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Flavor anomalies, Light Dark Matter and rare B decays with missing energy in $L_\mu - L_\tau$ model

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In recent times, several hints of lepton flavor universality violation (LFUV) have been observed in semileptonic B decays, which point towards the existence of New Physics beyond the Standard Model. In this context, we consider a new variant of $U(1)_{L_\mu - L_\tau}$ gauge extension of the Standard Model, containing three additional neutral fermions N_e, N_μ, N_τ, along with a $(\bar{3}, 1, 1/3)$ scalar leptoquark (SLQ) and an inert scalar doublet, to study the phenomenology of light dark matter, neutrino mass and flavor anomalies. The lightest mass eigenstate of the N_μ, N_τ neutral fermions, plays the role of dark matter. We constrain the new model parameters by using the LFUV observables $R_{K^{(*)}}$ and branching fraction of $b \to s\gamma$ decay processes. We then show the implications of the model on the branching fractions of some rare semileptonic B decay processes with missing energy, e.g., $B \to (K^{(*)}, \phi) + \not{E}$.

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1. Introduction

Though the Standard Model (SM) is an elegant and triumphant theory in explaining almost all the observed data so far, but still there are some unanswered questions, e.g., baryon asymmetry, dark matter and dark energy content of the universe, neutrino mass, etc. which necessitates the existence of Physics beyond it. Thus, understanding the Physics beyond the SM (BSM) is one of the prime objectives of present day particle physics research. In the absence of any direct observation of new heavy BSM particles at the LHC experiment, the recently observed flavor anomalies in the semileptonic B meson decays [1] play an intriguing role to probe the physics beyond the SM. In this context, we consider a new variant of $U(1)_{L_\mu-L_\tau}$ gauge extension of Standard Model, containing three additional neutral fermions N_e, N_μ, N_τ, along with a $(\bar{3}, 1, 1/3)$ scalar Leptoquark (SLQ) and an inert scalar doublet, to study the phenomenology of light dark matter, neutrino mass and flavor anomalies in a single platform.

2. Model Description

We consider a variant of $U(1)_{L_\mu-L_\tau}$ model [2], We now investigate the implications of the model on the rare decay modes $b \to s \not{E}$.with three new neutral fermions N_e, N_μ, N_τ and a scalar leptoquark $S_1(\bar{3}, 1, 1/3)$. Also an inert doublet η is added to generate the neutrino mass at one-loop level and a singlet ϕ_2 to spontaneously break the new $U(1)$ symmetry. In addition, we also impose an additional Z_2 symmetry for the stabilization of the dark matter, under which all the SM particles are even. The new particle gamut and their quantum numbers are presented in Table 1.

	Field	$SU(3)_C \times SU(2)_L \times U(1)_Y$	$U(1)_{L_\mu-L_\tau}$	Z_2
Fermions	N_e, N_μ, N_τ	$(\mathbf{1}, \mathbf{1}, 0)$	$0, 1, -1$	$-$
Scalars	η	$(\mathbf{1}, \mathbf{2}, 1/2)$	0	$-$
	ϕ_2	$(\mathbf{1}, \mathbf{1}, 0)$	2	$+$
	S_1	$(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$	-1	$-$
Gauge boson	V_μ	$(\mathbf{1}, \mathbf{1}, 0)$	0	$+$

Table 1: The new particles and their quantum numbers in the chosen $U(1)_{L_\mu-L_\tau}$ model.

The relevant Lagrangian terms in the gauge, fermion, gauge-fermion interaction and scalar sectors involving the new particles read as

$$\begin{aligned}
\mathcal{L}_G &= -\frac{1}{4}\left(\hat{\mathbf{W}}_{\mu\nu}\hat{\mathbf{W}}^{\mu\nu} + \hat{B}_{\mu\nu}\hat{B}^{\mu\nu} + \hat{V}_{\mu\nu}\hat{V}^{\mu\nu} + 2\sin\chi\,\hat{B}_{\mu\nu}\hat{V}^{\mu\nu}\right),\\
\mathcal{L}_f &= -\frac{1}{2}M_{ee}\overline{N_e^c}N_e - \frac{f_\mu}{2}\left(\overline{N_\mu^c}N_\mu\phi_2^\dagger + \text{h.c.}\right) - \frac{f_\tau}{2}\left(\overline{N_\tau^c}N_\tau\phi_2 + \text{h.c.}\right) - \frac{1}{2}M_{\mu\tau}(\overline{N_\mu^c}N_\tau + \overline{N_\tau^c}N_\mu),\\
&\quad - \sum_{l=e,\mu,\tau}(Y_{ll}(\overline{\ell_L})_l\tilde{\eta}N_{lR} + \text{h.c}) - \sum_{q=d,s,b}(y_{qR}\,\overline{d_{qR}^c}S_1N_\mu + \text{h.c.}),\\
\mathcal{L}_{G-f} &= g_{\mu\tau}\left(-\overline{\mu}\,\gamma^\mu\mu + \overline{\tau}\gamma^\mu\tau - \overline{\nu_\mu}\,\gamma^\mu(1-\gamma^5)\nu_\mu + \overline{\nu_\tau}\,\gamma^\mu(1-\gamma^5)\nu_\tau - \overline{N_\mu}\gamma^\mu\gamma^5N_\mu + \overline{N_\tau}\gamma^\mu\gamma^5N_\tau\right)\hat{V}_\mu,\\
\mathcal{L}_S &= \left|\left(i\partial_\mu - \frac{g}{2}\boldsymbol{\tau}^a\cdot\hat{\mathbf{W}}_\mu^a - \frac{g'}{2}\hat{B}_\mu\right)\eta\right|^2 + \left|\left(i\partial_\mu - \frac{g'}{3}\hat{B}_\mu + g_{\mu\tau}\,\hat{V}_\mu\right)S_1\right|^2 + \left|\left(i\partial_\mu - 2g_{\mu\tau}\,\hat{V}_\mu\right)\phi_2\right|^2. \qquad (1)
\end{aligned}$$

The $U(1)_Y$ and $U(1)_{L_\mu - L_\tau}$ gauge fields mix kinematically giving rise to the physical neutral gauge bosons Z and Z'. The new fermions N_μ and N_τ mix together giving rise to the mass eigenstates $N_\pm$, where the lightest fermion N_- serves as the dark matter candidate, while the CP even scalars mix and give $H_{1,2}$ respectively. Here H_1 stands for SM Higgs of 125 GeV.

3. Dark matter

A. Relic abundance

The dark matter pair ($N_- N_-$) can annihilate to ($\mu\overline{\mu}$, $\tau\overline{\tau}$, $\nu_\mu\overline{\nu}_\mu$, $\nu_\tau\overline{\nu}_\tau$) via s-channel Z' and η portals, and to ($d\overline{d}$, $s\overline{s}$) through t-channel SLQ portal. The key point is that the s-channel processes via light Z' provide a resonance in the propagator, thereby meeting the Planck relic density value [3] in the mass range $0.1 - 2.5$ GeV. The relevant plots are provided in Fig. 1.

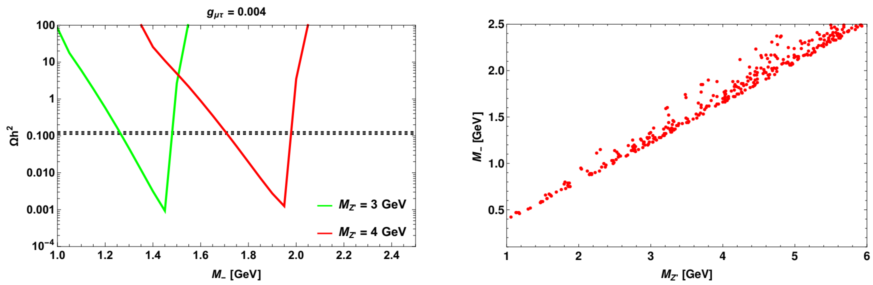

Figure 1: Relic density plotted against DM mass with black horizontal dotted lines denoting the 3σ range of Planck limit [3]. Right panel corresponds to the parameter space in the $M_- - M_{Z'}$ plane consistent with 3σ allowed region of Planck data.

B. Detection prospects

Moving to the direct detection prospects, the spin-dependent (SD) cross section can arise from the effective interaction in SLQ portal, given as

$$\mathcal{L}_{\rm eff}^{\rm SD} \simeq \frac{y_{qR}^2 \cos^2\beta}{4(M_{S_1}^2 - M_-^2)} \overline{N_-}\gamma^\mu\gamma^5 N_- \overline{q}\gamma_\mu\gamma^5 q \,, \tag{2}$$

and the corresponding SD cross section is given as [4]

$$\sigma_{\rm SD} = \frac{\mu_r^2}{\pi} \frac{\cos^4\beta}{(M_{S_1}^2 - M_-^2)^2} \left[y_{dR}^2 \Delta_d + y_{sR}^2 \Delta_s\right]^2 J_n(J_n + 1) \,, \tag{3}$$

where β is the fermion mixing angle, $J_n = \frac{1}{2}$, μ_r is the reduced mass and the quark spin functions Δ_q are provided in [4]. The obtained SD cross section for light GeV DM is well below the experimental upper limit from CDMSlite [5]. In other portals, the cross sections are insensitive to direct detection experiments.

4. Constraints on new parameters from the flavor sector

Now, we constrain the model parameters of LQ and Z' couplings using the lepton non-universality parameters, $R_{K^{(*)}}$ and the branching ratio of $B \to X_s\gamma$ decay mode. The most general effective Hamiltonian mediating the $b \to s\ell^+\ell^-$ transition is given as

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \left[\sum_{i=1}^{6} C_i(\mu)O_i + \sum_{i=7,9,10} \left(C_i(\mu)O_i + C_i'(\mu)O_i' \right) \right], \quad (4)$$

where C_i's are the Wilson coefficients and O_i's represent dimension-six current-current operators responsible for leptonic/semileptonic processes. The values of primed Wilson coefficient are zero in the SM, but can arise in the proposed $L_\mu - L_\tau$ model. The one-loop diagrams that provide non-zero contribution to the rare $b \to s\ell\ell$ processes are in Fig. 2. The loop functions of second and third diagrams have $m_q M_\pm / M_{S_1}^2$ factor suppression, hence provide minimal contribution and the dominant contribution arises only from the first diagram.

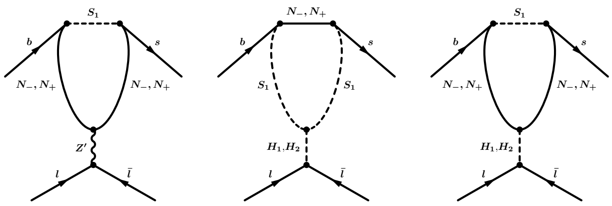

Figure 2: One loop penguin diagrams that provide non-zero contribution to $b \to s\ell\ell$ transitions.

In the presence of Z', the transition amplitude of semileptonic $b \to s\ell\ell$ decay process is [6]

$$\mathcal{M} = \frac{1}{2^5\pi^2} \frac{y_{qR}^2 g_{\mu\tau}^2}{(q^2 - M_{Z'}^2)} \mathcal{V}_{sb}(\chi_-, \chi_+) [\bar{u}(p_B)\gamma^\mu(1+\gamma_5)u(p_K))][\bar{v}(p_2)\gamma_\mu u(p_1))], \quad (5)$$

where p_B, p_K and $p_{1,2}$ represent the four momenta of initial B meson, final K meson and the charged leptons. The expression for the loop function $\mathcal{V}_{sb}(\chi_-, \chi_+)$ with $\chi_\pm = M_\pm^2/M_{S_1}^2$ can be found in [7]. In comparison with generalized effective Hamiltonian (4) gives new primed Wilson coefficient [6]

$$C_9'^{\rm NP} = \frac{\sqrt{2}}{2^4 \pi G_F \alpha_{\rm em} V_{tb}V_{ts}^*} \frac{y_{qR}^2 g_{\mu\tau}^2}{(q^2 - M_{Z'}{}^2)} \mathcal{V}_{sb}\left(\chi_-, \chi_+\right). \quad (6)$$

This new Wilson coefficient C_9' gives additional contribution to $B \to K^{(*)}\mu\mu$ processes and modify their branching fractions, while $B \to K^{(*)}ee$ processes remain unaffected as the new Z' gauge boson does not couple to electrons.

The lepton flavor violating observables associated with $b \to s\ell\ell$ transitions are defind as

$$R_{K^{(*)}} = \frac{{\rm BR}(B \to K^{(*)}\mu^+\mu^-)}{{\rm BR}(B \to K^{(*)}e^+e^-)}, \quad (7)$$

and their expected values in the SM are $\mathcal{O}(1)$. However, the recent measurement on $R_K = 0.846^{+0.044}_{-0.041}$ by LHCb experiment [8] in the low-q^2 regime [1.1,6] GeV^2 shows 3.1σ discrepancy with the SM prediction. Equivalently, recent LHCb measurements on R_{K^*} ratio in two bins of low-q^2 regions [9]:

$$R_{K^*}^{\rm LHCb} = \begin{cases} 0.660^{+0.110}_{-0.070} \pm 0.03 & q^2 \in [0.045, 1.1]\ {\rm GeV}^2, \\ 0.69^{+0.11}_{-0.07} \pm 0.05 & q^2 \in [1.1, 6.0]\ {\rm GeV}^2, \end{cases} \quad (8)$$

have respectively 2.1σ and 2.5σ deviations from their corresponding SM results.

$\boldsymbol{B \to X_s\gamma}$:

The $b \to s\gamma$ transition can occur at one loop level, where leptoquark and $N_\pm$ were driving in the loop. The branching ratio of $B \to X_s\gamma$ decay process induced by the $b \to s\gamma$ is

$$\mathrm{BR}(B \to X_s\gamma) = \mathrm{BR}(B \to X_s\gamma)\Big|^{\mathrm{SM}}\left(1 + \frac{C_7^{\gamma,\mathrm{NP}}}{C_7^{\gamma\,\mathrm{SM}}}\right)^2, \tag{9}$$

$$C_7^{\gamma,\mathrm{NP}} = -\frac{\sqrt{2}/3}{8G_F V_{tb}V_{ts}^*}\frac{y_{qR}^2}{M_{S_1}^2}\Big(J_1(\chi_-)\cos^2\alpha + J_1(\chi_+)\sin^2\alpha\Big), \tag{10}$$

with the loop functions $J_1(\chi_\pm)$ [7].

Using the values of the LFU observables $R_{K^{(*)}}$ and $\mathrm{BR}(B \to X_s\gamma)$, we show the $g_{\mu\tau} - M_{Z'}$ and $y_{qR} - M_-$ allowed parameter space in Fig. 3. The validity of the effective field theory description in the present model lies above electroweak scale i.e., $\sim (300 - 3000)$ GeV.

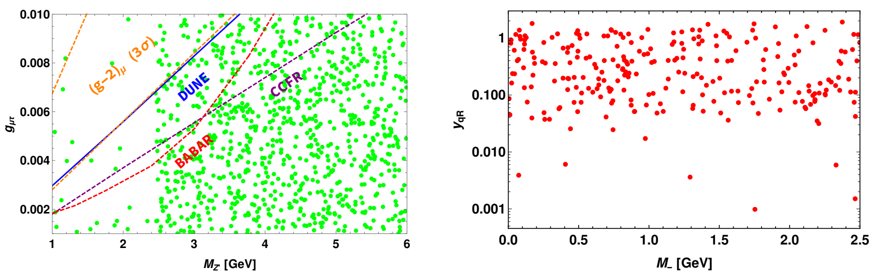

Figure 3: Constraints on $M'_Z - g_{\mu\tau}$ (left panel) and $M_- - y_{qR}$ (right panel), obtained by using the branching ratio of $B \to X_s\gamma$ and $R_{K^{(*)}}$ parameters. Lines in left panel denote the 3σ consistent region of muon $g-2$ [10], exclusion limit from BABAR [11], neutrino trident bounds from CCFR [12] and DUNE [13].

5. Footprints on $b \to s\ \not{E}$ decay modes

The SM treats neutrinos as the only carriers of missing energy in $b \to s$ transitions, i.e., $b \to s\ \not{E}$ can be described as $b \to s\nu\bar{\nu}$ processes. To see the implications of the model on rare B decays with missing energy, we consider the decay modes $b \to sN_-N_-$ in addition to the SM $b \to s\nu\bar{\nu}$ processes. These processes are mediated through one-loop diagrams and the dominant contribution arises come from the loop diagram as shown in the first diagram of Fig. 2, with the final $l\bar{l}$ pair replaced by N_-N_- pair. The branching fraction for these processes are given as, for example,

$$\mathrm{BR}(B \to K\ \not{E}) = \mathrm{BR}(B \to K\nu\bar{\nu}) + \mathrm{BR}(B \to KN_-\,N_-)\,, \tag{11}$$

and the detailed expressions for the branching fractions are found in [2]. Considering two sets of benchmark values for the model parameters consistent with dark matter and flavor observables as:

Bechmark-I: $y_{qR} = 2.0$, $g_{\mu\tau} = 0.002$, $M_- = 1.7$ GeV and $M_{Z'} = 4.0$ GeV,

Bechmark-II: $y_{qR} = 2.0$, $g_{\mu\tau} = 0.008$, $M_- = 1.8$ GeV and $M_{Z'} = 4.8$ GeV,

we obtain the branching ratios for various processes as given in Table-2. It should be noted that

$\text{Br}(b \to s \not{E})$	Benchmark-I	Benchmark-II	Experimental Limit [14]
$\text{Br}(B^0 \to K^0 \not{E})$	0.645×10^{-5}	0.457×10^{-5}	$< 2.6 \times 10^{-5}$
$\text{Br}(B^+ \to K^+ \not{E})$	0.697×10^{-5}	0.516×10^{-5}	$< 1.6 \times 10^{-5}$
$\text{Br}(B^0 \to K^{*0} \not{E})$	1.271×10^{-5}	0.981×10^{-5}	$< 1.8 \times 10^{-5}$
$\text{Br}(B^+ \to K^{*+} \not{E})$	1.381×10^{-5}	1.066×10^{-5}	$< 4.0 \times 10^{-5}$
$\text{Br}(B_s \to \phi \not{E})$	1.618×10^{-5}	1.24×10^{-5}	$< 5.4 \times 10^{-3}$

Table 2: The predicted branching ratios of $b \to s \not{E}$ processes for two different benchmark values of new parameters.

these predicted branching ratios are slightly lower than the the present upper limits and are expected to be measured by LHCb or Belle II experiments.

To conclude, we have investigated light GeV scale dark matter and flavor anolamies in a simple $U(1)_{L_\mu - L_\tau}$ variant model with three heavy neutral fermions and a scalar leptoquark.The associated gauge boson Z' plays a key role in obtaining the dark matter relic density.The proposed model successfully explains dark matter, flavor anomalies in $b \to s\ell\ell$ transitions and significantly enhances the $b \to s + \not{E}$ decay rates. The observation of these modes would provide strong hints for the existence of light fermionic dark matter.

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