Neutrino mass and charged lepton flavor violation in an extended left-right symmetric model

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Abstract

We consider an $U(1)_{L_\mu - L_\tau}$ extended left-right symmetric gauge theory where the neutrino masses are generated through inverse seesaw mechanism. In this model the muon $(g - 2)$ anomaly is accounted for by the mediation of $Z_{\mu\tau}$, the gauge boson of $U(1)_{L_\mu - L_\tau}$ symmetry. The symmetries of the model require the light neutrino mass matrix to have a particular two-zero texture, which leads to non-trivial constraints in the minimum neutrino mass. In addition, the model predicts observable charged lepton flavor violation in $\mu - \tau$ sector.

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I. INTRODUCTION

The prediction of the anomalous magnetic moment \((g - 2)\) is one of the triumphs of Quantum Field Theory (QFT) \([1, 2]\). The precise measurement of muon \((g - 2)\) \([3]\) revealed a tiny discrepancy with the standard model (SM) prediction. This deviation indicates potential existence of new physics \([4–10]\). The muon \((g - 2)\) anomaly is one of the most compelling reasons for the search for physics beyond the SM. At present, the discrepancy is at the 4.2σ level \([11]\). Extensive studies, both on experimental \([11–20]\) and theoretical \([21–28]\) frontiers, are being carried out with the aim of improving the precision of both the measured value and the SM prediction of muon \((g - 2)\).

The anomalous magnetic moment is characterized by the quantity \(a_\mu = (g - 2)/2\). The present theoretical prediction of \(a_\mu\) from SM is \([29]\)

\[
a_\mu^{\text{SM}} = 116591810(43) \times 10^{-11}. \tag{1}
\]

It is in disagreement with the nearly two decade old Brookhaven muon \((g - 2)\) collaboration (BNL) result \([3]\)

\[
a_\mu^{\text{BNL}} = 116592089(63) \times 10^{-11}, \tag{2}
\]

with \(\Delta a_\mu = (287 \pm 80) \times 10^{-11}\) at 3.7σ discrepancy. The theoretical prediction of \(a_\mu\) in the SM is a sum of contributions coming from Quantum Electrodynamics (QED), electroweak and hadronic sectors:

\[
a_\mu^{\text{SM}} = a_\mu^{\text{QED}} + a_\mu^{\text{electroweak}} + a_\mu^{\text{hadronic}}. \tag{3}
\]

Among these three contributions, the QED and the electroweak contributions have been verified to high precision \([30, 31]\). Therefore, it is possible that the discrepancy arises due some unknown loop contributions to \(a_\mu^{\text{hadronic}}\) \([32, 33]\). Another possibility is that the discrepancy is caused by new physics at TeV scale. Recently, the Fermilab muon \((g - 2)\) collaboration (FNAL) has announced an improved measurement \([11]\)

\[
a_\mu^{\text{FNAL}} = 116592040(54) \times 10^{-11}. \tag{4}
\]

This new result confirms the BNL measurement and increases the extent of discrepancy to 4.2σ level with \(\Delta a_\mu = (251 \pm 59) \times 10^{-11}\). On the theoretical frontier, a proposed experiment MUonE \([35]\), aims to reduce the theoretical uncertainty in \(a_\mu^{\text{hadronic}}\) by directly measuring the hadronic vacuum polarization more precisely. The theoretical studies to account for the muon \((g - 2)\) anomaly can be found in references \([4–8, 10, 36–51]\).

To address this anomaly most of the recent studies \([52–60]\) focus on new physics governed by \(U(1)_{L_\mu - L_\tau}\) symmetry. While the total lepton number, \(L\), is a sum of individual lepton numbers \(L_e\),
$L_{\mu}$ and $L_{\tau}$, one can always choose the difference between any pair of the lepton numbers, such as $L_e - L_{\mu}$ or $L_{\mu} - L_{\tau}$ or $L_e - L_{\tau}$, and gauge it to obtain an anomaly free theory. Of these, known phenomenology rules out any but the gauged $U(1)_{L_{\mu} - L_{\tau}}$ symmetry. The parameters associated with the new gauge boson, $Z_{\mu\tau}$, are not constrained by lepton and hadron colliders since it does not couple to electrons and quarks. Many of the new physics scenarios have explored the $U(1)_{L_{\mu} - L_{\tau}}$ extension of the SM in the context of neutrino masses and mixing, muon $(g-2)$ anomaly, dark matter and so on \cite{52-70}. By comparison the $U(1)_{L_{\mu} - L_{\tau}}$ extended left-right symmetric theories have been less explored. The left-right symmetric model (LRSM) \cite{71-78} is one of the successful beyond SM scenarios, which gives an unified answer to the origin of small neutrino masses as well as parity violation in low-energy weak interactions. LRSM naturally hosts a right-handed neutrino and offers rich phenomenological aspects in the context of explaining neutrino mass, lepton number violation (LNV), lepton flavor violation (LFV) and so on.

In this paper, we consider an $U(1)_{L_{\mu} - L_{\tau}}$ extended LRSM described in \cite{79}. We explore the constraints on the small neutrino masses in this model, arising from the new physics which explains the muon $(g-2)$ anomaly. In manifest LRSM the neutrino masses are generated through type-I+II seesaw mechanism, thus providing a very high scale for the right-handed symmetry breaking ($>10^{14}$ GeV) which is far beyond present collider reach. However, addition of extra particles to LRSM allows the generation of neutrino mass at a few TeV scale by low-scale seesaw mechanism such as linear seesaw, inverse seesaw, double seesaw and so on \cite{80-102}. In our previous work, described in \cite{79}, we have considered the LRSM inverse seesaw (LISS) scenario for the generation of neutrino masses. The symmetries of this model impose severe constraints on the structure of the light neutrino mass matrix and restrict the allowed values of the lightest neutrino mass and the CP-violating phase $\delta$. In addition, the model also allows charged lepton flavor violation at a level observable in near future.

The rest of the paper is organised as follows. In section \ref{sec:model} we outline the model of the $U(1)_{L_{\mu} - L_{\tau}}$ extended LRSM. In section \ref{sec:muon} we explore which of the contributions of the model to muon $(g-2)$ can explain the observed anomaly. In section \ref{sec:tau} we study the decay $\tau \to \mu\gamma$ and in section \ref{sec:neutrino} we study the model constraints on light neutrino masses and the CP-violating phase. We present our conclusion in the last section.

\section{The Model} \label{sec:model}

The model is an $U(1)_{L_{\mu} - L_{\tau}}$ extended left-right symmetric theory with the gauge group defined as

\[ G_{LR}^{\mu\tau} \equiv U(2)_L \times SU(2)_R \times U(1)_{B-L} \times SU(3)_C \times U(1)_{L_{\mu} - L_{\tau}}. \]  

(5)
The particle content of the model is given in table I.

| Fields | $SU(2)_L$ | $SU(2)_R$ | $B - L$ | $SU(3)_C$ | $U(1)_{L_\mu - L_\tau}$ |
|--------|-----------|-----------|---------|------------|------------------------|
| Fermions | $q_L$ | 2 | 1 | $1/3$ | 3 | 0 |
|          | $q_R$ | 1 | 2 | $1/3$ | 3 | 0 |
|          | $\ell_{eL}$ | 2 | 1 | -1 | 1 | 0 |
|          | $\ell_{\mu L}$ | 2 | 1 | -1 | 1 | 1 |
|          | $\ell_{eR}$ | 1 | 2 | -1 | 1 | 0 |
|          | $\ell_{\mu R}$ | 1 | 2 | -1 | 1 | 1 |
| Extra Steriles | $S_{eL}$ | 1 | 1 | 0 | 1 | 0 |
|          | $S_{\mu L}$ | 1 | 1 | 0 | 1 | 1 |
|          | $S_{\tau L}$ | 1 | 1 | 0 | 1 | 1 |
| Scalars | $\Phi$ | 2 | 2 | 0 | 1 | 0 |
|          | $H_L$ | 2 | 1 | 1 | 1 | 0 |
|          | $H_R$ | 1 | 2 | 1 | 1 | 0 |
| Extra Scalar | $\chi$ | 1 | 1 | 0 | 1 | 1 |

**TABLE I.** Particle content of the left-right symmetric theory extended with $U(1)_{L_\mu - L_\tau}$ gauge symmetry. The model contains three sets of extra sterile fermions ($S_L$) and one extra scalar ($\chi$) along with the usual fermions and scalars present in it.

We have considered a doublet-variant LRSM in this work [79]. Apart from the usual fermions and scalars present in the model, it contains a set of three extra fermions which are sterile and one extra scalar. The extra scalar which is singlet under left-right symmetry is non-trivially charged under $U(1)_{L_\mu - L_\tau}$ and helps to break the $U(1)_{L_\mu - L_\tau}$ symmetry. The extra sterile fermions help to generate the neutrino masses through LISS mechanism. We have termed this scenario as extended LRSM inverse seesaw (ELISS) scenario. More details about the choice and advantages of the model can be found in [79].

In the scheme, the non-zero vev of $H_R$ breaks the left-right symmetry to SM while $H_L$ is required for left-right invariance. Further, the spontaneous symmetry breaking (SSB) of SM to low energy theory occurs when the scalar bidoublet $\Phi$ takes a non-zero vev and that generates masses for charged
leptons and quarks. This is as in the usual LRSM. Additionally, the vev of $\chi$ accomplishes the SSB of $U(1)_{L_{\mu}-L_{\tau}}$. The vev structure of the Higgs spectrum is as follows:

$$\langle H_R \rangle = \begin{pmatrix} 0 \\ v_R \end{pmatrix}, \quad \langle H_L \rangle = \begin{pmatrix} 0 \\ v_L \end{pmatrix}, \quad \langle \Phi \rangle = \begin{pmatrix} v_1 & 0 \\ 0 & v_2 e^{i\alpha} \end{pmatrix}, \quad \langle \chi \rangle = u,$$

where $\alpha$ is the relative phase between the two vevs of the bidoublet. For the usual particle content of the double-variant LRSM the allowed Yukawa interactions for the leptons are given by,

$$-L_{Yuk} \supset \ell_L e_L \left[ Y_{\ell} \Phi + \tilde{Y}_{\ell} \tilde{\Phi} \right] \ell_L + \ell_{\mu L} \left[ Y_{\ell} \Phi + \tilde{Y}_{\ell} \tilde{\Phi} \right] \ell_{\mu L} + \ell_{\tau L} \left[ Y_{\ell} \Phi + \tilde{Y}_{\ell} \tilde{\Phi} \right] \ell_{\tau L} + \text{h.c.}$$

with $\tilde{\Phi} = \sigma_2 \Phi^* \sigma_2$ where $\sigma$’s are the Pauli matrices. Then, after SSB of $SU(2)_R$ and $SU(2)_L$, the masses for charged leptons and the Dirac masses for neutrinos can be expressed as

$$M_\ell \simeq \tilde{Y}_\ell v_1, \quad M'_D = Y_\ell v_1 + \tilde{Y}_\ell v_2 e^{-i\alpha} \simeq v_1 \left( Y_\ell + M_\ell \frac{v_2}{v_1} e^{-i\alpha} \right).$$

with $Y_\ell \ll \tilde{Y}_\ell$, $v_2 \ll v_1$. The $U(1)_{L_{\mu}-L_{\tau}}$ symmetry of our framework constrains $Y_\ell$ and $\tilde{Y}_\ell$ to be diagonal [79].

The sterile fermions of the ELISS scenario then provide additional contributions to the neutrino mass matrix. With charge assignments as in table I the relevant $U(1)_{L_{\mu}-L_{\tau}}$ invariant Yukawa interaction Lagrangian in this scheme is given by,

$$-L_{\text{ELISS}} \supset L_{\nu L N R} + L_{N R S L} + L_{S L S L} + L_{\chi}.$$  

The neutrino Dirac mass matrix $M'_D$ results from $L_{\nu L N R}$.

The mixing between the fields $N_R$ and $S_L$ arises from

$$L_{N R S L} \supset Y_{R S} \tilde{H}_R S_L = Y_{R S} \langle \tilde{H}_R \rangle \left[ \ell_{e L} S_{e L} + \ell_{\mu L} S_{\mu L} + \ell_{\tau L} S_{\tau L} \right].$$

The matrix $Y_{R S} \langle \tilde{H}_R \rangle \equiv M$ is also constrained to be diagonal due to $U(1)_{L_{\mu}-L_{\tau}}$ symmetry.

The bare Majorana mass term for extra steriles $S_L$ is given by,

$$L_{S L S L} = S_L^T \mu_S S_L = \left[ \mu_{ee} S_{e L} S_{e L} + \mu_{\mu \tau} S_{\mu L} S_{\tau L} + \mu_{\mu \tau} S_{\tau L} S_{\mu L} \right].$$

where the bare Majorana mass matrix can be expressed as,

$$\mu_S^{\text{bare}} = \begin{pmatrix} \mu_{ee} & 0 & 0 \\ 0 & \mu_{\mu \tau} & 0 \\ 0 & 0 & \mu_{\mu \tau} \end{pmatrix}.$$
The form of $\mu_{S}^{\text{bare}}$ is dictated by $U(1)_{L_{\mu} - L_{\tau}}$ symmetry. The extra scalar $\chi$, needed for the SSB of $U(1)_{L_{\mu} - L_{\tau}}$, couples to the sterile fields as

$$\mathcal{L}_\chi \supset \mu_{\mu S} S_{L_{\mu}}^T S_{L_{\mu}} \chi^* + \mu_{\tau S} S_{L_{\tau}}^T S_{L_{\tau}} \chi^* + \mu_{\mu S} S_{L_{\mu}}^T S_{L_{\mu}} \chi^* + \mu_{\tau S} S_{L_{\tau}}^T S_{L_{\mu}} \chi.$$  \hspace{1cm} (13)

When $\chi$ acquires a vev the above Lagrangian leads to a matrix $\mu_{S}^{SSB}$, which is of the form

$$\mu_{S}^{SSB} = \begin{pmatrix}
0 & \mu_{\mu S} & \mu_{\tau S} \\
\mu_{\mu S} & 0 & 0 \\
\mu_{\tau S} & 0 & 0
\end{pmatrix}. \hspace{1cm} (14)$$

The total $\mu_{S}$ matrix, whose elements are in general complex, is given by

$$\mu_{S} = \mu_{S}^{\text{bare}} + \mu_{S}^{SSB} = \begin{pmatrix}
\mu_{ee} & \mu_{\mu S} & \mu_{\tau S} \\
\mu_{\mu S} & 0 & \mu_{\mu \tau} \\
\mu_{\tau S} & \mu_{\mu \tau} & 0
\end{pmatrix}. \hspace{1cm} (15)$$

The complete $9 \times 9$ neutral fermion mass matrix in the basis $\{\nu_{L}, \nu_{R}^c, S_{L}\}$ takes the form

$$M = \begin{pmatrix}
0 & M_{D}^\nu & 0 \\
M_{D}^\nu & 0 & M^T \\
0 & M & \mu_{S}
\end{pmatrix}. \hspace{1cm} (16)$$

Thus, for mass hierarchy $M > M_{D}^\nu \gg \mu_{S}$, the light neutrinos masses in ELISS scenario is read as

$$m_{\nu} = M_{D}^\nu M^{-1} \mu_{S} \left(M_{D}^\nu M^{-1}\right)^T. \hspace{1cm} (17)$$

Parametrizing the diagonal matrices $M_{D}^\nu$ as $\text{dia}(a, b, c)$ and $M$ as $\text{dia}(M_{11}, M_{22}, M_{33})$, we find

$$m_{\nu} = \begin{pmatrix}
a^2 \mu_{ee} & ab \mu_{\mu S} & ac \mu_{\tau S} \\
ab \mu_{\mu S} & b^2 M_{11} & bc \mu_{\mu \tau} \\
ac \mu_{\tau S} & bc \mu_{\mu \tau} & c^2 M_{33}
\end{pmatrix}. \hspace{1cm} (18)$$

This complex symmetric matrix, when diagonalised by a unitary matrix, gives rise to three non-degenerate eigenvalues. It is possible to have sub-eV scale for these eigenvalues as shown below

$$\frac{m_{\nu}}{0.1 \text{ eV}} = \left(\frac{M_{D}^\nu}{100 \text{ GeV}}\right)^2 \frac{\mu_{S}}{\text{eV}} \left(\frac{M}{100 \text{ GeV}}\right)^{-2}. \hspace{1cm} (19)$$

Indeed the main advantage we derive from this construction is the sizeable light-heavy neutrino mixing ($V_{\nu \xi} = M_{D}^\nu M^{-1} \sim \mathcal{O}(0.1 - 1)$) with $M$ at few GeV scale. This plays an important role in the explanation of the muon anomaly as discussed in the next section. For more details of the neutrino mass structure one can refer to [79].
III. MODEL PREDICTION MUON \((g - 2)\) WITH FNAL DATA

In the model described in the previous section, the contributions to \(\Delta a_\mu\), arise from the interactions of:

- singly charged gauge bosons \((W_L, W_R)\) with heavy neutral lepton,
- neutral vector boson \((Z_R)\) with singly charged leptons,
- singly charged scalars with neutral lepton,
- neutral scalars with muons,
- extra new gauge boson \(Z_{\mu\tau}\) with muons.

In the following we write down the analytic expressions for each of the contributions and study numerically all these contributions to \(\Delta a_\mu\). Details of the analytical calculations and the numerical comparison with the BNL data are given in [79].

(a) Contribution due to heavy gauge boson mediation:

- **W \(_L\) mediation**:
  \[
  \Delta a_\mu(W_L) \simeq 9.06 \times 10^{-9} g_L^2 \sum_{i=1,\ldots,6} |V_{\nu\xi}^{\mu i}|^2, \tag{20}
  \]

- **W \(_R\) mediation**:
  \[
  \Delta a_\mu(W_R) \simeq 2.3 \times 10^{-11} \left(\frac{g_R}{g_L}\right)^2 \left(\frac{1 \text{ TeV}}{m_{W_R}}\right)^2, \tag{21}
  \]

- **Z \(_R\) mediation**:
  \[
  \Delta a_\mu(Z_R) \simeq -\frac{1}{4\pi^2 m_{Z_R}^2} \left[\left(\frac{1}{3}\right) |g_L^\rho|^2 + \left(\frac{5}{3}\right) |g_R^\rho|^2\right]. \tag{22}
  \]

with \(m_{W_L}, m_{W_R}, m_{Z_R} \gg m_\mu\) where \(m_{W_L}, m_{W_R}, m_{Z_R}\) and \(m_\mu\) are the respective masses for \(W_L, W_R, Z_R\) and muon and \(g_L\) and \(g_R\) are the respective gauge couplings of \(SU(2)_L\) and \(SU(2)_R\). In our previous work [79] it was shown that the contribution from Eq. 20 can explain the muon \(g - 2\) anomaly by itself provided the light-heavy neutrino mixing factor, \(V_{\nu\xi}^{\mu i}\), is in the range \(O(0.7 - 1)\). However, such large light-heavy neutrino mixing factors are forbidden by the constraints on the deviation from the unitarity in the mixing of the active flavors [106]. In particular, the constraint on such deviation for muon flavor is very strong \((|V_{\nu\xi}^{\mu}|^2)/2 \equiv |\eta_{\mu\mu}| \leq 8.0 \times 10^{-4}\) [114-117]. Hence, the contribution of heavy gauge boson exchange to muon \(g - 2\) is negligibly small \((< 10^{-11})\).

(b) Contribution due to scalar mediation: the scalar sector contributions of this model are coming
from the Higgs bi-doublet, $\Phi$.

Charged Scalar mediation: $\Delta a_\mu^{(CS)} \simeq -\frac{1}{4\pi^2} \frac{m_\mu^2}{m_{CS}^2} \left[ |g_{s1}^\mu|^2 \left( \frac{1}{12} \right) + |g_{p1}^\mu|^2 \left( \frac{1}{12} \right) \right]$, \hspace{1cm} (23)

Neutral Scalar mediation:

$\Delta a_\mu^{(NS)} \simeq \frac{1}{4\pi^2} \frac{m_\mu^2}{m_{NS}^2} \left[ |g_{s2}^\mu|^2 \left( -\frac{7}{12} - \log \left( \frac{m_\mu}{m_{NS}} \right) \right) + |g_{p2}^\mu|^2 \left( \frac{11}{12} + \log \left( \frac{m_\mu}{m_{NS}} \right) \right) \right]$, \hspace{1cm} (24)

where $m_{CS}$ and $m_{NS}$ are the masses of the charged and the neutral scalars respectively. The couplings $g_{s1}^\mu, g_{p1}^\mu, g_{s2}^\mu$ and $g_{p2}^\mu$ are related to muon Yukawa coupling which is of order $m_\mu/m_W \sim 10^{-3}$. The lower limits on scalar masses are

- $m_{CS} > 1.1$ TeV from direct search [118],
- $m_{NS} > 1870$ GeV through direct search for CP-even scalars [119],
- $m_{NS} > 20$ TeV through FCNC for CP-odd scalars [120].

Given these small couplings and large masses it is straightforward to show that the maximum possible contribution to $\Delta a_\mu$ from scalar exchange is $\mathcal{O}(10^{-16})$.

FIG. 1. Plot showing the contribution coming from new gauge boson $Z_{\mu\tau}$ vs mass of $Z_{\mu\tau}$.

(c) Contribution due to extra gauge boson, $Z_{\mu\tau}$ mediation:

$\Delta a_\mu^{(Z_{\mu\tau})} = \frac{g_{\mu\tau}^2 m_\mu^2}{12\pi^2 m_{Z_{\mu\tau}}^2}$, \hspace{1cm} (25)

where $m_{Z_{\mu\tau}}$ and $g_{\mu\tau}$ are the mass of the $Z_{\mu\tau}$ and coupling between the $Z_{\mu\tau}$ and $\mu$, respectively.
The contributions coming from new gauge boson $Z_{\mu\tau}$ to $\Delta a_\mu$ is presented in figure 1. Both $m_{Z_{\mu\tau}}$ and $g_{\mu\tau}$ are strongly constrained by the measurement of neutrino trident cross section by experiments like CHARM-II \[121\] and CCFR \[122\]. The present limits are $m_{Z_{\mu\tau}}$ in the range $(100 - 200)$ MeV and $g_{\mu\tau} \leq 10^{-3}$. In our numerical analysis we have fixed $g_{\mu\tau} = 8 \times 10^{-4}$ (just below the experimental limit) and varied the $m_{Z_{\mu\tau}}$ in its allowed range. We see that $m_{Z_{\mu\tau}}$ in the range $(140 - 190)$ MeV can account for the entire anomaly. The $Z_{\mu\tau}$ exchange is the mechanism to explain the muon $(g - 2)$ anomaly in our model because the contributions from both the heavy gauge boson exchange and the heavy scalar exchange are negligibly small.

**IV. CHARGED LEPTON FLAVOR VIOLATION**

Our model predicts observably large charged lepton flavor violation (cLFV) in the $\mu - \tau$ sector. Here we consider the radiative decay $\tau \to \mu\gamma$ whose branching ratio has the upper limit $\text{BR}(\tau \to \mu\gamma)$ is $< 1.5 \times 10^{-8}$ \[123\]. This decay can occur either through $W_L$ and $W_R$ mediation or through charged scalar mediation. The $U(1)_{L_\mu - L_\tau}$ symmetry forbids this decay through both $Z_R$ and $Z_{\mu\tau}$ mediation and through neutral scalar mediation.

![Feynman diagram for $\tau \to \mu\gamma$ process.](image)

The Feynman diagram for $\tau \to \mu\gamma$ through $W_L$ mediation is shown in figure 2. The expression for the branching ratio is given by \[37\]

$$
\text{BR}(\tau \to \mu\gamma) \sim \frac{3(4\pi)^3 \alpha_{em}}{4G_F^2} \left[ |A_{\mu\tau}^M|^2 + |A_{\mu\tau}^E|^2 \right],
$$

(26)

where $G_F$ is the Fermi’s constant of weak interactions and $\alpha_{em}$ is the electromagnetic fine structure constant. The quantities $A_{\mu\tau}^M$ and $A_{\mu\tau}^E$ are the magnetic and electric dipole transition amplitudes.
In the $W_L$ mediated diagram we have $m_\xi \simeq M_{W_L} \gg m_\tau$. In this limit, we have

$$A^M_{\mu \tau} = i A^E_{\mu \tau} \simeq -\frac{1}{16\pi^2 M_{W_L}^2} \left( \frac{g^2_L}{2} \right) \left( \frac{17}{12} \right) \frac{\nu^\mu \xi \nu^\mu_\xi}{\nu^\tau_\xi \nu^\mu_\xi} \quad (27)$$

$$\implies \text{BR}(\tau \to \mu \gamma) \simeq 6.43 \times 10^{-6} \left( \frac{1 \text{ TeV}}{M_{W_L}} \right)^4 \left| \nu^\mu_\tau \nu^\mu_\xi \right|^2 \simeq 0.16 \left| \nu^\tau_\xi \nu^\mu_\mu \right|^2. \quad (28)$$

The predicted branching ratio is of the order of the present upper limit if

$$\left| \nu^\tau_\xi \nu^\mu_\mu \right|^2 < 10^{-7}. \quad (29)$$

In the previous section we noted that the experimental bound on the deviation from unitarity in muon sector is $(|V^\mu_\mu|^2) \leq 1.6 \times 10^{-3}$. The corresponding limit in the tau sector is $(|V^\tau_\tau|^2) \leq 5.4 \times 10^{-3}$ \cite{113,114,115,116}. The values of light-heavy neutrino mixing needed to obtain observably large branching ratio of $\tau \to \mu \gamma$, given in Eq. 29, are well within these non-unitarity bounds.

For $W_R$ mediated diagram we will have expressions for $A^M_{\mu \tau}, A^E_{\mu \tau}$ and $\text{BR}(\tau \to \mu \gamma)$ similar to those in Eq. 28 with $M_{W_L}$ replaced by $M_{W_R}$. Since $M_{W_R}$ is at least an order of magnitude greater than $M_{W_L}$, this contribution is expected to be very small.

V. ESTIMATION OF NEUTRINO MASSES

In this section, we consider the constraints our model imposes on the parameters of light neutrino sector. In the framework of the LISS mechanism described in section II, the mass matrix for the neutral fermions $M_D$, given in Eq. 8, and the $N_R - S_L$ coupling matrix $M$, given in Eq. 10, are diagonal. The explicit form of light neutrino mass matrix $m_\nu$ is given in Eq. 18. This matrix is non-diagonal because the matrix $\mu_S$ is non-diagonal.

As discussed in section II the $U(1)_{L_\mu-L_\tau}$ symmetry of the model requires

$$(\mu_S)_{\mu \mu} = 0 = (\mu_S)_{\tau \tau} \implies (m_\nu)_{\mu \mu} = 0 = (m_\nu)_{\tau \tau}. \quad (30)$$

That is: the effective masses of $\nu_\mu$ and $\nu_\tau$ should vanish in this model. The different textures of neutrino mass matrices, with two zero elements are classified in \cite{121}. The texture with $(m_\nu)_{22} = 0 = (m_\nu)_{33}$ is labelled "C" in that classification. The compatibility of different two zero textures with precision neutrino oscillation data is studied in \cite{122}. The four solutions, shown in table II, give the predictions of their fit for the smallest neutrino mass, sum of light neutrino masses, the effective mass for neutrinoless double beta decay and the phases $\delta, \alpha_1$ and $\alpha_2$.

We note that in all four cases the sum of light neutrino masses exceeds the cosmological upper bound of 0.11 eV \cite{123}. The violation of the upper bound is much more modest in the case of
IH than in the case of NH. The symmetries of the model impose a particular two-zero texture on the light neutrino mass matrix. The texture constraints, when combined with neutrino oscillation data and the cosmological bound on the sum of light neutrino masses, show a strong preference for inverted hierarchy. They also require $\delta$, the CP violating phase in neutrino oscillations, to be close to maximal.

The neutrino data plus the constraints of the model strongly prefer inverted hierarchy. They also predict a value of $\delta$ which leads to a large CP violation in neutrino oscillations.

### VI. CONCLUSION

We have studied an $U(1)_{L_\mu - L_\tau}$ extended left-right theory. In this framework the neutrino masses are generated via inverse seesaw scenario. We did a numerical analysis of muon $(g - 2)$ anomaly in this model. Given the stringent constraints on deviation from unitarity on the mixings of active lepton flavors, we found that the muon $(g - 2)$ anomaly cannot be explained through the mediation of either heavy gauge bosons or heavy scalars. However the model contains a neutral light gauge boson $Z_{\mu\tau}$ arising from the gauged $U(1)_{L_\mu - L_\tau}$ symmetry. Both the mass and couplings of this gauge boson are strongly constrained by the neutrino trident cross section. The muon $(g - 2)$ anomaly can fully be accounted for the gauge coupling strength $g_{\mu\tau} = 8 \times 10^{-4}$ and $m_{Z_{\mu\tau}}$ in the range $(140 - 190)$ MeV, both of which are allowed by present data.

The model also predicts observable cLFV in $\mu - \tau$ sector. We studied the decay $\tau \rightarrow \mu \gamma$ in this model and found that an observable branching ratio is possible even while satisfying the stringent constraints on light-heavy neutrino mixing. Other interesting charged lepton flavor violation will be considered in future work.

The $U(1)_{L_\mu - L_\tau}$ symmetry of the model imposes the following constraints on the light neutrino
mass matrix : \((m_\nu)_{\mu\mu} = 0 = (m_\nu)_{\tau\tau}\). These two constraints can be satisfied simultaneously only for some very specific values of light neutrino masses. In the case of NH, the allowed value of the lightest neutrino mass is \(m_1 = 0.16\) eV which leads to a strong violation of the cosmological upper bound on the sum of light neutrino masses. In the case of IH, the allowed value of the lightest neutrino mass are \(m_3 = 0.035\) eV, which leads to a much milder violation of the cosmological upper bound. In the latter case, the combination of model constraints and the neutrino data require the value of \(\delta\) to be in the range which leads to a large CP violation in neutrino oscillations. The Majorana phases \(\alpha_1\) and \(\alpha_2\) are constrained to be close to 180 so that the necessary cancellations in \((m_\nu)_{\mu\mu}\) and \((m_\nu)_{\tau\tau}\) can take place. Thus the model predicts moderate values for the minimum neutrino mass and the effective mass \((m_\nu)_{ee}\) for neutrinoless double beta decay but predicts a very large CP violation in neutrino oscillations.

VII. ACKNOWLEDGEMENT

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