ATLAS – SEARCHES FOR LONG LIVED PARTICLES

G. Watts (UW/Seattle) on behalf of the ATLAS Collaboration
long lived particles

electrons
muons
tau’s
\( E_T^{\text{missing}} \)
jets
long lived particles

$0 < r < \sim 10 \ m$

$E_T^{\text{missing}}$ is not a primary signature

electrons
muons
tau’s
$E_T^{\text{missing}}$
jets

G. Watts (UW/Seattle)
calorimeter

muon spectrometer
recent analyses

<table>
<thead>
<tr>
<th>Hidden Valley</th>
<th>Jets appearing late</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charged, Massive Particles</td>
<td>$dE/dx$</td>
</tr>
<tr>
<td>Anomaly-Mediated SUSY Breaking</td>
<td>Truncated Tracks</td>
</tr>
</tbody>
</table>

![Diagram](image)
triggering is grim...

going long lived signatures on tape is tricky
- associated production
- specially designed triggers

specially designed triggers
- level 1 is typically hardware – restricted!!
  mostly designed at upper levels

Level 2/High level triggers
- room for innovation
- full event in HLT
- some hardware restrictions in Level 2 (ATLAS).
triggering is grim... ... and getting grimmer

single medium-\(p_T\) objects not an option!

bunch spacing, protons in bunch, beam tunes and focus

your favorite trigger squeezed here

rate limit driven by $$\$\$$ disk, cpu, etc.

unprescaled @ end of 2011

em: 1e@22, 2e@12, 1e@12+2e@6, 1\(\gamma\)@80, 2\(\gamma\)@20, 1e@20+\(E_T^{\text{miss}}\) > 40
muon: 1\(\mu\)@18, 1\(\mu\)@40sl, 1\(\mu\)@15+1\(\mu\)@10, 1\(\mu\)@15+\(E_T^{\text{miss}}\) > 30
tau: 1\(\tau\)@125, 1\(\tau\)@29+1\(\tau\)@20, 1\(\tau\)@29+\(E_T^{\text{miss}}\) > 35
jets: 1j@250, 3j@100, 4j@45, 5j@30, 1j@75+\(E_T^{\text{miss}}\) > 55, 1j@100+\(H_T\) > 400,
\quad 4j@40+\(H_T\) > 350
combo: 1\(\mu\)@18+1j@10, 1e@5+1\(\mu\)@6, 1\(\tau\)@20+1e@15, 1\(\tau\)@20+1\(\mu\)@15
offline analysis

standard analyses

jets $p_T > 50 \text{ GeV}$
electrons $p_T > 10 - 20 \text{ GeV}$
muons $p_T > 10 - 20 \text{ GeV}$
$E_T^{\text{miss}} > 50 \text{ GeV}$

long-lived searches

highly ionizing particles
highly displaced vertices
kinked tracks
truncated tracks
out-of-time energy deposits
hidden valley

The $\pi_\nu$ is long lived. It decays *late* in the detector.

calorimeter

muon spectrometer
Different techniques are required for each section of the detector.
the models

\[ m_h = 120 \text{ GeV, } 140 \text{ GeV} \]
\[ m_{\pi_v} = 20 \text{ GeV, } 40 \text{ GeV} \]

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

For a particular lifetime
long lived particle triggers

b-tagging triggers

good for a decay a few millimeters from primary vertex
commissioned
huge backgrounds from QCD $b\bar{b}$ production

long lived neutral particle triggers

neutral particle decays mid-detector
appearance trigger
run for full 2011 dataset (5 $fb^{-1}$)
3 triggers

trackless jet trigger

jet $E_T > 35$ GeV
no tracks with $p_T > 1$ GeV near jet

$\log(E_{had}/E_{EM})$
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 spectrometer cluster trigger
three RoI clusters all close by
no jets
no tracks
really very good efficiency

decays late in inner detector

decays beyond the EM calorimeter

decays beyond the calorimeter

ATL-PHYS-PUB-2009-082

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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 spectrometer cluster trigger
- three muon clusters all close by
- no jets
- no tracks
- really 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

>= 1 Muon Cluster Trigger
2 back-to-back Vertices found in the Muon Spectrometer
No Jet or Track activity near the vertex
\[ \Delta R(\text{jet, vertex}) \geq 0.7 \]
\[ \Delta R(5 \text{ GeV Track, vertex}) \geq 0.4 \]

In 1.94 \( fb^{-1} \) of data 0 events seen

Expected Backgrounds:

1 Trigger 1 Vertex
(15543)

1 Trigger 1 Vertex
(1)

P(2\text{nd Vertex}|\text{No Trigger})
(9.7 \pm 6.9) \times 10^{-7}

P(2\text{nd Vertex}|\text{Trigger})
(1.11 \pm 0.01) \times 10^{-2}

0.03 \pm 0.02
expected signal
limits

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_{\phi} = 140 GeV</td>
<td></td>
</tr>
<tr>
<td>m_{\phi} = 120 GeV</td>
<td>+19.7% -15.1%</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>

Table 7.2: List of the systematic uncertainties.

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

ATLAS

\[
95\% \text{ CL Limit: } m_h = 120 \text{ GeV, } m_{\nu} = 20 \text{ GeV} \\
95\% \text{ CL Limit: } m_h = 120 \text{ GeV, } m_{\nu} = 40 \text{ GeV} \\
95\% \text{ CL Limit: } m_h = 140 \text{ GeV, } m_{\nu} = 20 \text{ GeV} \\
95\% \text{ CL Limit: } m_h = 140 \text{ GeV, } m_{\nu} = 40 \text{ GeV}
\]

\[
\begin{array}{|c|c|c|}
\hline
m_{h,0} \text{ (GeV)} & m_{\pi_{\nu}} \text{ (GeV)} & \text{Excluded Region} \\
\hline
120 & 20 & 0.50 < c\tau < 20.65 \text{ m} \\
120 & 40 & 1.60 < c\tau < 24.65 \text{ m} \\
140 & 20 & 0.45 < c\tau < 15.8 \text{ m} \\
140 & 40 & 1.10 < c\tau < 26.75 \text{ m} \\
\hline
\end{array}
\]
anomaly-mediated SUSY breaking

compressed mass spectra

\[ \tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 \]

LSP, escapes detector, \( E_T^{\text{missing}} \)

small \( p_T \) - perhaps 100 MeV

mass differences between \( \tilde{\chi}_1^\pm \) and \( \tilde{\chi}_1^0 \) is 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 \( m_{\tilde{\chi}_1^\pm} = 90.2,117.8,147.7 \text{ GeV} \), \( \text{BR}(\tilde{\chi}_1^\pm \rightarrow \pi^\pm \tilde{\chi}_1^0) = 1.0 \)


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detector signature

$\tilde{\chi}_1^\pm$ decaying into $\tilde{\chi}_1^0 + \pi^\pm$

high-$p_T$ charged particle interacting with TRT material

low-$p_T$ charged particle scattered in materials resulting in badly measured track $p_T$

reconstructed track
true particle track

Pixel   | SCT   | TRT

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transition radiation tracker

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

![Graph showing ATLAS Preliminary data with tracks and hits distribution.]

\(\int L dt = 4.7 \text{ fb}^{-1}\)
\(\sqrt{s} = 7 \text{ TeV}\)

truncated Tracks have 5 hits or less

normal tracks
the analysis

trigger

1 jet, $p_T > 75$ GeV
$E_T^{\text{missing}} > 55$ GeV

offline

3 jets, $p_T > 130, 60, 60$ GeV
$E_T^{\text{missing}} > 130$ GeV
lepton veto
track: well measured, $\Delta R(\text{track}, p_T > 0.5$ GeV) > 0.1, $p_T > 10$ GeV
less than 5 hits in the TRT

the shape of the track $p_T$
spectra differentiates signal and backgrounds

304 events remain in $4.7 fb^{-1}$ of data
optimized for $514 < r < 863$ mm
backgrounds

\[ \tilde{\chi}_1^\pm \text{ decaying into } \tilde{\chi}_1^0 + \pi^\pm \]

- high-\(p_T\) charged particle interacting with TRT material
- low-\(p_T\) charged particle scattered in materials resulting in badly measured track \(p_T\)

---

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shape for high $p_T$ tracks that interact
select tracks with $N_{TRT}^{\text{outer}} > 10$.

shape for mismeasured low $p_T$
tracks
require $E_T^{\text{missing}} < 100$ GeV
no pixel hits
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

Fit prefers zero signal contribution!
primary uncertainty is the theoretical cross section (27%)
backgrounds are data driven and so have very small uncertainty

limit for the mass
previous LEP2 limit: $m_{\chi^0_0} > 92$ GeV

limit on production of truncated tracks
massive & long lived

Travel slowly through the detector ($\beta \ll 1$)
Lifetime makes them stable w.r.t. the ATLAS detector.

Two good handles to look for this sort of signal:

**Time-of-Flight**

TileCal can measure timing
Previous version of this analysis used this technique
Model dependence on interaction of R-Hadrons with TileCal material
Skipped for this version of the analysis

**Mass ($dE/dx$)**

Pixel detector fires if $> 3100e^-$ deposited
Measures time-above-threshold
Timer maximum is equivalent to about 8.5 MIPS for a track perpendicular to the pixel detector
A MIP is ~ 20Ke
Use Bethe-Block to infer mass
R-Hadron models

SUSY, but the LSP is colored

hadronizes into colored hadrons

\( \tilde{g}g, \tilde{q}q\bar{q}, \tilde{g}qqq, \tilde{q}q, \tilde{qq}, \text{etc.} \)

"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


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backup: 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.
$dE/dx$
mass resolution

[Graph showing mass resolution over the data period from March to August 2011]

[Graph showing simulation results for Gluino R-hadrons at 100, 300, 500, and 700 GeV]
analysis

trigger

no $dE/dx$ information available
MIP in Calorimeter means $E_T^{\text{missing}}$
$E_T^{\text{missing}} > 70$ GeV
20% efficient

offline

$E_T^{\text{missing}} > 85$ GeV
isolated track $p_T > 50$ GeV, $p > 100$ GeV
$\Delta R(\text{track}, p_T > 5$ 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 for the dE/dx cut

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

G. Watts (UW/Seattle)
results

ATLAS Preliminary

ATLAS Preliminary

G. Watts (UW/Seattle)
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 $r &gt; 4$ mm. Shown yesterday</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>
Search Strategies

Final State

Jet
Leptons
Etc.

Search Strategy

Life Time (m)

Physics
conclusions

- three analyses presented
  - Hidden Valley search, AMSB search, R-hadron search
- new triggering algorithms required
  - appearance triggers
  - unlikely possible to design new triggers for this run, but...
- non standard object ID
  - late appearance of jets, truncated tracks, out-of-time energy, displaced vertices
- improving algorithms all the time
  - pile-up is improving too...
- lots of information from the these detectors!!
  - how else can we combine this information to search for new things!?
stable, charged (µ-based)

electrically charged by the time they leave the calorimeter
charged, long lived particles
colored, but interact in calorimeter leading to a spray of charged particles in the muon spectrometer

GMSB SUSY

trigger is the muon drift tube

reconstruction method 1:
fit inner detector track to imperfect muon spectrometer segments
take into account $\beta$ which alters drift time
sub-par muon spectrometer segments also used

reconstruction method 2:
muon spectrometer based only
segment reconstruction starts from trigger information
efficiency is not great for low $\beta$.  

$L=37 \, pb^{-1}$
Stable, charged ($\mu$-based)
displaced vertices

trigger

vertex reconstruction
standard
use tracks that have no pixel hits
reject vertices near material sensitive starting at 4mm from PV

SUSY++
L=33 $pb^{-1}$

efficiency
displaced vertices
displaced vertices

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

95% CL limit
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

ATLAS 2010 Dataset

Timing Efficiency (%) vs. Gluino Lifetime (seconds)

- Uses Bunch Structure
- Uses Run Schedule

Key Points:
- Revolution Period
- Hour
- Day
- Bunch Crossing

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stopped particles

ATLAS

Leading Jet Energy > 100 GeV

\( N_{\text{jets}} = 1 \)

\[ \int \sqrt{s} = 7 \text{ TeV} \]

\[ L \, dt = 31 \text{ pb}^{-1} \]

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

\( M_\tilde{g} \) (GeV)