SEARCHES FOR LEPTON-JETS WITH THE ATLAS DETECTOR AT THE LHC

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On behalf of the ATLAS collaboration
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Outline

• Introduction
• Lepton-jets
  – Prompt and long-lived
• Search strategy
• Background
• Results and interpretations
Introduction

Conflicting results from astrophysical experiments inspired interesting models for production and decays of dark sector particles!

Originally proposed by N. A.-. Hamed, N. Weiner
arXiv: 0810.0714

- SM particles could couple to hidden sector via Higgs portal or kinetic mixing
- The lightest unstable particle ($\gamma_d$) in the hidden sector could couple back to SM via kinetic mixing
- Search at LHC for $\gamma_d$ production could constrain kinetic mixing ($\epsilon$), and mass ($m_{\gamma_d}$) parameters
Lepton-jets

- Low mass (O(1) GeV) dark photons, $\gamma_d$, may be produced with large boost in the decay chain of heavier states
- $\gamma_d$ can decay mostly into SM leptons ($e^+e^-$, or $\mu^+\mu^-$), and also into light mesons → collimated collection of energetic leptons form a "lepton-jet"
  - depending on the size of kinetic mixing ($\varepsilon$) and masses of $\gamma_d$ and leptons, the decay could be prompt or long-lived (typically $\varepsilon > 10^{-5}$ for prompt)
    $$\Gamma_l = \frac{1}{3} \alpha e^2 m_{\gamma_d} \sqrt{1 - \frac{4m_l^2}{m_{\gamma_d}^2}} \left(1 + \frac{2m_l^2}{m_{\gamma_d}^2}\right)$$
  - $\gamma_d$ decay branching fractions and lifetime are model-dependent
Analysis strategy

- ATLAS search is performed for events containing at least two lepton-jets (LJs) considering both prompt and displaced productions

- Search strategy is nearly model independent selection
  - no restrictions on other objects of event
  - study the γ_d mass in [0.1, 2] GeV range

- Prompt and displaced LJs have somewhat different reconstruction methods
  - displaced LJ search covers upto 7 m (first muon-trigger plane) transverse distance range of γ_d decay position from interaction point
    - γ_d decay into e^+e^- only within hadronic calorimeter to reduce background

- Results are interpreted for various topologies, such as Higgs → N γ_d +X, or squark + squark → N γ_d + X, where N>=2
Lepton-jets signal models

SUSY-mediated:
Due to smaller cross section of squark pair production, this model is yet more interesting for prompt LJ search.

Higgs-mediated:
γ_d production via SM Higgs portal has good sensitivity for both prompt and displaced LJ searches.

However, this talk considers this model for displaced LJ only.
Lepton-jets reconstruction

- **Prompt LJs** reconstructions are based on clustering tracks ($p_T \geq 10$ GeV) in a narrow cone, and pointing them to energy deposited in the calorimeter or to the tracks in muon spectrometers
  - overlapped tracks and energy clusters due to limited intrinsic resolution of ATLAS sub-detectors
    - reconst. eff upto $\sim 60\%$
  - overwhelming QCD background in $e$-channel
  - challenge in the calibrations

- Similar clustering technique for **displaced LJ** reconstruction, but veto against inner detector tracks to suppress bkg
  - reconst. eff upto $\sim 20\%$
  - substantial multi-jet and cosmic-ray bkg contributions
  - additional challenge in trigger and decay vertices reconstruction beyond precision tracking volume
    - this analysis ignores vertices reconstruction

\[ \Delta R \] between two muons of a reconstructed LJ from $\gamma_d$

\[ \sqrt{(\eta_1 - \eta_2)^2 + (\phi_1 - \phi_2)^2} \]
Lepton-jets selection

- Discriminating LJ variables against the QCD bkg and cosmic-ray
  - e.g high-$p_T$ tracks multiplicity, isolation in inner detector and calorimeter, profile of energy deposition of electrons in the calorimeters, timing
  - displaced LJ can have different shower profile compared to prompt LJ if $\gamma_d$ decayed in the middle of calorimeter
- requirement of $\geq 2$LJs per event suppresses all other backgrounds such as $W/Z/\gamma^*+$jets, di-bosons, and ttbar processes
Background (prompt LJ)

- Background due to QCD jet faking as lepton-jet is determined from two nearly uncorrelated discriminating variables using data-driven ABCD likelihood method
  - region A represents signal region
  - likelihood fit to all four regions to estimate background in region A
- Other backgrounds (e.g. ttbar, diboson) tiny, and estimated via MC simulation

<table>
<thead>
<tr>
<th>√s = 7 TeV @ 4.8 fb⁻¹</th>
<th>e-channel</th>
<th>μ-channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>15</td>
<td>3</td>
</tr>
<tr>
<td>Background</td>
<td>15.2 ± 2.7</td>
<td>0.5 ± 1.5</td>
</tr>
</tbody>
</table>

\[\int L \, dt = 4.8 \, fb^{-1}\]
\[\sqrt{s} = 7 \, TeV\]
Background (displaced LJ)

- Same data-driven technique for multi-jet bkg estimation
  - choice of ABCD variables is independent of lepton-jet type
- Cosmic-ray is additional source of background
  - determined from empty bunch crossings data

<table>
<thead>
<tr>
<th>8 TeV data @ 20.3 fb⁻¹</th>
<th>119</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cosmic-ray</td>
<td>40 ± 11 ± 9</td>
</tr>
<tr>
<td>Multi-jet</td>
<td>70 ± 58 ± 11</td>
</tr>
<tr>
<td>Total background</td>
<td>110 ± 59 ± 14</td>
</tr>
</tbody>
</table>
Interpretations (prompt LJ)

- No significant excess is found in 7 TeV data compared to background prediction
- 95 %CL limits are placed on the cross section x BR of two lepton-jets
  - limits are extracted for lepton-jet production via SUSY mediator

<table>
<thead>
<tr>
<th>Dark photon mass [MeV]</th>
<th>$\geq 2$ electron jets Obs (Exp) [pb]</th>
<th>$\geq 2$ muon jets Obs (Exp) [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>0.082 (0.082)</td>
<td>--</td>
</tr>
<tr>
<td>300</td>
<td>0.11 (0.11)</td>
<td>0.017 (0.011)</td>
</tr>
<tr>
<td>500</td>
<td>0.20 (0.21)</td>
<td>0.019 (0.012)</td>
</tr>
</tbody>
</table>

- Constraints on the Higgs portal topology could also be established based on search results
  - higher production cross section of $gg \rightarrow H$
- Extension of constraints for other masses of $\gamma_d$ upto 2 GeV are possible with relatively detailed studies on calibration
- Results with 8 TeV data are imminent with extended studies!
Interpretations (displaced LJ)

- No significant excess is found in 8 TeV data compared to background prediction
- 95 %CL limits are placed on the cross section x BR
  - limits are extracted for lepton-jet production via Higgs portal ($H \rightarrow 2\gamma_d + X$ or $H \rightarrow 4\gamma_d + X$) for 0.4 GeV $\gamma_d$

95%CL excluded kinetic mixing:
\[ 7.7 \times 10^{-7} \leq \epsilon \leq 2.7 \times 10^{-6} \]
Kinetic mixing vs mass exclusion

90%CL exclusion regions in kinetic mixing $\varepsilon$ and dark photon mass plane
- derived from $H \rightarrow 2\gamma_d + X$ process
- Higgs BR = 5%/10%/20%/40%

Excludes regions unconstrained by earlier experiments
Kinetic mixing vs mass exclusion

90% CL exclusion regions in kinetic mixing $\varepsilon$ and dark photon mass plane
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Excludes regions unconstrained by earlier experiments
Conclusions

• Lepton-jets in the final states are distinct signatures for various models of dark sector

• We have conducted a nearly model independent search for lepton-jets using Run I data at ATLAS.
  – prompt lepton-jets search results with 8 TeV data will be released soon!

• The observed number of lepton-jets are consistent with the background prediction.
  – 95%CL upper limits are established on $\gamma_d$ production in Higgs-mediated and SUSY-mediated topologies and 90%CL exclusions are extracted for $\gamma_d$ mass and lifetime.

• Continue with the lepton-jet searches in Run II with further improvement in strategies!
Thanks
The ATLAS detector

Lumi. Uncertainty = 3.9% (7 TeV)
= 2.8% (8 TeV)

SUSY2015: 08/27/15
M. Haleem: Search for LJs with the ATLAS
Few facts about ATLAS Run I sub-detectors

- **Pixels:**
  - Barrel radial distance from IP: $5 \text{ cm} < R < 12 \text{ cm}$
  - Pixel granularity: $50 \mu \text{m} \times 400 \mu \text{m}$ in $r\Phi \times Z$
  - Intrinsic resolution: $10 \mu \text{m} \times 115 \mu \text{m}$ in $r\Phi \times Z$

- **SCT:**
  - Barrel radial distance from IP: $12 \text{ cm} < R < 52 \text{ cm}$
  - Strips with $80 \mu \text{m}$ pitch and $40 \text{ mrad}$ stereo angle
  - Intrinsic resolution: $17 \mu \text{m} \times 580 \mu \text{m}$ in $r\Phi \times Z$

- **TRT:**
  - Barrel radial distance from IP: $56 \text{ cm} < R < 108 \text{ cm}$
  - Intrinsic resolution: $130 \mu \text{m}$ in $r\Phi$

- **Calorimeter:**
  - Barrel radial distance from IP: $120 \text{ cm} < R < 230 \text{ cm}$
  - Spatial granularity in the 2nd sampling: $0.025 \times 0.025$ in $\Delta\eta \times \Delta\Phi$

- **Muon spectrometer:**
  - Barrel radial distance from IP: $500 \text{ cm} < R < 1200 \text{ cm}$
  - EC longitudinal distance: $750 \text{ cm} < rZ < 2250 \text{ cm}$
  - Spatial size of L1 trigger ROI: $0.2 \times 0.2$ in $\Delta\eta \times \Delta\Phi$ for barrel and $0.1 \times 0.1$ in $\Delta\eta \times \Delta\Phi$ for end-cap.
Dark photons

• Existence of dark matter (DM) is supported by astrophysical measurements
  • one of the greatest mysteries unexplained by SM

• DM could be composed of massive particles that interact very weakly with ordinary matter
  • most theories predict mass range between a few MeV to a few TeV

• Possible candidates:
  • lightest SUSY stable particles, stable Kaluza-Klein modes, sterile neutrinos, dark sector particles predicted by hidden sector particle theories, WIMPs, etc..

This talk is focused on ~ 1 GeV mass dark photon
Lepton-jets signal models

\[ q \rightarrow \tilde{q}_i, q_j \rightarrow \tilde{\chi}_d \rightarrow l^+ l^- \]

\[ q \rightarrow \tilde{g} \rightarrow \tilde{\chi}_1^0 \rightarrow \gamma_d \rightarrow l^+ l^- \]

\[ q \rightarrow \tilde{q}_i, q_j \rightarrow \tilde{\chi}_d \rightarrow l^+ l^- \]
Displaced lepton-jets types

**LJ TYPE0**

**LJ TYPE1**

**LJ TYPE2**

- ID
- EMCAL
- HCAL
- MS

JHEP 1411 (2014) 088
Lepton-jets reconstruction efficiencies (I)

Reconstruction efficiencies for a few lepton-jet types as a function of $\gamma_d p_T$

**prompt electron LJ**

**displaced electron/pion LJ**

**displaced muon LJ**

$|d0| < 200$ mm and $|z0| < 270$ mm cuts on muon tracks in displaced LJ to suppress cosmic-ray by a factor of 200, while reducing signal efficiencies by 25-50%

JHEP 1411 (2014) 088
Lepton-jets reconstruction efficiencies (II)

Reconstruction efficiencies for a few lepton-jet types as a function of $\gamma_d$ decay length

Prompt lepton-jets have constant efficiency below decay length of 50 mm, and drops to zero afterwards.
Trigger efficiencies for long-lived $\gamma_d$ as a function of $\gamma_d p_T$

Electron channel suffers from loss in efficiency for $\gamma_d$ decaying well before calorimeter that fail to pass trigger cut on electromagnetic to hadronic energy ratio.

JHEP 1411 (2014) 088
Track reconstruction at small opening angle

Employ usual tag and probe method with $J/\psi \rightarrow \mu\mu$ to compare the reconstruction at small opening angle agreement in data and MC within 5.4%
Discriminating variables distributions of LJs

ATLAS

\[ \int L \, dt = 4.8 \, fb^{-1} \]
\[ \sqrt{s} = 7 \, TeV \]

Events / 0.02

Calorimeter Isolation

Events / 0.0005

Electron Cluster Lateral Shower Width

Events / 0.02

Fraction of High Threshold TRT Hits

Events / 0.01

Cluster Energy Concentration

ABCD likelihood method for background estimation

\[ \mu_A = \mu^U + \mu + \mu^K_A \]
\[ \mu_B = \mu^U \tau_B + \mu b + \mu^K_B \]
\[ \mu_C = \mu^U \tau_C + \mu c + \mu^K_C \]
\[ \mu_D = \mu^U \tau_B \tau_C + \mu d + \mu^K_D \]

\( \mu \): signal strength  
\( \mu^U \): background strength  
\( b, c, d \): signal contaminations  
\( \tau_B, \tau_C \): ratio of the background in side-bands  
\( \mu^K_A, \mu^K_B, \mu^K_C, \mu^K_D \): bkg estimate from MC

Minimize the likelihood \( \prod_{i=A,B,C,D} \frac{e^{-\mu_i} \mu_i^{n_i}}{n_i!} \) to extract the background \( \mu^U \).
Signal MC (prompt LJ)

- Background due to QCD processes is determined from two nearly uncorrelated discriminating variables using data-driven ABCD method
- Region A is denoted as signal region
Displaced LJ signal detection efficiency vs $c\tau$

- LJs are reconstructed that decayed after pixel and before muon trigger plane
- Detection efficiency depends on mean lifetime $c\tau$

![Graph showing the detection efficiency vs $c\tau$ for displaced LJs.](image-url)
Signal efficiencies

For prompt LJ search the signal efficiency ranges from 1.8% to 9.2% depending on $\gamma_d$ mass and channel.

<table>
<thead>
<tr>
<th>$\gamma_d$ mass (MeV)</th>
<th>Acceptance x eff (%) e-channel</th>
<th>Acceptance x eff (%) $\mu$-channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>$3.01 \pm 0.30$</td>
<td>--</td>
</tr>
<tr>
<td>300</td>
<td>$2.7 \pm 0.5$</td>
<td>$9.2 \pm 0.9$</td>
</tr>
<tr>
<td>500</td>
<td>$1.8 \pm 0.5$</td>
<td>$8.5 \pm 1.1$</td>
</tr>
</tbody>
</table>

The overall detection efficiency for two displaced LJs for signal selection is 0.15%
Prompt LJ 7 TeV data analysis systematics

<table>
<thead>
<tr>
<th>Source</th>
<th>Systematics uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>3.9%</td>
</tr>
<tr>
<td>Trigger</td>
<td>1.5% - 2%</td>
</tr>
<tr>
<td>ID track or muon reconstruction at small ΔR</td>
<td>11% - 13%</td>
</tr>
<tr>
<td>Muon momentum scale/resolution</td>
<td>1%</td>
</tr>
<tr>
<td>Electron energy scale</td>
<td>0.6%</td>
</tr>
<tr>
<td>Discriminating variables efficiency</td>
<td>1% - 10%</td>
</tr>
</tbody>
</table>
## Displaced LJ 8 TeV data analysis systematics

<table>
<thead>
<tr>
<th>Source</th>
<th>Systematics uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>2.8%</td>
</tr>
<tr>
<td>Trigger</td>
<td>5.8% - 11%</td>
</tr>
<tr>
<td>Muon reconstruction at small ΔR</td>
<td>5.4%</td>
</tr>
<tr>
<td>Muon momentum scale/resolution</td>
<td>1.0%</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>0.9% - 1.7%</td>
</tr>
<tr>
<td>Effect of pile-up</td>
<td>4.1%</td>
</tr>
<tr>
<td>Multi-jet background</td>
<td>15%</td>
</tr>
<tr>
<td>Cosmic-ray background</td>
<td>22%</td>
</tr>
</tbody>
</table>