Searches for unconventional signatures with the ATLAS detector at 13 TeV

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On behalf of the ATLAS collaboration
Outline

• Unconventional-ism
  • Definition
  • Question of stableness
  • Search requirements

• Searches
  • ATLAS Unconventional Signature Searches
  • Displacement-ness
  • Displaced jets in the calorimeter
  • Displaced lepton-jets

• Summary
Unconventional-ism
Definition of Unconventional-ism

Unconventional final-state usually refers to unique detector signatures

• Mostly refers to physics beyond the standard model (BSM)

• Many scenarios include new particles with relatively long life-time, enabling direct measurements

• Final states can include BSM particles

• The new particle interactions with the detector can differ from interactions involving SM particles
  • Can be massive and therefore are expected to travel at low velocities ($\beta < 1$)
  • If electrically charged, the new particle is expected to be highly ionizing ($\frac{dE}{dx} > \frac{dE}{dx_{MIP}}$)
Question of Stableness

- A particle is considered as long-lived (LLP) if it has a long-enough lifetime to be measured directly by the detector.

- **Two types of long-lived particles:**
  - Meta-stable
    - Decays inside the detector volume
    - The decay location is usually unknown and hence a range of lifetimes will be studied
  - Stable
    - Pass through the detector without decaying

- **Detector signature:**
  - Electrically charged LLPs will leave signal in all detector stations
  - If neutral, depending on the LLP lifetime, either large reconstructed $E_T^{miss}$ or unusual vertex locations will appear
  - Strongly interacting LLPs might flip their electric charge while interacting with the detector medium
  - In most cases the background sources are cavern/instrumental noise and badly reconstructed objects
Search Requirements

Usually requires unconventional analysis methods

• Detector-signature driven search

• Standard triggers are not designed for unusual objects

• Self-made object reconstructions is required

• Requires non-standard analysis strategies and tools
  • Custom made MC simulations
  • Background estimation is usually data driven
ATLAS Unconventional Signature Searches

EXOTIC Searches
• Public Results: [LINK]

SUSY Searches
• Public Results: [LINK]

© Many thanks to the talented artist: Emma Torro, University of Washington

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Displacement-ness

‘Displaced Vertices’:

- Some BSM models consider a possible production of a neutral metastable particle
- Depending on the LLP’s lifetime a decay is expected inside the detector
- Signal ‘appears’ inside one of the detector stations
- No trail leading to the Interaction-Point (IP) from the decay location, only decay products

Searches presented:

- Displaced jets
- Displaced Lepton-Jets (LJs)

Common:

- Neutral LLP decays inside the detector
- Background sources of multi-jet production, and Non-Collision Bkg (NCB)
  - NCB - (Cosmic-μ and beam halo (Beam Induced Bkg (BIB)))
  - Public results based on data sample of ~3 fb⁻¹ (2015)
  - Background estimation based on data-driven ABCD method with two discriminating variables

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Displaced Jets in the Calorimeter – 1/3

Scenario

• Hidden Sectors (HS) containing a new sector weakly coupled to the SM via a communicator particle
• The HS particles may decay to SM particles via the communicator

Detector signature

• The neutral LLPs will decay in the hadronic calorimeter
• Results in a-typical jet (mainly $b\bar{b}$ -quarks):
  • No tracks in the ID
  • No energy deposit in the electromagnetic calorimeter
• Final state of two displaced jets

A simplified HS model in which the SM sector and hidden sector are connected via a heavy neutral boson $\Phi$
• The $\Phi$ decays to two long-lived neutral scalars $S$: $\Phi \rightarrow SS$
• The neutral scalar $S$ decays to a pair of SM fermions: $S \rightarrow ff$
Displaced Jets in the Calorimeter – 2/3

Analysis Strategy

- LLP decay products are less separated when the decay occurs in the HCal resulting in a narrow jet
  - High ‘CaloRatio-jet’ - \( \left( \frac{E_{\text{HCal}}}{E_{\text{EM}}} \right) \)
  - No ID tracks
- MC simulations:
  - Heavy boson: \( m_{\Phi} = 400 \text{ GeV} \rightarrow 1 \text{ TeV} \)
  - Neutral scalars: \( m_{\Sigma} = 50 \rightarrow 400 \text{ GeV} \)
- Trigger selection: signature-driven trigger: ‘CaloRatio’
- Offline selection:
  - B1B removal algorithm
  - Boosted Decision Tree (BDT)
    - \( p_T \) cuts:
      - \( p_T > 150 \text{ GeV}, BDT > 2.0 \)
      - \( p_T > 120 \text{ GeV}, BDT > -0.2 \)

- Background rejection:
  - BDT value should be within \(-3 \text{ns} < t < 15 \text{ns} \)
  - Rejection of soft NCB jets \( p_T > 50 \text{ GeV} \)
  - \( \Delta \phi (\text{jet}_1^{\text{CaloRatio}}, \text{jet}_2^{\text{CaloRatio}}) > 0.75 \text{ rad} \)
- Background estimation using a data-driven ABCD method:
  - \( \sum \Delta R_{\text{min}} (\text{jet}, \text{tracks}) \)
  - \( \sum \text{BDT} \)
Displaced Jets in the Calorimeter – 3/3

Results

- The number of predicted background events (18.4±6.3(stat)±6.6(syst)) is within 1σ of the observed events (24)

- Limits were set on σ×BR of the signal as a function of the proper lifetime of the LLP:

<table>
<thead>
<tr>
<th>m_s (GeV)</th>
<th>m_s = 50 GeV</th>
<th>m_s = 100 GeV</th>
<th>m_s = 150 GeV</th>
<th>m_s = 400 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>m_{φ} = 400 GeV</td>
<td>(0.20, 2.4) m</td>
<td>(0.52, 4.6) m</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>m_{φ} = 600 GeV</td>
<td>(0.09, 2.7) m</td>
<td>–</td>
<td>(0.38, 8.2) m</td>
<td>–</td>
</tr>
<tr>
<td>m_{φ} = 1 TeV</td>
<td>(0.05, 2.0) m</td>
<td>–</td>
<td>(0.14, 7.2) m</td>
<td>(0.78, 16) m</td>
</tr>
</tbody>
</table>

- For m_{φ} = 1 TeV, a decay-length range of 0.05 m → 16 m is excluded (assuming 1 pb Xsec and 100% BR)

<table>
<thead>
<tr>
<th>Experiment</th>
<th>8 TeV CT (m)</th>
<th>13 TeV CT (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS</td>
<td>0.14 ≤ ct ≤ 8.32</td>
<td>0.05 ≤ ct ≤ 16</td>
</tr>
<tr>
<td>CMS</td>
<td>0.01 ≤ ct ≤ 3.5</td>
<td>–</td>
</tr>
</tbody>
</table>

arXiv:1501.04020

Phys. Rev. D 91 (2015) 012007
arXiv:1411.6530
Displaced Lepton-Jets (LJs) – 1/4

Scenario

- Light hidden photon $\gamma_d$ mixed kinetically with SM photon
- Expected small mass and hence produced boosted and long-lived
- The $\gamma_d$ lifetime depends on the kinetic mixing parameter
- At its lightest state the $\gamma_d$ will decay to SM particles, mainly leptons & mesons

Two FRVZ models used as benchmarks:

In both the hidden sector is communicating with the SM sector through the Higgs portal:

The Higgs boson decays to a pair of hidden fermions $f_{d2}$

the dark fermion $f_{d2}$ decays to a $\gamma_d$ and a Hidden-Lightest-Stable-Particle $f_{d1}$ (HLSP)

the dark fermion $f_{d2}$ decays to a dark scalar $s_{d1}$ and an HLSP
then the $s_{d1}$ decays to pairs of dark photons

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Displaced Lepton-Jets (LJs) – 2/4

Detector Signature

- The $\gamma_D$s are expected to decay two LJs, produced back-to-back in the azimuthal plane
- LJs are defined and classified according to the muon/jet content found within a cone of opening: $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$

Muons only – at least two muons, no jets

Muons + jet – at least two muons and only one jet

Jets only – no muons, jets only
Displaced Lepton-Jets (LJs) – 3/4

Analysis Strategy

• Searching for long-lived neutral particles decaying into collimated jets of light-leptons and mesons
• MC simulations:
  • 2 or 4 $\gamma_d$
  • $m_{\gamma_d} = 0.4$ GeV
  • $m_H = 125,800$ GeV
• Trigger selection – ‘OR’ combinations:
  • Narrow-scan — scan for $\mu$ object in a narrow cone
  • Tri-muon MS only — events with at least 3- $\mu$s with no ID info
  • CalRatio — isolated jets with low energy deposition in the EMcal
• Offline selection:
  - Two LJ objects passed the Bkg. Rejection
  - 1D-track isolation + $\Delta$φ between the two LJs
• Background estimation using a data-driven ABCD method:
  - $\max \Sigma p_T \leq 4.5$ GeV
  - $|\Delta \phi|_{LJ} \geq 0.628$ rad

<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>$\gamma_d$ limits</td>
<td>an impact parameter $</td>
</tr>
<tr>
<td>Type 1/2</td>
<td>jet timing $\Delta t_{calo}$</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 false 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>
Displaced Lepton-Jets (LJs) – 4/4

Results

- Consistency between the observed data (285) and expected background (231±12(stat)±62(syst))
- Upper-limits were set on (non-)SM Higgs decays to LJs:

For SM ggf $H$ production Xsec with $m_{Y_d} = 0.4$ GeV

The BR was found to be lower than 10% for $H$ with $m_H = 125$ GeV decaying to $Y_d$

- $H \rightarrow 2Y_d + X$ for $Y_d$ with $2.2 \text{ mm} \leq c\tau \leq 111.3 \text{ mm}$
- $H \rightarrow 4Y_d + X$ for $Y_d$ with $3.8 \text{ mm} \leq c\tau \leq 163 \text{ mm}$

For production XSec $\sigma \times \text{BR}$ of 5.0pb with $m_H = 800$ GeV decaying to $Y_d$:

- $H \rightarrow 2Y_d + X$ for $Y_d$ with $0.6 \text{ mm} \leq c\tau \leq 63 \text{ mm}$
- $H \rightarrow 4Y_d + X$ for $Y_d$ with $0.8 \text{ mm} \leq c\tau \leq 186 \text{ mm}$

<table>
<thead>
<tr>
<th>$m_H$ (GeV)</th>
<th>8 TeV</th>
<th>13 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>125</td>
<td>$14 \leq c\tau \leq 140$</td>
<td>$2.2 \leq c\tau \leq 163$</td>
</tr>
<tr>
<td>800</td>
<td>-</td>
<td>$0.6 \leq c\tau \leq 63$</td>
</tr>
</tbody>
</table>
Summary
Summary

- Many BSM models predict unconventional detector signatures
  - Custom analysis techniques are designed & used to achieve sensitivity to these final-states

- ATLAS Exotic meta-stable search results presented were based on 13 TeV data
  - No evidence for the existence of new physics was found
    - Higher limits were set at 95% CL on the new particles decay-length

- Other unconventional signature searches are ongoing
  - For some, results will be published already this summer

- LLP triggers are being updated/designed for phase-1/2 upgrade to address more scenarios (displaced 1D vertices, MS-Only objects, slow-particles…)
  - Improved technology that allows running more sophisticated algorithms

“…sometimes the most ordinary things could be made extraordinary, simply by doing them with the right people...”

-N. Sparks
Backup
Displaced Lepton-Jets (LJs)

- **MC simulations:**

<table>
<thead>
<tr>
<th>Benchmark model</th>
<th>$m_H$ [GeV]</th>
<th>$m_{q_2}$ [GeV]</th>
<th>$m_{H_{LSP}}$ [GeV]</th>
<th>$m_{q_1}$ [GeV]</th>
<th>$m_{\gamma_d}$ [GeV]</th>
<th>$c\tau_{\gamma_d}$ [mm]</th>
<th>Branching Ratio $\gamma_d \rightarrow e e$</th>
<th>Branching Ratio $\gamma_d \rightarrow \mu \mu$</th>
<th>Branching Ratio $\gamma_d \rightarrow \pi \pi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2 \gamma_d$</td>
<td>125</td>
<td>5.0</td>
<td>2.0</td>
<td>-</td>
<td>0.4</td>
<td>47.0</td>
<td>45%</td>
<td>45%</td>
<td>10%</td>
</tr>
<tr>
<td>$4 \gamma_d$</td>
<td>125</td>
<td>5.0</td>
<td>2.0</td>
<td>2.0</td>
<td>0.4</td>
<td>82.40</td>
<td>45%</td>
<td>45%</td>
<td>10%</td>
</tr>
<tr>
<td>$2 \gamma_d$</td>
<td>800</td>
<td>5.0</td>
<td>2.0</td>
<td>-</td>
<td>0.4</td>
<td>11.76</td>
<td>45%</td>
<td>45%</td>
<td>10%</td>
</tr>
<tr>
<td>$4 \gamma_d$</td>
<td>800</td>
<td>5.0</td>
<td>2.0</td>
<td>2.0</td>
<td>0.4</td>
<td>21.04</td>
<td>45%</td>
<td>45%</td>
<td>10%</td>
</tr>
</tbody>
</table>

- **Results of the ABCD Bkg. Est.:**

<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>

- **Expected number of LJ-pairs after full set of selection criteria:**

<table>
<thead>
<tr>
<th>Category</th>
<th>$m_H = 125$ GeV Higgs $\rightarrow 2\gamma_d + X$</th>
<th>$m_H = 125$ GeV Higgs $\rightarrow 4\gamma_d + X$</th>
<th>$m_H = 800$ GeV Higgs $\rightarrow 2\gamma_d + X$</th>
<th>$m_H = 800$ GeV Higgs $\rightarrow 4\gamma_d + X$</th>
</tr>
</thead>
<tbody>
<tr>
<td>All events</td>
<td>$113 \pm 2$</td>
<td>$96 \pm 2$</td>
<td>$53.0 \pm 0.6$</td>
<td>$112 \pm 1$</td>
</tr>
<tr>
<td>Type2–Type2 excluded</td>
<td>$111 \pm 2$</td>
<td>$96 \pm 2$</td>
<td>$43.0 \pm 0.5$</td>
<td>$109 \pm 1$</td>
</tr>
<tr>
<td>Type2–Type2</td>
<td>$2.0 \pm 0.5$</td>
<td>$0.34 \pm 0.10$</td>
<td>$10.0 \pm 0.3$</td>
<td>$3.2 \pm 0.2$</td>
</tr>
</tbody>
</table>

- **Ranges of $\gamma_d$ lifetime ($c\tau$) excluded at 95% CL:**

<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>

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Displaced Jets in the Calorimeter

- MC simulations:

<table>
<thead>
<tr>
<th>mφ [GeV]</th>
<th>mω [GeV]</th>
<th>LF=5 m</th>
<th>LF=9 m</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>cr [m]</td>
<td>Events</td>
<td>cr [m]</td>
</tr>
<tr>
<td>400</td>
<td>50</td>
<td>0.700</td>
<td>400k</td>
</tr>
<tr>
<td>100</td>
<td>1.46</td>
<td>400k</td>
<td>2.64</td>
</tr>
<tr>
<td>600</td>
<td>50</td>
<td>0.520</td>
<td>400k</td>
</tr>
<tr>
<td>150</td>
<td>1.72</td>
<td>400k</td>
<td>3.14</td>
</tr>
<tr>
<td>1000</td>
<td>50</td>
<td>0.380</td>
<td>400k</td>
</tr>
<tr>
<td>150</td>
<td>1.17</td>
<td>400k</td>
<td>2.11</td>
</tr>
<tr>
<td>400</td>
<td>3.96</td>
<td>400k</td>
<td>7.20</td>
</tr>
</tbody>
</table>

- Offline selection:

- Estimated number of events in the Signal-Region using the ABCD method:

<table>
<thead>
<tr>
<th>Region</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>Estimated A = BC/D</th>
</tr>
</thead>
<tbody>
<tr>
<td>SR: pt,1 &gt; 150 GeV; pt,2 &gt; 120 GeV:</td>
<td>24</td>
<td>16</td>
<td>39</td>
<td>34</td>
<td>18.0 ± 6.3</td>
</tr>
<tr>
<td>VR: pt,1 &gt; 140 GeV; 80 GeV &lt; pt,2 &lt; 120 GeV:</td>
<td>15</td>
<td>14</td>
<td>84</td>
<td>77</td>
<td>15.3 ± 4.7</td>
</tr>
<tr>
<td></td>
<td>42</td>
<td>38</td>
<td>57</td>
<td>53</td>
<td>40 ± 10</td>
</tr>
<tr>
<td></td>
<td>72</td>
<td>64</td>
<td>27</td>
<td>27</td>
<td>60 ± 19</td>
</tr>
</tbody>
</table>