ISSN 0027-1349, Moscow University Physics Bulletin, 2022, Vol. 77, No. 2, pp. 371–374. © Allerton Press, Inc., 2022.

NEUTRINOS

Non-Standard Interactions in Radiative Neutrino Mass Models[#]

Sudip Jana[*]

Max-Planck-Institut für Kernphysik, Heidelberg, 69117Germany

Received February 22, 2022

Abstract—I present a comprehensive analysis of neutrino non-standard interactions (NSI) generated by new scalars in radiative neutrino mass models. To this end, I propose a new nomenclature for classifying radiative neutrino mass models: those containing at least one SM particle in the loop are designated as type-I radiative models, while those without SM particles in the loop are designated as type-II radiative models. In terms of NSI, type-I radiative models are the most intriguing, since the neutrino couples directly to an SM fermion (matter field) and a new scalar, creating NSI at the tree level, in contrast to type-II radiative models. I summarized the maximum possible NSI in all type-I radiative models after accounting for numerous theoretical and experimental restrictions. Additionally, I demonstrate that using light charged scalars in radiative models can result in a Glashow-like resonance feature in the UHE neutrino event spectrum at the IceCube neutrino observatory and its high-energy upgrade IceCube-Gen2, which can probe a sizable fraction of the allowed NSI parameter space. This talk is based on results obtained with K.S. Babu, Bhupal Dev, Anil Thapa and Yicong Sui and presented in hep-ph 1907.09498 and 1908.02779.

Keywords: NSI, neutrino mass, radiative mechanism

DOI: 10.3103/S0027134922020461

The standard paradigm for explaining tiny neutrino masses and mixings is the seesaw mechanism, which generally generates an effective dimension-5 operator $\mathcal{O}_1 = (LLHH)/\Lambda$, suppressed by the mass scale Λ of the heavy right-handed neutrino. (L here denotes lepton doublets, while H is the Higgs doublet.) Oscillation data dictates that in this scenario $\Lambda \sim 10^{14}$ GeV, which is well beyond the reach of foreseeable experiments for direct scrutiny. An interesting alternative to the high scale seesaw mechanism is is "radiative mechanism." Neutrino masses are zero at tree level. Small, finite Majorana masses are generated at the quantum level. Typically, new heavy scalar fields introduced violates lepton number. The smallness of neutrino masses can be understood as originating from loop and chirality suppression factors. The scale of new physics can naturally be around a TeV in this scenario.

Recently, we propose [1] a nomenclature that greatly helps the classification of various radiative models of neutrino mass generation. One class of models can be described by lepton number violating effective higher dimensional operators. A prototypical example is the Zee model [2] which introduces a second Higgs doublet and a charged $SU(2)_L$-singlet scalar to the SM. Interactions of these fields violate lepton number, and would lead to the effective lepton number violating ($\Delta L = 2$) dimension 7 operator $\mathcal{O}_2 = L^i L^j L^k e^c H^l \epsilon_{ij}\epsilon_{kl}$ with indices $i, j, ...$ referring to $SU(2)_L$, and e^c standing for the $SU(2)_L$ singlet let-handed positron state. The induced neutrino mass has an explicit chiral suppression factor, proportional to the charged lepton mass inside the loop. We call radiative neutrino mass models of this type, having a loop suppression and a chirality suppression proportional to a light charged fermion mass, and expressible in terms of an effective higher dimensional operator as type-I radiative models [1]. A classification of low dimensional operators that violate lepton number by two units has been worked out in [3]. This category of type-I radiative neutrino mass models is populated by one-loop, two-loop, and three-loop models [1, 4]. From the perspective of neutrino NSI, these type-I radiative models are the most interesting, as the neutrino couples to a SM fermion and a new scalar directly, with the scalar mass near the TeV scale. We have analyzed the ranges of NSI possible in all these type-I radiative models here [1].

[*]E-mail: sudip.jana@mpi-hd.mpg.de

[#]Invited plenary talk at 20th Lomonosov Conference, Moscow, Russia, August 20, 2021.

A second class of radiative neutrino mass models has entirely new (i.e., non-SM) particles inside the loop diagrams generating the mass. These models cannot be derived from effective $\Delta L = 2$ higher-dimensional operators, as there is no way to cut the loop diagram and generate such operators. We term this class of models type-II radiative neutrino mass models [1]. The induced neutrino mass may have a chiral suppression, but this is not proportional to any light fermion mass. Effectively, these models generate operator $\mathcal{O}_1$, but with some loop suppression. From a purely neutrino mass perspective, the scale of new physics could be of order 10^{10} GeV in these models. However, there are often other considerations which make the scale near a TeV, a prime example being the identification of a WIMP dark matter with a particle that circulates in the loop diagram generating neutrino mass. A well-known example of the type-II radiative neutrino mass model is the scotogenic model [5] which assumes a second Higgs doublet and right-handed neutrinos N beyond the SM. A discrete Z_2 symmetry is assumed under which N and the second Higgs doublet are odd. If this Z_2 remains unbroken, the lightest of the Z_2-odd particles can serve as a dark matter candidate. The type-II radiative neutrino mass models will have negligible neutrino NSI, as the neutrino always couples to non-SM fermions and scalars. Any NSI would be induced at the loop level, which would be too small to be observable in experiments. As a result, in a comprehensive analysis of radiative neutrino mass models for NSI, one can safely ignore type-II models.

Now, I discuss the ranges of NSI possible in all these type-I radiative models. When the mediators of neutrino mass generation have masses around or below the TeV scale, they can induce sizable neutrino non-standard interactions (NSI) [6]. These NSI are of great phenomenological interest, as their presence would modify the standard three-neutrino oscillation picture. The NSI will modify scattering experiments, as the production and detection vertices are corrected; they would also modify neutrino oscillations, primarily through new contributions to matter effects. In this context, we recently explore the complementarity between LHC searches and neutrino experiments in probing neutrino non-standard interactions [7]. There have been a variety of other phenomenological studies of NSI in the context of oscillations, but relatively lesser effort has gone into the ultraviolet (UV) completion of models that yield such NSI (for a recent update, see [1, 8]). A major challenge in generating observable NSI in any UV-complete model is that there are severe constraints arising from charged-lepton flavor violation (cLFV). One possible way to avoid such constraints is to have light mediators for NSI. In contrast to these attempts, here I focus on heavy mediators, and study the range of NSI allowed in a class of radiative neutrino mass models. Apart from being consistent with cLFV constraints, these models should also be consistent with direct collider searches for new particles and precision electroweak constraints. Recently, we find [1] that the strengths of the diagonal NSI can be (20–50)% of the weak interaction strength for the flavor diagonal components in a class of popular models that we term as type-I radiative neutrino mass models, while they are absent at tree-level in another class, termed type-II radiative models. For our analysis, we have systematically analyzed these models for their predicted NSI, while being consistent with direct and indirect constraints from LEP and LHC searches, Higgs precision physics limits, EW T parameter bound, τ lifetime and universality constraints, lepton universality bound from W-decay, charge breaking minima limit, precision data and LFV searches. We then compare these model predictions for NSI with the direct constraints from neutrino oscillation and scattering experiments. We survey such models where neutrino masses arise at one, two and three loops. In the prototypical Zee model which generates neutrino masses via one-loop diagrams involving charged scalars, we find that diagonal NSI can be as large as (8%, 3.8%, 9.3%) for (ε_{ee}, $\varepsilon_{\mu\mu}$, $\varepsilon_{\tau\tau}$), while off-diagonal NSI can be at most (10^{-3}%, 0.56%, 0.34%) for ($\varepsilon_{e\mu}$, $\varepsilon_{e\tau}$, $\varepsilon_{\mu\tau}$). In one-loop neutrino mass models using leptoquarks (LQs), ($\varepsilon_{\mu\mu}, \varepsilon_{\tau\tau}$) can be as large as (21.6%, 51.7%), while ε_{ee} and ($\varepsilon_{e\mu}$, $\varepsilon_{e\tau}$, $\varepsilon_{\mu\tau}$) can at most be 0.6%. Other two- and three-loop LQ models are found to give NSI of similar strength. The most stringent constraints on the diagonal NSI are found to come from neutrino oscillation and scattering experiments, while the off-diagonal NSI are mostly constrained by low-energy processes, such as atomic parity violation and cLFV. We also comment on the future sensitivity of these radiative models in long-baseline neutrino experiments, such as DUNE. While our analysis is focused on radiative neutrino mass models, it essentially covers all NSI possibilities with heavy mediators. Results of our analysis are summarized in Fig. 1. The NSI predictions in all other models analyzed here will fall into one of the above categories.

Next, I discuss a new way [9] to probe NSI of neutrinos with matter using the ultra-high energy (UHE) neutrino data at current and future neutrino telescopes. We consider the Zee model of radiative neutrino mass generation as a prototype [9], which allows two charged scalar—one $SU(2)_L$-doublet and one singlet, both being leptophilic, to be as light as 100 GeV, thereby inducing potentially observable NSI with electrons. We show that these light charged Zee-scalars could give rise to a Glashow-like

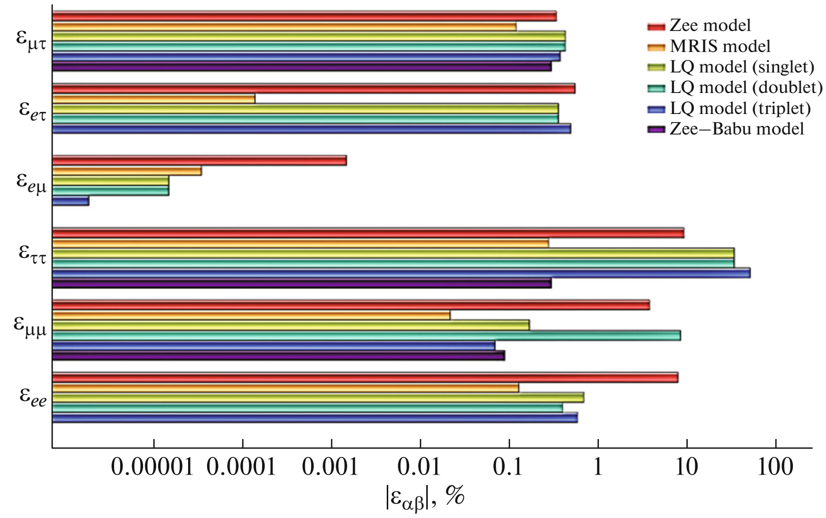

Fig. 1. Summary of maximum NSI strength $-\varepsilon_{\alpha\beta}-$ allowed in different classes of radiative neutrino mass models discussed here. Red, yellow, green, cyan, blue and purple bars correspond to the Zee model, minimal radiative inverse seesaw model, LQ model with singlet, doublet and triplet LQs, and Zee–Babu model respectively. Figure reproduced from [1].

resonance feature [9] in the UHE neutrino event spectrum at the IceCube neutrino observatory and its high-energy upgrade IceCube-Gen2, which can probe a sizable fraction of the allowed NSI parameter space.

Within the SM, the only resonance IceCube is sensitive to is the Glashow resonance [10], where electron anti-neutrinos hitting the target electrons in ice could produce an on-shell W-boson: $\bar{\nu}_e e^- \to W^- \to$ anything. The energy of the incoming neutrino required to make this resonance happen is fixed at $E_\nu = m_W^2/2m_e = 6.3$ PeV. One candidate Glashow event was identified in a partially-contained PeV event (PEPE) search with deposited energy of 5.9 ± 0.18 PeV, but has not been included in the event spectrum yet. The non-observation of Glashow events might be still consistent with the SM expectations within the error bars, given the uncertainty in the source type (pp versus $p\gamma$), as well as $(\nu_e, \nu_\mu, \nu_\tau)$ flavor composition $(1:2:0$ vs $0:1:0)$. On the other hand, the possibility of observing a Z-boson resonance (Z-burst) at IceCube due to UHE anti-neutrinos interacting with non-relativistic relic neutrinos is bleak, as the required incoming neutrino energy in this case turns out to be $E_\nu = m_Z^2/2m_\nu \gtrsim 10^{23}$ eV, well beyond the Greisen–Zatsepin–Kuzmin cut-off energy of $\sim 5 \times 10^{19}$ eV for the UHE cosmic rays—the most likely progenitors of the UHE neutrinos. Here, we propose the possibility of light charged scalar resonances at IceCube, which are intimately related to neutrino mass generation [9], as well as observable non-standard interactions (NSI) [9], neutrino magnetic moment [11] and "flavored $0\nu\beta\beta$ decay" [12]. While our analysis is focused on Zee model, it essentially covers various other theoretically motivated models [12–18] with light charged scalars.

To estimate the modification to the event spectrum, we compute the number of events in a given energy bin i as

$$N_i = T \int d\Omega \int_{E_i^{\min}}^{E_i^{\max}} dE \times \sum_\alpha \Phi_{\nu_\alpha}(E) A_{\nu_\alpha}(E, \Omega). \quad (1)$$

Here T is the exposure time for which we use $T_0 = 2653$ days, corresponding to 7.5 years of live data taking at IceCube; Ω is the solid angle of coverage and we integrate over the whole sky; E is the electromagnetic-equivalent deposited energy which is an approximately linear function of the incoming neutrino energy; the limits of the energy integration $E_i^{\min}$ and $E_i^{\max}$ give the size of the ith deposited energy bin over which the expected number of events is being calculated; $\Phi_{\nu_\alpha}(E)$ is the differential astrophysical neutrino+anti-neutrino flux for flavor α, for which we use a simple, single-component unbroken power-law, isotropic flux $\Phi(E_\nu) = \Phi_0(E_\nu/E_0)^{-\gamma}$ with the IceCube best-fit values of $\Phi_0 = 6.45 \times 10^{-18}$ GeV^{-1} cm^{-2} s^{-1} sr^{-1} and $\gamma = 2.89$; and A_{ν_α} is the effective area per energy per solid angle for the neutrino flavor ν_α, which includes the effective neutrino-matter cross section, number density of target nucleons/electrons and acceptance rates for the shower and track events. In presence of new interactions, only the neutrino-electron cross

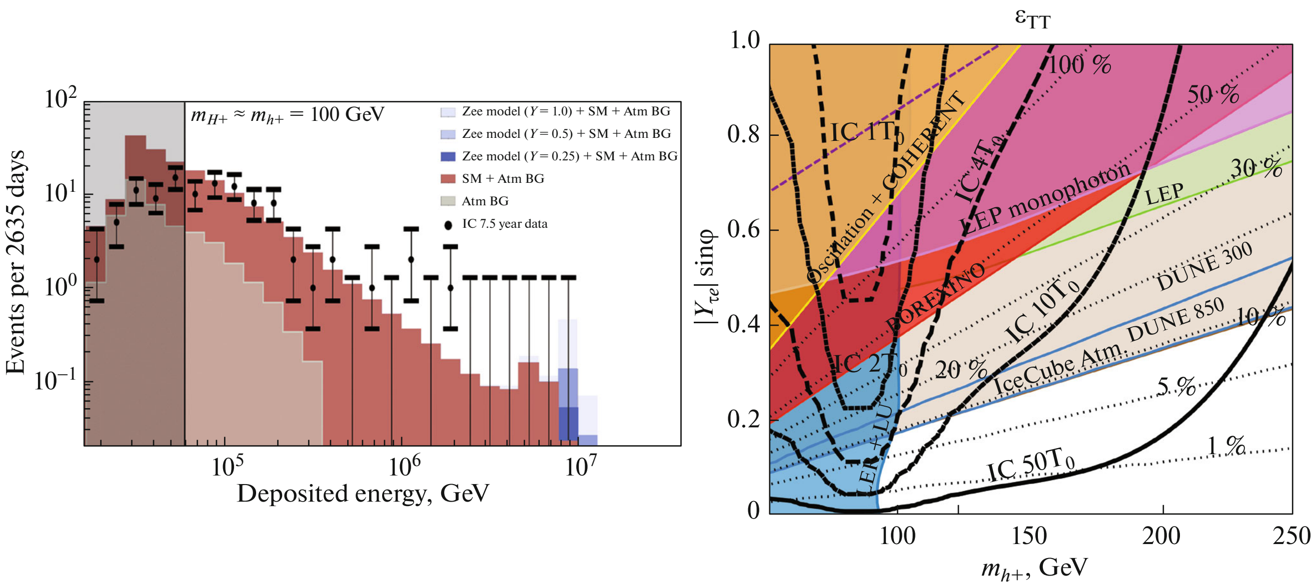

Fig. 2. Left: reconstructed event spectra for the expected atmospheric background (gray), SM best-fit with a single-component astrophysical flux (red) and the Zee model with $m_{h^+} \approx m_{H^+} = 100$ GeV, $\varphi = \pi/4$ and $Y_{\tau e} = 1, 0.5, 0.25$ (light, medium and dark blue, respectively), all compared with the 7.5-year IceCube data. The data points below 60 TeV (inside the vertical black-shaded band) are not included in the IceCube HESE analysis we are using here. Right: IceCube sensitivity (corresponding to one expected event in the resonance energy bins combined) for the parameter space relevant for $\varepsilon_{\tau\tau}$ are shown by thick black curves, for different exposure times (in terms of the current exposure $T_0 = 2653$ days). Figure reproduced from [9].

section gets modified, which in turn affects the effective area. In Fig. 2, I have shown reconstructed event spectra for the expected atmospheric background (gray), SM best-fit with a single-component astrophysical flux (red) and the Zee model with $m_{h^+} \approx m_{H^+} = 100$ GeV, $\varphi = \pi/4$ and $Y_{\tau e} = 1, 0.5, 0.25$ (light, medium and dark blue, respectively), all compared with the 7.5-year IceCube data. The data points below 60 TeV (inside the vertical black-shaded band) are not included in the IceCube HESE analysis we are using here. IceCube sensitivity (corresponding to one expected event in the resonance energy bins combined) for the parameter space relevant for $\varepsilon_{\tau\tau}$ are shown by thick black curves, for different exposure times (in terms of the current exposure $T_0 = 2653$ days).

CONFLICT OF INTEREST

The author declares that he has no conflicts of interest.

REFERENCES

1. K. S. Babu, P. S. B. Dev, S. Jana, and A. Thapa, J. High Energy Phys. **2020**, 006 (2020).
2. A. Zee, Phys. Lett. B **93**, 389 (1980).
3. K. S. Babu and C. N. Leung, Nucl. Phys. B **619**, 667–689 (2001).
4. Y. Cai, J. Herrero-García, M. A. Schmidt, A. Vicente, and R. R. Volkas, Front. Phys. **5**, 63 (2017).
5. E. Ma, Phys. Rev. D **73**, 077301 (2006).
6. L. Wolfenstein, Phys. Rev. D **17**, 2369–2374 (1978).
7. K. S. Babu, D. Gonçalves, S. Jana, and P. A. N. Machado, arXiv: 2003.03383 [hep-ph].
8. P. S. Bhupal Dev et al., SciPost Phys. Proc. **2**, 001 (2019).
9. K. S. Babu, P. S. Dev, S. Jana, and Y. Sui, Phys. Rev. Lett. **124**, 041805 (2020).
10. S. L. Glashow, Phys. Rev. **118**, 316–317 (1960).
11. K. S. Babu, S. Jana, and M. Lindner, J. High Energy Phys. **2010**, 040 (2020).
12. L. Graf, S. Jana, M. Lindner, W. Rodejohann, and X. J. Xu, arXiv: 2010.15109 [hep-ph].
13. A. Bally, S. Jana, and A. Trautner, Phys. Rev. Lett. **125**, 161802 (2020).
14. M. Berbig, S. Jana, and A. Trautner, Phys. Rev. D **102**, 115008 (2020).
15. S. Jana and V. P. K. S. Saad, Phys. Rev. D **101**, 115037 (2020).
16. K. S. Babu and S. Jana, J. High Energy Phys. **1902**, 193 (2019).
17. E. Bertuzzo, S. Jana, P. A. N. Machado, and R. Zukanovich Funchal, Phys. Lett. B **791**, 210–214 (2019).
18. E. Bertuzzo, S. Jana, P. A. N. Machado, and R. Zukanovich Funchal, Phys. Rev. Lett. **121**, 241801 (2018).