

Exploring Flavor Anomalies and Dark Matter in $U(1)_{L_e-L_\mu}$ model with a scalar Leptoquark

[In collaboration with Shivaramakrishna Singirala, Dhiren Panda and Rukmani Mohanta]

Manas Kumar Mohapatra

University of Hyderabad, India

**FPCP 2024,
Chulalongkorn University, Bangkok**



Outline

- Introduction (Motivation to study the $b \rightarrow sll$ quark decays)
- A $U(1)_{L_e-L_\mu}$ model with heavy fermions and \tilde{R}_2 leptoquark
- Sensitivity of new physics in $\Lambda_b \rightarrow \Lambda^*(\rightarrow pK)ll$ process
- Relic density of Majorana dark matter
- Conclusion

Introduction

- The updated results from LHCb confirmed that the measured values of $R_{K^{(*)}}$ observables are consistent with their SM predictions.
- However, there exist a variety of other observables in $b \rightarrow s \ell \ell$ transition in B decays which indicate remarkable deviations from the SM.

	q^2 bins	Theoretical predictions	Experimental measurements	Deviation
P'_5	[4.0,6.0]	-0.757 ± 0.074	-0.21 ± 0.15 (1; 2)	$\sim 3.3\sigma$
	[4.0, 8.0]	-0.881 ± 0.082	$-0.267^{+0.275}_{-0.269} \pm 0.049$ (3)	$\sim 2.1\sigma$
$\mathcal{B}(B_s \rightarrow \phi \mu^+ \mu^-)$	[1.1, 6.0]	$(5.37 \pm 0.66) \times 10^{-8}$	$(2.88 \pm 0.22) \times 10^{-8}$ (4; 5; 6)	$\sim 3.6\sigma$
$\mathcal{B}(B_s \rightarrow \mu^+ \mu^-)$	-	$(3.66 \pm 0.14) \times 10^{-9}$	$(3.09^{+0.46+0.15}_{-0.43-0.11}) \times 10^{-9}$ (7)	$\sim 1.2\sigma$

Table: Current status of $b \rightarrow s \ell^+ \ell^-$ decay observables

A $U(1)_{L_e-L_\mu}$ model with heavy fermions and \tilde{R}_2 leptoquark

	Field	$SU(3)_C \times SU(2)_L \times U(1)_Y$	$U(1)_{L_e-L_\mu}$	Z_2
Fermions	$Q_L \equiv (u, d)_L^T$	$(\mathbf{3}, \mathbf{2}, 1/6)$	0	+
	u_R	$(\mathbf{3}, \mathbf{1}, 2/3)$	0	+
	d_R	$(\mathbf{3}, \mathbf{1}, -1/3)$	0	+
	$\ell_{\alpha L} \equiv (\nu_\alpha, \alpha)_L, \alpha = e, \mu, \tau$	$(\mathbf{1}, \mathbf{2}, -1/2)$	1, -1, 0	+
	$\ell_R \equiv \alpha_R, \alpha = e, \mu, \tau$	$(\mathbf{1}, \mathbf{1}, -1)$	1, -1, 0	+
	N_e, N_μ, N_τ	$(\mathbf{1}, \mathbf{1}, 0)$	1, -1, 0	-
Scalars	H	$(\mathbf{1}, \mathbf{2}, 1/2)$	0	+
	η	$(\mathbf{1}, \mathbf{2}, 1/2)$	0	-
	ϕ_2	$(\mathbf{1}, \mathbf{1}, 0)$	2	+
	\tilde{R}_2	$(\mathbf{3}, \mathbf{2}, 1/6)$	1	-

- Adding three heavy fermions ($N_{\alpha R}$), which mix and the lightest mass eigenstate will be dark matter
- ϕ_2 breaks the new $U(1)$ and gives masses to N_α and Z'
- \tilde{R}_2 leptoquark along with N_α s and Z' provide new physics for $b \rightarrow s$ transition.
- η along with heavy fermions generates neutrino mass at one-loop.

- The relevant Lagrangian is given by

$$\begin{aligned}
\mathcal{L}_f &= -\frac{1}{2}M_{\tau\tau}\overline{N_\tau^c}N_\tau - \left(\frac{f_e}{2}\overline{N_e^c}N_e\phi_2^\dagger + \frac{f_\mu}{2}\overline{N_\mu^c}N_\mu\phi_2 + \text{h.c.} \right) - \frac{1}{2}M_{e\mu}(\overline{N_e^c}N_\mu + \overline{N_\mu^c}N_e) \\
&\quad - \sum_{l=e,\mu,\tau} (Y_{ll}(\overline{\ell}_L)_l\tilde{\eta}N_{lR} + \text{h.c.}) - (y_{qRN}\overline{Q}_L\tilde{R}_2N_{\mu R} + \text{h.c.}), \\
\mathcal{L}_{G-f} &= (-g_{e\mu}\bar{e}\gamma^\mu e + g_{e\mu}\bar{\mu}\gamma^\mu\mu - g_{e\mu}\bar{\nu}_e\gamma^\mu(1-\gamma^5)\nu_e + g_{e\mu}\bar{\nu}_\mu\gamma^\mu(1-\gamma^5)\nu_\mu) Z'_\mu \\
&\quad - g_{e\mu}\overline{N_e}Z'_\mu\gamma^\mu\gamma^5 N_e + g_{e\mu}\overline{N_\mu}Z'_\mu\gamma^\mu\gamma^5 N_\mu, \\
\mathcal{L}_S &= \left| \left(i\partial_\mu - \frac{g}{2}\boldsymbol{\tau}^a \cdot \mathbf{W}_\mu^a - \frac{g'}{6}B_\mu + g_{e\mu}Z'_\mu \right) \tilde{R}_2 \right|^2 + \left| (i\partial_\mu - 2g_{e\mu}Z'_\mu) \phi_2 \right|^2 \\
&\quad + \left| \left(i\partial_\mu - \frac{g}{2}\boldsymbol{\tau}^a \cdot \mathbf{W}_\mu^a - \frac{g'}{2}B_\mu \right) \eta \right|^2 - V(H, \tilde{R}_2, \eta, \phi_2). \tag{1}
\end{aligned}$$

- In the above, the new scalar doublets are denoted by η and \tilde{R}_2 are given by

$$\eta = \begin{pmatrix} \eta^+ \\ \eta^0 \end{pmatrix} \text{ and } \tilde{R}_2 = \begin{pmatrix} \tilde{R}_2^{2/3} \\ \tilde{R}_2^{-1/3} \end{pmatrix}.$$

- The fermion and scalar mass matrices take the form

$$M_N = \begin{pmatrix} \frac{1}{\sqrt{2}} f_e v_2 & M_{e\mu} \\ M_{e\mu} & \frac{1}{\sqrt{2}} f_\mu v_2 \end{pmatrix}, \quad M_S = \begin{pmatrix} 2\lambda_H v^2 & \lambda_{H2} v v_2 \\ \lambda_{H2} v v_2 & 2\lambda_2 v_2^2 \end{pmatrix}. \quad (2)$$

- One can diagonalize the above mass matrices by

$$U_{\delta(\zeta)}^T M_{N(S)} U_{\delta(\zeta)} = \text{diag} [M_{N_1(H_1)}, M_{N_2(H_2)}], \text{ where}$$

$$U_\theta = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix}, \quad (3)$$

with $\zeta = \frac{1}{2} \tan^{-1} \left(\frac{\lambda_{H2} v v_2}{\lambda_2 v_2^2 - \lambda_H v^2} \right)$ and $\delta = \frac{1}{2} \tan^{-1} \left(\frac{2M_{e\mu}}{(f_\mu - f_e)(v_2/\sqrt{2})} \right)$.

- We denote the scalar mass eigenstates as H_1 and H_2 , with H_1 is assumed to be observed Higgs at LHC with $M_{H_1} = 125.09$ GeV and $v = 246$ GeV.
- We indicate N_1 and N_2 to be the fermion mass eigenstates, with the lightest one (N_1) as the probable dark matter candidate in the present work.

Effective Hamiltonian

- The most general effective Hamiltonian mediating the $b \rightarrow sl^+l^-$ transition is given by (8)

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

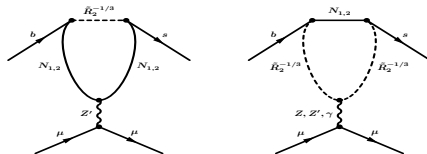
where G_F is the Fermi constant, $V_{tb}V_{ts}^*$ denote the CKM matrix elements.

- The O_i 's, represent dimension-six operators responsible for leptonic/semileptonic processes, are given as

$$\begin{aligned} O_9^{(\prime)} &= \frac{\alpha_{\text{em}}}{4\pi} (\bar{s}\gamma^\mu P_{L(R)}b)(\bar{l}\gamma_\mu l), \\ O_{10}^{(\prime)} &= \frac{\alpha_{\text{em}}}{4\pi} (\bar{s}\gamma^\mu P_{L(R)}b)(\bar{l}\gamma_\mu \gamma_5 l), \end{aligned} \quad (5)$$

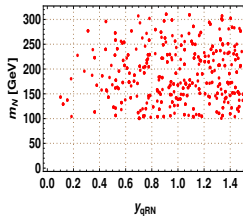
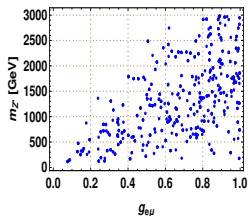
where α_{em} is the fine structure constant.

Constraints on NP coupling(s)



- The new Wilson coefficient is given as,

$$C_9^{\text{NP}} = -\frac{1}{4\pi} \frac{\sqrt{2}}{4G_F m_{Z'}^2} \frac{1}{\alpha_{em}} \frac{y_{qRN}^2 g_{e\mu}^2}{V_{tb} V_{ts}^*} \mathcal{R}(a, b), \quad \text{where } a(b) = \frac{m_{N_{1(2)}}^2}{m_{LQ}^2}. \quad (6)$$



Impact on the $\Lambda \rightarrow \Lambda^*(\rightarrow pK)\ell\ell$ process

- In light of anomalies present in $b \rightarrow s\ell\ell$ quark level transition decays, we perform an analysis of baryonic $\Lambda_b \rightarrow \Lambda^*(\rightarrow pK)\mu\mu$ process.
- The differential branching ratio $d\mathcal{B}/dq^2$, and the fraction of longitudinal polarization $F_L(q^2)$ are defined as

$$\begin{aligned}\frac{d\mathcal{B}}{dq^2} &= \frac{1}{3} \left[K_{1cc} + 2K_{1ss} + 2K_{2cc} + 4K_{2ss} + 2K_{3ss} \right], \\ F_L &= 1 - \frac{2(K_{1cc} + 2K_{2cc})}{K_{1cc} + 2(K_{1ss} + K_{2cc} + 2K_{2ss} + K_{3ss})},\end{aligned}\tag{7}$$

with $K_{(\dots)}$ are the angular coefficients.

Contd...

Analysis:

- $g_{e\mu} = 0.6$, $y_{qRN} = 0.3$, $m_{Z'}$ = 500 GeV, $m_N = 300$ GeV and $\delta = 30^\circ$.

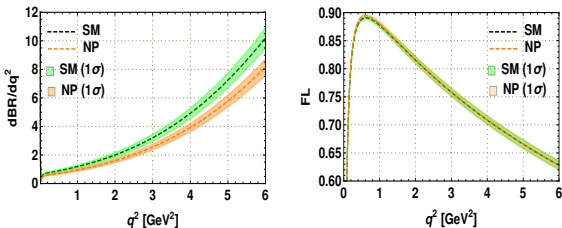


Figure: The q^2 dependency of branching ratio (left panel) and the polarisation asymmetry (right panel) in the SM and new physics.

- BR:** The presence of NP coupling reduces the branching ratio. However, in the low q^2 region, it becomes consistent with the SM contribution.
- FL:** We do not observe any new physics signatures despite the presence of NP coefficients.

Majorana dark matter

Relic density :

- The lightest fermion N_1 can annihilate via Z' , \tilde{R}_2 and $H_{1,2}$ portals and contribute to total relic density of the Universe.
- Via Z' boson, $N_1 N_1$ can annihilate to $e\bar{e}, \mu\bar{\mu}, \nu_e\bar{\nu}_e, \nu_\mu\bar{\nu}_\mu$ through s-channel.
- Mediated by $\tilde{R}_2^{2/3}$, $N_1 N_1$ can annihilate to $q_1 \bar{q}'_1$ with $q_1, q'_1 = u, c, t$. Via $\tilde{R}_2^{-1/3}$ $N_1 N_1$ produce $q_2 \bar{q}'_2$ as final state particles with $q_2, q'_2 = d, s, b$ through t-channel.
- With the mediation of scalar Higgs, $N_1 N_1$ can annihilate to $f\bar{f}, W^+W^-, ZZ, hh, Z'H_1$ through s-channel.
- The relic density of dark matter is computed by

$$\Omega h^2 = \frac{1.07 \times 10^9 \text{ GeV}^{-1}}{g_*^{1/2} M_{\text{Pl}}} \frac{1}{J(x_f)}, \text{ where } J(x_f) = dx \int_{x_f}^{\infty} \frac{\langle \sigma_{\text{eff}} v \rangle(x)}{x^2}. \quad (8)$$

$$\langle \sigma v \rangle(x) = \frac{x}{8M_{\text{DM}}^5 K_2^2(x)} \int_{4M_{\text{DM}}^2}^{\infty} \hat{\sigma} \times (s - 4M_{\text{DM}}^2) \sqrt{s} K_1 \left(\frac{x\sqrt{s}}{M_{\text{DM}}} \right) ds. \quad (9)$$

Analysis :

- $M_{Z'} = 500 \text{ GeV}$, $M_{H1} = 125 \text{ GeV}$, $M_{H2} = 800 \text{ GeV}$ (resonance at $M_{N_1} = M_{\text{prop}}/2$)
- $\zeta \sim 10^{-3}$, $\delta = 30^\circ$

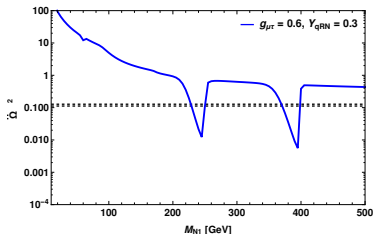
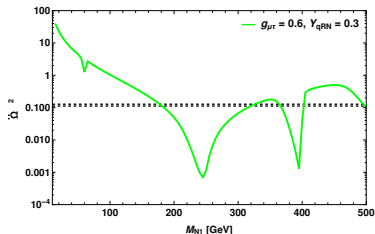


Figure: Relic density vs dark matter mass, displaying dominant Z' portal (left panel) and dictating \tilde{R}_2 portal (right panel). Horizontal dashed lines correspond to 3σ bound on relic abundance by Planck data.

Neutrino mass : Type-I radiative neutrino mass can be obtained at one-loop with heavy fermions and neutral inert doublet components running in the loop.

* Note : Direct detection and neutrino mass work is still in progress.

Conclusion

- We have investigated $U(1)_{L_e-L_\mu}$ extension of SM for a correlative study of dark matter and flavor anomalies.
- With three heavy neutral fermions, $\tilde{R}_2(3, 2, 1/6)$ scalar leptoquark and a $U(1)$ associated Z' , the model can provide new physics contribution to $b \rightarrow s$ transition (penguin loop).
- We have studied the $\Lambda_b \rightarrow \Lambda^*(\rightarrow pK)\mu\mu$ process pertaining to $b \rightarrow s\mu\mu$ transition.
- The differential branching ratio deviates, and also quite distinguishable from the SM contributions.
- The relic density of lightest Majorana fermion is obtained, consistent with Planck satellite data. The annihilation channels with fermion anti-fermion pair in final state contribute maximally, are mediated by scalar Higgs boson, Z' and \tilde{R}_2 leptoquark.

Thank you!

Reference

- [1] M. Aaboud *et al.*, “Angular analysis of $B_d^0 \rightarrow K^* \mu^+ \mu^-$ decays in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector,” *JHEP*, vol. 10, p. 047, 2018.
- [2] R. Aaij *et al.*, “Angular analysis of the $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ decay using 3 fb^{-1} of integrated luminosity,” *JHEP*, vol. 02, p. 104, 2016.
- [3] A. Abdesselam *et al.*, “Angular analysis of $B^0 \rightarrow K^*(892)^0 \ell^+ \ell^-$,” in *LHC Ski 2016: A First Discussion of 13 TeV Results*, 4 2016.
- [4] R. Aaij *et al.*, “Branching Fraction Measurements of the Rare $B_s^0 \rightarrow \phi \mu^+ \mu^-$ and $B_s^0 \rightarrow f_2'(1525) \mu^+ \mu^-$ Decays,” *Phys. Rev. Lett.*, vol. 127, no. 15, p. 151801, 2021.
- [5] R. Aaij *et al.*, “Differential branching fraction and angular analysis of the decay $B_s^0 \rightarrow \phi \mu^+ \mu^-$,” *JHEP*, vol. 07, p. 084, 2013.
- [6] R. Aaij *et al.*, “Angular analysis and differential branching fraction of the decay $B_s^0 \rightarrow \phi \mu^+ \mu^-$,” *JHEP*, vol. 09, p. 179, 2015.
- [7] R. Aaij *et al.*, “Analysis of Neutral B-Meson Decays into Two Muons,” *Phys. Rev. Lett.*, vol. 128, no. 4, p. 041801, 2022.
- [8] C. Bobeth, A. J. Buras, F. Kruger, and J. Urban, “QCD corrections to $\bar{B} \rightarrow X_{d,s} \nu \bar{\nu}$, $\bar{B}_{d,s} \rightarrow \ell^+ \ell^-$, $K \rightarrow \pi \nu \bar{\nu}$ and $K_L \rightarrow \mu^+ \mu^-$ in the MSSM,” *Nucl. Phys. B*, vol. 630, pp. 87–131, 2002.