LONG LIVED PARTICLE SEARCHES IN ATLAS

Karri Folan DiPetrillo
Second LHC Long-lived Particle Workshop
18 October 2017
Thanks to the organizers and ICTP!
Some thoughts on LLP Searches
We’re all here because

We think long-lived particles are well motivated
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We think long-lived particles are well motivated

Small Mass Splittings

Highly virtual couplings

Small couplings
But many ways to approach LLP searches

On a scale of

Theorist

Experimentalist
But many ways to approach LLP searches

On a scale of

- model
- lifetime
- final state
- mass

Theorist  Experimentalist
But many ways to approach LLP searches

On a scale of

- detector
- trigger
- reconstruction
- person power

Theorist  Experimentalist
Reality of LLP searches

Need to be cognizant of models that motivate searches, but....

Creatively utilizing resources that weren’t designed to look for every kind of LLP

the detector impacts fiducial acceptance

developing triggers for LLPs
OR triggering on prompt objects in the same event

using special reconstruction

with small groups of highly motivated people
Framing this talk: experiment → theory

I’ll break down ATLAS LLP searches in terms of what we can do with our experimental resources highlighting what is

Accomplished in Run 2
Accomplished in Run 1 but not Run 2
Feasible but not done
Feasible but with new resources

and then discuss the impact on physics coverage
The basics of ATLAS LLPs
Many thanks to Heather Russell for the ATLAS and LLP figures!
The ATLAS Detector

Inner Detector
charged particle tracks
Silicon Pixels (Pixel)
Silicon Strips (SCT)
Transition Radiation Tracker (TRT)
Electromagnetic Calorimeter
electron/photon energy and direction
Liquid Argon/Lead
The ATLAS Detector

Hadronic Calorimeter
measuring hadrons/jets/taus
Barrel (Steel/Scintillating Tile)
Endcap (Liquid Argon/Copper)
The ATLAS Detector

Muon Spectrometer
tracking and trigger chambers
to measure bending of muons
in toroidal magnetic field
What do we mean by long-lived?

In ATLAS, an LLP can be a particle that decays some reconstructable distance away from the p-p interaction point.
What do we mean by long-lived?

OR

charged and quasi-stable on the scale of our detector
What lifetimes can we probe?

Any given particle’s lifetime is sampled from an exponential distribution.

\[ P(\text{decay}) \]

Distance Travelled
What lifetimes can we probe?

Sometimes we can target specific lifetimes using certain parts of the detector.

eg. \( <\beta \gamma> \approx 30, \ c\tau = 10 \text{ cm} \)

Distance Travelled

<table>
<thead>
<tr>
<th>Distance</th>
<th>Prompt - 1%</th>
<th>Tracker - 27%</th>
<th>Calorimeter - 45%</th>
<th>Muon Spectrometer - 22%</th>
<th>Outside ATLAS - 3%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 m</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 m</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 m</td>
<td></td>
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</tbody>
</table>
What final states can we probe?
What final states can we probe?

- displaced leptons, lepton jets, or lepton pairs
- displaced multi-track vertices
- disappearing or kinked tracks
- non pointing or late photons
- emerging jets
- trackless low EMF-jets
- (meta-)stable charged particles

multi-track vertices in muon spectrometer
How do we trigger on these objects?

ATLAS trigger basics

- L1: calorimeter & muon information
- HLT: e/µ/γ/τ/jets/MET
- limited tracking info at HLT
- typically d0 requirements on e/µ

1. Design your own
   displaced lepton jets:
   “narrow scan” and “cal ratio”

2. Be sneaky
   displaced e: γ trigger
   displaced µ: Muon Spectrometer only trigger

3. Be lucky
   Inner Detector displaced vertices: multi-jet/MET

Is there room for improvement?
Many HLT ideas limited by L1 constraints
How do we reconstruct these signatures?

Lots of work in non-standard reconstruction
- Pixel tracklets
- Large radius tracking
- Slow muons
- Secondary Vertex finding

These methods are difficult, but essential
- computationally expensive
- require running on raw data
- filter out events using special data streams
- so we can run our non-standard reconstruction a single time
ATLAS LLP Searches
(Meta-)Stable Massive Charged Particles
(Meta-)Stable Massive Particles

Charged particles with lifetimes $\sim 0.4$ ns or more

- interaction of charged particles w/ detector
- particles are **slow** and **highly ionizing**

What ATLAS can do

- Pixel Detector: specific ionization from clusters, $dE/dx \rightarrow \beta\gamma$
- Calorimeters & Muon Spectrometer: timing, ToF $\rightarrow \beta$
Measure $\beta\gamma$ from $dE/dx$ with pixel clusters

- sensitive to $\beta\gamma$ between 0.3 and 1.5

**Improvements in Run 2**

- IBL reduces $dE/dx$ Tails
- Better electron/muon rejection

Can’t trigger on inner detector tracks… use MET trigger
Pixel + Tile Calorimeter

Make a mass estimate using:
- Pixel dE/dx
- Tile time of flight

Tile cell timing resolution:
1.3-2.5 ns after calibration

\[ \beta \text{ resolution: } \sigma(\beta) \sim 0.1 \]

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PLB 760 (2016) 647-665
13 TeV 3.2 fb\(^{-1}\)

JHEP 01 (2015) 068
8 TeV 19.1 fb\(^{-1}\)
ToF from Muon Spectrometer not yet used in Run 2!
Decays in the Inner Detector
Tracking Tricks
Triggering is difficult: use other objects in the event (MET and 1 offline jet)
Kinked Tracks/Displaced Leptons

similar to displaced track scenarios, but the secondary charged particle can be reconstructed
charged LLP $\rightarrow$ neutral stable particle $\quad + \text{reconstructed} \text{ charged particle}$

1. Kinked tracks
both tracks must have $p_T > 1$ GeV
similar trigger difficulties as disappearing track

2. Displaced Leptons
at higher $p_T$ leptons can trigger the event
using charged LLP track likely unnecessary

We haven’t done these searches!
but I think we could
Decays in the Inner Detector
Displaced Vertices
Displaced di-lepton vertices

Leptonic decays with inner detector displaced vertices
use large-d0 tracking and secondary vertex finding
to find displaced vertices in pixel barrel
require DV mass > 10 GeV and 2 leptons

Use the leptons to trigger
\( \gamma \) trigger on displaced electrons
Muon Spectrometer only trigger for
displaced muons

Non-standard Backgrounds
cosmics, random crossings,
material interactions

PRD 92 (2015) 072004
8 TeV 20.3 fb\(^{-1}\)

\( \sqrt{s} = 13 \text{ TeV}, L = 32.8 \text{ fb}^{-1}, \text{All Reconstructed Vertices} \)
Multi-track displaced vertices

Looking for displaced hadronic decays w/ a multi-track vertex signature
using large-d0 tracking & secondary vertex finding
require DV mass > 10 GeV and ≥ 5 tracks

Use other objects to trigger on the event
› standard MET & jet triggers
› muon spectrometer only trigger
› γ trigger for displaced e

Possible future improvements
› improve vertexing efficiency
› probe sensitivity to lower masses, fewer tracks
› probe shorter lifetimes, < 0.01 ns

arXiv:1710.04901
13 TeV 33 fb⁻¹
Run 2: DV+MET

PRD 92 (2015) 072004
8 TeV 20.3 fb⁻¹
Run 1: DV+e/µ, DV+jets, DV+MET

DV+jets
DV+MET
DV+µ
DV+e
Detecting Decays using the Calorimeter
Non-Pointing/Delayed Photons

Targeted decay:
neutral LLP → photon + invisible particle
photon might not point back to the primary vertex and/or arrive late compared to a prompt photon

Reconstruction: LAr calorimeter can measure photon **pointing** & ToF
Searching for long-lived particles decaying within the calorimeter

Trigger: Low EMF trigger - L1Tau seed

Analysis improvements in Run 2
Boosted Decision Tree to select displaced jets

Backgrounds
SM multi-jet
cosmic muons
beam induced background
Stopped Particles

what happens when your particle moves so slowly it gets stopped by the calorimeter…
and decays later!
Looking for \( R \)-hadrons stopped by the calorimeter
probe lifetimes up to order hours/days/years
sensitive to very small \( \beta \), neutral \( R \)-hadrons,
and when charge flips prevent reconstruction

Trigger: empty bunch crossings
no bunches at the interaction point
require a low \( p_T \) jet and \( E_T \)-miss

Non-standard backgrounds:
cosmic muons & beam-halo
veto on muon activity

PRD 88 (2013) 112003
8 TeV 27.9 fb\(^{-1}\)
not yet in Run 2!
Detecting Decays with the Muon Spectrometer
Displaced vertices in the muon system

Looking for displaced decays of hadronic jets
targets vertices between end of HCAL and start of 2nd MS station

Trigger: cluster of muon ROIs
in a cone of $\Delta R < 0.4$
preceded by little ID & Calo activity

MS vertex reconstruction
muon segments $\rightarrow$ tracklets $\rightarrow$ vertices

Backgrounds:
SM punch-through,
cosmics, and cavern background
Detecting Decays with multiple subdetectors
Emerging Jets

A new signature resulting from dark showers in QCD-like hidden sectors

Jet slowly emerges as LLPs decay to SM particles

Could get a handle on the event using high multiplicity of secondary vertices in the **Inner Detector** and non-standard jets in the **Calorimeter**
Displaced Lepton jets

Neutral long-lived particles decaying to collimated jets of leptons and mesons requires combination of **Calorimeter** & **Muon** information.

### Improved LLP Triggers

- **MS only:** cluster of muons w/ no nearby jets
- **Narrow Scan:** pairs of nearby muons, but only 1 seed at L1
- **Cal Ratio:** low EM fraction jets

ATLAS-CONF-2016-042
13 TeV 3.4 fb$^{-1}$
Displaced Lepton jets

Neutral long-lived particles decaying to collimated jets of leptons and mesons requires combination of **Calorimeter** & **Muon** information.

**Type 2: LJ Reconstruction Efficiency**

Run 2: Better Muon Reconstruction Efficiency for nearby muons.

**ATLAS Simulation**

Preliminary

- $m_H=125$ GeV, $\gamma_d \rightarrow ee$
- $m_H=800$ GeV, $\gamma_d \rightarrow ee$
- $m_H=125$ GeV, $\gamma_d \rightarrow \pi\pi$
- $m_H=800$ GeV, $\gamma_d \rightarrow \pi\pi$

**L$_{xy}$ [m]**

**L$_z$ [m]**
Tried to show how ATLAS uses experimental resources to search for long-lived particles.

<table>
<thead>
<tr>
<th>Particle Signature</th>
<th>Detector Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>(meta-)stable charged</td>
<td>Inner Detector</td>
</tr>
<tr>
<td>decays to leptons</td>
<td>Calorimeter</td>
</tr>
<tr>
<td>decays to hadrons</td>
<td>Muon Spectrometer</td>
</tr>
<tr>
<td>and more</td>
<td></td>
</tr>
</tbody>
</table>

- (meta-)stable charged particles
- Decays to leptons
- Decays to hadrons
- And more

- Inner Detector
- Calorimeter
- Muon Spectrometer

- Pixel dE/dx
- Tile ToF
- MDT/RPC ToF
- Dilepton DVs
- Displaced lepton jets
- Multi-track DVs
- HCAL jets
- MS vertices
- Stopped particles
- Emerging jets
- Non-pointing/delayed photons
- Disappearing tracks
- Displaced lepton jets
Now I’ll try to see how we do with your favorite models…
Physics Coverage
SUSY: charginos (small mass splittings)
SUSY: charginos (small mass splittings)

Tracks disappear in the SCT
Tracks disappear in the TRT

Stable Massive Particles 8 TeV

Pixel dE/dx 8 TeV

(r for η=0, βγ=1)

Lower limit on m_{\chi^\pm} [GeV]

τ [ns]

ct [m]

Status: March 2017
SUSY: charginos (small mass splittings)

Tracks disappear in the SCT

Even shorter pixel tracks?

Tracks disappear in the TRT

Pixel dE/dx

Stable Massive Particles

8 TeV

8 TeV

(r for \( \eta = 0, \beta \gamma = 1 \))

Inner Detector

Calo

MS

\( \tau \) [ns]

\( \alpha \tau \) [m]
SUSY: gluino R-hadrons (heavy mediator)

\[ \tilde{g} \text{ R-hadron} \rightarrow g/qq \tilde{\chi}_1^0; \ m_{\tilde{\chi}_1^0} = 100 \text{ GeV} \]

\[ \text{Status: July 2016} \]

\[ \text{Displaced vertices Phys. Rev. D92, 072004} \]

\[ \text{Stopped gluino Phys. Rev. D88, 112003} \]

\[ \text{Jets+}E_T^{\text{miss}} \text{ ATLAS-CONF-2015-062} \]

\[ \text{Pixel dE/dx Phys. Rev. D93, 112015} \]

\[ \text{Stable charged arXiv:1606.05129} \]

\[ \{ 5.0-22.9 \text{ fb}^{-1}, \sqrt{s}=7.8 \text{ TeV} \} \]

\[ \{ 3.2 \text{ fb}^{-1}, \sqrt{s}=13 \text{ TeV} \} \]
SUSY: gluino R-hadrons (heavy mediator)

\[ \tilde{g} \text{ R-hadron} \rightarrow g/qq \tilde{\chi}_1^0; m_{\tilde{\chi}_1^0} = 100 \text{ GeV} \]

Latest DV+MET result!

Pixel dE/dx 3.2 fb\(^{-1}\)

Stable Massive Particles 3.2 fb\(^{-1}\)

Stopped R-hadron 8 TeV

Will improve!

Status: 18 Oct 17
SUSY: gluino R-hadrons (heavy mediator)

Improvements at smaller radii?
Reinterpretation of prompt searches?

Pixel dE/dx
3.2 fb⁻¹

Stable Massive Particles
3.2 fb⁻¹

Stopped R-hadron
8 TeV

(r for η=0, βγ=1)

Beampipe
Inner Detector
Calo MS

τ [ns]

ct [m]
A lot of room to play with

Do prompt b-tagged searches have sensitivity to LLPs at short displacement?

Do we have coverage for collimated/resolved signatures?

How does targeting different production modes help with triggering?
Material for Reinterpretation

If you’re not satisfied w/ our interpretations… we’re providing parametrized efficiencies as aux material with prescriptions for easy use

**DV+MET Event & Vertex Level Efficiencies**

![ATLAS Simulation](image)

*ATLAS Simulation*

$0 \text{ mm} < R_{\text{decay}}^{\text{max}} < 1150 \text{ mm}$

Before Calorimeter

![Plot](image)

**ATLAS Simulation**

Vertex efficiency: Region 6

$73 \text{ mm} < R_{\text{decay}} < 84 \text{ mm}$

**$N_{\text{tracks}}$ (Truth vertex)**

**Vertex selection efficiency**
Conclusions
Overview of ATLAS LLP searches

Highlighted how we can make use of different parts of the detector

Discussed some of the specialized triggers and reconstruction methods used to search for LLPs

Showed how we measured up against some benchmark models

And how material is available for reinterpretation
Backups