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A class of three-loop models with neutrino mass and dark matter

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ABSTRACT

We study a class of three-loop models for neutrino mass in which dark matter plays a key role in enabling the mass diagram. The simplest models in this class have Majorana dark matter and include the proposal of Krauss, Nasri and Trodden; we identify the remaining related models, including the viable colored variants. The next-to-simplest models use either more multiplets and/or a slight modification of the loop-diagram, and predict inert N-tuplet scalar dark matter.

1. Introduction

In recent years the idea that the origin of neutrino mass and the existence of dark matter (DM) may be related has received much attention. The neutrino mass and DM problems are perhaps our most compelling pieces of evidence for physics beyond the Standard Model (SM), and it is therefore reasonable to consider unified solutions to these problems.

A simple model predicting a connection between these issues was proposed by Ma [1]. This model achieves one-loop neutrino mass with the DM being either an inert scalar-doublet or a Majorana fermion. The model is well studied in the literature [2]. In particular, it was shown that the model belongs to a larger class of models, all of which achieve neutrino mass by a loop-diagram with the same topology, while also giving DM candidates [3]. One of the related models uses a Majorana triplet-fermion [4], while the others employ Dirac fermions [3]. The latter models must have scalar DM, with singlet, doublet and triplet cases possible [3].

An earlier model proposing a common solution to the DM and neutrino mass problems was advocated by Krauss, Nasri and Trodden (KNT) [5] (for detailed studies see Refs. [6–9]). This model achieves neutrino mass at the three-loop level and predicts Majorana singlet-fermion DM. In analogy with the one-loop models, it is natural to ask if the KNT model could also belong to a larger class of three-loop models with DM candidates. In this paper we perform a systematic study for variants of the KNT model. We first consider generalizations that employ Majorana fermions, identifying the viable models and, in particular, presenting the viable colored-variants. We then show that Dirac fermions can also be used to generate a radiative mass-diagram with the same topology. The latter models require inert scalar DM, different from the KNT (and related) models.

The plan of this paper is as follows. In Section 2 we briefly summarize the KNT model and discuss related models in the literature. A systematic classification of the minimal variants of the KNT model is performed in Section 3. Section 4 discovers variants with Dirac mediators that achieve neutrino mass by a loop diagram with the same topology. Modifying the loop diagram slightly, we show that additional variants are possible in Section 5. We conclude in Section 6. Before proceeding we note that a number of other works have studied models with connections between neutrino mass and DM; for a selection see Refs. [10–13]. Also, there may be other interesting three-loop topologies beyond those considered here, in line with the general treatment of effective operators with $\Delta L = 2$ [14]. For a general discussion of neutrino mass see Ref. [15].

2. The KNT model

KNT proposed a simple model with a connection between the existence of massive neutrinos and DM [5]. The SM is extended to include the exotic scalars $S \sim (1,1,2)$ and $\phi \sim (1,1,2)$, and the fermions $\mathcal{F}_{iR} \sim (1,1,0)$, where i labels fermion generations. A discrete (Z_2) symmetry is also imposed, such that ϕ and $\mathcal{F}$ are Z_2-odd, $\{\phi, \mathcal{F}\} \to \{-\phi, -\mathcal{F}\}$, while S and the SM fields are Z_2-even. The Lagrangian then includes the terms

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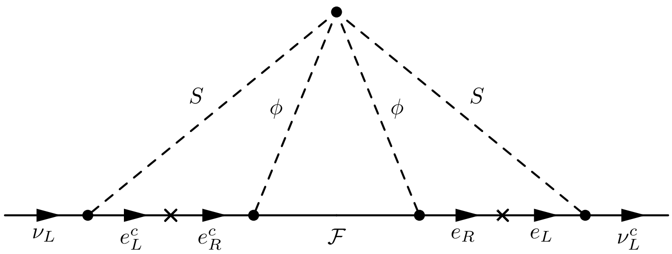

Fig. 1. A three-loop diagram for radiative neutrino mass, where S and ϕ are beyond-SM scalars and $\mathcal{F}$ is a beyond-SM fermion.

$$\mathcal{L} \supset \mathcal{L}_{\text{SM}} + \left\{ f_{\alpha\beta} \overline{L_\alpha^c} L_\beta S^+ + g_{i\alpha} \overline{\mathcal{F}_i^c} \phi^+ e_{\alpha R} + \text{H.c.} \right\} - \frac{1}{2} \overline{\mathcal{F}_i^c} \mathcal{M}_{ij} \mathcal{F}_j - V(H, S, \phi), \tag{1}$$

where the mass matrix is taken diagonal, without loss of generality; $\mathcal{M} = \text{diag}(M_1, M_2, M_3)$. We order the masses as $M_1 < M_2 < M_3$, and use Greek letters to label SM flavors, $\alpha, \beta \in \{e, \mu, \tau\}$.

The scalar potential contains the terms

$$V(H, S, \phi) \supset \frac{\lambda_S}{4} \left(S^*\right)^2 \phi^2 + \text{H.c.}, \tag{2}$$

and the combination of Eqs. (1) and (2) explicitly breaks lepton number symmetry. This results in Majorana neutrino masses at the three-loop level, as shown in Fig. 1. Calculating the loop diagram gives the mass matrix as

$$(\mathcal{M}_\nu)_{\alpha\beta} = \frac{\lambda_S}{(4\pi^2)^3} \frac{m_\sigma m_\rho}{M_\phi} f_{\alpha\sigma} f_{\beta\rho} g_{\sigma i}^* g_{\rho i}^* \times F\left(\frac{M_i^2}{M_\phi^2}, \frac{M_S^2}{M_\phi^2} \right), \tag{3}$$

where $F(x, y)$ is a function that encodes the loop integrals, whose explicit form is given in Ref. [8].

The Z_2 symmetry plays two roles in the model. Firstly, it prevents the Yukawa term $\bar{L}\tilde{H}F_L^c$, which would otherwise produce tree-level neutrino masses via a (Type-I) seesaw mechanism. Secondly, the lightest Z_2-odd field is absolutely stable. Provided this is the lightest neutrino $\mathcal{F}_1$, the model contains a viable DM candidate [8] and gives a unified solution to the DM and neutrino-mass problems. The DM and Z_2-odd fields must be relatively light, with $M_1 < 225$ GeV and $M_\phi < 245$ GeV, while the combination of neutrino experiments and the DM relic-density prefers $M_S > M_\phi$. The model can be probed at collider experiments [9] and can modify the branching fraction for Higgs decays to 2γ and $Z\gamma$. The signal from flavor-changing decays such as $\mu \to e + \gamma$ may be observable in future experiments [8]. In this model the DM is sequestered from SM neutrinos and propagates in the inner loop of the mass diagram.

2.1. Triplet variant of the KNT model

The seesaw mechanism can be generalized to a triplet (or Type-III) variant that employs $SU(2)_L$ triplet fermions with vanishing hypercharge [16]. Similarly, it was recently shown that the KNT model can be generalized to a triplet variant [17]. One retains the scalar S but ϕ and $\mathcal{F}$ are now $SU(2)_L$ triplets, $\phi \sim (1, 3, 2)$ and $\mathcal{F} \sim (1, 3, 0)$. The Z_2 symmetry is retained, $\{\phi, \mathcal{F}\} \to \{-\phi, -\mathcal{F}\}$, with all other fields being Z_2-even. The Lagrangian again contains the terms in Eq. (1), with $\mathcal{F}_i$ as triplet fermions, and the potential contains terms similar to (2),

$$V(H, S, \phi) \supset \frac{\lambda_S}{4} \left(S^*\right)^2 \phi_{ab} \phi_{cd} \epsilon^{ac} \epsilon^{bd} + \frac{\lambda_S^*}{4} (S)^2 \left(\phi^*\right)^{ab} \left(\phi^*\right)^{cd} \epsilon_{ac} \epsilon_{bd}. \tag{4}$$

We write the triplet as a symmetric matrix,

$$\phi_{11} = \phi^{++}, \qquad \phi_{12} = \phi_{21} = \frac{1}{\sqrt{2}} \phi^+, \qquad \phi_{22} = \phi^0. \tag{5}$$

The combination of these terms again breaks lepton-number symmetry, giving radiative neutrino mass at the three-loop level. The Feynman diagram has the same form as Fig. 1, except now there are three distinct diagrams with different sets of triplet fields propagating in the inner loop [17].

In this model the Z_2 symmetry again prevents tree-level neutrino mass via a (Type-III) seesaw mechanism, and ensures a stable DM candidate. The DM is the lightest neutral triplet-fermion, $\mathcal{F}_1^0$, as ϕ^0 DM is excluded by direct-detection experiments. The DM should have a mass $M_{\text{DM}} \sim 2$ TeV, making both ϕ and $\mathcal{F}$ too heavy to be probed at the LHC. However, the scalar S may be sufficiently light to appear at colliders, with $M_S = \mathcal{O}(10^2)$ GeV found to be consistent with the demands of neutrino experiments and the DM relic-density [17]. Flavor changing effects can also appear in next-generation experiments. The model is therefore a testable variant of the KNT proposal.

2.2. Larger representations

The seesaw mechanism can also be generalized to a quintuplet variant [18–20]. Similarly the KNT model can be generalized to a variant employing the fermion $\mathcal{F} \sim (1, 5, 0)$, and the scalar $\phi \sim (1, 5, 2)$ [21]. In these cases the most-general Lagrangian contains the terms in Eq. (1), as well as terms similar to Eq. (4) which break lepton number symmetry and give three-loop neutrino mass via the diagram in Fig. 1 (there are now five diagrams with different sets of fields in the inner loop).

There is one important difference, however, for the model with larger multiplets. Now the Z_2 symmetry need not be imposed to preclude tree-level neutrino masses. Thus, the quintuplet variant is a viable radiative model of neutrino-mass, irrespective of DM considerations. Also, the most-general Lagrangian contains a single Z_2 symmetry-breaking term, so the model contains a softly broken accidental Z_2 symmetry. In the limit that a single parameter vanishes, $\lambda \to 0$, this symmetry becomes exact and the lightest Z_2-odd field is a stable DM candidate. Even for $\lambda \neq 0$, one can always choose $\lambda \ll 1$ to obtain long-lived DM without imposing the Z_2 symmetry [21]. This feature differs from the KNT model and the triplet variant. In the analysis that follows we restrict our attention to multiplets no larger than the adjoint, though related generalizations may be possible if this restriction is relaxed.

3. A class of three-loop models with dark matter

We seek generalizations of the KNT model that retain the following features: (*i*) The models contain Z_2-odd fields, including the DM, that propagate in the inner loop of the neutrino mass diagram. (*ii*) The internal fermions in the outer loops are SM fields. (*iii*) The DM is non-colored. The generalized Feynman diagram for neutrino mass in this class of models appears in Fig. 2, where $\mathcal{F}$ and ϕ are Z_2-odd and S is Z_2-even. Here $f_{L,R}$ denotes an SM fermion. There are six cases to consider:

- $f_{L,R}^c = u_{L,R}^c$ being an up-type quark. The outer-left vertex then results from the operator $\overline{Q^c} L S_1$, where Q is the SM quark doublet. In this case the diagram cannot be closed without breaking gauge invariance so neutrino mass via Fig. 2 is not possible.[1]

[1] This is contrary to the claims of Ref. [22] which uses $f_{L,R} = u_{L,R}$. The resulting model possesses a lepton number symmetry under which only L, e_R and S trans-