Search for lepton flavour violation with the ATLAS detector

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◦ LHC and the ATLAS detector

◦ Searches:
  ◦ Decays of Standard-Model (SM) particles
  ◦ Decays of hypothetical particles / objects

◦ Summary
Introduction – Lepton Flavour Violation

- Flavour conservation is not a fundamental symmetry in the SM
- Fermions do change flavour:
  - Quarks: CKM matrix → quark mixing observed
  - Leptons: PMNS matrix → neutrino mixing observed
- How about charged leptons?
  - → (charged) Lepton Flavour Violation (cLFV)
  - Not observed yet
- In the SM
  - Loop with neutrino oscillations
  - Vanishingly small branching ratios
- BSM
  - Various models: Supersymmetry, extended gauge models, heavy neutrinos, etc.
  - Some predict LFV couplings to be tested at the LHC
  - Unambiguous signal: observation = new physics phenomena!
The Large Hadron Collider (LHC)

- World’s largest and most powerful particle accelerator
  - 27-km ring near Geneva, Switzerland
  - Completed first operational run (“Run 1”):
    - 2010-2011: $pp$ collisions at $\sqrt{s} = 7$ TeV ($5 \text{ fb}^{-1}$)
    - 2012: $pp$ collisions at $\sqrt{s} = 8$ TeV ($21 \text{ fb}^{-1}$)
  - Currently in second operational run (“Run 2”):
    - 2015-2018: $pp$ collisions at $\sqrt{s} = 13$ TeV (expecting $\sim 150 \text{ fb}^{-1}$)
The ATLAS detector

- General-purpose particle detector at the LHC
  - Inner detector (ID)
    - High-precision tracking
    - Silicon pixels / strips + transition radiation trackers
  - Calorimeters
    - EM: liquid argon (LAr)
    - Hadronic: scintillating tiles + LAr endcaps
  - Muon spectrometer (MS)
    - Muon identification and tracking
  - Magnet systems
    - Solenoidal (ID)
    - Toroidal (MS)
The ATLAS detector – Lepton efficiencies

**Loose/Medium/Tight**
electrons

**Loose (top) / Tight (bottom)**
muons

**Medium 1-prong \( \tau \)-leptons**
Searches with the ATLAS detector

- Decays of Standard-Model particles:
  - $Z \rightarrow e\mu; Z \rightarrow e\tau/\mu\tau$
  - $H \rightarrow e\tau/\mu\tau$
  - $\tau \rightarrow 3\mu$

- Decays of hypothetical particles / objects:
  - $Z' –$ Heavy gauge boson
  - $\tilde{\nu} –$ R-parity violating supersymmetry (RPV SUSY) sneutrino
  - QBH – Quantum black hole

New update!! arXiv:1804.09568

New update!! arXiv:1807.06573
$Z \rightarrow e\mu$

- **Dataset**
  - 20.3 fb$^{-1}$ of $pp$ collisions at $\sqrt{s} = 8$ TeV (2012)

- **Major backgrounds**
  - $Z \rightarrow \tau\tau \rightarrow e\mu\nu\bar{\nu}\bar{\nu}$
  - $WW \rightarrow e\mu\nu\bar{\nu}$
  - $t\bar{t} \rightarrow e\mu\nu\bar{b}\bar{b}$

- **Strategy**
  - Reject events with high-energy jets $\rightarrow$ suppress $t\bar{t}$
  - Reject events with large transverse missing energy ($E_T^{\text{miss}}$) $\rightarrow$ suppress $WW$
  - Fit $e\mu$ invariant mass spectrum $\rightarrow$ search for signal peaking near the $Z$ mass
\( Z \rightarrow e\mu \)

Rejection of events with high-energy jets \( (p_T^{\text{jet}}_{\text{max}}) \)

Rejection of events with large \( E_T^{\text{miss}} \)

Invariant mass \( (m_{e\mu}) \) spectrum after all cuts

\( s = 8 \text{ TeV}, 20.3 \text{ fb}^{-1} \)
$Z \rightarrow e\mu$

- Results and interpretation
  - Upper limit (95% CL) on the branching ratio is calculated by $\text{BR}(Z \rightarrow e\mu) < \frac{N_{95\%}}{\epsilon_{e\mu} N_Z}$
  - $N_Z = \text{total number of produced } Z \text{ bosons, estimated by } Z \rightarrow ee \text{ and } Z \rightarrow \mu\mu \text{ measurements}$
  - $\epsilon_{e\mu} = \text{reconstruction efficiency of } e\mu \text{ events}$
  - $N_{95\%} = \text{upper limit on number of } Z \rightarrow e\mu \text{ events, obtained by fitting } m_{e\mu} \text{ spectrum}$
  - Upper limit (95% CL): $\text{BR}(Z \rightarrow e\mu) < 7.5 \times 10^{-7}$
\[ Z \rightarrow e\tau/\mu\tau \]

- **Dataset**
  - 36.1 fb\(^{-1}\) of \(pp\) collisions at \(\sqrt{s} = 13\) TeV (2015-2016)
  - Results for \(Z \rightarrow \mu\tau\) combined with previous analysis with 20.3 fb\(^{-1}\) 8-TeV data (2012)

- **Focus on channels with hadronically-decaying \(\tau\)**

- **Major backgrounds**
  - \(Z \rightarrow \tau\tau \rightarrow \ell\tau_{\text{had}}\) \((\ell = e/\mu; \tau_{\text{had}} = \text{hadronically-decaying }\tau)\)
  - \(W (\rightarrow \ell\nu) + \text{jets}\) (jets mis-identified as \(\tau_{\text{had}},\) aka “jet \(\rightarrow\) \(\tau\) fakes”)
  - \(Z \rightarrow \ell\ell\) \((e/\mu\) mis-identified as \(\tau_{\text{had}},\) aka “\(\ell\) \(\rightarrow\) \(\tau\) fakes”)

- **Strategy**
  - Reject events with high \(m_T(\tau_{\text{had-vis}}, E_T^{\text{miss}})\) \(\rightarrow\) suppress \(Z \rightarrow \tau\tau / W + \text{jets}\)
  - Reject events with visible invariant mass \(\approx m_Z\) \(\rightarrow\) suppress \(Z \rightarrow \ell\ell\)
  - Estimate jet \(\rightarrow\) \(\tau\) fakes by data-driven method
  - Discriminate events by neural network (NN) and fit on output
Rejection of events with high $m_T(\tau_{\text{had-vis}}, E_T^{\text{miss}})$

*Plot for the $e\tau$ channel is similar*

Rejection of events based on visible invariant mass

$m(\text{track}, \ell)$: $\tau$ energy measured by ID tracking

$m(\tau_{\text{had-vis}}, \ell)$: $\tau$ energy measured by calorimeters

$Z \rightarrow \mu\mu$  

$Z \rightarrow ee$
$Z \rightarrow e\tau/\mu\tau$

- Data-driven jet $\rightarrow \tau$ fakes estimation
  - jet $\rightarrow \tau$ fakes not well modelled in simulation
  - Measure fake factors (FF) in calibration regions (CR) using data

1. Measure FF in CR:
   FF = ratio of events passing/failing $\tau$ identification

2. Apply FF in SR:
   Estimation = FF $\times$ events failing $\tau$ ID

- Neural network classifiers
  - 3 classifiers: signal against $Z \rightarrow \tau\tau$, $W$+jets, and $Z \rightarrow \ell\ell$ backgrounds
  - Trained with simulated events
  - Inputs: 4-momenta of $\ell$, $\tau$ and $E_T^{\text{miss}}$ + few high-level variables like inv. mass
  - Combined into one powerful classifier
$Z \to e\tau/\mu\tau$

- **Results and interpretation**
  - Predicted NN output distributions are fit to data
  - Free parameters: $\text{BR}(Z \to \ell\tau)$ and normalisations of $Z$ and jet $\to \tau$ fakes
  - Events with 1-prong and 3-prong $\tau_{\text{had}}$ are fit separately (but simultaneously)
  - Upper limits (95% CL):
    \[
    \begin{align*}
    \text{BR}(Z \to e\tau) &< 5.8 \times 10^{-5} \\
    \text{BR}(Z \to \mu\tau) &< 2.4 \times 10^{-5}
    \end{align*}
    \]
  - Combined with 8-TeV data*:
    \[
    \begin{align*}
    \text{BR}(Z \to \mu\tau) &< 1.3 \times 10^{-5}
    \end{align*}
    \]

*no 8-TeV ATLAS results on $Z \to e\tau$
\[ H \rightarrow e\tau/\mu\tau \]

- **Dataset**
  - 20.3 fb\(^{-1}\) of pp collisions at \( \sqrt{s} = 8 \) TeV (2012)

- **Consider both leptonically- and hadronically-decaying \( \tau \)**

- **Major backgrounds**
  - \( \ell\tau_{\text{lep}} \) channels: \( Z+\text{jets}, WW, t\bar{t} \)
  - \( \ell\tau_{\text{had}} \) channels: \( Z+\text{jets}, W+\text{jets}, \text{QCD multi-jet (jet} \rightarrow \tau \text{ fakes)} \)

- **Strategy**
  - \( \ell\tau_{\text{lep}} \) channels:
    - Focus on \( e\mu \) final state – exploit \( e \leftrightarrow \mu \) symmetry in SM, asymmetry for LFV signal
  - \( \ell\tau_{\text{had}} \) channels:
    - Make use of signal characteristics in \( m_T(\tau_{\text{had-vis}}, E_T^{\text{miss}}) \) and \( m_T(\ell, E_T^{\text{miss}}) \) (similar to \( Z \rightarrow \ell\tau_{\text{had}} \))

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$H \rightarrow e\tau/\mu\tau$

- $\ell\tau_{\text{lep}}$ channels ($e\mu$ final state)
  - Two categories: one for $p_T^e > p_T^\mu$ ($e\mu$) and one for $p_T^e < p_T^\mu$ ($\mu e$)
  - $e\mu \leftrightarrow \mu e$ symmetric in SM, asymmetric for LFV signal ($e/\mu$ from $\tau$ is softer)
  - Fit mass spectrum after correcting for asymmetry from trigger/reco. efficiencies and mis-identifications

\begin{align*}
  &\text{⊕} \\
  &\text{ATLAS} \\
  &\text{130 GeV} \\
  &\int L dt = 20.3 fb^{-1} \\
  &\text{Data } e\mu \text{ SR} \\
  &\text{Symm. background} \\
  &\text{Tot. background} \\
  &\text{Post-fit uncertainty} \\
  &e\mu, \text{ SR (no jets)} \\
  &\mu e, \text{ SR (no jets)} \\
  &e\mu, \text{ SR (with jets)} \\
  &\mu e, \text{ SR (with jets)}
\end{align*}
$H \rightarrow e\tau/\mu\tau$

- $\ell\tau_{\text{had}}$ channels
  - Two SRs: different background composition ($W$+jets or $Z \rightarrow \tau\tau$ dominating)
  - Event selection mainly based on $m_T(\tau_{\text{had-vis}}, E_T^{\text{miss}})$ and $m_T(\ell, E_T^{\text{miss}})$
\( H \rightarrow e\tau/\mu\tau \)

- **Results and interpretation**
  - All channels are statistically combined
  - Limit on \( \text{BR}(H \rightarrow e\tau) \) obtained under the assumption \( \text{BR}(H \rightarrow \mu\tau) = 0 \), and vice versa
  - Upper limits (95% CL):
    \[
    \text{BR}(H \rightarrow e\tau) < 1.04 \times 10^{-2} \\
    \text{BR}(H \rightarrow \mu\tau) < 1.43 \times 10^{-2}
    \]
\( \tau \rightarrow 3\mu \)

- **Dataset**
  - 20.3 fb\(^{-1}\) of pp collisions at \( \sqrt{s} = 8 \) TeV (2012)

- **Major backgrounds / challenges**
  - Almost background-free
  - Challenging for ATLAS (very low-energy and close-by muons)

- **Strategy**
  - Use \( \tau \) from \( W \rightarrow \tau \nu \) (large \( p_T^\tau \rightarrow \) muons close in angle; large recoil \( E_T^{\text{miss}} \))
  - Select events with 3 muons with common vertex and \( m_{3\mu} \approx m_\tau \)
  - Event selection mainly based on muon kinematics and vertex displacement
    - *Loose* selection for Boosted Decision Trees (BDT) training
    - *Tight* selection for BDT cut optimization
  - Regions are defined according to how close \( m_{3\mu} \) is to \( m_\tau \):
    - (close to \( m_\tau \)) **signal region** < **blinded region** < **sideband region** < **training region** (far from \( m_\tau \))
\[ \tau \to 3\mu \]

- Analysis procedures
  - Obtain background samples *(loose selection in training region)*
  - Train BDT – input features:
    - \(3\mu\) and \(E_T^{\text{miss}}\) kinematics
    - Vertex/track fitting probability/significance
  - Study rejection *(tight selection in sideband region)*
  - Define optimal BDT cut
  - Count events in the signal region for interpretation
Results and interpretation

- One event observed at 1860 MeV
- Upper limit (90% CL): $\text{BR}(\tau \to 3\mu) < 3.76 \times 10^{-7}$
$Z'/\tilde{\nu}/QBH \rightarrow e\mu/e\tau/\mu\tau$

- **Dataset**
  - 36.1 fb$^{-1}$ of $pp$ collisions at $\sqrt{s} = 13$ TeV (2015-2016)

- **Major backgrounds**
  - $t\bar{t}$ and single-top
  - $W+$jets and QCD multi-jet (channels with $\tau$)

- **Strategy**
  - Select events with high-mass $e\mu/e\tau_{had}/\mu\tau_{had}$ final state
  - Construct invariant mass
  - Estimate top background by extrapolating from low-mass regions
  - Estimate $W+$jets and QCD multi-jet by data-driven methods
  - Interpretations in three types of models ($Z'/\tilde{\nu}/QBH$) using Bayesian method
$Z'/\tilde{\nu}/QBH \rightarrow e\mu/e\tau/\mu\tau$

- **Background estimation**
  - **Top background:**
    - Very limited number of simulated events at high-mass
    - Fit smooth functions (3 parameters) in low-mass regions and extrapolate (vary fit parameters and fit range → uncertainty estimate)
  - $W+$jets (channels with $\tau$):
    - Measure jet $\rightarrow \tau$ fake rate in $W+$jets-enriched control region
    - Apply to simulated jets in signal region
  - QCD multi-jet (channels with $\tau$):
    - Idea similar to $Z \rightarrow \ell\tau$ Fake Factor method
    - Measure “pass”/“fail” ratio using events in CR (low-$p_T$, same-charge $\ell\tau$ pairs) (“pass”/“fail” referring to lepton isolation and $\tau$ identification criteria)
    - Multiply observed “fail” events in signal region by the ratio

New update!  arXiv:1807.06573

arXiv:1607.08079
$Z'/\tilde{\nu}/QBH \rightarrow e\mu/e\tau/\mu\tau$

$\mathcal{m}_{e\mu}$

$\mathcal{m}_{e\tau}$

$\mathcal{m}_{\mu\tau}$

New update! arXiv:1807.06573
Results and interpretations

Three models

- $Z'$: SM quark couplings; no SM lepton couplings. Upper limit set on $m_{Z'}$
- $\tilde{\nu}$: RPV SUSY sneutrino. Upper limit set on $m_{\tilde{\nu}}$
- QBH: Considered two extra-dimension models – ADD ($n=6$) and RS ($n=1$). Upper limit set on threshold mass $m_{\text{th}}$

Only one LFV coupling ($e\mu/e\tau/\mu\tau$) allowed at a time

Upper limits on $m_{Z'}/m_{\tilde{\nu}}/m_{\text{th}}$ (95% CL, Bayesian):

<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>$b$-veto</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LFV $Z'$</td>
<td>4.3</td>
<td>4.3</td>
</tr>
<tr>
<td>RPV SUSY $\tilde{\nu}$</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

- LFV searches performed in ATLAS:
  - Decays of SM $Z$, $H$ and $\tau$
  - Decays of hypothetical $Z'$, $\tilde{\nu}$ and QBH

- No evidence or discovery of LFV processes

- Upper limits set on considered models

- Ongoing analyses with full Run-2 data
  - Data taking complete this year (2018)
  - Can expect luminosity $\sim 150$ fb$^{-1}$

- Stay tuned!!

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Wing Sheung Chan (Nikhef)
Thank you!
Backup


\[ Z \rightarrow e\mu: \text{ Event selections, reconstruction efficiencies} \]

<table>
<thead>
<tr>
<th>( Z ) decay</th>
<th>Efficiency (%)</th>
<th>( N_Z ) (10^8)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( ee )</td>
<td>10.8 ± 0.3</td>
<td>7.85 ± 0.24</td>
</tr>
<tr>
<td>( \mu\mu )</td>
<td>17.8 ± 0.4</td>
<td>7.79 ± 0.17</td>
</tr>
<tr>
<td>( \langle ee, \mu\mu \rangle )</td>
<td>7.80 ± 0.15</td>
<td></td>
</tr>
<tr>
<td>( e\mu )</td>
<td>14.2 ± 0.4</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sources</th>
<th>MC</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channels</td>
<td>ee</td>
<td>( \mu\mu )</td>
</tr>
<tr>
<td>Initial</td>
<td>62.5</td>
<td>65.7</td>
</tr>
<tr>
<td>Triggered</td>
<td>31.1</td>
<td>51.6</td>
</tr>
<tr>
<td>Two Lepton, ( \eta ) and ( p_T ) cuts</td>
<td>67.9</td>
<td>66.9</td>
</tr>
<tr>
<td>( E_T^{\text{miss}} &lt; 17 \text{ GeV} )</td>
<td>84.9</td>
<td>81.7</td>
</tr>
<tr>
<td>( p_T^{\text{jet}} &lt; 30 \text{ GeV} )</td>
<td>96.4</td>
<td>96.3</td>
</tr>
<tr>
<td>( 70 &lt; m_{\ell\ell} &lt; 110 \text{ GeV} )</td>
<td>81.8</td>
<td>86.5</td>
</tr>
<tr>
<td>( 85 &lt; m_{\ell\ell} &lt; 95 \text{ GeV} )</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

16/08/2018

Wing Sheung Chan (Nikhef)
**Z → ℓτ: Event selections, CR definitions**

<table>
<thead>
<tr>
<th>Region</th>
<th>Change relative to SR selection</th>
<th>Purity [%]</th>
<th>eτ</th>
<th>μτ</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRZll</td>
<td>Two same-flavor opposite-charge light leptons with 81 &lt; m_ℓℓ &lt; 101 GeV</td>
<td>98</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CRW</td>
<td>m_T(ℓ, E_T^{miss}) &gt; 40 GeV and m_T(τ_{had-vis}, E_T^{miss}) &gt; 35(30) GeV in e\tau (μτ) events</td>
<td>84</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CRT</td>
<td>N_{b-jets} ≥ 2</td>
<td>98</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CRQ</td>
<td>Inverted light-lepton isolation</td>
<td>75</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Preselection

- one isolated tight light lepton with p_T > 30 GeV matched to a lepton selected at trigger level
- leading τ_{had-vis} with p_T > 20 GeV, N_{τ tracks} = 1 or 3 and passing tight identification
  - if N_{τ tracks} = 1: 0.0(0.1) < |η_τ| < 1.37 or 1.52 < |η_τ| < 2.2(2.5) in eτ(μτ) events
  - if N_{τ tracks} = 3: 0.0 < |η_τ| < 1.37 or 1.52 < |η_τ| < 2.5
- q_ℓ × q_τ = -1
- no b-jet, no additional light lepton

Signal Region

- m_T(τ_{had-vis}, E_T^{miss}) < 35(30) GeV in eτ (μτ) events
  - if N_{τ tracks} = 1 and |η_τ| < 2.0: m(track, ℓ) < 84 GeV or m(track, ℓ) > 105 GeV
  - if N_{τ tracks} = 1 and |η_τ| > 2.0: m(track, ℓ) < 80 GeV or m(track, ℓ) > 105 GeV
  - if N_{τ tracks} = 1 and 80 < m(τ_{had-vis}, ℓ) < 100 GeV: m(track, ℓ) > 40 GeV
### $Z \rightarrow \ell\tau$: Observed/post-fit events, NN inputs

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>$Z$ NN</th>
<th>Zll NN</th>
<th>W NN</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\hat{E}_{\text{lep}}$</td>
<td>light-lepton energy</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
</tr>
<tr>
<td>$p_T^{\text{had-vis}}$</td>
<td>$\tau_{\text{had-vis}}$ $p_T$</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
</tr>
<tr>
<td>$p_T^{\text{had-vis}}$</td>
<td>$\tau_{\text{had-vis}}$ $p_z$</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
</tr>
<tr>
<td>$E_{\text{had-vis}}$</td>
<td>$\tau_{\text{had-vis}}$ energy</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
</tr>
<tr>
<td>$p_T^\mu$</td>
<td>$E_T^\text{miss}$ component along $z$-axis</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
</tr>
<tr>
<td>$E^\text{miss}$</td>
<td>magnitude of $E_T^\text{miss}$</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
</tr>
<tr>
<td>$p_T^{\text{tot}}$</td>
<td>transverse component of total momentum</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
</tr>
<tr>
<td>$m_{\text{coll}}$</td>
<td>collinear mass</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
</tr>
<tr>
<td>$\Delta \alpha$</td>
<td>see Eq. (1) [47]</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
</tr>
<tr>
<td>$m(\ell, \tau_{\text{had-vis}})$</td>
<td>invariant mass of light lepton and $\tau_{\text{had-vis}}$</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
</tr>
</tbody>
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<th>$Z$ NN</th>
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<th>W NN</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\ell$</td>
<td>1-prong</td>
<td>89 294</td>
<td>35 148</td>
<td></td>
</tr>
<tr>
<td>$\ell$</td>
<td>3-prong</td>
<td>89 300±300</td>
<td>35 200±200</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Event Type</th>
<th>Total observed</th>
<th>Total post-fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e\tau$ events</td>
<td>89 294</td>
<td>89 300±300</td>
</tr>
<tr>
<td>$\mu\tau$ events</td>
<td>79 744</td>
<td>79 700±500</td>
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<tr>
<th>Component</th>
<th>1-prong</th>
<th>3-prong</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fakes</td>
<td>57 000±1000</td>
<td>21 500±500</td>
</tr>
<tr>
<td>$Z \rightarrow \tau\tau$</td>
<td>26 000±1000</td>
<td>11 500±500</td>
</tr>
<tr>
<td>$Z \rightarrow \ell\ell$</td>
<td>3200±100</td>
<td>250±150</td>
</tr>
<tr>
<td>Top</td>
<td>770±120</td>
<td>440±70</td>
</tr>
<tr>
<td>$W+\text{jets}$</td>
<td>540±100</td>
<td>950±180</td>
</tr>
<tr>
<td>Other</td>
<td>340±70</td>
<td>150±30</td>
</tr>
<tr>
<td>$Z \rightarrow \tau e$ signal</td>
<td>900±400</td>
<td>390±160</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Component</th>
<th>1-prong</th>
<th>3-prong</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fakes</td>
<td>52 000±1000</td>
<td>13 600±800</td>
</tr>
<tr>
<td>$Z \rightarrow \tau\tau$</td>
<td>26 000±1000</td>
<td>10 300±300</td>
</tr>
<tr>
<td>$Z \rightarrow \ell\ell$</td>
<td>240±110</td>
<td>80±40</td>
</tr>
<tr>
<td>Top</td>
<td>890±140</td>
<td>360±60</td>
</tr>
<tr>
<td>$W+\text{jets}$</td>
<td>610±120</td>
<td>680±130</td>
</tr>
<tr>
<td>Other</td>
<td>290±70</td>
<td>110±20</td>
</tr>
<tr>
<td>$Z \rightarrow \tau\mu$ signal</td>
<td>−20±360</td>
<td>−10±140</td>
</tr>
</tbody>
</table>
$H \rightarrow \ell\tau$: Event selections, region definitions

<table>
<thead>
<tr>
<th>Criterion</th>
<th>$\ell\tau_{\text{had}}$</th>
<th>$\ell\tau_{\text{lep}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_T(e)$</td>
<td>$&gt;26$ GeV</td>
<td>Light leptons $e^\pm\mu^\mp$</td>
</tr>
<tr>
<td>$p_T(\tau_{\text{had}})$</td>
<td>$&gt;45$ GeV</td>
<td>$\tau$ leptons veto</td>
</tr>
<tr>
<td>$</td>
<td>\eta(e) - \eta(\tau_{\text{had}})</td>
<td>$</td>
</tr>
<tr>
<td>$m_T^{e,E_{T\text{miss}}}^{\tau_{\text{had}}}$</td>
<td>$&gt;40$ GeV</td>
<td>$b$-jets $0$</td>
</tr>
<tr>
<td>$m_T^{\tau_{\text{had}},E_{T\text{miss}}}$</td>
<td>$&lt;30$ GeV</td>
<td>$p_T^{\ell_1} \geq 35$ GeV</td>
</tr>
<tr>
<td>$N_{\text{jet}}$</td>
<td>$-\geq 2$</td>
<td>$p_T^{\ell_2} \geq 12$ GeV</td>
</tr>
<tr>
<td>$N_{b\text{-jet}}$</td>
<td>$0 \geq 1$</td>
<td>$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\Delta \phi(\ell_2, E_{T\text{miss}}) \leq 0.7$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\Delta \phi(\ell_1, \ell_2) \geq 2.3$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\Delta \phi(\ell_1, E_{T\text{miss}}) \geq 2.5$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\Delta p_T(\ell_1, \ell_2) \geq 7$ GeV</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SR$_{\text{noJets}}$</th>
<th>SR$_{\text{withJets}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light leptons $e^\pm\mu^\mp$</td>
<td>$e^\pm\mu^\mp$</td>
</tr>
<tr>
<td>$\tau$ leptons veto</td>
<td>veto</td>
</tr>
<tr>
<td>Central jets $0 \geq 1$</td>
<td>$1\geq 1$</td>
</tr>
<tr>
<td>$b$-jets $0$</td>
<td>$0$</td>
</tr>
<tr>
<td>$p_T^{\ell_1} \geq 35$ GeV</td>
<td>$\geq 35$ GeV</td>
</tr>
<tr>
<td>$p_T^{\ell_2} \geq 12$ GeV</td>
<td>$\geq 12$ GeV</td>
</tr>
<tr>
<td>$</td>
<td>\eta e^\pm</td>
</tr>
<tr>
<td>$</td>
<td>\eta \mu^\mp</td>
</tr>
<tr>
<td>$\Delta \phi(\ell_2, E_{T\text{miss}}) \leq 0.7$</td>
<td>$\leq 0.5$</td>
</tr>
<tr>
<td>$\Delta \phi(\ell_1, \ell_2) \geq 2.3$</td>
<td>$\geq 1.0$</td>
</tr>
<tr>
<td>$\Delta \phi(\ell_1, E_{T\text{miss}}) \geq 2.5$</td>
<td>$\geq 1.0$</td>
</tr>
<tr>
<td>$\Delta p_T(\ell_1, \ell_2) \geq 7$ GeV</td>
<td>$\geq 1$ GeV</td>
</tr>
</tbody>
</table>
\( \tau \rightarrow 3\mu \): Region definitions, event counts

<table>
<thead>
<tr>
<th>Region</th>
<th>Range in ( m_{3\mu} ) [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal region</td>
<td>[1713, 1841]</td>
</tr>
<tr>
<td>Blinded region</td>
<td>[1690, 1870]</td>
</tr>
<tr>
<td>Sideband region</td>
<td>[1450, 1690] and [1870, 2110]</td>
</tr>
<tr>
<td>Training region</td>
<td>[750, 1450] and [2110, 2500]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Phase</th>
<th>Data SB</th>
<th>Data SR</th>
<th>Signal MC SR [out of 2 \times 10^5]</th>
</tr>
</thead>
<tbody>
<tr>
<td>loose</td>
<td>2248</td>
<td>580</td>
<td>12672</td>
</tr>
<tr>
<td>loose+(x&gt;x_0)</td>
<td>736</td>
<td>203</td>
<td>12557</td>
</tr>
<tr>
<td>tight</td>
<td>42</td>
<td>9</td>
<td>5503</td>
</tr>
<tr>
<td>tight+(x&gt;x_0)</td>
<td>28</td>
<td>7</td>
<td>5501</td>
</tr>
<tr>
<td>tight+(x&gt;x_1)</td>
<td>0</td>
<td>0</td>
<td>4616</td>
</tr>
</tbody>
</table>
$\tau \rightarrow 3\mu$: BDT input features

1. The calorimeter-based transverse mass, $m^\text{cal}_T$.
2. The track-based missing transverse momentum, $E^\text{miss}_T$.
3. The isolation variable, $\Sigma p_{T}^{\text{trk}} (\Delta R_{\text{max}}^{3\mu} + 0.20)/p_{T}^{3\mu}$.
4. The transverse component of the vector sum of the three-muon and leading jet momenta, $\Sigma T$.
5. The track-based transverse mass, $m_{T}^{\text{trk}}$.
6. The difference between the $E^\text{miss}_{T,\text{cal}}$ and $E^\text{miss}_{T,\text{trk}}$ directions, $\Delta \phi^\text{cal}_{3\mu}$.
7. The calorimeter-based missing transverse momentum, $E^\text{miss}_{T,\text{cal}}$.
8. The track-based missing transverse momentum balance $p_{T}^{3\mu} / E^\text{miss}_{T,\text{trk}} - 1$.
9. The difference between the three-muon and $E^\text{miss}_{T,\text{cal}}$ directions, $\Delta \phi^\text{cal}_{3\mu}$.
10. Three-muon vertex fit probability, $p$-value.
11. The three-muon vertex fit $a^0_{xy}$ significance, $S(a^0_{xy})$.
12. The track fit probability product, $P_{\text{trks}}$.
13. The three-muon transverse momentum, $p_{T}^{3\mu}$.
14. The number of tracks associated with the PV (after refitting the PV while excluding the three-muon tracks), $N_{\text{trk}}^{\text{PV}}$.
15. The three-muon vertex fit $L_{xy}$ significance, $S(L_{xy})$.
16. The calorimeter-based missing transverse momentum balance, $p_{T}^{3\mu} / E^\text{miss}_{T,\text{cal}} - 1$. 

16/08/2018

Wing Sheung Chan (Nikhef)
$Z' \rightarrow \ell\ell'$: Limit conversion from low-energy experiments
$\bar{\nu} \to \ell \ell'$: Limit conversion from low-energy experiments

![Graphs showing ATLAS results for $\bar{\nu} \to \ell \ell'$]

- **ATLAS**: $\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$
- **$\bar{\nu}_i \to e\mu$**
- **$\bar{\nu}_i \to e\mu$, b- veto**
- **$\bar{\nu}_i \to \tau$**
- **$\bar{\nu}_i \to \mu$**

16/08/2018
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