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Charged Lepton Flavor Violation in a class of Radiative Neutrino Mass Generation Models

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We investigate the charged lepton flavor violating processes $\mu \to e\gamma$, $\mu \to ee\bar{e}$ and $\mu - e$ conversion in nuclei for a class of three-loop radiative neutrino mass generation models with large electroweak multiplets. We show that the flavor violating processes $\mu \to e\gamma$ and $\mu - e$ conversion in nuclei become highly suppressed compared to $\mu \to ee\bar{e}$ process because of certain cancellations among various one-loop diagrams contributing to the effective $\mu e\gamma$ and μeZ vertices in these models. Therefore, the observation of such pattern in LFV processes may reveal the radiative mechanism behind neutrino mass generation.

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1. Introduction

Lepton flavor violation (LFV) is ubiquitous among neutrinos. On the other hand, in the SM, the LFV processes involving charged leptons are extremely rare. For example, the branching ratio of charged lepton violating process, $\mu \to e\gamma$, turns out to be about $\lesssim 10^{-50}$ which is beyond any experimental reach in the foreseeable future. But many physics beyond the standard model (BSM) scenario, specially new physics related to the generation and smallness of the neutrino mass, can lead to unsuppressed charged LFV processes which are within the reach of currently operating and future experiments. Therefore, we have studied the charged LFV processes in the generalized KNT model [1] (and references therein) which explains the small non-zero mass of the neutrino as a loop effect with BSM particles having masses at O(TeV) range and provides a candidate for the Dark Matter (DM) of the universe.

2. The Model

The generalized KNT model contains the following BSM fields, charged under SM gauge group, $SU(3)_c \times SU(2)_L \times U(1)_Y$,

$$\begin{aligned} \Phi &= \left(\phi^{(n_\phi+1)}, ..., \phi^{+}, \phi^{0}, \phi'^{-}, ..., \phi'^{(-n_\phi+1)}\right)^{T}_{Y=1}, \\ F_{i=1,2,3} &= \left(F_i^{(n_F)}, ..., F_i^{+}, F_i^{0}, F_i^{-}, ..., F_i^{(-n_F)}\right)^{T}_{Y=0} \end{aligned}$$

and a singly charged SU(2)-singlet scalar, S_1^+. Here n_ϕ and n_F are integer isospins of $SU(2)_L$ and the superscript of the component field in the multiplet denotes its electric charge according to, $Q = T_3 + Y$ where T_3 is the eigenvalue of SU(2)'s diagonal isospin generator.

The SM Lagrangian is augmented in the following way,

$$\mathscr{L} \supset \mathscr{L}_{SM} + \{f_{\alpha\beta}\overline{L^c_\alpha}.L_\beta S_1^+ + g_{i\alpha}\overline{F_i}.\Phi.e_{\alpha_R} + h.c\} - \frac{1}{2}\overline{F^c_i}M_{F_{ij}}F_j - V(H,\Phi,S_1) + h.c \tag{2.1}$$

where, c denotes the charge conjugation and dot sign, in shorthand, refers to appropriate $SU(2)$ contractions. Also L_α and e_{R_α} are the LH lepton doublet and RH charged leptons respectively and Greek alphabet α stands for generation index. Moreover, $f_{\alpha\beta}$ and $g_{i\alpha}$ are the elements of 3×3 complex antisymmetric and general complex matrices respectively. Finally, H denotes the SM Higgs doublet.

After electroweak symmetry breaking (EWSB), the mass splittings allowed by EWPO constraints [4] lead to $\Delta m^2_{ij}/M_0^2 \lesssim 10^{-3}$ for the scalar multiplet if $M_0 \gtrsim 10$ TeV. On the other hand, the mass splittings in fermionic component fields are zero at tree-level and only receive $O(100)$ MeV splittings due to radiative correction after EWSB. Therefore we consider such scenario as the **near-degenerate** case.

3. Charged LFV Processes in KNT model

3.1 $\mu \to e\gamma$

The $\mu \to e\gamma$ process involves effective $\mu e\gamma$ vertex given by the one-loop diagrams in Fig. 1 with the on-shell photon line attached to charged scalars (I & III) and fermions (II). In the near-degenerate limit there are cancellations among these one-loop diagrams where photon line is attached to the charged fermion and scalar component fields (Fig. 1 (I & II)). Therefore , the sum over all such diagrams are almost zero in triplet, 5-plet and 7-plet cases. For singlet, the only contribution comes from one-loop diagram with (ϕ^-, F_i^0) pair. Apart from this common non-zero contribution from (ϕ^-, F_i^0) pair, additional non-negligible contributions, in case of triplet, 5-plet and 7-plet are given by (ϕ^{--}, F_i^+) and (ϕ^-, F_i^0) pairs, (ϕ^{---}, F_i^{++}) and (ϕ^{--}, F_i^+) pairs and (ϕ^{----}, F_i^{+++}) and (ϕ^{---}, F_i^{++}) pairs respectively.

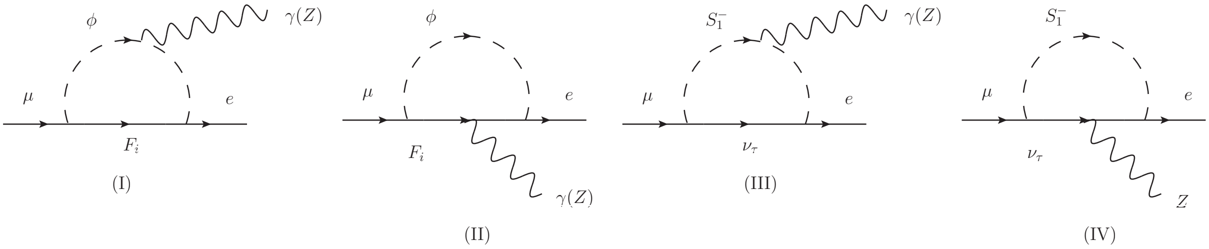

Figure 1: One loop diagrams contributing to effective $\mu e\gamma$ and μeZ vertices.

3.2 $\mu \to ee\bar{e}$

The $\mu \to ee\bar{e}$ process receives contribution from γ-penguin, Z-penguin and Box diagrams. The γ-penguin and Z-penguin diagrams can be obtained by attaching $e - \bar{e}$ fermion line to the photon and Z boson respectively in one-loop diagrams of Fig. 1. In the case of γ penguin contribution, similar cancellations as explained in section 3.1, will take place for triplet, 5-plet and 7-plet and consequently make its contribution to $\mu \to ee\bar{e}$ small.

On the other hand, in the near degenerate limit, the diagrams where Z boson is attached to fermions of opposite charges, contribute with alternative signs and therefore, summing over such diagrams gives zero contribution. The only non-zero Z-penguin contribution for all cases comes from diagram with (ϕ^-, F_i^0) pair.

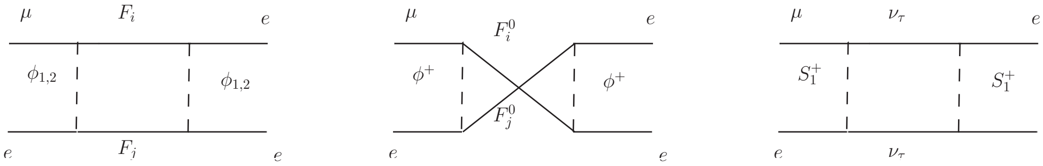

Figure 2: One-loop box topologies associated to Feynman diagrams contributing to $\mu \to ee\bar{e}$ process.

Lastly, the box diagrams shown in Fig. 2 contribute to the $\mu \to ee\bar{e}$. Unlike the cancellations among different γ and Z-penguin diagrams, all box diagrams add up coherently. Therefore, as the increase of the multiplet size leads to the increase of box diagrams, one can expect dominant contribution of them in $\mu \to ee\bar{e}$ compared to the penguin diagrams.

3.3 $\mu - e$ Conversion in Nuclei

For the generalized KNT model, the $\mu - e$ conversion rate receives the γ and Z penguin contributions where the quark line is attached to photon and Z-boson lines in the respective penguin diagrams. It also doesn't receive any box contribution because there is no coupling between Φ and quarks. Moreover, γ-penguin leads to an effective coupling with the quark which is proportional to the difference between dipole and non-dipole contribution given by effective $\mu e\gamma$ vertices so it is expected to be more suppressed than $\mu \to ee\bar{e}$.

4. Result and Discussion

The relevant parameter space of the generalized KNT model is described in [1]. The comparison among $\mu \to e\gamma$, $\mu \to ee\bar{e}$ and $\mu - e$ conversion rate is presented in Fig. 3.

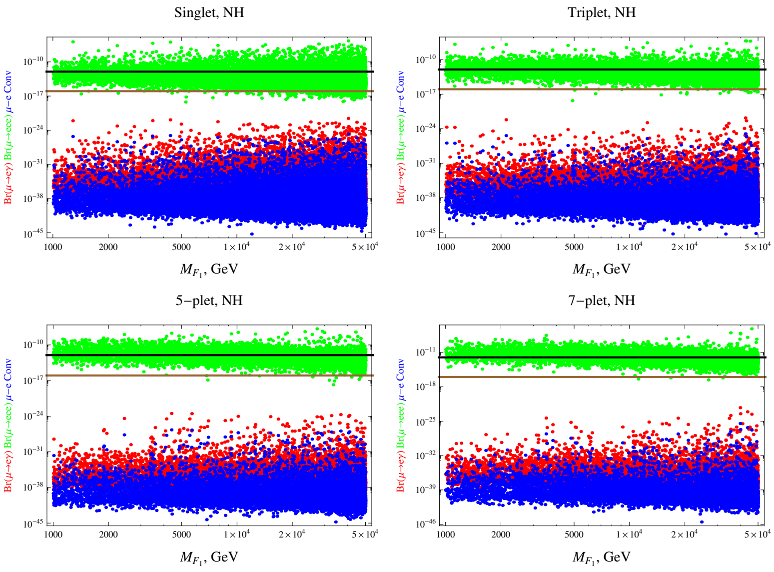

Figure 3: LFV Processes in singlet, triplet, 5-plet and 7-plet cases for normal hierarchy of neutrino masses. The black and brown horizontal lines are exclusion limits set by SINDRUM [2] and future Mu3e [3].

5. Conclusion and Outlook

We have investigated charged lepton flavor violating processes $\mu \to e\gamma$, $\mu \to ee\bar{e}$ and $\mu - e$ conversion in Au and Ti in the generalized KNT model with singlet, triplet, 5-plet and 7-plet. We have shown that due to the cancellation among several one-loop contributions, the rates of $\mu \to e\gamma$ and $\mu - e$ conversion in Au and Ti become highly suppressed compared to $\mu \to ee\bar{e}$. This is due to the coherent addition of one-loop box diagrams where no cancellations take place and leads to large box contribution to $\mu \to ee\bar{e}$ process. As a consequence, we have seen that for $M_{F_1} = 1 - 50$ TeV mass range, the region of viable parameter space set by neutrino sector is already excluded by the limit from SINDRUM and future Mu3e will have enough sensitivity to exclude almost all of the parameter space in this mass range and thus push the mass of lightest fermionic component larger than 50 TeV in generalized KNT model.

References

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