Heavy Neutrino searches at ATLAS & CMS

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on behalf of the ATLAS & CMS Collaboration
• SM:
  => Extremely successful theory.
  => Guided for a series of new particle discoveries.
  => Discovery of Higgs boson by ATLAS & CMS in 2012 again glorifies its success!

• However there exist a couple of experimental observations that SM cannot explain.
  => New Physics can be hiding there!
  e.g. Experimental signature of neutrino oscillation concludes neutrino has a very small mass.
  => Several searches performed with LHC data to explain the origin of a very small neutrino mass!
Several theories exist in Beyond Standard Model (BSM) to explain neutrino mass!

- **LRSM (Left Right Symmetric Model):**
  - Restores parity by introducing right-handed $W, Z$ bosons ($WR, ZR$) and right-handed neutrinos ($NR$ – $Ne, N\mu, N\tau$).
  - Includes the **Seesaw mechanism** (with heavy right-handed Majorana neutrino ($NR$) so explains small (SM neutrino) $\nu_L$ masses.
  - Seesaw mechanism couples $\nu_L$ masses to $NR$ through a mass mixing matrix. It allows heavy neutrinos to be GeV-TeV scale and therefore discoverable at LHC.

- **νMSM (neutrino Minimal Standard Model):**
  - Incorporates **Seesaw mechanism**.
  - Small neutrino masses result from large mass of $NR$ similar to LRSM.
  - Incorporates heavy-neutrino states **without additional vector bosons**.

**ATLAS & CMS latest 13 TeV results shown in this presentation.**
Latest heavy neutrino search in ATLAS with 36.1 fb$^{-1}$ of data:

- Based on LRSM theory.
- **Type-I seesaw mechanism** $\Rightarrow$ Majorana neutrino
- **Inverse seesaw mechanism** $\Rightarrow$ Dirac neutrino
- Keung–Senjanović (KS) process considered ($m_{NR} \leq 2m_{WR}$)

$$\begin{align*}
&\bar{q} q W_R^* N_R \\
&m_{WR} > m_{NR} \\
\end{align*}$$

$$\begin{align*}
&\bar{q} q W_R^* N_R \\
&m_{WR} < m_{NR} \\
\end{align*}$$

arXiv:1809.11105, submitted to JHEP
Analysis Strategy, Object & Event Selection:

- Always SF (same flavour) leptons (either electron (e) or muon(μ)) selected in final state.

- Exactly 2 leptons ($E_T/p_T > 25/30$ GeV) & 2 jets ($p_T > 100$ GeV) selected.

- SS (same-sign), OS (opposite-sign) lepton channels cover for both Majorana and Dirac hypotheses with the best sensitivity.

- 50%-50% probability assumed between SS & OS for Majorana case. 100% probability for OS corresponds to Dirac case.

- Dominating backgrounds: OS (ttbar, Z+jet(s)). SS(misidentification, diboson).

- Signal region (SR) defined mainly to reduce Z+jet(s).

arXiv:1809.11105, submitted to JHEP
Data-Prediction (Pred) Comparison in Analysis regions:

- Several analysis regions studied

<table>
<thead>
<tr>
<th>Region</th>
<th>Control region</th>
<th>Validation region</th>
<th>Signal region</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel</td>
<td>CR(ℓ⁺ℓ⁻)</td>
<td>CR(ℓ⁺ℓ⁻)</td>
<td>VR(ℓ⁺ℓ⁻)</td>
</tr>
<tr>
<td>m_electron [GeV]</td>
<td>[60, 110]</td>
<td>[110, 300]</td>
<td>[110, 400]</td>
</tr>
<tr>
<td>m_muon   [GeV]</td>
<td>[60, 110]</td>
<td>[60, 300]</td>
<td>[110, 400]</td>
</tr>
<tr>
<td>m_electron [GeV]</td>
<td>—</td>
<td>&gt; 400</td>
<td>—</td>
</tr>
</tbody>
</table>

- Data-Pred agreed within uncertainty in CR & VR.

Z+jet(s) mismodelling in OS addressed with data-driven reweighting factors as a function of m_{jj}.

**ATLAS**

\( \sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1} \)

Z+Jet(s) events

Peak = (0.24 \pm 0.01) \text{ TeV}

Width = (1.12 \pm 0.03) \text{ TeV}

Tail = -6.2 \pm 0.9

**ATLAS**

\( \sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1} \)

Dataset/simulation ratio

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Dataset/simulation ratio

arXiv:1809.11105, submitted to JHEP
• In SR reasonable agreement found between Data & Pred in both e & μ channels (& in both SS and OS channels).

• Almost no data in region with $m_{WR} > 3$TeV.
• No significant deviation found.

arXiv:1809.11105, submitted to JHEP
Final Result (Setting up limit):

- $e, \mu$ channels separately tested for Majorana hypothesis.

$m_{WR}$ up to 4.7 TeV are excluded at 95% CL, for $m_{NR}$ in 0.5–3.0 TeV region for the $g_R=g_L$ assumption.

- $e, \mu$ channels separately tested for Dirac hypothesis.
Latest heavy neutrino search in CMS with 35.9 fb$^{-1}$ of data with same final state:

- Based on LRSM theory: $$W_R \rightarrow \ell N_R \rightarrow \ell \ell W^*_R \rightarrow \ell \ell q\bar{q}', \ell = e \text{ or } \mu.$$

- No charge requirement on leptons.

- Dominating backgrounds: ttbar, DY+jet(s), tW, diboson.

- Inspired by previous WR search at 8 TeV with a 2.8$\sigma$ local excess $m_{eejj} \sim 2.1$ TeV.

- Leading & subleading leptons ($p_T > 60$ GeV & 53 GeV) & Particle Flow (PF) jets ($p_T > 40$ GeV) selected.

- Signal region (SR): $m_{lljj} > 600$ GeV, $m_{ll} > 200$ GeV (to reduce Z +jet(s)).

**$m_{ij}$ is invariant mass of objects ij**
Various Control Region (CR) studied to estimate most dominating backgrounds (DY+jet(s), ttbar).

### Analysis Regions

<table>
<thead>
<tr>
<th>CR for DY+jet(s)</th>
<th>Event Selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>2SF, OS e or μ (80 GeV &lt; m_{ll} &lt; 100 GeV), 2 jets, m_{lljj} &lt; 600 GeV</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>VR for DY+jet(s)</th>
<th>Event Selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>2SF, OS e or μ (m_{ll} &gt; 200 GeV), 2 jets, m_{lljj} &lt; 600 GeV</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CR for ttbar</th>
<th>Event Selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 e &amp; 1 μ (m_{ll} &gt; 200 GeV), 2 jets, m_{lljj} &gt; 600 GeV</td>
<td></td>
</tr>
</tbody>
</table>
No significant deviations found in data in SR.

Observed limit at 95% CL on WR mass ~ 4.4 TeV for both channels with \( m_{NR} = m_{WR}/2 \).
Latest heavy neutrino search in CMS with 12.9 fb$^{-1}$ of data in lepton + jets final state:

- Based on LRSM theory: $W_R \rightarrow \tau + N_\tau$, where $N_\tau \rightarrow \tau + W_R^* \rightarrow \tau + q\bar{q}$.

- Focussed on 1 $\tau(\tau_l)$ decays to e/µ. Other $\tau(\tau_h)$ decays hadronically.

- **PF algorithm** utilised to identify individual particles.

- Reconstruction of $\tau_h$ (hadrons-plus-strips algorithm), jets, missing energy performed with identified particles as inputs.

- Selection: e or µ with $p_T > 50$ GeV. $\tau_h$ with $p_T > 60$ GeV. Transverse momentum imbalance ($p_T^{\text{miss}}$) > 50 GeV. Invariant mass of e/µ + $\tau_h$ > 150 GeV.

- Identified e, µ, $\tau_h$ required to originate from same vertex with $\Delta R > 0.5$. 

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Observed (in data)-Expected(in simulation) comparison in SR: No deviation from SM found.

- ttbar background validated in e/μ + at least 2 jets final state.
- W+jets background estimated in W -> μν/ev + at least 3 jets with no b-tagged jet.
- Estimation of multi jet background performed by loosening τh ID, Isolation criteria.

Observed (expected) limit at 95% CL on mWR determined to be 2.9 (3.0)TeV with mNR = mWR / 2.
Based on LRSM theory with 2 final state \( \tau \) leptons decaying hadronically.

- All jets \( p_T > 30 \text{ GeV} \) (2 jets with \( p_T > 50 \text{ GeV} \)) . \( \tau_h > 32 \text{ GeV} \) (2 \( \tau_h > 70 \text{ GeV} \)).

- Dominating backgrounds : ttbar, Z+jet(s), multijet.

\[
m(\tau_{h1}, \tau_{h2}, j_1, j_2, p_T^{\text{miss}}) = \sqrt{(E_{\tau_{h1}} + E_{\tau_{h2}} + E_{j_1} + E_{j_2} + p_T^{\text{miss}})^2 - (\vec{p}_{\tau_{h1}} + \vec{p}_{\tau_{h2}} + \vec{p}_{j_1} + \vec{p}_{j_2} + \vec{p}_T^{\text{miss}})^2}.
\]

\( \approx m_{WR} \)

arXiv:1811.00806, Submitted to JHEP
Various Analysis regions comparisons and limit setup:

- **ttbar CR**: 2 muons + at least 1 b-tagged jet with $m_{\mu\mu} < 80$ GeV or $m_{\mu\mu} > 110$ GeV.

- **Z+jet(s) CR**: 2 muons with $80$ GeV < $m_{\mu\mu}$ < $110$ GeV.

- Data driven ABCD matrix method used for multijet event estimation: $p_T^{\text{miss}}$ (50 GeV) & $\tau_h$ isolation as discriminators between signal & QCD jets.

$m_{WR}$ below 3.50 TeV excluded at 95% CL (expected 3.35 TeV).

arXiv:1811.00806, Submitted to JHEP
Latest heavy neutrino search in CMS with 35.9 fb\(^{-1}\) of data νMSM theory:

- Also looked into N production via \(W\gamma\) fusion.
- **Same sign leptons** + (at least 2 jets (\(R = 0.4\)) / exactly 1 jet (\(R = 0.4\)) / at least 1 large jet (\(R = 0.8\)) in final state considered.
- No flavour conservation considered (ee or \(\mu\mu\) or \(e\mu\)).
- Limits estimated with matrix element describing mixing of N with SM ν of flavour e or \(\mu\).

arXiv:1806.10905, Submitted to JHEP
Large jet with $R = 0.8$ required to have $\tau_{21} < 0.6$ and a pruned jet mass between 40 & 130 GeV. (See Pierre-Antoine Delsart’s talk later).

$\mathbf{p}_T > 25(15)$ GeV for ee, $> 20(10)$ GeV for $\mu\mu$, $25(10)$ GeV for $e\mu$.

Different SR(s) studied based on $(m_N \gtrsim 80$ GeV or $m_N \lesssim 80$ GeV), combination of flavours and small jet or large jet selection:

=> low- & high mass SR1 : number of $R = 0.4$ jets $\geq 2$, $R = 0.8$ jets = 0.
=> low-mass SR2 : number of $R = 0.4$ jets = 1, number of $R = 0.8$ jets = 0.
=> high-mass SR2 : number of $R = 0.8$ jets $\geq 1$.

Several variables used simultaneously for optimized signal selection.
Limit setup with mixing matrix element:

CR(s) classified in following categories:

a. Multiple prompt leptons => diboson
b. Misidentified leptons => W+jets, ttbar
c. Sign mismeasurement => OS 2leptons

For N masses between 20 and 1600 GeV, upper limits on $|V_{\ln}|^2$ range between $2.3 \times 10^{-5}$ & 1.0.
Summary & Outlook

• A comprehensive set of searches for heavy neutrinos carried out (ongoing) in both ATLAS & CMS (With Type-III seesaw mechanism heavy neutrino search using 79.8 fb-1 of ATLAS data, glimpses in backup!).

• Until now no consistent deviation from SM prediction found.

• Searches with same final state performed at various centre of mass energies of LHC (e.g. 7 TeV, 8 TeV 13 TeV) helps in gaining deeper understanding of heavy neutrino theories.

• Exclusion limit reaches to 4.7 TeV m_{WR} with m_{N_R} 0.5–3.0 TeV. However it depends on the specific model used!

• Higher energy boosted scenarios can be explored to gain deeper insights for lower m_{N_R}!
• Final state: 2 jets + 2 leptons (SS or OS) + neutrinos
• No flavour conservation considered (ee or μμ or eμ)

<table>
<thead>
<tr>
<th></th>
<th>OS ($\ell^+\ell^- = e^+e^-, e^\pm\mu^\mp, \mu^+\mu^-$)</th>
<th>SS ($\ell^+\ell^- = e^\pm e^\pm, e^\pm\mu^\pm, \mu^\pm\mu^\pm$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Top CR $Z$+jets VR $m_{jj}$ VR SR</td>
<td>$Z$+jets VR $m_{jj}$ VR $m_{jj}$ CR SR</td>
</tr>
<tr>
<td>$N$(jet)</td>
<td>$\geq 2$ $\geq 2$ $\geq 2$ $\geq 2$</td>
<td>$\geq 2$ $\geq 2$ $\geq 2$ $\geq 2$</td>
</tr>
<tr>
<td>$N$(b-jet)</td>
<td>$\geq 2$ 0 0 0</td>
<td>$\geq 2$ 0 0 0</td>
</tr>
<tr>
<td>$m_{jj}$ [GeV]</td>
<td>[60,100) [60,100) [35,60) [100,125)</td>
<td>[60,100) [60,100) [60,100) [60,100)</td>
</tr>
<tr>
<td>$m_{\ell\ell}$ [GeV]</td>
<td>[110,∞) [70,110) [110,∞) [110,∞)</td>
<td>[70,100) [70,100) [100,∞) [100,∞)</td>
</tr>
<tr>
<td>Sig($E_T^{miss}$)</td>
<td>$\geq 5$ $\geq 5$ $\geq 10$ $\geq 10$</td>
<td>$\geq 5$ $\geq 5$ $\geq 5$ $\geq 7.5$</td>
</tr>
<tr>
<td>$\Delta\phi (E_T^{miss}, l_{min})$</td>
<td>&gt; 1</td>
<td>&gt; 1</td>
</tr>
<tr>
<td>$p_T(jj)$ [GeV]</td>
<td>[100,∞)</td>
<td>[60,∞)</td>
</tr>
<tr>
<td>$p_T(\ell\ell)$ [GeV]</td>
<td>[100,∞)</td>
<td>[100,∞)</td>
</tr>
<tr>
<td>$H_T + E_T^{miss}$ [GeV]</td>
<td>[300,∞) [300,∞)</td>
<td>[500,∞) [300,500)</td>
</tr>
</tbody>
</table>
**ATLAS Preliminary**

\( \sqrt{s} = 13 \text{ TeV}, 79.8 \text{ fb}^{-1} \)

**OS SR (e^+\mu^-)**

- Events
- Data
- Total SM
- Top quarks
- Diboson
- Drell-Yan
- Fakes

**Exclusion limit at 95% CL**

Expected 550 GeV observed and 560 expected.