ATLAS + CMS Searches Beyond Inclusive Resonances in Leptonic Final States

LHCP 2021, TeV-scale BSM,  
June 7, 2021

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on behalf of the ATLAS and CMS collaborations
• There are many searches performed in **leptonic final states** beyond the ones with inclusive resonances.

• **Covered in this talk:**
  • Processes with with a lepton and missing transverse momentum
  • Non-resonant processes in dilepton events
  • Lepton flavour violation searches
  • Multilepton processes and model independent searches

• The following topics will be covered **later this week:**
  • Resonances and heavy mediators (**Joint BSM session, Wednesday**)  
  • SUSY (**TeV-scale BSM: SUSY, Tuesday**)  
  • Leptoquarks and vector-like quarks (**TeV-scale BSM: Third generation and flavour, Thursday**)
• The tails of transverse mass $M_T$ in single lepton $W$+jets events with high missing transverse momentum can also be used for non-resonant searches.

$$M_T = \sqrt{2p_T^\ell E_T^{\text{miss}}} (1 - \cos[\Delta\phi(\ell, E_T)])$$

• Effective field theory (EFT) interpretations quantify potential deviations from SM expectations through the oblique electroweak $W$ parameter, as a correction to the propagator $qq \rightarrow W \rightarrow l\nu$, *Phys. Rev. D* 46, 381.

• Selection:
  - high transverse momentum electrons ($p_T > 240$ GeV) or muons ($p_T > 53$ GeV)
  - $E_T^{\text{miss}}$ with $p_T/E_T^{\text{miss}}$ between 0.4 and 1.5 and $\Delta\phi(p_T, E_T^{\text{miss}}) > 2.5$

• Fit result using 2017 and 2018 data:

$$W = -12^{+5}_{-6} \times 10^{-5}$$
• Events with \(\tau\)-leptons in the final state yield wide resonances due to secondary (hadronic) \(\tau\) decays.
• Looking for Sequential Standard Model (SSM) \(W'\) boson, \(Z.\ Phys.\ C\ 45\ (1989)\ 109\).
• Misidentification probability of jets as tau candidates propagated from control regions as transfer factors.
• \(W'\) masses excluded up to 5.0 TeV.
• Model-independent limits set on signal yields above certain transverse mass thresholds, \(m_{T^{\text{thresh}}}\).
Before searching for processes in dilepton events, backgrounds need to be modelled well.

**ATLAS-EXOT-2019-16**

- $m_{ll}$ distribution is fit from data by a parametric background function in a low-mass control region.
- Extrapolated to single-bin signal regions.
- Fit parameters $b$, $c$, $p_i$.

\[ f_b(m_{ll}) = f_{BW,Z}(m_{ll}) \cdot (1 - x^c)^b \cdot x^{\sum_{i=0}^2 p_i \log(x)} \]

**CMS-EXO-19-019**

- Dominant background: Drell-Yan process, estimated from simulation.
- Jets misidentified as electrons are estimated from data.
- Combined background shape normalised to data around the $Z$ boson mass.

![ATLAS Simulation](chart.png)

![CMS Comparison](chart.png)
• Lepton flavour universality violations, other flavour anomalies, would indicate a deviation from unity of the ratio of the dimuon to dielectron differential cross section, J. Phys. G: Nucl. Part. Phys. 46 023001.

• Mass distributions in data are unfolded after subtracting all backgrounds except for DY.

• Normalised to 1 in the range 200–400 GeV to correct efficiencies between $e/\mu$.

• Corrected with simulated DY events.

• Good agreement up to 1.5 TeV.

• One-sided $p$-values of 0.067 and 0.185.

$$R_{\mu^+\mu^-/e^+e^-} = \frac{d\sigma(q\bar{q} \rightarrow \mu^+\mu^-)/dm_{\ell\ell}}{d\sigma(q\bar{q} \rightarrow e^+e^-)/dm_{\ell\ell}}$$
• Quarks and leptons may be composite with at least one common constituent → effective four-fermion contact interaction at scale Λ, Rev. Mod. Phys. 56, 579, Phys. Rev. Lett. 50, 811.

• CMS studied the angle $\theta^*$ of the outgoing negatively charged lepton with respect to the z axis in the Collins–Soper frame (2 bins).

\[
p^\pm = \frac{1}{\sqrt{2}}(E \pm p_z) \quad \cos \theta^* = \frac{p_z(\ell^+\ell^-)}{|p_z(\ell^+\ell^-)|} \frac{2(p_1^+ p_2^- - p_1^- p_2^+)}{m(\ell^+\ell^-) \sqrt{m(\ell^+\ell^-)^2 + p_T(\ell^+\ell^-)^2}}
\]

• Lower limits on the contact interaction scale Λ are set:
  • ATLAS: from 22.3 to 35.8 TeV
  • CMS: from 23.9 to 36.4 TeV

• Same regions used to search for extra dimensions in ADD models,
To explain the asymmetries measured in the $B$-meson decays, the $bsll$ interaction would have to be different between electrons and muons → $bsll$ contact interaction with scale $\Lambda$ and coupling $g^*$, 

\begin{itemize}
  \item 4 categories: $e^+e^-/\mu^+\mu^-$ with 0 or 1 $b$-jet.
  \item Signal regions (SR) with lower bounds on $m_{ll}^{\text{min}}$ starting at 400 GeV.
\end{itemize} 

\begin{itemize}
  \item Top and multijet backgrounds estimated from simulation, extrapolated from a 2$b$ region using parametric functions.
  \item $Z$+jets fitted with for $130 < m_{ll} < 250$ GeV.
  \item Largest observed local significance $2.6 \sigma$.
  \item Lower limits: from 1.8 to 2.4 TeV.
\end{itemize}
The number of leptons of each family is conserved in weak interactions, and violation of this assumption is known as **lepton flavour violation** (LFV).

One in $10^{54}$ Z bosons would decay into a muon and a $\tau$-lepton via neutrino mixing, one in $10^5$ in presence of heavy neutrinos, *Phys. Rev. D* 63, 053004.

Searches performed in ATLAS with both **leptonically** and **hadronically** decaying $\tau$-leptons (accepted in Nature Physics).

Using multiple neural network classifiers (one per bkg.) and optimising their combination for the best sensitivity.

\[
\text{combined NN output} = 1 - \sqrt{\frac{\sum_i w_i \times (1 - NN_i)}{\sum_i w_i}}
\]
**Lepton Flavour Violating Z-boson Decays (2)**

- **8 signal regions:**
  - $\tau_{\text{lep}}$: $e\tau_{\text{lep}}$ and $\mu\tau_{\text{lep}}$ split by $p_T(l_2) < 20$ (25) GeV.
  - $\tau_{\text{had}}$: $e\tau_{\text{had}}$ and $\mu\tau_{\text{had}}$ split by the number of tracks $\tau$-leptons decay into (1P or 3P).
- **Signal region fit variable combined NN output.**
- **Z control region fit variable** $m_{\text{coll}}(l_1, l_2) =$ invariant mass of $l_1$–$l_2$–2$\nu$ system where neutrinos are assumed collinear with $l_2$.
- **Fitted parameters:**
  - $\tau_{\text{lep}}$: yields of signal, $Z \rightarrow \tau\tau$, top quarks, and misidentified leptons.
  - $\tau_{\text{had}}$: yields of signal, $Z \rightarrow \tau\tau$, misidentified $\tau$-jets separately for 1P or 3P $\tau_{\text{had}}$.
- **Combined limit on** $B(Z \rightarrow e\tau)$ set to $5 \times 10^{-6}$ and on $B(Z \rightarrow \mu\tau)$ to $6.5 \times 10^{-6}$.
• The seesaw mechanism: explaining the relative smallness of the neutrino masses.
• Minimal type-III seesaw — an extra fermionic triplet: one neutral ($N^0$) and two oppositely-charged leptons ($L^+, L^-$), \cite{Phys_C_Particles_and_Fields_1989_44_441, Eur_Phys_J_C_2012_72_1899}.
• Decays into a SM lepton and a $W$, $Z$ or $H$ boson, the highest branching ratio into $W$.
• Probed a few possible lepton/jet multiplicities:
  • two light leptons, at least two jets
  • three light leptons, zero or one jet
  • three light leptons, at least two jets
  • four light leptons, any number of jets

ATLAS-CONF-2021-023
ATLAS-EXOT-2018-33
11 signal regions (SR) in total:
• 6 dilepton SRs: all lepton flavour and charge combinations
• 3 trilepton SRs: on-Z and off-Z with 2+ jets, inclusive with 0-1 jets
• 2 four lepton SRs: sum of lepton charge 0 or 2
• High $E_T^{\text{miss}}$ with good reconstruction significance required — neutrinos.
• Demanding background estimation: large fraction of non-prompt and fake leptons, leptons with misreconstructed charge.
• Heavy leptons with masses below 910 GeV are excluded.
• What if LHC data can not be described with our preferred model? Can a more generalised search be performed?
  
• ATLAS: 22 single-bin signal regions
  
  • Measured number of signal events $\hat{N}_{\text{sig}}$ as difference between the estimated background and the data.
  
• CMS: about 60 classes
  
  • Search for regions: taking the ones with smallest $p$-value.
  
  • Global overview: observed deviations are compared with pseudo-experiments using the SM-only hypothesis.
ATLAS and CMS performed many non-resonant searches with leptons in the final state.

No significant excess from the Standard Model has been observed.

Many searches of full Run 2 data still being completed.

Run 3 just around the corner.

ATLAS Publications

CMS Publications
FOUR-FERMION CONTACT INTERACTION — ALL LIMITS (1)

ATLAS-EXOT-2019-16

CMS-EXO-19-019

ATLAS
\( \sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1} \)

Observed Limit

Expected Limit

1σ Expected

2σ Expected

Constructive

Destructive

CMS

\( \sqrt{s} = 13 \text{ TeV}, \text{ ee} \)

ee channel

95% CL lower limits

Observed

Median expected

68% expected

95% expected

At 137 fb\(^{-1}\) (13 TeV, ee)

140 fb\(^{-1}\) (13 TeV, \( \mu \mu \))

95% CL lower limits

Observed

Median expected

68% expected

95% expected

At 140 fb\(^{-1}\) (13 TeV, \( \mu \mu \))

ee + \( \mu \mu \) channels

95% CL lower limits

Observed

Median expected

68% expected

95% expected

Dilepton Combination

ee Channel

\( \mu \mu \) Channel

Dilepton Combination

ee Channel

\( \mu \mu \) Channel

Constructive

Destructive

Constructive

Destructive

Observed Limit

Expected Limit

1σ Expected

2σ Expected

CMS

Observed

Median expected

68% expected

95% expected

Observed

Median expected

68% expected

95% expected
FOUR-FERMION CONTACT INTERACTION — ALL LIMITS (2)

ATLAS-EXOT-2018-16

ATLAS
\( \sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1} \)
Limits at 95% CL
\( e^+e^- + 0b \) category

\begin{align*}
\sigma_{ee} \text{ [fb]} &= 13 \text{ TeV}, 139 \text{ fb}^{-1} \\
\text{Observed} \quad &\text{Expected} \\
\pm \sigma &\quad \pm 2\sigma \\
* \text{Strongest expected} \\
\text{Theory}
\end{align*}

\begin{align*}
\sigma_{ee} \text{ [fb]} &= 13 \text{ TeV}, 139 \text{ fb}^{-1} \\
\text{Observed} \quad &\text{Expected} \\
\pm \sigma &\quad \pm 2\sigma \\
* \text{Strongest expected} \\
\text{Theory}
\end{align*}

\begin{align*}
\sigma_{\mu\mu} \text{ [fb]} &= 13 \text{ TeV}, 139 \text{ fb}^{-1} \\
\text{Observed} \quad &\text{Expected} \\
\pm \sigma &\quad \pm 2\sigma \\
* \text{Strongest expected} \\
\text{Theory}
\end{align*}

\begin{align*}
\sigma_{\mu\mu} \text{ [fb]} &= 13 \text{ TeV}, 139 \text{ fb}^{-1} \\
\text{Observed} \quad &\text{Expected} \\
\pm \sigma &\quad \pm 2\sigma \\
* \text{Strongest expected} \\
\text{Theory}
\end{align*}
• Large difference between the energy scales of electroweak symmetry breaking and gravitation \(\rightarrow\) gravitational force could propagate into additional dimensions; models by Arkani-Hamed, Dimopoulos, and Dvali (ADD), Phys. Lett. B 429 (1998) 263.

• ATLAS recently performed reinterpretation of the contact interaction search.

• Dedicated CMS search.

• Lower limits on the model parameters in the different ADD conventions are set:
  • Giudice-Rattazzi-Wells
  • Hewett
  • Han-Lykken-Zhang

\[
\begin{array}{c}
\text{ADD models} \\
\text{with extra dimensions in dilepton events}
\end{array}
\]
# Lepton Flavour Violating Z-boson Limits

<table>
<thead>
<tr>
<th>Final state, polarization assumption</th>
<th>Observed (expected) upper limit on $\mathcal{B}(Z \rightarrow \ell \tau)$ [$\times 10^{-6}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$e\tau$</td>
</tr>
<tr>
<td>$\ell \tau_{\text{had}}$ Run 1 + Run 2, unpolarized $\tau$</td>
<td>8.1 (8.1)</td>
</tr>
<tr>
<td>$\ell \tau_{\text{had}}$ Run 2, left-handed $\tau$</td>
<td>8.2 (8.6)</td>
</tr>
<tr>
<td>$\ell \tau_{\text{had}}$ Run 2, right-handed $\tau$</td>
<td>7.8 (7.6)</td>
</tr>
<tr>
<td>$\ell \tau_{\nu}$ Run 2, unpolarized $\tau$</td>
<td>7.0 (8.9)</td>
</tr>
<tr>
<td>$\ell \tau_{\nu}$ Run 2, left-handed $\tau$</td>
<td>5.9 (7.5)</td>
</tr>
<tr>
<td>$\ell \tau_{\nu}$ Run 2, right-handed $\tau$</td>
<td>8.4 (11)</td>
</tr>
<tr>
<td>Combined $\ell \tau$ Run 1 + Run 2, unpolarized $\tau$</td>
<td>5.0 (6.0)</td>
</tr>
<tr>
<td>Combined $\ell \tau$ Run 2, left-handed $\tau$</td>
<td>4.5 (5.7)</td>
</tr>
<tr>
<td>Combined $\ell \tau$ Run 2, right-handed $\tau$</td>
<td>5.4 (6.2)</td>
</tr>
</tbody>
</table>
What if LHC data can not be described without preferred model? Can a more generalised search be performed?

Very important to estimate background contributions with high precision.

22 single-bin signal regions categorised by

- lepton count (3 or 4 leptons)
- presence of an on-Z lepton pair
- magnitude of invariant mass of all leptons
- $E_{\text{miss}}$ lower or higher than 50 GeV

Measured number of signal events $\hat{N}_{\text{sig}}$ is defined as the difference between the estimated background and the data.

No significant deviations observed.
• Kinematic distributions of interest:
  • scalar sum of $p_T$ of all objects (3+ bins)
  • invariant/transverse mass of all objects (1+ bins)
  • missing transverse momentum (3+ bins)
• Search for regions: taking the ones with smallest $p$-value.
• Global overview: observed deviations are compared with pseudo-experiments using the SM-only hypothesis.
• No significant deviations found in ~60 classes.