Low-Scale Majorana Neutrino Masses from Renormalizable Higgs Doublet Coupling

Weifeng Wang

Analytik Jena US LLC, Upland, CA 91786, USA

Email: wang_w01@yahoo.com

Abstract

Neutrino mass origins remain one of the central unsolved puzzles in particle physics. Leading mechanisms were established by the early 2000s, with limited essential breakthroughs observed in the past twenty years. These approaches often rely on the unobserved Higgs triplet field, non-renormalizable operators or the hypothetical coupling of the left-handed and right-handed neutrinos. In this work, we address these fundamental challenges by proposing a novel low-scale mechanism where neutrino masses are generated through a renormalizable, Higgs doublet-mediated interaction between the $SU(2)$ lepton doublet and the conjugated singlet, distinct from the conventional Higgs-Yukawa coupling formed between the lepton doublet and singlet. By presenting a fresh extension of the Standard Model (SM) where the $SU(2)$ representations are slightly misaligned with the neutrino chiral states, we were able to provide a theoretically coherent explanation for the Majorana neutrino mass generation without a priori assumption that neutrinos are their own antiparticles. Our model further eliminates the coupling of the left-handed and right-handed neutrinos after the spontaneous symmetry breaking, and meanwhile substantially reduces the fine-tuning of Yukawa couplings. We conclude by highlighting the key implications of our findings, including the minimal mixing between active and sterile neutrinos (consistent with current experiments) and the potential of the present SM extension in decoding the flavor mixing and CP violation phases.

Key words: Neutrino physics, Beyond the Standard Model, Neutrino mass, Majorana neutrino

1 Introduction

The discovery of neutrino oscillation has confirmed that neutrinos possess nonzero masses, in contradiction to the massless prediction from the Standard Model (SM) of particle physics [1–3]. Recent experiments with enhanced data accuracy further refined the mass squared differences Δm_{21}^2 and $|\Delta m_{32}^2|$, constraining the sum of neutrino masses to $\sum m_\nu < 0.07$ eV [4]. For decades, the origin of neutrino masses, orders of magnitude smaller than those of charged fermions, has remained a pressing question in neutrino physics [5].

Leading explanations on neutrino masses involve the Dirac or Majorana mass mechanisms, high-dimensional effective operators (e.g., the Weinberg operator), and the various realizations of seesaw mechanism [6–12]. The Dirac framework introduces the right-handed (RH) neutrinos (RHNs) that directly couple to the active left-handed (LH) neutrinos (LHNs), the only chiral neutrinos observed to date. However, this approach calls for the unnaturally small Yukawa couplings on the order of $10^{-12} - 10^{-13}$, posing a significant fine-tuning problem. On the other hand, the conventional Majorana mechanism, which posits that neutrinos are their own antiparticles, could be realized through a triplet Higgs field that is essential for preserving renormalizability. Yet this triplet is absent in SM and has not been observed experimentally. Alternative theories include generating Majorana neutrino masses through the Weinberg operator, a dimension-5 term which respects the $SU(2)_L \times U(1)_Y$ gauge invariance. Such high-dimensional operators, however, are intrinsically non-renormalizable and provide the effective descriptions requiring UV completion at energies far exceeding the electroweak symmetry breaking scale, thus adding significant theoretical complexity. Considered to be a compelling solution, the type I seesaw mechanism obtains the suppressed neutrino masses through the introduction of heavy RHNs, which likely points to physics beyond the SM, possibly at unification scales. Hence, current leading approaches face limitations, relying on the unobserved Higgs triplet, non-renormalizable operators, high-energy completion or the ad hoc LH and RH neutrino coupling. Besides, the continued absence of experimental RHN signals further motivates the search of alternative theoretical frameworks beyond the conventional paradigms.

It is the objective of the present work to develop a low-scale Majorana neutrino mass model in a renormalizable manner without resorting to the unobserved Higgs triplet field. To achieve this, we harness a Higgs doublet-mediated coupling that is gauge invariant and renormalizable exclusively for neutrinos. Within our framework, the small Majorana neutrino masses emerge naturally following a fresh extension of SM characterized by a slight misalignment of the $SU(2)$ representations and the neutrino chiral states. This misalignment further leads to the decoupling of the LH and RH mass terms after the spontaneous symmetry breaking (SSB), suggesting the active neutrino behaviors (such as oscillations) are unaffected by the RH sterile neutrinos. In the meantime, the present approach allows the Yukawa couplings to reach magnitudes comparable to those of charged leptons, thereby offering a promising resolution to the persistent fine-tuning problem.

2 The low-scale renormalizable Lagrangian

Let us consider the following Lagrangian of the Yukawa interaction of the leptons and the Higgs field

$$\mathcal{L}_Y = -\sqrt{2} \sum_{l'\, l} Y'_{l'l} \, \overline{\psi'^{d}_{l'}} \, \tilde{H} \, (\nu'^{s}_{l})^c + \text{h.c.} \,, \tag{1}$$

where $\overline{\psi'^{d}_{l'}}$ is the doublet of the non-Abelian gauge group $SU(2)$ with $l = e, \mu, \tau$, $\tilde{H} = i\sigma_2 H^*$ the conjugated Higgs doublet, $(\nu'^{s}_{l})^c = C\overline{(\nu'^{s}_{l})}^T$ the CP conjugated field of singlet ν'^{s}_{l}, and $Y'_{l'l}$ the dimensionless, complex Yukawa constant matrix. Unlike the conventional Higgs-mediated Dirac mass term, this equation substitutes the CP conjugate field $(\nu'^{s}_{l})^c$ into the singlet ν'^{s}_{l}. This fundamental distinction permits a natural generation of neutrino masses, as will be shown in the following sections. Note that the above dimension-4 Lagrangian is explicitly gauge invariant for neutrinos, preserving both the weak isospin ($SU(2)$) and hypercharge ($U(1)_Y$) and thus being renormalizable. This property is evident from the weak quantum number assignments in SM where the $SU(2)$ doublet component for a neutrino carry weak isospin $I_3 = +1/2$ and hypercharge $Y = -1$, while the singlet and its conjugate have $I_3 = 0$ and $Y = 0$. As such, Eq. (1) remains invariant under the $SU(2) \times U(1)_Y$ transformations. However, for charged leptons, whose singlets possess non-zero weak quantum numbers, this gauge invariance by nature won't be preserved.

After the SSB, we find from Eq. (1)

$$\mathcal{L}_Y = -v \sum_{l'\, l} Y_{l'l} \, \overline{\nu^{d}_{l'}} \, (\nu^{s}_{l})^c + \text{h.c.} \,, \tag{2}$$

where $v \approx 246$ GeV is the vacuum expectation value (VEV) of the Higgs boson. Here, we have converted the arbitrary basis to the flavor state $\nu^{d}_{l'}$ (the $SU(2)$ doublet component) and the conjugated singlet state $(\nu^{s}_{l})^c$, with $Y_{l'l}$ transformed from $Y'_{l'l}$ by a unitary matrix. It is noteworthy that up to this point, we have not assigned any chirality to the doublet component and singlet for neutrinos. However, if we follow SM by replacing $\nu^{d}_{l'}$ and ν^{s}_{l} with the LHN $\nu_{l'L}$ and the RHN ν_{lR} respectively, we will simply find $\mathcal{L}_Y$ in Eq. (2) is vanishing due to the mismatched chirality, i.e., $\overline{\nu_{l'L}}(\nu_{lR})^c = 0$.

3 Extension of the Standard Model

To obtain the non-zero neutrino mass from Eq. (2), we hereby propose a new minimal extension of SM in which the $SU(2)$ representations are marginally misaligned with the neutrino's chiral states, such that

$$\begin{pmatrix} \nu_{lL} \\ \nu_{lR} \end{pmatrix} = V_l^\dagger \begin{pmatrix} \nu_l^d \\ \nu_l^s \end{pmatrix}, \quad \begin{pmatrix} \nu_l^d \\ \nu_l^s \end{pmatrix} = V_l \begin{pmatrix} \nu_{lL} \\ \nu_{lR} \end{pmatrix}, \tag{3}$$

where V is a 2x2 unitary transform matrix given by

$$V_l = \begin{pmatrix} \cos\theta_l & \sin\theta_l \\ -\sin\theta_l & \cos\theta_l \end{pmatrix}, \tag{4}$$

with the mixing angle $\theta_l \in [0, \pi/2]$ quantifying the degree of the misalignment proposed. While a complete unitary transformation matrix should also contain the phase angles, neglecting these phases wouldn't affect the generality of our discussion. Therefore, each LHN in the present model resides in both the doublet component and singlet of $SU(2)$ with the dominant part assigned to the doublet component, whereas its RH counterpart primarily occupies the singlet with a minor presence in the doublet component.

From Eq. (3) and (4), we thus have

$$\begin{aligned} \overline{\nu_{l'}^d} &= \cos\theta_{l'}\, \overline{\nu_{l'L}} + \sin\theta_{l'}\, \overline{\nu_{l'R}} \\ (\nu_l^s)^c &= -\sin\theta_l\, \nu_{lL}^c + \cos\theta_l\, \nu_{lR}^c\,. \end{aligned} \tag{5}$$

Substituting (5) into (2) yields the following non-zero Lagrangian with decoupled LH and RH neutrinos

$$\mathcal{L}_Y = \mathcal{L}_{YL} + \mathcal{L}_{YR}\,, \tag{6}$$

where $\mathcal{L}_{YL}$ and $\mathcal{L}_{YR}$ denote the LHN and RHN mass terms respectively and can be derived below

$$\begin{aligned} \mathcal{L}_{YL} &= v \sum_{l'l} \cos\theta_{l'} \sin\theta_l\, Y_{l'l}\, \overline{\nu_{l'L}} \nu_{lL}^c + \text{h.c} \\ &\simeq v \sum_{l'l} \theta_l\, Y_{l'l}\, \overline{\nu_{l'L}}\, \nu_{lL}^c + \text{h.c.} \\ &= -\frac{1}{2} \overline{\nu_L} M_L \nu_L^c + \text{h.c.}\ . \end{aligned} \tag{7}$$

Here, we have used the approximations $\sin\theta_l \approx \theta_l$ and $\cos\theta_l \approx 1$ for the small misalignment of the $SU(2)$ representations and the neutrino chiral states, i.e., $\theta_l \approx 0$, and automatically expressed the mass term in the Majorana form using the LHN vector and its conjugate that are defined as

$$\nu_L = \begin{pmatrix} \nu_{eL} \\ \nu_{\mu L} \\ \nu_{\tau L} \end{pmatrix}, \quad \nu_L^c = \begin{pmatrix} \nu_{eL}^c \\ \nu_{\mu L}^c \\ \nu_{\tau L}^c \end{pmatrix}. \tag{8}$$

Factor 1/2 in Eq. (7) is included to avoid double counting the Majorana fermion fields. Note that the Majorana neutrino fields have entered the present mass framework without imposing the self-conjugacy condition a priori.

The neutrino mass matrix thus is found to be

$$(M_L)_{l'l} = -2vY_{l'l}\theta_l \,. \tag{9}$$

Since M_L is symmetric or Hermitian (if complex) for Majorana mass, a simple solution for the mixing angle would be $\theta = \theta_e = \theta_\mu = \theta_\tau$ (and thus $V = V_e = V_\mu = V_\tau$), assuming the Yukawa matrix maintains its symmetry for the Majorana mass structure. Hence, M_L is reduced to

$$(M_L)_{l'l} = -2\theta vY_{l'l} \,. \tag{10}$$

Similarly, a separate RH Majorana mass term reads

$$\mathcal{L}_{LR} = -\frac{1}{2}\overline{\nu_R}M_R\nu_R^c + \text{h.c.}\,, \tag{11}$$

with $(M_R)_{l'l} = 2\theta vY_{l'l}$ and

$$\nu_R = \begin{pmatrix} \nu_{eR} \\ \nu_{\mu R} \\ \nu_{\tau R} \end{pmatrix}, \quad \nu_R^c = \begin{pmatrix} \nu_{eR}^c \\ \nu_{\mu R}^c \\ \nu_{\tau R}^c \end{pmatrix}. \tag{12}$$

It was found that the off-diagonal terms in Eq. (6) are eliminated due to the chirality constraint that enforces $\overline{\nu_{l'L}}\nu_{lR}^c = 0$ and $\overline{\nu_{l'R}}\nu_{lL}^c = 0$, rendering the decoupling of ν_l and ν_R in the total Lagrangian after the SSB. That said, active neutrinos, in their pure LH chiral eigenstates, no longer participate in the interactions with RHNs, according to the present study.

4 Diagonalization of the mass matrices

In this section, we will derive the mass eigenstates with eigenvalues m_1, m_2, m_3 and determine the explicit form of the Majorana neutrino fields, through the diagonalization of the mass matrices. Focusing on the LHN fields only, we find

$$\mathcal{L}_{YL} = -\frac{1}{2}\overline{\nu^M} m_\nu \nu^M \,, \tag{13}$$

where m_ν is a 3x3 diagonal mass matrix with

$$m_i = -2\theta v y_i \,, \tag{14}$$

and ν^M is the Majorana field vector of our primary interest, and is given by

$$\nu^M = U^\dagger \nu_L + (U^\dagger \nu_L)^c \,, \tag{15}$$

with the unitary matrix U defined by equation

$$M_L = U m_\nu U^T \,. \tag{16}$$

Recall that factor vy_i in Eq. (14) is corresponding to a typical fermion Dirac mass in SM. This mass is now suppressed by a factor of 2θ, leading to a more natural origination of the tiny neutrino mass. In fact, if we take $\theta \simeq 10^{-7}$ which represents a very small mixing of the $SU(2)$ representations and the neutrino's chiral states, the Yukawa coupling is found to be on the same order for electron, i.e.,

$$y_\nu = \frac{m_h}{2\theta v} \approx 10^{-6} \,, \tag{17}$$

assuming a normal ordering of neutrino masses ($m_1 < m_2 < m_3$) with the heaviest neutrino $m_h = m_3 \approx 0.05$ eV [13]. Notably, the small mixing angle θ in the present model has unambiguous physics and symmetry protection. Setting it to zero will enhance symmetry through the removal of the misalignment of the $SU(2)$ representations and the neutrino's chiral states. Therefore, parameter θ is technically natural under 't Hooft's criterion [14].

Since in our picture LHNs are not completely tied to the doublet components, one cannot consider the unitary matrix U given in Eqs. (15) and (16) as identical to the well-known PMNS (Pontecorvo-Maki-Nakagawa-Sakata) matrix U_{PMNS}, which was traditionally used to relate the flavor states (the doublet components) to the mass eigenstates. Indeed, from Eq. (3) and (15), we find

$$\nu_L^M = U^\dagger \nu_L = U^\dagger \cos\theta \, \nu^d - U^\dagger \sin\theta \, \nu^s \,, \tag{18}$$

where the doublet component vector ν^d and the singlet vector ν^s take the forms

$$\nu^d = \begin{pmatrix} \nu_e^d \\ \nu_\mu^d \\ \nu_\tau^d \end{pmatrix} \,, \quad \nu^s = \begin{pmatrix} \nu_e^s \\ \nu_\mu^s \\ \nu_\tau^s \end{pmatrix} \,. \tag{19}$$

As shown, for $\theta \neq 0$, the mass eigenstates will involve both the doublet components (flavor states) and singlets. Only in the case of complete alignment of the $SU(2)$ representations and the neutrino's chiral states, can one have $\theta = 0$ and hence $\nu_L^M = U^\dagger \nu^d$, meaning $U = U_{\text{PMNS}}$.

5 Discussion and summary

The current mechanism successfully achieves the tiny neutrino masses through a renormalizable and Higgs doublet-mediated interaction at low scale, while permitting a more natural Yukawa coupling. The work simultaneously yields multiple significant physical implications.

First of all, the decoupling of the LH and RH mass terms after SSB and the proposed fresh SM extension, i.e, the slight misalignment of the $SU(2)$ representations and the neutrino's chiral states, rule out the large mixing of active and sterile neutrinos. This is in agreement with Daya Bay, NEOS and PROSPECT experimental searches conducted so far [15–17]. However, in high-sensitivity experiments, active neutrinos may exhibit observable sterile behaviors invoked by the singlet components embedded in them (rather than the coupling with RHNs).

Second, rigorously speaking, as a direct result of the misalignment of ν_L and the doublet component of $SU(2)$, active neutrinos no longer carry definite electroweak quantum numbers of weak isospin and hypercharge, posing a critical challenge to SM. Instead, it is the flavor states or the interaction eigenstates that form the doublet components and thus possesses definite quantum numbers. That's why we have used the general group notation $SU(2)$ instead of the chirality specific $SU(2)_L$ throughout this paper.

Third, while RHNs are decoupled from LHNs in the mass term after the spontaneous symmetry breaking, the RHN fields are indispensable in the present model to ensure the gauge invariance and renormalizability of the initial Lagrangian employed. The absence of ν_R means $\theta = 0$ and thus will result in the massless neutrinos (see the discussion following Eq. (2)).

Moreover, the present approach enables the Majorana fields to naturally enter the neutrino mass generation without a priori assumption that neutrinos are their own antiparticles. The $\Delta L = 2$ violation of lepton number offers a viable path to leptogenesis. Next-generation $(0\nu\beta\beta)$ experiments (LEGEND-200, nEXO, KamLAND2-Zen) [18–20] could deliver conclusive evidence for Majorana neutrinos.

One of the open questions from this study is that the mixing angle parameter θ, used to characterize the present SM extension, does not necessarily have to be diagonal in the family basis. Instead, it could be a complex matrix that may encode the flavor mixing with CP-violation phases. A thorough investigation into this situation would require additional symmetry considerations and is open to future explorations.

In summary, we begin with a Higgs doublet-mediated coupling which is distinct from the conventional Higgs mechanism by replacing the singlet with its CP conjugate. This low-scale and renormalizable approach, when incorporated with the misalignment of the $SU(2)$ representations and the neutrino chiral states, naturally generates the small Majorana neutrino masses with decoupled LH and RH neutrinos. The marginal mixing of the doublet component and singlet for a neutrino chiral state further offers a strong suppression on the fine tuning of Yukawa couplings. In the context of our theory, an active neutrino is composed of the dominant doublet component and a small fraction of singlet, marking a clear departure from the Standard Model.

References

[1] Y. Fukuda et al. (Super-Kamiokande Collaboration), Evidence for oscillation of atmospheric neutrinos, Phys. Rev. Lett. **81**, 1562 (1998).

[2] S. L. Glashow, Partial-symmetries of weak interactions, Nucl. Phys. **22**, 579 (1961).

[3] S. Weinberg, A model of leptons. Phys. Rev. Lett. **19**, 1264 (1967).

[4] A. G. Adame et al., DESI 2024 VI: cosmological constraints from the measurements of baryon acoustic oscillations, JCAP **02**, 021 (2025).

[5] R. R. Volkas, Neutrino theory: open questions and future opportunities, arXiv:2409.09992.

[6] P. Minkowski, $\mu \to e\gamma$ at a rate of one out of 1-billion muon decays?, Phys. Lett. B **67**, 421 (1977).

[7] S. Weinberg, Baryon and lepton nonconserving processes, Phys. Rev. Lett. **43**, 1566 (1979).

[8] André de Gouvêa, Neutrino mass models, Annu. Rev. Nucl. Part. Sci. **66**, 197 (2016).

[9] S. Bilenky, Introduction to the physics of massive and mixed neutrinos, Lecture notes in physics, 2nd ed. (Spinger, Berlin, 2018)

[10] S. F. King, Right-handed neutrinos: seesaw models and signatures, arXiv:2502.07877.

[11] S. F. King, Neutrino mass models, Rept. Prog. Phys. **67**, 107 (2004).

[12] Z. Z. Xing, Flavor structures of charged fermions and massive neutrinos, Phys. Rept. **854**, 1 (2020).

[13] N. Aghanim et al. (Planck Collaboration), Planck 2018 results. VI. Cosmological parameters, Astron. Astrophys. **641**, A6 (2020), arXiv:1807.06209.

[14] Hooft, G. (1980), Naturalness, Chiral symmetry, and spontaneous chiral symmetry breaking, NATO Sci. Ser. B, **59**:135, 1980.

[15] F. P. An et al., Observation of electron-antineutrino disappearance at Daya Bay, Phys. Rev. Lett. **108**, 171803 (2012).

[16] Y. J. Ko et al., Sterile neutrino search at NEOS Experiment, Phys. Rev. Lett. **118**, 121802 (2017).

[17] J. Ashenfelter et al., First search for short-baseline neutrino oscillations at HFIR with PROSPECT, Phys. Rev. Lett. **121**, 251802 (2018).

[18] H. Acharya et al., First results on the search for lepton number violating neutrinoless double beta decay with the LEGEND-200 experiment, arXiv:2505.10440.

[19] G Adhikari et al., nEXO: Neutrinoless double beta decay search beyond year half-life sensitivity, J. Phys. G: Nucl. Part. Phys. **49**, 015104 (2022).

[20] S. Abe et al. (KamLAND-Zen Collaboration), Search for the Majorana nature of neutrinos in the inverted mass ordering region with KamLAND-Zen, Phys. Rev. Lett. **130**, 051801 (2023).