Constraining right-handed neutrinos

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Outline

• Introduction
• Data compilation:
  – Indirect constraints: Universality tests
  – Direct constraints: Collider searches
• Parametrization of lepton mixing matrix
• Formalism
• 3 +1 scenario
• 3 + 3, 3 + 6 cases
• Conclusions

Work underway in collaboration with D.V. Forero, O. Miranda, M. Tórtola and J.W.F. Valle
Introduction

- In the SM neutrinos are massless particles contradicting the experimental observation of neutrino oscillations.
- Models beyond the SM invoke right handed neutrinos as messengers in order to induce neutrino mass
  
  They have both Dirac & Majorana mass terms
- Such “see-saw” mechanism accounts for the smallness of neutrino masses, type-I, type-II
  
  - Minkowski 77
  - Gellman Ramond Slansky 80
  - Glashow, Yanagida 79
  - Mohapatra Senjanovic 80
  - Lazarides Shafi Weterrich 81
  - Schechter-Valle, 80 & 82

- The neutral heavy states induce lepton flavor violation (LFV) and lepton number violating (LNV) processes, e.g. neutrinoless double beta decay
Simplest case: 3 + 1 formalism

- In this extension of the SM we introduce just one extra singlet

\[ \psi_L = \begin{pmatrix} \nu_{\alpha L} \\ l_{\alpha L} \end{pmatrix} ; \quad N_{\alpha R} \]

so the mixing matrix has to be written as

\[ U_{4x4} = \begin{pmatrix} W_{e1} & W_{e2} & W_{e3} & V_{e4} \\ W_{\mu1} & W_{\mu2} & W_{\mu3} & V_{\mu4} \\ W_{\tau1} & W_{\tau2} & W_{\tau3} & V_{\tau3} \\ T_{41} & T_{42} & T_{43} & B \end{pmatrix} \]

and mass eigensates

\[ \nu_{kL} = \sum_{1}^{3} W_{k\alpha} \nu_{\alpha L} + V_{k4} \hat{N}_{4L} \]
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\[ \nu_{kL} = \sum_{\alpha} W_{k\alpha} \nu_{\alpha L} + V_{k4} \hat{N}_{4L} \]
Current constraints on heavy neutrinos

- The mixing of heavy neutrinos would produce peaks in the spectra of leptonic decays of pions and kaons.
- They may also be produced directly at colliders.
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Atre, Han, Pascoli and Zhang (2009)
Current constraints on heavy neutrinos

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Current constraints on heavy neutrinos

- Neutrino oscillations:
  - The existence of a fourth neutrino would change the electron neutrino survival probability

\[
P_{ee} = \cos^4 \theta_{(14)} \left[ 1 - \cos^4 \theta_{(13)} \sin^2 2 \theta_{(12)} \sin^2 \Delta_{(12)} - \sin^2 2 \theta_{(13)} \sin^2 \Delta_{(13)} \right]
\]

introducing a factor which violates unitarity

\[
\cos^4 (\theta_{14}) = (1 - |V_{14}|^2) \quad \implies \quad |V_{14}|^2 \approx 0.04
\]

- Unfortunately the presence of an extra heavy lepton would not be enough to explain current neutrino anomalies. Hence we concentrate on constraints

- For this, we go into more detail on the parametrization of right-handed neutrinos in the charged current weak interaction using the symmetric parametrization
Why relevant? Future perspectives

- Future oscillation experiments could improve the constraints on heavy neutrino mixings. An example could be LENA, which number of events would be in presence of an extra heavy neutrino:

\[ N_i = \cos^4 \theta_{14} n_e \phi_{Cr} \Delta t \int_{T_i}^{T_{i+1}} \int \frac{d\sigma}{dT} R(T, T') dT' dT \]
If we extend the SM neutrino sector introducing n heavy neutrinos, we can write the U mixing matrix as

\[
U = \omega_{n-1} \omega_n \omega_{n-2} \ldots \omega_1 \omega_{n-2} \omega_{n-3} \ldots \omega_1 \omega_{n-1} \ldots \omega_2 \omega_3 \omega_1 \omega_2 \omega_1
\]

where \( \omega_{ij} \) are the rotation matrix in the ij plane

\[
(\omega_{ij})_{\alpha \beta} = \delta_{\alpha \beta} \sqrt{1 - \delta_{\alpha i} \delta_{\beta j} s_{ij}^2 - \delta_{\alpha j} \delta_{\beta i} s_{ij}^2} + \tilde{s}_{ij} \delta_{\alpha i} \delta_{\beta j} \bar{s}_{ij} \delta_{\alpha j} \delta_{\beta i}
\]

\[
\tilde{s}_{ij} = \sin \theta_{ij} e^{-i \phi_{ij}}
\]

\[
\bar{s}_{ij} = -\sin \theta_{ij} e^{i \phi_{ij}}
\]

The U matrix has this structure

\[
U_{n \times n} = \begin{pmatrix}
N_{3 \times 3} & S_{3 \times (n-3)} \\
T_{(n-3) \times 3} & V_{(n-3) \times (n-3)}
\end{pmatrix} = R^{NP} R^{SM}
\]
If we extend the SM neutrino sector introducing $n$ heavy neutrinos, we can write the $U$ mixing matrix as

\[
U = \omega_{n-1n} \omega_{n-2n} \ldots \omega_{1n} \omega_{n-2n-1} \omega_{n-3n-1} \ldots \omega_{1n-1} \ldots \omega_{23} \omega_{13} \omega_{12}
\]

where $\omega_{ij}$ are the rotation matrix in the $ij$ plane

\[
(\omega_{ij})_{\alpha\beta} = \delta_{\alpha\beta} \sqrt{1 - \delta_{\alpha i} \delta_{\beta j} s_{i j}^2 - \delta_{\alpha j} \delta_{\beta i} s_{i j}^2} + \bar{s}_{i j} \delta_{\alpha i} \delta_{\beta j} \bar{s}_{i j} \delta_{\alpha j} \delta_{\beta i}
\]

\[
\bar{s}_{i j} = \sin \theta_{ij} e^{-i \phi_{ij}}
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\omega_{n-1} & \omega_{n-2} & \ldots & \omega_1 & \omega_{n-2} & \ldots & \omega_{n-3} & \ldots & \omega_1 & \omega_{n-1}
\end{pmatrix} \cdot \begin{pmatrix}
\omega_{23} & \omega_{13} & \omega_{12}
\end{pmatrix}
\]

where \( \omega_{ij} \) are the rotation matrix in the \( ij \) plane

\[
(\omega_{ij})_{\alpha\beta} = \delta_{\alpha\beta} \sqrt{1 - \delta_{\alpha i} \delta_{\beta j} s_{ij}^2 - \delta_{\alpha j} \delta_{\beta i} s_{ij}^2 + \bar{s}_{ij} \delta_{\alpha i} \delta_{\beta j} \tilde{s}_{ij} \delta_{\alpha j} \delta_{\beta i}}
\]

\( \tilde{s}_{ij} = \sin \theta_{ij} e^{-i\phi_{ij}} \)
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T_{(n-3) \times 3} & V_{(n-3) \times (n-3)}
\end{pmatrix} = R_{NP} \ R_{SM}
\]
Technical comments on the method

- In this case, the matrix $N_{3 \times 3}$ involving the light neutrinos, which is not unitary, can be decomposed as

$$N = N^{NP} N^{SM} = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} N^{SM}$$

where the zero triangle submatrix characterize this decomposition.
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\alpha_{31} & \alpha_{32} & \alpha_{33}
\end{pmatrix} N^{SM}$$

where the zero triangle submatrix characterize this decomposition.

- The $\alpha_{ij}$ terms agglutinate extra heavy neutrino contributions:

$$\alpha_{11} = (\omega_{n-1}^n)_{11} (\omega_{n-2}^n)_{11} \cdots (\omega_{n-1}^n)_{14} = c_{1n} c_{1n-1} \cdots c_{14}$$
$$\alpha_{22} = c_{2n} c_{2n-1} \cdots c_{24}$$
$$\alpha_{33} = c_{3n} c_{3n-1} \cdots c_{34}$$
$$\alpha_{21} = c_{2n} c_{2n-1} \cdots c_{25} \tilde{s}_{24} \tilde{s}_{14} + c_{2n} c_{2n-1} \cdots \tilde{s}_{25} \tilde{s}_{15} c_{14} + \cdots + \tilde{s}_{2n} \tilde{s}_{1n} c_{1n-1} \cdots c_{14}$$
$$\alpha_{31} = c_{3n} c_{3n-1} \cdots c_{35} \tilde{s}_{34} \tilde{s}_{14} + c_{3n} c_{3n-1} \cdots \tilde{s}_{35} \tilde{s}_{15} c_{14} + \cdots + \tilde{s}_{3n} \tilde{s}_{1n} c_{1n-1} \cdots c_{14}$$
$$\alpha_{32} = c_{3n} c_{3n-1} \cdots c_{35} \tilde{s}_{34} \tilde{s}_{34} + c_{3n} c_{3n-1} \cdots \tilde{s}_{35} \tilde{s}_{25} c_{24} + \cdots + \tilde{s}_{3n} \tilde{s}_{2n} c_{2n-1} \cdots c_{24}$$
Simplest example: 3 + 1

- Introducing one heavy extra neutrino our formalism has the next expression

\[ U_{4x4} = \begin{pmatrix} N_{3x3} & S_{3x1} \\ T_{1x3} & V \end{pmatrix} \]

\[ N = N^{NP} N^{SM} = \]

\[
\begin{pmatrix}
\alpha_{11} & 0 & 0 \\
\alpha_{21} & \alpha_{22} & 0 \\
\alpha_{31} & \alpha_{32} & \alpha_{33}
\end{pmatrix}
\begin{pmatrix}
c_{12} c_{13} \\
\tilde{s}_{23} \tilde{s}_{13} + c_{23} \tilde{s}_{12} \\
c_{12} c_{23} \tilde{s}_{13} + \tilde{s}_{23} \tilde{s}_{12}
\end{pmatrix}
\begin{pmatrix}
\tilde{s}_{12} c_{13} \\
\tilde{s}_{23} \tilde{s}_{12} \tilde{s}_{13} + c_{23} c_{12} \\
c_{23} \tilde{s}_{12} \tilde{s}_{13} + \tilde{s}_{23} c_{12}
\end{pmatrix}
\]

\[
\begin{pmatrix}
\tilde{s}_{13} \\
\tilde{s}_{23} \tilde{s}_{12} \tilde{s}_{13} + c_{23} c_{12} \\
c_{23} \tilde{s}_{12} \tilde{s}_{13} + \tilde{s}_{23} c_{12}
\end{pmatrix}
\]
Simplest example: 3 + 1

- Introducing one heavy extra neutrino our formalism has the next expression

\[ U_{4x4} = \begin{pmatrix} N_{3x3} & S_{3x1} \\ T_{1x3} & V \end{pmatrix} \]

\[ N = N^{NP} N^{SM} = \]

\[
\begin{pmatrix}
\alpha_{11} & 0 & 0 \\
\alpha_{21} & \alpha_{22} & 0 \\
\alpha_{31} & \alpha_{32} & \alpha_{33}
\end{pmatrix}
\]

\[
\begin{pmatrix}
c_{12} c_{13} & \bar{s}_{12} c_{13} & \bar{s}_{13} \\
\bar{s}_{23} \bar{s}_{13} + c_{23} \bar{s}_{12} & \bar{s}_{23} \bar{s}_{12} + c_{23} c_{12} & c_{23} \bar{s}_{12} + c_{23} c_{12} \\
c_{12} c_{23} \bar{s}_{13} + \bar{s}_{23} \bar{s}_{12} & c_{23} \bar{s}_{12} + \bar{s}_{23} c_{12} & c_{23} \bar{s}_{12} + \bar{s}_{23} c_{12}
\end{pmatrix}
\]

\[
\alpha_{11} = c_{14} \\
\alpha_{22} = c_{24} \\
\alpha_{33} = c_{34} \\
\alpha_{21} = \bar{s}_{24} \bar{s}_{14} \\
\alpha_{31} = \bar{s}_{34} c_{24} \bar{s}_{14} \\
\alpha_{32} = \bar{s}_{34} \bar{s}_{24}
\]
**3 + 3 model**

- See-saw mechanisms introduce 3 or 6 extra singlets:

\[
U_{6\times6} = \begin{pmatrix} N_{3\times3} & S_{3\times3} \\ T_{3\times3} & V_{3\times3} \end{pmatrix}
\]

\[
N = N^{NP} N^{SM} = 
\]

\[
= \begin{pmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} \begin{pmatrix} c_{12} c_{13} & \tilde{s}_{12} c_{13} & \tilde{s}_{13} \\ \tilde{s}_{23} \tilde{s}_{13} + c_{23} \tilde{s}_{12} & \tilde{s}_{23} \tilde{s}_{12} \tilde{s}_{13} + c_{23} c_{12} & \tilde{s}_{13} \tilde{s}_{23} \\ c_{12} c_{23} \tilde{s}_{13} + \tilde{s}_{23} \tilde{s}_{12} & c_{23} \tilde{s}_{12} \tilde{s}_{13} + \tilde{s}_{23} c_{12} & c_{13} \tilde{s}_{23} \end{pmatrix}
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3 + 3 model

- See-saw mechanisms introduce 3 or 6 extra singlets:

\[
U_{6x6} = \begin{pmatrix}
N_{3x3} & S_{3x3} \\
T_{3x3} & V_{3x3}
\end{pmatrix}
\]

\[
N = N^{NP} N^{SM} =
\]

\[
\begin{pmatrix}
\alpha_{11} & 0 & 0 \\
\alpha_{21} & \alpha_{22} & 0 \\
\alpha_{31} & \alpha_{32} & \alpha_{33}
\end{pmatrix}
\begin{pmatrix}
c_{12} c_{13} & \tilde{s}_{12} c_{13} & \tilde{s}_{13} \\
\tilde{s}_{23} \tilde{s}_{13} + c_{23} \tilde{s}_{12} & \tilde{s}_{23} \tilde{s}_{12} \tilde{s}_{13} + c_{23} c_{12} & c_{13} \tilde{s}_{23} \\
c_{12} c_{23} \tilde{s}_{13} + \tilde{s}_{23} \tilde{s}_{12} & c_{23} \tilde{s}_{12} \tilde{s}_{13} + \tilde{s}_{23} c_{12} & c_{13} c_{23}
\end{pmatrix}
\]

\[
\begin{align*}
\alpha_{11} &= c_{16} c_{15} c_{14} \\
\alpha_{22} &= c_{26} c_{25} c_{24} \\
\alpha_{33} &= c_{36} c_{35} c_{34} \\
\alpha_{21} &= c_{14} \tilde{s}_{26} \tilde{s}_{16} c_{15} + c_{26} \tilde{s}_{25} \tilde{s}_{15} c_{14} + \tilde{s}_{26} c_{25} \tilde{s}_{24} \tilde{s}_{14} \\
\alpha_{31} &= c_{36} c_{35} c_{34} c_{24} \tilde{s}_{14} + c_{36} \tilde{s}_{35} c_{25} \tilde{s}_{15} \tilde{s}_{14} + \tilde{s}_{36} c_{26} \tilde{s}_{16} c_{15} c_{14} + c_{36} \tilde{s}_{35} \tilde{s}_{25} \tilde{s}_{24} \tilde{s}_{14} + \\
&\quad + \tilde{s}_{36} \tilde{s}_{26} c_{25} \tilde{s}_{24} \tilde{s}_{14} + \tilde{s}_{36} \tilde{s}_{26} \tilde{s}_{25} \tilde{s}_{15} c_{14} \\
\alpha_{32} &= c_{36} c_{35} \tilde{s}_{34} \tilde{s}_{24} + c_{36} c_{35} \tilde{s}_{25} c_{24} + \tilde{s}_{36} \tilde{s}_{26} c_{25} c_{24}
\end{align*}
\]
Conclusions

- Extra neutral heavy leptons are motivated in order to introduce neutrino mass.
- Signatures of heavy neutrinos arising from their mixing with light ones could be looked for at laboratory experiments.
- A compilation of these is useful to give some light to models beyond SM and probe the scale of neutrino mass generation.
- Such heavy neutrino (seesaw) models imply a high number of parameters.
- The symmetric parametrization of lepton mixing provides the most useful way to separate “new physics” from SM physics.
Thank you!
Backup slides
Current constraints on heavy neutrinos

- The presence of extra heavy fermions would imply the non-unitarity of $W_{3\times3}$ and would modify some SM observables.

- Universality tests:
  
  $\mu - e$ tests
  
  \[
  \pi \to e \bar{\nu} \\
  \pi \to \mu \bar{\nu}
  \]

  \[
  \begin{pmatrix} g_e \\ g_\mu \end{pmatrix}^2 = \frac{1 - |V_{e4}|^2}{1 - |V_{\mu4}|^2}
  \]

  \[
  \sum_1^3 |U_{ui}|^2 = \left( \frac{G_F}{G_\mu} \right) \sqrt{1 - |V_{e4}|^2} = \frac{1}{1 - |V_{\mu4}|^2}
  \]

  $|V_{e4}|^2 < 0.0084 (0.0124)$ ; $|V_{\mu4}|^2 < 0.0005 (0.0011)

- $\mu - \tau$ tests

  \[
  \begin{pmatrix} g_e \\ g_\mu \end{pmatrix}^2 = \frac{1 - |V_{\tau4}|^2}{1 - |V_{\mu4}|^2}
  \]

  $|V_{e4}|^2 < 0.0207 (0.0264)$
# Bounds

<table>
<thead>
<tr>
<th>Mixing</th>
<th>Range of $m_4$</th>
<th>EW measure</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>V_{e4}</td>
<td>^2$</td>
</tr>
<tr>
<td>$</td>
<td>V_{\mu 4}</td>
<td>^2$</td>
</tr>
<tr>
<td>$</td>
<td>V_{\tau 4}</td>
<td>^2$</td>
</tr>
</tbody>
</table>

del Aguila, de Blas and Pérez Victoria (2008)
LHC

- Limits coming from LHC

Buphal, Pilaftsis and Yang (2014)
As we know, if we introduce any extra heavy neutrino the unitarity is violated

$$|N_{e_1}|^2 + |N_{e_2}|^2 + |N_{e_3}|^2 = |\alpha_{11}|^2$$