Searches for new phenomena with tau leptons in the final state using the ATLAS detector

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The Large Hadron Collider

- Completed in 2008, CERN, Geneva
- Physics runs in 2010 - 2012 (Run 1) and 2015 - 2018 (Run 2)

- pp collisions at
  $\sqrt{s} = 7$ TeV (3.5 + 3.5) for 2010-11
  $\sqrt{s} = 8$ TeV (4 + 4) for 2012
- also Pb+Pb, p+Pb (not covered here)
- Long Shutdown (LS1) 2013-2014

- Run 2 from 2015 running @ $\sqrt{s} = 13$ TeV (design value = 14 TeV)
- LS2 planned 2019-2020
- Run 3 till 2023
LHC luminosity

- Run 1
  - 2011, ~5 fb\(^{-1}\) @ 7TeV
  - 2012, ~20 fb\(^{-1}\) @ 8TeV

- Peak lumi in Run 1
  0.75\(\times 10^{34}\) cm\(^{-2}\) s\(^{-1}\)

- Run 2: peak lumi 2\(\times 10^{34}\)
  (2018) @ 13TeV (design: 1\(\times 10^{34}\))

- 2015-16: 36.1 fb\(^{-1}\)
- 2015-17: ~80 fb\(^{-1}\)
The ATLAS detector

- Inner Detector tracking (Pixel, SCT, TRT) $|\eta|<2.5$
- EM (LAr) and hadron (Tile+LAr) calorimeters $|\eta|<4.9$
- Muon Spectrometer with toroid magnets $|\eta|<2.7$
Search for BSM with $\tau$’s

• 3rd generation (heaviest) lepton may be a unique clue of BSM signatures, e.g.
  – stau in SUSY often considered to be lightest slepton
  – strongest leptonic coupling to Higgs

• Experimentally more complicated than e/$\mu$
  – largest BR to hadrons: separation from jets
  – leptonic decays hard to distinguish from e/$\mu$
  – includes at least one $\nu$ (missing $E_T$)

• Sophisticated identification methods
  – Refer to talk by A.-C. Le Bihan
τ ID in ATLAS (in short)

• 1-track and 3-track τ had-vis candidates, seeded from anti-kₜ jets with R=0.4
• Identification using Boosted Decision Tree using calorimeter- and track-related variables
• loose, medium and tight working points
  – e.g. in W’→τ ν search, loose criteria are used
  – Efficiency ~ 60% @ p_T=100 GeV, 30% @ 2 TeV

References:
Run 1 paper: EPJC75(2015)303 1412.7086
Run 2 update: ATL-PHYS-PUB-2015-045
Run 2 performance: ATLAS-CONF-2017-029
Searches covered in this talk

• $\tau$ b resonance (3rd gen. scalar leptoquark)
  – Lepton-quark unification: bosons with both $B$ and $L$
  – 7 TeV result

• Multi ($\geq$3) lepton production (excited $l/\nu$, $H^{\pm\pm}$)
  – Compositeness: excited states of fermions
  – 7 TeV and 8 TeV results

• di-$\tau$ resonance search ($Z' \rightarrow \tau \tau$, $H \rightarrow \tau \tau$)
  – Extension of gauge sectors: heavier states of $Z/W$
  – 7 TeV, 8 TeV and 13 TeV results

• $\tau$ and missing momentum ($W' \rightarrow \tau \nu$)
  – 13 TeV result
Searches NOT covered here

• For **SUSY** searches, refer to F. Lyu’s talk

• For **di-Higgs** and **BSM Higgs** searches, refer to talks by P. Bokan and C. Caputo

• For **LFV signatures**, refer to B. Le’s talk

• For **H→leptons (incl. \( \tau \ \tau \))**, refer to L. Schildgen’s

• And, B. Winter’s talk on \( \tau \) polarization in \( Z→\tau \ \tau \)
3rd gen. scalar leptoquarks

• $LQ_3LQ_3 \rightarrow \tau b \tau b$ (100% BR assumed)
• $e \tau_{\text{had-}vis}bb+3 \nu$ and $\mu \tau_{\text{had-}vis}bb+3 \nu$ channels
• $m(LQ_3) > 534$ GeV

$S_T$: scalar sum of $p_T$ of e/\mu, \tau, 2 jets and missing $E_T$
Generic multi-lepton search

\[ \Lambda \leq 3e/\mu, \quad 2e/\mu + \geq 1 \tau_{\text{had}}, \quad \text{on-Z and off-Z} \]

Model-independent \( \sigma_{\text{vis}} \) limit interpreted as \( H^{\pm+} \rightarrow e^{\pm} \tau^{\pm}/\mu^{\pm} \tau^{\pm} \) and excited leptons

\( \tau^* \rightarrow \tau Z, \nu \tau^* \rightarrow \tau W, \) etc.

For \( m(l^*)=\Lambda, m(\tau^*)\geq 2.5 \text{ TeV}, m(\nu^*) \geq 1.6 \text{ TeV} \)

\( \Lambda \): compositeness scale
• Analysis results for BSM H search (see C. Caputo’s talk) interpreted for $Z' \rightarrow \tau \tau$ limits
  • $\tau$ lep $\tau$ had and $\tau$ had $\tau$ had channels (b-veto and b-tag selections in H search were merged)
  • $m(Z'_{SSM}) < 2.42$ TeV excluded for Sequential Standard Model
• Results also interpreted in G(221) model (shown later)
**τ +MET resonance search**

- First search on this channel by ATLAS
- $\tau_{\text{had-vis}}$ with $p_T > 50$ GeV, $E_{\text{T,miss}} > 150$ GeV
- $0.7 < p_T/E_{\text{T,miss}} < 1.3, \Delta \phi > 2.4$
- Main background (BG) from $W\rightarrow \tau \nu$ (from MC)
  - Jet($\rightarrow \tau_{\text{had}}$) BG from $W/Z+$jets, multi-jets (estimated data-driven)
  - Other BG: $W/Z/\gamma^*$, pair/single-top, diboson (from MC)

**Figure 1:** Transverse mass distribution after the event selection. The total impact of the statistical and systematic uncertainties on the SM background is depicted by the hatched area. The ratio of the data to the estimated SM background is shown in the lower panel. The prediction for $W_0^{\text{SSM}}$ and $W_0^{\text{NU}}$ ($\cot \nu = 5.5$) bosons with masses of 3 TeV are superimposed.

**Figure 2:** Upper limits are set on the production of a high-mass resonance decaying to $\tau\nu$. The statistical analysis uses a likelihood function constructed as the Poisson probability describing the total number of observed events given the signal-plus-background expectation. Systematic uncertainties in the expected number of events are incorporated into the likelihood via nuisance parameters constrained by Gaussian prior probability density distributions. Correlations between signal and background are taken into account. A signal-strength parameter, with a uniform prior probability density distribution, multiplies the expected signal. The dominant relative uncertainties in the expected signal and background contributions are shown in Figure 2 as a function of the $m_T$ threshold.

**Figure 3:** Model-independent upper limits on the visible $\tau\nu$ production cross section, $(pp \rightarrow \tau\nu + X)A'$, as a function of the $m_T$ threshold, where $A$ is the fiducial acceptance (including the $m_T$ threshold) and $'\tau$ is the reconstruction efficiency. Model-specific limits can be derived by evaluating $A$ and $'\tau$ for the model in question and checking if the corresponding visible cross section is excluded at any $m_T$ threshold. This
τ ν resonance search: results

• Model-independent $\sigma \times A \times \varepsilon$ limits with $m_\tau$ thresholds
(Acceptance etc. can be found in www.hepdata.net/record/80812)
• Sequential Standard Model: $m(W'_{SSM}) > 3.7$ TeV
Non-universal $G(221)$ model

- Also known as “topflavor”
- $\text{SU}(2)_l \times \text{SU}(2)_h \times \text{U}(1)$ split gauge groups for light($e/\mu$) and heavy($\tau$) fermions
- $\phi$: mixing of light/heavy
- $\tau$ coupling enhanced by $\cot \phi_{\text{NU}}$ w.r.t. $W'_{\text{SSM}}$
- $W'_{\text{NU}}$ and $Z'_{\text{NU}}$ degenerate
- $\tau \nu$ channel gives enhanced sensitivity than $\tau \tau / \mu \mu / ee$ for large parameter space
Conclusions

• Final states with $\tau$ leptons could be key signatures for Beyond-SM physics

• Search results shown for following topologies, bringing constraints on specific models:
  – $\tau b$ resonance (leptoquarks)
  – 3 or more leptons (excited leptons)
  – $\tau^+ \tau^-$ resonance ($Z'_{SSM}$ and $Z'_{NU}$)
  – $\tau \nu$ resonance ($W'_{SSM}$ and $W'_{NU}$)

• Stay tuned for more 13 TeV results to come!
The significance of the data given the fitted model and its uncertainty is computed in each bin following Ref. and the background processes are obtained from the fit under the hypothesis of no signal. The combined prediction for with underflows and overflows included in the first and last bins, respectively. The predictions and uncertainties for into the statistical fit discussed in Section 4.

Figure 5:

Distributions of bosons with masses of 300, 500 and 800 GeV and tan$\beta$ are shown in Figure 6.

G(221) constraints in $Z'\rightarrow\tau\tau$

95% CL limits

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<tr>
<th>ATLAS</th>
<th>$\tau\tau$ search</th>
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<tbody>
<tr>
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<td>Indirect (EWPT)</td>
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<td></td>
<td>Indirect (LFV)</td>
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<td>Indirect (CKM)</td>
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<td>Indirect (Z-pole)</td>
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ATLAS $\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$

95% CL limits

Non-universal G(221) model

$\sin^2\phi$