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A model of neutrino and Higgs physics at the electroweak scale

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Abstract

We present and explore the Higgs physics of a model that in addition to the Standard Model fields includes a lepton number violating singlet scalar field. Based on the fact that the only experimental data we have so far for physics beyond the Standard Model is that of neutrino physics, we impose a constraint for any addition not to introduce new higher scales. As such, we introduce right-handed neutrinos with an electroweak scale mass. We study the Higgs decay $H \to \nu\nu$ and show that it leads to different signatures compared to those in the Standard Model, making it possible to detect them and to probe the nature of their couplings.

1. Introduction

Neutrino physics has received a tremendous amount of experimental input in the last decade [1–7]. Neutrino oscillations are now completely determined and thus neutrinos are massive. On the theoretical side, the origin of neutrino masses and their observed patterns (for the neutrino mass squared differences) as well as the mixing angles still represent a mystery [8]. There are some ideas that have been widely used in order to explore the situation, like the Zee model [9] or the seesaw mechanism [10,11] in its several incarnations [12], but we are far from a profound understanding. Most of the actual realizations of these mechanisms postpone much of the desired knowledge to very high, experimentally unaccessible, energy scales. Concretely, since the introduction of right-handed (RH) neutrinos seem to be the obvious addition needed in order to write a Dirac mass for the neutrinos, and the seesaw can be used to explain the smallness of the neutrino mass scale, most models assume their existence with a mass scale typically of size $\sim 10^{13-16}$ GeV [11,12].

In this Letter we adhere to the idea that our current (experimental) knowledge of particle physics should be explored by a "truly minimal" extension of the Standard Model (SM). In this tenor we consider the possibility of having only one scale associated with all the high energy physics (HEP) phenomena. Since the SM is consistent with all data so far (modulo neutrino masses), we propose a minimal extension of the SM where new phenomena associated to neutrino physics can also be explained by physics at the electroweak (EW) scale which we take to be in the range from 10 GeV to 1 TeV (similar approaches can be found in [13–16]). Thus, we assume

- SM particle content and gauge interactions.
- Existence of three RH neutrinos with a mass scale of EW size.
- Global $U(1)_L$ spontaneously (and/or explicitly) broken at the EW scale by a single complex scalar field.
- All mass scales come from spontaneous symmetry breaking (SSB). This leads to a Higgs sector that includes a Higgs $SU(2)_L$ doublet field Φ with hypercharge 1 (i.e., the usual SM Higgs doublet) and an SM singlet complex scalar field η with lepton number -2.

This approach will have an effect on the type of signals usually expected from the Higgs sector of the SM, where the hierarchy (naturalness) problem resides. By enlarging the SM

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to explain the neutrino experimental results, we can get a richer spectrum of signals for Higgs physics and it is expected that once the LHC starts, it will allow us to test some of the theoretical frameworks created thus far. In any case, in order to fully probe whether the Higgs bosons have "Dirac" and/or "Majorana" couplings, we might have to wait until we reach a "precision Higgs era" at a linear collider [17].

2. The model

Taking into account the previous assumptions it is straightforward to write the Lagrangian. The relevant terms for Higgs and neutrino physics are

$$\mathcal{L}_{\nu H} = \mathcal{L}_{\nu y} - V, \tag{1}$$

with

$$\mathcal{L}_{\nu y} = -y_{\alpha i}\bar{L}_\alpha N_{Ri}\Phi - \frac{1}{2}Z_{ij}\eta\bar{N}^c_{Ri}N_{Rj} + \text{h.c.}, \tag{2}$$

where N_R represents the RH neutrinos, $\psi^c = C\gamma^0\psi^*$ and $\psi^c_R \equiv (\psi_R)^c = P_L\psi^c$ has left-handed chirality. The potential is given by

$$V = \mu_D^2\Phi^\dagger\Phi + \frac{\lambda}{2}(\Phi^\dagger\Phi)^2 + \mu_S^2\eta^*\eta + \lambda'(\eta^*\eta)^2 + \kappa(\eta\Phi^\dagger\Phi + \text{h.c.}) + \lambda_m(\Phi^\dagger\Phi)(\eta^*\eta). \tag{3}$$

Note that the fifth term in the potential breaks explicitly the U(1) associated to lepton number. This is going to be relevant when we consider the Majoron later in the Letter.

Assuming that the scalar fields acquire vacuum expectation values (vevs) in such a way that Φ and η are responsible for EW and global $U(1)_L$ symmetry breaking respectively, and using the notation

$$\Phi = \begin{pmatrix} 0 \\ \frac{\phi^0+v}{\sqrt{2}} \end{pmatrix} \quad \text{and} \quad \eta = \frac{\rho + u + i\sigma}{\sqrt{2}}, \tag{4}$$

where $v/\sqrt{2}$ and $u/\sqrt{2}$ are the vevs of Φ and η, respectively, we obtain the following minimization conditions:

$$\mu_D^2 = -\frac{1}{2}(\lambda v^2 + \lambda_m u^2 - 2\sqrt{2}\kappa u), \tag{5}$$

$$\mu_S^2 = -\frac{1}{2u}(2\lambda' u^3 + \lambda_m u v^2 + \sqrt{2}\kappa v^2). \tag{6}$$

We can also obtain the mass matrix for the scalar fields and it is given by

$$M_S^2 = \begin{pmatrix} \lambda v^2 & vu(\lambda_m - \sqrt{2}r) \\ vu(\lambda_m - \sqrt{2}r) & 2\lambda' u^2 + \frac{1}{\sqrt{2}}rv^2 \end{pmatrix}, \tag{7}$$

where $r \equiv -\kappa/u$. The mass for the σ (Majoron) field is

$$M_\sigma^2 = \frac{rv^2}{\sqrt{2}}. \tag{8}$$

Note that, as expected, M_σ^2 is proportional to the parameter κ associated to the explicit breaking of the $U(1)_L$ symmetry.

We are working under the assumption that the explicit breaking is very small, i.e., $\kappa \ll$ EW scale. This is why we are minimizing the potential with respect to η thus assuming it does break the symmetry spontaneously. Furthermore we expect the SSB generated by the vev of $\langle\eta\rangle = u$ to be of EW scale size and so we work under the assumption $r \equiv -\kappa/u \ll 1$. For example, taking $-\kappa \sim$ keV one obtains $r \sim 10^{-7-9}$ which then leads to a Majoron mass of hundreds of keV.

From Eq. (7) we see that it is useful to define the mass eigenstates

$$\mathcal{H} = \begin{pmatrix} \phi^0 \\ \rho \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix}\begin{pmatrix} h \\ H \end{pmatrix}. \tag{9}$$

Using these definitions to rewrite Eq. (2) we obtain

$$\begin{aligned}\mathcal{L}_{\nu y} &\supset -y_{\alpha i}\bar{\nu}_{L\alpha}N_{Ri}\frac{\phi^0}{\sqrt{2}} - \frac{1}{2}Z_{ij}\frac{(\rho + i\sigma)}{\sqrt{2}}\bar{N}^c_{Ri}N_{Rj} + \text{h.c.} \\ &= \left(-\frac{y_{\alpha i}}{\sqrt{2}}\bar{\nu}_{L\alpha}N_{Ri}(c_\alpha h - s_\alpha H) + \text{h.c.}\right) \\ &\quad - \left(\frac{i}{2\sqrt{2}}Z_{ij}\bar{N}^c_{Ri}N_{Rj}\sigma + \text{h.c.}\right) \\ &\quad - \left(\frac{1}{2\sqrt{2}}Z_{ij}\bar{N}^c_{Ri}N_{Rj}(s_\alpha h + c_\alpha H) + \text{h.c.}\right).\end{aligned} \tag{10}$$

We now make some comments regarding neutrino mass scales. Since we are interested in RH neutrinos at the EW scale, we take their masses to be in that scale, i.e., anywhere from a few to hundreds of GeV. The Dirac part on the other hand will be constrained from the seesaw. Writing the neutrino mass matrix as

$$m_\nu = \begin{pmatrix} 0 & m_D \\ m_D & M_M \end{pmatrix}, \tag{11}$$

where $(m_D)_{\alpha i} = y_{\alpha i}v/\sqrt{2}$. As an example let us consider the third family of SM fields and one RH neutrino, thus Eq. (11) becomes a 2×2 matrix. Assuming $m_D \ll M_M$ we obtain the eigenvalues $m_1 = -m_D^2/M_M$ and $m_2 = M_M$ and by requiring $m_1 \sim$ O (eV) and $m_2 \sim$ (10–100) GeV and using $v = 246$ GeV we obtain an upper bound estimate for the coupling $y_{\tau i} \leqslant 10^{-6}$.

The mass eigenstates are denoted by ν_1 and ν_2 and are such that

$$\begin{aligned}\nu_\tau &= \cos\theta\nu_{L1} + \sin\theta\nu_{R2}, \\ N &= -\sin\theta\nu_{L1} + \cos\theta\nu_{R2},\end{aligned} \tag{12}$$

where $\theta = \sqrt{m_D/m_2} \approx 10^{-(5-6)}$.

The relevant terms in the Lagrangian become

$$\begin{aligned}\mathcal{L} \supset &\left[h\bar{\nu}^c_{L1}\nu_{L1}\left(-\frac{Z}{2\sqrt{2}}s_\theta^2 s_\alpha\right) + h\bar{\nu}^c_{R2}\nu_{R2}\left(-\frac{Z}{2\sqrt{2}}c_\theta^2 s_\alpha\right) + \text{h.c.}\right] \\ &+ h\bar{\nu}_{L1}\nu_{R2}\left(\frac{y_\nu}{\sqrt{2}}(s_\theta^2 - c_\theta^2)c_\alpha\right) \\ &+ h\bar{\nu}_{R2}\nu_{L1}\left(\frac{y_\nu}{\sqrt{2}}(s_\theta^2 - c_\theta^2)c_\alpha\right),\end{aligned} \tag{13}$$

where $y_\nu^* = y_\nu$ and $Z \equiv Z_{11}$.

As discussed in the introduction we are interested in exploring the Higgs decays to neutrinos and their signatures in this model. The possible decay modes involving the Majoron and its relation to dark matter will be considered elsewhere. Then, using Eq. (13) we compute the following decay widths[1]:

$$\Gamma(h \to \bar{\nu}_1 \nu_1) = \frac{m_h}{64\pi} |Z|^2 s_\theta^4 s_\alpha^2, \tag{14}$$

$$\Gamma(h \to \bar{\nu}_2 \nu_2) = \frac{m_h}{64\pi} |Z|^2 c_\theta^4 s_\alpha^2 \left(1 - \frac{4m_2^2}{m_h^2}\right)^{3/2}, \tag{15}$$

$$\Gamma(h \to \bar{\nu}_1 \nu_2) = \frac{m_h}{16\pi} y_\nu^2 \left(s_\theta^2 - c_\theta^2\right)^2 c_\alpha^2 \left(1 - \frac{m_2^2}{m_h^2}\right)^2. \tag{16}$$

3. Numerical results

We have computed the branching ratios for the Higgs decays and the results are presented in Fig. 1. In each plot we have included the results for three values of $\cos\alpha$ (0.1, 0.5 and 0.9). The three graphs correspond to the values of $m_2 = 10$, 60 and 100 GeV, respectively. Only the dominant contributions are shown for clarity, i.e., $h \to \nu_2\bar{\nu}_2$, ZZ, WW, $b\bar{b}$ and $\tau\bar{\tau}$. It is interesting to note that for the whole range where it is possible, the decay $h \to \nu_2\bar{\nu}_2$ dominates in all three cases for small $\cos\alpha$ and it is still relevant for large $\cos\alpha$. This is a clear distinctive signature of our model.

In order to study the specific signatures that would be observed in this scenario, we consider the ν_2 decays. In Table 1 we present the possible signatures of these decays.

Since we are interested in a Higgs mass in the natural window of 100–200 GeV, and in neutrino masses such that they can appear in Higgs decays, we will consider neutrino masses of order 10–100 GeV, therefore we need to consider the 2- and 3-body decays $\nu_2 \to V + l$ and $\nu_2 \to \nu_1 + V^*(\to f\bar{f}')$, where $V^* = W^*, Z^*$.

One can also evaluate the branching ratios for the neutrino radiative decay, but since this is a loop-process, it is quite suppressed unless the mass differences among the right and left-handed neutrinos are very small. We have not included such process in this work.

Consider the process in Fig. 2. Its decay width is given by

$$\Gamma = \frac{m_2^5}{384\pi^3 M_v^4}\left[\left(B^2 + C^2\right)\left(a_f^2 + b_f^2\right)\right], \tag{17}$$

where

$$(V = W) \to \begin{cases} a_f = -b_f \equiv a = \frac{g}{2\sqrt{2}}, \\ B = -C = a s_\theta, \end{cases}$$

$$(V = Z) \to \begin{cases} a_f = \frac{g}{2c_w}\left(T_f^3 - 2Q_f s_w^2\right), \\ b_f = -\frac{g}{2c_w} T_f^3, \\ B = a_\nu c_\theta s_\theta, \\ C = b_\nu c_\theta s_\theta. \end{cases}$$

For the 2-body decays the result is

$$\Gamma = \frac{(B^2 + C^2)(m_2^2 - M_v^2)^2 \left(1 + 2\frac{M_v^2}{m_2^2}\right)}{8\pi M_v^2 m_2^2}. \tag{18}$$

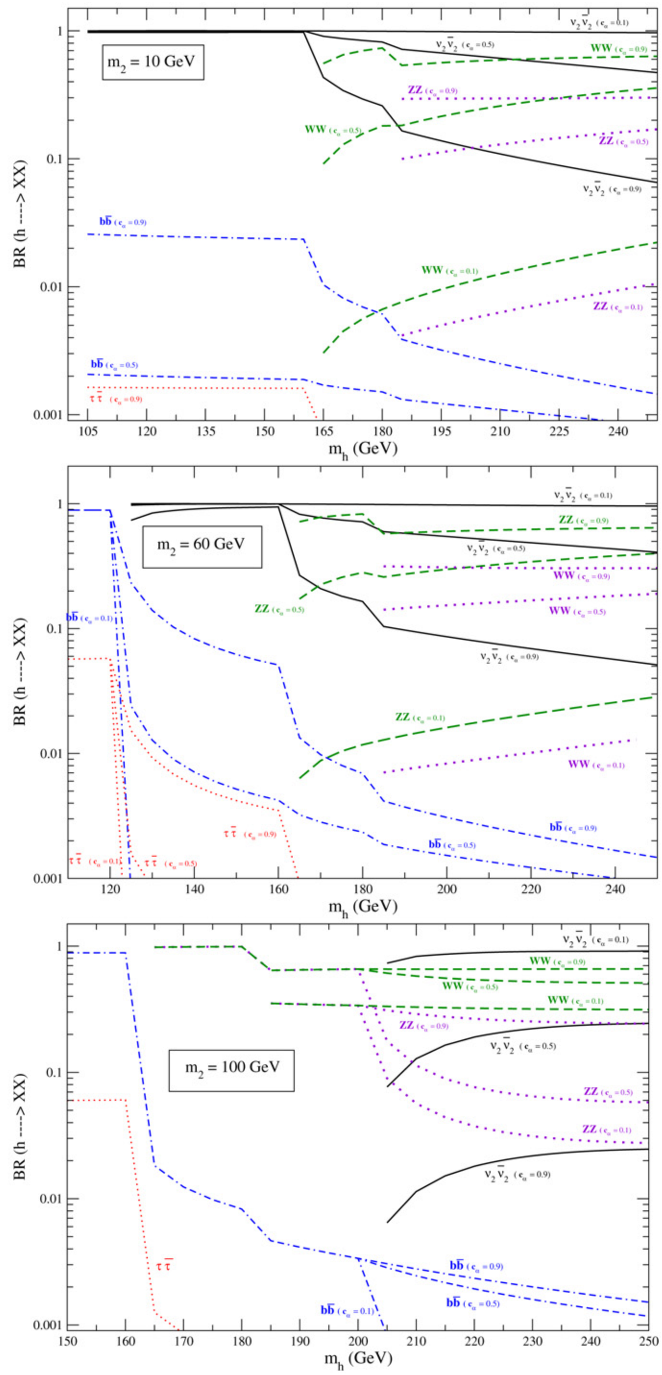

Fig. 1. Dominant branching ratios for Higgs decays. Three cases are presented for $m_2 = 10$, 60 and 100 GeV, respectively. Each plot includes results for the three values of $\cos\theta = 0.1$, 0.5 and 0.9 as discussed in the text.

Table 1
Signatures for the Higgs decays considered in the text

Higgs decay	$\nu_2 \to \nu_1 Z^*$	$\nu_2 \to l W^*$	$\nu_2 \to \nu_1 \gamma$
$h \to \nu_1\nu_2$	$l^+l^- + \text{inv.}$ $q\bar{q} + \text{inv.}$	$l + l' + \text{inv.}$ $l + q\bar{q}' + \text{inv.}$	$\gamma + \text{inv.}$
$h \to \nu_2\nu_2$	$l^+l^- + l^+l^- + \text{inv.}$ $l^+l^- + q\bar{q} + \text{inv.}$ $q\bar{q} + q\bar{q} + \text{inv.}$	$l + l' + l'' + l''' + \text{inv.}$ $l + l' + l'' + q\bar{q} + \text{inv.}$ $l + l' + q\bar{q} + q\bar{q} + \text{inv.}$	$\gamma + \gamma + \text{inv.}$
$h \to \nu_1\nu_1$	–	–	–

[1] All SM decay widths will include an extra factor of c_α^2.

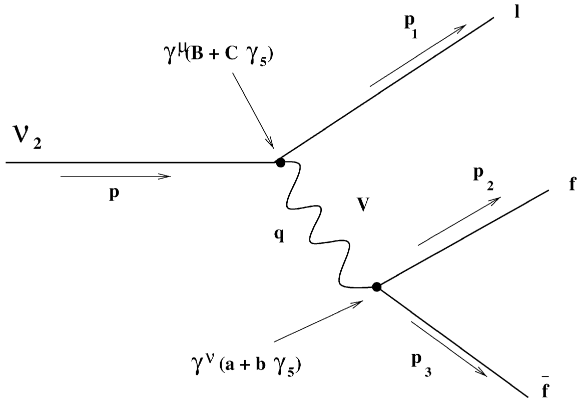

Fig. 2. Three body decay for ν_2.

Table 2
Branching ratios for the ν_2 two and three body decays discussed in the text

m_2 (GeV)	$Z\nu$	Wl	νl^+l^-	$\nu\nu\nu$	$\nu q_u\bar{q}_u$	$\nu q_d\bar{q}_d$	$l^\pm l^\pm \nu$	$l^\pm q\bar{q}'$
10	–	–	0.013	0.025	0.029	0.055	0.293	0.586
60	–	–	0.013	0.025	0.029	0.055	0.293	0.586
100	0.117	0.883	0.006	0.005	0.126	0.024	0.294	0.589

We have evaluated the branching ratios for these processes and they are presented in Table 2. We show the results for $m_2 =$ 100 GeV as the results are similar in all the m_2 range considered in this Letter. We find that the dominant contributions are the ones associated to the W^* decay process.

4. Discussion and conclusions

A longstanding question in neutrino physics has been to determine whether neutrino masses are of Dirac or Majorana type, which in turn motivates the terminology used in calling the neutrinos either Dirac or Majorana. As the Higgs mechanism employed in this Letter is at the root of the origin of both types of masses, we find it reasonable to ask the same question for the Higgs couplings, namely, we would like to determine whether the Higgs couplings are dominated by its Dirac or Majorana components.

In fact, the interaction eigenstates that appear in our model, Φ^0 and η^0, do have well-defined couplings to neutrinos: of Dirac type the former and Majorana type the latter. Although one may think that such a question is academic, we argue that it is not the case, and that it will be possible to study the experimental signatures that would distinguish among both types of couplings at coming colliders.

At the base of our discussion is the fact that the Dirac couplings $\phi^0\bar{\nu}_l\nu_R$, involve both types of chiralities (L and R), whereas the Majorana one $\eta^0\nu_R^c\nu_R$, involves only one chirality. Therefore, in a Higgs decay of Dirac type, one would have a fermion of a given chirality and an anti-fermion with the opposite chirality, while in the Majorana case, the Higgs decay would involve a fermion pair of like chiralities. In our model, as the decays $h \to \nu_1\nu_1$ would escape detection, while the decay $h \to \nu_1\nu_2$ will only have one detectable neutrino, which does not allow the possibility to correlate chiralities, we are left only with the decay: $h \to \nu_2\nu_2$. Let us follow the decay chain produced after the neutrino decays into a lepton and a pair of jets, namely $\nu_2 \to l + qq'$. It is then possible to have a pair of same-sign charged leptons, plus jets, which should help in order to discriminate against backgrounds. Furthermore, the charged leptons will inherit the chiralities of the neutrinos, and its measurement will allow to test the Higgs couplings. A detailed simulation study is needed, but this is beyond the scope of the present Letter.

We close this discussion with a few comments on the possibility to measure the Dirac or Majorana coupling of the Higgs bosons in models with a richer Higgs spectrum. For instance we could have models with Higgs triplets that will include double-charged Higgs states δ^{++}, which then couple to a lepton pair, therefore violating lepton number. As such state would decay into e^+e^+ or $\mu^+\mu^+$, it would then be possible to measure the chiralities of those light leptons appearing in the final state, and therefore to test the Dirac or Majorana nature of their couplings.

It is quite interesting that the Higgs sector presented in this Letter can lead to substantial modification of the signatures of the Higgs bosons. Although these signatures seem quite different from those expected in the SM, they represent the kind of variations that one would have when new physics beyond the SM is included, which in our case is well motivated by the plethora of recent neutrino physics experiments. As the LHC is expected to start operation very soon, it is very important to have an open mind regarding possible variations of the signals expected from the SM Higgs.

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