Searches for BSM Physics using Challenging and Long-Lived Signatures with the ATLAS Detector

Giuliano Gustavino
on behalf of the ATLAS collaboration

12 January 2022
The ‘new’ dimension

LHC experiments have extensively searched for New Physics in the prompt regime or ‘invisible’ final states.

- detectors ideal to look for prompt signatures
  - higgs boson discovery

More and more BSM theories motivates displaced signatures

- (nearly) mass-degenerate spectra
- small couplings
- highly virtual intermediate states

White Paper
to define benchmark signals

_White Paper_ to define benchmark signals

_J. Phys. G 47 (2020) no.9, 090501_
A vast LLP search program

H. Russell
A vast LLP search program

Here just focusing on some of the most RECENT results!
LLPs - in the tracker

Search of DVs in ZH channel:

- take advantage of associated production!
  - use promptly produced leptons to trigger

1. select events with displaced jet candidates:
   - low charged hadron fraction
   - few tracks matched to primary vertex

2. use Large Radius Tracking (LRT) algorithm:
   - to select high $d_0$ tracks

3. reconstruct 2 displaced vertices in the ID:
   - matched to jets

Key selection variables:

- $n_{\text{trk}}$ per vertex
- $m/\Delta R_{\text{max}}$ reduced mass
  - ratio of reco vertex invariant mass and $\Delta R_{\text{max}}$(track, DV)
Data-driven bkg estimate

- per-jet probability of DVs in CR
  - in $p_T$ vs b-tag discriminant plane
- $B = 1.30 \pm 0.08 \pm 0.27$

**No events observed** in the signal region

Set limits of $B(H \rightarrow aa) < 10\%$ for $10 \leq c\tau_a \leq 100 \text{ mm}$

closing the gap between prompt and LLP searches in ATLAS
LLPs - in the spectrometer

Searching for narrow, high multiplicity hadron showers in muon detector

- no matched tracks in the ID

* Dedicated **Trigger**
  - selecting events with a **cluster of at least 3 (4) “region of interest”** in the barrel (endcaps) in a $\Delta R$ cone of 0.4 around L1_2MU10
  - JINST 8 (2013) P07015

* Dedicated **vertex algorithm**
  - reco vertices with at least 3 (4) **tracklets** in the barrel (endcaps)
    - exploiting multilayer separation in MDT chambers
  - JINST 9 (2014) P02001
LLPs - in the spectrometer (2)

- Primary bkgs come from
  - punch-through jets
  - beam induced bkg (BIB)

- Data-driven bkg estimation
  - based on main and zero bias streams

\[ N_{2Vx} = 0.32 \pm 0.05 \]

No events observed in SR

- Limits set to less than 0.1% BR level in the SM higgs scenario
Search for light LLPs decaying into collimated jet structures of leptons or light hadrons

Collimated bunch of muons w/o tracks in the ID
- Low-$p_T$ muons hard to trigger
- Cosmic-ray muons bkg

Displaced jet with most of energy deposit in the HCAL
- High bkg from QCD events

small couplings $\rightarrow$ displaced decays

More details on Alessandro’s poster
**LLPs - lepton-jets (2)**

Two production modes

- **ggH**
  - dedicated NarrowScan (μ) and CaloRatio (had) triggers
  - QCD, cosmics, BIB

- **WH**
  - single lepton triggers
  - V+jets bkg

**6 channels defined:**
- μ-μ (ggH), μ-calo (ggH & WH), 1-calo (WH), calo-calo (ggH & WH)

**NN taggers**

- Dense **NN**-based (per track) tagger in **μ-channels** to reject cosmics (90%)

- Convolutional **NN**-based taggers in **calo-channels** to reject QCD (94%) and BIB (68%)
  - trained on low-level inputs
    - (3D jet images from calorimetric clusters)
The data-driven ABCD method is used to estimate the residual background in the signal regions. No data excess is found.

- **ggF**
  - $2\mu$: CRB = 55, CRC = 61, CRD = 389, SR expected = 357 ± 67, SR observed = 269
  - $c+\mu$: CRB = 169, CRC = 471, CRD = 301, SR expected = 108 ± 12, SR observed = 110
  - $2c$: CRB = 97, CRC = 1113, CRD = 12146, SR expected = 1065 ± 112, SR observed = 1045

- **WH**
  - $c$: CRB = 1850, CRC = 3011, CRD = 155, SR expected = 95 ± 13, SR observed = 103
  - $c+\mu$: CRB = 30, CRC = 49, CRD = 31, SR expected = 19 ± 7, SR observed = 20
  - $2c$: CRB = 79, CRC = 155, CRD = 27, SR expected = 14 ± 5, SR observed = 15

**μ-exclusion of B(h→f_d f_d)**

The exclusion of $B(h\rightarrow f_d f_d)$ is achieved down to 0.1% ($\sim B(h\rightarrow 4\nu)$).

**First time exclusion in the fully electron channel**
**LLPs - everywhere**

**Resonant searches**

Prompt resonances can be reinterpreted. b-tagging algorithms can be performant for sizeable lifetimes!

**LLP searches**

Unique signatures helps to strongly reduce bkg: → bkg-zero channel

**MET+X searches**

Displaced jet can contribute with further fake-MET!

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G. Gustavino
LLPs - everywhere (2)

$\sqrt{s} = 13$ TeV, 139 fb$^{-1}$

$H \rightarrow ss$

$m_H = 125$ GeV

**Monojet**

- $m_s = 5$ GeV
- $m_s = 35$ GeV
- $m_s = 55$ GeV

**ATLAS-CONF-2021-005**

- $m_s = 16$ GeV
- $m_s = 35$ GeV
- $m_s = 55$ GeV

**JHEP 10 (2018) 031**

- $m_s = 20$ GeV
- $m_s = 30$ GeV
- $m_s = 60$ GeV

**EPJC 79 (2019) 481**

- $m_s = 5$ GeV
- $m_s = 15$ GeV
- $m_s = 40$ GeV

**arXiv:2102.10874**

- $H \rightarrow \text{inv (Monojet)}$
- $H \rightarrow \text{inv (Combination)}$

**ATLAS-CONF-2020-052**
LLPs - everywhere (2)

95% CL upper limit on $B(H \rightarrow ss)$

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$m_H = 125$ GeV

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**EPJC 79 (2019) 431**
- $H \rightarrow \text{inv (Monojet)}$

**arXiv:2102.10874**
- $H \rightarrow \text{inv (Combination)}$

**ATL-PHYS-PUB-2021-020**
LLPs - future

LRT is an additional ID tracking algorithm that is run after standard tracking

- Run on leftover hits with relaxed tracking cuts

New implementation optimised for fake reduction

- Factor x20 reduction in fakes
- Run together w/ standard ATLAS reco chain
  - No filters needed anymore!

DV algorithm hugely benefits from LRT overhaul!

- Dramatic reduction of fake vertices
  - Particularly outside of pixel detector

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see also Julian's talk
LLPs - future future

**ITK**

Higher reco efficiency:
- improved geometry
- larger silicon volume
- lower material budget

- more hits-on-track with higher resolution
- minimum number of hits after decay
- tracker-based triggers can further boost sensitivity
Conclusions

Vast search program in ATLAS focused on

- extending the reaches and fill the gaps!
  - reinterpretations
  - new developments (e.g. LRT)
  - new technologies
  - new triggers for Run-3 and beyond
  - creativity

Many LLP searches are statistically limited!
- Background-zero searches sensitivity $\propto \mathcal{L}$
- Gain by exploiting new detector technologies

Run-3 is fast approaching…the best still needs to come!
BACK UP
LLPs - in the tracker

\[ P_1 = \sum_{i=1}^{4} P_DV(j_i) \times \prod_{k \neq i} (1 - P_DV(j_k)) \]

\[ P_{\geq 2} = 1 - P_0 - P_1 \]

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<table>
<thead>
<tr>
<th>Selection type</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Track pruning</td>
<td>[</td>
</tr>
<tr>
<td>Vertex preselection</td>
<td>[ \chi^2/n_{\text{DoF}} &lt; 5 ] [ r &lt; 300 \text{ mm} ] [</td>
</tr>
<tr>
<td>Vertex selection</td>
<td>[ n_{\text{trk}} &gt; 2 ] [ m/\Delta R_{\text{max}} &gt; 3 \text{ GeV} ] [ r/\sigma(r) &gt; 100 ] [ \max(</td>
</tr>
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<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty [%]</th>
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<tr>
<td>Theory</td>
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<tr>
<td>Luminosity</td>
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<tr>
<td>Pile-up reweighting</td>
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<tr>
<td>Electron identification</td>
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<tr>
<td>Electron calibration</td>
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<tr>
<td>Muon reconstruction</td>
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<tr>
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<td>LRT</td>
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<tr>
<td>Total</td>
<td>7.4–14</td>
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</table>
LLPs - in the tracker

![Graphs showing LLPs in the tracker]

- ATLAS
  - $\ell s = 13$ TeV, 139 fb$^{-1}$
  - Data vs Bkg. prediction

- Efficiencies versus mean proper lifetime $c\tau_a$ [m]
  - $m_a = 55$ GeV
  - $m_a = 45$ GeV
  - $m_a = 35$ GeV
  - $m_a = 25$ GeV
  - $m_a = 16$ GeV

- 95% CL upper limits on $\ell H \rightarrow aa \rightarrow b\bar{b}b\bar{b}$

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LLPs - in the spectrometer

Event passes Muon RoI Cluster trigger
Event has a PV with at least two tracks with $p_T > 500$ MeV
Event has at least one MS DV

MS DV matched to the triggering muon-RoI cluster ($\Delta R(DV, RoI \text{ cluster}) < 0.4$).
In the case of two muon-RoI clusters, the second vertex should be
matched to the second cluster.

$300 \leq n_{MDT} < 3000$

<table>
<thead>
<tr>
<th>Barrel</th>
<th>Endcaps</th>
</tr>
</thead>
<tbody>
<tr>
<td>MS DV with $</td>
<td>\eta_{vx}</td>
</tr>
<tr>
<td>MS DV with $3 \text{ m} &lt; L_{xy} &lt; 8 \text{ m}$</td>
<td>MS DV with $L_{xy} &lt; 10 \text{ m}$ and $5 \text{ m} &lt;</td>
</tr>
<tr>
<td>$n_{RPC} \geq 250$</td>
<td>$n_{TGC} \geq 250$</td>
</tr>
</tbody>
</table>

$$N_{2Vx} = N_{1cl}^{1cl} \times P_{noMStrip}^{2cl} + N_{UMBcl}^{2cl} \times P_{Bcl}^{Vx} + N_{UMEcl}^{2cl} \times P_{Ecl}^{Vx} = 0.32 \pm 0.05$$

# non-signal events with 1 cluster in fiducial region and 2 vertices
# non-signal events with 2 clusters in fiducial region and 2 vertices
LLPs - in the spectrometer
# LLPs - lepton-jets

## ggH

<table>
<thead>
<tr>
<th>Requirement / Region</th>
<th>$\text{SR}_{2\mu}^{ggF}$</th>
<th>$\text{SR}_{2c}^{ggF}$</th>
<th>$\text{SR}_{c+\mu}^{ggF}$</th>
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</thead>
<tbody>
<tr>
<td>Number of $\mu$DPJs</td>
<td>2</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Number of caloDPJs</td>
<td>0</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Tri-muon MS-only trigger</td>
<td>yes</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Muon narrow-scan trigger</td>
<td>yes</td>
<td>-</td>
<td>yes</td>
</tr>
<tr>
<td>CalRatio trigger</td>
<td>-</td>
<td>yes</td>
<td>-</td>
</tr>
<tr>
<td>$</td>
<td>\Delta t_{\text{caloDPJs}}</td>
<td>$ [ns]</td>
<td>-</td>
</tr>
<tr>
<td>caloDPJ JVT</td>
<td>-</td>
<td>$&lt; 0.4$</td>
<td>-</td>
</tr>
<tr>
<td>$\Delta \phi_{\text{DPI}}$</td>
<td>$&gt; \pi/5$</td>
<td>$&gt; \pi/5$</td>
<td>$&gt; \pi/5$</td>
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<tr>
<td>BIB tagger score</td>
<td>-</td>
<td>$&gt; 0.2$</td>
<td>$&gt; 0.2$</td>
</tr>
<tr>
<td>$\text{max}(\sum p_T)$ [GeV]</td>
<td>$&lt; 4.5$</td>
<td>$&lt; 4.5$</td>
<td>$&lt; 4.5$</td>
</tr>
<tr>
<td>$\text{</td>
<td></td>
<td>QCD tagger}$</td>
<td>-</td>
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</table>

## WH

<table>
<thead>
<tr>
<th>Requirement / Region</th>
<th>$\text{SR}_{c}^{WH}$</th>
<th>$\text{SR}_{2c}^{WH}$</th>
<th>$\text{SR}_{c+\mu}^{WH}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of $\mu$DPJs</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Number of caloDPJs</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Single lepton trigger ($\mu,e$)</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>$m_T$ [GeV]</td>
<td>$&gt; 120$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$</td>
<td>t_{\text{caloDPJ}}</td>
<td>$ [ns]</td>
<td>$&lt; 4$</td>
</tr>
<tr>
<td>leading (far) caloDPJ width</td>
<td>$&lt; 0.08$</td>
<td>$&lt; 0.10$</td>
<td>(0.15)</td>
</tr>
<tr>
<td>caloDPJ $p_T$ [GeV]</td>
<td>$&gt; 30$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>JVT</td>
<td>$&lt; 0.6$</td>
<td>$&lt; 0.6$</td>
<td>$&lt; 0.6$</td>
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<tr>
<td>$\text{min}(\Delta \phi)$</td>
<td>$&lt; 3\pi/5$</td>
<td>$&lt; 3\pi/10$</td>
<td>$&lt; 7\pi/20$</td>
</tr>
<tr>
<td>$\text{min}(\text{QCD tagger})$</td>
<td>$&gt; 0.99$</td>
<td>$&gt; 0.91$</td>
<td>$&gt; 0.9$</td>
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</table>
Figure 6: The per-event distributions in the ABCD planes defined for the ggF search channels. Figures (a, b, c) show data, while Figures (d, e, f) show simulated signal events. FRVZ signal samples with a SM Higgs boson and a $\gamma_d$ mass of 400 MeV are shown.
Figure 7: The per-event $\min(\Delta\phi)$ vs. $\min(\text{QCD tagger})$ distributions for the WH search channels. Figures (a, b, c) show data, while Figures (d, e, f) show simulated signal events. FRVZ signal samples with a SM Higgs boson and a $\gamma_d$ mass of 100 MeV are shown for the $\text{SR}^{\text{WH}}_c$ and $\text{SR}^{\text{WH}}_{2c}$ search regions, while a $\gamma_d$ mass of 400 MeV is shown for $\text{SR}^{\text{WH}}_{c+\mu}$. 
LLPs - lepton-jets

ATLAS Simulation Preliminary

\( \gamma_d \rightarrow \mu^+\mu^- \); \(|\Delta| < 1 \)

- FRVZ \((m_{\gamma_d}, m_{\mu}) = \langle 125, 0.4 \rangle \text{ GeV} \); \(c_{\gamma_d} = 50 \text{ mm} \)
- FRVZ \((m_{\gamma_d}, m_{\mu}) = \langle 800, 0.4 \rangle \text{ GeV} \); \(c_{\gamma_d} = 10 \text{ mm} \)
- HAHM \((m_{\gamma_d}, m_{\mu}) = \langle 125, 0.4 \rangle \text{ GeV} \); \(c_{\gamma_d} = 25 \text{ mm} \)

ATLAS Simulation Preliminary

\( \gamma_d \rightarrow e^+e^- \); \(|\Delta| < 1.1 \)

- FRVZ \((m_{\gamma_d}, m_{e}) = \langle 125, 0.4 \rangle \text{ GeV} \); \(c_{\gamma_d} = 50 \text{ mm} \)
- FRVZ \((m_{\gamma_d}, m_{e}) = \langle 800, 0.4 \rangle \text{ GeV} \); \(c_{\gamma_d} = 10 \text{ mm} \)
- HAHM \((m_{\gamma_d}, m_{e}) = \langle 125, 0.4 \rangle \text{ GeV} \); \(c_{\gamma_d} = 25 \text{ mm} \)

ATLAS Preliminary

Relative Uncertainty

- Total uncertainty
- Muon uncertainties
- Normalisation uncertainties
- NN taggers
- Triggers
- Jet uncertainties

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