Tests of Neutrino Mass Models at CMS

Sungbin Oh
Seoul National University
On behalf of CMS collaboration

NuFACT 2021 @ Cagliari, Italy
Introduction

- Discovery of neutrino oscillations

- At least two neutrinos are **massive**
- Direct measurement of $m_{\nu_e}$ at KATRIN experiment: $< 1.1$ eV

- What is the mechanism of neutrino mass generation?
  - Yukawa? Then, where are **right-handed** fields?
  - Why neutrinos have such **small masses**?
• Seesaw mechanism - Majorana and Yukawa mass terms

\[
\begin{pmatrix}
\bar{V}_L & \bar{N}_R^C
\end{pmatrix}
\begin{pmatrix}
0 & M_D \\
M_D^T & M_M
\end{pmatrix}
\begin{pmatrix}
V_L^C \\
N_R
\end{pmatrix}
\]

Diagonalize mass matrix \( M_D << M_M \)

\[
\begin{align*}
M_1 &= M_M \\
M_2 &= -\frac{M_D^2}{M_M}
\end{align*}
\]

Heavy Majorana neutrino
Small neutrino masses

• **Origin** and **smallness** of neutrino masses are explained

• The left-right symmetry model
  • Maximum parity violation of the Standard Model (SM) - Why?
  • Spontaneous symmetry breaking of the left-right symmetric group
  • \( SU(2)_L \times SU(2)_R \times U(1)_{B-L} \)
    • Extra gauge bosons \( Z', W_{R^\pm} \) and right-handed neutrinos \( \nu_R \)
    • \( B-L : \) baryon number - lepton number
      • Matter/anti-matter asymmetry of the universe
    • Natural seesaw mechanism via VEVs of scalar fields
• Signal processes at proton-proton collisions
  • Type-I seesaw model (TISM)
    Two leptons
    Three leptons
    mTISM : JHEP01(2019)122
    Long-lived : CMS-EXO-20-009 NEW!!

• Left-right symmetric model (LRSM)
  W_R & HNL
  Z' & HNL pair
  ττ : JHEP07(2017)121
  JHEP03(2017)077
  Soon!! ee, μμ : CMS-EXO-20-006
  Soon!! ee, μμ : CMS-EXO-20-002
  NEW!!
The Compact Muon Solenoid

- Multi-purpose detector
  - Silicon tracker (pixel & strip)
  - PbWO₄ ECAL
  - Brass - Scintillator tile HCAL
  - Superconducting magnet - 3.8 T
  - Gaseous muon system

- Reconstruct particles using all sub-detectors
  - The particle-flow algorithm
  - Energy/momentum resolutions
    - $e/\gamma$ : 1 (0.6) % @ 20 (100) GeV
    - muon : 1 (2) % @ 20 (100) GeV
    - Jets : 10 (5) % @ 100 (1000) GeV
Type-I seesaw Model (TISM)
3-leptons with long-lived heavy neutrino
TISM 3-leptons : Long-lived

- The life-time of heavy neutral lepton (HNL)
  - \( \tau_N \propto \frac{1}{m_N^5} V_{LN}^2 \)
    where \( V_{LN} \) is mixing between HNL and \( \nu_L \) (\( L = e, \mu, \) and \( \tau \))
  - Significant where \( m_N < 20 \text{ GeV} \) : several cm \( \sim \) few m

- Majorana HNL
  - \( N \rightarrow W^* \ell \)
    - No opposite-sign same flavor (OSSF) dilepton
    - Background reduction

![Diagram of Majorana and Dirac leptons]
• Only one among $V_{\text{eN}}$, $V_{\mu N}$, and $V_{\tau N}$ is nonzero

• Event selection
  • Using electrons and muons
  • One prompt lepton ($l_1$) + two displaced leptons ($l_2$, $l_3$)
  • $1 \text{ GeV} < m_N < 20 \text{ GeV}$
    • Small opening angle between $l_2$ and $l_3$
    • Large angular separations between $l_1$ and $l_2$, $l_3$
  • OSSF dilepton mass veto: $\omega$, $\phi$, $J/\psi(1S, 2S)$, $Y(1S, 2S, 3S)$, and $Z$
  • Secondary vertex of $l_2$, $l_3$
    • $\Delta_{2D}$: transverse position of $l_2$, $l_3$ vertex
    • $\Delta_{2D}/\sigma(\Delta_{2D}) > 20$
  • No bottom quark tagged jet: B meson semi-leptonic decay background
  • For $V_{\mu N}$, $\mu\mu\mu$, $\mu\pm\mu\mp e\pm$ (Dirac), and $\mu\pm\mu\pm e\mp$ (Majorana)
  • For $V_{\text{eN}}$, $\text{eee}$, $e\pm e\mp\mu\pm$ (Dirac), and $e\pm e\pm\mu\mp$ (Majorana)
• Further categories

\[
m(\ell_2 \ell_3) \text{ (GeV)} \quad \Delta_{2D} \text{ (cm)}
\]

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;0.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5–1.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.5–4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&gt;4</td>
<td>&lt;0.5</td>
<td></td>
</tr>
<tr>
<td>&gt;4</td>
<td>&gt;0.5</td>
<td></td>
</tr>
</tbody>
</table>

• No excess beyond the expected background

• Binned likelihood fit is performed to exclude \(|V_{LN}|^2\) as functions of HNL masses
• Limits on $V_{LN}$ vs $m_N$ planes
• Regions inside curves are excluded
• Short-lived at top-right corner
• Not sensitive

• Clear improvement w.r.t. DELPHI results in the displaced regime

• World best sensitivity where $m_N$ is 1~14 GeV

Majorana HNL

Dirac HNL
Left-right Symmetric Model
$W_R + \text{heavy Majorana neutrino}$
Simultaneous search for extra gauge boson ($W_R$) and HNL

- Challenging kinematic signature
  - Boosted HNL
  - $m_{W_R} >> m_N$
  - A lepton and two jets are merged

Multiple object definitions

- Loose and tight leptons: different isolation criteria
  \[ \sum_i p_T^{\text{Particle}} < \text{Cut}, \] where $p_T$ is transverse momentum

- Jets
  - Merged debris of parton shower and hadronization: anti-$k_T$ algorithm
  - AK4 and AK8 jets: different merging cone sizes ($\Delta R = 0.4$ and 0.8)
The Lepton Subjet Fraction (LSF)

For boosted HNL

Recluster the jet into 3-subjets with exclusive kt algorithm: Rewinding the parton shower back to the hardest splitting

Signal lepton is from hard process $\rightarrow$ left alone until the last steps

Good discriminating power between background and signal

Event selection

Resolved: two tight leptons + at least two AK4 jets

Boosted: one tight lepton + at least one AK8 jet with $\text{LSF} > 0.75$

Additional cuts on $W_R$ and HNL candidate masses

$$\text{LSF} = \frac{p_T(\text{lepton})}{p_T(\text{subjet})}$$

arXiv:1410.0362
• Reconstructed $W_R$ mass plots

• No significant excess beyond the expected background

• Set exclusion curve in $(m_{W_R}, m_N)$ space using binned likelihood
• Expected limit is improved in both resolved and boosted regions
  • Expected (observed) lower limit at 95% CL
    • $m_N=200$ GeV : 5.0 (4.6) TeV in $ee$ and 5.3 (5.4) TeV in $\mu\mu$
    • $m_N=mW_R/2$ : 5.2 (4.7) TeV in $ee$ and 5.2 (5.0) TeV in $\mu\mu$
  • Significant improvements in the boosted ($m_N \ll mW_R$) regions
    • The world best limit in the boosted region
Summary

• Nonzero and smallness of neutrino masses arise questions for mass generation mechanism of neutrinos

• It could be related with more fundamental questions such as matter/anti-matter asymmetry of the universe

• Various models for neutrino masses have been tested at CMS
  • Two new interesting searches
  • TISM 3-lepton targeting long-lived HNL and LRSM $W_R + HNL$

• New techniques improved sensitivity much
  • The improvement is ongoing
  • LHC Run 3 will start next year
  • Interesting results are waiting for us - Stay tuned!