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The Minimal 3 + 2 Neutrino Model vs. Higgs Decays

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Abstract

The minimal 3+2 neutrino model is a Type-I seesaw model with two Weyl fermions, singlets under the Standard Model. Apart from light neutrino masses and mixings, this model can be fully described by four additional parameters. In this work, we study the minimal 3+2 neutrino model in scenarios where the singlets have masses at the GeV scale. This can lead to Higgs decays into heavy neutrinos, which could be observable as displaced vertices at the LHC.

1. The Minimal 3+2 Neutrino Model

The Type-I seesaw mechanism [1, 2, 3, 4] is generally invoked to explain the difference between neutrino masses and the rest of the fermions. The mechanism consists in adding a certain number of heavy Weyl singlets which couple both to the Higgs and to the Standard Model (SM) neutrinos. Once electroweak symmetry is broken, a small mass is given to the latter. In this case, the lightness of their masses is due to a suppression coming from the large masses of the singlets.

In this work, we study the minimal 3+2 neutrino model, which is a Type-I seesaw model with two singlets. We are interested in scenarios where the latter have masses at the GeV scale. This leads to Higgs decays into heavy neutrinos, which could be observable at the LHC.

This scenario is of interest for several reasons. Observing such decays means that the Higgs couples to light and heavy neutrinos, suggesting that the seesaw mechanism is at work. Furthermore, the size of the couplings, along with the "lightness" of the heavy masses, would also suggest the existence of an approximate lepton-number symmetry [5].

In addition, observing this decay would also imply a future measurement of lepton flavour violating processes, which would be a valuable cross-check for the model.

The model is described by 11 parameters [6]: two non-zero light neutrino masses, two heavy neutrino masses, three mixing angles and two CP phases (contained within the U_{PMNS} matrix) and one complex angle participating in active-heavy neutrino mixing.

For the normal hierarchy, the active-heavy mixing matrix is:

$$U_{ah} = i\, U_{\text{PMNS}} \begin{pmatrix} 0 \\ H\, m_\ell^{1/2} R^\dagger M_h^{-1/2} \end{pmatrix}, \qquad (1)$$

with:

$$R = \begin{pmatrix} \cos(\theta_{45} + i\gamma_{45}) & \sin(\theta_{45} + i\gamma_{45}) \\ -\sin(\theta_{45} + i\gamma_{45}) & \cos(\theta_{45} + i\gamma_{45}) \end{pmatrix}. \qquad (2)$$

Here, m_ℓ and M_h are 2×2 diagonal matrices describing the two non-zero light and heavy neutrino masses, respectively. The 2×2 matrix H is a function these parameters and those in R. It is hermitian, and close to the identity. Notice that a large γ_{45} maximizes the mixing.

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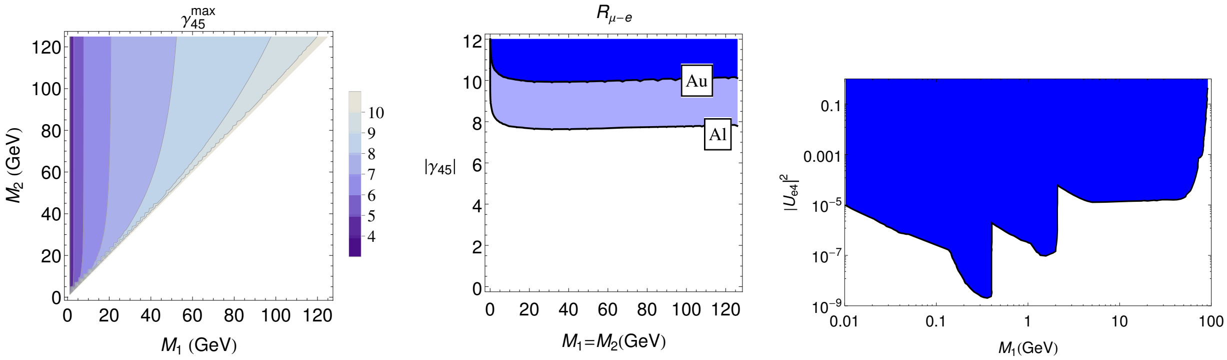

Figure 1: Left: Maximum value of γ_{45} allowed by the non-observation of neutrinoless double beta decay. The bound vanishes for degenerate masses. Centre: Bounds from $\mu - e$ conversion in nuclei, for the case of degenerate masses. The dark blue area is excluded, while the light blue area can be probed in the future. Right: Constraints on active-heavy mixing coming from the combination of TRIUMF, PS191, CHARM and DELPHI experiments. The blue area is ruled out.

2. Constraints

Among others, we find three important constraints on the parameter space. These are shown on Figure 1.

The first constraint comes from neutrinoless double beta decay ($0\nu\beta\beta$). The non-observation of this process can put very strong bounds on the active-heavy mixing, ruled by γ_{45}. The maximum value of this parameter allowed by $0\nu\beta\beta$ is shown on the left panel of Figure 1. The bound can be avoided by having degenerate heavy neutrinos, which brings a cancellation [7]. Such degeneracy can be justified by introducing an approximate lepton-number symmetry.

Lepton flavour violation (LFV) also plays an important role when constraining active-heavy mixing. This involves, in particular, $\mu \to e\gamma$ decay and $\mu - e$ conversion in nuclei [8], the latter placing the strongest bounds. As these processes have not been observed, γ_{45} is bounded from above, even in the degenerate case. This is shown on the central panel of Figure 1.

Finally, we also need to apply direct search bounds. Many experiments have tried to produce, and detect, these heavy neutrinos. Again, the lack of signal provides upper bounds on active-heavy mixing. We have taken the data of [9], shown on the right panel of Figure 1, to constrain the mixing.

We find that the combined bounds heavily restrict the parameter space.

3. Higgs decays into heavy neutrinos

As the Higgs is coupled to one active and one sterile neutrino through the Yukawa interaction, the Higgs can decay into one light and one heavy neutrino [10, 11, 12] if the process is dynamically allowed. This can be written in terms of the active-heavy neutrino mixing, leading to the following branching ratio:

$$\Gamma(h \to \nu_i N_j) = \frac{g^2}{32\pi}\frac{M_j^2}{m_W^2} m_h \left(1 - \frac{M_j^2}{m_h^2}\right)^2 \left|C_{ij}\right|^2 \quad (3)$$

$$C_{ij} = i \begin{pmatrix} 0 \\ H^2 m_\ell^{1/2} R^\dagger M_h^{-1/2} \end{pmatrix}_{ij} , \quad (4)$$

where m_h is the mass of the Higgs. Again, we see the process can be enhanced by a large γ_{45}.

In the following, we explore the possibility of having heavy neutrinos with large lifetimes, which would lead to displaced vertices at the LHC.

To this end, we use SusHi [13] to calculate the differential cross section for Higgs production via gluon fusion, in terms of the modulus of transverse momentum p_{h_T} and pseudorapidity η_h. We evaluate this differential cross section at 13 TeV. This is then convoluted with the Higgs differential decay width, in terms of the modulus of the heavy neutrino transverse momentum p_{N_T} and its angle with respect to the Higgs transverse momentum, ϕ_{Nh}. Thus, the expected number of events with a displaced vertex is obtained through:

$$N = \mathcal{L} \int dp_{h_T} d\eta_h \, dp_{N_T} d\phi_{Nh} \frac{d^2\sigma(gg \to h)}{dp_{h_T} d\eta_h} \frac{\gamma_h}{\Gamma_h} \frac{d^2\Gamma(h \to N_i \nu)}{dp_{N_T} d\phi_{Nh}} \theta(\ell_N - \ell_{\min})\, \theta(\ell_{\max} - \ell_N) \ . \quad (5)$$

Here, Γ_h is the Higgs total width in the model, and γ_h is the relativistic factor due to the boost of the Higgs. The parameter $\mathcal{L}$ is the total luminosity at the experiment. The transverse decay length is ℓ_N, which is required to be larger than $\ell_{\min} = 1$ mm and smaller than $\ell_{\max} = 1$ m.

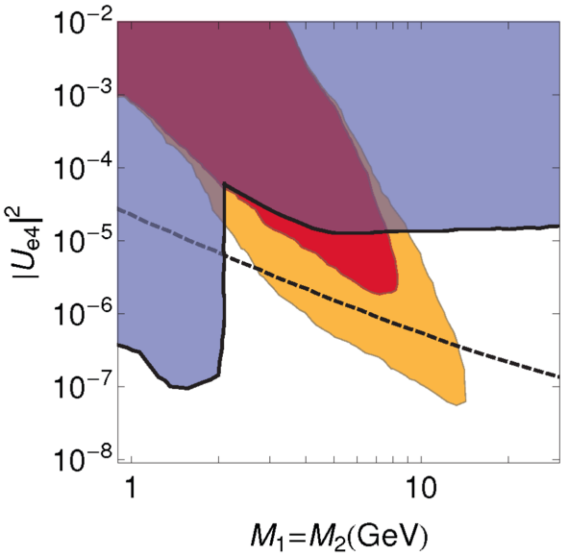

Figure 2: Region of the heavy neutrino parameter space giving at least one displaced vertex. Red (orange) region is valid for a luminosity of 300 fb^{-1} (3000 fb^{-1}). Blue area is excluded, while dashed line indicates the region that can be probed by future LFV experiments.

Preliminary results are shown in Figure 2. We show the area of parameter space leading to at least one event with a displaced vertex. Apart from the heavy neutrino lifetime, this mainly depends on the Higgs branching ratio not being too small. The blue area is excluded by direct search experiments. The dashed line indicates the area that could be probed by future $\mu - e$ conversion experiments. The red area can be probed by a luminosity of 300 fb^{-1}, while the orange area can be probed by 3000 fb^{-1}. Results are consistent with those of [14], which follows a similar analysis.

Note we are not analyzing any particular final state, so we expect the region of interest to be substantially reduced in a realistic scenario. A full study including possible final states is currently underway [15].

4. Conclusion

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 other experiments, we find a small region where such decays could leave a signature. For this, we need a high luminosity LHC, with up to 3000 fb^{-1}. The region of interest consists of heavy neutrinos with masses between 2−10 GeV, and active-heavy mixing of order $10^{-5} - 10^{-7}$.

Note these results are preliminary, with the next stage of the study involving more detailed considerations of the displaced vertex signature.

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