Searches for displaced hadronic and lepton-jets at ATLAS

Edward Moyse
Introduction

• Many theories which predict existence of ‘long-lived’ particles.

• Will cover two existing ATLAS 8 TeV results
  
  • Long-lived, weakly interacting particles decaying to hadronic jets
    
  
  • Pair produced, long-lived neutral particles decaying to hadronic jets
    

• One NEW ATLAS 13 TeV result:
  
  • Search for long-lived neutral particles decaying into "lepton-jets" with the ATLAS detector in proton-proton collision data at sqrt(s) = 13 TeV
    
    • ATLAS-CONF-2016-042
  
  • See Antonio’s poster for more details:
    
    • 8 Aug 2016, 18:30, Riverwalk A/B
Hadronic jets
Physics models - hadronic jets

- ‘Hidden valley’ refers to a general class of models in which a hidden sector (ν-sector) is added to SM
- ν-particles don’t couple directly to SM, so need communicator particles:
  - Depending on coupling, this can lead to long lifetimes for the lightest ν-particles
  - One benefit of having a large detector, is we have the ability to look for them!

Scalar boson
Scalar-boson mixing with hidden-sector boson, \( \Phi_{\text{HS}} \).
\( \Phi_{\text{HS}} \) decays to a pair of π\( _{\nu} \)s.

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\( \Phi_{\text{HS}} \)

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Reconstructing displaced jets

• Triggering - most standard triggers are linked to primary vertex, and are so very inefficient. Instead several specialised triggers are used by the various searches, including:

  • **Calo-Ratio trigger**: looks for >1 narrow jet with relatively little energy deposited in the EM calorimeter, and no charged tracks pointing towards to jet

  • **Muon-Rol-Cluster trigger**: looks for decays of neutral particles in the MS.
Reconstructing muon vertices

- The spatial separation between the two multilayers inside a single MDT chamber provides a powerful tool for pattern recognition.
  - Generates ‘tracklets’ inside a single chamber.
  - Specialised algorithm reconstructs straight line segments in multilayers, then matches segments using two parameters
    - $\Delta b$ - minimum distance between segments at centre of chamber
    - $\Delta \alpha$ - angle between segments (can measure momenta for low pT muons)

Efficiency for reconstructing a vertex for $\pi\nu$ decays in the barrel muon spectrometer as a function of the radial decay position of the $\pi\nu$ for $\pi\nu$ decays that satisfy the Muon RoI Cluster trigger

“Standalone vertex finding in the ATLAS muon spectrometer”
Results


- No significant excess observed with 20.3 fb\(^{-1}\) of pp collisions

<table>
<thead>
<tr>
<th>Sample ((m_H, m_{\pi_v}) \text{ [GeV]})</th>
<th>Expected yields</th>
<th>Global acceptance (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>126, 10</td>
<td>536 ± 23</td>
<td>0.139 ± 0.006</td>
</tr>
<tr>
<td>126, 25</td>
<td>941 ± 44</td>
<td>0.244 ± 0.011</td>
</tr>
<tr>
<td>126, 40</td>
<td>365 ± 31</td>
<td>0.095 ± 0.008</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Background</th>
<th>Expected events</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM Multi-jets</td>
<td>23.2 ± 8.0</td>
</tr>
<tr>
<td>Cosmic rays</td>
<td>0.3 ± 0.2</td>
</tr>
<tr>
<td>Total Expected Background</td>
<td>23.5 ± 8.0</td>
</tr>
<tr>
<td>Data</td>
<td>24</td>
</tr>
</tbody>
</table>

- Limits set on \(\pi_v\) proper decay lengths for different \(\pi_v\) masses:

- (See paper for limits set for different \(\Phi\) masses)
Results


![Graph showing 95% CL upper limit on σ × BR / σ_{SM}](image)

- No significant excess observed with 19.5 fb^{-1} (Muon RoI cluster trigger - see below) and 20.3 fb^{-1} (Jet + missing ET trigger)

- Limits set on π_{v} proper decay lengths

- (See paper for limits set for different Φ and gluino masses)

<table>
<thead>
<tr>
<th>Topology</th>
<th>m_{π_{v}} [GeV]</th>
<th>Expected events</th>
<th>Observed events</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Signal</td>
<td>Background</td>
</tr>
<tr>
<td>IDVx+MSVx</td>
<td>10</td>
<td>1.9 ± 1.4</td>
<td>2.0 ± 0.4</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>62 ± 8</td>
<td>41 ± 6</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 MSVx</td>
<td>10</td>
<td>234 ± 15</td>
<td></td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>690 ± 26</td>
<td>0.4 ± 0.3</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>313 ± 18</td>
<td></td>
</tr>
</tbody>
</table>

Expected signal for scalar boson model m_{H}=125 GeV and cτ=2m

Table X. Expected number of signal events at 19 fb^{-1} for Higgs boson benchmarks, with m_{H} = 125 GeV and cτ = 2 m.

Expected signal for scalar boson model m_{H}=125 GeV and cτ=2m
Lepton-jets
Physics models - Lepton-jets

- Signature models are Falkowsky-Ruderman-Volansky-Zupan (FRVZ) where Higgs boson decays to pairs of hidden fermions:

  ![Diagram](image1)

  ![Diagram](image2)

  In the first benchmark model, the dark fermion decays to a $\gamma_d$ and a lighter dark fermion $f_{d1}$, HLSP (Hidden Lightest Stable Particle).

  In the second model, the dark fermion $f_{d2}$ decays to an HLSP and a dark scalar $s_{d1}$ that in turn decays to pairs of dark photons.

- Photons typically produced with large boost
  - collimated jet-like structures containing pairs of muons/electrons and/or pions
    - “lepton-jets”
  - Limited granularity of detectors makes resolving constituents challenging…
Lepton-jets

• Search for long-lived neutral particles decaying into displaced lepton-jets in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector (2015 data)
  
  • ATLAS-CONF-2016-042

• Integrated luminosity for search is 3.57 fb$^{-1}$

  • However despite lower integrated luminosity, sensitivity is comparable to 2012 dataset at 8 TeV, due to:
    
    • Improvements in trigger sensitivity and reconstruction efficiency for close-by muons
    
    • Higher cross section for Higgs production at 13 TeV
Lepton jet reconstruction

- At detector level, LJs categorised according to content:
  - Muonic LJs reconstructed by ‘clustering’ all muon tracks within the cone, seeded from highest-\(p_T\) muon track.

- Acceptance * Efficiency vs transverse decay distance:
Results - Lepton-jets

- No excess -> so set limits (excluding Type2-Type2 channel, which has low efficiency and high background):

<table>
<thead>
<tr>
<th>Category</th>
<th>Observed events</th>
<th>Expected background</th>
</tr>
</thead>
<tbody>
<tr>
<td>All events</td>
<td>285</td>
<td>$231 \pm 12$ (stat) $\pm 62$ (syst)</td>
</tr>
<tr>
<td>Type2-Type2 excluded</td>
<td>46</td>
<td>$31.8 \pm 3.8$ (stat) $\pm 8.6$ (syst)</td>
</tr>
<tr>
<td>Type2-Type2 only</td>
<td>239</td>
<td>$241 \pm 41$ (stat) $\pm 65$ (syst)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>FRVZ model</th>
<th>$m_H$ (GeV)</th>
<th>Excluded $c\tau$ [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Higgs $\rightarrow 2\gamma_d + X$</td>
<td>125</td>
<td>$2.2 \leq c\tau \leq 111.3$</td>
</tr>
<tr>
<td>Higgs $\rightarrow 4\gamma_d + X$</td>
<td>800</td>
<td>$3.8 \leq c\tau \leq 163.0$</td>
</tr>
<tr>
<td>Higgs $\rightarrow 2\gamma_d + X$</td>
<td>125</td>
<td>$0.6 \leq c\tau \leq 63$</td>
</tr>
<tr>
<td>Higgs $\rightarrow 4\gamma_d + X$</td>
<td>800</td>
<td>$0.8 \leq c\tau \leq 186$</td>
</tr>
</tbody>
</table>
Conclusion

• Presented two 8 TeV analyses for long-lived particles decaying to hadronic jets
  

• Presented 13 TeV results for Displaced lepton-jets
  
  • ATLAS-CONF-2016-042

• Thank you very much for your time and attention.
Backup
• Pair produced, long-lived neutral particles decaying to hadronic jets
  

• “Calo-ratio”
Calo ratio - data and samples

- **Data**: 20.3 fb-1 taken in 2012
- **MC**

The HV Monte Carlo (MC) samples are generated with PYTHIA 8.165 [16] and the PDF MSTW2008 [17] to simulate gluon fusion $gg \rightarrow \Phi$ production and the $\Phi_{hs}$ decay $\Phi_{hs} \rightarrow \pi v\pi v$ for different $\Phi$ and $\pi v$ masses (Table 1). $\Phi$ masses below 300 GeV are considered low-mass samples and the rest are considered high-mass samples. The $\pi v$ lifetime is fixed in each sample to ensure decays throughout the ATLAS detector. The $\Phi$ is simulated in PYTHIA by replacing the Higgs boson with the $\Phi$ and having the $\Phi$ decay to $\pi v$ 100% of the time.

**Table 1**: The $\Phi$ mass or Higgs boson mass, $\Phi$ gluon fusion production cross section, and $\pi v$ mass of each benchmark Hidden Valley model generated. The cross-sections are based on the assumption in the benchmarked model that the $\Phi$ boson production mechanism is the same as the Higgs boson production mechanism. The decay branching ratios of the $\pi v$ as a function of the $\pi v$ mass are listed in the second table as determined in the simulation samples.

<table>
<thead>
<tr>
<th>$m_H$ [GeV]</th>
<th>$\sigma$ [pb]</th>
<th>$\pi v$ Mass [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>126</td>
<td>19.0</td>
<td>10, 25, 40</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\Phi$ Mass [GeV]</th>
<th>$\sigma$ [pb]</th>
<th>$\pi v$ Mass [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>29.7</td>
<td>10, 25</td>
</tr>
<tr>
<td>140</td>
<td>15.4</td>
<td>10, 20, 40</td>
</tr>
<tr>
<td>300</td>
<td>3.59</td>
<td>50</td>
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<tr>
<td>600</td>
<td>0.52</td>
<td>50, 150</td>
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<tr>
<td>900</td>
<td>0.06</td>
<td>50, 150</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\pi v$ Mass [GeV]</th>
<th>BR $bb$ [$%$]</th>
<th>BR $\tau^+\tau^-$ [$%$]</th>
<th>BR $c\bar{c}$ [$%$]</th>
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<tbody>
<tr>
<td>10</td>
<td>70.0</td>
<td>16.4</td>
<td>13.4</td>
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<tr>
<td>20</td>
<td>86.3</td>
<td>8.0</td>
<td>5.6</td>
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<tr>
<td>25</td>
<td>86.6</td>
<td>8.1</td>
<td>5.3</td>
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<tr>
<td>40</td>
<td>86.5</td>
<td>8.5</td>
<td>5.0</td>
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<tr>
<td>50</td>
<td>86.2</td>
<td>8.8</td>
<td>4.9</td>
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<tr>
<td>150</td>
<td>84.8</td>
<td>10.2</td>
<td>4.8</td>
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</tbody>
</table>
Calo ratio - trigger

- looks for >1 narrow jet with relatively little energy deposited in the EM calorimeter, and no charged tracks pointing towards to jet

The trigger is tuned to look for events containing at least one narrow jet with little energy deposited in the ECal and no charged tracks pointing towards the jet.

At the first level the trigger selects only narrow jets by requiring at least 40 GeV of transverse energy ($E_T$) in the calorimeter in a $0.2 \times 0.2$ ($|\eta| \times |\phi|$) region using topological jets [15, 22], in contrast to the default algorithm in which the energy in a $0.4 \times 0.4$ region is summed.

The 40 GeV $E_T$ threshold requirement is fully efficient at an offline jet $E_T$ of 60 GeV. To select jets with a high fraction of their energy in the HCal the second level of the trigger requires these narrow jets to have $\log_{10}(E_H/E_{EM}) > 1.2$, where $E_H/E_{EM}$ is the ratio of the energy deposited in the HCal ($E_H$) to the energy deposited in the ECal ($E_{EM}$). The trigger also requires no tracks with $p_T > 1$ GeV in the region $0.2 \times 0.2$ ($|\eta| \times |\phi|$) around the jet axis. The third

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**Fig. 1:** The probability ($v_{\pi}$) for a single $\pi_0$ to pass the trigger as a function of the $\pi_0$ (a) radial decay length in the barrel and (b) the $z$ position of the decay vertex in the endcaps for several $\Phi$ and $\pi_0$ masses.
The largest contribution to the expected background comes from SM multi-jet events.

- Cosmics rays much less, and beam halo negligible

To estimate the multi-jet background contribution, a multi-jet data sample is used to derive the probability that a jet passes the trigger and analysis selection.

The multi-jet data sample contains events that pass single-jet triggers with an ET threshold of 15 GeV or higher.

- Require >2 back to back jets
  - 1 jet must pass the modified ATLAS good-jet criteria used by the analysis.
  - 2nd used to measure two probabilities:
    - P, for a jet to pass the trigger and the ET > 60 GeV jet requirement
    - Q, for a jet to satisfy the requirement ET > 40 GeV.
  - For both P and Q the jet must also pass the log10(EH/EEM), track isolation, and all other analysis jet selection requirements including the modified ATLAS good-jet criteria.
Calo ratio - backgrounds (2)

• Cosmic ray:
  • Particles from a cosmic-ray shower may pass through and deposit energy in the calorimeter without passing through the ID. These energy deposits can be reconstructed as trackless jets.
  • Reduce with jet-timing and Etmiss requirements
  • Study with empty BC

• BIB
  • beam-halo muon that undergoes bremsstrahlung in the HCal.
  • A jet-timing requirement is imposed because most of the jets produced by beam-halo interactions are not coincident in time with jets from pp interactions. In addition, events are rejected when track segments in the endcap muon chambers, from the entering beam-halo muon, align in $\phi$ with a jet. These two requirements reduce the background considerably with no discernible effect on the signal
Calo ratio - systematic uncertainties

• The uncertainty on the signal MC samples due to parton distribution functions (PDF) is calculated by reweighting each event using three different PDF sets (MSTW2008nlo68cl [17], CT10 [27], and NNPDF2.3 [28]) and their associated error sets. The RMS change in acceptance for the error sets of each PDF is calculated and combined with the difference in acceptances for each of the three PDFs.

• Pile-up primarily affects the acceptance by adding extra tracks and degrading the track isolation of a jet. All MC samples are reweighted to reproduce the observed distribution of the number of interactions per bunch crossing in the data. To determine if pile-up is simulated properly in the MC samples, a direct comparison of data and MC multi-jet samples is performed. The jet ET, EMF, η, φ, associated tracks and timing distributions as a function of the mean number of pile-up interactions are compared in data and MC simulation. A 10% systematic uncertainty is assigned to the acceptance covers all the observed differences.

<table>
<thead>
<tr>
<th>Sample m_H, m_E [GeV]</th>
<th>H σ [%]</th>
<th>JES [%]</th>
<th>Trigger [%]</th>
<th>E_T^{miss} [%]</th>
<th>Time Cut [%]</th>
<th>Total [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>126, 10</td>
<td>+10.4</td>
<td>+2.2</td>
<td>±1.1</td>
<td>+5.5</td>
<td>+1.6</td>
<td>+16.4</td>
</tr>
<tr>
<td>126, 25</td>
<td>+10.4</td>
<td>+1.5</td>
<td>±1.3</td>
<td>+3.1</td>
<td>+0.8</td>
<td>+15.6</td>
</tr>
<tr>
<td>126, 40</td>
<td>+10.4</td>
<td>+2.6</td>
<td>±1.1</td>
<td>+7.7</td>
<td>+1.9</td>
<td>+18.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sample m_Φ, m_E [GeV]</th>
<th>Φ σ [%]</th>
<th>JES [%]</th>
<th>Trigger [%]</th>
<th>E_T^{miss} [%]</th>
<th>Time Cut [%]</th>
<th>Total [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>100, 10</td>
<td>+11.1</td>
<td>+2.3</td>
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<td>+16.7</td>
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<tr>
<td>100, 25</td>
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<td>+5.5</td>
<td>±1.2</td>
<td>+3.4</td>
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<td>+17.0</td>
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<td>140, 10</td>
<td>+10.1</td>
<td>+0.6</td>
<td>±0.5</td>
<td>+4.0</td>
<td>+1.9</td>
<td>+15.6</td>
</tr>
<tr>
<td>140, 20</td>
<td>+10.1</td>
<td>+1.2</td>
<td>±1.0</td>
<td>+3.9</td>
<td>+0.4</td>
<td>+15.5</td>
</tr>
<tr>
<td>140, 40</td>
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<td>+1.3</td>
<td>±1.5</td>
<td>+6.3</td>
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<td>+16.5</td>
</tr>
<tr>
<td>300, 50</td>
<td>+9.6</td>
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<td>±0.3</td>
<td>+9.0</td>
<td>+0.5</td>
<td>+13.9</td>
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<td>600, 50</td>
<td>+11.2</td>
<td>+0.0</td>
<td>±0.2</td>
<td>+11.7</td>
<td>+2.2</td>
<td>+17.0</td>
</tr>
<tr>
<td>600, 150</td>
<td>+11.2</td>
<td>+0.2</td>
<td>±0.3</td>
<td>+11.5</td>
<td>+2.7</td>
<td>+17.5</td>
</tr>
<tr>
<td>900, 50</td>
<td>+12.8</td>
<td>+0.0</td>
<td>±0.1</td>
<td>+12.6</td>
<td>+1.0</td>
<td>+18.5</td>
</tr>
<tr>
<td>900, 150</td>
<td>+12.8</td>
<td>+0.2</td>
<td>±0.2</td>
<td>+11.8</td>
<td>+0.9</td>
<td>+18.1</td>
</tr>
</tbody>
</table>
Calo - results and limits

- CLs method used to derive an upper limit on the $\sigma(\Phi) \times \text{BR}(\Phi \rightarrow \pi\pi\pi\nu)$.

- A profile likelihood ratio is used as the test statistic and a frequentest calculator is used to generate toy data.

- The likelihood includes a Poisson probability term describing the total number of observed events. Systematic uncertainties are incorporated as nuisance parameters through their effect on the mean of the Poisson functions and through convolution with their assumed Gaussian distributions. The number of expected events in signal MC samples, together with the estimate of expected background, the observed collision events and all the systematic uncertainties are provided as input for computing the CLs value, which represents the probability for the given observation to be compatible with the signal + background hypothesis.

<table>
<thead>
<tr>
<th>Sample $(m_H, m_{\pi\nu} \text{[GeV]})$</th>
<th>Expected yields</th>
<th>Global acceptance (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>126, 10</td>
<td>536 ± 23</td>
<td>0.139 ± 0.006</td>
</tr>
<tr>
<td>126, 25</td>
<td>941 ± 44</td>
<td>0.244 ± 0.011</td>
</tr>
<tr>
<td>126, 40</td>
<td>365 ± 31</td>
<td>0.095 ± 0.008</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sample $(m_H, m_{\pi\nu} \text{[GeV]})$</th>
<th>Expected yields</th>
<th>Global acceptance (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100, 10</td>
<td>440 ± 29</td>
<td>0.073 ± 0.005</td>
</tr>
<tr>
<td>100, 25</td>
<td>424 ± 37</td>
<td>0.070 ± 0.006</td>
</tr>
<tr>
<td>140, 10</td>
<td>525 ± 20</td>
<td>0.168 ± 0.006</td>
</tr>
<tr>
<td>140, 20</td>
<td>900 ± 37</td>
<td>0.287 ± 0.012</td>
</tr>
<tr>
<td>140, 40</td>
<td>641 ± 30</td>
<td>0.205 ± 0.010</td>
</tr>
<tr>
<td>300, 50</td>
<td>444 ± 11</td>
<td>0.609 ± 0.015</td>
</tr>
<tr>
<td>600, 50</td>
<td>35 ± 1</td>
<td>0.330 ± 0.010</td>
</tr>
<tr>
<td>600, 150</td>
<td>41 ± 2</td>
<td>0.386 ± 0.015</td>
</tr>
<tr>
<td>900, 50</td>
<td>3.5 ± 0.1</td>
<td>0.304 ± 0.011</td>
</tr>
<tr>
<td>900, 150</td>
<td>4.6 ± 0.2</td>
<td>0.397 ± 0.016</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Background</th>
<th>Expected events</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM Multi-jets</td>
<td>23.2 ± 8.0</td>
</tr>
<tr>
<td>Cosmic rays</td>
<td>0.3 ± 0.2</td>
</tr>
<tr>
<td>Total Expected Background</td>
<td>23.5 ± 8.0</td>
</tr>
<tr>
<td>Data</td>
<td>24</td>
</tr>
</tbody>
</table>
Search for long-lived, weakly interacting particles that decay to displaced hadronic jets in proton–proton collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector

• Long-lived, weakly interacting particles decaying to hadronic jets

• “MS/ID vertexing”
Vertex - analysis strat

- Hadronic decays that are displaced from the IP leave a unique detector signature that can be reconstructed as a displaced vertex. This analysis searches for events with two displaced vertices in either the ID or MS, or one in each.

- This analysis studies two separate channels, defined by the triggers used to select events.

  - ATLAS Muon RoI Cluster trigger is used to preselect events that satisfy displaced-decay criteria in the MS. The search for both the scalar boson and Stealth SUSY models makes use of events selected by the Muon RoI Cluster trigger. The sample of events selected by this trigger belongs to the Muon Cluster channel.

  - A jet plus $E_T^{miss}$ trigger: The large multiplicity of long-lived particles in the $Z'$ benchmark samples causes many events to fail to satisfy the isolation criteria of the Muon RoI Cluster trigger, but also provides other objects on which to trigger.

- To reduce backgrounds, two vertices req.

<table>
<thead>
<tr>
<th>Trigger</th>
<th>Applicable topologies</th>
<th>Benchmarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muon RoI Cluster</td>
<td>IDVx+MSVx, 2MSVx</td>
<td>Scalar boson,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stealth SUSY</td>
</tr>
<tr>
<td>Jet+$E_T^{miss}$</td>
<td>2IDVx, IDVx+MSVx, 2MSVx</td>
<td>$Z'$</td>
</tr>
</tbody>
</table>
Data / MC

The dataset used in this analysis was recorded by the ATLAS detector in the 2012 run during periods in which all subdetectors relevant to the analysis were operating efficiently. The integrated luminosity is 20.3 fb\(^{-1}\). The Muon Cluster channel uses only 19.5 fb\(^{-1}\) of data because the trigger was not active at the beginning of the run. The uncertainty on the integrated luminosity, estimated following the methodology described in Ref. [31], is 2.8%.

<table>
<thead>
<tr>
<th>Scalar boson mass [GeV]</th>
<th>πν mass [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>10, 25</td>
</tr>
<tr>
<td>125</td>
<td>10, 25, 40</td>
</tr>
<tr>
<td>140</td>
<td>10, 20, 40</td>
</tr>
<tr>
<td>300</td>
<td>50</td>
</tr>
<tr>
<td>600</td>
<td>50, 150</td>
</tr>
<tr>
<td>900</td>
<td>50, 150</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Z′ mass [TeV]</th>
<th>πν mass [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50</td>
</tr>
<tr>
<td>2</td>
<td>50</td>
</tr>
<tr>
<td>2</td>
<td>120</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ĝ mass [GeV]</th>
<th>Š, S mass [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>110</td>
<td>100, 90</td>
</tr>
<tr>
<td>250</td>
<td>100, 90</td>
</tr>
<tr>
<td>500</td>
<td>100, 90</td>
</tr>
<tr>
<td>800</td>
<td>100, 90</td>
</tr>
<tr>
<td>1200</td>
<td>100, 90</td>
</tr>
</tbody>
</table>
The Muon RoI Cluster trigger is a signature-driven trigger that selects decays of neutral particles in the MS. It is used to select candidate events for the scalar boson and Stealth SUSY searches, and is efficient for hadronic decays occurring in the region from the outer radius of the HCal to the middle of the MS. The trigger selects events with a cluster of muon RoIs contained in a $\Delta R = 0.4$ cone that are preceded by little or no activity in the ID or calorimeters. This isolation requirement reduces backgrounds from muon bremsstrahlung and punch-through jets. A punch-through jet is a hadronic or electromagnetic shower not contained in the calorimeter volume, which results in tracks in the MS. The details of the performance and implementation of this trigger on both a set of MC simulated benchmark samples and data can be found in Ref. [27].

B. Jet+$E_T^{\text{miss}}$trigger

A single-jet plus $E_T^{\text{miss}}$trigger is employed for the $Z'$search. The trigger uses a leading jet $E_T$ threshold of 110 GeV and an $E_T^{\text{miss}}$ threshold of 75 GeV. Offline requirements are a leading jet $p_T \geq 120$ GeV and $E_T^{\text{miss}} \geq 200$ GeV, which result in a constant trigger efficiency as a function of both $p_T$ and $E_T^{\text{miss}}$. For events passing the offline requirements, the trigger efficiency is 87–100%, depending on the MC simulated $Z'$benchmark sample.
Lepton jets
**LJ - triggers**

- **Narrow-Scan**: The Narrow-Scan trigger was introduced for the 2015 data-taking, and adopts a specialised and novel approach for a wide range of signal models featuring highly collimated muons such as in the LJ case. The Narrow-Scan algorithm begins with requiring at least one L1 trigger muon object. Other multi-muon triggers, which usually require more L1 trigger muon objects, have large associated signal efficiency losses in the case where the muons are produced close together.

- **Tri-muon MS-only [51]**: selects events with at least three MS-only muons with $p_T \geq 6$ GeV. It is seeded at L1 by a cluster of three muon ROIs in a $\Delta R = 0.4$ cone, and is required to have no reconstructed jets within a cone of $\Delta R = 0.5$. 

- **CalRatio [51]**: selects events with an isolated jet of low EM fraction. The CalRatio trigger is seeded by a L1 tau-lepton trigger with $p_T \geq 60$ GeV. A L1 tau-lepton seed was chosen over a jet seed because the L1 $\tau$ seed uses a narrower calorimeter region than the L1 jet seed. Decays of $\gamma d$ in the HCAL tend to produce narrow jets. The trigger requires the jet to have $|\eta| \leq 2.4$ (to ensure that ID tracks can be matched to it) and $E_T \geq 30$ GeV. A selection requirement on the calorimeter energy ratio is then imposed, requiring $\log(E_{HCAL}/E_{ECAL}) \geq 1.2$. Finally, ID track isolation selection around the jet axis (no track with $p_T \geq 2$ GeV within $\Delta R \leq 0.2$ from the jet axis) and BIB tagging are performed to reject fake jets from beam-halo muons.
LJ - backgrounds

- Cosmic-ray muons that cross the detector in time coincidence with a pp interaction constitute the main source of background to the Type0 signal, and a sub-dominant background to the Type1 and Type2 signals.

![Figure 3](image)

Figure 3: The muon impact parameter $|z_0|$ (left) for muonic LJ constituents in empty bunch-crossings (cosmic-ray muons) and for muonic LJ constituents in the $m_H = 125$ GeV FRVZ Higgs $\rightarrow 4\gamma_d + X$ case. The jet timing, $\Delta t_{\text{Calo}}$, (right) of Type2 LJs from signal MC and single jet triggered events in empty bunch-crossings. In both plots, data refers to the 2015 data taking.

Removing jets with $\Delta t_{\text{Calo}}$ outside the interval between $-4$ ns and $+4$ ns removes a large fraction of the cosmic-ray jets, with a loss of signal less than 5%.

A selection requirement $|z_0| \leq 280$ mm is used; in this way only 5% of the signal in the Higgs $\rightarrow 4\gamma_d + X$ sample is lost while eliminating 96% of the cosmic-ray background.
Multijet production constitutes the main background to the Type2 LJ signal. The search explicitly targets γd decays in the HCAL, resulting in most of the energy deposition occurring in the HCAL rather than in the ECAL. Therefore, low EM fraction is an effective criterion to distinguish jets in Type1 and Type2 LJs from multijet background.

Another effective discriminating variable is the jet width \( W \), defined as the average distance of a jet constituent to the jet direction weighted with the energy of the constituent.

Beam-induced background (BIB), consisting of high energy beam-halo muons undergoing hard bremsstrahlung in the calorimeters, is another sub-dominant source of background for Type2 LJs. The bremsstrahlung manifests itself as a calorimeter deposit that is reconstructed as a jet; if it occurs in the HCAL, the fake jet is reconstructed with a very low EM fraction. BIB “tagging” searches for two track segments parallel to the beam line in the forward MDT chambers, together with a low EM fraction HCAL jet, all within 4 degrees in \( \phi \). Such an HCAL jet is tagged as BIB and removed from the data set.
5.7 Summary of preselection requirements

A summary of the LJ signal selection requirements is given in Table 3.

<table>
<thead>
<tr>
<th>LJ type</th>
<th>Selection requirement</th>
<th>Requirement description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 0/1</td>
<td>$z_0$ limits</td>
<td>an impact parameter $</td>
</tr>
<tr>
<td>Type 1/2</td>
<td>jet timing $\Delta t_{\text{Calo}}$</td>
<td>remove jets outside the $\pm 4$ ns time window</td>
</tr>
<tr>
<td>Type 2</td>
<td>tile-gap scint.</td>
<td>max energy in tile-gap scintillators $\leq 10%$ of the jet energy</td>
</tr>
<tr>
<td>Type 2</td>
<td>EM fraction</td>
<td>EM fraction of the jet $&lt; 0.1$</td>
</tr>
<tr>
<td>Type 2</td>
<td>jet width</td>
<td>$W &lt; 0.058$</td>
</tr>
<tr>
<td>Type 2</td>
<td>JVT</td>
<td>JVT variable $\leq 0.56$</td>
</tr>
<tr>
<td>Type 2</td>
<td>BIB</td>
<td>use BIB tagging to remove fake jets from beam-halo muons</td>
</tr>
<tr>
<td>Type 0/1</td>
<td>no-CB</td>
<td>all muons of the LJ to be non-combined (“no-CB”)</td>
</tr>
</tbody>
</table>

Table 3: LJ signal selection requirements.
LJ - background estimation

- In order to extract the signal yield, taking into account the multijet and the cosmic-ray background residual contaminations, a data-driven likelihood-based ABCD method is used. This is a simultaneous data-driven background estimation and signal hypothesis test in the signal and control regions, robust against control regions with small number of events.

![Diagram showing the ABCD method in the (|Δφ|, Max Σ |p_T|) plane with the definition of the ABCD regions.]

### Table 4: Summary of systematic uncertainties on the expected number of signal events.

<table>
<thead>
<tr>
<th>Systematic Uncertainty</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>2.1%</td>
</tr>
<tr>
<td>Trigger: Narrow Scan</td>
<td>6.0%</td>
</tr>
<tr>
<td>Trigger: Tri-muon-MS-only</td>
<td>5.8%</td>
</tr>
<tr>
<td>Trigger: CalRatio</td>
<td>11.0%</td>
</tr>
<tr>
<td>Reconstruction e^ of single d</td>
<td>15.0%</td>
</tr>
<tr>
<td>Effect of pile-up on</td>
<td>3.4%</td>
</tr>
<tr>
<td>p_ID</td>
<td>5.1%</td>
</tr>
<tr>
<td>Reconstruction of the</td>
<td>10.0%</td>
</tr>
<tr>
<td>p_T of the</td>
<td></td>
</tr>
</tbody>
</table>

Figure 8: Schematic of the ABCD method in the (|Δφ|, Max Σ |p_T|) plane with the definition of the ABCD regions.
Limits

In the absence of a signal, the results of the search for LJ production with the likelihood-based ABCD method are used to set upper limits on the product of cross section and Higgs decay branching fraction to LJs, as a function of the $\gamma_d$ mean lifetime, in the FRVZ models. Taking into account the relatively low signal efficiency for the Type2–Type2 event in all models and the high background, the Type2–Type2 events are excluded from the limit setting. The $CL_s$ method [58] is used to determine these limits, where the signal region is populated from the data-driven background estimate and from the appropriate signal hypothesis.

In order to determine these limits as a function of the $\gamma_d$ lifetime the following procedure is used. The acceptance times efficiency with the selection criteria described above for the $\gamma_d$ is evaluated as a function of the decay position $L_{xy}$ (barrel) or $L_z$ (endcap) and as a function of the $p_T$ of the $\gamma_d$ in the MC simulated FRVZ samples with lifetime $c\tau = 47$ mm. A large number of MC pseudo experiments with different $c\tau$ (ranging from 0.5 to 5000 mm) for the Higgs $\rightarrow 2\gamma_d + X$ model are produced. For each $\gamma_d$ of the pseudo experiments, the $p_T$ and the $\eta$ are extracted from the signal MC events at truth level, and the decay length from an exponential distribution with the proper decay length $c\tau$ of the pseudo experiment; in this way the $\gamma_d$ decay point in the detector is obtained. Using a matrix (constructed using the signal MC) describing the efficiency for reconstructing a $\gamma_d$ of a given $p_T$ and $c\tau$, each event is weighted by the detection probability of its dark photons. The number of selected events in each pseudo experiment are then rescaled by the ratio of the integrated detection efficiency at a given $c\tau$, $\varepsilon(c\tau)$, to the efficiency for the reference sample, $\varepsilon(47 \text{ mm})$. This procedure is repeated separately for the Higgs $\rightarrow 4\gamma_d + X$ benchmark model. Figure 9 shows, for the Higgs $\rightarrow 2\gamma_d + X$ model, the ratio $\varepsilon(c\tau)/\varepsilon(47 \text{ mm})$ as a function of $c\tau$. The solid black diamonds in the Figure show the relative efficiency found using full simulation Monte Carlo samples with $c\tau = 4.7$ mm, 20 mm, 47 mm, and 470 mm, indicating a good agreement with the pseudo experiment process.
While the data sample is less than one-fifth the size of that employed in the similar
for the Higgs
to set upper limits on non-SM Higgs boson decays to LJs in two benchmark models, where one predicts
is found, and the observed data in the signal region after applying the full set of selection criteria are
defined. No significant signal-like behaviour
The ATLAS detector at the LHC is used to search for the production of displaced LJs in a 3.4 fb

Figure 10: The 95% upper limits on the $\sigma \times \text{BR}$ for the FRVZ 125 GeV Higgs $\rightarrow 2\gamma_d + X$ (left) and Higgs $\rightarrow 4\gamma_d + X$ (right) benchmark models as a function of the $\gamma_d$ lifetime ($c\tau$). The horizontal lines correspond to $\sigma \times \text{BR}$ for two values of the BR of the Higgs boson decay to dark photons.

Figure 11: The 95% upper limits on the $\sigma \times \text{BR}$ for the FRVZ 800 GeV Higgs $\rightarrow 2\gamma_d + X$ benchmark model as a function of the $\gamma_d$ lifetime ($c\tau$). The horizontal lines correspond to a $\sigma \times \text{BR}$ of 5 pb.
Figure 1. Cross-sectional view of ATLAS in the $r$–$z$ projection at $f = p/2$, from ref. [1]. The barrel MDT chambers are shown in green, the endcap MDT chambers are blue. In the barrel (endcaps), the RPC (TGC) chambers are shown outlined in black (solid purple).

multiple scattering of charged particles, which makes it an ideal instrument for multi-track vertex reconstruction. The vertex-reconstruction technique described in this paper was a key element in a search for a light Higgs boson decaying to long-lived neutral particles [8].

The paper is organized as follows: section 2 describes the muon spectrometer, section 3 discusses the benchmark model and the Monte Carlo (MC) samples, sections 4 and 5 describe the tracking and vertex-finding algorithms and section 6 discusses the performance of the vertex-finding algorithm.

2 Muon spectrometer

ATLAS is a multi-purpose detector [1], consisting of an inner tracking system (ID), electromagnetic and hadronic calorimeters and a muon spectrometer. The ID is inserted inside a superconducting solenoid, which provides a 2 T magnetic field parallel to the beam direction.

The electromagnetic and hadronic calorimeters cover the region $|\eta| \leq 4.9$ and have a total combined thickness of 9.7 interaction lengths at $\eta = 0$. The MS, the outermost part of the detector, is designed to measure the momentum of charged particles escaping the calorimeter in the region $|\eta| \leq 2.7$ and provide trigger information for $|\eta| \leq 2.4$. It consists of one barrel and two endcaps, shown in figure 1, that have fast detectors for triggering and precision chambers for track reconstruction. Three stations of resistive plate chambers (RPCs) and thin gap chambers (TGCs) are used for triggering in the barrel ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the $z$-axis coinciding with the beam pipe axis. The $x$-axis points from the IP to the centre of the LHC ring, and the $y$-axis points upward. Cylindrical coordinates ($r$, $\phi$) are used in the transverse plane, $\phi$ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle $\eta$ as $\eta = \ln \tan(\eta/2)$. 