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New class of two-loop neutrino mass models with distinguishable phenomenology

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ABSTRACT

We discuss a new class of neutrino mass models generated in two loops, and explore specifically three new physics scenarios: (A) doubly charged scalar, (B) dark matter, and (C) leptoquark and diquark, which are verifiable at the 14 TeV LHC Run-II. We point out how the different Higgs insertions will distinguish our two-loop topology with others if the new particles in the loop are in the simplest representations of the SM gauge group.

1. Introduction

The minimal particle content of the standard model (SM) of quarks and leptons does not allow a nonzero neutrino mass at the level of a renormalizable Lagrangian. However, it has long been known [1] that an effective dimension-five operator exists for obtaining a nonzero Majorana neutrino mass, i.e.

$$\mathcal{L}_5 = -\frac{\kappa_{ij}}{\Lambda}(\nu_i\phi^0 - l_i\phi^+)(\nu_j\phi^0 - l_j\phi^+) + H.c., \quad (1)$$

where $(\nu_i, l_i), i = 1, 2, 3$ are the three left-handed lepton doublets of the SM and (ϕ^+, ϕ^0) is the one Higgs scalar doublet. As ϕ^0 acquires a nonzero vacuum expectation value $\langle\phi^0\rangle = v/\sqrt{2} = 174$ GeV, the neutrino mass matrix is given by

$$\mathcal{M}^{\nu}_{ij} = \frac{\kappa_{ij} v^2}{\Lambda}. \quad (2)$$

Tree-level [2–6] and one-loop realizations [7–12] of this operator have been discussed extensively in the literature, as well as some two-loop [12–22] and three-loop [23–25] examples. The two-loop case is particularly inviting because the smallness of the neutrino mass, i.e. of order 0.1 eV, agrees well with a mass scale of $\mathcal{O}(1)$ TeV for the heavy particles in the loops, without unduly small and large Yukawa and scalar couplings, as would be the case with one-loop and three-loop realizations.

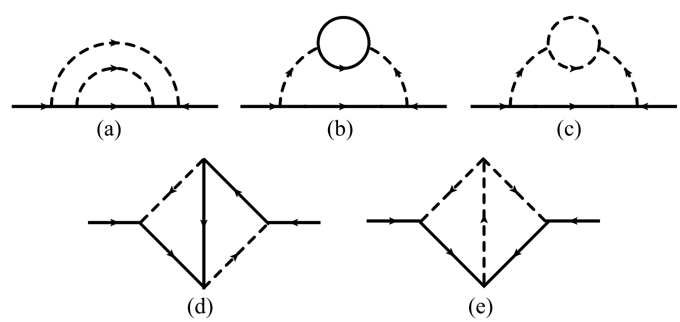

Fig. 1. Two-loop skeleton diagrams for neutrino mass before the Higgs insertions.

Generic structures of the two-loop diagrams involving fermions and scalars are shown in Fig. 1, where the external Higgs lines are yet to be inserted [21]. To minimize the particle content inside the loops, we assume that the topology of each diagram exhibits a left-right or central symmetry. Under such a condition, Figs. 1(a)–(d) may very well have a singlet Majorana fermion that could itself generate a neutrino mass at tree level. The only exception is

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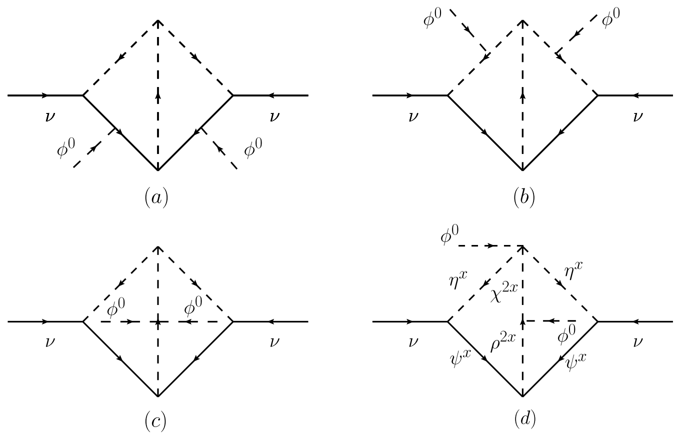

Fig. 2. Two-loop diagrams for neutrino mass with Higgs insertions onto fermion lines (a), scalar lines (b), converging on the center scalar line connecting to neutrinos (c) and one Higgs line at the top and one Higgs line at the center (d).

Table 1
Loop particles under $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \otimes Z_2$ of the three models, where Z_2 applies only to (B) and ψ denotes l_R, E_R, d_R in (A), (B) and (C), respectively.

Model	η	χ	ρ	ψ
(A)	$(1, 2, -\frac{1}{2})$	$(1, 2, \frac{3}{2})$	$(1, 1, 2)$	$(1, 1, -1)$
(B)	$(1, 2, -\frac{1}{2}, -)$	$(1, 2, \frac{3}{2}, +)$	$(1, 1, 2, +)$	$(1, 1, -1, -)$
(C)	$(3, 2, \frac{1}{6})$	$(\bar{6}, 2, \frac{1}{6})$	$(\bar{6}, 1, \frac{2}{3})$	$(3, 1, -\frac{1}{3})$

Fig. 1(e) which is thus a truly two-loop effect. In the following, we will focus on this case and examine the different Higgs insertions.

One obvious way of inserting two external Higgs lines is onto the two fermion lines connecting to the external neutrino lines as shown in Fig. 2(a). Another is onto the corresponding scalar lines as shown in Fig. 2(b). A third way also exists with the two Higgs lines converging onto the center scalar line as shown in Fig. 2(c). Specific realizations of all these have been studied previously. In this paper we consider for the first time specific examples of the fourth option [20] with one Higgs line at the top and one Higgs line at the center as shown in Fig. 2(d).

We show that there are some discriminative collider signatures among these four topologies under the simplest representations of the new particles in the loop due to the different Higgs insertions. Such collider signatures may then be used to distinguish our two-loop topology (Fig. 2(d)) with others (Figs. 2(a, b, c)).

The electric charge assignments of fermion ψ^x, scalar doublets (η^{x+1}, η^x), (χ^{2x+1}, χ^{2x}), and singlet ρ^{2x} are as shown in Fig. 2(d). There are at least three natural realizations of this diagram: (A) $x = -1$ with $\psi_R = l_R$; (B) $x = -1$ with $\psi_R = E_R$ which is a new heavy fermion with a Dirac partner E_L such that both E and η are odd under a dark Z_2 symmetry; (C) $x = -1/3$ with $\psi_R = d_R$. The quantum numbers of the particles in the loop under $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ are collected in Table 1. It is obvious that the doubly charged scalar is predicted in (A) and (B), while a dark matter candidate is embedded in (B). The leptoquark and diquark scalars are related to the neutrino mass generation in (C). It is easy to generate the neutrino mass around 0.1 eV when the new particles are $\mathcal{O}(1)$ TeV, without unduly small or large Yukawa and scalar couplings in these models. The effective Lagrangian related to our study is

$$\mathcal{L}_\nu \supset f_{ij}\bar{\nu}_i\eta^{-x}\psi^x_{Rj} + h.c. \\ + h_{ij}\overline{(\psi^x_{Ri})^c}\psi^x_{Rj}\rho^{-2x} + \frac{\lambda v}{\sqrt{2}}\eta^x\eta^x\chi^{-2x}, \quad (3)$$

where $i, j = 1, 2, 3$ is the family index. Details of the neutrino mass generation are shown in the Appendix.

Next we perform a collider simulation to explore the potential of the Large Hadron Collider (LHC) on discovering the three models. We focus on a 14 TeV LHC with an integrated luminosity ($\mathcal{L}$) of 100 fb^{-1} and also the high-luminosity (HL) phase of 3000 fb^{-1} in this study, and for simplicity, we assume the neutrino mass matrix is diagonal for the collider phenomenology analysis.

2. Collider phenomenology of model (A)

2.1. Discovery potential

The best way to probe our model is the pair production of the doubly charged scalar (χ^{++})

$$pp \to \chi^{++}\chi^{--},\ \chi^{++} \to \ell^+\ell^+,\ \chi^{--} \to \ell^-\ell^-,$$

where $\ell^\pm$ represents the electron ($e^\pm$) and muon ($\mu^\pm$). The event topology is characterized by four isolated charged leptons. The dominant backgrounds are $\gamma\gamma$, $Z\gamma$, ZZ, four leptons (4ℓ), and four charged leptons plus one jet ($4\ell 1j$). The null result in the search of doubly charged scalars via the pair production at the 8 TeV LHC imposes a bound, $m_{\chi^{++}} > 400$ GeV, assuming χ^{++} decays entirely into electron or muon pairs [26–28].

We generate both the signal and the background processes at the parton level using MadEvent [29] and impose basic cuts as follows: $p_T^{\ell^\pm,j} > 5$ GeV with $\left|\eta^{\ell^\pm,j}\right| < 5$, where p_T and η denote the transverse momentum and rapidity, respectively. We require the angular distance $\Delta R_{mn} \equiv \sqrt{(\eta^m - \eta^n)^2 + (\phi^m - \phi^n)^2}$ between the objects m and n to be greater than 0.4 to obtain isolated objects. At the analysis level, all the signal and background events are required to pass a set of selection cuts [26,30]:

$$p_T^{\ell_1} > 20\text{ GeV}, \quad p_T^{\ell_2} > 15\text{ GeV}, \quad p_T^{\ell_{3,4}} > 10\text{ GeV}, \\ |\eta^\ell| \le 2.5, \qquad \not{E}_T < 40\text{ GeV}, \quad (4)$$

where ℓ_i with $i = 1, 2, 3, 4$ denotes the lepton ordered in accord with their p_T^ℓ's. We demand only four leptons in the central region of the detector and veto extra jets if $p_T^j > 10$ GeV or $|\eta^j| > 3.5$. In addition, we require the invariant mass of lepton pair to be away from m_Z, with $|m(\ell\ell') - m_Z| > 10$ GeV, to suppress the dominant background containing Z-boson resonances. In order to suppress the $4\ell 1j$ background, we require $m(\ell^\pm\ell^\mp) > 50$ GeV. We end up with 26.05 background events in total at the LHC with $\mathcal{L} = 100$ fb^{-1}, i.e. $\gamma\gamma$ (1.18), $Z\gamma$ (2.67), ZZ (3.62), 4ℓ (12.03) and $4\ell 1j$ (6.56). The number inside the parenthesis denotes the number of events of each individual background.

We obtain a 5 standard deviations (σ) statistical significance using

$$S = \sqrt{-2\left[(n_b + n_s)\log\frac{n_b}{n_s + n_b} + n_s\right]} = 5, \quad (5)$$

where n_b and n_s represent the numbers of the signal and background events, respectively. Fig. 3 displays the discovery potential of χ^{++} with BR$(\chi^{++} \to \ell^+\ell^+) = 1$ at the LHC. The χ^{++} with $m_{\chi^{++}} < 566$ GeV could be discovered with $\mathcal{L} = 100$ fb^{-1} (red line). The HL–LHC extends the coverage to $m_{\chi^{++}} < 806$ GeV (blue line).

2.2. Model discrimination

The doubly charged scalar appears in all the two-loop models depicted in Fig. 2 and yields exactly the same collider signature.