The Minimal 3+2 Neutrino Model Versus Higgs Decays

Alexander Moreno Briceño

Centro de Investigaciones, Universidad Antonio Nariño

In collaboration with
A. Gago, P. Hernández, J. Jones-Pérez and M. Losada

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Introduction

We study the minimal 3+2 neutrino model (minimal in the sense that is the minimal model beyond the Standard Model that explains the neutrino masses) in scenarios where the singlets have masses at the GeV scale. This can lead to Higgs decays into heavy neutrinos, which would be observable at the LHC. What are the implications of this?:

- We would be observing new neutral fermions,
- the Higgs coupling to light and heavy neutrinos would suggest the seesaw mechanism is at work,
- the size of the couplings, along with the "lightness" of the heavy masses, would suggest the existence of an approximate lepton-number symmetry
- and this can be further correlated to future measurements of lepton flavor violating processes.

Introduction (cont'd)

The most general Lagrangian, which consists of the addition of $n + n'$ fermion gauge singlets, N_i, to the SM particle content without imposing lepton number conservation, is given by:

$$\mathcal{L} = \mathcal{L}_{\mathcal{SM}} + \mathcal{L}_{kin} - Y_{\alpha i} \bar{N}_i \hat{\Phi}^\dagger L_\alpha - \frac{1}{2} \bar{N}_i M_{ij} N_j^c + h.c.$$

The naive seesaw expectation

$$m \sim Y^2 \frac{\upsilon^2}{M}$$

and, therefore, for $M \sim GeV$, $Y^2 \sim 10^{-12}$ which is too small to measure.

In the minimal 3+2 neutrino model, an approximate $U(1)_L$ symmetry could be assumed and this naive scaling does not work: Y and flavour effects can be large. This requires quasi-degenerate (quasi-Dirac) heavy neutrinos.

Introduction (cont'd)

The structure of the mass matrix is approximately

$$\begin{pmatrix} 0 & Y & \epsilon \\ Y & \epsilon & M \\ \epsilon & M & \epsilon \end{pmatrix}$$

Neutrino masses are suppressed with ϵ, but Y can be large.

The degeneracy can be lifted in the so-called extended seesaw

$$\begin{pmatrix} 0 & Y & \epsilon \\ Y & \mu & M \\ \epsilon & M & \epsilon \end{pmatrix}$$

which also leads to $m \sim \epsilon$ for an arbitrary μ (the degeneracy of the heavy states is controlled by μ, which is not small in this case) but only at tree level. Loop corrections give $m \sim \mu$.

J. Lopez-Pavon, S. Pascoli and Chan-fai Wong, Phys. Rev. D87 (2013) 9, 093007 [arXiv:1209.5342[hep-ph]]

The Minimal 3+2 Neutrino Model: Normal and Inverted Hierarchies

For the normal hierarchy, the 5×5 neutrino mixing matrix is defined through:

$$\mathcal{M}_\nu = U^\star diag(0, m_2, m_3, M_1, M_2) U^\dagger .$$

U can be decomposed into four blocks:

$$U = \begin{pmatrix} U_{al} & U_{ah} \\ U_{sl} & U_{sh} \end{pmatrix} ,$$

and each block in the following way:

$$U_{al} = U'_{PMNS} \begin{pmatrix} 1 & 0 \\ 0 & H \end{pmatrix} , \qquad U_{ah} = iU'_{PMNS} \begin{pmatrix} 0 \\ H m_l^{1/2} R^\dagger M_h^{-1/2} \end{pmatrix} ,$$

$$U_{sl} = i \begin{pmatrix} 0 & \bar{H} M_h^{-1/2} R m_l^{1/2} \end{pmatrix} , \quad U_{sh} = \bar{H}$$

A. Donini et al., JHEP 1207 (2012) 161 [arXiv:1205.5230[hep-ph]] where

$$M_h = diag(M_1, M_2),$$

$$m_l = diag(m_2, m_3) = diag(\sqrt{\Delta m^2_{sol}}, \sqrt{\Delta m^2_{atm}}),$$

$$H = (I + m_l^{1/2} R^\dagger M_h^{-1} R m_l^{1/2})^{-1/2}$$
$$\bar{H} = (I + M_h^{1/2} R m_l R^\dagger M_h^{-1/2})^{-1/2}$$

and

$$R = \begin{pmatrix} \cos(\theta_{45} + i\gamma_{45}) & \sin(\theta_{45} + i\gamma_{45}) \\ -\sin(\theta_{45} + i\gamma_{45}) & \cos(\theta_{45} + i\gamma_{45}) \end{pmatrix}$$

The model is then described by 11 parameters: 3 mixing angles and 2 CPV phases from the U_{PMNS} matrix, 2 non-zero light neutrino masses, 2 heavy neutrino masses and a complex angle participating in active-heavy neutrino mixing

A. Donini et al., JHEP 1207 (2012) 161 [arXiv:1205.5230[hep-ph]]

For the inverted hierarchy, the 5×5 neutrino mixing matrix is defined through:

$$\mathcal{M}_\nu = V^\star diag(m_2, m_3, 0, M_1, M_2) V^\dagger .$$

V can be decomposed into four blocks:

$$V = \begin{pmatrix} V_{al} & V_{ah} \\ V_{sl} & V_{sh} \end{pmatrix},$$

and each block in the following way:

$$V_{al} = U''_{PMNS} \begin{pmatrix} H & 0 \\ 0 & 1 \end{pmatrix}, \qquad V_{ah} = iU''_{PMNS} \begin{pmatrix} H m_l^{1/2} R^\dagger M_h^{-1/2} \\ 0 \end{pmatrix},$$
$$V_{sl} = i \begin{pmatrix} \bar{H} M_h^{-1/2} R m_l^{1/2} & 0 \end{pmatrix}, \quad V_{sh} = \bar{H}$$

The inverse hierarchy just implies a rearrangement of the rows and columns of the mixing matrix.

Neutrino Couplings

Now we need to write the Dirac and Majorana mass terms, m_Y and M_N, in terms of the parameters shown before (i.e. H, R, M_h and m_l). These terms enter the neutrino Majorana mass matrix:

$$M_\nu = \begin{pmatrix} 0 & m_Y \\ m_Y^T & M_N \end{pmatrix} .$$

After projecting out the zero eigenvalue of the neutrino mass matrix, we get for the normal hierarchy

$$m_Y^{(n.h.)} = U'^{\star}_{PMNS} \begin{pmatrix} 0 \\ -iH^\star m_l^{1/2}(m_l R^\dagger + R^T M_h) M_h^{-1/2} \bar{H} \end{pmatrix} ,$$

and for the inverted hierarchy

$$m_Y^{(i.h.)} = U''^{\star}_{PMNS} \begin{pmatrix} -iH^\star m_l^{1/2}(m_l R^\dagger + R^T M_h) M_h^{-1/2} \bar{H} \\ 0 \end{pmatrix} .$$

For M_N we obtain

$$M_N = \bar{H}^\star (M_h - M_h^{-1/2} R^\star m_l^2 R^\dagger M_h^{-1/2}) \bar{H} .$$

Now we can apply the perturbativity bounds on the Yukawa coupling, $\sqrt{2}m_Y/\upsilon$. For definiteness we follow the condition

$$Tr\left[\frac{2}{\upsilon^2}m_Y m_Y^\dagger\right] \leq 3.$$

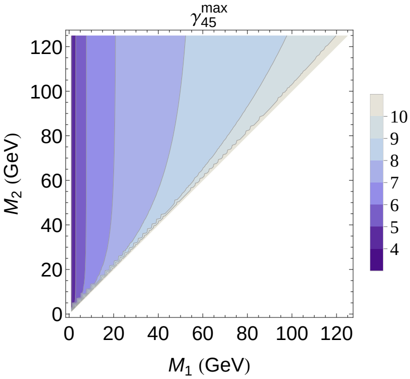
.

J. A. Casas et al., JHEP 1103 (2011) 034 [arXiv:1010.5751[hep-ph]]

When both heavy masses are of $\mathcal{O}(GeV)$, then $\gamma_{45} \leq 40 - 50$ for perturbativity to hold. For larger masses, the bound drops to $\gamma_{45} \leq 10 - 20$, when $M_1 M_2 \geq \mathcal{O}(10^5 GeV^2)$.

Constraints

- $0\nu\beta\beta$ in the minimal $3+2$ seesaw.

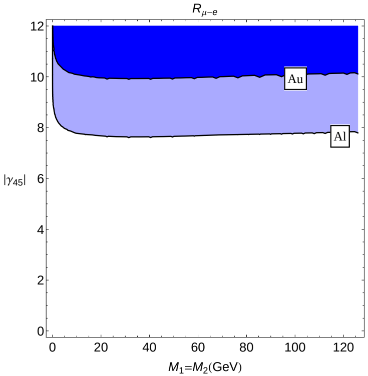


$0\nu\beta\beta$ strongly constrains active-heavy mixing, ruled by γ_{45}. This bound can be avoided by having degenerate heavy neutrinos, which brings a cancellation. Such degeneracy can be justified by introducing an approximate lepton-number symmetry.

M. Blennow, E. Fernandez-Martínez, J. López-Pavón and J. Menéndez; JHEP 1007 (2010) 096 [arXiv:1005.3240 [hep-ph]]

Constraints (cont'd)

- **Lepton Flavor Violation**.

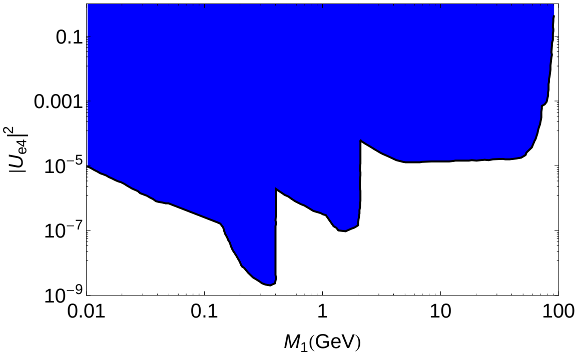


LFV involves the $\mu \to e\gamma$ decay and the $\mu - e$ conversion in nuclei. This gives an upper bound on γ_{45}, even on the degenerate case.

R. Alonso, M. Dhen, M. B. Gavela and T. Hambye; JHEP 1301 (2013) 118 [arXiv:1209.2679 [hep-ph]]

Constraints (cont'd)

- **Direct Search Bounds**.



Many experiments have tried to directly produce and detect heavy neutrinos. This provides upper bounds on active-heavy mixing.

A. Atre, T. Han, S. Pascoli and B. Zhang; JHEP 0905 (2009) 030 [arXiv:0901.3589 [hep-ph]]

Higgs Decays into Neutrinos

The decay rate of a Higgs decaying into two fermions of different mass is given by

$$\Gamma = \frac{\omega}{8\pi} m_h \left(1-2\frac{m_1^2+m_2^2}{m_h^2}+\frac{(m_1^2-m_2^2)^2}{m_h^4}\right)^{1/2}\left[(S+P)\left(1-\frac{(m_1+m_2)^2}{m_h^2}\right)+4P\left(\frac{m_1 m_2}{m_h^2}\right)\right]$$

where S and P indicate the scalar and pseudoscalar coupling of the Higgs to the two fermions. The factor ω is a statistical factor, equal to 1/2 if the particles in the final states are identical and equal to unity otherwise.

Higgs Decay in the $3+2$ Seesaw

The Yukawa coupling of the Higgs to two neutrinos is $Y_\nu = \sqrt{2} m_Y / \upsilon$. For $h \to \nu_i \nu_j$ we have

$$S = \frac{g^2}{4m_W^2}((m_{\nu_i} + m_{\nu_j}) Re[C_{ij}])^2,$$

$$P = \frac{g^2}{4m_W^2}((m_{\nu_j} - m_{\nu_i}) Im[C_{ij}])^2,$$

with

$$C_{ij} = \sum_{k=1}^{3} U_{ki}^\star U_{kj}.$$

Thus, we have

$$\Gamma(h \to \nu_i \nu_j) = \omega \frac{g^2}{32\pi} \frac{(m_{\nu_i}^2 + m_{\nu_j}^2)}{m_W^2} m_h \left(1 - 2\frac{m_{\nu_i}^2 + m_{\nu_j}^2}{m_h^2} + \frac{(m_{\nu_i}^2 - m_{\nu_j}^2)^2}{m_h^4}\right)^{1/2} \times \\ \left[\left([C_{ij}]^2 + \frac{2m_{\nu_i} m_{\nu_j}}{m_{\nu_i}^2 + m_{\nu_j}^2}(Re[C_{ij}]^2 - Im[C_{ij}]^2)\right)\left(1 - \frac{(m_{\nu_i} + m_{\nu_j})^2}{m_h^2}\right) + \\ \frac{(m_{\nu_j} - m_{\nu_i})^2}{m_{\nu_i}^2 + m_{\nu_j}^2} Im[C_{ij}]^2 \left(\frac{m_{\nu_i} m_{\nu_j}}{m_h^2}\right)\right]$$

Higgs Decay in the $3+2$ Seesaw (cont'd)

- Higgs decay into two light neutrinos, n_k $(m_{\nu_k} \to 0)$

$$\Gamma(h \to n_i n_j) = \omega \frac{g^2}{32\pi} \frac{(m_{\nu_i}^2 + m_{\nu_j}^2)}{m_W^2} m_h \left([C_{ij}]^2 + \frac{2 m_{\nu_i} m_{\nu_j}}{m_{\nu_i}^2 + m_{\nu_j}^2} (Re[C_{ij}]^2 - Im[C_{ij}]^2) \right),$$

where

$$C_{ll'} = \begin{pmatrix} 1 & 0 \\ 0 & H^2 \end{pmatrix}$$

- Higgs decay into one light neutrino $(m_{\nu_i} \to 0)$, and one heavy neutrino N_j, with mass M_j

$$\Gamma(h \to n_i N_j) = \frac{g^2}{32\pi} \frac{M_j^2}{m_W^2} m_h \left(1 - \frac{M_j^2}{m_h^2} \right)^2 |C_{ij}|^2,$$

where

$$C_{lh} = i \begin{pmatrix} 0 \\ H^2 m_l^2 R^\dagger M_h^{-1/2} \end{pmatrix}$$

Higgs Decay in the $3+2$ Seesaw (cont'd)

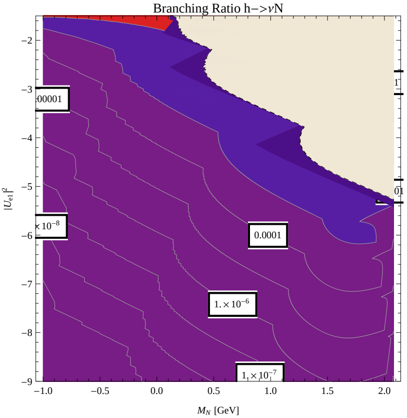
- Higgs decay into two identical heavy neutrinos

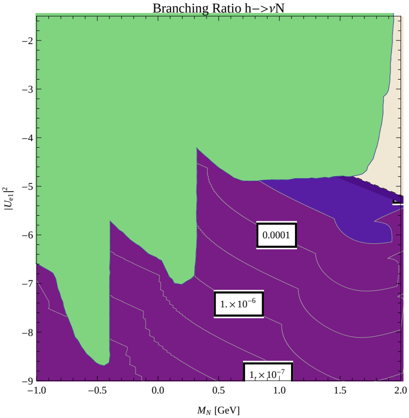
$$\Gamma(h \to N_i N_i) = \omega \frac{g^2}{16\pi} \frac{M_i^2}{m_W^2} m_h \left(1 - 4\frac{M_i^2}{m_h^2}\right)^{3/2} Re|C_{ij}|^2,$$

where

$$C_{hh'} = M_h^{-1/2} R m_l^{1/2} H^2 m_l^{1/2} R^\dagger M_h^{-1/2}$$

Higgs Decay in the $3 + 2$ Seesaw (cont'd)





Modification of the Higgs Width

- The CMS experiment has recently used lineshape studies to derive an upper bound on the Higgs width, such that $\Gamma_h < 4.2\Gamma_h^{SM}$. This can be translated into an upper bound on the branching ratio to non-SM particle, $Br(h \to invisibles) < 0.76$.

CMS Collaboration [CMS Collaboration], CMS-PAS-HIG-14-002

F. Caola and K. Melnikov, Phys. Rev. D 88 (2013) 054024 [arXiv:1307.4935 [hep-ph]]

- For the ATLAS collaboration, assuming no energy-scale dependence of the relevant Higgs boson couplings, a combination with the on-shell measurement of $\mu_{on-shell}$ in the $H \to ZZ \to 4l$ channel yields an observed (expected) 95% confidence level upper limit on Γ_h/Γ_h^{SM} in the range 4.8-7.7 (7.0-12.0).

ATLAS Collaboration [ATLAS Collaboration], ATLAS-COM-CONF-2014-052

Modification of the Higgs Width (cont'd)

- By restricting the couplings of the Higgs to gauge bosons not to exceed their SM values one finds that with $300fb^{-1}$ ($3000fb^{-1}$), the LHC could place limits of $Br(h \to invisibles) < 0.14 - 0.18$ ($Br(h \to invisibles) < 0.07 - 0.11$).

S. Dawson et al., arXiv:1310.8361 [hep-ex]

- Post-LHC experiments have the capacity of measuring the width directly. ILC could measure the width with a precision of about 5%, while TLEP could achieve a 1% precision. Assuming these measurements coincide with the SM width, they would place bounds on the non-SM branching ratio of the order of $Br(h \to invisibles) \leq 0.09$ and $Br(h \to invisibles) \leq 0.02$, respectively.

S. Dawson et al., arXiv:1310.8361 [hep-ex]

Heavy Neutrino Decays

For heavy enough neutrinos we have two body decays:

- $N \to Z\nu$ which would contribute to $h \to \nu\bar{\nu}jj, h \to \nu\bar{\nu}bb, h \to \nu\bar{\nu}l^{\pm}l^{\mp}, h \to \nu\bar{\nu}\tau^{\pm}\tau^{\mp}$ and $h \to \nu\bar{\nu}\nu\bar{\nu}$
- $N \to W^{\pm}l^{\mp}$ which would contribute to $h \to l\bar{\nu}jj', h \to l\bar{\nu}bj, h \to l^{\pm}\bar{\nu}l'^{\mp}\nu$ and $h \to l^{\pm}\bar{\nu}\tau^{\mp}\nu$

For lower values of the heavy neutrino mass we have

- $N \to Z^{\star}\nu$ which would contribute to three body decays.
- $N \to W^{\star\pm}l^{\mp}$ which would contribute to three body decays.

- Given the small active-heavy mixing, it is conceivable to have long-lived heavy neutrinos. In that case, it would be possible to observe displaced vertices

Decay Channels

For $M_i > m_Z$, we have two body decay channels with one gauge boson in the final state:

$$\Gamma(N_j \to l_i^{\pm} W^{\mp}) = \frac{G_F}{8\sqrt{2}\pi} M_i^3 \left(1 - \frac{m_W^2}{M_i^2}\right)^2 \left(1 + 2\frac{m_W^2}{M_i^2}\right) |(U_{ah})_{ij}|^2,$$

$$\Gamma(N_j \to \nu_i Z) = \frac{G_F}{8\sqrt{2}\pi} M_i^3 \left(1 - \frac{m_Z^2}{M_i^2}\right)^2 \left(1 + 2\frac{m_Z^2}{M_i^2}\right) |(U_{al}^{\dagger})_{ik}(U_{ah})_{kj}|^2,$$

$$\Gamma(N_j \to \nu_i h) = \frac{G_F}{8\sqrt{2}\pi} M_i^3 \left(1 - \frac{m_h^2}{M_i^2}\right)^2 |(U_{al}^{\dagger})_{ik}(U_{ah})_{kj}|^2.$$

Status and Prospects

- The $N \to Z\nu$ decay, with Z decaying into two light neutrinos, would lead to an invisible final state, which could dominate over the invisible Higgs decay mode.
- The currents bounds are of $Br(h \to inv.) < 0.65 (0.75)$, by ATLAS (CMS). The LHC could bound the Higgs branching ratio to invisible decays to 0.09-0.22 (0.06-0.1) for $300 fb^{-1}$ ($3000 fb^{-1}$). The ILC could lower this bound to about 0.01, while TLEP might reach 0.002.

S. Dawson et al., arXiv:1310.8361 [hep-ex]

- The contribution to $h \to \nu\bar{\nu} l^{\pm} l'^{\mp}$ has been studied in an inverse seesaw model. For $m_h = 125$ GeV and $m_h > M_i$, a neutrino Yukawa coupling larger than 0.01 is excluded. For $m_h < M_i$, in which no heavy neutrinos are generated on-shell, a neutrino Yukawa coupling larger than 1 is excluded.

P. S. Bhupal et al., Phys. Rev. D 86 (2012) 093010 [arXiv:1207.2756 [hep-ph]]

Status and Prospects (cont'd)

- The combined decays $h \to l\bar{\nu}jj'$ and $h \to l\bar{\nu}bj$ have also been studied. They claim a sensitivity for their y parameter around 0.02 for $M_i \approx 95$ GeV, and $\mathcal{L} = 10fb^{-1}$ at 14 TeV.

A. Ibarra, E. Molinaro and S. T. Petcov, JHEP 1009(2010) 108 [arXiv:1007.2378 [hep-ph]]

- The only unexplored channels are $h \to \nu\bar{\nu}jj$, $h \to \nu\bar{\nu}b\bar{b}$, $h \to \nu\bar{\nu}\tau^{\pm}\tau^{\mp}$, $h \to \nu\bar{\nu}\nu\bar{\nu}$ and $h \to l^{\pm}\bar{\nu}\tau^{\mp}\nu$, as well as the exclusive $h \to l\bar{\nu}bj$. Furthermore, no joint analysis on $h \to \nu\bar{\nu}l^{\pm}l'^{\mp}$ and $h \to l\bar{\nu}jj'$ has been done, as well as no studies on final states with displaced vertices.

J. Helo, M. Hirsch and S. Kovalenko, Phys. Rev. D 89 (2014) 073005 [arXiv:1312.2900 [hep-ph]]

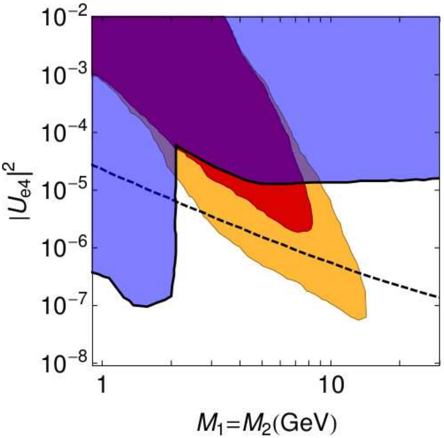
Displaced Vertices at the LHC

We explore the possibility of having heavy neutrinos with large lifetimes, which would lead to displaced vertices at the LHC. Using SusHi we calculate the maximum area of the parameter space which can be probed by this process. We focus on Higgs production by gluon fusion, at 13 TeV. We require a transverse decay length larger than 1mm and smaller than 1m.

R. V. Harlander, S. Liebler and H. Mantler; Computer Physics Communications 184 (2013) 1605-1617 [arXiv:1212.3249 [hep-ph]]

J. Helo, M. Hirsch and S. Kovalenko, Phys. Rev. D 89 (2014) 073005 [arXiv:1312.2900 [hep-ph]]

Displaced Vertices at the LHC (cont'd)



Area of parameter space where displaced vertex is visible and Higgs branching ratio is not too small. Red area can be probed by a luminosity of 300 fb^{-1}, orange area can be probed by 3000 fb^{-1}.

Conclusions and Outlook

- We have completed the first stage of a feasibility study for the observation of Higgs decays into heavy neutrinos. The study is done in the context of the minimal 3+2 neutrino model.
- We have concentrated on decays where the heavy neutrino would generate a displaced vertex. After imposing constraints from experiments, we find a small region where such decays could leave a signature. For this, we need a high luminosity at the LHC of 3000 fb^{-1}.
- The region of interest consists of heavy neutrinos with masses between $2-10$ GeV, and active-heavy mixing of order $10^{-5}-10^{-7}$.