Search for Supersymmetry in Final States with Measurable Lifetimes with the ATLAS Detector

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19th International Conference on Supersymmetry and Unifications of Fundamental Interactions
Mechanism & Motivation

- Several SUSY models allow a particle with decay length > ATLAS
  - Split, RPV, Stealth, GMSB (and hidden valley!)
  - New coupling, small phase space, large scales
- Cosmological & sBBN $^7\text{Li}$ / $^6\text{Li}$ discrepancy
  - Convenient delayed neutron source: $\tau \sim< 100$ sec

Long Lived Particle?

Any 400 GeV particle in your detector is BSM
R-hadron Signature

• Not your Grandmother’s particle!
• Given an LLP w/ color charge ($\tilde{g}, \tilde{b}, \tilde{t}, \ldots$)
  - Hadronize w/ SM quarks $\rightarrow$ glueball/meson/baryon
  - Spectator quarks dominate nuclear interaction
  - $R$-hadron exchanges electric charge with nuclei!
• Energy loss: $dE/dX$, nuclear scatter & trapping
• Nuclear xsec and hadron spectrum unknown

Where in ATLAS are the $R$-hadrons charged?
Search Signatures

- Inner Detector + Calorimeter
- Muon Spectrometer
- Stopped Particle

Phenomenology + Selection
Detection Methods
Backgrounds
Results

doi:10.1016/j.physletb.2011.05.010

SUSY 11/LLP Final States in ATLAS, Fermilab, Aug 28 2011
Production Model

LLP's produced near threshold

Kinetic Energy
\[ \approx M_{LLP} \]

From Theory
Analysis Selection

SUSY 11/LLP Final States in ATLAS,
Fermilab, Aug 28 2011

doi:10.1016/j.physletb.2011.05.010
**ID and Calorimeter: Phenomenology**

**Production Model**
- LLP’s produced near threshold
- Kinetic Energy \( \approx M_{LLP} \)
- Candidate Track \( p_T > 50 \text{ GeV} \)
- \( \beta < 1 \)

**Graphical Representation**
- From Theory
- Analysis Selection

**Additional Information**
- LLP’s produced near threshold
- Kinetic Energy \( \approx M_{LLP} \)
- Candidate Track \( p_T > 50 \text{ GeV} \)
- \( \beta < 1 \)

**Reference**
- doi:10.1016/j.physletb.2011.05.010

**Conference Details**
- SUSY 11/LLP Final States in ATLAS,
  Fermilab, Aug 28 2011
**ID and Calorimeter: Phenomenology**

**Production Model**

- **LLP's produced near threshold**
- Kinetic Energy \( \approx M_{LLP} \)
- Candidate Track \( p_T > 50 \text{ GeV} \)
- TileCal ToF \( \beta < 1 \)
- dE/dX in Pixel \( > 1.8 \text{ MeV cm}^2 /\text{g} \)

**From Theory**

**Analysis Selection**

**ATLAS**

- R-hadrons
  - \( m_g = 300 \text{ GeV} \)
  - \( m_g = 500 \text{ GeV} \)
  - \( m_g = 700 \text{ GeV} \)

**SUSY 11/LLP Final States in ATLAS, Fermilab, Aug 28 2011**

** doi:10.1016/j.physletb.2011.05.010**
**ID and Calorimeter: Phenomenology**

*Production Model*

- LLP’s produced near threshold
- Kinetic Energy $\approx M_{LLP}$
- LLP’s leave small fraction of their energy in ATLAS

- Total EM energy loss $\approx 10$ GeV

*Candidate Track*

- $p_T > 50$ GeV

*From Theory*

- Analysis Selection

*ATLAS*

- $R$-hadrons
  - $m_g = 300$ GeV
  - $m_g = 500$ GeV
  - $m_g = 700$ GeV

- $\beta < 1$

*TileCal ToF*

- $\beta < 1$

*TileCal ToF*

- $dE/dX$ in Pixel
  - $> 1.8$ MeV cm$^2$ /g

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SUSY 11/LLP Final States in ATLAS, Fermilab, Aug 28 2011

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LLP’s leave small fraction of their energy in ATLAS

Total EM energy loss ≈ 10 GeV

Trigger on MET > 40 GeV

dE/dX in Pixel > 1.8 MeV cm^2 /g

TileCal ToF β < 1

ISR jet still very large

Candidate Track p_T > 50 GeV

Vertical Redshift β < 1

From Theory
Analysis Selection

doi:10.1016/j.physletb.2011.05.010

SUSY 11/LLP Final States in ATLAS, Fermilab, Aug 28 2011
Each cell $\delta t = 1-2$ ns

Average cells over 500 MeV $\Rightarrow \delta t \approx 1$ ns

$\beta = 1 \Delta t \approx 6$ ns

$\beta = 0.8 \Delta t \approx 8$ ns

Pixel Tracker

$dE/dX$

SM Particles (Fast)

Heavy LLP (Slow)

$\beta \gamma < 1$

$\beta \gamma > 1$

- MIPS leave $\sim 1$ MeV cm$^2$/g
- LLP leave 2-10 MeV cm$^2$/g

SUSY 11/LLP Final States in ATLAS, Fermilab, Aug 28 2011

doi:10.1016/j.physletb.2011.05.010
SM Backgrounds
• Top and EW biggest
  • Not real massive particles
  • Instrumental effects!
• After all cuts too few statistics
• Need to estimate high mass yield

Instrumental Backgrounds
• Combine measured $p$ with random $\beta$
  • PDF($\beta$) derived from data
  • Many random $\beta$’s for each $p$
• Calculate $m_{\text{Tile}}$
• Similar treatment for $m_{\text{Pixel}}$ and combination $\rightarrow N_{\text{bkg}} < 1$

SUSY 11/LLP Final States in ATLAS,
Fermilab, Aug 28 2011

[Graph and diagram showing data points and distributions]
ID and Calorimeter: Results

**Cut** | **Data** | **Background** | **600 GeV ~g**
--- | --- | --- | ---
Preselection | 49205 | $4.94 \times 10^3$ | 4.13
$p_T > 50$ GeV | 5116 | $6.56 \times 10^3$ | 3.95
1 Mass Cut | 36 | 56.0 | 2.75
Both Mass Cuts | 0 | 0.028 | 2.62

No signal like events observed
- In 34 pb$^{-1}$ of data
- Studied several mass regions
- Proceed to set 95% CL$_S$ limit
  - Interpret as $R$-hadron
  - 30% bkgd systematic
  - 10% on eff from PYTHIA scale

\[ m_{\tilde{b}} > 294 \text{ GeV} \quad m_{\tilde{g}} > 586 \text{ GeV} \quad m_{\tilde{t}} > 309 \text{ GeV} \]

doi:10.1016/j.physletb.2011.05.010

SUSY 11/LLP Final States in ATLAS,
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Search Signatures

Inner Detector + Calorimeter

Muon Spectrometer

Stopped Particle

Phenomenology + Selection

Detection Methods

Backgrounds

Results

arXiv:1106.4495v1 [hep-ex]
Muon Spectrometer: Phenomenology

Production Model

- LLP's produced near threshold
- Kinetic Energy $\approx M_{LLP}$

From Theory
Analysis Selection

arXiv:1106.4495v1 [hep-ex]

SUSY 11/LLP Final States in ATLAS, Fermilab, Aug 28 2011
Muon Spectrometer: Phenomenology

**Production Model**

**LLP’s produced near threshold**

Kinetic Energy \( \approx M_{LLP} \)

- **Candidate Track** \( p_T > 60 \text{ GeV} \)
- **\( \beta < 0.95 \)**
- **Late Arrival to MS**

From Theory
Analysis Selection

arXiv:1106.4495v1 [hep-ex]
Muon Spectrometer: Phenomenology

Production Model

LLP’s produced near threshold

Candidate Track
\( p_T > 60 \text{ GeV} \)

\( \beta < 0.95 \)

Late Arrival to MS

Trigger on “\( \mu \)”
\( p_T > 40 \text{ GeV} \)

Total EM energy loss \( \approx 10 \text{ GeV} \)

LLP’s traverse the muon system

From Theory
Analysis Selection

arXiv:1106.4495v1 [hep-ex]

SUSY 11/LLP Final States in ATLAS,
Fermilab, Aug 28 2011
Muon Spectrometer: Phenomenology

Production Model

**LLP’s** produced near threshold

Kinetic Energy ≈ $M_{LLP}$

**LLP’s** traverse the muon system

R-hadron might not be charged in ID

Total EM energy loss ≈ 10 GeV

Candidate Track

$p_T > 60$ GeV

$\beta < 0.95$

Late Arrival to MS

Trigger on “µ”

$p_T > 40$ GeV

Drop Inner Detector info…

From Theory

Analysis Selection

arXiv:1106.4495v1 [hep-ex]
Muon Spectrometer: Phenomenology

Production Model

LLP’s produced near threshold

Kinetic Energy $\approx M_{LLP}$

LLP’s traverse the muon system

Candidate Track $p_T > 60$ GeV

$\beta < 0.95$

Late Arrival to MS

Trigger on “$\mu$” $p_T > 40$ GeV

Drop Inner Detector info…

Optimized 2nd set of cuts for slepton search (using ID tracking as well)!

Total EM energy loss $\approx 10$ GeV

R-hadron might not be charged in ID

From Theory

Analysis Selection

SUSY 11/LLP Final States in ATLAS, Fermilab, Aug 28 2011
Muon Spectrometer: Detector

- Use Resistive Plate Chamber for ToF
- Not so easy for Drift Tube Tracking
  - Provides high spatial resolution (20 µm)
  - Need to recalculate drift times for $\beta \neq 1$

arXiv:1106.4495v1 [hep-ex]
Muon Spectrometer: Detector

- Use Resistive Plate Chamber for ToF
- Not so easy for Drift Tube Tracking
  - Provides high spatial resolution (20 µm)
  - Need to recalculate drift times for $\beta \neq 1$

**Reconstructed drift circles from a slow particle**

Try tracking with $\beta = 1$

[arXiv:1106.4495v1 [hep-ex]]

SUSY 11/LLP Final States in ATLAS, Fermilab, Aug 28 2011
Muon Spectrometer: Detector

Reconstructed drift circles from a slow particle

Try tracking with $\beta = 1$
Try tracking with $\beta = 0.8$
Try tracking with $\beta = 0.6$

- Use Resistive Plate Chamber for ToF
- Not so easy for Drift Tube Tracking
  - Provides high spatial resolution (20 $\mu$m)
  - Need to recalculate drift times for $\beta \neq 1$

arXiv:1106.4495v1 [hep-ex]

SUSY 11/LLP Final States in ATLAS, Fermilab, Aug 28 2011
Muon Spectrometer: Detector

- Use Resistive Plate Chamber for ToF
- Not so easy for Drift Tube Tracking
  - Provides high spatial resolution (20 µm)
  - Need to recalculate drift times for $\beta \neq 1$

Try tracking

- with $\beta = 1$
- with $\beta = 0.8$
- with $\beta = 0.6$

Reconstructed drift circles from a slow particle

Correctly Reconstructed LLP Track

arXiv:1106.4495v1 [hep-ex]
SM Backgrounds

- Basically, no slow muons ($m_{\mu} \approx 0$)
  - $\text{PDF}(\beta) \not\equiv \delta(\beta-1)$ ??
  - Instrumental effects!
  - And ~1.3 cosmics in sample
- Need to estimate $\beta < 1$ yield from mis-measured muons

Instrumental Backgrounds

- Combine measured $p$ with random $\beta$
  - $\text{PDF}(\beta)$ derived from data
  - Many random $\beta$’s for each $p$
  - $\text{PDF}$ calculated in $\eta$ slices
- Calculate $m_{\text{LLP}}$
- $N_{\text{bkg}} = 2.3$ (for $m_{\text{LLP}} > 250$ GeV)

~ Underlying muon $PDF$

arXiv:1106.4495v1 [hep-ex]
Muon Spectrometer: Results

<table>
<thead>
<tr>
<th>Cut</th>
<th>Data</th>
<th>$&lt;N_{bkgd}&gt;$</th>
<th>$&lt;N_{sig}&gt;$ 600 GeV $\sim g$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preselection</td>
<td>6334</td>
<td>--</td>
<td>3.8</td>
</tr>
<tr>
<td>$\beta$ Quality</td>
<td>4998</td>
<td>--</td>
<td>3.3</td>
</tr>
<tr>
<td>$\beta &lt; 0.95$</td>
<td>830</td>
<td>0.7</td>
<td>2.2</td>
</tr>
<tr>
<td>$M &gt; 350$ GeV</td>
<td>1</td>
<td>0.7</td>
<td>2.2</td>
</tr>
</tbody>
</table>

No excess of events observed

- In 37 pb$^{-1}$ of data
- Studied several mass regions
- Proceed to set 95% CL$_S$ limit
  - Interpret as $R$-hadron/Stau
  - 20% bkgd systematic
  - 6% systematic on signal yield

\[ m_{\tilde{g}} > 544 \text{ GeV} \]
\[ m_{\tilde{\tau}} > 136 \text{ GeV} \]

$N_5 = 3$, $m_{\text{messenger}} = 250$ TeV, $\mu > 0$, $\tan \beta = 5$

arXiv:1106.4495v1 [hep-ex]

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Stopped Particle

Phenomenology + Selection

Detection Methods

Backgrounds

Results
Stopped Particles: Phenomenology

Production Model

**LLP’s** produced near threshold

\[ \beta = 300 \text{ GeV} \]
\[ m_{\ell} = 500 \text{ GeV} \]
\[ m_{\ell} = 700 \text{ GeV} \]

ATLAS

\( \bar{\nu} \)-hadrons

\( m_{\ell} = 300 \text{ GeV} \)
\( m_{\ell} = 500 \text{ GeV} \)
\( m_{\ell} = 700 \text{ GeV} \)

Some going really slow
Stopped Particles: Phenomenology

Production Model

LLP’s produced near threshold

\(\frac{dE}{dX} \approx \beta^{-2}\)

Occasional nuclear scatter

SUSY 11/LLP Final States in ATLAS, Fermilab, Aug 28 2011
**Stopped Particles: Phenomenology**

**Production Model**

- LLP's produced near threshold

- dE/dX ≈ β⁻²

- Occasional nuclear scatter

- Some LLPs stop in detector, and decay much later

**Graph**

**ATLAS**

- X-hadrons
- m_θ = 300 GeV
- m_θ = 500 GeV
- m_θ = 700 GeV

**Note**

Some going really slow
**Stopped Particles: Phenomenology**

**Production Model**

- LLP’s produced near threshold
- Not all “bunches” have protons
- Look for decay in “empty” bunches

**From Theory**

**Analysis Selection**

- dE/dX $\approx \beta^{-2}$
- Occasional nuclear scatter
- Some LLPs stop in detector, and decay much later

**ATLAS**

- Some going really slow

**SUSY 11/LLP Final States in ATLAS, Fermilab, Aug 28 2011**
Stopped Particles: Phenomenology

Production Model

$\frac{dE}{dX} \approx \beta^{-2}$

Occasional nuclear scatter

$LLP's$ produced near threshold

Not all "bunches" have protons

Look for decay in "empty" bunches

Handle non-collision backgrounds

Some $LLPs$ stop in detector, and decay much later

SUSY 11/LLP Final States in ATLAS, Fermilab, Aug 28 2011
Stopped Particles: Detector

Bunch Type

- Colliding
- Empty
- Unpaired

Diagram

LLP!

Bang!

LLP!

LLP??

Proton Bunch

Study Beam Halo...

SUSY 11/LLP Final States in ATLAS, Fermilab, Aug 28 2011
Stopped Particles: Backgrounds

Cosmic Ray Muon

Remove these events by vetoing muon segments

April 6th 2010
9:26 CEST
Stopped Particles: Backgrounds

MIP trail

Hard Scatter

μ segment parallel to beam line

Beam Halo Muon

October 24th 2010
19:45 CEST
Stopped Particles: Backgrounds

Cosmic Ray Muons
- Veto with muon segment
- Scale with data taking time
- Estimate with early 2010
  - Essentially signal free!

Beam Halo Muons
- Veto with jet location, jet shape
- Scales with
  - LHC vacuum, collimators
  - Filling scheme, etc.
- Need sideband in late 2010 data
- Estimate with unpaired bunches!

ATLAS Preliminary

<table>
<thead>
<tr>
<th>Halo</th>
<th>With Muon</th>
<th>No Muon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unpaired</td>
<td>2021</td>
<td>2</td>
</tr>
<tr>
<td>Empty</td>
<td>429</td>
<td>.43±.3!!</td>
</tr>
</tbody>
</table>

Same running conditions, orthogonal sample

The estimate
(1st Jet E > 50 GeV)

SUSY 11/LLP Final States in ATLAS, Fermilab, Aug 28 2011
Background Agreement
- Showing distribution after Trigger and Data Quality
- Samples scaled to amount of time ATLAS “live”
- Agreement is excellent!!
- Dominant background scales with time (i.e., cosmics)
Stopped Particles: Results

No excess of events observed
- In 31 pb\(^{-1}\) of data
- Studied single-and multi-jet yield
- Limits not ready to show
  - Full efficiency ~0.3%

Extra Inefficiencies
- Stopping: Particles aren’t trapped
  - Model dependent ~10%
  - Studied “Generic” + “Regge”
- Timing: Particles decay when ATLAS not ready
  - Complicated function of lifetime
  - 37% when \(\tau\) in \([10^{-5}, 10^{3}]\) sec

<table>
<thead>
<tr>
<th># of Events</th>
<th>#Jets</th>
<th>Obs</th>
<th>Exp</th>
<th>Signal</th>
<th>Bkgd</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>0</td>
<td>.3</td>
<td>.23</td>
<td>1.06</td>
</tr>
<tr>
<td></td>
<td>&gt;1</td>
<td>1</td>
<td>.6</td>
<td>.23</td>
<td>1.06</td>
</tr>
</tbody>
</table>

ATLAS Preliminary 2010 Dataset
- Uses Bunch Structure
- Uses Run Schedule

Stopping: Particles aren’t trapped
- Model dependent ~10%
- Studied “Generic” + “Regge”

Timing: Particles decay when ATLAS not ready
- Complicated function of lifetime
- 37% when \(\tau\) in \([10^{-5}, 10^{3}]\) sec
Conclusion

• 3 ATLAS direct detection searches for long lived particles
  – $dE/dX$ in Pixel, ToF in Tile
  – ToF + Drift Circle in Muon System
  – Decays in the empty bunches
• No significant excesses…
• Keep an eye out for 2011 updates!
Back Up

• It begins here.
Full Beam Halo Event

Beam Halo Muon

October 24th 2010
19:45 CEST
• 3 layer silicon pixel detector calculates dE/dX
  – Reconstructs trajectory of LLP |η| < 2.5 & R < 12 cm
  – Truncated mean of clusters’ charge on the track

• Tile Calorimeter ToF with 2.3 < r < 4.3 m
  – 6 independent time measurements (δt = 1-2 ns)
  – Average all cells > 500 MeV → δt ~ 1ns

• Muon Spectrometer ToF with 5 < r < 10 m
  – Uses drift tubes and fast RPC/TGC
ID and Calorimeter Search

• Theoretical Needs. Think:\n  \[ \text{gg} \xrightarrow{\text{Threshold}} 2 \, \text{R-hadron} \]
  – \( m_{\text{LLP}} > 100 \text{ GeV} \) & charged in pixel and tile
  – Decays outside of ATLAS (Trigger MET > 40)

• Use \( dE/dX \) in pixel (\( \beta \gamma \)) and ToF in Tile (\( \beta \))
  – Both independently calculate mass!
  – Candidate \( pT > 50 \text{ GeV} \)

• 10% \( dE/dX \) resolution using simplified Bethe Bloch parameterization

\[ 5 \text{ constants optimized for } 0.2 < \beta \gamma < 1.5 \]
ID and Calo: Background

- Handle pixel and tile separately
- Data noise estimate
  - Apply selection
  - Extract mass PDF
- Combined estimate
  - Only generate $p_!$
  - Agrees with observed data very well

Random $p$, $dE/dX$ given $10 < p_T < 20$

$\mathcal{N}_{\text{predicted}} < 1$

Random $p$, $\beta$

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