Prompt and non-prompt leptonic decays as a window into the dark sector with ATLAS

9 May 2016 – Pheno2016
Heather Russell, on behalf of the ATLAS collaboration
$U(1)_{\text{dark}}$ is a simple extension to the Standard Model (SM) that adds a vector boson, $Z_d$ (also know as: $A'$, $Z'$, $\gamma_d$)

- **Kinetic mixing** between SM and dark sector: \[ \frac{1}{2} \epsilon F'_{\mu\nu} B^{\mu\nu} \]

$Z$-$Z_d$ mixing leads to:

- Can generate $Z_d$ mass by introducing a dark scalar

 Allows for decays:

Not discussed in this talk: Drell-Yan production ($pp \rightarrow Z_d \rightarrow l^+l^-$)
See JHEP 02 (2015) 157 for a discussion of DY prospects

Heather Russell, University of Washington
9 May 2016
How does the $Z_d$ decay?

- Depending on the $Z_d$ mass, to leptons or quarks
- Leptons provide a distinct, clean search channel with low backgrounds

- Collimation of leptons depends on the $Z_d$ boost/mass:

  - Resolved leptons
  - Lepton jets

JHEP 02 (2015) 157
Very similar analysis to $H \rightarrow ZZ^*$, except now $H \rightarrow ZZ^*$ is an irreducible background!

Two pairs of same flavour, opposite sign (SFOS) leptons:

- $50 < m_{12} < 106 \text{ GeV}$
- $12 < m_{34} < 115 \text{ GeV}$

Mass of 4 leptons required to be consistent with the SM Higgs:

- $115 < m_{4l} < 130 \text{ GeV}$

$Z_d$ would present as a peak in $m_{34}$: scan for signal peak in 1 GeV steps (15 GeV – 55 GeV)

No excess of events: set limits on branching ratio for $H \rightarrow Z Z_d$ or kinetic mixing parameter
No distinction between lepton pairs: both $Z_d$ are on-shell, and both $Z_d$ have the same mass

- same 4l mass requirement as $H \rightarrow ZZ_d$: $115 < m_{4l} < 130$ GeV
- select e, $\mu$ lepton pairs to minimize $\Delta m = |m_{12} - m_{34}|$

- Veto $J/\psi$, $\Upsilon$ by requiring $m_{ll} > 12$ GeV, veto $Z$ with $|m_{ll} - m_Z| > 10$ GeV, where $m_{ll}$ is any SFOS lepton pair

- Loose selection requires $m_{ij} < m_H / 2$, four events pass loose selection

- Final event selection restricts lepton pair invariant mass depending on flavour and $m_{Z_d}$:

| $|\text{Im}_{Z_d} - m_{ij}|$ | channel |
|-----------------------------|---------|
| 5 GeV                       | 4e      |
| 3 GeV                       | 4$\mu$  |
| 4.5 GeV                     | 2e2$\mu$|
Total background is < 0.1 event in all channels

Two events pass final signal selection:

<table>
<thead>
<tr>
<th>$m_{12}$</th>
<th>$m_{34}$</th>
<th>consistent $m_{Z_d}$</th>
<th>channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>18 GeV</td>
<td>23.2 GeV</td>
<td>20.5 – 21.0 GeV</td>
<td>4$\mu$</td>
</tr>
<tr>
<td>21.8 GeV</td>
<td>28.1 GeV</td>
<td>23.5 – 26.5 GeV</td>
<td>4e</td>
</tr>
</tbody>
</table>

Limits can be set on BR($H \rightarrow Z_d Z_d$) or the kinetic mixing parameter, $\kappa$
Prompt lepton jets

SUSY production of lepton jets, with dark sector candidate $X_d$:

and Higgs-portal production in Falkowski-Ruderman-Volansky-Zupan (FVRZ) models:

**HLSP**: Hidden lightest stable particle (simulated mass is 2 GeV)
High dark photon boost

Very collimated leptons

**Reconstruction:**

1. Cluster tracks in $\Delta R = 0.5$ cone
2. Search for leptons within $\Delta R = 0.5$ of track axis
3. Can find three types of lepton jet:
   - electron (eLJ):
     $\geq 1$ electron, no muons, $\geq 2$ tracks
   - muon (muLJ):
     $\geq 2$ muons, no electrons, $\geq 2$ tracks
   - electron+muon (emuLJ):
     $\geq 1$ muon, $\geq 1$ electron, $\geq 2$ tracks

**Six possible 2-LJ event topologies:**

- eLJ-eLJ
- muLJ-muLJ
- eLJ-emuLJ
- emuLJ-emuLJ
- eLJ-muLJ
- muLJ-emuLJ
Prompt lepton jets: results

- Dominant background is QCD jets faking lepton jets
  → estimate with ABCD likelihood method using pairs of approximately uncorrelated variables for each 2-LJ topology
- Diboson (includes γ*), $t\bar{t}$ backgrounds estimated from MC

---

**No significant excess of events in any topology:**

<table>
<thead>
<tr>
<th>Channel</th>
<th>Background (ABCD-likelihood method)</th>
<th>Background (total)</th>
<th>Observed events in data</th>
</tr>
</thead>
<tbody>
<tr>
<td>eLJ–eLJ</td>
<td>2.9 ± 0.9</td>
<td>4.4 ± 1.3</td>
<td>6</td>
</tr>
<tr>
<td>muLJ–muLJ</td>
<td>2.9 ± 0.6</td>
<td>4.4 ± 1.1</td>
<td>4</td>
</tr>
<tr>
<td>eLJ–emuLJ</td>
<td>6.7 ± 1.4</td>
<td>7.1 ± 1.4</td>
<td>2</td>
</tr>
<tr>
<td>eLJ–emuLJ</td>
<td>7.8 ± 2.0</td>
<td>7.8 ± 2.0</td>
<td>5</td>
</tr>
<tr>
<td>muLJ–emuLJ</td>
<td>20.2 ± 4.5</td>
<td>20.3 ± 4.5</td>
<td>14</td>
</tr>
<tr>
<td>emuLJ–emuLJ</td>
<td>1.3 ± 0.8</td>
<td>1.9 ± 0.9</td>
<td>0</td>
</tr>
</tbody>
</table>
What if the dark photons have a non-zero proper lifetime?

Higgs portal model gives three types of LJs:

- LJ TYPE0
- LJ TYPE1
- LJ TYPE2

Sensitivity regions:

- 0.3 $\rightarrow$ 5 m (mu-mu LJ)
- 1 – 4 m (e-e or pi-pi LJ)

From two types of decays:

ID
EMCAL
HCAL
MS

More muon system
Displaced lepton jets: reconstruction

**TYPE0:** $\geq 2$ displaced muons and no jet

**TYPE1:** $\geq 2$ displaced muons and one jet

**TYPE2:** one low-EMF jet

Reconstruction efficiency depends on *where the dark photon decays:*
Displaced lepton jets: results

Main backgrounds are cosmic rays and QCD jets

- Estimate QCD background using ABCD likelihood method (same region for all LJ topologies):
- Cosmic ray background estimated using data collected in empty bunches during collision runs

### No significant excess of events in any topology:

<table>
<thead>
<tr>
<th></th>
<th>All LJ pair types</th>
<th>TYPE2-TYPE2 LJs excluded</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>119</td>
<td>29</td>
</tr>
<tr>
<td>Cosmic rays</td>
<td>40 ± 11 ± 9</td>
<td>29 ± 9 ± 29</td>
</tr>
<tr>
<td>Multi-jets (ABCD)</td>
<td>70 ± 58 ± 11</td>
<td>12 ± 9 ± 2</td>
</tr>
<tr>
<td>Total background</td>
<td>110 ± 59 ± 14</td>
<td>41 ± 12 ± 29</td>
</tr>
</tbody>
</table>

Background from TYPE2-TYPE2 (2 low-EMF jets) topology largest – signal contribution is not → better limits without TYPE2-TYPE2 signal region.
Dark photon lifetime depends on kinetic mixing parameter

Small $\varepsilon \rightarrow$ long lifetime

Limits here are *model dependent* – based on FRVZ model $H \rightarrow 2\gamma_D + X$. Other limits are from direct searches (beam dump, etc.)
Many channels investigated in Run 1:

<table>
<thead>
<tr>
<th></th>
<th>one $Z_d$</th>
<th>two $Z_d$</th>
<th>four $Z_d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>prompt, non-collimated $Z_d$</td>
<td>$\checkmark$</td>
<td>$\checkmark$</td>
<td></td>
</tr>
<tr>
<td>displaced, non-collimated $Z_d$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>prompt, collimated $Z_d$</td>
<td>$\checkmark$</td>
<td>$\checkmark$</td>
<td>$\checkmark$</td>
</tr>
<tr>
<td>displaced, collimated $Z_d$</td>
<td>$\checkmark$</td>
<td>$\checkmark$</td>
<td>$\checkmark$</td>
</tr>
</tbody>
</table>

No excesses found, but parameter space is still open:

Will fill in the gaps and push the boundaries with Run 2!

All ATLAS Exotics public results can be found here:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults

Heather Russell, University of Washington 9 May 2016