Beyond exclusive leptonic resonances with the ATLAS detector

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on behalf of the ATLAS Collaboration
Cylindrical coordinates \((r, \varphi)\) are used in the transverse plane:
- \(\varphi\) azimuthal angle around the beam pipe
- \(\theta\) polar angle \(\eta = -\ln(\tan(\theta/2))\)
Why beyond exclusive leptonic resonances

High-mass resonances have been already searched using the full data recorded by the ATLAS experiment (139 \( fb^{-1} \))

- **observable:**
  - dilepton (\( m_{ll} \)) invariant mass, \( l = e, \mu \)
  - transverse mass

**No significant deviation from the standard model is observed**

- **signature:**
  - bump on smoothly-falling background
Beyond exclusive leptonic resonances

Search for non-resonant features in dilepton mass spectra:

- Resonance above the scale of direct detection at the LHC
  - High energy $\Lambda$ → Interference at lower mass

$$\sigma_{tot}(m_{ll}) = \sigma_{DY}(m_{ll}) - n_{ij} \frac{F_I(m_{ll})}{\Lambda^2} + \frac{F_C(m_{ll})}{\Lambda^4}$$

Indication of:
- massive mediator boson
- quark/leptons compositeness

Search for a right-handed gauge boson decaying into a high-momentum heavy neutrino and a charged lepton

Based on Left-Right Symmetric Model (LRSM) theory with right handed Neutrino ($N_R$) mass smaller than right handed gauge boson ($W_R$):

$$m_{N_R}/m_{W_R} < 0.1$$

Explanation of:
- the relative smallness of the neutrino masses
- parity violation in the SM
- existence of the right-handed charged current
Contact interaction

Contact Interaction (CI) scale leads to interference at lower masses

\[ \sigma_{tot}(m_{ll}) = \sigma_{DY}(m_{ll}) - n_{ij} \frac{F_I(m_{ll})}{\Lambda^2} + \frac{F_C(m_{ll})}{\Lambda^4} \]

Interference

Pure contact interaction

CI production enhances the high mass tail of the spectrum @ \( \sim 4 \) TeV

DrellYan

Contact interaction

- constructive interference
- destructive interference

Signal model parameters:

- Sign of the interference (constructive or destructive)
- Chirality of the fermions (LL, LR, RL, RR)
- Energy scale \( \Lambda \)
Data and event selection

Analysis with ATLAS run 2 data (2015/2016) corresponding to 36 $fb^{-1}$

**Electron selection**

- electron candidates identified through:
  - Tracker
  - Electromagnetic calorimeter
- required to have:
  - transverse energy ($E_T$) > 30 GeV
  - $0 < |\eta| < 1.37$ or $1.52 < |\eta| < 2.47$

high efficiency selection $\sim$95% $\rightarrow$ $E_T$ @ 1.5 TeV

**Muon selection**

- muon candidates required to have:
  - Transverse momentum ($p_T$) > 30 GeV
  - $|\eta| < 2.5$
  - a cut based on the charge over momentum measurement

efficiency selection $\sim$ 70% $\rightarrow$ $p_T$ @ 1 TeV

leading $E_T$ ($p_T$) electron(muon) pair is selected
Invariant mass distribution

- The primary background is Drell-Yan production (DY)
- Additional backgrounds from top and diboson production, and multi-jet events
- Functional fit to Drell-Yan MC to take into account low MC stat

No significant deviation has been observed
- The ee and $\mu\mu$ results are combined statistically to set limits on $\Lambda$
- highest expected limit for the constructive hypothesis is 31 TeV
- highest expected limit for the destructive hypothesis is 24 TeV
$W_R$ into a high-momentum $N_R$ and a charged lepton

Analysis with ATLAS run 2 data (2015-2017) $80 \text{ fb}^{-1}$

- two same-flavour leptons (no charge requirement)
- Isolated leading lepton
- at least 1 trimmed large jet, $p_T > 200 \text{ GeV}$, $|\eta| < 2$
- Leading lepton - large jet, $\Delta \phi > 2$
- Sub-leading lepton contained inside the large jet
- $m_{ll} > 200 \text{ GeV}$, $l = e, \mu$

Electron selection
- electron candidates identified by:
  - tracker
  - Electromagnetic calorimeter
- required to have:
  - transverse energy ($E_T$) $> 26 \text{ GeV}$
  - $0 < |\eta| < 1.37$ or $1.52 < |\eta| < 2.47$
  - large jet mass $> 50 \text{ GeV}$

Muon selection
- muon candidates tracks from:
  - inner detector (ID)
  - muon spectrometer (MS)
- required to have:
  - Transverse momentum ($p_T$) $> 28 \text{ GeV}$
  - $|\eta| < 2.5$
**Analysis strategy**

Regions definition based on the observable: $m_{WR}$

<table>
<thead>
<tr>
<th>Region</th>
<th>Range of $m_{WR}^{\text{reco}}$</th>
<th>Lepton flavour</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal region (SR)</td>
<td>$&gt; 2$ TeV</td>
<td>Same flavour</td>
</tr>
<tr>
<td>Control region (CR)</td>
<td>$&lt; 2$ TeV</td>
<td>Same flavour</td>
</tr>
<tr>
<td>Validation region (VR)</td>
<td>All</td>
<td>Mixed flavour (leading: muon; subleading: electron)</td>
</tr>
</tbody>
</table>

- CR is dominated by $t\bar{t}$ events
- SR $Z$+jets events larger at higher masses
- $W$+jets, single-top-quark and multijet processes are negligible

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**Dielectron**

**Dimuon**
Background fit strategy

- $t\bar{t}$ background derived by a data-driven CR fit (400-1800 GeV) performed & extrapolated to SR

- Zjets dominates in higher mass range, Dilepton Zjets MC fit (400-4000 GeV) parameters also taken into account in resultant total fit to data
Expected background and observed events are reported in the table.

No significance deviation is observed in the electron and muon channel.

<table>
<thead>
<tr>
<th></th>
<th>Electron Channel</th>
<th>Muon Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal ((m_{WR} = 3 \text{ TeV}, m_{NR} = 150 \text{ GeV}))</td>
<td>346^{+48}_{-75}</td>
<td>411^{+36}_{-48}</td>
</tr>
<tr>
<td>Signal ((m_{WR} = 3 \text{ TeV}, m_{NR} = 300 \text{ GeV}))</td>
<td>471^{+42}_{-69}</td>
<td>429^{+29}_{-40}</td>
</tr>
<tr>
<td>Signal ((m_{WR} = 4 \text{ TeV}, m_{NR} = 400 \text{ GeV}))</td>
<td>66^{+6}_{-10}</td>
<td>57^{+4}_{-4}</td>
</tr>
<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>
The goal of the $q/p$ cut is to reject muons in the tails of the $\sigma_{p_T}/p_T$ distributions.

The selection is based on a cut on the relative uncertainty of the $q/p$ measurement.

Full ATLAS Run2 corresponding to 139 $fb^{-1}$ data have been used for evaluating the new uncertainty.

$q/p$ criteria uncertainty:

- Raw syst., $|\eta| < 1.3$, 139 $fb^{-1}$
- Function-fit syst., $|\eta| < 1.3$, 139 $fb^{-1}$
- Raw syst., $|\eta| < 1.05$, 36 $fb^{-1}$
- Function-fit syst., $|\eta| < 1.05$, 36 $fb^{-1}$

**ATLAS** Preliminary

$\sqrt{s} = 13$ TeV
Summary

- Exclusive dilepton resonance in the mass range of 250 GeV to 6 TeV with the full run 2 data have been searched and no deviations from the SM have been observed.

It is necessary to go beyond this paradigm:

- Search for new non-resonant high-mass phenomena in dielectron and dimuon final states with $36 \, fb^{-1}$ is presented.

  - Lower limits on the qqll contact interaction scale are set between 2.4 TeV and 40 TeV.

- Search for a right-handed gauge boson, decaying into a boosted right-handed heavy neutrino, in the framework of LRSM with $80 \, fb^{-1}$ is presented.

  - Mass values of the $W_R$ smaller than 3.8–5 TeV are excluded for $N_R$ in the mass range 0.1–1.8 TeV.

New ATLAS searches beyond exclusive leptonic resonances with the full run 2 data and several updates coming very soon :)!
Backup
Search for non-resonant phenomena in dilepton mass spectra

Systematic uncertainties

- Relative systematic uncertainties in the total expected number of events at a dilepton mass of 2TeV (4TeV)

  - Dielectron channel dominant uncertainty is due to isolation efficiency
  
  - Dimuon channel dominant uncertainty is due to reconstruction efficiency

<table>
<thead>
<tr>
<th>Source</th>
<th>Dielectron channel [%]</th>
<th>Dimuon channel [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Signal</td>
<td>Background</td>
</tr>
<tr>
<td>Luminosity</td>
<td>3.2 (3.2)</td>
<td>3.2 (3.2)</td>
</tr>
<tr>
<td>MC statistical</td>
<td>&lt;1.0 (&lt;1.0)</td>
<td>&lt;1.0 (&lt;1.0)</td>
</tr>
<tr>
<td>Beam energy</td>
<td>2.0 (4.1)</td>
<td>1.9 (3.1)</td>
</tr>
<tr>
<td>Pile-up effects</td>
<td>&lt;1.0 (&lt;1.0)</td>
<td>&lt;1.0 (&lt;1.0)</td>
</tr>
<tr>
<td>DY PDF choice</td>
<td>&lt;1.0 (8.4)</td>
<td>&lt;1.0 (1.9)</td>
</tr>
<tr>
<td>DY PDF variation</td>
<td>8.7 (19)</td>
<td>7.7 (13)</td>
</tr>
<tr>
<td>DY PDF scales</td>
<td>1.0 (2.0)</td>
<td>&lt;1.0 (1.5)</td>
</tr>
<tr>
<td>DY $\alpha_S$</td>
<td>1.6 (2.7)</td>
<td>1.4 (2.2)</td>
</tr>
<tr>
<td>DY EW corrections</td>
<td>2.4 (5.5)</td>
<td>2.1 (3.9)</td>
</tr>
<tr>
<td>DY $\gamma$-induced corrections</td>
<td>3.4 (7.6)</td>
<td>3.0 (5.4)</td>
</tr>
<tr>
<td>Top quarks theoretical</td>
<td>&lt;1.0 (&lt;1.0)</td>
<td>&lt;1.0 (&lt;1.0)</td>
</tr>
<tr>
<td>Dibosons theoretical</td>
<td>&lt;1.0 (&lt;1.0)</td>
<td>&lt;1.0 (&lt;1.0)</td>
</tr>
<tr>
<td>Reconstruction efficiency</td>
<td>&lt;1.0 (&lt;1.0)</td>
<td>10 (17)</td>
</tr>
<tr>
<td>Isolation efficiency</td>
<td>9.1 (9.7)</td>
<td>1.8 (2.0)</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>&lt;1.0 (&lt;1.0)</td>
<td>&lt;1.0 (&lt;1.0)</td>
</tr>
<tr>
<td>Identification efficiency</td>
<td>2.6 (2.4)</td>
<td>N/A</td>
</tr>
<tr>
<td>Lepton energy scale</td>
<td>4.1 (6.1)</td>
<td>&lt;1.0 (&lt;1.0)</td>
</tr>
<tr>
<td>Lepton energy resolution</td>
<td>&lt;1.0 (&lt;1.0)</td>
<td>&lt;1.0 (6.7)</td>
</tr>
<tr>
<td>Multi-jet &amp; $W$+jets</td>
<td>10 (129)</td>
<td>N/A</td>
</tr>
<tr>
<td>Total</td>
<td>18 (132)</td>
<td>14 (24)</td>
</tr>
</tbody>
</table>
Search for a right-handed gauge boson decaying into a high-momentum heavy neutrino and a charged lepton

Validation region

![Validation region graph]

\( \sqrt{s} = 13 \text{ TeV}, 80 \text{ fb}^{-1} \)

- Data
- \( \bar{t} \bar{t} \)
- Single-\( t \)
- Diboson
- MC stat. unc.

Events / 100 GeV

Data / Pred.

Mixed flavour

\( m_{\mu \nu} \) [GeV]

1000 | 1500 | 2000 | 2500 | 3000

0.5 | 1 | 1.5 | 2 | 2.5

\( \times 10^0 \) | \( \times 10^1 \) | \( \times 10^2 \) | \( \times 10^3 \)

\( \times 10^0 \) | \( \times 10^1 \) | \( \times 10^2 \) | \( \times 10^3 \)
Search for a right-handed gauge boson decaying into a high-momentum heavy neutrino and a charged lepton

Systematic uncertainties

<table>
<thead>
<tr>
<th>Component</th>
<th>Electron channel [%]</th>
<th>Muon channel [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lepton identification</td>
<td>4–20</td>
<td>4–8</td>
</tr>
<tr>
<td>Lepton isolation</td>
<td>4–5</td>
<td>1.0–1.5</td>
</tr>
<tr>
<td>Lepton reconstruction</td>
<td>4–5</td>
<td>1–4</td>
</tr>
<tr>
<td>Lepton trigger</td>
<td>4–5</td>
<td>0.5</td>
</tr>
<tr>
<td>Pile-up</td>
<td>&lt; 0.5</td>
<td>2–3</td>
</tr>
<tr>
<td>Luminosity</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Theory</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>

- Dominant uncertainty is related to the electron and muon identification

- The relative uncertainty of the background yield in the SR is about 25% for both channels

- Theory uncertainty of the signal yield is evaluated by varying the renormalisation and factorisation scales by factors of 2 and 0.5, and using alternative PDF sets
Beyond exclusive leptonic resonances

Search for non-resonant features in dilepton mass spectra:

Resonance above the scale of direct detection at the LHC

High energy $\Lambda \rightarrow$ Interference at lower mass

Indication of:
- massive mediator boson
- quark/leptons compositeness

Search for leptoquark pair production:

Scalar leptoquark (LQ) pair production

Can enable:
- violation of lepton flavour universality
- mediation of flavour changing neutral currents

Search for Quantum Black Holes in 1 lepton and 1 jet channel:

Quantum Black Holes (QBHs) detectable at LHC

by lowering the scale of quantum gravity ($M_D$) to the TeV region

Solutions to:
the mass hierarchy problem

Search for type-III seesaw heavy leptons:

One neutral ($N^0$) and two oppositely charge leptons ($L^+L^-$)

Explaining the relative smallness of the neutrino masses
Why beyond exclusive leptonic resonances

High-mass dilepton resonances have been already searched using the full data recorded by the ATLAS experiment ($139 \, fb^{-1}$)

- **observable:**
  - dilepton ($m_{ll}$) invariant mass
  - $l = e, \mu$

- **signature:**
  - bump on smoothly-falling background

No significant deviation from the standard model is observed
heavy charged boson in events with a charged lepton and missing transverse momentum have been already searched using the full data recorded by the ATLAS experiment (139 $fb^{-1}$)

- **observable:**
  Transverse mass

- **signature:**
  bump on smoothly-falling background

No significant deviation from the standard model is observed