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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

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

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:

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

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

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

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

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