Constraining sterile neutrinos from precision Higgs data

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Higgs Physics, Saturday, 07/07/2018

Based on :1704. 00880
Building Blocks of Nature

Solved many things and having unsolved issues such as gauge hierarchy problem, existence of tiny neutrino mass

Our point of interest today

\[ \text{SM} = \text{SU}(3)_C \times \text{SU}(2)_L \times \text{U}(1)_Y \]
Discovery of Higgs boson

CMS Preliminary

\( \sqrt{s} = 7 \text{ TeV}, L = 5.1 \text{ fb}^{-1} \)

\( \sqrt{s} = 8 \text{ TeV}, L = 5.3 \text{ fb}^{-1} \)

- S/B Weighted Data
- S+B Fit
- Bkg Fit Component

\( \pm 1 \sigma \)

\( \pm 2 \sigma \)

Nobel Prize in 2012

Higgs boson mass around 125 GeV
Results in the neutrino Sector

Super- Kamiokande, Sudbury Neutrino Observatory 1999, Neutrino oscillation between mass and flavor eigenstates

Neutrinos are very special

Physicists Nobel Prize 2015

Neutrino oscillation data

<table>
<thead>
<tr>
<th>$\Delta m^2_{21}$</th>
<th>$7.6 \times 10^{-5}\text{eV}^2$</th>
<th>SNO</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>\Delta m^2_{31}</td>
<td>^2$</td>
</tr>
<tr>
<td>$\sin^2 2\theta_{12}$</td>
<td>0.87</td>
<td>KamLAND, SNO</td>
</tr>
<tr>
<td>$\sin^2 2\theta_{23}$</td>
<td>0.999</td>
<td>T2K</td>
</tr>
<tr>
<td></td>
<td>0.90</td>
<td>MINOS</td>
</tr>
<tr>
<td>$\sin^2 2\theta_{13}$</td>
<td>0.084</td>
<td>DayaBay2015</td>
</tr>
<tr>
<td></td>
<td>0.1</td>
<td>RENO</td>
</tr>
<tr>
<td></td>
<td>0.09</td>
<td>DoubleChooz</td>
</tr>
</tbody>
</table>
There are many unsolved questions regarding the nature of the conversion between the flavor and mass mixings.

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix}
= U_{PMNS}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

(Non-)Unitary?

How do the neutrinos get mass: seesaw mechanism is the simplest idea. Apart from that there are many other (next-to) simple models like inverse seesaw, linear seesaw etc.

These models describe different natures (Majorana/Dirac) of neutrino mass. However, yet to be fixed.
In the presence of right-handed neutrinos \( \nu R \), neutrino decay to a charged lepton and the same as the Pontecorvo-Maki-Nakagawa-Sakata mixing space. In Sec. 4, we also make conservative predictions for the current best limits for sterile neutrino masses in the vicinity of the LHC data in the region of the neutrino mass matrix.

Assuming the hierarchy of Higgs doublet, respectively, and the Majorana mass matrix of the right-handed neutrinos is

\[
\mathcal{L} \supset - \sum_{i=1}^{3} \sum_{j=1}^{2} Y_D^{ij} \bar{\ell}_L^i H N_R^j - \frac{1}{2} \sum_{k=1}^{2} m_N^k N_R^k C N_R^k + \text{H.c.}
\]

Dirac Mass term

Majorana Mass term

**Neutrino mass matrix**

\[
M_\nu = \begin{pmatrix}
0 & m_D^T \\
m_D & m_N
\end{pmatrix}
\]

**diagonalizing**

\[
m_\nu \simeq -m_D m_N^{-1} m_D^T.
\]

Flavor eigenstate can be expressed in terms of the mass eigenstate

\[
\nu_\ell \simeq U_{\ell m} \nu_m + V_{\ell n} N_n
\]

**PMNS matrix**

\[
M_D M_N^{-1}
\]
Charged Current interaction

\[
\mathcal{L}_{\text{CC}} = - \frac{g}{\sqrt{2}} W_\mu \bar{\ell} \gamma^\mu p_L \left[ U_{\ell m} \nu_m + V_{\ell n} N_n \right] + \text{H.c.},
\]

Neutral Current interaction

Expanding \( \nu \ell \) (twice)

\[
\mathcal{L}_{\text{NC}} = - \frac{g}{2 \cos \theta_w} Z_\mu \left[ (U^\dagger U)_{mn} \bar{\nu}_m \gamma^\mu p_L \nu_n \right.
\]
\[
+ (U^\dagger V)_{mn} \bar{\nu}_m \gamma^\mu p_L N_n + (V^\dagger V)_{mn} \bar{N}_m \gamma^\mu p_L N_n \]
\[
+ \text{H.c.},
\]

The interaction between the heavy right handed neutrinos and the SM gauge bosons are suppressed by the powers of the mixing (V) parameter.
\[ \mathcal{L}_Y \supset -Y_{D \ell m} \bar{L}_\ell \phi N_m + H.c. \]

**SU(2) \_L lepton doublet**

\[ \langle \phi^0 \rangle = v \quad M_D = v Y_D \quad Y_D = VM_N / v, \text{ which is also suppressed by } V \]

\[ N \rightarrow \ell^- W^+, \nu_\ell Z, \nu_\ell h \]

**SU(2) \_L Higgs doublet**

**SM Higgs boson, physical remnant of \( \phi \)**

**Decay Widths**

\[ \Gamma(N \rightarrow \ell^- W^+) = \frac{g^2 |V_{\ell N}|^2 M_N^3}{64 \pi} \left( 1 - \frac{M_W^2}{M_N^2} \right)^2 \left( 1 + \frac{2 M_W^2}{M_N^2} \right) \]

\[ \Gamma(N \rightarrow \nu_\ell Z) = \frac{g^2 |V_{\ell N}|^2 M_N^3}{128 \pi} \left( 1 - \frac{M_Z^2}{M_N^2} \right)^2 \left( 1 + \frac{2 M_Z^2}{M_N^2} \right) \]

\[ \Gamma(N_1 \rightarrow \nu_\ell h) = \frac{|V_{\ell N}|^2 M_N^3}{128 \pi} \left( 1 - \frac{M_h^2}{M_N^2} \right)^2 \]

Antusch, Atre, Chen, Deppisch, Dev, Drewes, Franceschini, Gao, Kamon, Kim, Mohapatra, Fischer, Han, Pascoli, Pilaftsis, Senjanovic

Das, Okada; Das, Konar, Majhi; Deppisch, Dev, Pilaftsis: Review

arXiv:1502.06541
\[ M_N < M_W \]

\[ N \to \ell^- W^+ \]
- leptons

\[ \Gamma(N \to \ell^- \ell^+ \ell^-) \approx \frac{|V_{\ell_1 N}|^2 G_F^2 M_N^5}{96\pi^3} (g_L g_R + g_L^2 + g_R^2 + 1 + 2g_L) \]

\[ N \to \ell^- W^+ \]
- hadrons

\[ \Gamma(N \to \ell^- j j) \approx 3 \frac{|V_{\ell N}|^2 G_F^2 M_N^5}{192\pi^3} \]

\[ N \to \nu \ell Z \]
- leptons

\[ \Gamma(N \to \nu \ell^+ \ell^-) \]

\[ \Gamma(N \to \nu \ell^- \ell^+) \]

\[ \Gamma(N \to \nu \ell^- \ell^-) \approx \frac{|V_{\ell_1 N}|^2 G_F^2 M_N^5}{96\pi^3} (g_L g_R + g_L^2 + g_R^2 + 1 + 2g_L) \]

\[ N \to \nu \ell Z \]
- hadrons

\[ \Gamma(N \to \nu \ell j j) \approx 3 \frac{|V_{\ell N}|^2 G_F^2 M_N^5}{96\pi^3} (g_L g_R + g_L^2 + g_R^2) \]

\[ g_L = -\frac{1}{2} + \sin^2 \theta_w, \quad g_R = \sin^2 \theta_w \]
Heavy Neutrino Production from Higgs Decay

\[ \Gamma_h = \Gamma_{\text{SM}} + \Gamma_{\text{new}} \]

\[ \Gamma_{\text{SM}} \approx 4.1 \text{ MeV for } M_h = 125 \text{ GeV} \]

\[ \Gamma_{\text{new}} = \frac{Y_D^2 M_h}{8\pi} \left(1 - \frac{M_N^2}{M_h^2}\right)^2 \]

\[ h \rightarrow WW^* \rightarrow 2\ell 2\nu \quad h \rightarrow \nu N \rightarrow 2\ell 2\nu \]

<table>
<thead>
<tr>
<th>Region</th>
<th>Mass range</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( M_N &lt; M_W )</td>
</tr>
<tr>
<td>2</td>
<td>( M_W &lt; M_N &lt; M_Z )</td>
</tr>
<tr>
<td>3</td>
<td>( M_Z &lt; M_N &lt; M_h )</td>
</tr>
<tr>
<td>4</td>
<td>( M_N &gt; M_h )</td>
</tr>
</tbody>
</table>
$pp \rightarrow h \rightarrow \nu N \rightarrow 2\ell 2\nu. \; \ell = e, \mu$

**Final States:**

OSSF: $\mu\bar{\mu}\nu\bar{\nu}$ and $e\bar{e}\nu\bar{\nu}$

OSOF: $\mu\bar{e}\nu\bar{\nu}$ and $e\bar{\mu}\nu\bar{\nu}$

We consider all sorts of charge combinations as Higgs can decay into heavy and anti-heavy neutrinos for Dirac type heavy neutrino or for a Majorana type case the heavy neutrino can decay into both positively and negatively charged leptons.

**Selection Cuts**

<table>
<thead>
<tr>
<th>$\mu\bar{\mu}$</th>
<th>$p_{T,\ell_2,\text{sub-leading}}$</th>
<th>$p_{T,\ell_1,\text{leading}}$</th>
<th>$p_{T,j}$</th>
<th>$m_{\ell\ell}$</th>
<th>$E_T$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$&gt; 10 \text{ GeV}$</td>
<td>$&gt; 22 \text{ GeV}$</td>
<td>$&gt; 25 \text{ GeV}$</td>
<td>$&gt; 12 \text{ GeV}$</td>
<td>$&gt; 40 \text{ GeV}$</td>
</tr>
<tr>
<td>$</td>
<td>\eta^{\ell_{1,2}}</td>
<td>&lt; 2.4$</td>
<td>$</td>
<td>\eta^{\ell}</td>
<td>&lt; 2.4$</td>
</tr>
</tbody>
</table>

Dilepton transverse momentum is away from the MET

$\Delta \phi^{\ell\ell,\text{MET}} > \frac{\pi}{2}$

$p_{T,\ell\ell} > 30 \text{ GeV}$

**ATLAS** Phys. Rev. D 92, 012006
Same as the previous slide except $|\eta^{1,2}| < 2.47$

The transverse mass cut is common in the three cases

$$m_T: \frac{3}{4} M_h < m_T < M_h.$$ 

$$m_T = \sqrt{(E_{\ell\ell} + p_T^{\nu\nu})^2 - |p_T^{\ell\ell} + p_T^{\nu\nu}|^2} \quad E_T^{\ell\ell} = \sqrt{(p_T^{\ell\ell})^2 + (m_{\ell\ell})^2}$$

$$p_T^{\nu\nu}(p_T^{\ell\ell}) = \text{Vector sum of the neutrino (lepton) transverse momenta}$$

$$\bar{p}_T^{\nu\nu}(p_T^{\ell\ell}) \text{ is the magnitude}$$

For more detailed analysis of the backgrounds and separation techniques, see Refs. [111-114] of arXiv:1704.0880.
in Ref. specific kinematic features, see Refs.
detailed discussion of the background separation using (of the SM Higgs boson using the selection cuts listed above. For the total width presence of the sterile neutrino, respectively, calculated efficiencies for the decays mediated by the SM and in the of the heavy neutrino mass,
of the light-heavy neutrino mixing parameter as a function OSOF) to compute the corresponding bounds on the square above, we calculate the yield of events from the detector

The relevant backgrounds to these final states is mainly
[...]

\[M_N = 100 \, \text{GeV}\]

Limits on the mixing angle

After applying the cuts from ATLAS we calculate the yield

\[ \mathcal{N}(M_N, |V_{\ell N}|^2) = L \cdot \sigma^\text{SM}_h \left[ \epsilon^\text{SM} \frac{\Gamma(h \to WW^* \to \ell \bar{\ell} \nu\bar{\nu})}{\Gamma_{\text{SM}} + \Gamma_{\text{New}}} + \sum_{j,k} \epsilon_{jk} \frac{\Gamma(h \to \nu N + \text{c.c.} \to \ell_j \bar{\ell}_k \nu \bar{\nu})}{\Gamma_{\text{SM}} + \Gamma_{\text{New}}} \right] \]

\[ L \text{ = Integrated luminosity} \quad \sigma^\text{SM}_h(p p \to h) = \text{SM Higgs production cross section} \]

\[ \epsilon^\text{SM}, \epsilon_{jk} \text{ = efficiencies for the decays mediated by SM and in presence of heavy neutrino, respectively} \]

Calculated using cuts of ATLAS

\[ \Gamma(h \to WW^* \to \ell \bar{\ell} \nu \bar{\nu}), \quad \Gamma^\text{SM} \]

S. Heinemeyer et al. (LHC Higgs Cross Section Working Group), arXiv:1307.1347.

\[ \sigma^\text{SM}_h \]

8 TeV

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageAt8TeV.

14 TeV, 100 TeV

\[|V_{\ell N}|^2 \rightarrow \mathcal{N}(M_N, |V_{\ell N}|^2) < \mathcal{N}_{\text{expt}}\]

Maximal values

\[\mathcal{N}_{\text{expt}} = 169\]


for \(M_h = 125 \text{ GeV}\) at \(\sqrt{s} = 8 \text{ TeV}\) with \(L = 20.3 \text{ fb}^{-1}\)

Assuming the same \(\mathcal{N}_{\text{expt}}\) for \(\sqrt{s} = 14\) and 100 TeV colliders, but with an integrated luminosity of 3000 fb\(^{-1}\),

we also show the corresponding future limits.
CONSTRAINING STERILE NEUTRINOS FROM PRECISION PHYSICAL REVIEW D 115013 (2017)

Future sensitivity @100 can go down to 10% precise result at 100 TeV pp collider: arXiv:1606.09408

Future limit considering Majorana heavy neutrinos only

FCC-ee : Limits from Z decay

W-decay @LHC

Future limits

\( \mu \rightarrow e\gamma \)

\( \sim \) future branching ratio \( O(10^{-15}) \)
Heavy neutrino production from $\ell\nu jj$

$W$ boson produced in the Higgs decay to $\nu N \rightarrow \nu \ell W$

$W \rightarrow \text{Br}(lv) : 22\%$, $\ell = e, \mu$

$W \rightarrow \text{Br}(jj) : 67\%$

**Large irreducible backgrounds** $WW$ and $WZ$.

Practically, the purely leptonic modes are more clean turning out the signal sensitivity better than those with the jets, however, reconstruction is easier due to one neutrino in the final state.
Apart from the Higgs decay, the heavy neutrino can display the same final states through the CC and NC interactions. Finally after the decays of the W, Z bosons hadronically, we can get same final states.
Selection cuts

\[ \sqrt{s} = 8 \text{ TeV} \]

\[ \begin{align*}
  p_T^\ell &> 20 \text{ GeV} \\
  |\eta^\ell| &< 2.5 \\
  \Delta R_{\ell j} &> 0.3 \\
  \Delta R_{j j} &> 0.4 \\
  m_i - 20 &< m_i < m_i + 20, \quad m_i = M_N, m_W \text{ or } m_Z
\end{align*} \]

\[ \sqrt{s} = 14 \text{ TeV} \]

\[ \begin{align*}
  p_T^\ell &> 30 \text{ GeV} \text{ and } p_T^{j_{1,2}} > 32 \text{ GeV}
\end{align*} \]

\[ \sqrt{s} = 100 \text{ TeV} \]

\[ \begin{align*}
  p_T^\ell &> 53 \text{ GeV} \text{ and } p_T^{j_{1,2}} > 35 \text{ GeV}
\end{align*} \]

Depending upon the process

Other cuts remain the same
$M_N = 100$ GeV

**Significance**

$\sqrt{s} = 14$ TeV

$\sqrt{s} = 100$ TeV

Two different choices of $|V_{\ell N}|^2$
We have studied the production processes of the heavy neutrinos from Higgs at the LHC and future colliders.

We have studied dilepton plus MET final state and constrained it from the recent ATLAS search ($h \rightarrow WW^*$) at the 8 TeV to put current and prospective upper limits on the mixing angles.

We have also studied the single lepton final state with dijet and MET from all possible channels including CC and NC and Higgs. Which can be improved from the Higgs+ISR final state, when Higgs decays into heavy neutrino. (See, Das, Gao, Kamon: arXiv:1704.00881 [hep-ph]).

Thank you