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A three-loop radiative neutrino mass model with dark matter

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ABSTRACT

We present a model that generates small neutrino masses at three-loop level due to the existence of Majorana fermionic dark matter, which is stabilized by a Z_2 symmetry. The model predicts that the lightest neutrino is massless. We show a prototypical parameter choice allowed by relevant experimental data, which favors the case of normal neutrino mass spectrum and the dark matter with $m \sim 50$–135 GeV and a sizable Yukawa coupling. It means that new particles can be searched for in future e^+e^- collisions.

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1. Introduction

The discovery of very small, but non-zero neutrino masses and the existence of dark matter (DM) in the Universe may provide important information to guide us in the search for new physics beyond the standard model (SM). In recent years the idea to incorporate both phenomena in a unified framework has received much attention. And among the simplest realizations is the inert doublet model [1–3], which generates one-loop neutrino masses with the DM being either an extra scalar-doublet or a Majorana fermion whose stability is protected by an exact Z_2 symmetry.

Due to the smallness of the neutrino mass scale, a number of models were proposed to generate neutrino masses via higher loop processes, especially via 3-loop ones with the loop suppression $(g^2/16\pi^2)^3 \sim 10^{-13}$ (g being an electroweak-sized coupling) to naturally explain the large hierarchy $m_\nu/v \sim 10^{-13}$ (v being electroweak scale). An earlier model [4] advocated by Krauss, Nasri and Trodden (KNT) extends the SM to include two charged scalar singlets and a right-handed neutrino. Meanwhile, the model has an additional discrete symmetry, which makes neutrino masses be first obtained at the 3-loop level via the new particles with the masses of order of TeV. Therefore, this model is phenomenologically interesting, and is well studied in the subsequent literature [5–11]. Moreover, the generation of 3-loop neutrino masses also appears in the cocktail model [12], which adds to the SM two scalar singlets (singly and doubly charged) and a scalar doublet.

In this paper, we present a new model by substituting a scalar triplet with hypercharge $Y = 0$ for a charged scalar singlet in the KNT model. Similarly, due to the additional Z_2 symmetry and the field content of the model, Majorana neutrino masses are also first generated at the 3-loop level, and the lightest Z_2-odd right-handed Majorana fermion could be a DM candidate.

The paper is organized as follows. In Section 2 we describe the model, obtain the neutrino mass matrix, and calculate the DM annihilation processes. Various constraints on the model are analyzed numerically in Section 3. Then conclusions appear in Section 4.

2. A model for neutrino masses and dark matter

2.1. The model

In addition to SM fields, our model includes several right-handed Majorana fermions N_{iR}, a charged $SU(2)_L$ singlet scalar S^- and a triplet scalar Δ with hypercharge $Y = 0$:

$$\Delta = \begin{pmatrix} \frac{1}{\sqrt{2}}\Delta^0 & \Delta^+ \\ \Delta^- & -\frac{1}{\sqrt{2}}\Delta^0 \end{pmatrix}. \quad (1)$$

The number of N_{iR} will be explained below. Moreover, we introduce a Z_2 symmetry under which the new fields are all odd, whereas the SM fields are even. Given the symmetry and particle content of the model, the extra Lagrangian will be

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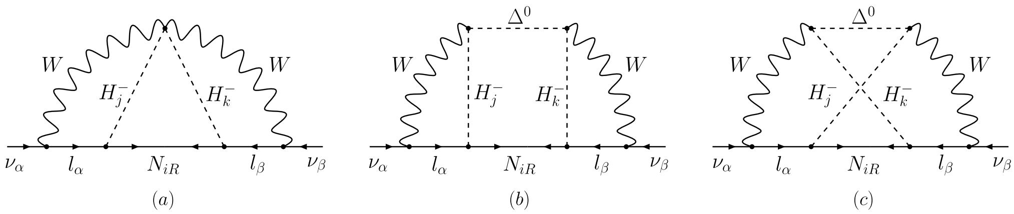

Fig. 1. Three-loop diagrams for radiative neutrino masses.

$$\Delta\mathcal{L} = \frac{1}{2}\mathrm{Tr}\big[(D_\mu\Delta)^2\big] + \big(D_\mu S^-\big)^\dagger D^\mu S^- + i\overline{N_{iR}}\partial\!\!\!/ N_{iR} - \left(\frac{1}{2}m_{N_i}N_{iR}^T C N_{iR} + g_{i\alpha}N_{iR}^T C l_{\alpha R}S^+ + \mathrm{h.c.}\right) - V\big(\Delta, S^-, \Phi\big), \tag{2}$$

where C is the matrix of the charge conjugation and the covariant derivatives take the forms

$$D_\mu\Delta = \partial_\mu\Delta - i\frac{g}{2}\big[W_\mu^a\tau^a, \Delta\big], \tag{3}$$

$$D_\mu S^- = \partial_\mu S^- + ig' B_\mu S^-. \tag{4}$$

Here τ^a $(a = 1, 2, 3)$ is the Pauli matrix. The scalar potential of the new fields and the SM-like doublet Φ looks like

$$\begin{aligned} V\big(\Delta, S^-, \Phi\big) &= -\mu_H^2\Phi^\dagger\Phi + \mu_S^2 S^+S^- + \mu_\Delta^2\,\mathrm{Tr}\big[\Delta^2\big] + \lambda_1\big(\Phi^\dagger\Phi\big)^2 \\ &\quad + \lambda_2\big(S^+S^-\big)^2 + \lambda_3\big(\mathrm{Tr}\big[\Delta^2\big]\big)^2 + \lambda_4\big(\Phi^\dagger\Phi\big)\big(S^+S^-\big) \\ &\quad + \lambda_5\,\mathrm{Tr}\big[\Delta^2\big]\big(S^+S^-\big) + \lambda_6\Phi^\dagger\Phi\,\mathrm{Tr}\big[\Delta^2\big] \\ &\quad + \big(\lambda_7\Phi^\dagger\Delta\tilde{\Phi}S^+ + \mathrm{h.c.}\big), \end{aligned} \tag{5}$$

where $\tilde{\Phi} = i\tau^2\Phi^\dagger$.

As Z_2 is exact, Δ has no vacuum expectation value. After electroweak symmetry breaking, for $\lambda_7 \neq 0$ the charged Z_2-odd scalars Δ^- and S^- will mix:

$$m^2\big(\Delta^-, S^-\big) = \begin{pmatrix} 2\mu_\Delta^2 + \lambda_6 v^2 & \frac{\lambda_7}{2}v^2 \\ \frac{\lambda_7}{2}v^2 & \mu_S^2 + \frac{\lambda_4}{2}v^2 \end{pmatrix}, \tag{6}$$

where $v \approx 246$ GeV is the vacuum expectation value of Φ. They will give rise to two charged mass eigenstates

$$\begin{pmatrix} H_1^- \\ H_2^- \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix}\begin{pmatrix} \Delta^- \\ S^- \end{pmatrix}. \tag{7}$$

Now the extra scalars are H_1^-, H_2^- and Δ^0 with masses

$$m_{H_1} \leq m_{\Delta^0} = \sqrt{\cos^2\beta\, m_{H_1}^2 + \sin^2\beta\, m_{H_2}^2} \leq m_{H_2}. \tag{8}$$

2.2. Neutrino masses

Explicitly, the Lagrangian in Eq. (2) breaks lepton number, and can generate a Majorana mass for the left-handed neutrinos. However, the Z_2 symmetry strictly forbids the generation of neutrino masses at either 1- or 2-loop order, and, therefore, the leading contributions to neutrino masses appear at 3-loop level shown in Fig. 1.

If the model has a single N_R, the neutrino mass matrix will predict two vanishing mass eigenvalues like the case in Ref. [4] and contradict the neutrino oscillation data [6]. In order to solve the problem, one can add small perturbations to the original mass matrix, add more scalars or right-handed Majorana fermions, and so on. In this paper, we employ two right-handed fermions N_{iR} $(i = 1, 2)$ with $m_{N_1} < m_{N_2}$, which means that the Yukawa couplings $g_{i\alpha}$ can be complex and bring about three physical CP violation phases. However, in the following discussion, we leave aside the problem of CP violation for simplicity, so $g_{i\alpha}$ takes real number.

For the case of $m_{H_2} > m_{\Delta^0} \gg m_{H_1}, m_{N_i}, m_W$, it is appropriate to neglect the complicated contributions of Figs. 1(b) and 1(c). Following the method in [7], we obtain the neutrino mass matrix elements arising from the remaining Fig. 1(a)

$$(M_\nu)_{\alpha\beta} = \sum_{i=1,2} g_{i\alpha}g_{i\beta}m_\alpha m_\beta I_i, \tag{9}$$

where I_i is the three-loop integral

$$\begin{aligned} I_i = \frac{g^4\sin^2(2\beta)m_{N_i}}{6(16\pi^2)^3 m_W^4}\int_0^\infty \frac{r\,\mathrm{d}r}{r + m_{N_i}^2} &\times \Big\{12\big[F_2\big(r, m_{H_1}^2, m_{H_2}^2\big) - F_1\big(r, m_{H_1}^2, m_{H_2}^2\big)\big]^2 \\ &+ \big[G_2\big(r, m_{H_1}^2, m_{H_2}^2\big) - G_1\big(r, m_{H_1}^2, m_{H_2}^2\big)\big]^2 \\ &- F_2\big(r, m_{H_1}^2, m_{H_2}^2\big)\big[5F_2\big(r, m_{H_1}^2, m_{H_2}^2\big) - 6F_1\big(r, m_{H_1}^2, m_{H_2}^2\big) \\ &- G_2\big(r, m_{H_1}^2, m_{H_2}^2\big) + G_1\big(r, m_{H_1}^2, m_{H_2}^2\big)\big]\Big\}. \end{aligned} \tag{10}$$

Here four integral functions have been introduced:

$$\begin{aligned} F_1\big(r, m_{H_1}^2, m_{H_2}^2\big) &= \int_0^1 \mathrm{d}x\ln\frac{x(1-x)r + xm_{H_1}^2}{m_W^2} - (m_{H_1} \to m_{H_2}), \\ F_2\big(r, m_{H_1}^2, m_{H_2}^2\big) &= \int_0^1 \mathrm{d}x\ln\frac{(1-x)(xr + m_W^2) + xm_{H_1}^2}{m_W^2} - (m_{H_1} \to m_{H_2}), \\ G_1\big(r, m_{H_1}^2, m_{H_2}^2\big) &= \frac{r + m_{H_1}^2}{m_W^2}\int_0^1 \mathrm{d}x\,x\ln\frac{x(1-x)r + xm_{H_1}^2}{m_W^2} - (m_{H_1} \to m_{H_2}), \\ G_2\big(r, m_{H_1}^2, m_{H_2}^2\big) &= \frac{r - m_W^2 + m_{H_1}^2}{m_W^2}\int_0^1 \mathrm{d}x\,x\ln\frac{(1-x)(xr + m_W^2) + xm_{H_1}^2}{m_W^2} - (m_{H_1} \to m_{H_2}). \end{aligned} \tag{11}$$

The elements of the neutrino Majorana mass matrix M_ν can be related to the mass eigenvalues

$$M_\nu = UD_\nu U^T \quad \text{with } D_\nu = \mathrm{Diag}(m_1, m_2, m_3), \tag{12}$$

where U is the Pontecorvo–Maki–Nakagawa–Sakata (PMNS) leptonic mixing matrix [13] parameterized by

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