Electroweak scale neutrinos and decaying Majorons

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Abstract. We study the Higgs phenomenology of a model of electroweak scale neutrinos that incorporates the presence of a lepton number violating singlet scalar. In order to verify its viability, we perform an analysis of the pseudoscalar-Majoron field. In particular we study the Majoron decay \( J \rightarrow \nu \nu \) and use the bounds on the Majoron mass and width obtained in a modified Majoron Decaying Dark Matter scenario.

We would like to be able to explore neutrino masses at Colliders. One way this could be achieved is if right-handed neutrinos exist that have a mass in the electroweak scale range. Then it is possible to generate light masses with the use of the seesaw mechanism [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11]. In this presentation we review the results in [12] where a model has been presented that incorporates a minimum set of additions to the Standard Model (SM), namely the addition of three right-handed neutrinos and a lepton number violating singlet scalar. The model contains a pseudoscalar-Majoron field that can be a candidate for decaying dark matter. An analysis regarding this possibility is presented in order to verify the viability of the model.

1. The Model

The model adds to the SM particle content the following: three right-handed neutrinos \((N_{Ri}, i=1,2,3)\) with a mass of electroweak (EW) scale size, and a SM singlet complex scalar field \((\eta)\) that breaks global \(U(1)_L\) symmetry. The field \(\eta\) has lepton number \(-2\). The relevant terms in the Lagrangian are given by

\[
\mathcal{L}_{\nu H} = \mathcal{L}_{\nu y} - V ,
\]

\[
\mathcal{L}_{\nu y} = -y_{\nu i} T_{L} \Phi N_{Ri} - \frac{1}{2} Z_{ij} \eta N_{Ri} \eta N_{Rj} + h.c. ,
\]

\[
V = \mu_{H}^2 \bar{\Phi} \Phi + \frac{\lambda}{2} (\Phi \dagger \Phi)^2 + \mu_{2}^2 \eta \eta + \lambda(\eta^* \eta)^2 + \kappa (\eta \Phi \dagger \Phi + \eta^* \Phi \dagger \Phi) + \lambda_m (\Phi \dagger \Phi)(\eta^* \eta) ,
\]

where \(\tilde{\Phi} = i \sigma^2 \Phi^*, (\Psi_R)^c = P_L \Psi^c, \Psi^c = C \gamma^0 \Psi^*,\) and where

\[
\Phi = \begin{pmatrix} 0 \\ \phi^+ + \phi^- \end{pmatrix}, \quad \eta = \frac{\rho + u + iJ}{\sqrt{2}},
\]
where $v/\sqrt{2}$ and $u/\sqrt{2}$ are the vacuum expectation values (vevs) of $\Phi$ and $\eta$ respectively ($v(u)$ denoting vev of $\Phi(\eta)$).

And we define the mass eigenstates:

\[
\begin{pmatrix}
\phi^0 \\
\rho
\end{pmatrix} =
\begin{pmatrix}
\cos \alpha & -\sin \alpha \\
\sin \alpha & \cos \alpha
\end{pmatrix}
\begin{pmatrix}
h \\
H
\end{pmatrix}
\] (5)

\[
\begin{pmatrix}
L_i \\
N_i
\end{pmatrix} =
\begin{pmatrix}
\cos \theta & \sin \theta \\
-\sin \theta & \cos \theta
\end{pmatrix}
\begin{pmatrix}
\nu_{Li} \\
\nu_{Ri}
\end{pmatrix}
\] (6)

The model assumes that there is only one high energy scale, the EW scale and both $u$ and $v$ are of this order. We assume too that the explicit $U(1)_L$ breaking is very small so $|\kappa| \ll EW$ scale.

The model has eight free parameters: $y, Z, u, v, \kappa, \lambda, \lambda', \lambda_m$. ($\mu_D$ and $\mu_S$ are fixed by minimization conditions). First we simplify the neutrino terms and neglect inter-family interactions. We make the assumption that the coupling constants of each family are of the same order, that is: $Z_{ij} = y_{ij} = 0$ for $i \neq j$ and $Z = Z_{11} \approx Z_{22} \approx Z_{33}$, $y = y_{11} \approx y_{22} \approx y_{33}$. We take $m_L \sim O(\text{eV})$ and we obtain $\theta \approx 10^{-6}$ which gives us EW scale masses for right-handed neutrinos [5].

2. Analysis

Now we assume that dark matter is composed of Majorons $J$. With the modified $\Lambda CDM$ which has the decaying dark matter (DDM) idea [13], we fix the Majoron mass and its decay rate [14]:

\[\Gamma_\sigma < 1.3 \times 10^{-19} s^{-1}\] (7)

\[0.12 \text{keV} < m_\sigma < 0.17 \text{keV}\] (8)

From the model we obtain the decay rate and mass of the Majoron

\[\Gamma_J = \frac{Z^2 \sin^4 \theta}{4\pi M_J} \left(1 - \frac{4m_\nu^2}{M_J^2}\right)^{1/2} m_\nu,\] (9)

\[M_J^2 = -\frac{\kappa v^2}{\sqrt{2}u},\] (10)

Saturating the bounds on the width and mass of the Majoron requires $Z$ to be of $O(10^{-2})$. Together with assuming $u \sim O(\text{EW})$, which gives us nicely the masses of right-handed neutrinos in the EW scale, and $|\kappa|/(GeV) \sim 10^{-9} \ll 1$. Now we explore the phenomenology of the Higgs in this model. All SM processes get suppressed by a factor $\cos(\alpha)^2$ [5], thus we look for situations where $\cos(\alpha) \sim 1$. The parameters used in this case are $\lambda = 1.5$, $\lambda' = 0.09$, and $\lambda_m = 0.002$ which represent a typical set under these requirements.

The Higgs mass is then given as a function of $u$, and for the required values of $\alpha$ we obtain plausible values (see figure 1).
The Higgs branching ratios are shown in figure 2 for a characteristic set of parameters (see [12]). We generally observe that the invisible decay to Majorons dominates over most of the parameter space.

**Figure 1.** Scalar spectrum for the case described in the text. The horizontal line in the lower left corresponds to the 114 GeV lower bound from LEP2 [15].

**Figure 2.** Branching ratios for the decay $h \to XX$ for the set of parameters shown in Figure 1.
3. Conclusions
We have shown that the model meets all the desired requirements for it to be plausible and well motivated. The parameter space was restricted by imposing Higgs mass constraints as well as information from the cosmological microwave observations of WMAP. Furthermore we have shown that its phenomenology is dominated by the invisible Higgs decay to Majorons and that it is within the reach of present colliders.

Acknowledgements
This work was supported by CONACYT and SNI.

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