Searches with Displaced Lepton-Jet Signatures

LHC Searches for Long-Lived BSM Particles: Theory Meets Experiment
University of Massachusetts Amherst  Nov 13 2015

Miriam Diamond
University of Toronto ATLAS Group
Outline

• What is a Displaced Lepton-Jet?
• Signatures of What?
  ▫ Dark Photons
  ▫ Hidden Sector
  ▫ BSM Higgs
  ▫ SUSY
  ▫ Inelastic Dark Matter
• Challenges for Displaced LJ Searches
• Potentially Useful Handles
• Results from LHC Run 1 Searches
• Plans for Run 2 Searches
What is a Displaced LJ?

- **LJ**: Collimated jet-like structure containing pair(s) of muons and/or electrons (and/or pions)
- **Displaced**: Produced far from primary interaction vertex of event

**Defined using**
- Basic clustering algorithm with $\Delta R$ cone, or
- Displaced vertex-finding

**Key properties:**
- Type of decay products
- Angular aperture of decay products
- Invariant mass
- Vertex displacement

[ATLAS EXOT-2013-22 Aux]
Signatures of What?

• Many BSM theories predict some sort of hidden sector, weakly coupled to visible sector

• Collider production of unstable hidden states?
  ▫ Low-mass $\rightarrow$ boosted $\rightarrow$ highly-collimated decay products
  ▫ Decaying back to SM with sizeable BR $\rightarrow$ dileptons (and/or pions) in final state
  ▫ Long-lived $\rightarrow$ displaced vertex

Displaced Lepton-Jet Signature

“Smoking Gun”
Dark Photons

- **Vector portal**: add U(1)’ whose massive gauge boson (A’ or z_d or γ_d) mixes kinetically with SM photon

\[
\mathcal{L} \supset \frac{\epsilon_Y}{2} F_{Y,\mu\nu} F_{D,\mu\nu} - \frac{1}{4} F_{D}^{\mu\nu} F_{D,\mu\nu} + \frac{m_{A'}^2}{2} A'^\mu A'^\mu + g_D J_{A'}^{\mu} A'^\mu
\]

  - Field re-definition removes kinetic mixing term, generates coupling \( \epsilon e A'_{\mu} J_{EM}^{\mu} \) \( (\epsilon \equiv \epsilon_Y \cos \theta_W) \)

- Much parameter space for long-lived boosted low-mass

  \( \gamma_d \rightarrow l^+l^- \)
  - Lifetime varies with \( \epsilon \)
  - BRs vary with mass

[arXiv:1002.2952]
Hidden Sector

- $\gamma_d$ accompanied by zoo of other “hidden” particles?
- $G_{\text{dark}}$ bigger than $U'(1)$?

- Production of multiple boosted $\gamma_d$ from long decay chains → multiple displaced LJs
BSM Higgs

- In some BSM models with additional neutral heavy Higgses, can have $H^0 \rightarrow$ dark sector $\rightarrow$ LJs
- Or dark Higgs in decay chain ending with LJs

• Hidden Abelian Higgs models (Higgs Portal):

[arXiv:1002.2952]
SUSY

- Can embed range of discrete dark symmetries (accidental or exact, global or gauged) within SUSY
- Standard SUSY production at LHC, followed by sparticles $\rightarrow$ dark sector $\rightarrow$ LJs

[arXiv:0810.0714]
Inelastic Dark Matter

- Dirac fermion charged under $G_{\text{dark}}$
- Spontaneously broken symmetry allows Majorana masses, yielding mass eigenstates $\chi_1$ and $\chi_2$ with dominantly off-diagonal interactions

- $\gamma_d$ and $\chi_2$ with $c\tau \sim \mathcal{O}(\text{metre})$ in much of parameter space relevant for “thermal target”
- Displaced LJ + ISR jet + MET

[arXiv:1508.03050]
Challenges for Displaced LJ Searches

Detector issues:

- No particularly convenient trigger object
  - Want low lepton $p_T$ thresholds to cover low-mass phase space
  - But, in the face of low signal rate, also want to avoid pre-scaling
- Collimated final-state particles difficult to reconstruct (detector granularity)
- Tracks with displaced decay vertices difficult to reconstruct (no primary vertex constraint)
  - Even more difficult if displaced past inner detector
- Electron/pion LJs generally more difficult than muon LJs
  - Close-together energy deposits in calorimeters, without Muon Spectrometer information to aid reconstruction, are messy
Challenges for Displaced LJ Searches

Range of possible LJ topologies:

- Varying number of constituents
  - “Dense” LJ (e.g. hidden cascade decays)
  - “Sparse” LJ (e.g. lone dark photon)
- Unknown dynamics in hidden sector
  - QCD-like broadening of LJs?
- LJ shape influenced by boost
  - Depends upon unknown hidden particle masses
Challenges for Displaced LJ Searches

Potential backgrounds:

- 4 muons from $b\bar{b}$: via semileptonic decays, or via resonances
- Cosmic-ray muon bundles
- Combinatorics of prompt muons, mis-reconstructed/pileup: $W+$jets, $Z+$jets, $tt$bar, single-top, $WW$, $WZ$, $ZZ$, etc.
- QCD multi-jet (for electron/pion LJs)
- 4 muons from electroweak production (small)
- 4 muons from direct $J/\psi$ pair production (small)
Potentially Useful Handles

- LJ constituent selection:
  - Clustering algorithm using ΔR cone
  - Displaced vertex fit
  - Invariant mass window
- LJ isolation
  - Maximum $\Sigma p_T$ of charged tracks within ΔR cone centered on momentum vector of candidate LJ, excluding tracks of LJ constituents
- Require two LJs, consistent with same pp interaction
  - Small $|z_{1LJ} - z_{2LJ}|$ (nearby projected z coordinates at point of closest approach to beamline)
  - Cut on azimuthal angle $\Delta \phi$ between LJs
Run 1 Results: ATLAS

Targets $\gamma_d$ decays beyond pixel detector, up to muon spectrometer

- Muon pairs: have only spectrometer information
- Electron / pion pairs: appear as jets in calorimeters
- LJ categorization:

[arXiv:1409.0746]
Run 1 Results: ATLAS

- **Trigger for muon LJs:** tri-muon MSonly, $p_T > 6\text{GeV}$, not pre-scaled
- **Trigger for electron/pion LJs:** single-jet, low $E_T$ threshold, low EM fraction, isolated energy deposition in narrow region, not pre-scaled
- **LJ-finding:** clustering algorithm with $\Delta R = 0.5$ cone

**Selection criteria:**

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two reconstructed LJs</td>
<td>select events with at least two reconstructed LJs</td>
</tr>
<tr>
<td>$\eta$ range (TYPE1)</td>
<td>remove jets with $</td>
</tr>
<tr>
<td>$\eta$ range (TYPE2)</td>
<td>remove jets with $</td>
</tr>
<tr>
<td>EM fraction (TYPE2)</td>
<td>require EM fraction of the jet $&lt; 0.1$</td>
</tr>
<tr>
<td>Jet width $W$ (TYPE2)</td>
<td>require width of the jet $&lt; 0.1$</td>
</tr>
<tr>
<td>Jet timing (TYPE1/TYPE2)</td>
<td>require jets with timing $-1 \text{ ns} &lt; t &lt; 5 \text{ ns}$</td>
</tr>
<tr>
<td>NC muons (TYPE0/TYPE1)</td>
<td>require muons without ID track match</td>
</tr>
<tr>
<td>ID isolation</td>
<td>require $\max{\Sigma p_T} \leq 3 \text{ GeV}$</td>
</tr>
<tr>
<td>$\Delta \phi$</td>
<td>require $</td>
</tr>
</tbody>
</table>

[arXiv:1409.0746]
**Run 1 Results: ATLAS**

Events (+/- stat. +/- sys.)

<table>
<thead>
<tr>
<th>Type</th>
<th>Data (+/- stat. +/- sys.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>119</td>
</tr>
<tr>
<td>Cosmic rays</td>
<td>40 ± 11 ± 9</td>
</tr>
<tr>
<td>Multi-jets (ABCD)</td>
<td>70 ± 58 ± 11</td>
</tr>
<tr>
<td>Total background</td>
<td>110 ± 59 ± 14</td>
</tr>
</tbody>
</table>

**FRVZ benchmark model (with gg fusion):**

![Diagram of FRVZ benchmark model with gg fusion](image)

<table>
<thead>
<tr>
<th>Model Description</th>
<th>Excluded cτ [mm]</th>
<th>BR(10%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H → 2γd + X</td>
<td>14 ≤ cτ ≤ 140</td>
<td></td>
</tr>
<tr>
<td>H → 4γd + X</td>
<td>15 ≤ cτ ≤ 260</td>
<td></td>
</tr>
</tbody>
</table>

[arXiv:1409.0746]
Run 1 Results: ATLAS

- To allow easy re-casting: trigger & reco efficiency tables as a function of dark photon $c\tau$ and $p_T$
- Produced using “LJ Gun” MC tool, which simulates detector response to LJs of one or two dark photons

| $L_{xy}$ (cm) | $\gamma_d \rightarrow \mu\mu$ with $m_{\gamma_d} = 0.4$ GeV in the ATLAS barrel ($|\eta| \leq 0.9$) |
|--------------|--------------------------------------------------------------------------------------------------|
| 580-780      | $0.021 \pm 0.006 \quad 0.005 \pm 0.002 \quad 0.005 \pm 0.001 \quad 0.003 \pm 0.001 \quad 0.002 \pm 0.001 \quad 0.001 \pm 0.001$ |
| 500-580      | $0.095 \pm 0.014 \quad 0.072 \pm 0.008 \quad 0.040 \pm 0.005 \quad 0.026 \pm 0.009 \quad 0.017 \pm 0.004 \quad 0.013 \pm 0.003 \quad 0.003 \pm 0.002$ |
| 420-500      | $0.158 \pm 0.014 \quad 0.085 \pm 0.008 \quad 0.047 \pm 0.005 \quad 0.047 \pm 0.011 \quad 0.027 \pm 0.005 \quad 0.015 \pm 0.003 \quad 0.007 \pm 0.002$ |
| 340-420      | $0.208 \pm 0.012 \quad 0.133 \pm 0.008 \quad 0.090 \pm 0.007 \quad 0.056 \pm 0.012 \quad 0.041 \pm 0.006 \quad 0.026 \pm 0.004 \quad 0.017 \pm 0.004$ |
| 275-340      | $0.240 \pm 0.012 \quad 0.198 \pm 0.010 \quad 0.139 \pm 0.008 \quad 0.099 \pm 0.016 \quad 0.076 \pm 0.008 \quad 0.037 \pm 0.005 \quad 0.029 \pm 0.005$ |
| 210-275      | $0.210 \pm 0.009 \quad 0.215 \pm 0.009 \quad 0.159 \pm 0.008 \quad 0.111 \pm 0.016 \quad 0.118 \pm 0.010 \quad 0.072 \pm 0.006 \quad 0.036 \pm 0.006$ |
| 145-210      | $0.215 \pm 0.007 \quad 0.217 \pm 0.008 \quad 0.190 \pm 0.008 \quad 0.159 \pm 0.017 \quad 0.114 \pm 0.009 \quad 0.076 \pm 0.006 \quad 0.042 \pm 0.006$ |
| 80-145       | $0.210 \pm 0.006 \quad 0.231 \pm 0.007 \quad 0.200 \pm 0.008 \quad 0.160 \pm 0.016 \quad 0.130 \pm 0.009 \quad 0.098 \pm 0.007 \quad 0.070 \pm 0.007$ |
| 14-80        | $0.117 \pm 0.003 \quad 0.152 \pm 0.005 \quad 0.145 \pm 0.006 \quad 0.117 \pm 0.011 \quad 0.102 \pm 0.007 \quad 0.070 \pm 0.005 \quad 0.062 \pm 0.007$ |

[ATLAS EXOT-2013-22 Aux]
Run 1 Results: CMS

Targets $\gamma_d$ decays within the pixel detector, into muon LJs only

- **Trigger:** dimuon, $p_T > 17$ GeV (leading), $p_T > 8$ GeV (subleading)
- **Selection criteria:**

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 offline muon candidates</td>
<td>Particle Flow algorithm</td>
</tr>
<tr>
<td>Muon $p_T$, $</td>
<td>\eta</td>
</tr>
<tr>
<td>High-energy muon</td>
<td>At least one muon with $p_T &gt; 17$ GeV, $</td>
</tr>
<tr>
<td>Dimuon pair</td>
<td>Two oppositely-charged pairs</td>
</tr>
<tr>
<td>Dimuon invariant mass</td>
<td>$m(\mu+\mu-) &lt; 5$ GeV</td>
</tr>
<tr>
<td>Dimuon common vertex</td>
<td>$P_v(\mu+\mu-) &gt; 1%$ or $\Delta R(\mu+\mu-) &lt; 0.01$</td>
</tr>
<tr>
<td>Dimuon fiducial</td>
<td>$\geq 1$ hit in first layer of pixel barrel or endcaps</td>
</tr>
<tr>
<td>Dimuon isolation</td>
<td>$I_{\text{sum}} &lt; 2$ GeV</td>
</tr>
<tr>
<td>Dimuons from same interaction</td>
<td>$</td>
</tr>
</tbody>
</table>

[arXiv:1506.00424]
Run 1 Results: CMS

Model-independent 95% CL:

\[ \sigma(pp \rightarrow 2a + X) B^2(a \rightarrow 2\mu) \alpha_{\text{gen}} \leq 0.24 + 0.09 \exp \left( -\frac{(m_{\mu\mu} - 0.32)^2}{2 \times 0.03^2} \right) \]

\[ = \tilde{N}(m_{\mu\mu}) / (\mathcal{L}\bar{\tau}) \]

Dark SUSY benchmark model (with gg fusion):

\[ \alpha = \text{kinematic & geometrical acceptance} \]
\[ \varepsilon = \text{selection efficiency} \]
\[ r = \frac{\varepsilon_{\text{data}}}{\alpha_{\text{gen}}} \]

<table>
<thead>
<tr>
<th>$m_{\gamma_D}$ [GeV]</th>
<th>0</th>
<th>0.5</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c\tau_{\gamma_D}$ [mm]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\varepsilon_{\text{sim}}$ [%]</td>
<td>8.85 ± 0.12</td>
<td>1.76 ± 0.05</td>
<td>0.23 ± 0.03</td>
</tr>
<tr>
<td>$\alpha_{\text{gen}}$ [%]</td>
<td>14.32 ± 0.14</td>
<td>2.7 ± 0.06</td>
<td>0.31 ± 0.03</td>
</tr>
<tr>
<td>$\varepsilon_{\text{sim}} / \alpha_{\text{gen}}$</td>
<td>0.62 ± 0.01</td>
<td>0.65 ± 0.02</td>
<td>0.74 ± 0.13</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$m_{\gamma_D}$ [GeV]</th>
<th>0</th>
<th>1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c\tau_{\gamma_D}$ [mm]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\varepsilon_{\text{sim}}$ [%]</td>
<td>6.13 ± 0.23</td>
<td>4.73 ± 0.07</td>
</tr>
<tr>
<td>$\alpha_{\text{gen}}$ [%]</td>
<td>8.89 ± 0.28</td>
<td>6.98 ± 0.09</td>
</tr>
<tr>
<td>$\varepsilon_{\text{sim}} / \alpha_{\text{gen}}$</td>
<td>0.69 ± 0.03</td>
<td>0.68 ± 0.01</td>
</tr>
</tbody>
</table>

$[\text{arXiv:1506.00424}]$

$m_{n_1} = 10\text{ GeV}, m_{n_{D}} = 1\text{ GeV}$
Run 1 Results: ATLAS + CMS

Combined results for $\gamma_d$ interpretation:

- Complementary coverage in $\gamma_d$ parameter space
- In regions other experiments were unable to reach!
  - ATLAS & CMS limits have extra parameter (BR for $h \rightarrow$ hidden)

[arXiv:1506.00424]
Run 2 Plans

**ATLAS**
- Extension of search to higher $\gamma_d$ masses: $\mathcal{O}(10 \text{ GeV})$
- Extension to higher BSM $H^0$ masses: $\mathcal{O}(\text{TeV})$
- New triggers, including “narrow scan” dimuon, to improve efficiency
- More efficient reconstruction of collimated MSonly muons
- More benchmark models (e.g. Higgs Portal, dark SUSY, iDM)

**CMS**
- New trigger to loosen $|\eta|$ constraints, allowing model-independent search in broader fiducial region
- Improved dimuon vertex reconstruction, to increase sensitivity up to $c\tau \sim 20 \text{ cm}$
- Inclusion of electron LJs
Conclusions

- **Displaced Lepton-Jets**: smoking-gun signature of long-lived, boosted, low-mass hidden states decaying to SM
  - Especially dark photons
  - Predicted in wide range of BSM models
- Challenging searches, due to detector limitations and wide range of possible topologies, which aren’t background-free
- But have several handles available
- Run 1: complementary ATLAS & CMS searches established limits in large region of dark photon parameter space unexplored by previous experiments
- Run 2: plans underway to extend and enhance displaced LJ searches
References


Lepton-Jet Gun
Table 1:
Reconstruction efficiency table for $\gamma \rightarrow \mu \mu$ with $m_{\gamma} = 0.4$ GeV in the ATLAS barrel (mid#eta < 0.9) as function of the $\gamma$ p_{T} and decay distance L_{xy}. The reconstruction efficiency is evaluated using a "LJ gun" Monte Carlo generator and processing the generated events through the full ATLAS simulation chain. The reconstruction efficiency is defined in each p_{T} and L_{xy} interval as the ratio between the number of reconstructed $\gamma \rightarrow \mu \mu$ and the corresponding number of generated ones. The $\gamma$ selection criteria are defined in EXOT-2013-22. Errors are statistical only.

![png](228kB) ![pdf](101kB)

Table 2:
Reconstruction efficiency table for $\gamma \rightarrow \mu \mu$ with $m_{\gamma} = 0.4$ GeV in the ATLAS endcap (1.2 < mid#eta < 2.5) as function of the $\gamma$ p_{T} and decay distance L_{xy}. The reconstruction efficiency is evaluated using a "LJ gun" Monte Carlo generator and processing the generated events through the full ATLAS simulation chain. The reconstruction efficiency is defined in each p_{T} and L_{xy} interval as the ratio between the number of reconstructed $\gamma \rightarrow \mu \mu$ and the corresponding number of generated ones. The $\gamma$ selection criteria are defined in EXOT-2013-22. Errors are statistical only.

![png](236kB) ![pdf](100kB)

Table 3:
Reconstruction efficiency table for $\gamma \rightarrow e e$ (m#tau#tau) with $m_{\gamma} = 0.4$ GeV in the ATLAS barrel (mid#eta < 1.0) as function of the $\gamma$ p_{T} and decay distance L_{xy}. The reconstruction efficiency is evaluated using a "LJ gun" Monte Carlo generator and processing the generated events through the full ATLAS simulation chain. The reconstruction efficiency is defined in each p_{T} and L_{xy} interval as the ratio between the number of reconstructed $\gamma \rightarrow e e$ (m#tau#tau) and the corresponding number of generated ones. The $\gamma$ selection criteria are defined in EXOT-2013-22. Errors are statistical only.

![png](189kB) ![pdf](100kB)

Table 4:
Reconstruction efficiency table for $\gamma \rightarrow e e$ (m#tau#tau) with $m_{\gamma} = 0.4$ GeV in the ATLAS endcap (1.5 < mid#eta < 2.4) as function of the $\gamma$ p_{T} and decay distance L_{xy}. The reconstruction efficiency is evaluated using a "LJ gun" Monte Carlo generator and processing the generated events through the full ATLAS simulation chain. The reconstruction efficiency is defined in each p_{T} and L_{xy} interval as the ratio between the number of reconstructed $\gamma \rightarrow e e$ (m#tau#tau) and the corresponding number of generated ones. The $\gamma$ selection criteria are defined in EXOT-2013-22. Errors are statistical only.

![png](190kB) ![pdf](100kB)
Table 1:
Reconstruction efficiency table for $\gamma_d \rightarrow \mu \mu$ with $m_{\gamma_d} = 0.4$ GeV in the ATLAS barrel ($\mid \eta \mid \leq 0.9$) as function of the $p_T$ and decay distance $L_{xy}$. The reconstruction efficiency is evaluated using a "LJ gun" Monte Carlo generator and processing the generated events through the full ATLAS simulation chain. The reconstruction efficiency is defined in each $p_T$ and $L_{xy}$ interval as the ratio between the number of reconstructed $\gamma_d \rightarrow \mu \mu$ and the corresponding number of generated ones. The $\gamma_d$ selection criteria are defined in EXOT-2013-22. Errors are statistical only.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.021 ± 0.006</td>
<td>0.005 ± 0.002</td>
<td>0.005 ± 0.001</td>
<td>0.003 ± 0.001</td>
<td>0.002 ± 0.001</td>
<td>0.001 ± 0.001</td>
<td>0.026 ± 0.009</td>
<td>0.017 ± 0.004</td>
<td>0.013 ± 0.003</td>
</tr>
<tr>
<td>$p_T$ interval (Gev)</td>
<td>10-20</td>
<td>20-30</td>
<td>30-40</td>
<td>40-50</td>
<td>50-60</td>
<td>60-80</td>
<td>80-100</td>
<td>10-20</td>
<td>20-30</td>
</tr>
</tbody>
</table>

Table 2:
Reconstruction efficiency table for $\gamma_d \rightarrow \mu \mu$ with $m_{\gamma_d} = 0.4$ GeV in the ATLAS endcap ($1.2 \leq \mid \eta \mid \leq 2.5$)

Table 3:
Reconstruction efficiency table for $\gamma_d \rightarrow ee$ $(\pi \pi)$ with $m_{\gamma_d} = 0.4$ GeV in the ATLAS barrel ($\mid \eta \mid \leq 1.0$)

Table 4:
Reconstruction efficiency table for $\gamma_d \rightarrow ee$ $(\pi \pi)$ with $m_{\gamma_d} = 0.4$ GeV in the ATLAS endcap ($1.5 \leq \mid \eta \mid \leq 2.4$)
“LJ Gun” MC tool: simulates or

- Allows us to determine ATLAS detector response to LJs as a function of: composition, lifetime, opening angle, $p_T$, $\eta$
- $\gamma_d$ mass determines BRs to \{e$^+$e$^-$, $\mu^+$e$^-$, $\pi^+$e$^-$\}
- $\gamma_d$ polarization state can be set to longitudinal or transverse
- Multiple interactions in same bunch crossing have been added to the simulation, to model pile-up. But, no primary vertex
- Generated events processed through full ATLAS simulation chain based on GEANT4
Using LJ Gun for Displaced Decays

- When using LJ Gun to produce MC samples: \( \gamma_d \) lifetime chosen such that, taking boost into account, 80% of decays occur inside fiducial volume
  - Defined as cylinder 8 m radius and 28 m tall, centred on detector
- All \( \gamma_d \) decaying outside fiducial volume get re-generated, until decay is inside fiducial volume
- This equally populates all detector regions, independent of \( \gamma_d \ p_T \)
Figure 6. Reconstruction efficiency of TYPE0 LJs as a function of $p_T$ (left) and $L_{xy}$ (right) of the $\gamma_d$ for $\gamma_d \rightarrow \mu\mu$ obtained from the LJ gun MC samples with $\gamma_d$ masses 0.4, 0.9 and 1.5 GeV. The uncertainties are statistical only.
Figure 7. Reconstruction efficiency of TYPE2 LJs as a function of $p_T$ (left) and $L_{xy}$ (right) of the $\gamma_d$ for $\gamma_d \rightarrow ee/\pi\pi$ obtained from the LJ gun MC samples with $\gamma_d$ masses 0.05, 0.15, 0.4, 0.9 and 1.5 GeV. The uncertainties are statistical only.
Figure 8. Reconstruction efficiency of TYPE0 (top left), TYPE1 (top right) and TYPE2 (bottom) LJs as a function of the $p_T$ of the $s_{a_1}$ for LJs with two dark photons for an $s_{a_1}$ mass of 2 GeV. For the $\gamma_d$, only the kinematically allowed masses are considered. The distributions for the other $s_{a_1}$ masses are very similar. The uncertainties are statistical only.
Backup

ATLAS Analysis
Single dark photon decaying to muon pair

Multi-jet control region: selected by single-jet triggers, 15 and 35 GeV
# Full Analysis Cut-Flow

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two reconstructed LJs</td>
<td>select events with at least two reconstructed LJs</td>
</tr>
<tr>
<td>$\eta$ range (TYPE1)</td>
<td>remove jets with $</td>
</tr>
<tr>
<td>$\eta$ range (TYPE2)</td>
<td>remove jets with $</td>
</tr>
<tr>
<td>EM fraction (TYPE2)</td>
<td>require EM fraction of the jet $&lt; 0.1$</td>
</tr>
<tr>
<td>Jet width W (TYPE2)</td>
<td>require width of the jet $&lt; 0.1$</td>
</tr>
<tr>
<td>Jet timing (TYPE1/TYPE2)</td>
<td>require jets with timing $-1 \text{ ns} &lt; t &lt; 5 \text{ ns}$</td>
</tr>
<tr>
<td>NC muons (TYPE0/TYPE1)</td>
<td>require muons without ID track match</td>
</tr>
<tr>
<td>ID isolation</td>
<td>require $\max(\Sigma p_T) \leq 3 \text{ GeV}$</td>
</tr>
<tr>
<td>$\Delta \phi$</td>
<td>require $</td>
</tr>
</tbody>
</table>
Table 2. Number of selected data events at different stages of the selection process and for each of the LJ pair types, for the full 2012 data sample.
Backgrounds

- **Cosmics** (studied using empty bunch crossings sample):
  - Muon LJs: 80% eliminated by NC requirement
  - Muon LJs: reduced by factor of 200 by cut on impact parameters of MS track at PV (\(|d_0| < 200 \text{ mm}, |z_0| < 270 \text{ mm}\))
  - Electron/pion LJs: almost entirely eliminated by jet timing cut

- **Multijet** (studied using control sample, ABCD method in \(\Sigma p_T\) vs \(\Delta R\) plane):
  - EM fraction cut provides 99.9% rejection
  - Track isolation cut provides 97% rejection
  - Jet width cut provides 80% rejection
Backgrounds

<table>
<thead>
<tr>
<th>LJ pair types</th>
<th>0-0</th>
<th>0-1</th>
<th>0-2</th>
<th>1-1</th>
<th>1-2</th>
<th>2-2</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger selection</td>
<td>161951</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Good primary vertex</td>
<td>not applicable</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Two reconstructed LJs</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\eta$ range (TYPE1/TYPE2)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EM fraction (TYPE2)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jet width W (TYPE2)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jet timing (TYPE1/TYPE2)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NC muons (TYPE0/TYPE1)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ID isolation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$</td>
<td>\Delta\phi</td>
<td>$</td>
<td>6</td>
<td>0</td>
<td>6</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>Rescaled to interactions</td>
<td>$15 \pm 6$</td>
<td>$0^{+3.1}_{-3.0}$</td>
<td>$14 \pm 6$</td>
<td>$0^{+3.1}_{-3.0}$</td>
<td>$11 \pm 7$</td>
<td>$40 \pm 10$</td>
<td></td>
</tr>
</tbody>
</table>

Table 3. Result of applying the LJ selection to events triggered in the empty bunch crossings. Number of selected data events at different stages of the selection process and for each LJ pair types. Except for the last row, all these numbers are not rescaled by the ratio of filled to empty bunches in the LHC operation. The quoted uncertainties are statistical only.

<table>
<thead>
<tr>
<th>Data Type</th>
<th>Events in B</th>
<th>Events in C</th>
<th>Events in D</th>
<th>Expected Events in A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cosmic-ray data</td>
<td>0</td>
<td>0</td>
<td>60 $\pm$ 13</td>
<td>40 $\pm$ 10</td>
</tr>
<tr>
<td>Data (cosmic rays subtracted)</td>
<td>362 $\pm$ 19</td>
<td>99 $\pm$ 10</td>
<td>19 $\pm$ 16</td>
<td>70 $\pm$ 58</td>
</tr>
</tbody>
</table>

Table 4. Event yields in the four ABCD regions used to estimate the multi-jet background with the ABCD method in the LJ signal region. All LJ pair types are used. The quoted uncertainties are statistical only.
Figure 9. Muon trigger efficiency, $\varepsilon(2\text{mu6})$, as a function of $p_T$ (left) and $\eta$ (right) of the $\gamma_d$ for $\gamma_d \rightarrow \mu\mu$ obtained from the LJ gun MC samples with $\gamma_d$ masses 0.4, 0.9 and 1.5 GeV. The uncertainties are statistical only.
Figure 10. Calorimetric trigger efficiency as a function of $p_T$ (left) and $\eta$ (right) of the $\gamma_d$ for $\gamma_d \rightarrow ee/\pi\pi$ obtained from the LJ gun MC samples with $\gamma_d$ masses 0.05, 0.15, 0.4, 0.9 and 1.5 GeV. Similar distributions are obtained for LJs containing two dark photons. The uncertainties are statistical only.
**Signal Efficiencies**

<table>
<thead>
<tr>
<th>LJ pair types</th>
<th>0-0</th>
<th>0-1</th>
<th>0-2</th>
<th>1-1</th>
<th>1-2</th>
<th>2-2</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of events</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>39730 ± 100</td>
</tr>
<tr>
<td>Trigger selection</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1330 ± 30</td>
</tr>
<tr>
<td>Good primary vertex</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1330 ± 30</td>
</tr>
<tr>
<td>Two reconstructed LJs</td>
<td>86</td>
<td>9</td>
<td>40</td>
<td>0</td>
<td>1</td>
<td>39</td>
<td>175 ± 7</td>
</tr>
<tr>
<td>η range (TYPE1/TYP2E2)</td>
<td>86</td>
<td>8</td>
<td>27</td>
<td>0</td>
<td>1</td>
<td>23</td>
<td>145 ± 6</td>
</tr>
<tr>
<td>EM fraction (TYPE2)</td>
<td>86</td>
<td>8</td>
<td>23</td>
<td>0</td>
<td>1</td>
<td>12</td>
<td>130 ± 6</td>
</tr>
<tr>
<td>Jet width W (TYPE2)</td>
<td>86</td>
<td>8</td>
<td>23</td>
<td>0</td>
<td>1</td>
<td>12</td>
<td>130 ± 6</td>
</tr>
<tr>
<td>Jet timing (TYPE1/TYP2E2)</td>
<td>86</td>
<td>6</td>
<td>23</td>
<td>0</td>
<td>1</td>
<td>11</td>
<td>128 ± 6</td>
</tr>
<tr>
<td>NC muons (TYPE0/TYP1)</td>
<td>50</td>
<td>4</td>
<td>17</td>
<td>0</td>
<td>0</td>
<td>11</td>
<td>82 ± 5</td>
</tr>
<tr>
<td>ID isolation</td>
<td>37</td>
<td>2</td>
<td>13</td>
<td>0</td>
<td>0</td>
<td>10</td>
<td>63 ± 4</td>
</tr>
<tr>
<td>(</td>
<td>Δφ</td>
<td>)</td>
<td>35 ± 3</td>
<td>2 ± 1</td>
<td>12 ± 2</td>
<td>0^{+0.6}_{-0}</td>
<td>0^{+0.6}_{-0}</td>
</tr>
</tbody>
</table>

**Table 7.** Expected number of LJ events for the two-γ_d FRVZ model, using the parameter values in table 6. The numbers refer to selected signal events at different stages of the selection process and for each LJ pair type. The number of signal events is rescaled to the 20.3 fb^{-1} total integrated luminosity and the quoted uncertainties are statistical only. The detection efficiency is $1.5 \times 10^{-3}$. 
Figure 14. Ratio of the integrated detection efficiency at a given $c\tau$ to the detection efficiency at $c\tau = 47$ mm of the reference $H \rightarrow 2\gamma_d + X$ MC sample.
Systematics

- Luminosity
- Higgs production cross-section
- Trigger efficiency
- Muon reconstruction efficiency
- Muon momentum resolution
- Jet energy scale
- Effect of pile-up on $\Sigma p_T$
- Multi-jet background
- Cosmics background
- $\gamma_d$ detection efficiency, $p_T$ resolution