Neutrino Mass, Dark Matter and Anomalous Magnetic Moment of Muon in a $U(1)_{L_\mu - L_\tau}$ Model

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Abstract

The observation of neutrino masses, mixing and the existence of dark matter are amongst the most important signatures of physics beyond the Standard Model (SM). In this paper, we propose to extend the SM by a local $L_\mu - L_\tau$ gauge symmetry, two additional complex scalars and three right-handed neutrinos. The $L_\mu - L_\tau$ gauge symmetry is broken spontaneously when one of the scalars acquires a vacuum expectation value. The $L_\mu - L_\tau$ gauge symmetry is known to be anomaly free and can explain the beyond SM measurement of the anomalous muon $(g - 2)$ through additional contribution arising from the extra $Z_{\mu\tau}$ mediated diagram. Small neutrino masses are explained naturally through the Type-I seesaw mechanism, while the mixing angles are predicted to be in their observed ranges due to the broken $L_\mu - L_\tau$ symmetry. The second complex scalar is shown to be stable and becomes the dark matter candidate in our model. We show that while the $Z_{\mu\tau}$ portal is ineffective for the parameters needed to explain the anomalous muon $(g - 2)$ data, the correct dark matter relic abundance can easily be obtained from annihilation through the Higgs portal. Annihilation of the scalar dark matter in our model can also explain the Galactic Centre gamma ray excess observed by Fermi-LAT. We show the predictions of our model for future direct detection experiments and neutrino oscillation experiments.

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I. INTRODUCTION

Explaining the origin of nonzero neutrino masses and dark matter (DM) are two of the principal challenges which theoretical high energy physics has been facing over the last few decades. Neutrinos were predicted to be massless in the Standard Model (SM) of particle physics. However, in 1998 the neutrino oscillation (oscillation between mass and flavour eigenstates) which requires nonzero mass differences between different generation of neutrinos and mixing between them, was unambiguously observed by the Super-Kamiokande atmospheric neutrino experiment [2]. Existence of neutrino mass and mixing requires the extension of the SM. Neutrino oscillations have now been established at a very high confidence level by many outstanding experimental observations by experiments such as SNO [3] (solar neutrino experiment), KamLand [4] (reactor neutrino experiment), Daya Bay [5], RENO [6], Double Chooz [7] (reactor neutrino experiments with short baselines), T2K [8, 9] and NOνA [10, 11] (accelerator neutrino experiments). At present for normal (inverted) mass ordering scenarios, the best fit values [12] of neutrino oscillation parameters obtained from global neutrino oscillation data are:

\[
\begin{align*}
\Delta m^2_{21} &= 7.37 \times 10^{-5} \, \text{eV}^2, \\
|\Delta m^2_{\text{atm}}| &= 2.50 (2.46) \times 10^{-5} \, \text{eV}^2 \\
\theta_{12} &= 33.02^\circ, \quad \theta_{23} = 41.38^\circ (48.97^\circ), \quad \theta_{13} = 8.41^\circ (8.49^\circ)
\end{align*}
\]

(1)

On other hand, the existence of dark matter in the Universe has been confirmed to a very high statistical significance by many indirect evidences such as the flatness of rotation curves of spiral galaxies [13], collision of galaxies in a galaxy cluster (bullet cluster and others) [14, 15], gravitational lensing [16] and the measurements of the Cosmic Microwave Background (CMB) [17, 18]. The satellite borne CMB experiments, WMAP [17] and Planck [18], have measured the fractional contribution of dark matter to the present energy density of the Universe (commonly known as DM relic density) to be around 0.25 with an extremely good accuracy, while the contribution of the visible baryonic matter is only around 0.05. The rest \( \sim 70\% \) of energy density of the Universe is also coming from an mysterious energy called the Dark Energy [19]. The current best observed value of DM relic density is [18]

\[
\Omega_{\text{DM}} h^2 = 0.1197 \pm 0.0022.
\]

(2)

Like the neutrino sector mentioned before, the SM of particle physics does not have any stable particle(s) which can play the role of viable DM candidate(s). Therefore beyond Standard Model (BSM) scenario is required to explain these two long standing puzzles. Weakly Interacting Massive Particles (WIMP) [20, 21] have been proposed as one of the most promising candidates to

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1 We define \( \Delta m^2_{ij} = m_i^2 - m_j^2 \). The mass squared difference \( \Delta m^2_{\text{atm}} = m_3^2 - ((m_2^2 + m_1^2)/2) \), where we use the notation given in [12].
explain the dark matter puzzle of the Universe. Many direct detection experiments like LUX \cite{22}, XENON \cite{23} and CDMS \cite{24} have been trying to detect WIMPs through their spin independent as well as spin dependent elastic scattering with the detector nuclei. However, no convincing signature of WIMPs has been observed yet in the direct detection experiments, giving bounds on the WIMP-nucleon scattering cross section. Recently, the LUX collaboration has reported the most stringent upper bound on DM-nucleon spin independent scattering cross section to be around $2.2 \times 10^{-46}$ cm$^{-2}$ \cite{25} for a $\sim 50$ GeV DM particle.

Signature of DM can also appear in indirect detection experiments, looking for high energy neutrinos, gamma rays and charged cosmic rays (electrons, positrons, protons and antiprotons) coming from the annihilation or decay of DM particles \cite{26}. In this work, we will briefly discuss about the Galactic Centre gamma-ray excess in the energy range 1-3 GeV which has been observed by the Fermi-LAT collaboration \cite{27}. Although, there are some astrophysical explanations such as unresolved point sources (e.g. millisecond pulsar) \cite{28, 29} for this excess gamma-ray flux, but in this work we will explain this anomalous excess by the process of DM annihilation into $b\bar{b}$ final state. The authors of Ref. \cite{30} have given constraints on DM mass and its annihilation cross section $\langle \sigma v \rangle$ to explain the gamma-ray excess which are $48^{+6.4}_{-5.2}$ GeV and $1.75^{+0.28}_{-0.26} \times 10^{-26}$ cm$^3$/s for the $b\bar{b}$ annihilation channel respectively. In the present model we can explain this excess gamma-ray flux in the energy range 1-3 GeV.

The SM has accidental U(1) global symmetries like the baryon ($B$) and the lepton number ($L$) conservation. However, if we want to convert these global symmetries into a local one then they become anomalous. The anomaly free situation can be obtained if instead of considering $B$ and $L$ separately one uses some combinations between them. There are only four non-anomalous combinations possible, and these are $B - L$, $L_e - L_\mu$, $L_\mu - L_\tau$ and $L_e - L_\tau$ where $L_e$, $L_\mu$ and $L_\tau$ are the respective lepton numbers of generations associated with leptons $e$, $\mu$ and $\tau$ while $L = L_e + L_\mu + L_\tau$ is the total lepton number. Out of these four possible combinations, axial vector anomaly \cite{31, 32} and gravitational gauge anomaly \cite{33, 34} of local $B - L$ symmetric models can be cancelled by the introduction of extra chiral fermions to the SM such as three right handed neutrinos \cite{35} or two left and right handed singlet fermions with appropriate $B - L$ charges \cite{36}. However, unlike the $B - L$ case, the anomaly cancellation does not require any extra chiral fermionic degrees of freedom for the last three cases where the linear combinations of different generational lepton numbers \cite{37, 39} are considered. Here anomalies cancel between different leptonic generations. Among these three possible scenarios U(1)$_{L_\mu - L_\tau}$ extension \cite{40, 69} of SM is less constrained as in this case the extra neutral gauge boson does not couple to electron and quarks and therefore $Z_{\mu\tau}$ is free from any constraints coming from lepton and hadron colliders such as LEP \cite{70, 71} and LHC \cite{72}. Therefore, the mass of $Z_{\mu\tau}$ can be as light as $\mathcal{O}$ (100 MeV) for a low value of gauge coupling $g_{\mu\tau} \lesssim 10^{-3}$ which is required to satisfy the constraints arising from neutrino trident production \cite{73}. One of the phenomenological motivation for the U(1)$_{L_\mu - L_\tau}$
extension of the SM is that it can explain the muon \((g - 2)\) anomaly between the theoretical value predicted by the SM \([74]\) which is \(a^\text{th}_\mu = 1.1659179090(65) \times 10^{-3}\) and the experimental value \([75]\) which is \(a^\text{exp}_\mu = 1.16592080(63) \times 10^{-3}\). The difference between theoretical and experimental value \([75]\) is,

\[
\Delta a_\mu = a^\text{exp}_\mu - a^\text{th}_\mu = (29.0 \pm 9.0) \times 10^{-10}.
\] (3)

In this work, we have considered the gauged \(U(1)_L_{\mu - L_\tau}\) extension of the SM. Among the main motivations for our choice of this model is that it provides \(\mu - \tau\) flavor symmetry which could naturally explain the peculiar neutrino mixing parameters (cf. Eq. (1)) wherein \(\theta_{23}\) is close to maximal and \(\theta_{13}\) is small. As mentioned above, this model can also explain the muon \((g - 2)\) anomaly \([77]-[81]\) for a range of \(Z_{\mu\tau}\) mass and \(g_{\mu\tau}\) consistent with collider constraints. We will further extend this model with a complex scalar, which will become a viable DM candidate.

\(U(1)_L_{\mu - L_\tau}\) extended Ma model \([82]\) has been studied earlier in the context of small neutrino mass generation in one loop level \([83]\) and dark matter \([84]\). A review on earlier works about \(\mu - \tau\) flavour symmetry in neutrino sector can be found in \([40]\) and references therein. In order to generate neutrino masses through the Type-I seesaw mechanism \([85]-[88]\) in the present scenario, we have introduced three right handed neutrinos \((N_e, N_\mu, N_\tau)\) with \(L_\mu - L_\tau\) charges 0, 1 and -1 respectively in the fermionic sector of SM. The scalar sector of the model is also enlarged by the addition of two complex scalar singlets \((\phi_H\text{ and }\phi_{DM})\) with nonzero \(L_\mu - L_\tau\) charge. The proposed \(L_\mu - L_\tau\) symmetry is broken spontaneously when \(\phi_H\) acquires vacuum expectation value \((\text{VEV})\) \(v_{\mu\tau}\) and thereby making \(Z_{\mu\tau}\) massive. The breaking of \(L_\mu - L_\tau\) symmetry also results in additional terms in the neutrino mass matrix. In particular, the \(\mu - \tau\) symmetry is broken and we can generate neutrino masses and mixing parameters consistent with current bounds. We show that the complex scalar \(\phi_{DM}\) is stable in our model and hence becomes the DM candidate satisfying the constraints from Planck, LUX and LHC results. We show that a sub-region of the parameter space that is consistent with Planck, LUX and LHC results can also explain the Galactic Centre gamma ray excess observed by Fermi-LAT.

The rest of the article is organised as follows. In Section II we describe the model for the present work. In Section III and Section IV we discuss muon \((g - 2)\) and neutrino masses and mixing angles, respectively. In Section V we study the DM constraints and its related phenomenology. In section VI we conclude.

II. MODEL

In this present work, we have considered a minimal extension of the SM where we have imposed an extra local \(U(1)_{L_\mu - L_\tau}\) symmetry to the SM Lagrangian, where \(L_\mu\) and \(L_\tau\) denote the muon lepton number and tau lepton number respectively. Therefore, the Lagrangian of
the present model remains invariant under the SU(3)c × SU(2)L × U(1)Y × U(1)Lµ−Lτ gauge symmetry. This model is free from axial vector and mixed gravitational gauge anomalies as these anomalies cancel between second and third generations of leptons without the requirement of any additional chiral fermion. The full particle content of our model and their respective charges under SU(2)L × U(1)Y × U(1)Lµ−Lτ gauge groups are listed in Tables I and II. In order to break the U(1)Lµ−Lτ symmetry spontaneously, we need a complex scalar field φH with a non-trivial Lµ−Lτ charge assignment such that the Lµ−Lτ symmetry is broken spontaneously when φH picks up a vacuum expectation value vµτ. Spontaneous breaking of the Lµ−Lτ symmetry generates mass for the extra neutral gauge boson Zµτ. It has been shown that the spontaneously broken Lµ−Lτ model can explain the anomalous muon g − 2 signal. The Lµ−Lτ symmetry is a flavor symmetry and hence can be used to explain the peculiar mixing pattern of the neutrinos. In our model we generate small neutrino masses through the Type-I seesaw mechanism. To that end we introduce three right handed neutrinos (Ne, Nµ, Nτ) with Lµ−Lτ charges of 0, 1 and −1 respectively, such that their presence do not introduce any further anomaly. In the U(1)Lµ−Lτ symmetric limit the right-handed neutrino mass has exact µ−τ symmetry. We will show that the spontaneous breaking of the gauged U(1)Lµ−Lτ symmetry leads to additional terms in the right-handed neutrino mass matrix, providing a natural explanation of the neutrino masses and mixing parameters observed in neutrino oscillation experiments, given in Eq. (1).

We also add another complex scalar field φDM in the model, with a chosen Lµ−Lτ charge nµτ such that the Lagrangian does not contain any term with odd power of φDM. Also the scalar field φDM does not acquire any VEV and consequently in this model φDM becomes odd under a remnant Z2 symmetry after the spontaneous breaking of the gauged U(1)Lµ−Lτ symmetry, which ensure its stability. Hence φDM can be a viable dark matter candidate.

| Gauge Group | Baryon Fields | Lepton Fields | Scalar Fields |
|-------------|---------------|---------------|--------------|
| SU(2)L     | Q′L = (u′L, d′L)T u′R | L′L = (ν′L, e′L)T e′R | φh, φH, φDM |
| U(1)Y      | 2 1 1         | 2 1 1         | 2 1 1        |
|            | 1/6 2/3 −1/3  | −1/2 −1 0    | 1/2 0 0      |

Table I: Particle contents and their corresponding charges under SM gauge group.

We now write the Lagrangian of present model, which is given by

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_N + \mathcal{L}_{DM} + (D_\mu \phi_H)^\dagger (D^\mu \phi_H) - V(\phi_h, \phi_H) - \frac{1}{4} F_{\mu\nu}^\alpha F_{\mu\nu\alpha\beta},$$  (4)
where $\mathcal{L}_{SM}$ is the usual SM Lagrangian while the Lagrangian for the right handed neutrinos containing their kinetic energy terms, mass terms and Yukawa terms with the SM lepton doublets, is denoted by $\mathcal{L}_N$ which can be written as

$$\mathcal{L}_N = \sum_{i=e,\mu,\tau} \left[ i \frac{1}{2} \overline{N_i} \gamma^\mu D_\mu N_i - \frac{1}{2} M_{ee} \overline{N_e} N_e - \frac{1}{2} M_{\mu\tau} (\overline{N_\mu} N_\tau + \overline{N_\tau} N_\mu) \right. $$

$$ - \frac{1}{2} h_{e\mu} (\overline{N_\mu} N_e + \overline{N_e} N_\mu) \phi_H^\dagger - \frac{1}{2} h_{e\tau} (\overline{N_\tau} N_e + \overline{N_e} N_\tau) \phi_H $$

$$ - \sum_{i=e,\mu,\tau} y_i \overline{\tilde{L}_i} \phi_H N_i + h.c. \tag{5} $$

with $\tilde{\phi}_h = i \sigma_2 \phi_h^\dagger$ and $M_{ee}, M_{\mu\tau}$ are constants having dimension of mass while the Yukawa couplings $h_{e\mu}, h_{e\tau}$ and $y_i$ are dimensionless constants. In Eq. (4), $\mathcal{L}_{DM}$ represents the dark sector Lagrangian including the interactions of $\phi_H$ with other scalar fields. The expression of $\mathcal{L}_{DM}$ is given by

$$\mathcal{L}_{DM} = (D^\mu \phi_{DM})^\dagger (D_\mu \phi_{DM}) - \lambda_{DM}(\phi_H^\dagger \phi_{DM})^2 - \lambda_{DH}(\phi_H^\dagger \phi_{DM})(\phi_H^\dagger \phi_H). \tag{6}$$

Moreover, the quantity $V(\phi_h, \phi_H)$ in Eq. (4) contains all the self interaction of $\phi_H$ and its interaction with SM Higgs doublet. Therefore,

$$V(\phi_h, \phi_H) = \mu_H^2 \phi_H^\dagger \phi_H + \lambda_H (\phi_H^\dagger \phi_H)^2 + \lambda_{hH}(\phi_h^\dagger \phi_h)(\phi_H^\dagger \phi_H). \tag{7}$$

The expressions of all the covariant derivatives appearing in Eqs. (4)-(6) can be written in a generic form which is given as

$$D_\mu X = (\partial_\mu + i g_{\mu\tau} Q_{\mu\tau}(X) Z_{\mu\tau}) X, \tag{8}$$

where $X$ is any field which is singlet under SM gauge group but has a $L_\mu - L_\tau$ charge $Q_{\mu\tau}(X)$ (see Table III) and $g_{\mu\tau}$ is the gauge coupling of the $U(1)_{L_\mu-L_\tau}$ group. Furthermore, the last term in Eq. (4) represents the kinetic term for the extra neutral gauge boson $Z_{\mu\tau}$ in terms of its field strength tensor $F_{\mu\tau} = \partial_\mu Z_{\mu\tau} - \partial_\tau Z_{\mu\tau}^\alpha \phi_{DM}.$

The $L_\mu - L_\tau$ symmetry breaks spontaneously when $\phi_H$ acquires VEV and consequently the corresponding gauge field $Z_{\mu\tau}$ becomes massive, $M_{Z_{\mu\tau}} = g_{\mu\tau} v_{\mu\tau}.$ In the unitary gauge, the
expressions of $\phi_h$ and $\phi_H$ after spontaneous breaking of the $\text{SU}(2)_L \times \text{U}(1)_Y \times \text{U}(1)_{L_\mu-L_\tau}$ gauge symmetry are

$$
\phi_h = \begin{pmatrix} 0 \\ v + H \end{pmatrix}, \quad \phi_H = \begin{pmatrix} v_{\mu\tau} + H_{\mu\tau} \\ \sqrt{2} \end{pmatrix},
$$

where $v$ and $v_{\mu\tau}$ are the VEVs of $\phi_h$ and $\phi_H$ respectively. Presence of the mutual interaction term in Eq. (7) between $\phi_h$ and $\phi_H$ introduces mass mixing between the scalar fields $H$ and $H_{\mu\tau}$. The scalar mass matrix with off-diagonal elements proportional to $\lambda_{hH}$ is given by

$$
M^2_{\text{scalar}} = \begin{pmatrix} 2\lambda_h v^2 + \lambda_{hH} v_{\mu\tau} v \\ \lambda_{hH} v_{\mu\tau} v & 2\lambda_H v_{\mu\tau}^2 \end{pmatrix}. \tag{10}
$$

From the expression of $M^2_{\text{scalar}}$, it is evident that if $\lambda_{hH} = 0$ (i.e. the interaction between $\phi_h$ and $\phi_H$ is absent), there is no mixing between $H$ and $H_{\mu\tau}$ and hence they can represent two physical states. In our model however $\lambda_{hH} \neq 0$ and consequently the states representing the physical scalars will be obtained after the diagonalization of matrix $M^2_{\text{scalar}}$. The new physical states which are linear combinations of $H$ and $H_{\mu\tau}$ can be written as

$$
h_1 = H \cos \alpha + H_{\mu\tau} \sin \alpha, \\
h_2 = -H \sin \alpha + H_{\mu\tau} \cos \alpha. \tag{11}
$$

The mixing angle $\alpha$ and the corresponding eigenvalues (masses of $h_1$ and $h_2$) are given by

$$
\tan 2\alpha = \frac{\lambda_{hH} v_{\mu\tau} v}{\lambda_h v^2 - \lambda_H v_{\mu\tau}^2}, \tag{12}
$$

$$
M^2_{h_1} = \lambda_h v^2 + \lambda_H v_{\mu\tau}^2 + \sqrt{(\lambda_h v^2 - \lambda_H v_{\mu\tau}^2)^2 + (\lambda_{hH} v v_{\mu\tau})^2}, \tag{13}
$$

$$
M^2_{h_2} = \lambda_h v^2 + \lambda_H v_{\mu\tau}^2 - \sqrt{(\lambda_h v^2 - \lambda_H v_{\mu\tau}^2)^2 + (\lambda_{hH} v v_{\mu\tau})^2}. \tag{14}
$$

We have considered $h_1$ as the SM-like Higgs boson \(^2\) which has recently been discovered by ATLAS \(^90\) and CMS \(^91\) collaborations. Therefore its mass $M_{h_1}$ and VEV $v$ are kept fixed at 125.5 GeV and 246 GeV respectively. The mass of dark matter candidate $\phi_{DM}$ takes the following form

$$
M^2_{DM} = \mu^2_{DM} + \frac{\lambda_{DH} v^2}{2} + \frac{\lambda_{DH} v_{\mu\tau}^2}{2}. \tag{15}
$$

\(^2\) Eq. (13, 14) are valid when $M_{h_1} > M_{h_2}$. On the other hand, the expressions of $M_{h_1}$ and $M_{h_2}$ will be interchanged for $M_{h_2} > M_{h_1}$ resulting an change in sign to the mixing angle $\alpha$. 

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7
In this model our ground state is defined as \( \langle \phi_h \rangle = \frac{v}{\sqrt{2}} \), \( \langle \phi_H \rangle = \frac{\nu_{\mu\tau}}{\sqrt{2}} \) and \( \langle \phi_{DM} \rangle = 0 \) this requires \( \mu_h^2 < 0, \mu_H^2 < 0 \) and \( \mu_{DM}^2 > 0 \). \( \text{(16)} \)

The stability of the ground state (vacuum) requires the following inequalities \[92\] among the quartic couplings of scalar fields

\[
\begin{align*}
\lambda_h & \geq 0, \lambda_H \geq 0, \lambda_{DM} \geq 0, \\
\lambda_{hH} & \geq -2\sqrt{\lambda_h \lambda_H}, \\
\lambda_{Dh} & \geq -2\sqrt{\lambda_h \lambda_{DM}}, \\
\lambda_{DH} & \geq -2\sqrt{\lambda_H \lambda_{DM}}, \\
\sqrt{\lambda_{hH} + 2\sqrt{\lambda_h \lambda_H}} \sqrt{\lambda_{Dh} + 2\sqrt{\lambda_h \lambda_{DM}}} \sqrt{\lambda_{DH} + 2\sqrt{\lambda_H \lambda_{DM}}} \\
&+ 2\sqrt{\lambda_h \lambda_H \lambda_{DM}} + \lambda_{hH} \sqrt{\lambda_{DM}} + \lambda_{Dh} \sqrt{\lambda_H} + \lambda_{DH} \sqrt{\lambda_h} \geq 0.
\end{align*}
\] \( \text{(17)} \)

Besides the above inequalities, the upper bound on quartic, gauge and Yukawa couplings can be obtained from the condition of perturbativity. For a scalar quartic coupling \( \lambda \) (\( \lambda = \lambda_h, \lambda_H, \lambda_{DM}, \lambda_{hH}, \lambda_{Dh}, \lambda_{DH} \)) this condition will be ensured when \[93\]

\[ \lambda < 4\pi, \] \( \text{(18)} \)

while for gauge coupling \( g_{\mu\tau} \) and Yukawa coupling \( y \) (\( y = y_e, y_\mu, y_\tau, h_{e\mu} \) and \( h_{e\tau} \)) it is \[93\]

\[ g_{\mu\tau}, y < \sqrt{4\pi}. \] \( \text{(19)} \)

The above quadratic and quartic couplings of scalars fields \( \phi_h \) and \( \phi_H \) namely \( \mu_h^2, \mu_H^2, \lambda_h, \lambda_H \) and \( \lambda_{hH} \) can be expressed in terms of physical scalar masses \( (M_{h_1}, M_{h_2}) \), mixing angle \( \alpha \) and VEVs \( (v, v_{\mu\tau}) \), which have been given in \[92\].

III. MUON \((g - 2)\)

It is well known that from the Dirac equation, the magnetic moment of muon \( \vec{M} \) can be written in terms of its spin \( \vec{S} \), which is

\[ \vec{M} = g_\mu \frac{e}{2m_\mu} \vec{S}, \] \( \text{(20)} \)

where \( m_\mu \) is the mass of muon and \( g_\mu = 2 \) is the gyromagnetic ratio. However, if we calculate \( g_\mu \) using QFT then contributions arising from loop corrections slightly shift the value of \( g_\mu \) from 2. Hence one can define a quantity \( a_\mu \) which describes the deviation of \( g_\mu \) from its tree level value,

\[ a_\mu = \frac{g_\mu - 2}{2}. \] \( \text{(21)} \)
In general, the contribution to the theoretical value of $a_\mu$ ($a_{\mu}^{\text{th}}$) comes from the following sources [73]

$$a_{\mu}^{\text{th}} = a_{\mu}^{\text{QED}} + a_{\mu}^{\text{EW}} + a_{\mu}^{\text{Had}},$$

(22)

where the contributions arising from Quantum Electrodynamics (QED), Electroweak theory and hadronic process are denoted by $a_{\mu}^{\text{QED}}$, $a_{\mu}^{\text{EW}}$ and $a_{\mu}^{\text{Had}}$, respectively. The SM prediction of $a_\mu$ including the above terms is [75]

$$a_{\mu}^{\text{th}} = 1.1659179090(65) \times 10^{-3}.$$  

(23)

On the other hand, $a_\mu$ has been precisely measured experimentally, initially by the CERN experiments and later on by the E821 experiment, and the current average experimental value is [78]

$$a_{\mu}^{\text{exp}} = 1.16592080(63) \times 10^{-3}.$$ 

(24)

From the above one can see that although the theoretically predicted and the experimentally measured values of $a_\mu$ are quite close to each other, there still exists some discrepancy between these two quantities at the 3.2$\sigma$ significance which is [75],

$$\Delta a_\mu = a_{\mu}^{\text{exp}} - a_{\mu}^{\text{th}} = (29.0 \pm 9.0) \times 10^{-10}.$$  

(25)

Therefore, in order to reduce the difference between $a_{\mu}^{\text{exp}}$ and $a_{\mu}^{\text{th}}$ we need to explore BSM scenarios where we can get extra contributions from some extra diagrams. In our $U(1)_{L_\mu - L_\tau}$ model we have an additional one loop diagram compared to the SM, which is mediated by the extra neutral gauge boson $Z_{\mu \tau}$ and gives nonzero contribution to $a_{\mu}^{\text{th}}$ as shown in Fig. 1. The additional contribution to $a_{\mu}^{\text{th}}$ from this diagram is given by [76, 77],

$$\Delta a_\mu(Z_{\mu \tau}) = \frac{g_{\mu \tau}^2}{8\pi^2} \int_0^1 dx \frac{2x(1-x)^2}{(1-x)^2 + rx},$$

(26)

where, $r = (M_{Z_{\mu \tau}}/m_\mu)^2$ is the square of the ratio between masses of gauge boson ($Z_{\mu \tau}$) and muon. As mentioned in the Introduction, although a $\mathcal{O}(100$ MeV) $Z_{\mu \tau}$ is allowed, its coupling strength ($g_{\mu \tau}$) is strongly constrained to be less than $\sim 10^{-3}$ from the measurement of neutrino trident cross section by experiments like CHARM-II [94] and CCFR [95]. In our analysis, we find that for $M_{Z_{\mu \tau}} = 100$ MeV and $g_{\mu \tau} = 9 \times 10^{-4}$ the value of $\Delta a_\mu = 22.6 \times 10^{-10}$, which lies around the ballpark value given in Eq. (25). In what follows, we will use $M_{Z_{\mu \tau}} = 100$ MeV and $g_{\mu \tau} = 9.0 \times 10^{-3}$ as our benchmark point for the analyses of neutrino masses and dark matter phenomenology.
IV. NEUTRINO MASSES AND MIXING

Majorana neutrino masses are generated via the Type-I seesaw mechanism by the addition of three right handed neutrinos to the model. Using Eq. (5) we can write the Majorana mass matrix for the three right handed neutrinos as

\[
M_R = \begin{pmatrix}
M_{ee} & \frac{v_{\mu\tau}}{\sqrt{2}} h_{e\mu} & \frac{v_{\mu\tau}}{\sqrt{2}} h_{e\tau} \\
\frac{v_{\mu\tau}}{\sqrt{2}} h_{e\mu} & 0 & M_{\mu\tau} e^{i\xi} \\
\frac{v_{\mu\tau}}{\sqrt{2}} h_{e\tau} & M_{\mu\tau} e^{i\xi} & 0
\end{pmatrix},
\tag{27}
\]

where all parameters in \(M_R\) in general can be complex. However, by proper phase rotation one can choose all the elements except the \(\mu\tau\) component of \(M_R\) to be real \cite{83}. Thus, \(M_R\) depends on the real parameters \(M_{ee}, M_{\mu\tau}, h_{e\mu}\) and \(h_{e\tau}\) and the phase \(\xi\). On the other hand, from the Yukawa term in Eq. (5) one can easily see that the Dirac mass matrix \(M_D\) between left handed and right handed neutrinos is diagonal and for simplicity we have chosen all the Yukawa couplings \((y_e, y_\mu\) and \(y_\tau\)) are real. The expression of \(M_D\) is

\[
M_D = \begin{pmatrix}
f_e & 0 & 0 \\
0 & f_\mu & 0 \\
0 & 0 & f_\tau
\end{pmatrix},
\tag{28}
\]
where \( f_i = \frac{y_i}{\sqrt{2}} v \) with \( i = e, \mu \) and \( \tau \). Now, with respect to the basis \( (\bar{\nu}_\alpha^L (N_\alpha^R)^T \) and \( ((\nu_\alpha^L)^c N_\alpha^R)^T \) we can write the mass matrix of both left as well as right handed neutrinos which is given as

\[
M = \begin{pmatrix} 0 & M_D \\ M_D^T & M_R \end{pmatrix},
\]

where \( M \) is a \( 6 \times 6 \) matrix and both \( M_D \) and \( M_R \) are \( 3 \times 3 \) matrices given by Eqs. (27) and (28). After diagonalization of the matrix \( M \) one obtains two fermionic states for each generation which are Majorana in nature. Therefore we have altogether six Majorana neutrinos, out of which three are light and rest are heavy. Using block diagonalization technique, we can find the mass matrices for light as well as heavy neutrinos which are given as

\[
m_{\nu} \simeq -M_D M_R^{-1} M_D^T,
\]

\[
m_{N} \simeq M_R,
\]

Here both \( m_{\nu} \) and \( m_N \) are complex symmetric matrices. Also Eqs. (30)-(31) are derived using an assumption that \( M_D \ll M_R \) i.e. the eigenvalues of \( M_D \) is much less than those of \( M_R \) and therefore terms with higher powers of \( M_D/M_R \) are neglected. Using the expressions of \( M_R \) and \( M_D \) given in Eqs. (27-28) the light neutrino mass matrix in this model takes the following form

\[
m_{\nu} = \frac{1}{2p} \begin{pmatrix} 2 f_e^2 M_{\mu \tau}^2 e^{i\xi} & -\sqrt{2} f_e f_\mu h_{e\tau} v_{\mu \tau} & -\sqrt{2} f_e f_\tau h_{e\mu} v_{\mu \tau} \\ -\sqrt{2} f_e f_\mu h_{e\tau} v_{\mu \tau} & f_\mu^2 h_{e\mu}^2 v_{\mu \tau}^2 e^{-i\xi} & f_\mu^2 f_\tau (M_{ee} M_{\mu \tau} - p e^{-i\xi}) \\ -\sqrt{2} f_e f_\tau h_{e\mu} v_{\mu \tau} & f_\mu f_\tau (M_{ee} M_{\mu \tau} - p e^{-i\xi}) & f_e^2 h_{e\mu}^2 v_{\mu \tau}^2 e^{-i\xi} \end{pmatrix},
\]

where \( p = h_{e\mu} h_{e\tau} v_{\mu \tau}^2 - M_{ee} M_{\mu \tau} e^{i\xi} \). The masses and mixing angles of the light neutrinos are found by diagonalising this matrix \[96\] and are compared against the corresponding experimentally allowed ranges obtained from global analysis of the data (cf. Eq. (1)).

There are eight independent parameters in the light neutrino mass matrix \( m_{\nu} \), namely, \( f_e, f_\mu, f_\tau, M_{ee}, M_{\mu \tau}, V_{e\tau} = \frac{v_{e\tau}}{\sqrt{2}} h_{e\tau}, V_{e\mu} = \frac{v_{e\mu}}{\sqrt{2}} h_{e\mu} \) and \( \xi \). All of these parameters have mass dimension GeV except the dimensionless phase factor \( \xi \) which is in radian. In order to find the model parameter space allowed by the neutrino oscillation experiments, we have varied the above mentioned parameters in the following range

\[
\begin{align*}
0 & \leq \xi \text{[rad]} \leq 2\pi, \\
1 & \leq M_{ee}, M_{\mu \tau} \text{[GeV]} \leq 10^4, \\
1 & \leq V_{e\mu}, V_{e\tau} \text{[GeV]} \leq 280, \\
0.1 & \leq \frac{(f_e, f_\mu, f_\tau)}{10^{-4}} \text{[GeV]} \leq 10.
\end{align*}
\]
The allowed parameter space satisfies the following constraints from the neutrino sector

- cosmoological upper bound on the sum of all three light neutrinos, \( \sum m_i < 0.23 \) eV at 2\( \sigma \) C.L. [18],

- mass squared differences \( 6.93 < \frac{\Delta m_{21}^2}{10^{-5}} \text{ eV}^2 < 7.97 \) and \( 2.37 < \frac{\Delta m_{31}^2}{10^{-3}} \text{ eV}^2 < 2.63 \) in 3\( \sigma \) range [12],

- all three mixing angles \( 30^\circ < \theta_{12} < 36.51^\circ, 37.99^\circ < \theta_{23} < 51.71^\circ \) and \( 7.82^\circ < \theta_{13} < 9.02^\circ \) also in 3\( \sigma \) range [12].

All the Yukawa couplings appearing in the light as well as heavy Majorana neutrino mass matrices (\( m_\nu \) and \( M_R \)) are enforced to always lie within the perturbative range mentioned in Eq. (19). Furthermore, we scan the allowed areas in the model parameter space for only for the normal mass ordering which corresponds to \( \Delta m_{31}^2 > 0 \).

Figure 2: Left (Right) panel: Allowed region in \( f_e - f_\mu \) (\( f_e - f_\tau \)) plane which satisfies all the experimental constraints considered in this work.

In the left and right panels of Fig. 2 we have shown the allowed regions in \( f_e - f_\mu \) and \( f_e - f_\tau \) planes respectively, where we have varied \( f_e, f_\mu, f_\tau \) in the range \( 10^{-5} \) GeV to \( 10^{-3} \) GeV while the other parameters have been scanned over the entire considered range as given in Eq. (33). From both the panels it is clear that there is (anti)correlation between the parameters \( f_e - f_\mu \) and \( f_e - f_\tau \). We find that for the lower values of \( f_e \) higher values of \( f_\mu, f_\tau \) are needed to satisfy the experimental constraints in the 3\( \sigma \) range and vice versa. Moreover, although there are smaller
number of allowed points when both $f_e$ and $f_i$ ($i = \mu, \tau$) are small but the present experimental bounds on the observables of the neutrino sector forbid the entire region in the $f_e - f_\mu$ and $f_e - f_\tau$ planes for both $f_e$ and $f_i > 2 \times 10^{-4}$ GeV ($i = \mu, \tau$). Also, unlike the parameters $f_\mu$ and $f_\tau$, we do not get any allowed values of $f_e$ beyond $8 \times 10^{-4}$ GeV.

Figure 3: Left panel: Allowed region in $f_\mu - f_\tau$ plane. Right panel: Variation of $\theta_{23}$ with $f_e$ (blue dots), $f_\mu$ (green dots) and $f_\tau$ (red dots).

The allowed parameter space in $f_\mu - f_\tau$ plane has been shown in the left panel of Fig. 3. From the figure it is seen that there is a correlation between the parameters $f_\mu$ and $f_\tau$. That means unlike the previous plots here most of allowed points in $f_\mu - f_\tau$ plane are such that for the lower (higher) values of the parameter $f_\mu$ we also need lower (higher) values of $f_\tau$ to reproduce the experimental results. On the other hand, in the right panel of Fig. 3 we show the variation of $\theta_{23}$ with $f_e$ (blue dots), $f_\mu$ (green dots) and $f_\tau$ (red dots). We see from the plot that the region around maximal $\theta_{23}$ mixing angle is ruled out in this model. The reason is that while in the $L_\mu - L_\tau$ symmetric limit, the neutrino mass matrix had a $\mu - \tau$ symmetry and hence $\theta_{23} = \pi/4$ and $\theta_{13} = 0$, once the $L_\mu - L_\tau$ symmetry is spontaneously broken, $\theta_{23}$ shifts away from maximal and $\theta_{13}$ becomes non-zero, making the model consistent with the neutrino oscillations data. The plot also shows that the allowed values of mixing angle $\theta_{23}$ lie in two separate ranges between $38^\circ \lesssim \theta_{23} \lesssim 42^\circ$ (lower octant, $\theta_{23} < 45^\circ$) and $48^\circ \lesssim \theta_{23} \lesssim 51.5^\circ$ (higher octant, $\theta_{23} > 45^\circ$) for the variation of entire considered range of parameters $f_i$ ($i = e, \mu, \tau$) from $10^{-5}$ GeV to $10^{-3}$ GeV. Therefore, we can conclude that our model is insensitive to the octant of $\theta_{23}$.

The allowed regions for the other remaining parameters $M_{ee} - M_{\mu\tau}$ and $V_{e\mu} - V_{e\tau}$ have been shown in Fig. 4. The left panel of Fig. 4 shows the (anti)correlation between the allowed values
Figure 4: Left (Right) panel: Allowed region in $M_{ee} - M_{\mu\tau}$ ($V_{e\mu} - V_{e\tau}$) plane which satisfies all the experimental constraints considered in this work.

of the parameters $M_{ee}$ and $M_{\mu\tau}$. The neutrino oscillation data rules out the parameter region $M_{ee} \gtrsim 500$ GeV, $M_{\mu\tau} \gtrsim 500$ GeV and $M_{ee} \lesssim 5$ GeV, $M_{\mu\tau} \lesssim 5$ GeV. In the right panel Fig. 4 we have shown the allowed region in the $V_{e\mu} - V_{e\tau}$ plane. In order to keep the Yukawa couplings $h_{e\mu}$ and $h_{e\tau}$ within the perturbative regime (see Eq. (19)) we have restricted variation of both $V_{e\mu}$ and $V_{e\tau}$ up to 280 GeV. From this plot it is clearly seen that the higher values of $V_{e\mu}$ and $V_{e\tau}$ ($V_{e\mu}, V_{e\tau} \gtrsim 10$ GeV) are mostly preferred by the neutrino experiments over the smaller ones.

In the left panel of Fig. 5, we have shown the variation of the phase $\xi$ with respect to the parameter $M_{\mu\tau}$. Only a very narrow range of value of $\xi$, placed symmetrically with respect to the line $\xi = \pi$, are allowed, which reproduce the neutrino observables in the 3$\sigma$ range. It is also seen from this figure that there are no points along $\xi = \pi$ line (blue dashed line), which indicates that for the present model, at least one element in the right handed neutrino mass matrix (here we have considered $2 \times 3$ element of $M_R$) has to be a complex number to satisfy the experimental results. The variation of sum of all three neutrino masses with $\Delta m_{21}^2$ is presented in the right panel of Fig. 5. The variation of $\Delta m_{\text{atm}}^2$ is also shown in the same figure. From this plot, it is evident that in this model lower values of $\sum m_i$ ($\sum m_i \leq 0.18$ eV) are more favourable.

In the left and right panels of Fig. 6, we have shown the predicted ranges of the mixing angles and the Dirac CP phase. The left panel shows that for both lower and higher octant, the whole range of $\theta_{13}$ is allowed here. In the right panel of Fig. 6, we have plotted the predicted Dirac CP phase with respect to the mixing angle $\theta_{12}$. We find that in our model the predicted values of Dirac CP phase are very small and symmetric around $0^\circ$. One can also note that the absolute
Figure 5: Left pane: Allowed values of the parameters $M_{\mu\tau}$ and $\xi$. Blue dashed line represents $\xi = \pi$. Right panel: Variation of $\sum_i m_{\nu_i}$ with the mass square differences $\Delta m_{21}^2$ and $\Delta m_{32}^2$.

Figure 6: Left panel: Variation of $\theta_{13}$ with $\theta_{23}$. Right panel: Variation of Dirac CP phase $\delta_{CP}$ with mixing angle $\theta_{12}$.

The predicted value of $|\delta_{CP}|$ increases with the mixing angle $\theta_{12}$. 
V. DARK MATTER

Being stable as well as electrically neutral, $\phi_{DM}$ can serve as a dark matter candidate. In this section, we will compute the relic abundance of $\phi_{DM}$ at the present epoch and its spin independent scattering cross section relevant for direct detection experiments. The viability of $\phi_{DM}$ as a dark matter candidate will be tested by comparing its relic abundance and spin independent scattering cross section with the results obtained from Planck and LUX experiments. Finally, at the end of this section we will compute the $\gamma$-ray flux due to the annihilation of $\phi_{DM}$ and compare this flux with Fermi-LAT observed $\gamma$-ray excess from the regions close to the Galactic Centre (GC).

A. Relic Density

In the present model, since $\phi_{DM}$ is a complex scalar field with a nonzero $L_\mu - L_\tau$ charge $n_{\mu\tau}$, therefore we have a non-self-conjugate DM scenario where DM particle and its antiparticle are different with respect to $n_{\mu\tau}$. In this work we assume that there is no asymmetry between the number densities of $\phi_{DM}$ and $\phi_{DM}^\dagger$ in the early Universe. The evolution of total DM number density $n = n_{\phi_{DM}} + n_{\phi_{DM}^\dagger}$ is governed by the well known Boltzmann equation which is given by [20]

$$\frac{dn}{dt} + 3nH = -\frac{1}{2}\langle \sigma v \rangle \left( n^2 - n_{eq}^2 \right),$$

(34)

where $n_{eq}$ is the sum of equilibrium number densities of both $\phi_{DM}$ and $\phi_{DM}^\dagger$ and $H$ is the Hubble parameter. Moreover, $\langle \sigma v \rangle$ is the thermally averaged annihilation cross section between $\phi_{DM}$ and $\phi_{DM}^\dagger$ for the processes shown in Fig. 7. In this work, we have considered DM mass in the range 30 GeV to 500 GeV. Therefore depending on the value of $M_{DM}$, $\phi_{DM}$ and $\phi_{DM}^\dagger$ can annihilate into the following final states: $\phi_{DM}\phi_{DM}^\dagger \rightarrow f\bar{f}, W^+W^-, ZZ, Z_{\mu\tau}Z_{\mu\tau}, h_1h_1, h_2h_2, h_1h_2, N_1\bar{N}_2$ and $N_1\bar{N}_3$ where $f$ is any SM fermion. The expressions of $\langle \sigma v \rangle$ involving actual annihilation cross section $\sigma$ and modified Bessel functions is given in [20]. The factor $1/2$ appearing in the right hand side of the Boltzmann equation is due to the non-self-conjugate nature of DM [20]. In terms of two dimensionless quantities $Y$ and $x$ the above equation can be written in the following form

$$\frac{dY}{dx} = -\left( \frac{45G}{\pi} \right)^{\frac{1}{2}} \frac{M_{DM} \sqrt{g_*}}{x^2} \frac{1}{2} \langle \sigma v \rangle \left( Y^2 - (Y_{eq})^2 \right),$$

(35)

We have not shown $Z_{\mu\tau}$ mediated diagrams as the coupling strength of $Z_{\mu\tau}$ with $\phi_{DM}$ and $\phi_{DM}^\dagger$ is proportional to $g_{\mu\tau}$ which is needed to be very small ($\sim 10^{-3}$) for the explanation of muon $(g-2)$ anomaly (see Section III).
Figure 7: Feynman diagrams dominantly contributing to the annihilation cross section and hence towards the relic density of $\phi_{DM}$ and $\phi_{DM}^\dagger$.

where $Y = \frac{n_s}{s}$ is the total comoving number density of $\phi_{DM}$ and $\phi_{DM}^\dagger$ and $x = \frac{M_{DM}}{T}$ where $T$ is the temperature of the Universe. Also, Newton’s gravitational constant is denoted by $G$ while $g_*$ is a function of effective degrees of freedom corresponding to both energy and entropy densities of the Universe [20]. Therefore, the relic density of $\phi_{DM}$ and $\phi_{DM}^\dagger$ at the present epoch is given by [97, 98]

$$\Omega_{DM}h^2 = 2.755 \times 10^8 \left( \frac{M_{DM}}{\text{GeV}} \right) Y(T_0).$$

(36)

$Y(T_0)$ is the total comoving number density of $\phi_{DM}$ and $\phi_{DM}^\dagger$ for the present temperature of the Universe ($T_0 \sim 10^{-13} \text{ GeV}$), which can be obtained by solving Eq. (35).

**B. Direct detection**

Dark matter direct detection experiments use the principle of elastic scattering between dark matter particles and detector nuclei. If DM particles scatter off the detector nuclei elastically then the information about the nature of DM particles and their interaction type with SM particles (quarks) can be obtained by measuring the recoil energy of the nuclei. Since the DM particles are nonrelativistic (cold dark matter), therefore the energy deposited to the nuclei are extremely small ($\sim \text{keV}$ range). Hence in order to measure it accurately, low background as well as low threshold detector is required. In the present model, the elastic scattering of both $\phi_{DM}$ and $\phi_{DM}^\dagger$ can occur only through the exchange of scalar bosons $h_1, h_2$. Unlike the other $U(1)$ extensions of the SM where the extra neutral gauge bosons can interact with the quarks (such as $U(1)_{B-L}$ model [92]), here $Z_{\mu\nu}$ does not couple with the quark sector and consequently, the spin independent scattering cross sections of the DM particle and its antiparticle are equal. The
expression of spin independent scattering cross section of DM with nucleon (N) is given by

$$\sigma_{SI} = \frac{\mu^2}{4\pi} \left[ \frac{M_N f_N \cos \alpha}{M_{DM} v} \left( \frac{\tan \alpha g_{\phi_{DM} \phi_{DM} h_2}^2}{M_{h_2}^2} - \frac{g_{\phi_{DM} \phi_{DM} h_1}^2}{M_{h_1}^2} \right) \right]^2,$$

where $\mu$ is the reduced mass between DM and N while $f_N \sim 0.3$ [99] is the nuclear form factor. $g_{\phi_{DM} \phi_{DM} h_i}$ is the vertex factor involving fields $\phi_{DM}$, $\phi_{DM}^\dagger$ and $h_i$ ($i = 1, 2$) and its expression is given in Table [III].

C. Results

We have computed the relic density of DM using micrOMEGAs [100] package and the implementation of the present model in micrOMEGAS has been done using the LanHEP [101] package. For the relic density calculation, we have considered the following benchmark values of the parameters related to the neutrino sector,

- Masses of the three heavy neutrinos: $M_{N_1} = 332.88$ GeV, $M_{N_2} = 279.06$ GeV and $M_{N_3} = 168.28$ GeV,
- Yukawa couplings: $h_{e\mu} = 2.44$ and $h_{e\tau} = 1.28$.

We have checked that these adopted values of right handed neutrino masses and Yukawa couplings reproduce all the experimentally measurable quantities of the neutrino sector within their $1\sigma$ range [12]. Moreover like the previous section, here also we have used our benchmark point $M_{Z_{\mu\tau}} = 100$ MeV and $g_{\mu\tau} = 9 \times 10^{-4}$, which are required to explain the muon $(g - 2)$ anomaly.
Table III: All relevant vertex factors required for the computation of DM annihilation as well as scattering cross sections.

In the left panel of Fig. 9, we show the variation of the DM relic density with its mass for three different values of the scalar mixing angle, $\alpha = 0.01$ rad, 0.045 rad and 0.09 rad respectively. From this plot it is clearly seen that DM relic density satisfies the central value of Planck limit

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4 We have checked that these values of mixing angle $\alpha$ are allowed by the LHC results on Higgs signal strength [74] and invisible decay width [102].
\( n_{\nu\tau} = 0.15 \)
\( \alpha = 0.01 \)
\( \alpha = 0.045 \)
\( \alpha = 0.09 \)
\( \Omega_{DM} h^2 = 0.1197 \)

\( \Omega_{DM} h^2 \) only around the two resonance regions where the mass of DM is nearly equal to half of the mediator mass i.e. \( M_{DM} \sim M_{h_i}/2 \) \((i = 1, 2)\). Therefore the first resonance occurs when DM mass is around 62 GeV and it is due to the SM-like Higgs boson \( h_1 \) while the second one is due to extra Higgs boson \( h_2 \) of mass 200 GeV. Like the left panel of Fig. 9, the right panel also shows the variation of \( \Omega_{DM} h^2 \) with \( M_{DM} \) but in this case three different plots are generated for three different values of \( M_{h_2} = 200 \) GeV (blue dashed dot line), 300 GeV (green dashed line) and 400 GeV (red solid line), respectively. Similar to the left panel, here also the DM relic density satisfies the Planck limit only around the resonance regions. However in this plot, as we have varied the mass of \( h_2 \), therefore instead of getting a single resonance region for \( h_2 \) (as in the left panel) we have found three resonance regions at \( M_{DM} \sim 100 \) GeV, 150 GeV and 200 GeV for \( M_{h_2} = 200 \) GeV, 300 GeV and 400 GeV, respectively. For all three cases the resonance due to the SM-like Higgs boson \( h_1 \) occurs at the same value of \( M_{DM} \sim 62.5 \) GeV as we have fixed the mass of \( h_1 \) at 125.5 GeV. Plots in both panels are generated for \( n_{\mu\tau} = 0.15 \).

Left and right panels of Fig. 10 represent the variation of relic density \( \Omega_{DM} h^2 \) with the dark matter mass \( \phi_{DM} \) for there different values of parameter \( \lambda_{DH} \) and \( \lambda_{Dh} \), respectively. These plots also show the appearance of two resonance regions due to the two mediating scalar bosons. However, from this figure one can notice the effect of parameters \( \lambda_{Dh} \) and \( \lambda_{DH} \) on the DM relic density with respect to the variation of \( M_{DM} \). In the low mass region \((M_{DM} \lesssim 80 \) GeV\), SM-like Higgs boson mediated diagrams dominantly contribute to the pair annihilation processes of \( \phi_{DM} \).
and $\phi_{DM}^\dagger$ while the contribution of extra Higgs mediated diagrams become superior for the high DM mass region ($M_{DM} \gtrsim 80$ GeV). From the expression of $\phi_{DM} \phi_{DM}^\dagger h_1$ vertex factor given in Table III, one can see that the effect of the parameter $\lambda_{DH}$ on $\langle \sigma v \rangle$ is mixing angle suppressed (i.e. multiplied by $\sin \alpha$). Therefore, in the left panel for low DM mass region the effect of $\lambda_{DH}$ to $\Omega_{DM} h^2$ is small. On the other hand, in the expression of vertex factor of $\phi_{DM} \phi_{DM}^\dagger h_1$, the parameter $\lambda_{Dh}$ appears with $\cos \alpha$ and hence we see a considerable effect of $\lambda_{Dh}$ on $\Omega_{DM} h^2$ in the right panel (low DM mass region). For the extreme right region of both panels ($M_{DM} \gtrsim 200$ GeV), the dominant pair annihilation channel is $\phi_{DM} \phi_{DM}^\dagger h_1 \rightarrow h_2 h_2$. Hence, the impact of $\lambda_{DH}$ and $\lambda_{Dh}$ to $\Omega_{DM} h^2$ can well be understood from the expression of $\phi_{DM} \phi_{DM}^\dagger h_2 h_2$ vertex factor (see Table III). In the intermediate region (80 GeV < $M_{DM}$ < 200 GeV), $\phi_{DM} \phi_{DM}^\dagger \rightarrow W^+ W^-, ZZ$ and $h_1 h_1$ channels mainly contribute to DM relic density and in the right panel for 100 GeV < $M_{DM}$ < 200 GeV, the variation of $\Omega_{DM} h^2$ with respect to $\lambda_{Dh}$ resulting from DM pair annihilation into $h_1 h_1$ final state.

In the left panel of Fig. 10, we show the allowed values of $M_{h_2}$ which reproduce the correct DM relic density for the variation of $M_{DM}$ in the range 30 GeV to 500 GeV. In this plot we have varied the mass of extra Higgs boson $M_{h_2}$ in the range 60 GeV to 450 GeV and $\lambda_{DH}$ from 0.001 to 0.1. From this plot it is evident that for a particular value of dark matter mass the corresponding allowed values of $M_{h_2}$ lie around 2$M_{DM}$. The reason behind this nature is that the relic abundance of dark matter (both $\phi_{DM}$ and $\phi_{DM}^\dagger$) satisfies the observed DM density
Figure 11: Left Panel: Allowed values of $M_{h_2}$ with respect to the variation of the dark matter mass $M_{DM}$ for two different values of mixing angle $\alpha$. Right panel: Variation of spin independent scattering cross sections of dark matter with its mass. All the points in both plots satisfy the Planck limit on DM relic density in 1σ range ($\Omega_{DM}h^2 = 0.1197 \pm 0.0022$ [18]) and these two plots are generated for $\lambda_{DH} = 0.001$.

only around the resonance regions (when mediator mass $M_{h_i} \sim 2 \times M_{DM}$, $i = 1, 2$ see Fig.9 and Fig.10). The allowed range of $M_{h_2}$ for a particular DM mass does not vary much for the change of mixing angle $\alpha$ from 0.01 rad (red coloured region) to 0.05 rad (green colour region). Moreover, we restrict $M_{h_2}$ up to 430 GeV to remain within the perturbative regime ($\lambda_H < 4\pi$) and hence the relic density condition is not satisfied beyond $M_{DM} = 215$ GeV. Furthermore, near $M_{DM} \sim 60$ GeV, one can see that a broad range of $M_{h_2}$ values are allowed, which indicates that in this region the SM-like Higgs contributes dominantly giving the wide range of $M_{h_2}$ values for which the DM relic density is satisfied. Spin independent elastic scattering cross section ($\sigma_{SI}$) of DM with with its mass has been plotted in the the right panel of Fig.11 for two different values of $\alpha = 0.01$ rad (green coloured region) and 0.05 rad (red coloured region) respectively. This plot is also generated for $60$ GeV $\leq M_{h_2} \leq 430$ GeV, 0.001 $\leq \lambda_{DH} \leq 0.1$ and $\lambda_{Dh} = 0.001$ and all the points within the red and green coloured patch satisfy the Planck result. For comparison with current experimental limits on $\sigma_{SI}$ from DM direct detection experiments we have plotted the result of LUX-2016 (blue solid line) in the same figure. Moreover, we have also shown the predicted results from the “ton-scale” direct detection experiments like XENON 1T [23] (blue dashed line) and DARWIN [103] (long dashed purple line). From this figure it is evident that the validity of our model can be explored in near future by these “ton-scale” experiments.
D. Indirect detection: Fermi-LAT γ-ray excess from the Galactic Centre

Over the past few years, the existence of an unidentified excess of γ-rays with energy 1-3 GeV from the direction of the Galactic Centre has been reported by several groups [30, 104–114] after analysing the Fermi-LAT publicly available data [27]. There are some astrophysical explanations such as unresolved point sources (e.g. millisecond pulsar) around the GC which may be responsible for this anomalous gamma-ray excess [28, 29]. However, the spectrum and morphology of this gamma-ray excess is also very similar to that expected from the annihilation [115] or decay (see [116] and references therein) of dark matter in the GC. In terms of an annihilating DM scenario this excess can be well explained by a dark matter of mass around $48.7^{+6.4}_{-5.2}$ GeV and with an annihilation cross section $\langle \sigma v b \bar{b} \rangle = 1.75_{-0.26}^{+0.28} \times 10^{-26}$ cm$^3$/s into $b\bar{b}$ final state [30]. Thereafter these $b$ quarks produce excess γ-ray from their hadronization processes. The above quantities $M_{DM}$ and $\langle \sigma v b \bar{b} \rangle$ depend on the specific choice of dark matter halo profile. In Ref. [30] authors have used an NFW halo profile [117] with index $\gamma = 1.26$, $r_s = 20$ kpc, local dark matter density $\rho_\odot = 0.4$ GeV/cm$^3$ and a region of interest (ROI) around GC where galactic latitude $b$, longitude $l$ vary in the range $2^0 < |b| < 20^0$, $|l| < 20^0$ respectively during

![Figure 12: Gamma-ray flux obtained from the pair annihilation of $\phi_{DM}$ and $\phi_{DM}^*$ at the Galactic Centre for $M_{DM} = 52$ GeV, $\langle \sigma v b \bar{b} \rangle = 3.856 \times 10^{-26}$ cm$^3$/s and $A = 1.219$](image-url)
the analysis of Fermi-LAT data. Since our knowledge about the exact values of DM halo profile parameters such as $\gamma$ and $\rho_\odot$ is limited, there are some uncertainties in these profile parameters and this can affect the calculated value of $\langle \sigma v_{\bar{b}b} \rangle$. Due to this uncertainty the allowed values of annihilation cross section for the $\bar{b}b$ channel can vary in the range $A \times \langle \sigma v_{\bar{b}b} \rangle$ which is $1.75 \times 10^{-26} \text{cm}^3/\text{s}$ while $A$ can be any number between 0.17 to 5.3 [30]. For $\gamma = 1.26$, $\rho_\odot = 0.4 \text{GeV/cm}^3$ and $r_s = 20 \text{kpc}$ and the value of $A = 1$, we have found that in the present $L_\mu - L_\tau$ symmetric model with a DM candidate $\phi_{DM}$ such explanation of this anomalous gamma-excess is indeed possible from the pair annihilation of $\phi_{DM}$ and $\phi_{DM}^\dagger$ at the Galactic Centre. In our earlier work [92] we have done a detailed computation of $\gamma$-ray flux resulting from the annihilation of a complex scalar dark matter at the GC. Therefore, the process of computing gamma-ray flux from the pair annihilation of $\phi_{DM}$ and $\phi_{DM}^\dagger$ for the present scenario is very similar to that work and hence these intermediated steps are not repeated here. Note that since we are dealing with non-self-conjugate dark matter, therefore, there will be an extra half factor in the expression for the differential gamma-ray flux [92] [118]. Hence in our case, the best fit value of $\langle \sigma v_{\bar{b}b} \rangle$ will be $3.50 \times 10^{-26} \text{cm}^3/\text{s}$. Following the same procedure given in [92] we have found that, for the present model, the excess gamma-rays flux observed by Fermi-LAT can be reproduced for an annihilating dark matter of mass $M_{DM} = 52 \text{GeV}$ and $\langle \sigma v_{\bar{b}b} \rangle = 3.856 \times 10^{-26} \text{cm}^3/\text{s}$. In this case, DM annihilation to $\bar{b}b$ channel dominantly occurs through the resonance of extra Higgs boson ($h_2$) with resonating mass $M_{h_2} = 104.025 \text{GeV}$ and coupling parameters $\lambda_{DH} = 0.01$, $\lambda_{Dh} = 0.001$ and scalar mixing angle $\alpha = 0.045 \text{rad}$.

In Fig. 12 green solid line represents the $\gamma$-ray flux that we have computed for a $M_{DM} = 52 \text{GeV}$ while the value of $\bar{b}b$ annihilation cross section is $3.856 \times 10^{-26} \text{cm}^3/\text{s}$. The correlated systematic errors are represented by the yellow boxes while the Fermi-LAT uncorrelated statistical uncertainties are shown by the black error bars taken from [119]. We have found that in order to reproduced the Fermi-LAT observed $\gamma$-ray flux for a 52 GeV non-self-conjugate DM, the quantity $A \times \langle \sigma v_{\bar{b}b} \rangle$ must be $4.7 \times 10^{-26} \text{cm}^3/\text{s}$ [92]. This requires DM halo profile error parameter $A$ to be $\sim 1.22$, well inside its allowed range between 0.17 to 5.3 [30].

VI. SUMMARY AND CONCLUSION

Although Standard Model (SM) is a well established theory of elementary particle physics, it cannot explain the muon $(g-2)$ anomaly, the small neutrino masses and peculiar mixing pattern, and the existence of Dark Matter (DM). Therefore, the SM has to be extended to explain these observational evidences. In the present work we have extended the SM gauge group $\text{SU}(3) \times \text{SU}(2)_L \times \text{U}(1)_Y$ by a local $U(1)_{L_\mu - L_\tau}$ gauge group. Since we require $U(1)_{L_\mu - L_\tau}$ to be local, we get an extra gauge boson, $Z_{\mu\tau}$. One of the most appealing aspects of the gauged $U(1)_{L_\mu - L_\tau}$ extension of the SM is that it does not introduce any anomaly in the theory [37] [39].
We introduce a scalar with non-trivial $L_\mu - L_\tau$ number which picks up a VEV, breaking the $U(1)_{L_\mu - L_\tau}$ symmetry spontaneously and making $Z_{\mu\tau}$ massive. This extra massive $Z_{\mu\tau}$ provides additional contributions to the magnetic moment of the muon, which can explain the observed data on muon $(g - 2)$ for $Z_{\mu\tau}$ of $\mathcal{O}(100\text{ MeV})$ and low values of gauge coupling $g_{\mu\tau} \lesssim 10^{-3}$. We fixed the value of $g_{\mu\tau}$ and $M_{Z_{\mu\tau}}$ such that they are allowed by the neutrino trident process [73] and calculated the muon $(g - 2)$ to within $3.2\sigma$ of the measured value. We kept $g_{\mu\tau}$ and $M_{Z_{\mu\tau}}$ fixed at these values throughout the rest of the paper.

The $L_\mu - L_\tau$ symmetry, being also a flavor symmetry, provides a natural way of explaining the peculiar mixing pattern of the light neutrinos. We added to the particle content, three right-handed neutrinos ($N_e, N_\mu, N_\tau$) and generated small neutrino masses naturally through the canonical Type-I seesaw mechanism. The $N_e, N_\mu, N_\tau$ are given $L_\mu - L_\tau$ flavor numbers, making the right-handed neutrino mass matrix and as a result the light Majorana neutrino mass matrix $\mu - \tau$ symmetric. This leads to $\theta_{23} = \pi/4$ and $\theta_{13} = 0$, inconsistent with the neutrino oscillation data. However, when the $L_\mu - L_\tau$ symmetry gets spontaneously broken, it generates additional terms in the right-handed and consequently light neutrino mass matrix giving a good explanation of the global neutrino oscillation data. We scanned the five-dimensional model parameter space of our model and found the regions of this space that are consistent with the allowed neutrino oscillation parameters within their $3\sigma$ ranges. We discussed the correlations between the model parameters. We also presented the oscillation parameters predicted by our model. In particular, we showed that our model can explain the observed value of $\theta_{13}$ very naturally, predicts a value of $\theta_{23}$ that is not maximal, does not distinguish between the two octants of $\theta_{23}$ and predicts the Dirac $\delta_{CP}$ phase to be very close to 0. Hence our model predicts that no discernible CP violation will be observed in the long baseline experiments.

We next introduced another complex scalar $\phi_{DM}$ which does not take a VEV and hence is a good candidate for DM. The stability of this complex scalar is ensured by giving it a suitable $L_\mu - L_\tau$ charge, making it impossible to write any decay terms in the Lagrangian, even after the $L_\mu - L_\tau$ symmetry is broken spontaneously. We showed that due to the very small gauge coupling $g_{\mu\tau}$ required to explain the anomalous muon $(g - 2)$ data, the $Z_{\mu\tau}$-portal diagrams do not contribute to the DM phenomenology. The relic abundance and signature of our model in direct and indirect experiments come through the Higgs portal. We calculated the relic abundance of DM in this model and showed that the observational constraints from Plank can be satisfied for the two resonance regions corresponding to the scenario where $M_{DM} \simeq M_{h_1}/2$ and $M_{DM} \simeq M_{h_2}/2$, respectively, where $M_{h_1}$ and $M_{h_2}$ are the masses of $h_1$ and $h_2$, the two Higgs scalars in our model. We presented the prediction of our model in forthcoming direct detection experiments and showed that for a wide range of model parameter space, XENON 1T and DARWIN could see a positive signal for $\phi_{DM}$. Likewise, they can constrain large parts of the model parameter in case they do not observe any WIMP signal. We also showed that for
\( \phi_{DM} \simeq 52 \text{ GeV} \), our model can explain the galactic centre gamma ray excess in the \( 1 - 3 \text{ GeV} \) range observed by FermiLAT.

In conclusion, we propose a gauged \( L_\mu - L_\tau \) extension of the SM with two additional scalars and three additional right-handed neutrinos. This model can explain the anomalous muon \( (g - 2) \) data, small neutrino masses and peculiar mixing pattern, and provides a viable dark matter candidate. It can explain the relic abundance as well as the galactic centre gamma ray excess while satisfying all other experimental bounds. It also predict no CP violation in neutrino oscillation experiments. This model is phenomenologically rich and predictive and should be testable in forthcoming high energy physics experiments, including collider experiments, dark matter experiments as well as neutrino oscillation experiments.

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