Searches for new Physics in events with multiple leptons with the ATLAS detector

Luca.Fiorini@cern.ch
(IFIC - U. of Valencia - CSIC)
on behalf of ATLAS collaboration

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Many models predict Beyond Standard Model (BSM) physics with final states with leptons. Leptons are clean probes for new particles with good signal over background (S/B) ratio at hadron colliders. Typically new particles production is predicted to happen in pairs → expect large multiplicity of leptons in the final states.

Covered in this talk: All 8 TeV results!

• Model Independent:
  • 3 or more leptons searches

• Model testing:
  • WZ resonances
  • Excited Leptons
  • Type III seesaw

Event with 2 reconstructed muons and 1 photon
Multilepton searches

Reference: ATLAS-CONF-2013-070

• General Selection criteria:
  • Events with at least 3 charged, prompt and isolated leptons: 
    $\geq 3 \, e/\mu$ and $2 \, e/\mu + =1 \tau$
  • Leading lepton: $p_T > 26 \, \text{GeV}$
  • Other leptons: $p_T > 15 \, \text{GeV}$
  • $p_T(\tau_{\text{had}}) > 20 \, \text{GeV}$

• Categories:
  1) On-Z 3e/µ
  2) On-Z 2 e/µ + τ_{had}
  3) Off-Z 3e/µ
  4) Off-Z 2 e/µ + τ_{had}

92 Signal Regions in total:

<table>
<thead>
<tr>
<th>Variable</th>
<th>Signal Region Definition</th>
<th>Additional Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_T^{\ell\ell}$</td>
<td>Inclusive</td>
<td>$\geq 200 , \text{GeV}$</td>
</tr>
<tr>
<td>Min. $p_T^{\ell}$</td>
<td>Inclusive</td>
<td>$\geq 50 , \text{GeV}$</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$</td>
<td>Inclusive</td>
<td>$\geq 100 , \text{GeV}$</td>
</tr>
<tr>
<td>$m_{\text{eff}}$</td>
<td>Inclusive</td>
<td>$\geq 600 , \text{GeV}$</td>
</tr>
<tr>
<td>$m_{\text{eff}}$</td>
<td>Inclusive</td>
<td>$\geq 600 , \text{GeV}$</td>
</tr>
<tr>
<td>$b$-tags</td>
<td>Inclusive</td>
<td>$\geq 1$</td>
</tr>
</tbody>
</table>

Selection variables:

1) $H_T^{\ell\ell}$: Sum of 3 lepton $p_T$
2) $H_T^{\text{jets}}$: Sum of all jet $p_T$
3) ETmiss: Missing transverse energy
4) meff: $H_T^{\ell\ell}$ + $H_T^{\text{jets}}$ + ETmiss
5) Min. $p_T(\ell)$: $p_T$ of 3rd lepton
6) $b$-tags: number of b-tagged jets

on-Z: $|m_{tt} - m_Z| < 20 \, \text{GeV}$

off-Z: $|m_{tt} - m_Z| > 20 \, \text{GeV}$

• Backgrounds:
  • Irreducible: WZ/ZZ (tt+W/Z,Zγ)
  • Reducible: W/Z+jets, tt
**Multileptons Control Regions**

- $tt$ control region defined by the presence of 2 same sign $e/\mu$ and 1 b-tagged jet.
- $H_T^{jets} < 500$ GeV cut to reduce eventual contamination of new physics.
- Main background is composed by $tt$ $l+$jets decay mode.

- $Z \rightarrow \tau_\mu \tau_{had}$ control region is defined by presence of two same sign leptons: $\mu + \tau$
- $H_T^{jets} < 500$ GeV cut to reduce eventual contamination of new physics.
Irreducible backgrounds are dominant in the 3 e/µ signal regions.

WZ/ZZ backgrounds modelled by Sherpa generator.

Reducible backgrounds (with fake leptons) are larger in the 2 e/µ + τ signal regions.

They are modelled with data-driven methods, in control regions were the lepton identification criteria are relaxed.
Multileptons Results

Deviation from expected yields divided by total uncertainty

- Fiducial efficiencies ($\varepsilon_{\text{fid}}$) are also given as a function of the $p_T$ and $\eta$ of all leptons along with instructions to calculate upper limits on the cross section of specific model testing.

$$\sigma_{95}^{\text{fid}} = \frac{N_{95}}{(\varepsilon_{\text{fid}} \cdot \int L \, dt)}$$

- All tables made available as HEPDATA and RIVET code.
Testing of Specific Models

- **WZ resonances:** EXOT-2013-07 (arXiv:1406.4456)
- **Excited Leptons:** New J. Phys. 15 (2013) 093011
- **Type III seesaw:** ATLAS-CONF-2013-019
Motivation:

- Many NP theories predict diboson resonances at high mass: GUT, Little Higgs, Extended Gauge Model, Heavy Vector Triplet and Extra Dimensions among others.

General Selection Criteria:

- 3 e/µ selected with $p_T > 25$ GeV and event $E_{T}^{\text{miss}} > 25$ GeV
- $|m_{\ell\ell} - m_Z| < 20$ GeV is required for a pair of same flavour, different charge leptons.
- $\Delta y(W,Z) < 1.5$ to increase signal to background ratio.
- Low Mass (High Mass) region defined by $\Delta \varphi(\ell, E_{T}^{\text{miss}}) > 1.5 (< 1.5)$

SM Background:

- VV and ttV (estimated from MC, but checked in WZ Control Region)
- $Z\gamma$ modelled by MC (Sherpa)
- $Z$+jets, ttbar, and other $\ell\ell$+jets sources, where a jet is misidentified as a lepton are estimated from data.
- SM WZ production is the main background.
- \( W' \rightarrow WZ \) final state expectations are superimposed.
- Good agreement between data and predictions in the signal regions.
- No significant excess is observed.
95% Confidence Limits are set as a function of $m_{WZ}$

- $W' \rightarrow WZ$ limit and HVT are explicitly derived:
  - $M_{W'} > 1.52$ TeV @ 95% CL
  - HVT mass limits for the 3 chosen benchmark models
Excited Leptons

General Selection Criteria:
• Assume excited leptons ($\ell^*$) are produced in contact interactions, hence their masses must be less than the compositeness scale $\Lambda$.
• Looking for events $pp \rightarrow \ell\ell^* \rightarrow \ell\ell\gamma$

SM Background:
• $Z + \text{jets}$ (MC sample normalised in CR to account for misidentification of jets as photons)
• $Z + \gamma$ (MC)
tt and diboson processes (MC)
• $W + \gamma + \text{jets}$ (MC sample normalised with a likelihood fit to account for the misidentification of jets to electrons)
# Excited Leptons Selection

**Electrons**
- Electron $p_T > 40(30)$ GeV for leading (subleading)
- Electron (muon) $|\eta| < 2.47$
- Electron candidates are "medium"
- Isolated and prompt
- No jet overlap

**Muons**
- Muon $p_T > 25$ GeV for both
- Muon $|\eta| < 2.5$
- Isolated and prompt
- No jet overlap

**Photons**
- Photon $p_T > 30$ GeV
- Photon $|\eta| < 2.37$
- Photon candidates are "tight"
- Well Isolated
- No jet overlap

**Selection Criteria**
- Z-veto ($m_{\ell\ell} > 110$ GeV)
- $m_{\ell\ell\gamma} > 1050$ GeV for $m_{\ell\ast} \geq 900$ GeV
- $m_{\ell\ell\gamma} > m_{\ell\ast} + 150$ GeV for $m_{\ell\ast} < 900$ GeV

<table>
<thead>
<tr>
<th>Samples</th>
<th>Regions (GeV)</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>$70 &lt; m_{ee} &lt; 110$</td>
</tr>
<tr>
<td>$Z + \gamma$</td>
<td>1235 ± 25</td>
</tr>
<tr>
<td>$Z + jets$</td>
<td>371 ± 48</td>
</tr>
<tr>
<td>$t\bar{t}$, diboson</td>
<td>18 ± 1</td>
</tr>
<tr>
<td>$W + \gamma + jets$</td>
<td>9 ± 9</td>
</tr>
<tr>
<td>Total MC</td>
<td>1633 ± 55</td>
</tr>
<tr>
<td>Data</td>
<td>1633</td>
</tr>
</tbody>
</table>
Excited Leptons Results

For $\Lambda = m_{\ell^*}$, excited-electron and excited-muon masses below 2.2 TeV are excluded.
Motivations:
- Mechanisms to extend the SM for neutrino mass generation:
  - Introduce Majorana and Dirac mass terms, seesaw mechanism to explain neutrinos light mass:
    - Type I: at least two additional $\nu_R$ heavy neutrinos
    - Type II: masses generated in the Higgs sector adding additional Higgs triplet
    - Type III: introduced one or more leptonic triplets

• Selection criteria:
  - $5.8 \text{ fb}^{-1}$ at 8 TeV is used
  - $Z(\ell\ell)+2\ell$ with $p_T > 25,10,10,10$ GeV
  - $N^+$ is fully reconstructed:
    - Same flavour $\ell^+\ell^-$ with $|m_Z-m_\ell|<10$ GeV
    - third lepton is the closest in phi to the $Z$
  - Events with a second $Z$ candidate are rejected to reduce diboson background.
Heavy Leptons backgrounds

SM Backgrounds:
- ZZ production (MC normalised to data in CR)
- VVV production (MC)
- ttV and Z+ jets (MC)

- ZZ CR defined by reverting the second Z-boson veto
Results:

- Scenario of maximum allowed mixing angles with SM leptons.
- Exclusion limit on $m_N$ is 245 GeV.
- Limits are also set for different $N^0,\pm$ BR hypothesis and mass:
  - It translates in limits on $m_N$ between 230 and 350 GeV
Summary

- Prompt isolated leptonic final states are excellent probes for BSM physics.

- Both inclusive searches and specific searches for New Physics models are being performed with ATLAS data.

- ATLAS recent result on WZ resonances interpreted in terms of $W'$ exclusion.

- Model-independent 3 or more lepton searches do not reveal BSM yet
- Your favourite model not shown here?
  → use our RIVET routines for quick tests.
  - Rivet link  HEPDATA link

- New Physics has not been observed yet at LHC 7-8 TeV.

- Looking forward for LHC Run2 with $E_{CM} \geq 13$ TeV!
Bonus Slides
Excited Leptons Control Regions

- \( Z^+ g \) CR defined by \( 70 < m_{\ell\ell} < 110 \) GeV
Heavy Lepton Selection

Leptons

- Lead Lepton $p_T > 25$ GeV (in order to pass trigger)
- Three subleading leptons $p_T > 10$ GeV
- Electron (muon) $|\eta| < 2.47(2.5)$
- Electron candidates are "tight"
- Muon candidates have combined tracks (ID and MS)
- Isolated and prompt
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Motivation:
• Many NP final states have same-sign isolated prompt leptons: doubly charged Higgs, $W_R$ decays, b'b' decays among others.

General Selection Criteria:
• $e^±e^±$, $\mu^±\mu^±$ pairs are selected with lepton $p_T$ > 20 GeV (25 GeV for the leading electron).
• $m_{\ell\ell}$ > 15 GeV, 70 < $m_{ee}$ < 110 GeV is vetoed to reject the large background from misidentified charge.

SM Background:
• With same sign leptons: VV and $t\bar{t}V$ (estimated from MC)
• With opposite sign or misidentified leptons: $Z$+jets, ttbar, $W(\gamma)+$jets (charge and lepton misidentification estimated from data).
Good agreement between data and predictions in the signal regions.

Events with a misidentified charge are the main backg. in the $ee$ final state, while $WZ$ with prompt same-sign leptons are the dominant background in $\mu\mu$ and $e\mu$ channels.

No significant excess is observed.
Same-sign Results

- 95% Confidence Limits are converted into fiducial cross section limits

\[ \sigma_{95}^{\text{fid}} = \frac{N_{95}}{\epsilon_{\text{fid}} \cdot \int L dt} \]

- Fiducial efficiencies vary from 43-72%
- Table and fiducial data available for specific model testing (UED, seesaw, vector-like quarks, Zee-Babu models, etc...).

- H^{++} limits are explicitly derived:
  - \( H^{\pm \pm}_L \) mass > 409 GeV 95% CL
  - \( H^{\pm \pm}_R \) mass > 322 GeV 95% CL