PROCEEDINGS OF SCIENCE

Type-II seesaw effects on neutrino trident scattering

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In this talk, we have briefly discussed the Type-II seesaw contributions to the W mass, charged lepton flavor violation (CLFV), and neutrino trident scattering. Based on CLFV experimental data, we have derived a lower limit on the triplet vacuum expectation value (vev) v_Δ as a function of the triplet scalar mass m_Δ: $v_\Delta > 6.3$ eV $(100\ \text{GeV}/m_\Delta)$. This result indicates that the effect of the triplet vev v_Δ on the W mass could be neglected. We also find that the Type-II seesaw reduces the standard model (SM) neutrino trident scattering cross section, but the deviation ratio remains above 0.98 at the 3σ confidence level.

12th Neutrino Oscillation Workshop (NOW2024)
2-8, September 2024
Otranto, Lecce, Italy

[*]Speaker

PoS(NOW2024)036

1. Introducetion

In Type-II seesaw model[1–6], SM is extended by a elecroweak triplet scalar

$$\Delta = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix} \tag{1}$$

that couples to a pair of lepton doublet via Yukawa interactions,

$$\begin{aligned} \mathcal{L}_Y =& Y_{\alpha\beta}\overline{L^c_\alpha}P_L L_\beta \Delta + \text{ h.c.} \\ =& \overline{\nu^c_\alpha}Y_{\alpha\beta}P_L\nu_\beta\Delta^0 - \frac{1}{2}(\overline{\nu^c_\alpha}Y_{\alpha\beta}P_L e_\beta\Delta^+ + \overline{e^c_\alpha}Y_{\alpha\beta}P_L\nu_\beta\Delta^+) - \overline{e^c_\alpha}Y_{\alpha\beta}P_L e_\beta\Delta^{++} + \text{ h.c.} , \end{aligned} \tag{2}$$

where $\alpha, \beta = e, \mu, \tau$. With a non-zero vev $\langle\Delta^0\rangle = v_\Delta/\sqrt{2}$, the coupling term between neutrinos and Δ^0 can generate the tiny Majorana neutrino mass matrix $(M_\nu)_{\alpha\beta} = m_{\alpha\beta} = \sqrt{2}Y_{\alpha\beta}v_\Delta$, which can be diagonalized by a similarity transformation $U^T M_\nu U = \text{diag}\{m_1, m_2, m_3\}$ where U is the PMNS matrix and m_i are the masses of the neutrino mass eigenstates. A non-zero v_Δ also affects the electroweak parameter $\rho = m_W^2/(m_Z^2\cos^2\theta_W) = 1 - 2v^2/(v^2 + 2v_\Delta^2)$ through the gauge boson masses, making it to be less than 1 as predicted by standard model (SM). Besides, for the other extended Yukawa interaction terms that introduce the coupling between charged leptons and triplet scalars, not only do they contribute to the CLFV processes such as $\mu \to e\gamma$, but they also have contributions that suppress the SM rare neutrino trident production [7]. In the following discussion, we will provide more details on these results.

2. CLFV violation constraints on Type-II seesaw model.

Mediated by Δ^{++} and Δ^+ at the one loop level, CLFV process $l_\alpha \to l_\beta\gamma$ will be induced in Type-II seesaw model,

$$\text{Br}\left(l^-_\alpha \to l^-_\beta\gamma\right) = \frac{m^5_{l_\alpha}\alpha_{\text{em}}\tau_\alpha}{(192\pi^2)^2}\left|(Y^\dagger Y)_{\beta\alpha}\right|^2\left(\frac{1}{m^2_{\Delta^+}} + \frac{8}{m^2_{\Delta^{++}}}\right)^2 = \frac{m^5_{l_\alpha}\alpha_{\text{em}}\tau_\alpha}{(192\pi^2)^2}\left(\frac{9\left|(M^\dagger_\nu M_\nu)_{\beta\alpha}\right|}{2m^2_\Delta v^2_\Delta}\right)^2 , \tag{3}$$

where we assume degenerate triplet Higgs spectrum. Currently, experimental searches for these processes have yielded null results, imposing stringent constraints on the model parameters. Among them, the most stringent constraint[8] comes from the process $\mu \to e\gamma$, which provides the lower bound for v_Δ,

$$\text{Br}(\mu \to e\gamma) < 4.2\times 10^{-13} \Rightarrow v_\Delta > \sqrt{\frac{9\left|(M^\dagger_\nu M_\nu)_{e\mu}\right|}{m^2_\Delta}} \times 15.3\text{TeV} . \tag{4}$$

To explicit this constraint, we can find the lower bound for neutrino mass matrix elements combine with the neutrino oscillation parameters [9],

$$\left|(M^\dagger_\nu M_\nu)_{e\mu}\right| = |U_{\mu 2}U^*_{e2}\Delta m^2_{21} + U_{\mu 3}U^*_{e3}\Delta m^2_{31}| \gtrsim 2.26\times 10^{-4}\text{eV}^2 . \tag{5}$$

Then we can express the lower bound in function of m_Δ,

$$v_\Delta > \sqrt{\frac{9\left|(M_\nu^\dagger M_\nu)_{e\mu}\right|}{m_\Delta^2}} \times 15.3\text{TeV} > \sqrt{\frac{9\left|(M_\nu^\dagger M_\nu)_{e\mu}\right|_{\min}}{m_\Delta^2}} \times 15.3\text{TeV} = 6.25\text{eV}\left(\frac{100\text{GeV}}{m_\Delta}\right) . \quad (6)$$

The bounds for the NO and IO cases are approximately the same. In the future, the sensitivity of MEG II for the $\mu \to e\gamma$ process is expected to reach 6×10^{-14} [10], allowing an examination of v_Δ in the range of 6.25 eV$(100\text{GeV}/m_\Delta)$ to 39 eV$(100\text{GeV}/m_\Delta)$.

3. Type-II seesaw effects on W mass

From the kinetic terms of Higgs bosons,

$$\mathcal{L}_{\text{kin}} = (D^\mu\Phi)^\dagger \left(D_\mu\Phi\right) + \text{Tr}\left[(D^\mu\Delta)^\dagger \left(D_\mu\Delta\right)\right] , \quad (7)$$

we can derive the gauge boson mass after spontaneous symmetry breaking,

$$m_W^2 = \frac{g^2(v_d^2 + 2v_\Delta^2)}{4} , \quad m_Z^2 = \frac{(g^2 + g'^2)(v_d^2 + 4v_\Delta^2)}{4} , \quad (8)$$

where Φ is usual scalar $SU(2)_L$ doublet with vev v_d. Therefore, the electroweak vev v can be inferred as $v^2 \equiv 1/(\sqrt{2}G_F) = 4m_W^2/g^2 = v_d^2 + 2v_\Delta^2 = (246\text{GeV})^2$ [8]. Besides, there is a minimal effects on ρ

$$\rho = \frac{m_W^2}{m_Z^2\cos^2\theta_W} = 1 + \Delta\rho = 1 - \frac{2v_\Delta^2}{v_d^2 + 4v_\Delta^2} = 1 - \frac{2v_\Delta^2}{v^2 + 2v_\Delta^2} . \quad (9)$$

since usually $v_\Delta \ll v$. Previous constraint on parameter is given by [8] $\rho = 1.00038 \pm 0.00020$. The recent measurement [8] of $m_W^{\text{CDF}} = 80,433.5 \pm 9.4\text{MeV}$ is 7σ level above the SM prediction $m_W^{\text{SM}} = 80,357 \pm 6\text{MeV}$. With the new value for m_W, the central value of would be enhanced by a factor $(m_W^{\text{CDF}}/m_W^{\text{SM}})^2$, making $\rho = 1.0019$ which is bigger than before value. But v_Δ in type-II seesaw model reduces ρ moving in the modification in the wrong direction. However, significant effect on ρ needs v_Δ to be of order a GeV or so. Considering the constraint from the previous section, $v_\Delta > 6.25$ eV$(100\text{GeV}/m_\Delta) = 6.25$ GeV$(10^{11}\text{GeV}/m_\Delta)$, we can conclude that there is a large parameter space where the contribution of the Type-II seesaw vev v_Δ to m_W is negligible. This is because m_Δ could be much smaller than 10^{11} GeV under the current experimental limits [8].

It's also worth noting that if in the model there are multi-scalars H_i with vevs v_i, one would have $\rho = \sum_i(I_i(I_i+1) - Y_i^2)v_i^2/2\sum_i Y_i^2 v_i^2$, where I_i and Y_i are the weak isospin and hypercharge of H_i. If the reason for a ρ larger than 1 is due to new scalars, their hypercharge to be zero will maximize the effects. An example is to add a new triplet ξ transforming as $(1,\ 3,\ 0)$ in our model. In this case $\rho = 1 - 2v_\Delta^2/(v^2 + 4v_\Delta^2) + 4v_\xi^2/(v^2 + 4v_\Delta^2)$ [11]. To produce a deviation of 0.0019 for $\Delta\rho$, v_ξ needs to be about 5.4 GeV.

4. Type-II seesaw contribution to neutrino trident scattering

Exchanging Δ^+ at tree level, the following operator will be generated from $\mathcal{L}_Y$

$$\frac{(M_\nu)_{\alpha\beta}(M_\nu)^*_{\lambda\eta}}{m_\Delta^2 v_\Delta^2}\overline{\nu_\alpha^c}\gamma^\mu P_L e_\beta \overline{e_\eta}\gamma_\mu P_L \nu_\lambda^c = \frac{m_{\alpha\beta}m^*_{\lambda\eta}}{2m_\Delta^2 v_\Delta^2}\overline{\nu_\lambda}\gamma^\mu P_L \nu_\alpha \overline{e_\eta}\gamma_\mu P_L e_\beta . \quad (10)$$

This BSM interaction operator will contribute to neutrino trident scattering and modify the measured cross section σ, with contributions to $\nu_\mu N \to N\mu\bar{\mu}\nu_\mu$ having the opposite sign compared to the SM contribution. If there's no correction to the SM contribution, the value of $\sigma/\sigma_{\rm SM}$ is equal to 1. It is important to note that not only does the Type-II seesaw contribute to $\nu_\mu N \to N\mu\bar{\mu}\nu_\mu$, but there are also contributions to $\nu_\mu N \to N\mu\bar{\mu}(\nu_e + \nu_\tau)$. Since the flavors of the final neutrinos are not experimentally identified, one should sum over all final states. The final modification is given by the following expression:

$$\frac{\sigma}{\sigma_{SM}} = \frac{\left(1+4s_W^2 - \frac{|m_{\mu\mu}|^2 v^2}{2m_\Delta^2 v_\Delta^2}\right)^2 + \left(1 - \frac{|m_{\mu\mu}|^2 v^2}{2m_\Delta^2 v_\Delta^2}\right)^2 + 2\left(\frac{|m_{\mu\mu}|^2 v^2}{2m_\Delta^2 v_\Delta^2}\right)^2 \left(\frac{|m_{e\mu}|^2+|m_{\tau\mu}|^2}{|m_{\mu\mu}|^2}\right)}{\left(1+4s_W^2\right)^2+1} \tag{11}$$

where $s_W = \sin\theta_W$, and θ_W is the Weinberg angle. For convenience, we can write the ratio as a quadratic function of $1/(m_\Delta^2 v_\Delta^2)$,

$$\frac{\sigma}{\sigma_{\rm SM}} = a\left(\frac{1}{m_\Delta^2 v_\Delta^2}\right)^2 + b\left(\frac{1}{m_\Delta^2 v_\Delta^2}\right) + 1\ , \tag{12}$$

where

$$a = \frac{\left(v^2|m_{\mu\mu}|^2\right)^2\left(1+\frac{|m_{e\mu}|^2+|m_{\tau\mu}|^2}{|m_{\mu\mu}|^2}\right)}{2\left(\left(1+4s_W^2\right)^2+1\right)}\ , \quad b = -\frac{v^2|m_{\mu\mu}|^2(2+4s_W^2)}{\left(1+4s_W^2\right)^2+1}\ . \tag{13}$$

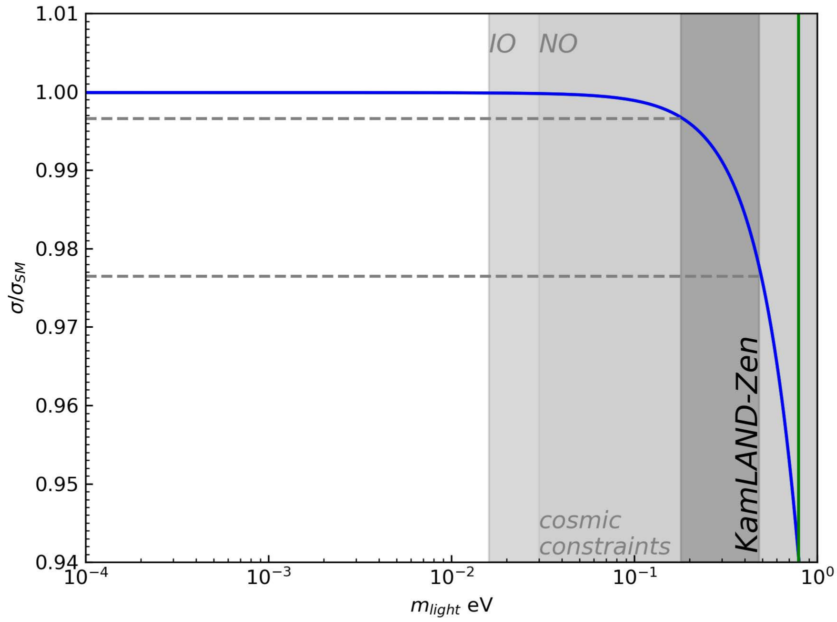

Figure 1: The maximum deviation of σ/σ_{SM} with 3σ constraints from $\mu \to e\gamma$.

Considering the constraints in eq.(6), we can give the range of $1/(m_\Delta^2 v_\Delta^2)$ directly,

$$0 < \frac{1}{m_\Delta^2 v_\Delta^2} < \left(\frac{1}{6.3\text{eV}100\text{GeV}}\right)^2\ . \tag{14}$$

Using the properties of a quadratic function, the maximum and minimum values of the parameters $m_{e\mu}, m_{\mu\mu}, m_{\tau\mu}$ can be determined. These values depend on the lightest neutrino mass $m_{\rm light}$ and the neutrino oscillation parameters. By employing particle swarm optimization, the lower bound of $\sigma/\sigma_{\rm SM}$ is calculated and shown in Fig. 1, based on oscillation parameter data at the 3σ confidence level [9]. (Since the upper bound of $\sigma/\sigma_{\rm SM}$ is always 1, it is not shown in the plot.)

In Fig. 1, the region to the right of the green line is excluded by the KATRIN experimental data [12]. The dark gray shaded area represents the upper limit on the lightest neutrino mass derived from KamLAND-Zen neutrinoless double beta decay data [13], with the region to the right excluded. The dashed gray lines indicate the maximum (minimum) deviation of $\sigma/\sigma_{\rm SM}$, based on the stronger (weaker) limits from the KamLAND-Zen results. Considering these constraints, $\sigma/\sigma_{\rm SM}$ can reach a maximum of 0.98 (corresponding to a few percent deviation from the SM prediction, as shown by the dashed gray lines) at the 3σ confidence level, which is closer to the current experimental central value [14–16]. The light gray shaded region is excluded by the cosmological constraints reported by the Planck collaboration [17]. Under these limits, the effect of Δ on $\sigma/\sigma_{\rm SM}$ is constrained to be less than 0.1%, which is a challenge to experimental test.

5. Acknowledgments

I am grateful to Yu Cheng, Xiao-Gang He, and Zhong-Lv Huang for their collaboration and insightful discussions. I would also like to thank the organisers of the Neutrino Oscillation Workshop 2024 for kindly inviting me to present this talk. This work was supported by the NSFC (Grant No. 123B2079).

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PoS(NOW2024)036