Neutrino Masses in the Two Higgs Doublet Model

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Based on:
AI, C. Simonetto, JHEP 1111 (2011) 022
D. Hehn, AI, arXiv:1208.3162
J.A. Casas, AI, F. Jimenez-Alburquerque JHEP 0704 (2007) 064

Vienna
6 December 2012
• Introduction.

• Neutrino masses in the presence of right-handed neutrinos.

• Neutrino masses in the presence of right-handed neutrinos and *extra* Higgs doublets.

• The dark matter connection.

• Conclusions
Present status in the determination of neutrino parameters:

<table>
<thead>
<tr>
<th>parameter</th>
<th>best fit</th>
<th>$1\sigma$ range</th>
<th>$2\sigma$ range</th>
<th>$3\sigma$ range</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta m^2_{21} \ [10^{-5}\text{eV}^2]$</td>
<td>7.62</td>
<td>7.43–7.81</td>
<td>7.27–8.01</td>
<td>7.12–8.20</td>
</tr>
<tr>
<td>$</td>
<td>\Delta m^2_{31}</td>
<td>\ [10^{-3}\text{eV}^2]$</td>
<td>2.55</td>
<td>2.46–2.61</td>
</tr>
</tbody>
</table>
| \begin{align*}
\sin^2 \theta_{12} \\
\sin^2 \theta_{23} \\
\sin^2 \theta_{13} \\
\delta
\end{align*} | \begin{align*}
0.320 &
0.613 (0.427)^a \\
0.600 &
0.0246 \\
0.0250 &
0.80\pi \\
-0.03\pi
\end{align*} | \begin{align*}
0.303–0.336 &
0.400–0.461 \& 0.573–0.635 \\
0.569–0.626 &
0.0218–0.0275 \\
0.0223–0.0276 &
0
\end{align*} | \begin{align*}
0.29–0.35 &
0.38–0.66 \\
0.39–0.65 &
0.019–0.030 \\
0 &
0
\end{align*} | \begin{align*}
0.27–0.37 &
0.36–0.68 \\
0.37–0.67 &
0.017–0.033 \\
0–2\pi &
0–2\pi \\
0–2\pi &
0–2\pi
\end{align*} |

WMAP, $0\nu 2\beta \rightarrow m_\nu \lesssim 0.5 \text{ eV}$

No information about CP violation or about the neutrino mass spectrum

Forero, Tortola, Valle
arXiv::1205.4018
Even with this limited information about the neutrino sector, we can already notice some features:

- **Neutrino masses are tiny**, $m_\nu \approx \mathcal{O} \left( 0.1 \text{ eV} \right)$
- **Two large mixing angles** ($\theta_{\text{atm}} \approx \pi/4$, $\theta_{\text{sol}} \approx \pi/6$)
- **One small mixing angle** ($\theta_{13} \approx 0$)

\[
U_{\text{lep}} \simeq \begin{pmatrix}
\sqrt{2/3} & \sqrt{1/3} & 0 \\
-\sqrt{1/6} & \sqrt{1/3} & -\sqrt{1/2} \\
-\sqrt{1/6} & \sqrt{1/3} & \sqrt{1/2}
\end{pmatrix}
\]

- **The two heaviest neutrinos present a mild mass hierarchy**

\[
\Delta m_{\text{atm}}^2 = m_3^2 - m_1^2 \rightarrow m_3 = \sqrt{\Delta m_{\text{atm}}^2 - m_1^2}
\]

\[
\Delta m_{\text{sol}}^2 = m_2^2 - m_1^2 \rightarrow m_2 = \sqrt{\Delta m_{\text{sol}}^2 - m_1^2}
\]
Even with this limited information about the neutrino sector, we can already notice some features:

- Neutrino masses are tiny, $m_\nu \sim O(0.1 \text{ eV})$
- Two large mixing angles ($\theta_{\text{atm}} \approx \pi/4$, $\theta_{\text{sol}} \approx \pi/6$)
  One small mixing angle ($\theta_{13} \approx 0$)

$$U_{\text{lep}} \approx \begin{pmatrix} \sqrt{2/3} & \sqrt{1/3} & 0 \\ -\sqrt{1/6} & \sqrt{1/3} & -\sqrt{1/2} \\ -\sqrt{1/6} & \sqrt{1/3} & \sqrt{1/2} \end{pmatrix}$$

- The two heaviest neutrinos present a mild mass hierarchy

$$\frac{m_3}{m_2} \lesssim 6$$
Compare to the quark sector
\[
\begin{align*}
m_u &= 1.7 \text{ to } 3.3 \text{ MeV} \\
m_c &= 1.27^{+0.07}_{-0.09} \text{ GeV} \\
m_t &= 172.0 \pm 0.9 \pm 1.3 \text{ GeV} \\
m_d &= 4.1 \text{ to } 5.8 \text{ MeV} \\
m_s &= 101^{+29}_{-21} \text{ MeV} \\
m_b &= 4.19^{+0.07}_{-0.09} \text{ GeV}
\end{align*}
\]
\[
\begin{align*}
m_t/m_c &\simeq 140 \\
m_c/m_d &\simeq 500
\end{align*}
\]
vs. \( m_3/m_2 \lesssim 6 \)

\[
|U_{\text{CKM}}| = \begin{pmatrix}
0.97 & 0.23 & 0.004 \\
0.23 & 0.973 & 0.04 \\
0.008 & 0.04 & 1
\end{pmatrix}
\]
vs. \(|U_{\text{lep}}| \simeq \begin{pmatrix}
0.82 & 0.56 & 0 \\
0.41 & 0.56 & 0.71 \\
0.41 & 0.56 & 0.71
\end{pmatrix}\)

Compare also to the charged lepton sector
\[
\begin{align*}
m_e &= 0.51 \text{ MeV} \\
m_\mu &= 106 \text{ MeV} \\
m_\tau &= 1.78 \text{ GeV}
\end{align*}
\]
\[
\begin{align*}
m_\tau/m_\mu &\simeq 17 \\
m_\mu/m_e &\simeq 208
\end{align*}
\]

The neutrino sector presents a completely different pattern
Any model of neutrino masses should address the following questions:

- **Why tiny masses?**
- **Why mild mass hierarchy?**
- **Why large mixing angles?**

And preferably, the model should be testable
A very popular neutrino mass model: the (type I) see-saw model

Add to the Standard Model at least two right-handed neutrinos

\[-\mathcal{L}^{\nu} = (Y_{\nu})_{ij} \bar{l}_{Li} \nu_{Rj} \tilde{\Phi} - \frac{1}{2} M_{Mij} \bar{\nu}_{Ri} \nu_{Rj} + \text{h.c.}\]

\[M_{\text{Maj}} \gg M_Z\]

\[-\mathcal{L}^{\nu, \text{eff}} = \frac{1}{2} \kappa_{ij} (\bar{l}_{Li} \tilde{\Phi})(\tilde{\Phi}^T l_{Lj}^C) + \text{h.c.}\]

\[\kappa = (Y_{\nu} M_M^{-1} Y_{\nu}^T) \quad \mathcal{M}_\nu = \frac{\nu^2}{2\kappa}\]

Very compelling explanation to the small neutrino masses

Furthermore, this model predicts charged lepton flavour violation:

\[\text{BR}(\mu \rightarrow e\gamma) \sim 10^{-57}, \text{ in } \text{excellent} \text{ agreement with experiments.}\]
Can the type I see-saw mechanism accommodate a mild mass hierarchy?

The high energy theory, spanned by \{Y_\nu, M_{maj}\}, depends on 18 parameters

The low energy theory, spanned by \{M_\nu\}, depends on 9 parameters

There is a lot of freedom at high energies

It would not be surprising if the see-saw mechanism could accommodate \(m_3/m_2 < 6\).
Can the type I see-saw mechanism accommodate a mild mass hierarchy?

The high energy theory, spanned by \( \{Y_\nu, M_{\text{maj}}\} \), depends on 18 parameters

The low energy theory, spanned by \( \{M_\nu\} \), depends on 9 parameters

There is a lot of freedom at high energies

It would not be surprising if the see-saw mechanism could accommodate \( m_3/m_2 < 6 \).

The answer is yes. In fact the see-saw mechanism can accommodate anything

\[
Y_\nu = \frac{1}{\langle \Phi^0 \rangle} U_{\text{lep}}^* \sqrt{D_m} R^T \sqrt{D_M}
\]

\[
R = \begin{pmatrix}
\hat{c}_2 \hat{c}_3 & -\hat{c}_1 \hat{s}_3 - \hat{s}_1 \hat{s}_2 \hat{c}_3 & \hat{s}_1 \hat{s}_3 - \hat{c}_1 \hat{s}_2 \hat{c}_3 \\
\hat{c}_2 \hat{s}_3 & \hat{c}_1 \hat{c}_3 - \hat{s}_1 \hat{s}_2 \hat{s}_3 & -\hat{s}_1 \hat{c}_3 - \hat{c}_1 \hat{s}_2 \hat{s}_3 \\
\hat{s}_2 & \hat{s}_1 \hat{c}_2 & \hat{c}_1 \hat{c}_2
\end{pmatrix}
\]

\[
D_M = \text{diag}(M_1, M_2, M_3)
\]

But there is a price...
The price is that the resulting Yukawa coupling could be “weird”

For example, taking $M_1=10^9$ GeV, $M_2=10^{11}$ GeV, $M_3=10^{13}$ GeV and $R(z_1=2i, z_2=0, z_3=0)$, one obtains the matrix

$$Y_\nu = \begin{pmatrix}
1.9 \times 10^{-4} & 0.011 & 0.11i \\
-8.6 \times 10^{-5} & 0.012 - 0.031i & 0.32 + 0.12i \\
8.6 \times 10^{-5} & -0.012 - 0.031i & 0.32 - 0.12i
\end{pmatrix}$$

Which reproduces, by construction, the low energy neutrino data ($m_3=0.05$ eV, $m_2=0.0083$ eV, $\sin^2 \theta_{12}=0.3$, $\sin^2 \theta_{23}=1$, and $m_1=m_2/6$, $\theta_{13}=0$ and no CP violation)

However, the eigenvalues are

$$y_3 = 0.50$$
$$y_2 = 1.3 \times 10^{-3}$$
$$y_1 = 2.2 \times 10^{-4}$$

This Yukawa coupling does not seem to be generated by the same mechanism that generates $Y_u$, $Y_d$, $Y_e$ (whatever it is...)
A more interesting question is not whether the see-saw can accommodate the data, but whether the see-saw can accommodate the data with our present (very limited) understanding of the origin of flavour.

Can the see-saw mechanism accommodate the oscillation data when the neutrino Yukawa couplings are hierarchical?

Not so easy... The see-saw mechanism tends to produce very large neutrino mass hierarchies

Casas, AI, Jimenez-Alburquerque
“Naïve see-saw” (no mixing)

\[ m_1 \sim \frac{y_1^2}{M_1} \langle \Phi^0 \rangle^2, \quad m_2 \sim \frac{y_2^2}{M_2} \langle \Phi^0 \rangle^2, \quad m_3 \sim \frac{y_3^2}{M_3} \langle \Phi^0 \rangle^2 \]

- Assume hierarchical Yukawa couplings
  
  \[ y_1 : y_2 : y_3 \sim 1 : 20 : 20^2 \] (down-type quark Yukawas)
  
  \[ y_1 : y_2 : y_3 \sim 1 : 300 : 300^2 \] (up-type quark Yukawas)

- For the right-handed neutrino masses, we don't know
  
  Hierarchy in \( \nu_R \) as in \( Y_\nu \) \[ \frac{m_3}{m_2} \sim 20 - 300 \]
  
  Degenerate \( \nu_R \) \[ \frac{m_3}{m_2} \sim 400 - 90000 \] far from \( \frac{m_3}{m_2} \lesssim 6 \)

A more rigorous analysis shows that generically

\[ \frac{m_3}{m_2} \gtrsim \frac{y_3^2 M_3}{y_2^2 M_2} \] Hierarchical \( \nu_R \)

\[ \frac{m_3}{m_2} \gtrsim \mathcal{O}(10^{3-7}) \] far from \( \frac{m_3}{m_2} \lesssim 6 \)

\[ \frac{m_3}{m_2} \gtrsim \mathcal{O}(10^{2-5}) \] Degenerate \( \nu_R \)
Consider a model with just two right-handed neutrinos

Assume

\[
\begin{align*}
  y_1 : y_2 &= 1 : 300 \\
  M_1 : M_2 &= 1 : 300
\end{align*}
\]

(inspired by the hierarchy in the up-quark sector)

The neutrino mass hierarchy depends just on the mixing angle in the right-handed sector, \( \theta_R \), and on the Majorana phase \( \alpha \).

\[ \alpha = 0 \]
Consider a model with just two right-handed neutrinos

Assume

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y_1 : y_2 &= 1 : 300 \\
M_1 : M_2 &= 1 : 300
\end{align*}
\] (inspired by the hierarchy in the up-quark sector)

The neutrino mass hierarchy depends just on the mixing angle in the right-handed sector, \( \theta_R \), and on the Majorana phase \( \alpha \).

\( \alpha = \pi/4 \)
Consider a model with just two right-handed neutrinos

Assume

\[
y_1 : y_2 = 1 : 300
\]

\[
M_1 : M_2 = 1 : 300
\]

(inspired by the hierarchy in the up-quark sector)

The neutrino mass hierarchy depends just on the mixing angle in the right-handed sector, \( \theta_R \), and on the Majorana phase \( \alpha \).

\[
\alpha = 0.7 \pi/2
\]
Consider a model with just two right-handed neutrinos

Assume

\[
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y_1 : y_2 &= 1 : 300 \\
M_1 : M_2 &= 1 : 300
\end{align*}
\]  

(inspired by the hierarchy in the up-quark sector)

The neutrino mass hierarchy depends just on the mixing angle in the right-handed sector, \( \theta_R \), and on the Majorana phase \( \alpha \).

\( \alpha = 0.9 \pi/2 \)
Consider a model with just two right-handed neutrinos

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The neutrino mass hierarchy depends just on the mixing angle in the right-handed sector, \( \theta_R \), and on the Majorana phase \( \alpha \).

\( \alpha = 0.97 \, \pi/2 \)
Consider a model with just two right-handed neutrinos

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\]

(inspired by the hierarchy in the up-quark sector)

The neutrino mass hierarchy depends just on the mixing angle in the right-handed sector, \( \theta_R \), and on the Majorana phase \( \alpha \).

\( \alpha = \pi/2 \)
Consider a model with just two right-handed neutrinos. Assume the neutrino mass hierarchy depends just on the mixing angle in the right-handed sector, $\theta_R$, and on the Majorana phase $\alpha$.

The see-saw mechanism (with two right-handed neutrinos) with hierarchical Yukawa eigenvalues and RH masses can accommodate the observed neutrino mass hierarchy, but only for very special choices of parameters.

\[ \cos^2 \theta_R \simeq \frac{M_2 y_2^2 - M_1 y_1^2}{(M_1 + M_2)(y_2^2 - y_1^2)} \]

and 

\[ \alpha \simeq \pi/2 \]
There are two situations where the see-saw mechanism can naturally generate a mild neutrino mass hierarchy (without tunings):

**“naive see-saw”**  \[
\frac{m_2}{m_1} \sim \frac{y_2^2}{y_1^2} \frac{M_1}{M_2} \lesssim 6
\]

**Very mild hierarchies**
\[
y_1 \approx y_2 \\
M_1 \approx M_2
\]
\[
y_1 : y_2 = 1 : 2 \\
M_1 : M_2 = 1 : 6
\]

**Very strong hierarchy in RH masses**
\[
M_1 : M_2 \approx y_1^2 : y_2^2
\]
\[
y_1 : y_2 = 1 : 300 \\
M_1 : M_2 = 1 : 90000
\]
There are two situations where the see-saw mechanism can naturally generate a mild neutrino mass hierarchy (without tunings):

**“naive see-saw”**
\[
\frac{m_2}{m_1} \sim \frac{y_2^2 M_1}{y_1^2 M_2} \lesssim 6
\]

**Very mild hierarchies**
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y_1 \simeq y_2 \\
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\]
\[
y_1 : y_2 = 1 : 2 \\
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**Very strong hierarchy in RH masses**
\[
M_1 : M_2 \simeq y_1^2 : y_2^2
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y_1 : y_2 = 1 : 300 \\
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There are two situations where the see-saw mechanism can naturally generate a mild neutrino mass hierarchy (without tunings):

“naive see-saw” \( \frac{m_2}{m_1} \sim \frac{y_2^2}{y_1^2} \frac{M_1}{M_2} \lesssim 6 \)

**Very mild hierarchies**

\[ y_1 \approx y_2 \]
\[ M_1 \approx M_2 \]

\[ y_1 : y_2 = 1 : 2 \]
\[ M_1 : M_2 = 1 : 6 \]

**Very strong hierarchy in RH masses**

\[ M_1 : M_2 \approx y_1^2 : y_2^2 \]

\[ y_1 : y_2 = 1 : 300 \]
\[ M_1 : M_2 = 1 : 90000 \]

\( m_2/m_1 \)

\( \alpha = 0.7 \pi/2 \)
There are two situations where the see-saw mechanism can naturally generate a mild neutrino mass hierarchy (without tunings):

**“naive see-saw”** \( \frac{m_2}{m_1} \sim \frac{y_2^2 M_1}{y_1^2 M_2} \lesssim 6 \)

### Very mild hierarchies

- \( y_1 \approx y_2 \)
- \( M_1 \approx M_2 \)

\[
\begin{align*}
y_1 : y_2 &= 1 : 2 \\
M_1 : M_2 &= 1 : 6
\end{align*}
\]

### Very strong hierarchy in RH masses

- \( M_1 : M_2 \approx y_1^2 : y_2^2 \)

\[
\begin{align*}
y_1 : y_2 &= 1 : 300 \\
M_1 : M_2 &= 1 : 90000
\end{align*}
\]
There are two situations where the see-saw mechanism can naturally generate a mild neutrino mass hierarchy (without tunings):

- “naive see-saw” \( \frac{m_2}{m_1} \sim \frac{y_2^2}{y_1^2} \frac{M_1}{M_2} \lesssim 6 \)

- Very mild hierarchies
  \( y_1 \approx y_2 \)
  \( M_1 \approx M_2 \)
  \( y_1 : y_2 = 1 : 2 \)
  \( M_1 : M_2 = 1 : 6 \)

- Very strong hierarchy in RH masses
  \( M_1 : M_2 \approx y_1^2 : y_2^2 \)
  \( y_1 : y_2 = 1 : 300 \)
  \( M_1 : M_2 = 1 : 90000 \)

\( \alpha = 0.97 \pi/2 \)
There are two situations where the see-saw mechanism can naturally generate a mild neutrino mass hierarchy (without tunings):

“naive see-saw” \( \frac{m_2}{m_1} \sim \frac{y_2^2}{y_1^2} \frac{M_1}{M_2} \ll 6 \)

**Very mild hierarchies**

\[ y_1 \approx y_2 \]
\[ M_1 \approx M_2 \]
\[ y_1 : y_2 = 1 : 2 \]
\[ M_1 : M_2 = 1 : 6 \]

**Very strong hierarchy in RH masses**

\[ M_1 : M_2 \approx y_1^2 : y_2^2 \]
\[ y_1 : y_2 = 1 : 300 \]
\[ M_1 : M_2 = 1 : 90000 \]

Only if \( \theta_R \approx 0 \)!!
The case with three right-handed neutrinos

\[ y_1 : y_2 : y_3 = 1 : 300 : 300^2 \]
\[ M_1 : M_2 : M_3 = 1 : 300 : 300^2 \]
The see-saw mechanism generates a neutrino mass hierarchy much larger than the observed experimentally, except:

- When the Yukawa eigenvalues and right-handed masses present a mild mass hierarchy.
- In the case of hierachical Yukawa eigenvalues, for very special choices of the parameters.

The see-saw mechanism provides a very compelling explanation to the smallness of neutrino masses, while keeping all the successes of the Standard Model. However, it fails to provide a compelling explanation to why the neutrino mass hierarchy is so mild.
With a second higgs doublet, quantum corrections can soften the neutrino mass hierarchy.

Even if at tree level $m_3/m_2$ is very large, as generically expected in the (standard) see-saw mechanism, the quantum corrections can generate $m_3/m_2 \sim 6$. 

Grimus, Neufeld
AI, Simonetto
Consider the Standard Model extended by right-handed neutrinos and at least one extra Higgs doublet (no ad-hoc discrete symmetries)

\[ -\mathcal{L}^\nu = (Y_{\nu}^a)_{ij} \bar{L}_i \nu_{Rj} \tilde{\Phi}_a - \frac{1}{2} M_{M_{ij}} \bar{\nu}_{Ri} \nu_{Rj} + \text{h.c.} \]

\[ M_{\text{Maj}} \gg m_H, M_Z \]

\[ -\mathcal{L}^\nu, \text{ eff} = \frac{1}{2} \kappa_{ij}^{ab} (\bar{L}_i \tilde{\Phi}_a) (\tilde{\Phi}_b^T \bar{L}_j) + \text{h.c.} \]

\[ \kappa^{ab}(M_1) = (Y_{\nu}^a M^{-1}_M Y_{\nu}^b)^T(M_1) \]

Work in the basis where only \( \Phi_1 \) acquires a vev

\[ \mathcal{M}_\nu(M_1) = \frac{\nu^2}{2} \kappa^{11}(M_1) \]

The neutrino mass matrix is affected by quantum corrections below \( M_1 \)
Quantum effects generate a correction to the coefficient of the dimension 5 operator which generates neutrino masses:

$$\delta \kappa^{11} \simeq B_{1a} \kappa^{a1} + \kappa^{1a} B_{1a}^T + b \kappa^{22}$$

Different operators mix:

Is corrected by $B_{12} \kappa^{21}$

Grimus, Lavoura
Quantum effects generate a correction to the coefficient of the dimension 5 operator which generates neutrino masses:

\[ \delta \kappa^{11} \simeq B_{1a} \kappa^{a1} + \kappa^{1a} B_{1a}^T + b \kappa^{22} \]

Different operators mix:

Is corrected by \( b \kappa^{22} \)
Quantum effects generate a correction to the coefficient of the dimension 5 operator which generates neutrino masses:

\[ \delta \kappa^{11} \simeq B_{1a} \kappa^{a1} + \kappa^{1a} B^T_{1a} + b \kappa^{22} \]

Different operators mix.

Compare to the correction in the “one Higgs doublet model”:

\[ \delta \kappa \simeq B \kappa + \kappa B^T \]

New qualitative features?
To highlight the new features, consider a model with one right-handed neutrino and two Higgs doublets (no ad-hoc discrete symmetries imposed):

$$-\mathcal{L}^\nu = (Y^1_\nu)_i \bar{l}_{Li} \nu_R \tilde{\Phi}_1 + (Y^2_\nu)_i \bar{l}_{Li} \nu_R \tilde{\Phi}_2 - \frac{1}{2} M_{\text{Maj}} \nu^C_R \nu_R + \text{h.c.}$$

$$M_{\text{Maj}} \gg m_H, M_Z$$

$$-\mathcal{L}^\nu, \text{ eff} = \frac{1}{2} \kappa^{ab}_{ij} (\bar{l}_{Li} \tilde{\Phi}_a) (\tilde{\Phi}^T_b \bar{l}_{Lj}^C) + \text{h.c.}$$

Work in the basis where only $\Phi_1$ acquires a vev

$$\mathcal{M}_\nu (M_{\text{Maj}}) = \frac{v^2}{2} \kappa^{11} (M_{\text{Maj}})$$

Rank 1. At tree level

$$m_3 = \frac{|Y^1_\nu|^2 v^2}{2 M_{\text{Maj}}}$$

$$m_2, m_1 = 0$$
RGE effects

\[ \delta \kappa^{11} \simeq B_{1a} \kappa^{a1} + \kappa^{1a} B_{1a}^T + b \kappa^{22} \]

\[ m_3 = \frac{|Y_\nu^1|^2 \nu^2}{2M_{\text{maj}}} + \text{small corrections} \]

\[ m_2 = \frac{1}{16\pi^2} \frac{|\lambda_5| \nu^2}{M_{\text{maj}}} \left[ |Y_\nu^2|^2 - \frac{|Y_\nu^{2\dagger} Y_\nu^1|^2}{|Y_\nu^1|^2} \right] \log \frac{M_{\text{maj}}}{m_H} \]

\[ m_1 = 0 \]

A second neutrino mass is generated from the same right-handed neutrino mass scale \( M_{\text{maj}} \) → a mild mass hierarchy might be naturally accommodated.
Assume:

- $M_{\text{maj}}$ large, to implement the see-saw mechanism
  
  $m_H << M_{\text{maj}}$ (e.g. $m_H = 100$ GeV-1 TeV)

- Neutrino Yukawa couplings misaligned (new sources of flavour violation are required)

- $|Y_{\nu}^1| \sim |Y_{\nu}^2|$

- $\lambda_5 \sim O(1)$

\[
\begin{align*}
m_3 &= \frac{|Y_{\nu}^1|^2 v^2}{2M_{\text{maj}}} \\
m_2 &= \frac{1}{16\pi^2} \frac{|\lambda_5| v^2}{M_{\text{maj}}} \left[ |Y_{\nu}^2|^2 - \frac{|Y_{\nu}^2|^2 |Y_{\nu}^1|^2}{|Y_{\nu}^1|^2} \right] \log \frac{M_{\text{maj}}}{m_H}
\end{align*}
\]

**Neutrino mass hierarchy:**

$|m_2| / |m_3| \sim \frac{|\lambda_5| |Y_{\nu}^2|^2}{8\pi^2 |Y_{\nu}^1|^2} \log \left( \frac{M_{\text{maj}}}{m_H} \right) \sim 0.2$
Assume:

- $M_{\text{maj}}$ large, to implement the see-saw mechanism
  $m_{H} \ll M_{\text{maj}}$ (e.g. $m_{H} = 100$ GeV-1 TeV)
- Neutrino Yukawa couplings misaligned (new sources of flavour violation are required)
- $\lambda_{5} \sim O(1)$

\[
\begin{align*}
    m_{3} &= \frac{|Y_{\nu}^{1}|^{2} v^{2}}{2 M_{\text{maj}}} \\
    m_{2} &= -\frac{1}{16 \pi^{2}} \frac{|\lambda_{5}| v^{2}}{M_{\text{maj}}} \left[ |Y_{\nu}^{2}|^{2} - \frac{|Y_{\nu}^{2}Y_{\nu}^{1}|^{2}}{|Y_{\nu}^{1}|^{2}} \right] \log \left( \frac{M_{\text{maj}}}{m_{H}} \right)
\end{align*}
\]

**Neutrino mass hierarchy:**

Yukawa couplings to the same generation of right-handed neutrinos (more details later)

\[
\begin{align*}
    \left| Y_{\nu}^{1} \right| &\sim \left| Y_{\nu}^{2} \right| \\
    \left| m_{2} \right| &\sim \left| m_{3} \right| \approx \frac{|\lambda_{5}| |Y_{\nu}^{2}|^{2}}{8 \pi^{2} |Y_{\nu}^{1}|^{2}} \log \left( \frac{M_{\text{maj}}}{m_{H}} \right) \approx 0.2
\end{align*}
\]
Assume:

- $M_{\text{maj}}$ large, to implement the see-saw mechanism
- $m_H << M_{\text{maj}}$ (e.g. $m_H = 100\text{ GeV-1 TeV}$)
- Neutrino Yukawa couplings misaligned (new sources of flavour violation are required)
- $|Y^1_\nu| \sim |Y^2_\nu|$
- $\lambda_5 \sim O(1)$

Neutrino mass hierarchy:

$$m_3 = \frac{|Y^1_\nu|^2 v^2}{2M_{\text{maj}}}$$
$$m_2 = -\frac{1}{\sqrt{2}} \lambda_5 \frac{|Y^2_\nu|^2}{\lambda_5} \left[ \frac{1 - |Y^1_\nu|^2}{1 - |Y^1_\nu|^2} \right] \left( \frac{M_{\text{maj}}}{m_H} \right)$$

Lepton flavour violation? Electric dipole moments?

$$\left| \frac{m_2}{m_3} \right| \approx \frac{\lambda_5 |Y^2_\nu|^2}{8\pi^2 |Y^1_\nu|^2} \log \left( \frac{M_{\text{maj}}}{m_H} \right) \approx 0.2$$
\[ m_3 = \frac{|Y^1_\nu|^2 v^2}{2M_{maj}} \]

\[ m_2 = \frac{-1}{2} |\lambda_5| v^2 \left[ \frac{1}{2} |Y^2_\nu|^2 + \frac{1}{2} |Y^3_\nu|^2 \right] \left( \frac{M_{maj}}{M_H} \right) \]

**Lepton flavour violation? Electric dipole moments?**

**Neutrino mass hierarchy:**

Assume:

- \( M_{maj} \) large, to implement the see-saw mechanism
  \( m_H << M_{maj} \) (e.g. \( m_H = 100 \text{ GeV} - 1 \text{ TeV} \))

- Neutrino Yukawa couplings misaligned (new sources of flavour violation are required)

- \( |Y^1_\nu| \sim |Y^2_\nu| \)

- \( \lambda_5 \sim O(1) \)

Logarithmic dependence with \( m_H \), while the rate for \( \mu \rightarrow e \gamma \) decreases as \( m_H^4 \)

\[ \left| \frac{m_2}{m_3} \right| \sim \frac{\lambda_5 |Y^2_\nu|^2 v^4}{8\pi^2 |Y^1_\nu|^2 v^2} \log \left( \frac{M_{maj}}{m_H} \right) \approx 0.2 \]
Messages to take home:

The Standard Model extended with $\geq 1$ right-handed neutrino and $\geq 1$ Higgs doublet can naturally explain the smallness of neutrino masses and the existence of a mild mass hierarchy, without jeopardizing any of the successes of the Standard Model, since all extra particles decouple at low energies.

No need to introduce flavour symmetries to explain the intergenerational mass differences in the neutrino sector, although they might be necessary to explain the observed pattern of mixing angles.
Comparison to the two right-handed neutrino model

Effective theory of the 2RHN-1HDM
Comparison to the two right-handed neutrino model

Effective theory of the 1RHN-2HDM

\[ \tilde{Y}^1_v = Y^1_v + B_{1a} Y^a_v \]
The effective theories are identical
The effective theories are identical

\[
\begin{align*}
\{Y_{\nu1}, Y_{\nu2}, M_1, M_2\} &\leftrightarrow \{\tilde{Y}_{\nu1}^1, Y_{\nu2}^2, M_{Maj \_1}, M_{Maj \_2}/b\}
\end{align*}
\]

However, there are important differences in the way the can generate the mild neutrino mass hierarchy.
First part of the talk: the 2RHN-1HDM can generate a neutrino mass hierarchy in agreement with experiments when:

- When the Yukawa eigenvalues and right-handed masses present a mild hierarchy.

- When there are hierarchical Yukawa eigenvalues, only for very special choices of the parameters.
First part of the talk: the 2RHN-1HDM can generate a neutrino mass hierarchy in agreement with experiments when:

- When the Yukawa eigenvalues and right-handed masses present a mild hierarchy.
- When there are hierarchical Yukawa eigenvalues, only for very special choices of the parameters.

\[ \{ Y_{\nu 1}, Y_{\nu 2}, M_1, M_2 \} \]

- Yukawa couplings to different generation of RH neutrinos.
  Possibly hierarchical eigenvalues

- Two different right-handed neutrino masses.
  Hierarchy completely unknown
First part of the talk: the 2RHN-1HDM can generate a neutrino mass hierarchy in agreement with experiments when:

- When the Yukawa eigenvalues and right-handed masses present a mild hierarchy.
- When there are hierarchical Yukawa eigenvalues, only for very special choices of the parameters.

\[
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First part of the talk: the 2RHN-1HDM can generate a neutrino mass hierarchy in agreement with experiments when:

- When the Yukawa eigenvalues and right-handed masses present a mild hierarchy.

- When there are hierarchical Yukawa eigenvalues, only for very special choices of the parameters.

\[ \{ Y_{\nu 1}, Y_{\nu 2}, M_1, M_2 \} \leftrightarrow \{ \tilde{Y}_{\nu 1}^1, Y_{\nu 2}^2, M_{Maj}, M_{Maj}/b \} \]

\[ b = -\frac{\lambda_5}{8\pi^2} \log \left( \frac{M_{Maj}}{m_H} \right) \]

Yukawa couplings to the same generation of RH neutrinos. Eigenvalues expected to be similar.

The “equivalent” right-handed neutrino masses naturally have a mild hierarchy.
First part of the talk: the 2RHN-1HDM can generate a neutrino mass hierarchy in agreement with experiments when:

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Yukawa couplings to the same generation of RH neutrinos. Eigenvalues expected to be similar.

The “equivalent” right-handed neutrino masses naturally have a mild hierarchy.
A remarkable difference with respect to the two right-handed neutrino model:

Possibly, new phenomena at low energies, apart from neutrino masses

LFV processes could be observable, if not too suppressed by \( m_H \).

\[
\text{BR}(\mu \rightarrow e \gamma) = \frac{8 \alpha^3}{3 \pi^3} \left| \frac{Y_{e12}^2}{|Y_{e22}|^2} \right|^2 \left| \frac{Y_{e21}^2}{|Y_{e22}|^2} \right|^2 \left| f\left(\frac{m_t^2}{m_H^2}\right) \cos \alpha - \frac{Y_{u33}^2}{Y_{u33}^1} \frac{m_t^2}{m_H^2} \log^2 \frac{m_t^2}{m_H^2} \right|^2
\]

Could be present at tree level. If not, generated radiatively by the neutrino Yukawa couplings.

Paradisi, Hisano, Sugiyama, Yamanaka
Mixing angles

New flavour structures in $\kappa_{22}$ and $Y_e^2$ modify, through quantum corrections, the flavour structure of the neutrino mass operator $\kappa_{11}$ and the charged lepton Yukawa coupling $Y_e^1$.

**Leptonic mixing matrix**

$$\delta U_{\kappa} = U^{(0)} T$$

**Charged lepton Yukawa coupling**

$$l_L \rightarrow V^L e L l_L$$

$$\delta U_{Y_e} = (V^L e - 1)^T U^{(0)}$$

**Summing up both contributions**

$$U^{(1)} = V^L e T U^{(0)} + U^{(0)} T$$
New flavour structures in $\kappa^{22}$ and $Y_e^2$ can induce radiatively a non-vanishing $\theta_{13}$ and a deviation from maximal atmospheric mixing.

\[ \delta U_{13} = -\frac{1}{16\pi^2} \frac{Y_{\nu 1}^{2*}}{|Y_{\nu 1}^1|} \left[ 3\text{Tr}(Y_u^{1\dagger}Y_u^2 + Y_d^{1\dagger}Y_d^{2\dagger}) + 2\lambda_6^* + 2\lambda_5^* \frac{Y_{\nu 2\dagger}Y_{\nu 1}}{|Y_{\nu 1}|^2} \right] \log \frac{M_{\text{maj}}}{m_H} \]

\[ + \frac{1}{16\pi^2} \frac{(Y_{\nu 1}^{1\dagger}(Y_{e 1}^1)^{\dagger}Y_{e 1}^{2\dagger})_1}{|Y_{\nu 1}|} \left[ 3\text{Tr}(Y_u^{2\dagger}Y_u^1 + Y_d^{2\dagger}Y_d^{1\dagger}) \right] \log \frac{M_{\text{maj}}}{m_H} \]
New flavour structures in $\kappa^{22}$ and $Y_e^{2}$ can induce radiatively a non-vanishing $\theta_{13}$ and a deviation from maximal atmospheric mixing.

$$\delta U_{13} = -\frac{1}{16\pi^2} \frac{Y_{\nu_1}^{2*}}{|Y_{\nu_1}|} \left[ 3\text{Tr}(Y_u^{1\dagger}Y_u^{-2} + Y_d^{1\dagger}Y_d^{-2\dagger}) + 2\lambda_1 + 2\lambda_5^* \frac{Y_{\nu}^{2\dagger}Y_{\nu}^{1}}{|Y_{\nu}^{1}|^2} \right] \log \frac{M_{\text{maj}}}{m_H}$$

$$+ \frac{1}{16\pi^2} \frac{(Y_{\nu}^{1\dagger}(Y_e^{1})^{-1}Y_e^{2\dagger})_1}{|Y_{\nu}^{1}|} \left[ 3\text{Tr}(Y_u^{-2\dagger}Y_u^{1} + Y_d^{-2}Y_d^{1\dagger}) \right] \log \frac{M_{\text{maj}}}{m_H}$$

Similar to $m_2/m_3 \rightarrow \delta U_{13}$ can easily be $\sim 0.2$
New flavour structures in $\kappa^{22}$ and $Y_e^2$ can induce radiatively a non-vanishing $\theta_{13}$ and a deviation from maximal atmospheric mixing.

Additional effects if the cut-off $\Lambda$ is larger than $M_{\text{maj}}$, through the quantum effects from the neutrino Yukawa couplings $Y_\nu^1$, $Y_\nu^2$.

\[
\delta U_{13} = -\frac{1}{16\pi^2} \frac{Y_{\nu 1}^{2*}}{|Y_\nu^1|} \left\{ \left[ 3\text{Tr}(Y_u^{1\dagger}Y_u^2 + Y_d^{1\dagger}Y_d^2) + \text{Tr}(Y_\nu Y_\nu^1) + 2Y_{\nu 1}^{1\dagger}(Y_e^1)^{-1}Y_e^2Y_\nu^1 \right] \log \frac{\Lambda}{M_{\text{maj}}} \\
+ \left[ 3\text{Tr}(Y_u^{1\dagger}Y_u^2 + Y_d^{1\dagger}Y_d^2) + 2\lambda_6^* + 2\lambda_5^* \frac{Y_\nu^{2\dagger}Y_\nu^1}{|Y_\nu^1|^2} \right] \log \frac{M_{\text{maj}}}{m_H} \right\} \\
+ \frac{1}{16\pi^2} \frac{(Y_{\nu 1}^{1\dagger}(Y_e^1)^{-1}Y_e^2)_{1}}{|Y_\nu^1|} \left\{ \text{Tr}(Y_\nu Y_\nu^1) \log \frac{\Lambda}{M_{\text{maj}}} + 3\text{Tr}(Y_u^{2\dagger}Y_u^1 + Y_d^{2\dagger}Y_d^1) \log \frac{\Lambda}{m_H} \right\}
\]
Some speculations about the mixing angles

The third column of the leptonic mixing matrix seems to follow a pattern, at least at lowest order: \( \theta_{13} = 0, \theta_{23} = \pi/4 \).

The second column does not seem to follow any pattern: the solar mixing angle is neither minimal nor maximal.

In the 1RHN-2HDM

\[
U_{i3} \approx \begin{pmatrix} 0 \\ 1 \\ 1 \end{pmatrix}
\]

\[
U_{i2} \approx \begin{pmatrix} O(1) \\ O(1) \\ O(1) \end{pmatrix}
\]

Possible patterns:
- Third column of \( U_{lep} \) with a pattern (if \( Y_{\nu}^1 \) has a pattern)
- Second column of \( U_{lep} \) with a pattern (if \( Y_{\nu}^2 \) has a pattern)
Some speculations about the mixing angles

The third column of the leptonic mixing matrix seems to follow a pattern, at least at lowest order: $\theta_{13}=0$, $\theta_{23}=\pi/4$.

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In the $1RHN-3HDM$, (more higgs doublets!)

Third column of $U_{\text{lep}}$
Possibly with a pattern
(if $Y^1_\nu$ has a pattern)

Second column of $U_{\text{lep}}$
Even if each Yukawa coupling had an structure, the combination of them gives a “structureless” $U_{i2}$. 

\[
U_{i3} \approx \begin{pmatrix} 0 \\ 1 \\ 1 \end{pmatrix}
\]

\[
U_{i2} \approx \begin{pmatrix} O(1) \\ O(1) \\ O(1) \end{pmatrix}
\]
Some speculations about the mixing angles

The third column of the leptonic mixing matrix seems to follow a pattern, at least at lowest order: $\theta_{13}=0$, $\theta_{23} = \frac{\pi}{4}$.

The second column does not seem to follow any pattern: the solar mixing angle is neither minimal nor maximal.

In the 1RHN-3HDM, (more higgs doublets!)

In the third column of $U_{lep}$
Possibly with a pattern
(if $Y_\nu^1$ has a pattern)

second column of $U_{lep}$
Even if each Yukawa coupling had an structure, the combination of them gives a “structureless” $U_{i2}$.
The dark matter connection

The explanation of the observed neutrino flavour transitions and the nature of the dark matter of the Universe could be completely unrelated problems.
The dark matter connection

The explanation of the observed neutrino flavour transitions and the nature of the dark matter of the Universe could be completely unrelated problems.

*Or perhaps not...*
Ma's model

<table>
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<tr>
<th></th>
<th>$L_1, L_2, L_3$</th>
<th>$e_{R1}, e_{R2}, e_{R3}$</th>
<th>$\Phi$</th>
<th>$\chi_1, \chi_2, \chi_3$</th>
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<tr>
<td><strong>$Z_2$</strong></td>
<td>+</td>
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<td>+</td>
<td>−</td>
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If the $Z_2$ symmetry is exact (or very weakly broken) the model contains a dark matter candidate ($\eta$ or $\chi_1$).
If the $Z_2$ symmetry is exact (or very weakly broken) the model contains a dark matter candidate ($\eta$ or $\chi_1$).

Due to the $Z_2$ symmetry, $\eta$ does not acquire a vev $\rightarrow$ no neutrino mass at tree level.
Ma's model

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If the Z₂ symmetry is exact (or very weakly broken) the model contains a dark matter candidate (η or χ₁).

Due to the Z₂ symmetry, η does not acquire a vev → no neutrino mass at tree level.

All neutrino masses are generated at the one loop level

For appropriate choices of the parameters, the masses of the new particles could be at the TeV scale → Collider signatures
If the $Z_2$ symmetry is exact (or very weakly broken) the model contains a dark matter candidate ($\eta$ or $\chi_1$).

Due to the $Z_2$ symmetry, $\eta$ does not acquire a vev $\rightarrow$ no neutrino mass at tree level.

All neutrino masses are generated at the one loop level

$$ (\mathcal{M}_\nu)_{ij} = \frac{\lambda_5 v^2}{8 \pi^2} \sum_k \frac{h_{ik} h_{jk}}{M_k} \left[ \ln \frac{M_k^2}{m_0^2} - 1 \right]. $$

However, the model generically predicts large neutrino mass hierarchies
If the $Z_2$ symmetry is exact (or very weakly broken) the model contains a dark matter candidate ($\eta_1$ or $\chi$).

Due to the $Z_2$ symmetry, $\eta_1, \eta_2$ do not acquire a vev → no neutrino mass at tree level.

All neutrino masses are generated at the one loop level

\[
(M_\nu)_{ij} \simeq - \frac{Y_i^{(a)} Y_j^{(b)} \lambda_5^{(ab)} v^2}{8\pi^2} \left( \frac{m_{\eta_a}^2}{m_{\eta_a}^2 - m_{\eta_b}^2} \log \frac{m_{\eta_a}^2}{m_{\eta_b}^2} + \log \frac{m_{\eta_a}^2}{M^2} \right) \]

\[|Y^{(1)}| \sim |Y^{(2)}| \quad (coupling \ to \ the \ same \ \chi)\]

\[
\lambda_5^{(11)} \sim \lambda_5^{(12)} \sim \lambda_5^{(22)}\]

Mild mass hierarchy generically expected
Features:

- Small neutrino mass due to the see-saw mechanism.
- Mild neutrino mass hierarchy due to the presence of a second scalar doublet.
- No need to invoke a flavor symmetry to explain the intergenerational mass hierarchy in the neutrino sector, although it might be necessary to explain the pattern of mixing angles.
- The model contains a dark matter candidate and can generate the observed matter-antimatter asymmetry in the Universe through leptogenesis.
## Conclusions

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*Thank you for your attention!*