Searches for long-lived particles in ATLAS

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Masahiko Saito (ICEPP, University of Tokyo)
on behalf of the ATLAS Collaboration
Why is it important to search for long-lived particles?

- We have not found BSM yet
- ATLAS searches are designed primarily to find prompt BSM particles
  - We could miss an important phase space
- **Long-lived particles** appear in many BSM models if
  - Small coupling with SM
  - Heavy intermediator
  - Small mass difference
  - ...
- Long-lived particles leave **characteristic signatures** in the detector
  - Special trigger, object reconstruction, identification, background estimation

\[
\tau^{-1} = \Gamma \propto g^4 \cdot \frac{m_\mu^5}{m_W^4} \cdot I \left( \frac{m_e^2}{m_\mu^2} \right) \lim_{x \to 1} I(x) = 0
\]
Recent (~1 year) results of long-lived searches in ATLAS

A, C: Displaced vertex
- Displaced vertex + displaced muon
- Displaced Inner Detector + Muon Spectrometer

B: Displaced leptons
- Search for displaced lepton-jets
- Displaced lepton pairs
- Prompt and Displaced Heavy Neutral Lepton
  - JHEP 10 (2019) 265

D: Displaced jets in the calorimeter
- Displaced hadronic jets in the calorimeter
- CalRatio jet reinterpretation
  - ATL-PHYS-PUB-2020-007

E: Metastable charged particles
- Monopole, stable high-electric-charge objects
- Pixel dE/dx Calorimeter and muon timing

This talk

From Heather Russell
Displaced lepton-jets

2015-2016 data, 36.1 fb$^{-1}$

Accepted by EPJC, arXiv: 1909.01246

**Vector portal model** FRVZ model as a benchmark

- Dark photon couples with the SM. Small mixing results in a long-lived dark photon
- Assuming dark photon mass of 400 MeV, resulting in collimated fermions: Dark Photon jet (DPJ)

**Dark Photon Jet Reconstruction**

- Muonic DPJ ($\mu$DPJ) ($\gamma_d \rightarrow \mu\mu$)
  - Collimated muon tracks (>=2) in Muon Spectrometer
  - No Inner Detector tracks and jets around DPJ
- Hadronic DPJ ($had$DPJ) ($\gamma_d \rightarrow ee, \pi\pi$)
  - Jets with large $E_{had}/E_{em}$ ratio (CalRatio)
  - No Inner Detector tracks and muons around DPJ
- Background rejection using BDT
  - cosmic muon ($\mu$DPJ), multi-jets ($had$DPJ)
Displaced lepton-jets

Trigger
- Three Muon Spectrometer tracks (pT > 6 GeV)
- Muon narrow scan trigger:
  - Single muon at L1 (pT > 20 GeV)
  - At HLT, search a 2nd muon (pT > 6-15 GeV) in a cone of ΔR = 0.5 around L1 candidate
- CalRatio jet trigger:
  - Single jets (pT > 60 GeV) with large $E_{\text{had}}/E_{\text{em}}$
  - No Inner Detector tracks within ΔR < 0.2
Displaced lepton-jets

Background estimation

- ABCD method:
  - Track isolation (sum of track pT around DPJ) (signals are isolated) (A, D)
  - Opening angle ($\Delta\phi$) between the 2 DPJs (signals are back-to-back) (A, B)

<table>
<thead>
<tr>
<th>DPJ pair type</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>Expected A</th>
<th>A</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu$DPJ–$\mu$DPJ</td>
<td>24</td>
<td>92</td>
<td>463</td>
<td>$128 \pm 26$ (stat.) $\pm 3$ (syst.)</td>
<td>113</td>
</tr>
<tr>
<td>$\mu$DPJ–hDPJ</td>
<td>8</td>
<td>2</td>
<td>45</td>
<td>$177 \pm 86$ (stat.) $\pm 4$ (syst.)</td>
<td>179</td>
</tr>
<tr>
<td>hDPJ–hDPJ</td>
<td>13</td>
<td>2</td>
<td>15</td>
<td>$97 \pm 48$ (stat.) $\pm 2$ (syst.)</td>
<td>69</td>
</tr>
</tbody>
</table>

No excess

Result

Data

Signal

ATLAS
$\sqrt{s}=13$ TeV 36.1 fb$^{-1}$

$\mu$DPJ–$\mu$DPJ

$H \rightarrow 2\gamma + X$, $m_{\gamma} = 125$ GeV

$\mu$DPJ–$\mu$DPJ

ATLAS Simulation
$\sqrt{s}=13$ TeV 36.1 fb$^{-1}$

$H \rightarrow 2\gamma + X$, $m_{\gamma} = 125$ GeV

$\mu$DPJ–$\mu$DPJ
Displaced lepton-jets

Interpretation

• Set upper limits on $\sigma \times Br$ as a function of the dark photon decay length
  • For $H \rightarrow 2\gamma_d + X$, $\sigma \times Br > 4$ pb, $1.5$ mm $< c\tau < 307$ mm
• Exclusion limits on dark photon mass vs kinetic mixing parameter ($\epsilon$)
  • Excluded lower $\epsilon$ region (longer lifetime) seamlessly not covered in the previous prompt/displaced lepton-jet analysis in Run-1

\[ \mu_{\text{DPJ}} \rightarrow \mu_{\text{DPJ}} \text{ channel} \]

\[ m_H = 125 \text{ GeV} \]
\[ m_{\gamma_d} = 400 \text{ MeV} \]

\[ B(H \rightarrow 2\gamma_d + X) = 10\% \]

\[ \text{ATLAS} \]

36.1 fb$^{-1}$ $\sqrt{s} = 13$ TeV

\[ \text{FRVZ Model} \]
90% CL exclusions
$L = 36.1$ fb$^{-1}$
$m_H = 125$ GeV
$H \rightarrow 2\gamma_d + X$
Displaced jets in the ID & MS

Hidden Sector model (HS)

- Neutral scalar (s) decays into a SM fermion pair through their mixing. Small mixing results in long-lived.

Target objects

- Displaced vertex in Inner Detector
  - Reconstructed from tracks with a large impact parameter.

Large Radius Tracking (LRT)
- ATL-PHYS-PUB-2017-014, Displaced Vertex reconstruction

- Displaced vertex in Muon spectrometer
  - Reconstructed using >=3 MS tracklets

Trigger: Muon RoI Cluster trigger:

Two muons at L1 (pT > 10 GeV). At HLT, require 3-4 muons within ΔR =0.4
Displaced jets in the ID & MS

Displaced jets selection

• Muon spectrometer Vertex (MSVx)
  • Isolated from jets and ID tracks (punch-through jets)
  • minimum $n_{MDT}$, $n_{RPC}$ and $n_{TGC}$ (cosmic muon, electric noise)
  • maximum $n_{MDT}$ (noise burst)

• Inner Detector Vertex (IDVx)
  • Material veto (SM hadronic interactions)
  • Vertex fit quality (random crossing)
  • DV $d_0 > 4$ mm (b-hadron)
  • N of associated tracks ($n_{trk}$) $\geq 4$
  • Vertex mass ($m_{vtx}$) $\geq 3$ GeV

• Angular separation of $\Delta R$ (MSVx, IDVx) $> 0.4$
Displaced jets in the ID & MS

Background estimation
- Data-driven background estimation

<table>
<thead>
<tr>
<th>IDVx requirement</th>
<th>MSVx requirement</th>
<th>Background events</th>
<th>Muon RoI Cluster trigger events with a good MSVx</th>
</tr>
</thead>
<tbody>
<tr>
<td>Has IDVx passing full signal selection</td>
<td>Bkg+IDVx</td>
<td>Bkg</td>
<td>Sig</td>
</tr>
<tr>
<td>Agnostic to IDVx</td>
<td>Bkg</td>
<td></td>
<td>Sig–IDVx</td>
</tr>
</tbody>
</table>

\[
N_{\text{bkg pred}}^{\text{Sig}} = N_{\text{Sig}–\text{IDVx}} \times \frac{N_{\text{Bkg+IDVx}}}{N_{\text{Bkg}}} 
\]

The prob. that background events contain good IDVx
\[
= (7.4 \pm 1.1 \text{ (stat.)}) \times 10^{-6}
\]

Result

<table>
<thead>
<tr>
<th>Region</th>
<th>(n_{\text{obs}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bkg</td>
<td>6,099,660</td>
</tr>
<tr>
<td>Bkg+IDVx</td>
<td>45</td>
</tr>
<tr>
<td>Sig–IDVx</td>
<td>156,805</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Region</th>
<th>(n_{\text{pred}})</th>
<th>(n_{\text{obs}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Val, 2-trk</td>
<td>11,269 ± 46 (stat.)</td>
<td>11,470</td>
</tr>
<tr>
<td>Trig, 3-trk</td>
<td>1750 ± 64 (stat.)</td>
<td>2132</td>
</tr>
<tr>
<td>Sig</td>
<td>1.16 ± 0.18 (stat.) ± 0.29 (syst.)</td>
<td>1</td>
</tr>
</tbody>
</table>

No excess
Inner Tracker Displaced Vertex

IDVx
R = 29.1 mm
z = 143 mm
η = 2.3
nTrk = 4
M = 3.34 GeV

Muon Spectrometer Displaced Vertex

MSVx
R = 4.97 m
z = 12.5 m
η = 1.65
Interpretation

- Limits on HS models using a scalar mediator with mass from 125 to 1000 GeV, decaying into pairs of long-lived scalars (s) with mass from 8 GeV to 400 GeV. Extending exclusion limits in $5 \text{ cm} < \tau < 1 \text{ m}$
- Greater sensitivity for low-mass, long-lived scalars at shorter lifetimes than the previously published searches.

Complementary to the previous analysis:
- MS-only analysis (1710.04901)
- Hadronic calorimeter analysis (1902.03094)
Reinterpretation of Displaced hadronic jets in the calorimeter


- Targeted Hidden Sector model
- Long-lived scalars decay in the hadronic calorimeter
- Key object is a jet with large $E_{\text{had}}/E_{\text{em}}$ ratio (CalRatio jets)

<table>
<thead>
<tr>
<th>Region</th>
<th>Estimation</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-$E_T$</td>
<td>$5.3^{+2.1}_{-1.6}$</td>
<td>7</td>
</tr>
<tr>
<td>High-$E_T$</td>
<td>$8.5^{+2.3}_{-2.0}$</td>
<td>10</td>
</tr>
</tbody>
</table>

Reinterpretation

- Various BSM models predict long-lived particles, which can be constrained by the previously published analysis
- Difficult to reproduce a physics result exactly due to the unconventional techniques (trigger/reconstruction/machine learning).

RECAST framework

Other RECAST reinterpretation: ATL-PHYS-PUB-2019-032
Reinterpretation of Displaced hadronic jets in the calorimeter

Reinterpreted signal models & Exclusion limits

A. Stealth SUSY

ATLAS Preliminary $\sqrt{s} = 13$ TeV

- RECAST result, high-$E_T$ selection [33.0 fb$^{-1}$]
- Exp. ± 1σ, 2σ
- MS displaced jets result (2x) [36.1 fb$^{-1}$] — Obs.

95% CL Upper Limit on $\sigma \times B$ [pb]

Singlino proper decay length ($c\tau$) [m]

$m_\chi = 250$ GeV, $c\tau_{gen} = 0.96$ m

B. Higgs Portal baryogenesis

ATLAS Preliminary $\sqrt{s} = 13$ TeV

- RECAST result, high-$E_T$ selection [33.0 fb$^{-1}$]
- Exp. ± 1σ, 2σ
- MS displaced jets result (Comb) [36.1 fb$^{-1}$] — Obs.

95% CL Upper Limit on $\sigma \times B$ [pb]

χ proper decay length ($c\tau$) [m]

$\chi \to \nu b$  \hspace{1cm}  $m_\chi = 125,10$ GeV, $c\tau_{gen} = 0.92$ m

C. Dark photon

ATLAS Preliminary $\sqrt{s} = 13$ TeV

- RECAST result, high-$E_T$ selection [33.0 fb$^{-1}$]
- Exp. ± 1σ, 2σ
- Displaced lepton-jets result [36 fb$^{-1}$] — Obs.

95% CL Upper Limit on $\sigma \times B$ [pb]

$\gamma'_d$ proper decay length ($c\tau$) [m]

$H \to 2\gamma' + X$  \hspace{1cm}  $m_{\nu}, m_{\gamma'} = [800,0.4]$ GeV, $c\tau_{gen} = 0.01176$ m
Summary

- Long-lived particles appear in various BSM models
- Characteristic / challenging signature
- No deviation from the SM yet
- but we continue to develop new techniques to extend the uncovered discovery reach
- We show a part of Run-2 full data. New results with Run-2 full data are being analysed carefully. Stay tuned!