Search for lepton-flavor violation in high-mass dilepton final states with the ATLAS detector

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• Direct charged-lepton flavor violation (LFV) is forbidden in the Standard Model

• Hypothetic new physics models
  - Scalar particle: R-Parity Violating (RPV) SUSY $\tilde{\nu}_\tau$
  - Vector particle: Sequential Standard Model (SSM) $Z'$
  - Tensor particle: Quantum Black Hole (QBH)

• Aim of this analysis: search for a new resonance with two leptons of different flavor ($e\mu, e\tau, \mu\tau$) in high mass region. Otherwise, set limits on the parameters of new physics models

• Clear experimental signature
  - Low background from SM processes
  - The invariant mass of the heavy neutral particle can be reconstructed

Data and signal simulation samples

- Dataset recorded with the ATLAS detector in 2015 and 2016 at $\sqrt{s} = 13$ TeV, corresponding to an integrated luminosity of 36.1 fb$^{-1}$

- Signal MC Samples
  - $Z'$: Pythia8
  - QBH: QBH+Pythia8
  - SUSY $\tilde{\nu}_\tau$: MadGraph + Pythia8
Object and Event selection

- **Muon**
  - $P_T > 65\text{GeV}; |\eta| < 2.5$
  - ID: high-$p_T$ operating point
  - Isolation: track-based
  - Track: $|d_0/\sigma_{d_0}| < 3$; $|\Delta z_0 \sin \theta| < 0.5 \text{mm}$

- **Electron**
  - $P_T > 65\text{GeV}; |\eta| < 2.5$
    - except $1.37 \sim 1.52$
  - ID: likelihood Tight
  - Isolation: calorimeter-based
  - Track: $|d_0/\sigma_{d_0}| < 5$; $|\Delta z_0 \sin \theta| < 0.5 \text{mm}$

- **Tau**
  - $P_T > 65\text{GeV}; |\eta| < 2.5$
    - except $1.37 \sim 1.52$
  - ID: BDT Loose
  - Track: 1 or 3 prongs
  - Charge: $\pm 1$

- **Event selection**
  - Pre-selection: remove events with error status flag on detectors
  - Pass single-electron or single-muon triggers and at least 1 trigger matched lepton ($P_T$ threshold of 50 GeV for muons and 60 or 120 GeV for electrons)
  - 3rd lepton veto: events with an additional good lepton are rejected.
  - DeltaPhi: $\Delta \phi (ll') > 2.7$
  - Look for events with masses above 120 GeV
Background estimation

- **Irreducible background** (processes produce two different-flavor prompt leptons)
  - $Z/\gamma^* \rightarrow \tau\tau$: Powheg
  - Diboson: Sherpa
  - Top($t\bar{t}$, single Top): Powheg + Pythia and Sherpa (limited for dilepton invariant masses above 1 TeV)
  - Extrapolation is applied with 2 functions on the Top background.

\[
1) \quad \frac{a}{(m_{\ell\ell'} + b)^c} \quad 2) \quad a \cdot m_{\ell\ell'}^b \cdot m_{\ell\ell'}^c \cdot \ln(m_{\ell\ell'})
\]

- **Reducible background** (estimated by data-driven)
  - $W+$jets and multi-jet processes
  - $e\mu \sim 5\%$
  - $e\tau/\mu\tau \sim 50$-$60\%$
Reducible background estimation in $e\mu$

- A 2 X 2 Matrix Method is performed to estimate the jet faked background in $e\mu$ channel

\[
\begin{bmatrix}
N_{TT} \\
N_{LT}
\end{bmatrix} = \begin{bmatrix}
r_e & f_e \\
1 & 1
\end{bmatrix} \begin{bmatrix}
N_{RR} \\
N_{FR}
\end{bmatrix}
\]

- $N_{TT}$: sample where both the electron and the muon pass the tight cut
- $N_{LT}$: sample where electron loose and the muon pass the tight cut

- $r_e$: real electron efficiency
  - The probability of a “loose” electron (looser ID and without isolation requirement) matched to a generated electron to pass the full object selection
  - Estimated by Zee MC samples

- $f_e$: electron fake rate
  - The probability that a jet is misidentified as an electron
  - Estimated in a multi-jet CR
Reducible background estimation in $e\tau/\mu\tau$

- **W+jets estimation** (jet misidentified as $\tau$)
  - Weight simulated $W$+jets events with the $\tau$ fake rate
  - The $\tau$ fake rate is measured in a $W$+jets control region, using the same selection as the signal region, but reverses the back-to-back criterion
  - Contributions from non-$W$+jets processes are subtracted using simulation

- **Multi-jet estimation**
  - Use the events in three control regions to evaluate the contribution

<table>
<thead>
<tr>
<th>R1</th>
<th>Object selection</th>
<th>Lepton-pair charges</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Non-isolated $e/\mu$ &amp; $\tau_{\text{had-vis}}$ failing $\tau$ ID requirements ($p_{T\ell}$ &amp; $p_{T\tau} &lt; 200$ GeV)</td>
<td>Same-charge</td>
</tr>
<tr>
<td>R2</td>
<td>Isolated $e/\mu$ &amp; pass ID $\tau_{\text{had-vis}}$ ($p_{T\ell}$ &amp; $p_{T\tau} &lt; 200$ GeV)</td>
<td>Same-charge</td>
</tr>
<tr>
<td>R3</td>
<td>Non-isolated $e/\mu$ &amp; $\tau_{\text{had-vis}}$ failing $\tau$ ID requirements</td>
<td>Same-charge + Opposite-charge</td>
</tr>
</tbody>
</table>

- The final contribution is estimated as $N_{MJ} = N_{R3} \times N_{R2} / N_{R1}$
Background estimation validation

The validation of the background estimation in the W+jets control region
### Systematic uncertainties

- **Summary of the systematic uncertainties as a percentage of the total background**
- **The PDF uncertainties and the uncertainty on the extrapolation to estimate the top-quark are dominant**

<table>
<thead>
<tr>
<th>Source</th>
<th>1 TeV</th>
<th>2 TeV</th>
<th>3 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$e\mu$</td>
<td>$e\mu$</td>
<td>$e\tau$</td>
</tr>
<tr>
<td>Luminosity</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Top-quark extrapolation</td>
<td>5</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Top scale</td>
<td>7</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>PDF</td>
<td>16</td>
<td>15</td>
<td>12</td>
</tr>
<tr>
<td>Pile-up</td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Dilepton $p_T$ modeling</td>
<td>7</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Electron iden. and meas.</td>
<td>4</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Muon iden. and meas.</td>
<td>3</td>
<td>4</td>
<td>-</td>
</tr>
<tr>
<td>$\tau$ iden. and meas.</td>
<td>-</td>
<td>-</td>
<td>2</td>
</tr>
<tr>
<td>$\tau$ reconstruction eff.</td>
<td>-</td>
<td>-</td>
<td>2</td>
</tr>
<tr>
<td>$\tau$ fake rate</td>
<td>-</td>
<td>-</td>
<td>6</td>
</tr>
<tr>
<td>Multijet transf. factor</td>
<td>-</td>
<td>-</td>
<td>31</td>
</tr>
<tr>
<td>Reducible $e\mu$ estimation</td>
<td>2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Jet eff. and resol.</td>
<td>1</td>
<td>4</td>
<td>9</td>
</tr>
<tr>
<td>$b$-tagging</td>
<td>-</td>
<td>3</td>
<td>-</td>
</tr>
<tr>
<td>$E_T^{miss}$ resol. and scale</td>
<td>-</td>
<td>-</td>
<td>3</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>19</td>
<td>20</td>
<td>37</td>
</tr>
</tbody>
</table>
Results

<table>
<thead>
<tr>
<th></th>
<th>eμ Signal Region</th>
<th>et Signal Region</th>
<th>μτ Signal Region</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top</td>
<td>145.3 ± 28.0</td>
<td>165.9 ± 53.2</td>
<td>98.3 ± 26.6</td>
</tr>
<tr>
<td>Diboson</td>
<td>50.7 ± 8.1</td>
<td>53.0 ± 11.3</td>
<td>36.2 ± 9.5</td>
</tr>
<tr>
<td>Mutijet and W+jets</td>
<td>24.2 ± 9.5</td>
<td>328.4 ± 139.4</td>
<td>136.1 ± 44.3</td>
</tr>
<tr>
<td>Z-&gt;ll</td>
<td>1.4 ± 0.3</td>
<td>26.9 ± 6.0</td>
<td>15.2 ± 4.5</td>
</tr>
<tr>
<td>Total background</td>
<td>221.6 ± 37.5</td>
<td>575.2 ± 156.4</td>
<td>297.5 ± 116.3</td>
</tr>
<tr>
<td>Data</td>
<td>197</td>
<td>509</td>
<td>269</td>
</tr>
</tbody>
</table>

No significant excess beyond SM expectation observed
Limit setting: $e\mu$ channel

<table>
<thead>
<tr>
<th>Model</th>
<th>Expected limit [TeV]</th>
<th>Observed limit [TeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$e\mu$ ($b$-veto)</td>
<td>$e\tau$</td>
</tr>
<tr>
<td>LFV $Z'$</td>
<td>4.3 4.3</td>
<td>3.7</td>
</tr>
<tr>
<td>RPV SUSY $\tilde{\nu}_\tau$</td>
<td>3.4 3.4</td>
<td>2.9</td>
</tr>
<tr>
<td>QBH ADD $n = 6$</td>
<td>5.6 5.5</td>
<td>4.9</td>
</tr>
<tr>
<td>QBH RS $n = 1$</td>
<td>3.3 3.4</td>
<td>2.8</td>
</tr>
</tbody>
</table>
Limit setting: $e\tau$ channel

<table>
<thead>
<tr>
<th>Model</th>
<th>Expected limit [TeV]</th>
<th>Observed limit [TeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$e\mu$</td>
<td>$e\mu$</td>
</tr>
<tr>
<td><strong>(b-veto)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LFV $Z'$</td>
<td>4.3</td>
<td>4.3</td>
</tr>
<tr>
<td>RPV SUSY $\tilde{\nu}_\tau$</td>
<td>3.4</td>
<td>3.4</td>
</tr>
<tr>
<td>QBH ADD $n = 6$</td>
<td>5.6</td>
<td>5.5</td>
</tr>
<tr>
<td>QBH RS $n = 1$</td>
<td>3.3</td>
<td>3.4</td>
</tr>
</tbody>
</table>

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Limit setting: $\mu\tau$ channel

<table>
<thead>
<tr>
<th>Model</th>
<th>Expected limit [TeV]</th>
<th>Observed limit [TeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$e\mu$ (b-veto)</td>
<td>$e\mu$ (b-veto)</td>
</tr>
<tr>
<td>$\text{LFV } Z'$</td>
<td>4.3</td>
<td>4.3</td>
</tr>
<tr>
<td>RPV SUSY $\tilde{\nu}_\tau$</td>
<td>3.4</td>
<td>3.4</td>
</tr>
<tr>
<td>QBH ADD $n = 6$</td>
<td>5.6</td>
<td>5.5</td>
</tr>
<tr>
<td>QBH RS $n = 1$</td>
<td>3.3</td>
<td>3.4</td>
</tr>
</tbody>
</table>
Summary

- Presented search for a heavy particle decaying into an $e\mu$, $e\tau$ or $\mu\tau$ final state using $36.1 \text{ fb}^{-1}$ of $\sqrt{s} = 13$ TeV $pp$ data collected by the ATLAS experiment at the LHC during the 2015 and 2016 run periods.

- Bayesian lower limits at 95% credibility level are set on the mass of a $Z'$ vector boson, supersymmetric $\tau$-sneutrino and the threshold mass for quantum black-hole production, reaching out to the TeV regime.

- For the second round, a full run-II analysis is ongoing with almost 4 times the integrated luminosity.
BACKUP
Coupling limits Z’

- For LFV Z’ and RPV SUSY $\tilde{\nu}_\tau, \sigma \times BR$ limits can be converted to coupling limits to facilitate comparison with low-energy precision measurements.

- ATLAS limits
  - Assumed a Sequential Standard Model (SSM) Z’ with addition LFV coupling
  - LFV terms are assumed to have V-A structure as SM Z coupling to lepton pairs: $Q_{ll'}$ is the ratio of the LFV Z’ coupling to $ll'$ compare to the Z coupling to $ll$
  - The limit on $Q_{ll'}$ is $(\sigma \times BR)_{ll'}^{lim} / (\sigma \times BR)_{ll'}^{theory}$

- Low energy limits
  - $e\mu$ channel: most significant limits are from $\mu$ to $e$ conversion
  - $e\tau$ channel: most significant limits are from $\tau \rightarrow eee$ and $e\mu\mu$
  - $\mu\tau$ channel: most significant limits are from $\tau \rightarrow \mu\mu\mu$ and $\mu ee$

- $e\mu$ channel: low-energy limits are significantly more stringent, but there are model dependencies (different for low-energy and ATLAS)
- $e\tau/\mu\tau$ channels: ATLAS limits are better than those from low-energy experiments, but, as before, there are different model dependencies
Coupling limits $Z'$

The 95% CL upper limits on the couplings as a from the cross-section times branching ratio (solid lines) and from low-energy experiments (dashed lines).
Coupling limits RPV

- For LFV Z’ and RPV SUSY $\tilde{\nu}_\tau$, $\sigma \times BR$ limits can be converted to coupling limits to facilitate comparison with low-energy precision measurements.

- ATLAS limits
  - Assumed only coupling to $l l'$ and $d \bar{d}$
  - $\sigma \propto |\lambda'|^2$ and $BR(\ell \ell') = \frac{\Gamma_{\ell \ell'}}{\Gamma_{\ell \ell'} + \Gamma_{d \bar{d}}} = \frac{2|\lambda|^2}{2|\lambda|^2 + 3|\lambda'|^2}$
  - $\left( \frac{2|\lambda|^2|\lambda'|^2}{2|\lambda|^2 + 3|\lambda'|^2} \right) < \frac{\sigma \times BR}{\sigma \times BR_{MC}} \left( \frac{|\lambda|^2|\lambda'|^2}{2|\lambda|^2 + 3|\lambda'|^2} \right)_{MC}$, where $\lambda_{MC} = 0.07$ and $\lambda'_{MC} = 0.11$

- Low energy limits
  - $e\mu$ channel: most significant limits are from $\mu$ to $e$ conversion
  - $e\tau$ channel: most significant limits are from $\tau \rightarrow e\eta$
  - $\mu\tau$ channel: most significant limits are from $\tau \rightarrow \mu\eta$
The 95% CL upper limits on the couplings as a from the cross-section times branching ratio limits and from low-energy experiments.