Tau physics in ATLAS

23rd Rencontres de Blois
Particle Physics and Cosmology

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on behalf of the ATLAS collaboration
Outline and Introduction

Outline:
• Tau lepton identification and reconstruction in ATLAS
• Standard Model processes with tau leptons: $Z \rightarrow \tau\tau$ and $W \rightarrow \tau_h\nu$
• Higgs boson search in tau decay channels: MSSM $A/H/h \rightarrow \tau\tau$ and $H^+ \rightarrow \tau\nu$

Processes with tau leptons important for
- “New” physics searches:
  Higgs boson
  Supersymmetry
  Exotic models
- Measurement and understanding of $Z \rightarrow \tau\tau$
  and $W \rightarrow \tau_h\nu$ as backgrounds for searches
Tau leptons

Properties:
\[ m_\tau = 1.78 \text{ GeV} \]
\[ c\tau = 87 \text{ \(\mu\)m} \]

Decay modes:
Leptonic \((e, \mu + \nu\nu)\) 35.2%
Hadronic 1 prong 49.5%
Hadronic 3 prong 15.2%

Hadronically decaying tau leptons:

- Tracks of 1 or 3 charged hadrons
- Collimated calorimeter energy depositions

Shower width and composition (shower radius and isolation, EM fraction)
Tau reconstruction and identification in ATLAS

- Hadronically decaying tau candidates seeded by calorimeter jets and tracks matched to candidates
- Distinction between tau leptons and jets:
  Different identification criteria: cut based, boosted decision tree (BDT), likelihood (LLH)

Cuts based on 3 variables
- Shower width in em. Calorimeter
- Track width
- Leading track momentum

- Performance: Signal MC $Z \rightarrow \tau\tau$ and $W \rightarrow \tau\nu$, Background dijet data

→ Good agreement between data and Monte Carlo

trained separately for #prongs

ATLAS-CONF-2011-077
SM processes: $W \to \tau_h \nu$ observation

Selection for analysis with 546 nb$^{-1}$:
- $\tau_h + E_T^{\text{miss}}$ trigger
- Tight $\tau_h$ with $20 \text{ GeV} < p_T < 60 \text{ GeV}$
- Veto on leptons with $p_T > 5 \text{ GeV}$
- $\Delta \phi(\text{jet}, E_T^{\text{miss}}) > 0.5 \text{ rad}$
- $E_T^{\text{miss}} > 30 \text{ GeV}$
- $E_T^{\text{miss}}$ significance $> 6$

Backgrounds: Multijet (estimated from data), $W \to l \nu$, $Z \to ll$, $Z \to \tau\tau$

- Observation:
  78 events in data selected
  55 $\pm$ 12 events observed signal
  55 $\pm$ 16 events expected signal from MC

- Main systematic uncertainties: energy scale, MC model

Analysis on full dataset in preparation

$\rightarrow$ Observed signal consistent with SM expectation
$\rightarrow$ hadronically decaying tau leptons in data established
SM processes: $Z \to \tau\tau$ cross section measurement

Measurement of $Z \to \tau\tau$ cross section with 36 pb$^{-1}$ combining 4 channels:
$\tau_\mu \tau_h$ channel, $\tau_e \tau_h$ channel, $\tau_e \tau_\mu$ channel and $\tau_\mu \tau_\mu$ channel

Selection for $Z \to \tau_h \tau_l$:
- Single lepton trigger
- One $e$ $p_T > 16$ GeV or one $\mu$ $p_T > 15$ GeV
- One tight $\tau_h$ $p_T > 20$ GeV, 1 or 3 tracks
- Tight lepton isolation
- $M_T < 50$ GeV and $\Sigma \cos\Delta\phi(l, E_T^{\text{miss}}) > -0.15$
- Opposite charge of lepton and $\tau_h$
- 35 GeV $< m_{\text{visible}} < 75$ GeV

Multijet suppression:
- Tight lepton isolation
- Sum of transverse momentum of tracks in $\Delta R = 0.4$ cone divided by lepton $p_T$
- Sum of energy in calorimeter in $\Delta R = 0.4/0.3$ cone divided by lepton $p_T$
SM processes: $Z \rightarrow \tau\tau$ cross section measurement

Multijet background estimation from data:
- ABCD method OS/SS and lepton isolation

\[ N^A = N^B \left( \frac{N^C}{N^D} \right) = N^B R_{\text{ISO}} \]

EW, tt background subtracted in control regions

W+jets background:
- Normalization in W-dominated control region from data
- Shape from MC

Result for $Z \rightarrow \tau_h \tau_l$: Visible mass and $\#\text{track}(\tau)$ distributions for $\tau_\mu \tau_h$ and $\tau_e \tau_h$ channels

**ATLAS Preliminary**

- $\sqrt{s} = 7$ TeV
- $L_{\text{int}} = 35.5$ pb$^{-1}$
- $p_{\text{track}} > 1$ GeV
SM processes: $Z \rightarrow \tau \tau$ cross section measurement

### Selection for $Z \rightarrow \tau_e \tau_\mu$:
- One $e, p_T > 15$ GeV and one $\mu, p_T > 10$ GeV of opposite charge and tight isolated
- $\Sigma \cos \Delta \phi(l, E_{T\text{miss}}) > -0.15$
- $\Sigma E_T + E_{T\text{miss}} < 150$ GeV
- $25$ GeV $< m_{e\mu} < 80$ GeV

- Multijet background estimated from data
- 85 events in data selected
- 76 $\pm$ 10 events observed signal

### Selection for $Z \rightarrow \tau_\mu \tau_\mu$:
- One $\mu, p_T > 15$ GeV and one $\mu, p_T > 10$ GeV of opposite charge and isolated
- $25$ GeV $< m_{\mu\mu} < 65$ GeV
- BDT using 4 variables trained to separate $Z \rightarrow \tau_\mu \tau_\mu$ and $\gamma^*/Z \rightarrow ll$

- Multijet background estimated from data
- 90 events in data selected
- 43 $\pm$ 10 events observed signal

$\rightarrow \gamma^*/Z \rightarrow ll$ suppressed and $Z \rightarrow \tau_\mu \tau_\mu$ signal visible
SM processes: $Z \rightarrow \tau\tau$ cross section measurement

Fiducial cross section: 

$$\sigma^{fid}(Z \rightarrow \tau\tau) \times B(\tau \rightarrow l\nu, \tau \rightarrow l\nu/\tau_{had}\nu) = \frac{N_{obs} - N_{bkg}}{C_Z \cdot L}$$

Total cross section in invariant mass of $66 < m_{\tau\tau} < 116$ GeV:

$$\sigma(Z \rightarrow \tau\tau) \times B(\tau \rightarrow l\nu, \tau \rightarrow l\nu/\tau_{had}\nu) = \frac{N_{obs} - N_{bkg}}{A_Z \cdot C_Z \cdot L}$$

- $C_Z$ correction factor taking into account detector effects (e.g. $l_d$ efficiencies)
- $A_Z$ geometrical acceptance
- Corrections included for events outside the invariant mass window

<table>
<thead>
<tr>
<th>Final State</th>
<th>Measured Fiducial Cross-section</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_\mu\tau_h$</td>
<td>$23 \pm 2,(stat) \pm 3,(syst) \pm 1,(lumi)$ pb</td>
</tr>
<tr>
<td>$\tau_e\tau_h$</td>
<td>$27 \pm 3,(stat) \pm 5,(syst) \pm 1,(lumi)$ pb</td>
</tr>
<tr>
<td>$\tau_e\tau_\mu$</td>
<td>$7.5 \pm 1.0,(stat) \pm 0.5,(syst) \pm 0.3,(lumi)$ pb</td>
</tr>
<tr>
<td>$\tau_\mu\tau_\mu$</td>
<td>$4.5 \pm 1.1,(stat) \pm 0.6,(syst) \pm 0.2,(lumi)$ pb</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Final State</th>
<th>Measured Total Cross-section (66 &lt; $m_{inv}$ &lt; 116 GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_\mu\tau_h$</td>
<td>$0.86 \pm 0.08,(stat) \pm 0.12,(syst) \pm 0.03,(lumi) \pm 0.003,(theo)$ nb</td>
</tr>
<tr>
<td>$\tau_e\tau_h$</td>
<td>$1.14 \pm 0.14,(stat) \pm 0.20,(syst) \pm 0.04,(lumi) \pm 0.004,(theo)$ nb</td>
</tr>
<tr>
<td>$\tau_e\tau_\mu$</td>
<td>$1.06 \pm 0.14,(stat) \pm 0.08,(syst) \pm 0.04,(lumi) \pm 0.004,(theo)$ nb</td>
</tr>
<tr>
<td>$\tau_\mu\tau_\mu$</td>
<td>$0.96 \pm 0.22,(stat) \pm 0.13,(syst) \pm 0.03,(lumi) \pm 0.002,(theo)$ nb</td>
</tr>
</tbody>
</table>

Main systematic uncertainties:
- Energy scale $\tau_\mu\tau_h$ 11 %
- Tau efficiency $\tau_\mu\tau_h$ 8.6%
- Muon efficiency 4%
- Electron efficiency 3-10%
- $A_Z$ 3%
- Luminosity 3.4%
Combination:

\[ \sigma_{\text{combined}} = 0.97 \pm 0.07 \text{ (stat.)} \pm 0.07 \text{ (syst.)} \pm 0.03 \text{ (lumi.)} \text{ nb} \]

\[ \sigma_{\text{theo}} = 0.96 \pm 0.05 \text{ nb} \]

→ Total cross section of \( \gamma^*/Z \rightarrow \tau\tau \) in invariant mass of \( 66 < m_{\text{inv}} < 116 \text{ GeV} \) in good agreement with theoretical expectation
Higgs boson search: $A/H/h \rightarrow \tau\tau$

MSSM: 2 Higgs doublets
- 5 Higgs bosons $\phi = h, H, A, H^\pm$
- $m_h^{\text{max}}$ benchmark scenario
- Free parameters: $\tan\beta$ and $m_A$
- Strong coupling to down-type fermions, production $\alpha \tan\beta^2$
- Dominant production
Direct $bb\phi$  $gg \rightarrow \phi$

Selection for $A/H/h \rightarrow \tau_h \tau_l$ with 36 pb$^{-1}$:
- Single lepton trigger
- One isolated e $p_T > 20$ GeV or $\mu p_T > 15$ GeV
- One loose $\tau_h p_T > 20$ GeV, 1 or 3 tracks
- Opposite charge of lepton and $\tau_h$
- $E_T^{\text{miss}} > 20$ GeV
- $M_T < 30$ GeV

Selected events in 36 pb$^{-1}$:

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td><strong>Data</strong></td>
<td>206</td>
</tr>
<tr>
<td><strong>Sum MC expectation without Multijet</strong></td>
<td>218 ± 5</td>
</tr>
<tr>
<td>$A/H/h$ ($m_A = 120$ GeV, $\tan\beta = 40$)</td>
<td>53.3 ± 0.9</td>
</tr>
<tr>
<td><strong>MC W+jets</strong></td>
<td>66 ± 3</td>
</tr>
<tr>
<td><strong>MC $Z \rightarrow \tau\tau$</strong></td>
<td>117 ± 4</td>
</tr>
</tbody>
</table>

Results for $A/H/h \rightarrow \tau_h \tau_l$ and $A/H/h \rightarrow \tau_e \tau_\mu$

Main backgrounds:
$Z \rightarrow \tau\tau$, W+jets, ($Z \rightarrow ll$ and Multijets)
Background estimate for $A/H/h \rightarrow \tau_\tau$:

Estimate using same-sign sample from data

$$n_{OS}^{Bkg}(m_{vis}) = r_{QCD} \cdot n_{SS}^{QCD}(m_{vis}) + r_{W+jets} \cdot n_{SS}^{W+jets}(m_{vis}) + n_{OS}^{Z+jets}(m_{vis}) + n_{OS}^{other}(m_{vis})$$

Assumption $r_{QCD} = \frac{\text{#events (OS)}}{\text{#events (SS)}} = 1$ (confirmed by MC and data control region)

$W$+jets factor $r_{W+jets}$ from $W$ control region in data

$Z \rightarrow \tau \tau$ from MC, checked with embedding technique using data

- Visible mass distribution after all cuts

- Main systematic uncertainties on background yields:

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Same-sign background estimate</td>
<td>25%</td>
</tr>
<tr>
<td>$W$+jets background estimate</td>
<td>15%</td>
</tr>
<tr>
<td>Tau and jet energy scale</td>
<td>2-32%</td>
</tr>
<tr>
<td>Tau efficiency</td>
<td>4%</td>
</tr>
<tr>
<td>Signal acceptance</td>
<td>14%</td>
</tr>
</tbody>
</table>
Higgs boson search: $A/H/h \rightarrow \tau\tau$

**Selection for $A/H/h \rightarrow \tau_e \tau_\mu$ with 36 pb$^{-1}$:**
- Single electron trigger
- One $e$ $p_T > 20$ GeV and $\mu$ $p_T > 10$ GeV, opposite charge and tight isolated
- $p_T(e) + p_T(\mu) + E_T^{\text{miss}} < 120$ GeV
- $\Delta\phi(e, \mu) > 2$ rad
- Discriminating variable: Effective mass
  $$M_{\tau\tau}^{\text{effective}} = \sqrt{(p_e + p_\mu + p_{\text{miss}})^2}$$

**Selected events in 36 pb$^{-1}$:**

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<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td><strong>Data</strong></td>
<td>70</td>
</tr>
<tr>
<td><strong>MC expectation without Multijet</strong></td>
<td>$60.4 \pm 1.2$</td>
</tr>
<tr>
<td><strong>Multijet</strong></td>
<td>$2.1 \pm 3.1$</td>
</tr>
<tr>
<td><strong>A/H/h ($m_\beta = 120$ GeV, $\tan = 40$)</strong></td>
<td>$15.2 \pm 0.3$</td>
</tr>
</tbody>
</table>

- Main background $Z \rightarrow \tau\tau$ estimated from MC and shape validated with embedding technique using data
- Multijet background estimated from data: ABCD method

- Systematic uncertainties:
  - Electron efficiency ~ 7-9%
  - MC background cross sections 5-10%
  - Multijet estimate, Mass shape uncertainty
Higgs boson search: $A/H/h \rightarrow \tau\tau\tau$ Limit

- Exclusion limits from analysis of visible/effective mass shape using profile likelihood method
- Cross section, couplings, masses, BR from LHC Higgs XSection WG + matching between 4-flavor and 5-flavor calculation
In MSSM if $m(H^+) < m(t)$ dominant production for $H^+$ in $tt$ with $t \rightarrow H^+ b$ and $H^+ \rightarrow \tau_\tau \nu$

$H^+$ with hadronic $\tau$ decays: Test of data-driven background estimates
- $p_T(\tau_h) > 20$ GeV
- If $W \rightarrow qq$: Jets, $E_T^{miss} > 20$ GeV, $E_T^{miss}$ significance $> 3$,
  $120$ GeV $< m(jet,jet,b-jet) < 240$ GeV
- If $W \rightarrow l\nu$: $E_T^{miss} > 60$ GeV, $\Sigma E_T > 200$ GeV, b-jet

Discriminating variable: $m_T = \sqrt{2p_T^\tau E_T^{miss}(1 - \cos \Delta\phi)}$

A) Backgrounds with fake $\tau$ jets
   → Measure fake rate
B) Backgrounds with true $\tau$s
   → Embedding
C) Multijet background
   → Fit with shape from control region

→ Given this sensitivity no limit is extracted, further studies with more data
Summary

• Identification of hadronically and leptonically decaying tau leptons in ATLAS established

• Total $\gamma^*/Z \rightarrow \tau\tau$ cross section in invariant mass of $66 < m_{\tau\tau} < 116$ GeV measured to

$$\sigma_{\text{combined}} = 0.97 \pm 0.07 \text{ (stat)} \pm 0.07 \text{ (syst)} \pm 0.03 \text{ (lumi)} \text{ nb}$$

In good agreement with Standard Model expectation

• Searches for $H^+$ ready

• Limit set for $H/A/h \rightarrow \tau\tau$, no excess observed

  Limit in ($\tan\beta$-$m_A$)-plane, regions excluded beyond Tevatron or LEP exclusions

→ Looking forward to results with more data in tau decay channels
- ATLAS-CONF-2011-077 (Tau identification)
- ATLAS-CONF-2010-097 ($W \rightarrow \tau_h \nu$ observation)
- ATLAS-CONF-2011-010 ($Z \rightarrow \tau_h \tau_l$ observation)
- ATLAS-CONF-2011-045 ($Z \rightarrow \tau\tau \rightarrow e\mu + 4\nu$ observation)
- ATLAS-CONF-2011-051 ($H^+ \text{ with hadronic } \tau \text{ decays}$)
- ATLAS-CONF-2011-018 ($H^+ \text{ with leptonic } \tau \text{ decays}$)
- ATLAS-CONF-2011-024 (MSSM $A/H/h \rightarrow \tau\tau$)
Hadronic tau decays

\[ \tau^- \rightarrow e^- \bar{\nu}_e \nu_\tau \quad 17.8\% \]
\[ \mu^- \bar{\nu}_\mu \nu_\tau \quad 17.4\% \]
\[ \pi^- \pi^0 \nu_\tau \quad 25.5\% \]
\[ \pi^- \nu_\tau \quad 10.9\% \]
\[ \pi^- 2\pi^0 \nu_\tau \quad 9.3\% \]
\[ K^- (N\pi^0) (NK^0) \nu_\tau \quad 1.5\% \]
\[ \pi^- 3\pi^0 \nu_\tau \quad 1.0\% \]
\[ \pi^- \pi^- \pi^+ \nu_\tau \quad 9.0\% \]
\[ \pi^- \pi^- \pi^+ \pi^0 \nu_\tau \quad 4.6\% \]

\[ \{ \text{leptonic } 35.2\% \} \]
\[ \{ 1 \text{ prong } 49.5\% \} \]
\[ \{ 3 \text{ prong } 15.2\% \} \]

In the detector:
- Shower width (shower radius and isolation)
- Particle multiplicity (e.g. number of tracks, clusters)
- Shower composition (e.g. EM fraction)

→ Calorimeter cluster-based variables (e.g. number of clusters, mass), Tracking variables (e.g. track width, track mass), Variables which combine calorimeter and tracking information (e.g. E/p)
Hadronic Tau reconstruction and identification in ATLAS

- Tau jet candidates seeded by calorimeter jets (candidate calorimeter jets reconstructed with AntiKt algorithm, starting from topological clusters)
- Tracks matched to candidate calorimeter jets
- Distinction between tau leptons and jets:
  Different identification criteria: cut based, boosted decision tree (BDT), likelihood LLH)
- Cuts based on 3 variables

- BDT and LLH use further variables
- Rejection of electrons passing tau lepton selection (electron veto)

Transverse energy weighted shower width in em. Calorimeter

\[ p_T \] weighted track width

Leading track momentum

ATLAS-CONF-2011-077
Performance: Signal Monte Carlo $Z \rightarrow \tau \tau$ and $W \rightarrow \tau h \nu$, Background dijet data events
Trained in bins of $\#text{prong}$ and $p_T$

Efficiency systematics evaluated on Monte Carlo:
- Looser working point 4-7%
- Tighter working point ~10%

→ Good agreement between data and Monte Carlo

Tight cuts:
30% signal efficiency
Dijet efficiency 2-6%
$W \rightarrow \tau_h \nu$ candidate event display

$W \rightarrow \tau \nu$ candidate in 7 TeV collisions

$E_T^{\min} = 39$ GeV
$\Delta\phi(\tau, E_T^{\min}) = 3.1$
$m_\tau = 68$ GeV

Run 155697, Event 6769403
Time 2010-05-24, 17:38 CEST
SM processes: $W \to \tau_h \nu$ observation

Multijet background estimated from data: ABCD method

$$N_{QCD}^A = N^B N^C / N^D$$

Observation of $W \to \tau_h \nu$ with 546 nb$^{-1}$

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>78</td>
</tr>
<tr>
<td>Multijet background</td>
<td>$11.1 \pm 2.3$ (stat.) $\pm 3.2$ (syst.)</td>
</tr>
<tr>
<td>EW background</td>
<td>$11.8 \pm 0.4$ (stat.) $\pm 3.7$ (syst.)</td>
</tr>
<tr>
<td>Expected signal</td>
<td>$55.3 \pm 1.4$ (stat.) $\pm 16.1$ (syst.)</td>
</tr>
<tr>
<td>Observed signal</td>
<td>$55.1 \pm 10.5$ (stat.) $\pm 5.2$ (syst.)</td>
</tr>
</tbody>
</table>
Systematic uncertainties:

<table>
<thead>
<tr>
<th></th>
<th>( W \rightarrow \tau_h \nu_\tau ) (MC expectation)</th>
<th>EW background (MC expectation)</th>
<th>QCD background (data-driven estimate)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central values [events]</td>
<td>55.3</td>
<td>11.8</td>
<td>11.1</td>
</tr>
<tr>
<td>Statistical uncertainty [events]</td>
<td>±1.4</td>
<td>±0.4</td>
<td>±2.3</td>
</tr>
<tr>
<td>Systematic uncertainties</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Theoretical cross section</td>
<td>± 5%</td>
<td>±5%</td>
<td>–</td>
</tr>
<tr>
<td>Luminosity</td>
<td>± 11%</td>
<td>±11%</td>
<td>–</td>
</tr>
<tr>
<td>Energy scale</td>
<td>±21%</td>
<td>±14%</td>
<td>–</td>
</tr>
<tr>
<td>Lepton veto</td>
<td>–</td>
<td>±19%</td>
<td>–</td>
</tr>
<tr>
<td>Pile-up</td>
<td>±1%</td>
<td>±0.2%</td>
<td>–</td>
</tr>
<tr>
<td>Monte Carlo model</td>
<td>±16%</td>
<td>±17%</td>
<td>–</td>
</tr>
<tr>
<td>QCD background estimation</td>
<td>–</td>
<td>–</td>
<td>±29%</td>
</tr>
<tr>
<td>Total systematic uncertainty [events]</td>
<td>±16.1</td>
<td>±3.7</td>
<td>±3.2</td>
</tr>
</tbody>
</table>
$Z \rightarrow \tau^+_h \tau^-_l$ candidate event display

\[ p_T(\mu) = 18 \text{ GeV} \]
\[ p_T^{\text{vis}}(\tau_h) = 26 \text{ GeV} \]
\[ m_{\text{vis}}(\mu, \tau_h) = 47 \text{ GeV} \]
\[ m_T(\mu, E_T^{\text{miss}}) = 8 \text{ GeV} \]
\[ E_T^{\text{miss}} = 7 \text{ GeV} \]

Run Number: 160613, Event Number: 9209492
Date: 2010-08-03 02:12:37 CEST

Candidate in 7 TeV Collisions

3-prong hadronic tau decay
SumCosDeltaPhi:
\[ \sum \cos \Delta \phi = \cos (\phi(\ell) - \phi(E_T^{\text{miss}})) + \cos (\phi(\tau_h) - \phi(E_T^{\text{miss}})) \]

Transverse Mass:
\[ m_T(\ell, E_T^{\text{miss}}) = \sqrt{2 p_T(\ell) \cdot |E_T^{\text{miss}}| \cdot (1 - \cos \Delta \phi(\ell, E_T^{\text{miss}}))} \]
SM processes: $Z \rightarrow \tau_+ \tau_-$: W+jets normalization

W+jets background shape taken from MC and normalized to data in W enriched region

- inverted W+jets suppression cuts

before tau ID

after tau ID

muon channel
### SM processes: $Z \rightarrow \tau\tau$ cross section measurement

#### ATLAS Preliminary

<table>
<thead>
<tr>
<th></th>
<th>$\tau_\mu\tau_h$</th>
<th>$\tau_e\tau_h$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{obs}$</td>
<td>213</td>
<td>151</td>
</tr>
<tr>
<td>$N_{obs} - N_{bkg}$</td>
<td>$164 \pm 16 \pm 4$</td>
<td>$114 \pm 14 \pm 3$</td>
</tr>
<tr>
<td>$A_Z$</td>
<td>$0.117 \pm 0.0002 \pm 0.004$</td>
<td>$0.101 \pm 0.0002 \pm 0.003$</td>
</tr>
<tr>
<td>$C_Z$</td>
<td>$0.21 \pm 0.002 \pm 0.03$</td>
<td>$0.120 \pm 0.002 \pm 0.019$</td>
</tr>
<tr>
<td>$B$</td>
<td>$0.2250 \pm 0.0009$</td>
<td>$0.2313 \pm 0.0009$</td>
</tr>
<tr>
<td>$\mathcal{L}$</td>
<td>$35.5 \pm 1.2 \text{ pb}^{-1}$</td>
<td>$35.7 \pm 1.2 \text{ pb}^{-1}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>$\tau_e\tau_\mu$</th>
<th>$\tau_\mu\tau_\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{obs}$</td>
<td>85</td>
<td>90</td>
</tr>
<tr>
<td>$N_{obs} - N_{bkg}$</td>
<td>$76 \pm 10 \pm 1$</td>
<td>$43 \pm 10 \pm 3$</td>
</tr>
<tr>
<td>$A_Z$</td>
<td>$0.114 \pm 0.0004 \pm 0.003$</td>
<td>$0.156 \pm 0.001 \pm 0.011$</td>
</tr>
<tr>
<td>$C_Z$</td>
<td>$0.29 \pm 0.005 \pm 0.02$</td>
<td>$0.27 \pm 0.006 \pm 0.01$</td>
</tr>
<tr>
<td>$B$</td>
<td>$0.0620 \pm 0.0002$</td>
<td>$0.0301 \pm 0.0001$</td>
</tr>
<tr>
<td>$\mathcal{L}$</td>
<td>$35.5 \pm 1.2 \text{ pb}^{-1}$</td>
<td>$35.5 \pm 1.2 \text{ pb}^{-1}$</td>
</tr>
</tbody>
</table>
SM processes: $Z \rightarrow \tau \tau$ cross section measurement

**Selection** for $Z \rightarrow \tau_e \tau_\mu$:

- One electron $p_T > 15$ GeV and one muon $p_T > 10$ GeV of opposite charge
- Tight lepton isolation
- $\Sigma \cos \Delta \phi(l, E_T^{miss}) > -0.15$
- $p_T^{\tau_e} + p_T^{\tau_\mu} + p_T^{jets} + E_T^{miss} < 150$ GeV
- $25$ GeV $< m_{visible} < 80$ GeV

- Multijet background estimated from data: ABCD method using OS/SS ratio vs. lepton isolation
- $W$ normalization checked in control region in data

$$\begin{array}{c|c}
N_{obs} & \tau_\tau \mu \\
N_{obs} - N_{bkg} & 76 \pm 10 \pm 1
\end{array}$$

→ Distributions of lepton $p_T$ and visible mass after all cuts beside mass window cut
**SM processes: \( Z \rightarrow \tau \tau \) cross section measurement**

**Selection** for \( Z \rightarrow \tau_\mu \tau_\mu \):
- One isolated muon \( p_T > 15 \) GeV and one isolated muon \( p_T > 10 \) GeV of opposite charge
- \( 25 \) GeV < \( m_{\mu\mu} \) < 65 GeV
- Boosted decision tree to separate \( Z \rightarrow \tau_\mu \tau_\mu \) and \( \gamma^*/Z \rightarrow ll \)

**BDT input variables:**
- \( \Delta \phi(\mu_1, \mu_2) \)
- \( \Delta \phi(\mu_1, E_T^{\text{miss}}) \)
- \( (p_T(\mu_1) - p_T(\mu_2)) \)
- \( |d_0(\mu_1)| + |d_0(\mu_2)| \)

**Distribution of visible mass after all cuts**

<table>
<thead>
<tr>
<th>( N_{\text{obs}} )</th>
<th>( \tau_\mu \tau_\mu )</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>43 ± 10 ± 3</td>
</tr>
</tbody>
</table>

\( \gamma^*/Z \rightarrow ll \) suppressed and \( Z \rightarrow \tau_\mu \tau_\mu \) signal visible
Higgs boson search: Charged Higgs $H^+$

In MSSM if $m(H^+) < m(t)$ dominant production for $H^+$ in $t\bar{t}$ with $t \to H^+ b$ and $H^+ \to \tau \nu$

1. $H^+$ with hadronic $\tau$ decays: Test of data-driven background estimates

A) Backgrounds with fake $\tau$ jets → Measure fake rate

B) Backgrounds with true $\tau$s → Embedding

C) Multijet background → Fit with shape from control region
Z/H $\rightarrow\tau\tau\ (lh)$ in ATLAS

- Lepton identification: muon $\rightarrow$ muon system and tracking or electron $\rightarrow$ tracking and electromagnetic calorimeter
- Neutrinos: missing energy $\rightarrow$ $4\pi$ calorimeter with high granularity
- Tau identification: electromagnetic calorimeter and tracking

![Diagram of ATLAS detector](image-url)