Searches for Exotic Phenomena in ATLAS

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Interpreting the LHC Run 2 Data and Beyond

ICTP Trieste
28.05.2019
Open Questions

- DM?
- $m_H << \Lambda_P$?
- $m_e << m_t$?
- baryon asym.?
- gravitation?
- $\alpha = \alpha_W = \alpha_S$?
- $m_\nu$?
- 3 gen.?
- lepton & quark?
Answers?

DM?

$m_H << \Lambda_P$?

$m_e << m_t$?

extra dimensions

composite Higgs

mono X

boson boson

boson quark
Answers?

DM?

$m_H \ll \Lambda_P$?

$m_e \ll m_t$?

extra dimensions

composite Higgs

mononucleosynthesis

tomorrow morning

boson

boson

boson
quark
for an axion helioscope [32]. Inspired by the ATLAS barrel and end-cap toroids, a large superconducting toroidal magnet is currently being designed to fulfill the requirements of IAXO. The new toroid will be built up from eight, 1m-wide and 21m-long, racetrack coils. The innovative magnet system is sized 5.2 m in diameter and 25 m in length. It is designed to realize a peak magnetic field of 5.4 T with a stored energy of 500 MJ at the operational current of 12.3 kA.

2.1 Figure of merit and lay-out optimization

The general guideline to define the lay-out of the new toroidal magnet has been to optimize the MFOM

\[ M_{FM} = \frac{L^2 B^2}{A} \]

as defined in [32], where \( L \) is the magnet length, \( B \) the effective magnetic field and \( A \) the aperture covered by the x-ray optics. Currently, the MFOM of the CAST magnet is 21 T m^4. As discussed in [32], an MFOM of 300 relative to CAST is necessary for IAXO to aim at sensitivities to \( g_a \) of at least one order of magnitude beyond the current CAST bounds. Accordingly, we have adopted the latter value as the primary design criterion for the definition of the toroidal magnet system, together with other practical constraints such as the maximum realistic size and number of the x-ray optics (section 3) and the fact that the design should rely on known and well proven engineering solutions and manufacturing techniques.

To determine the MFOM, the magnet straight section length \( L \) is set to 20 m and the integration \( R B^2(x,y) dxdy \) is performed over the open area covered by the x-ray optics. Hence, to perform the

\[ \text{Figure 2.} \]

Schematic view of IAXO. Shown are the cryostat, eight x-ray optics and detectors, the flexible lines guiding services into the magnet, cryogenics and powering services units, inclination system and the rotating disk for horizontal movement. The dimensions of the system can be appreciated by a comparison to the human figure positioned by the rotating table.

Thursday morning session
Tackling New Physics with Distinct Signatures

- long-lived
- boson
- boson
- quark
- leptons
- leptons
- quark
- quark
- quark
No significant deviations from the SM observed so far.

One single discovery may turn particle physics upside down.
m_H << \Lambda_P ?

signal:
? \rightarrow \text{boson} + \text{boson}

No. of events

background

m(\text{boson}+\text{boson})
Novel boson tagging
• track-calo clusters: up to x2 better $D_2$ res.
• tagger optimized for sensitivity ($\varepsilon / (a/2 + \sqrt{B})$) in this analysis
Allhadronic Di-W/Z

Selection

- 2 boson-tagged large-R jets
- Small $\Delta \eta$
- Good $p_T$ symmetry

ATLAS Preliminary

WW SR

$\chi^2/DOF = 3.7/2$

Events / 0.1 TeV

ATLAS Preliminary

$\chi^2/DOF = 0.9/2$

Events / 0.1 TeV
• 12 diboson searches combined
• Various complementary final states
• Including VBF signatures

<table>
<thead>
<tr>
<th>Channel</th>
<th>Diboson state</th>
<th>Leptons</th>
<th>$E_T^{miss}$</th>
<th>Jets</th>
<th>b-tags</th>
<th>VBF cat.</th>
</tr>
</thead>
<tbody>
<tr>
<td>qqqq</td>
<td>WW/WZ/ZZ</td>
<td>0</td>
<td>veto</td>
<td>2J</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>vqqq</td>
<td>WZ/ZZ</td>
<td>0</td>
<td>yes</td>
<td>1J</td>
<td>–</td>
<td>yes</td>
</tr>
<tr>
<td>ℓvqq</td>
<td>WW/WZ</td>
<td>1e, 1μ</td>
<td>yes</td>
<td>2j, 1J</td>
<td>–</td>
<td>yes</td>
</tr>
<tr>
<td>ℓℓqq</td>
<td>WZ/ZZ</td>
<td>2e, 2μ</td>
<td>–</td>
<td>2j, 1J</td>
<td>–</td>
<td>yes</td>
</tr>
<tr>
<td>ℓℓvv</td>
<td>ZZ</td>
<td>2e, 2μ</td>
<td>yes</td>
<td>–</td>
<td>0</td>
<td>yes</td>
</tr>
<tr>
<td>ℓℓℓv</td>
<td>WZ</td>
<td>1e+1μ</td>
<td>yes</td>
<td>–</td>
<td>0</td>
<td>yes</td>
</tr>
<tr>
<td>ℓℓℓℓ</td>
<td>ZZ</td>
<td>3e, 2e+1μ, 1e+2μ, 3μ</td>
<td>yes</td>
<td>–</td>
<td>0</td>
<td>yes</td>
</tr>
<tr>
<td>qqqb</td>
<td>WH/ZH</td>
<td>0</td>
<td>veto</td>
<td>2J, 1J</td>
<td>1, 2</td>
<td>–</td>
</tr>
<tr>
<td>vvvb</td>
<td>ZH</td>
<td>0</td>
<td>yes</td>
<td>2j, 1J</td>
<td>1, 2</td>
<td>–</td>
</tr>
<tr>
<td>ℓvvb</td>
<td>WH</td>
<td>1e, 1μ</td>
<td>yes</td>
<td>2j, 1J</td>
<td>1, 2</td>
<td>–</td>
</tr>
<tr>
<td>ℓℓbb</td>
<td>ZH</td>
<td>2e, 2μ</td>
<td>veto</td>
<td>2j, 1J</td>
<td>1, 2</td>
<td>–</td>
</tr>
</tbody>
</table>

**ATLAS**

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

- Large number of interpretations:
  - explicit final states: $W' \rightarrow WZ, \ldots$
  - heavy vector triplet models: $V' \rightarrow VV + VH, \ldots$

- 2D limits on couplings for given mass
- scalars, KK gravitons, …

---

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

- Observed 95% CL limit
- Expected 95% CL limit
- Expected ± 1σ
- Expected ± 2σ
- HVT model A
- HVT model B
Planck scale

? ?

bound states of a new strong force

m_e << m_t ?

m_H << Λ_P ?

elektroweak scale
proton mass
electron mass

10^{19} \text{ GeV}

10^2 \text{ GeV}

10^0 \text{ GeV}

10^{-3} \text{ GeV}
m_T < 1.31 TeV for all BRs into SM particles
VLQ Combination

\[ T, B \]

\[ Z \]

\[ t, b \]

\[ W \]

\[ b, t \]

\[ H \]

\[ t, b \]

\[ m_B = 800 \text{ GeV} \]

\[ 0 \]

\[ 0.2 \]

\[ 0.4 \]

\[ 0.6 \]

\[ 0.8 \]

\[ 1 \]

\[ 0 \]

\[ 0.2 \]

\[ 0.4 \]

\[ 0.6 \]

\[ 0.8 \]

\[ 1 \]

\[ m_B = 900 \text{ GeV} \]

\[ 0 \]

\[ 0.2 \]

\[ 0.4 \]

\[ 0.6 \]

\[ 0.8 \]

\[ 1 \]

\[ m_B = 950 \text{ GeV} \]

\[ 0 \]

\[ 0.2 \]

\[ 0.4 \]

\[ 0.6 \]

\[ 0.8 \]

\[ 1 \]

\[ m_B = 1000 \text{ GeV} \]

\[ 0 \]

\[ 0.2 \]

\[ 0.4 \]

\[ 0.6 \]

\[ 0.8 \]

\[ 1 \]

\[ m_B = 1050 \text{ GeV} \]

\[ 0 \]

\[ 0.2 \]

\[ 0.4 \]

\[ 0.6 \]

\[ 0.8 \]

\[ 1 \]

\[ m_B = 1100 \text{ GeV} \]

\[ 0 \]

\[ 0.2 \]

\[ 0.4 \]

\[ 0.6 \]

\[ 0.8 \]

\[ 1 \]

\[ m_B = 1150 \text{ GeV} \]

\[ 0 \]

\[ 0.2 \]

\[ 0.4 \]

\[ 0.6 \]

\[ 0.8 \]

\[ 1 \]

\[ m_B = 1200 \text{ GeV} \]

\[ 0 \]

\[ 0.2 \]

\[ 0.4 \]

\[ 0.6 \]

\[ 0.8 \]

\[ 1 \]

\[ m_B = 1300 \text{ GeV} \]

\[ 0 \]

\[ 0.2 \]

\[ 0.4 \]

\[ 0.6 \]

\[ 0.8 \]

\[ 1 \]

\[ m_B = 1400 \text{ GeV} \]

\[ 0 \]

\[ 0.2 \]

\[ 0.4 \]

\[ 0.6 \]

\[ 0.8 \]

\[ 1 \]

\[ \text{ATLAS} \]

\[ \sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1} \]

\[ \text{Exp. exclusion} \]

\[ \text{Obs. exclusion} \]

\[ \text{SU(2) (T,B) doublet} \]

\[ \text{SU(2) (B,Y) doublet} \]

\[ \text{SU(2) singlet} \]

\[ 95\% \text{ CL expected exclusion} \]

\[ m_B < 1.03 \text{ TeV} \text{ for all BRs into SM particles} \]
Figure 4: Maximum single heavy quark production cross sections at the LHC with 8 TeV (left) and 13 TeV (right), for selected quark multiplets. The dotted part of the lines indicate the range of masses already excluded by direct searches. In the left plot, the shaded area corresponds to cross sections below 1 fb, uninteresting for the luminosity $L \approx 20$ fb$^{-1}$ collected.

The $Y$ quark decays into $W^- b$ with 100% branching ratio, so the signal resulting from its single production is $Y \bar{b} \rightarrow W^- b \bar{b}$, which may be distinguished from the production of $W^+$ jets by the large $Wb$ invariant mass and the presence of a forward jet. For $T \bar{b}$, the $T$ scalar decays into $W^+ b$, $Zt$, and $Ht$ with branching ratios around 0.25:0.25:0.

The resulting signal $W^+ b \bar{b}$ should be visible over the $W^+ jets$ background; in the $Zt$ decay channel the leptonic $Z$ mode gives a clean signal but with a small branching ratio and the signal in the Higgs channel might be identified by requiring several $b$ tags and a forward jet. The same can be said about $B \bar{b}$ with $B \rightarrow Hb, Zb$, which have branching ratios around 0.25.

For the $(BY)$ doublet. More detailed studies of the LHC sensitivity to single $T$ production have been given in [73–75].
Interference with W+jets and single top

**Interactions**

\[ q \rightarrow W^+ b \]

\[ q' \rightarrow W^+ b \]

**Figure 4:** Maximum single heavy quark production cross sections at the LHC with 8 TeV (left) and 13 TeV (right), for selected quark multiplets. The dotted part of the lines indicate the range of masses already excluded by direct searches. In the left plot, the shaded area corresponds to cross sections below 1 fb, uninteresting for the luminosity \( L \approx 20 \text{ fb}^{-1} \) collected.

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For the (BY) doublet, more detailed studies of the LHC sensitivity to single \( T \) production have been given in [73–75].

Using the explicit expressions for the Lagrangians collected in Appendix A, the limits on mixing angles presented in the previous section can be directly translated into constraints contributions of different vector-like multiplets (and/or other types of new physics), as we have discussed above. Whether the large mixings necessary to make these processes phenomenologically relevant are compatible with precision electroweak data needs to be checked for each model of this kind.

---

**ATLAS Simulation**

\( \sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1} \)

- **Standard Model**
- \( Y \) LH 900 GeV, \( c_L^{Wb} = 0.29, x 5 \)
- \( Y \) LH 1200 GeV, \( c_L^{Wb} = 0.33, x 5 \)
- \( Y \) LH 1600 GeV, \( c_L^{Wb} = 0.91, x 5 \)
Interference with W+jets and single top

ATLAS Simulation
\( \sqrt{s}=13 \text{ TeV}, \ 36.1 \text{ fb}^{-1} \)

- Standard Model
- Y LH: 900 GeV, \( c_{\ell Wb} = 0.29, \times 5 \)
- Y LH: 1200 GeV, \( c_{\ell Wb} = 0.33, \times 5 \)
- Y LH: 1600 GeV, \( c_{\ell Wb} = 0.91, \times 5 \)

95% CL Exclusion Limits
- Observed
- Expected
- Expected ± 1 \( \sigma \)
- Expected ± 2 \( \sigma \)

Indirect EW constraint (S,T) on \(|\sin \theta_L|\)

13 TeV

Single-VLQ → Wb

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---

\( W \rightarrow \ell \nu \)
Single-VLQ → Zt

- 3ℓ and 2ℓ for Z → ℓℓ
- generally more sensitive
- boosted top + E_T^{miss} for Z → νν
- increases sensitivity at high m

ATLAS
13 TeV, 36.1 fb⁻¹

\[ m_T \text{ [GeV]} \]

ATLAS
\( s = 13 \text{ TeV}, \, 36.1 \text{ fb}^{-1} \)
ATLAS-CONF-2018-024

Single-VLQ \rightarrow Hb

- Low BR, but very low background
- Non-resonant $\gamma\gamma$ from data sidebands in $m_{\gamma\gamma}$

- Diagram showing the decay chain $q \rightarrow Z \rightarrow H \rightarrow \gamma\gamma$
- ATLAS Preliminary graph showing data and backgrounds for $m_{\gamma\gamma}$
- Obs. Limit (95% CL) and Exp. Limit (95% CL)
- Doublet model prediction (LO) $B(Y)$

80 fb$^{-1}$
long-lived leptons
boson
boson
quark
lepton
quark
quark
mediator
?
m_H << \Lambda_P ?
DM ?
quark
quark
• Background estimate with sliding windows
• Improved sensitivity compared to analysis with 2015/16 data
## Trigger strategies

**Low-mass searches limited by jet-trigger thresholds**

<table>
<thead>
<tr>
<th>Trigger</th>
<th>Typical offline selection</th>
<th>Trigger Selection</th>
<th>Level-1 Peak Rate (kHz)</th>
<th>HLT Peak Rate (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Level-1 (GeV)</td>
<td>HLT (GeV)</td>
<td></td>
</tr>
<tr>
<td><strong>Single leptons</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Two leptons</td>
<td></td>
<td>Two (\mu) s, each (p_T &gt; 15 \text{ GeV})</td>
<td>2 \times 10</td>
<td>2 \times 14</td>
</tr>
<tr>
<td></td>
<td>Two (\mu) s, (p_T &gt; 23, 9 \text{ GeV})</td>
<td>20</td>
<td>22.8</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>Two very loose (e) s, each (p_T &gt; 18 \text{ GeV})</td>
<td>2 \times 15 (1)</td>
<td>2 \times 17</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td>One (e) s &amp; one (\mu), (p_T &gt; 30 \text{ GeV})</td>
<td>15, 10</td>
<td>17, 14</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>One (e) s &amp; one (\mu), (p_T &gt; 27, 9 \text{ GeV})</td>
<td>22 (1, 1)</td>
<td>26, 8</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td>Two (\mu) s, (p_T &gt; 40, 30 \text{ GeV})</td>
<td>20 (1, 12) (+jets, topo)</td>
<td>25, 25</td>
<td>5.1</td>
</tr>
<tr>
<td></td>
<td>One (\tau) s &amp; one isolated (\mu), (p_T &gt; 30, 15 \text{ GeV})</td>
<td>12 (1), 10 (jets)</td>
<td>25, 14 (1)</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td>One (\tau) s &amp; one isolated (\mu, p_T &gt; 30, 18 \text{ GeV})</td>
<td>12 (1), 15 (1) (+jets)</td>
<td>25, 17 (1)</td>
<td>3.9</td>
</tr>
<tr>
<td><strong>Three leptons</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Two photons</td>
<td></td>
<td>One loose (\tau), (p_T &gt; 145 \text{ GeV})</td>
<td>22 (1)</td>
<td>140</td>
</tr>
<tr>
<td></td>
<td>Two (\mu) s, (p_T &gt; 55, 35 \text{ GeV})</td>
<td>2 \times 20</td>
<td>50, 50</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td>Two medium (\mu), (p_T &gt; 30, 25 \text{ GeV})</td>
<td>2 \times 20</td>
<td>35, 25</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td>Two tight (\mu) s, (p_T &gt; 25, 25 \text{ GeV})</td>
<td>2 \times 15 (1)</td>
<td>2 \times 20 (1)</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td>Two (\mu) s &amp; one loose (\mu), (p_T &gt; 30 \text{ GeV})</td>
<td>2 \times 10 (\mu s)</td>
<td>2 \times 10, 12</td>
<td>2.0</td>
</tr>
</tbody>
</table>
|                                  | Two \(\mu\) s & one loose \(\nu\), \(p_T 
\right)\)                                  | 2 \times 8, 10           | 2 \times 8, 12, 10 | 1.6     | 0.2 |
| **Leptons**                      |                                                                                           |                           |                         |                    |
| Four jets, each \(p_T = 125 \text{ GeV}\)   |                                                                                           | 4 \times 10              | 4 \times 115 | 0.5             | 16  |
| Five jets, each \(p_T = 95 \text{ GeV}\)   |                                                                                           | 5 \times 15              | 5 \times 85   | 4.9             | 10  |
| Six jets, each \(p_T = 70 \text{ GeV}\)   |                                                                                           | 6 \times 15              | 6 \times 55   | 4.9             | 13  |
| **b–jets**                       |                                                                                           |                           |                         |                    |
| One \(b\) (\(e \leq 0.4\)) \(p_T > 235 \text{ GeV}\)                           | 100                         | 225                      | 3.4               | 15  |
| Two \(b\) \(e \leq 0.6\)) \(p_T > 185, 70 \text{ GeV}\)   | 2 \times 15, 10 \text{ GeV}                                | 175, 60               | 3.4             | 12  |
| One \(b\) (\(e \leq 0.40\)) \& brems jets, each \(p_T > 85 \text{ GeV}\)   | 4 \times 15                  | 4 \times 75          | 4.9             | 15  |
| Two \(b\) (\(e \leq 0.40\)) \& one jet, \(p_T > 65, 105 \text{ GeV}\) | 2 \times 30, 85            | 2 \times 30, 150     | 4.7             | 15  |
| Two \(b\) (\(e \leq 0.6\)) \& two jets, each \(p_T > 45 \text{ GeV}\)   | 4 \times 15                  | 4 \times 30          | 4.9             | 13  |
| **B-Physics**                    |                                                                                           |                           |                         |                    |
| Two \(\mu\) s, \(p_T > 6, 8 \text{ GeV}\)                                  | 2 \times 8 (16, 16) \text{ GeV} | 11, 6             | 11, 6 (60-\mu) | 3.1  | 50  |
| Two \(\mu\) s, \(p_T > 6, 8 \text{ GeV}\)                                  | 2 \times 6 (12, 12) \text{ GeV} | 6, 6 (6-\mu)       | 1.8             | 39  |
| Two \(\mu\) s, \(p_T > 6, 8 \text{ GeV}\)                                  | 2 \times 6 (12, 12) \text{ GeV} | 6, 6 (6-\mu)       | 1.8             | 39  |
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| **Total Rate**                   |                                                                                           |                           |                         |                    |
|                                  |                                                                                           | 85                        | 1550            |                  |
Trigger strategies

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<td>20</td>
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</tr>
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<td>22 (t)</td>
<td>26 (t)</td>
<td>26 (i)</td>
</tr>
<tr>
<td></td>
<td>Single $\mu$, $p_T &gt; 52$ GeV</td>
<td>20</td>
<td>26 (t)</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>Single $\tau$, $p_T &gt; 170$ GeV</td>
<td>100</td>
<td>160</td>
<td>1.2</td>
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<tr>
<td></td>
<td>One $e$ &amp; one $\mu$, $p_T &gt; 18$, 15 GeV</td>
<td>15, 10</td>
<td>17, 14</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>One $e$ &amp; one $\mu$, $p_T &gt; 23$, 9 GeV</td>
<td>20 (e, t)</td>
<td>26, 8</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td>Two $\tau$'s, $p_T &gt; 40$, 30 GeV</td>
<td>2 x 10 (e), 12 (µ) (jets, top)</td>
<td>25, 14 (i)</td>
<td>3.1</td>
</tr>
<tr>
<td></td>
<td>One $\tau$ &amp; one isolated $\mu$, $p_T &gt; 30$, 15 GeV</td>
<td>25 (t), 10 (jets)</td>
<td>25, 14 (t)</td>
<td>3.1</td>
</tr>
<tr>
<td></td>
<td>Three loose $e$'s, $p_T &gt; 25$, 13, 13 GeV</td>
<td>20, 2 x 10</td>
<td>24, 2 x 12</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>One photon</td>
<td>One loose $\gamma$, $p_T &gt; 145$ GeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Two photons</td>
<td>Two medium $\gamma$'s, $p_T &gt; 40$, 30 GeV</td>
<td>2 x 20</td>
<td>35, 25</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td>Two tight $\gamma$'s, $p_T &gt; 25$, 23 GeV</td>
<td>2 x 15 (t)</td>
<td>2 x 20 (t)</td>
<td>2.4</td>
</tr>
<tr>
<td>Single jet</td>
<td>Jet ($R = 0.4$), $p_T &gt; 435$ GeV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Jet ($R = 1.0$), $p_T &gt; 480$ GeV</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

20.47

twiki.cern.ch.twiki/bin/view/AtlasPublic/TriggerPublicResults
Low-Mass Dijet with ISR

Single-γ or γ+jet trigger

- better at high m (lower γ-\(p_T^{\text{min}}\))
- worse for low m (higher jet-\(p_T^{\text{min}}\))
Low-Mass Dijet with ISR

Single-$\gamma$ or $\gamma$+jet trigger

- better at high m (lower $\gamma$-p$_T^{min}$)
- worse for low m (higher jet-p$_T^{min}$)

$\gamma$, q

2-b-tag selection

Flavor-inclusive selection

$\mathbf{ATLAS}$

$m_{Z'} = 550 \text{ GeV}, \ g_q = 0.1$

Data, 76.6 fb$^{-1}$

combined trigger

$m_{Z'} = 250 \text{ GeV}, \ g_q = 0.1$

Data, 79.8 fb$^{-1}$

single-photon trigger

Background fit

$X \times 15 \sigma$

$Z', \sigma \times 15$

- BH p-value = 0.97
- $\chi^2$ p-value = 0.77

- BH p-value = 0.63
- $\chi^2$ p-value = 0.52

Events / Bin

Significance

200 300 400 500 600 700 1000

Events / Bin

Significance

$10^{-4}$

$10^2$

$10^3$

$10^4$

$10^2$

$10^3$

$10^4$

$10^2$

$10^3$

$10^4$
• 2-b-tag selection sensitive to models with enhanced couplings to b-quarks
• 2-b-tag sensitivity to flavour-inclusive couplings even slightly better than flavour-inclusive selection
**Low-Mass $b\bar{b}$ with ISR**

**Trigger high-$p_T$ ISR jet**

- Candidate jet:
  - $p_T > 480$ GeV
  - $70 < m < 230$ GeV
  - 2 b-tags

**Graphs**

- ATLAS Preliminary
  - Data
  - SM Higgs ($\mu_H = 5.8$)
  - QCD Fit
  - $V+$Jets ($\mu_V = 1.5$)
  - QCD Fit $\pm 1\sigma$
  - Top

- Events / 5 GeV

- Data-QCD-fit

- Data-QCD-fit $V$

- Signal candidate large-$R$ jet mass [GeV]
Complementary to dijet+$\gamma$
\( \bar{t}t \) (all hadronic)

- Low mass: multijet final state (“resolved”)
- QCD suppressed by “buckets of tops” + b-tags
- High mass: two large-R jets (“boosted”)
- QCD suppressed by top-tagging + b-tags
• Focus on right-handed $W'$ (no interference with SM)

• Boosted top $\Rightarrow$ only track isolation for leptons
• Focus on right-handed $W'$ (no interference with SM)
• Boosted top $\Rightarrow$ only track isolation for leptons
• All hadronic and $\ell+$jets comparable sensitivity for $m > 2$ TeV

\[ \sqrt{s} = 13 \text{ TeV, } 36.1 \text{ fb}^{-1} \]

$\bar{t}b (\ell+\text{jets})$

**ATLAS**

- Observed
- Expected
- $W_R' \rightarrow \bar{t}b \rightarrow b\bar{b}\ell\nu$
- $W_R' \rightarrow \bar{t}b \rightarrow b\bar{b}q\bar{q}'$
- $W_R' \rightarrow \bar{t}b$ (combined)

\[ \sigma(pp \rightarrow W'_R) \times B(W'_R \rightarrow \bar{t}b) \text{ [pb]} \]
lepton & quark?
Light Quark + e/µ (neutrino)

Do LQ explain flavor anomalies?
- $B \to K^* \mu \mu$?
- $\to 2^{nd}$ generation couplings?

- Separate BDTs trained for $\ell \nu qq \ (\beta \neq 1)$ & $\ell \ell qq \ (\beta = 1)$

---

**ATLAS**
13 TeV, 36.1 fb$^{-1}$

$\mu$ channel

- Expected
- Expected $\pm 1\sigma$
- Expected $\pm 2\sigma$
- Observed
Do LQs explain flavor anomalies?
• $B \to D^* \tau \nu$ ?
→ $3^{rd}$ generation couplings?
• Reoptimizations/reinterpretations of 5 analyses (HH/SUSY)

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

- observed
- expected

- $tt + E_T^{\text{miss}} - 0\ell$
- $tt + E_T^{\text{miss}} - 1\ell$
- $\tau\tau b + E_T^{\text{miss}}$
- $b\tau b\tau$
- $bb + E_T^{\text{miss}}$

$B(LQ_3^u \to b\tau)$ vs $m(LQ_3^u)$ [GeV]
Do LQs explain flavor anomalies?

- $B \rightarrow D^* \tau \nu$?
- $\rightarrow 3^{rd}$ generation couplings?

- Reoptimizations/reinterpretations of 5 analyses (HH/SUSY)

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

- observed
- expected

- $tt + E_T^{miss} - 0\ell$
- $tt + E_T^{miss} - 1\ell$
- $\tau\tau b + E_T^{miss}$
- $b\tau b\tau$
- $bb + E_T^{miss}$
long-lived

leptons

m_\nu?
Heavy Neutrino

\[ W_R^* \rightarrow N \rightarrow e, \mu \]

\[ W_R \rightarrow q, q \]

assuming no mixing between flavors:

\[ \sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1} \]

\[ g_R = g_L \]

Dirac-\( N_R \) \( \rightarrow \ell^+\ell^- \) only

Majorana-\( N_R \) \( \rightarrow \ell^\pm\ell^\pm \) & \( \ell^+\ell^- \)

\( m(W_R) > m(N_R) \rightarrow m_{\ell\ell qq} \sim m(W_R) \)

else \( \rightarrow m_{qq} \sim m(W_R) \)

dominated by same-sign analysis
Heavy Neutrino (boosted)

- Lepton in large-R jet and no isolation in 2\textsuperscript{nd} lepton
- Electron as part large-R jet \implies \text{checks on}
  - $e^{\pm}$ efficiency vs. $\Delta R$
  - Jet mass & energy scales
- Counting experiment for $m_{W_R}^{\text{reco}} > 2$ TeV

\[ JES \]

\[ E_{e^2} / E_j \]

\[ \text{ATLAS} \quad \text{Simulation} \quad \sqrt{s} = 13 \text{ TeV} \]

\[ m_{W_R} (4 \text{ TeV}), m_{N_R} (400 \text{ GeV}) \quad m_{W_R} (3 \text{ TeV}), m_{N_R} (150 \text{ GeV}) \]

\[ m_{W_R} (5 \text{ TeV}), m_{N_R} (500 \text{ GeV}) \quad m_{W_R} (3 \text{ TeV}), m_{N_R} (300 \text{ GeV}) \]
ATLAS
$\sqrt{s} = 13$ TeV, 80 fb$^{-1}$

Electron channel
- Obs. 95% CL
- Exp. 95% CL
- Obs. resolved 95% CL
- Exp. 1 $\sigma$ Band
- Exp. 2 $\sigma$ Band
- Not covered
- Excluded

- Improved sensitivity at high boost

arXiv:1904.12679
A search for a heavy right-handed neutrino decaying into a boosted right-handed neutrino.

Both electron and muon final states are analysed for the decay into two same-flavour leptons, using jet and lepton cuts. In the electron final state, the analysis makes use of a large-statistics data sample.

The observed yields and expected background yields in the signal region are presented in Table 1. The significance and the confidence level are set on the expected exclusion contour.

**Table 1**

<table>
<thead>
<tr>
<th></th>
<th>Electron Channel</th>
<th>Muon Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expected background</td>
<td>$2.8^{+0.5}_{-0.7}$</td>
<td>$1.9^{+0.5}_{-0.7}$</td>
</tr>
<tr>
<td>Observed events</td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td>Significance</td>
<td>$2.4\sigma$</td>
<td>$1.2\sigma$</td>
</tr>
<tr>
<td>$p$-value</td>
<td>0.0082</td>
<td>0.12</td>
</tr>
</tbody>
</table>

**Figure**

- **ATLAS**
  - $\sqrt{s} = 13$ TeV, 80 fb$^{-1}$
  - Electron channel
    - Obs. 95% CL
    - Exp. 95% CL
    - Obs. resolved 95% CL
  - Muon channel
    - Exp. 1 $\sigma$ Band
    - Exp. 2 $\sigma$ Band
  - Not covered

- **Improvement sensitivity at high boost**
**Heavy ν (prompt+displaced)**

- **Prompt search:**
  - $2e+\mu$ or $2\mu+e$
  - same charge for same flavor

- **Small masses $\Rightarrow$ long $\tau$**

- **Displaced-vertex search:**
  - $\mu +$ displaced vertex with
  - $d = 4$-$300$mm & $m > 4$ GeV

\[ \sqrt{s} = 13 \text{ TeV}, \ W \rightarrow \mu N \rightarrow \mu \mu e \nu \]

**ATLAS Simulation**

- $m_N = 10$ GeV, prompt
- $m_N = 5$ GeV, displaced
- $m_N = 7.5$ GeV, displaced
- $m_N = 10$ GeV, displaced
- $m_N = 12.5$ GeV, displaced

**Selection efficiency** vs. $ct$ [mm]
Heavy $\nu$ (prompt+displaced)

$W \rightarrow N, e, \mu$

$\nu_e, \nu_\mu, \mu, e$

Kinematic suppression due to W-boson decay

$cT \sim 1$-30 mm

$\sqrt{s} = 13$ TeV, 32.9-36.1 fb$^{-1}$

95% CL exclusion

- Observed (prompt, LNV)
- Observed (displaced, LNV)
- Observed (displaced, LNC)
- Expected
- Expected ± 1σ
- Expected ± 2σ

$|U_{\mu}^2|$ vs $m_N$ [GeV]
- Convolution of a generic signal BW with resolution
- Interpretation in a variety of models
  - spin-0, -1, -2
  - SSM
  - HVT
  - ...

**ATLAS**

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

\[ Z' \rightarrow \ell\ell \]
EXOT-2018-30 (to be submitted soon)  \( W' \rightarrow \ell v \)

\[
\begin{align*}
\Gamma(W') / m(W') &= 0.01 \\
\Gamma(W') / m(W') &= 0.02 \\
\Gamma(W') / m(W') &= 0.05 \\
\Gamma(W') / m(W') &= 0.10 \\
\Gamma(W') / m(W') &= 0.15 
\end{align*}
\]

Observed limits at 95% CL

\[ m_\nu > 0.3 \text{ m}(W') \]
long-lived
- LLP with $q = 2-7e$ and $\tau \gg L_{\text{ATLAS}}/\beta\gamma$
- Signature:
  - $\mu$-like with high $dE/dx$ significance (compared to $\mu$) in Pixel, TRT, MDT

\[
\text{Data} \quad \text{Mass 200 GeV, } z=2.0 \\
\text{Mass 1400 GeV, } z=2.0
\]

\[
\gamma s = 13 \text{ TeV, } 36.1 \text{ fb}^{-1}
\]
• LLP with $q = 2-7e$ and $\tau \gg \beta \gamma$

• Signature:
  • $\mu$-like with high dE/dx significance (compared to $\mu$) in Pixel, TRT, MDT

• At high $q$ and high mass:
  
  $dE/dx \Rightarrow$ trigger timing

• At low mass: not always central

• At high $q$: $p_T > q/e \cdot 50$ GeV

---

**ATLAS**

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

Overall signal efficiency [%]

MCP mass [GeV]
• LLP with $q = 2-7e$ and $\tau \gg L_{\text{ATLAS}}/\beta\gamma$

• Signature:
  • $\mu$-like with high $dE/dx$ significance
  (compared to $\mu$)

• At high $q$ and high mass:
  $dE/dx \Rightarrow$ trigger timing

• At low mass: not always central

No events observed
with background expectations:

$z = 2 : \quad 0.15 \pm 0.05(\text{stat.}) \pm 0.10(\text{syst.})$

$z > 2 : \quad 0.029 \pm 0.004(\text{stat.}) \pm 0.022(\text{syst.})$
• Magnetic monopole \( q = N \cdot q_D \triangleq q = N \cdot 68.5e \) or LLP with \( q = 20–100e \)

• Large charge \( \Rightarrow \) large \( dE/dx \) \( \Rightarrow \) fully absorbed in ECAL

• L1: ECAL + HCAL veto — HLT: high-threshold TRT hits

• Sensitivity limited for high charge (particles stop before ECAL)

**Magnetic Monopoles**

ATLAS

\( \sqrt{s} = 13 \text{ TeV}, 34.4 \text{ fb}^{-1} \)

MoEDAL limit

(PLB 782 (2018) 510)

\[ m \] [GeV]
• LLP with large mass & $\tau \geq L_{\text{CALO}}/\beta \gamma$
• Signature: large $p_T$ but slow
  • $\beta \gamma$ from Pixel $dE/dx$
  • $\beta$ from TOF (TILE, MDT, RPC)
Heavy Charged

- LLP with large mass & $\tau \geq L_{\text{CALO}}/\beta \gamma$
- Signature: large $p_T$ but slow
  - $\beta \gamma$ from Pixel $dE/dx$
  - $\beta$ from TOF (TILE, MDT, RPC)

- Selections w/ & w/o muon system
- Also sensitive to meta-stable LLP
  - complementary to using only Pixel $dE/dx$ (PLB 788 (2019) 96)
Displaced Jets (MS)

- Pair-produced neutral LLP that decay in (or just before) the muon system
- Signature:
  - 2 vertices in the muon system
  - isolated from tracks and jets
  - high multiplicity (many hits)

1 vertex + $E_T^{\text{miss}}$
2nd LLP decays before MS
$\Rightarrow$ small $\Delta\phi$
obs.: 7/1
compatible w/ bkg.

2 isolated vertices
obs.: 0
exp.: $0.027\pm0.011$

- Pair-produced neutral LLP that decay in (or just before) the muon system
- Signature:
  - 2 vertices in the muon system
  - isolated from tracks and jets
  - high multiplicity (many hits)
• Pair-produced neutral LLP that decay in (or just before) the HCAL
• Signature: 2 jets with
  • no tracks
  • large E(HCAL)/E(ECAL)
  • narrow jet shapes

- NN regression for decay vertex
- BDTs vs. QCD & BIB

Displaced Jets (HCAL)

ATLAS Simulation
\( \sqrt{s} = 13 \text{ TeV} \)

ATLAS
\( \sqrt{s} = 13 \text{ TeV}, 33.0 \text{ fb}^{-1} \)
Combination of the two displaced-jet searches

\[ \text{ATLAS} \quad \sqrt{s} = 13 \text{ TeV} \]

\[ m_\phi = 400 \text{ GeV}, \quad m_s = 50 \text{ GeV} \]

- CR limit [33.0 fb\(^{-1}\)]
- MS2 limit [36.1 fb\(^{-1}\)]
- Obs.
- Exp. ± 1σ
- CR+MS2 limit

95% CL Upper Limit on \( \sigma \times B_{\phi \rightarrow ss} \) [pb]

s proper decay length [m]
## What improved sensitivity has relied on until now:

<table>
<thead>
<tr>
<th>Comments (21-Feb-2019 12:08:02)</th>
<th>BIS status and SMP flags</th>
<th>B1</th>
<th>B2</th>
</tr>
</thead>
<tbody>
<tr>
<td>LS2</td>
<td>Link Status of Beam Permits</td>
<td>false</td>
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</tr>
<tr>
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<td>Global Beam Permit</td>
<td>false</td>
<td>false</td>
</tr>
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<td></td>
<td>Setup Beam</td>
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<td></td>
<td>Beam Presence</td>
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<td>Moveable Devices Allowed In</td>
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<td>Stable Beams</td>
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<td>AFS: 75_150ns_733Pb_733_702_468_42bpi_20inj</td>
<td>PM Status B1</td>
<td>ENABLED</td>
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</tr>
<tr>
<td></td>
<td>PM Status B2</td>
<td>ENABLED</td>
<td></td>
</tr>
</tbody>
</table>
What improved sensitivity has relied on until now:

- Larger $\sqrt{s}$
- Larger $L_{\text{int}}$
What improved sensitivity has relied on until now:

- Larger $\sqrt{s}$
- Larger $L_{\text{int}}$
- Better reco.
What improved sensitivity has relied on until now:

- Larger $\sqrt{s}$
- Larger $L_{\text{int}}$
- Better reco.
- Combinations
What improved sensitivity has relied on until now:

- Larger $\sqrt{s}$
- Larger $L_{\text{int}}$
- Better reco.
- Combinations
- New signals
What improved sensitivity has relied on until now:

- Larger $\sqrt{s}$
- Larger $L_{\text{int}}$
- Better reco.
- Combinations
- New signals
BACKUP
# LLP Summary Plot

## ATLAS Long-lived Particle Searches* - 95% CL Exclusion

Status: March 2019

<table>
<thead>
<tr>
<th>Model</th>
<th>Signature</th>
<th>$\langle L dt \rangle$ [fb$^{-1}$]</th>
<th>Lifetime limit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>RPV $\chi_1^0 \rightarrow e e u / e u \mu / \mu u$</td>
<td>displaced lepton pair</td>
<td>20.3</td>
<td>$\chi_1^0$ lifetime</td>
<td>$7.740$ mm</td>
</tr>
<tr>
<td>GGM $\chi_1^0 \rightarrow Z \tilde{C}$</td>
<td>displaced vtx + jets</td>
<td>20.3</td>
<td>$\chi_1^0$ lifetime</td>
<td>$6.480$ mm</td>
</tr>
<tr>
<td>GGM $\chi_1^0 \rightarrow Z \tilde{C}$</td>
<td>displaced dimuon</td>
<td>32.9</td>
<td>$\chi_1^0$ lifetime</td>
<td>$0.029-18.6$ m</td>
</tr>
<tr>
<td>GMSB</td>
<td>non-pointing or delayed $\gamma$</td>
<td>20.3</td>
<td>$\chi_1^0$ lifetime</td>
<td>$0.08-5.4$ m</td>
</tr>
<tr>
<td>AMSB $pp \rightarrow \chi_1^0 \chi_1^0, \chi_1^0 \chi_1^0$</td>
<td>disappearing track</td>
<td>20.3</td>
<td>$\chi_1^0$ lifetime</td>
<td>$0.22-3.0$ m</td>
</tr>
<tr>
<td>AMSB $pp \rightarrow \chi_1^0 \chi_1^0, \chi_1^0 \chi_1^0$</td>
<td>disappearing track</td>
<td>36.1</td>
<td>$\chi_1^0$ lifetime</td>
<td>$0.057-1.53$ m</td>
</tr>
<tr>
<td>AMSB $pp \rightarrow \chi_1^0 \chi_1^0, \chi_1^0 \chi_1^0$</td>
<td>large pixel dE/dx</td>
<td>18.4</td>
<td>$\chi_1^0$ lifetime</td>
<td>$1.31-9.0$ m</td>
</tr>
<tr>
<td>Stealth SUSY</td>
<td>2 ID/MS vertices</td>
<td>19.5</td>
<td>$\tilde{s}$ lifetime</td>
<td>$&gt;6.9$ m</td>
</tr>
<tr>
<td>Split SUSY</td>
<td>large pixel dE/dx</td>
<td>36.1</td>
<td>$\tilde{g}$ lifetime</td>
<td>$0.12-9.0$ m</td>
</tr>
<tr>
<td>Split SUSY</td>
<td>displaced vtx + $E_T^{miss}$</td>
<td>32.8</td>
<td>$\tilde{g}$ lifetime</td>
<td>$0.03-13.2$ m</td>
</tr>
<tr>
<td>Split SUSY</td>
<td>0 $\ell$, 2 - 6 jets + $E_T^{miss}$</td>
<td>36.1</td>
<td>$\tilde{g}$ lifetime</td>
<td>$0.05-2.1$ m</td>
</tr>
<tr>
<td>$H \rightarrow ss$</td>
<td>low-EMF trik-less jets, MS vtx</td>
<td>36.1</td>
<td>$s$ lifetime</td>
<td>$0.19-120.0$ m</td>
</tr>
<tr>
<td>FRVZ $H \rightarrow 2\gamma + X$</td>
<td>2 $e^-, \mu^-$-jets</td>
<td>20.3</td>
<td>$\gamma_\gamma$ lifetime</td>
<td>$0.022-1.113$ m</td>
</tr>
<tr>
<td>FRVZ $H \rightarrow 2\gamma + X$</td>
<td>2 $e^-, \mu^-$-jets</td>
<td>3.4</td>
<td>$\gamma_\gamma$ lifetime</td>
<td>$0.038-1.63$ m</td>
</tr>
<tr>
<td>FRVZ $H \rightarrow 4\gamma + X$</td>
<td>2 $e^-, \mu^-$-jets</td>
<td>3.4</td>
<td>$\gamma_\gamma$ lifetime</td>
<td>$0.009-24.0$ m</td>
</tr>
<tr>
<td>$H \rightarrow Z\tilde{d}\tilde{d}$</td>
<td>displaced dimuon</td>
<td>32.9</td>
<td>$Z\tilde{d}$ lifetime</td>
<td>$0.22-5.3$ m</td>
</tr>
<tr>
<td>$H \rightarrow ZZ\tilde{d}$</td>
<td>2 $e, \mu$ + low-EMF trackless jet, MS vtx</td>
<td>36.1</td>
<td>$Z\tilde{d}$ lifetime</td>
<td>$0.06-52.4$ m</td>
</tr>
<tr>
<td>VH with $H \rightarrow ss \rightarrow bbbb$</td>
<td>1 - 2$\ell$ + multi-$b$-jets</td>
<td>36.1</td>
<td>0-3 mm</td>
<td>$2(10^{10})$</td>
</tr>
<tr>
<td>$\phi(200$ GeV$) \rightarrow ss$</td>
<td>low-EMF trik-less jets, MS vtx</td>
<td>36.1</td>
<td>$\phi$ lifetime</td>
<td>$0.41-51.5$ m</td>
</tr>
<tr>
<td>$\phi(600$ GeV$) \rightarrow ss$</td>
<td>low-EMF trik-less jets, MS vtx</td>
<td>36.1</td>
<td>$\phi$ lifetime</td>
<td>$0.04-21.5$ m</td>
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<tr>
<td>$\phi(1$ TeV$) \rightarrow ss$</td>
<td>low-EMF trik-less jets, MS vtx</td>
<td>36.1</td>
<td>$\phi$ lifetime</td>
<td>$0.06-52.4$ m</td>
</tr>
<tr>
<td>$HV Z'$ (1 TeV$) \rightarrow q \bar{q}$</td>
<td>2 ID/MS vertices</td>
<td>20.3</td>
<td>$\tilde{q}$ lifetime</td>
<td>$0.1-4.9$ m</td>
</tr>
<tr>
<td>$HV Z'$ (2 TeV$) \rightarrow q \bar{q}$</td>
<td>2 ID/MS vertices</td>
<td>20.3</td>
<td>$\tilde{q}$ lifetime</td>
<td>$0.3-10.1$ m</td>
</tr>
</tbody>
</table>

*Only a selection of the available lifetime limits is shown.

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[$\sqrt{s} = 8$ TeV] [$\sqrt{s} = 13$ TeV]

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atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS