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A New Aspect of Two-Loop Neutrino Mass Generation

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Abstract

We propose a class of models which the neutrino masses are generated at two-loop level. In this mechanism, only the right-handed leptonic Yukawa interaction is involved without imposing any new symmetry but the Standard Model gauge symmetry. Neutrino mass spectrum is predicted to be normal hierarchy. The novel feature of the direct relation between the neutrino masses and the Yukawa couplings enable us pin down the neutrino parameters such as the absolute scale, the Dirac CP phase via the leptonic processes. The dynamics of lepton number breaking and some collider phenomenology of this model are studied.

Keywords: Neutrino, Mass Hierarchy, Higgs Diphoton Decay, Higher Charged Scalar

Two biggest discoveries, the Standard Model (SM) like Higgs particle was found in both ALTAS [1] and CMS [2] collaborations and the large θ_{13} mixing angle observed in Daya Bay experiment [3]. Both results influence the particle physics significantly. The Higgs doublet (H) not only breaks the electroweak gauge symmetries $SU(2)_L \times U(1)_Y$ to $U(1)_Q$ but also gives masses to the SM fermions except the neutrinos, $\nu_L' s$. The new particle may provide us the clue about these issues. So far this new boson decays to the SM gauge bosons pairs are consistent with the SM Higgs except the branching ratio of the diphoton channel excess about 1.5 - 2 times larger than the SM prediction. Large θ_{13} leads the measurements of neutrino mass hierarchy and CP violation in next generation neutrino experiments. We propose a class of models in which the Majorana neutrino masses are generated at two-loop level and enable us to address the above issues in both LHC and neutrino experiments.

It is known that lepton number is an accidental global symmetry of the SM, so if the neutrinos are Majorana fermions lepton number is broken either explicitly or spontaneously. It is appealing that the seesaw mechanism could generate tiny neutrino masses at tree level, there are three variants: the extension to fermion sector, the so-called Type-I [4] and Type-III seesaw mechanism [5], and the Type-II seesaw for the extension to scalar sector [6]. In these cases the tiny neutrino masses are suppressed by the large lepton number breaking scale. Interestingly, the idea that quantum correction induces the neutrino masses was first proposed by A. Zee in 1980 [7] to explain the neutrino mass is much smaller than the other known fermion masses. Theories of this type usually only the ν_L are employed with some extension of the scalar sector. In this article, we adopt the existence of charged scalars motivated by the neutrino physics, causing the enhancement of $H \to \gamma\gamma$. We go to the higher representations of scalar bosons to avoid the tree level neutrino mass generation, and at the same time, the higher charged scalar bosons appear. It turns out that a class of models which generate neutrino masses at two-loop level exist naturally.

If color interactions are not involved among the scalar sector, three other renormalizable Yukawa interactions can exist as long as other representations of scalar sector are present. Namely,

$$f_{ab}\bar{L}^c_a L_b s\ , \quad g_{ab}\bar{L}^c_a L_b T\ , \quad \text{and} \quad y_{ab}\bar{l}^c_{R_a} l_{R_b}\Phi. \qquad (1)$$

Here L (l_R) is the left-handed (right-handed) lepton, a, b denotes e, μ, τ, and c is the charged conjugation. T is $SU(2)_L$ triplet with hypercharge $Y = 2$ while s and Φ

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are $SU(2)_L$ singlet scalar fields with hypercharge $Y = 2$ and $Y = 4$ respectively[1] in which T will generate neutrino mass at tree level after developing vacuum expectation value (VEV), this is referred to the Type-II seesaw mechanism [6] and s^+ is used in Zee model [7]. An extension of Zee model with additional $\Phi^{\pm\pm}$ field was studied in Ref. [8]. We assume only the third Yukawa interaction in Eq. (1) appears at tree level and the SM gauge symmetry and renormalizability are the guidelines used in our model. We simply introduce a scalar field ξ, $\xi = \mathbf{5}, \mathbf{7}, \mathbf{9}, \mathbf{11}$...(odd representations higher than $\mathbf{3}$), under $SU(2)_L$ gauge symmetry with $Y = 2$ to get rid of the first and second Yukawa interactions in Eq. (1) without imposing any *ad hoc* condition. The general potential reads

$$\begin{aligned} V(H,\xi,\Phi^{\pm\pm}) &= -\mu_H^2|H|^2 + \lambda_H|H|^4 - \mu_\xi^2|\xi|^2 \\ &+ \lambda_\xi|\xi|^4 + \mu_\Phi^2|\Phi|^2 + \lambda_\Phi|\Phi|^4 \\ &+ \lambda_{H\xi}|H|^2|\xi|^2 + \lambda_{H\Phi}|H|^2|\Phi|^2 \\ &+ \lambda_{\xi\Phi}|\xi|^2|\Phi|^2 + [\mu\xi\xi\Phi + \text{h.c.}], \end{aligned} \quad (2)$$

here we used the short-handed notation for $|\xi|^4$ and $|H|^2|\xi|^2$ which contain three and two invariant terms with couplings denoted $\lambda_\xi^{(1),(2),(3)}$ and $\lambda_{H\xi}^{(1),(2)}$ respectively. Also notice that all terms in the potential are self-hermitian except the last μ-term and the dynamics of lepton number breaking is associated with it. We will come to this in later discussion. Furthermore, for even representations, $\xi = \mathbf{2}, \mathbf{4}, \mathbf{6}$..., the product $\xi\xi$ can be expressed as $\sum_{\text{indices}} \xi_{ijk...}\xi_{i'j'k'...}$ with odd subscripts $i, j, k, ...$ We have

$$\begin{aligned} \xi\xi &= \epsilon_{ii'}\epsilon_{jj'}\epsilon_{kk'}...\xi_{ijk...}\xi_{i'j'k'...} \\ &= -\epsilon_{i'i}\epsilon_{j'j}\epsilon_{k'k}...\xi_{ijk...}\xi_{i'j'k'...} = 0, \end{aligned} \quad (3)$$

ϵ is an anti-symmetric matrix with $\epsilon_{12} = 1$, then the μ-term vanishes. This explains why we consider odd representations of ξ and the minimal choice is quintuplet. It is well-known that a Higgs sector containing triplet or higher representations must be constrained by ρ parameter, $\rho = 1$ at the tree level. For arbitrary representations, the tree level ρ parameter is given by [9]

$$\rho = \frac{\sum_i [I_i(I_i+1) - \frac{1}{4}Y_i^2]v_i^2}{\sum_i \frac{1}{2}Y_i^2 v_i^2}. \quad (4)$$

Current value given in PDG $\rho = 1.0004^{+0.0003}_{-0.0004}$ [10], in general, this will set the limit on the VEV $\langle\xi^0\rangle \leqslant \mathcal{O}(1)$ GeV. From now on we take $\xi = (\xi^{+++}, \xi^{++}, \xi^+, \xi^0, \xi^-)^T$, the quintuplet, in the rest discussions, however, one shall bear in mind that the results are held for higher representation ξ. After spontaneous symmetry breaking both ξ^0 and H^0 develop VEVs, $\langle\xi^0\rangle = \frac{v_\xi}{\sqrt{2}}$ and $\langle H^0\rangle = \frac{v}{\sqrt{2}}$, the leading contribution to neutrino masses is given at two-loop level shown in Fig. 1. It is clear that the μ-term mix $\xi^{\pm\pm}$ with $\Phi^{\pm\pm}$ which plays an important role in this mechanism and can be expressed in the basis (ξ^{++}, Φ^{++}) as

[1] We use the convention $Q = I_3 + Y/2$ in this paper.

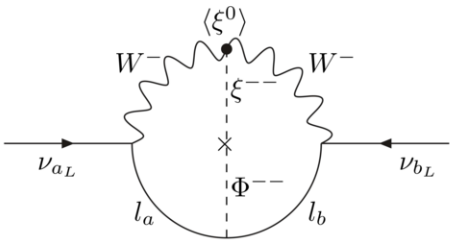

Figure 1: Two-loop diagram of neutrino mass generation.

$$\begin{pmatrix} -\frac{1}{4}(v^2\lambda_{H\xi}^{(2)} + v_\xi^2\lambda_\xi^{(2)}) & \sqrt{2}\mu v_\xi \\ \sqrt{2}\mu v_\xi & \mu_\Phi^2 + \frac{1}{2}\lambda_{\xi\Phi}v_\xi^2 + \frac{1}{2}\lambda_{H\Phi}v^2 \end{pmatrix}, \quad (5)$$

we can define the mixing angle $\tan\theta = -\frac{8\sqrt{2}\mu v_\xi}{8\mu_\Phi^2 + v^2(2\lambda_{H\xi}^{(2)} + 4\lambda_{H\Phi})}$ to rotate into the mass eigenbasis (P_1^{++}, P_2^{++}). In Ref. [11] where a discrete symmetry Z_2 is applied, here only the SM gauge symmetry is utilized and a class of models exist. The theory is renormalizable and the neutrino masses are calculable,

$$\begin{aligned} m_{\nu_{ab}} &= \frac{1}{\sqrt{2}} g^4 m_a m_b v_\xi y_{ab} \sin 2\theta \\ &\times [I(M_W^2, M_{P_1}^2) - I(M_W^2, M_{P_2}^2)] \end{aligned} \quad (6)$$

The integral I is given by

$$\begin{aligned} I(M_W^2, M_{P_i}^2) &= \int \frac{d^4q}{(2\pi)^4} \int \frac{d^4k}{(2\pi)^4} \frac{1}{k^2} \frac{1}{k^2 - M_W^2} \\ &\times \frac{1}{q^2 - M_W^2} \frac{1}{q^2} \frac{1}{(k-q)^2 - M_{P_i}^2} \\ &\simeq \frac{1}{(4\pi)^4} \frac{1}{M_{P_i}^2} \log^2(\frac{M_W^2}{M_{P_i}^2}), \end{aligned} \quad (7)$$

we have ignored the charged lepton masses, $m_{a,b} = 0$, and used the limit $M_{P_i} > M_W$ here. Note that the neutrino mass is suppressed by two-loop factor, $SU(2)_L$ gauge coupling, charged lepton mass, mixing angle θ, and VEV of ξ without tuning Yukawa couplings y_{ab}. The neutrino mass matrix is of the form : *overall factor*$\times\frac{m_a m_b}{M_W^2} y_{ab}$, the inverted hierarchy spectrum is incompatible with oscillation data if one require the perturbative bound on y_{ab}. The model predicts neutrino mass