed by many BSM theories.

- If produced at LHC they would travel with $\beta < 1$
- $m = \frac{p}{\beta \gamma}$ would produce a peak at the LLP mass

GMSB:
- The LSP is the gravitino
- Small coupling to gravitino $\rightarrow$ NLSP is long lived
- 2 $\tilde{\tau}$ LLPs and additional leptons in each event

R-hadrons:
- Gluino NLSP hadronizes to long lived R-hadron
- 2 gluinos produced directly – low $\beta$
- R-hadron may change charge from ID to MS
- How often is model dependent

$\beta$ measurements from ToF:
- Calo, RPC, MDT combined

Background are muons with mismeasured $\beta$

**Search for LLPs with the MS $\beta = 0.997 \pm 0.048$**
LONG-LIVED CHARGED PARTICLES

(previous 2010-data analysis)

• Background estimation from data
  – Convolute $p$ with $\beta$ to get bkg mass spectrum

• No deviation of data from the background estimate is observed

• Limits are set using the CLs method

$m(\tilde{\tau}) > 136$ GeV

EW produced LLPs: $m(\tilde{l}) > 110$ GeV

Previous limits: $m > 98$ GeV
displaced vertices

SUSY++

L=33 $pb^{-1}$
displaced vertices

ATLAS

\[ \int L dt = 33 \text{ pb}^{-1} \]

- Data 2010
- Signal MC

Signal region

KLS\[ \uparrow \downarrow \]

Number of tracks in vertex

Vertex mass [GeV]
displaced vertices

95% CL limit
ATLAS

44m

25m

Muon chambers

Solenoid magnet

Transition radiation tracker

Semiconductor tracker

Pixel detector

LAr electromagnetic calorimeters

LAr hadronic end-cap and forward calorimeters

Tile calorimeters

Toroid magnets