Connecting the $b \to s\ell\ell$ decays with dark sector in the light of scalar leptoquark $\tilde{R}_2$

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PPC 2024,
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Outline

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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 $b \to s\ell\ell$ 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)	$\sim 2.1\sigma$
$\mathcal{B}(B_s \to \phi\,\mu^+\,\mu^-)$	[1.1, 6.0]	$(5.37 \pm 0.66) \times 10^{-8}$	$(2.88 \pm 0.22) \times 10^{-8}$ (4; 5; 6)	$\sim 3.6\sigma$
$\mathcal{B}(B_s \to \mu^+\,\mu^-)$	-	$(3.66 \pm 0.14) \times 10^{-9}$	$(3.09^{+0.46+0.15}_{-0.43-0.11}) \times 10^{-9}$ (7)	$\sim 1.2\sigma$

Table: Current status of $b \to s\,\ell^+\,\ell^-$ 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_αs and Z' provide new physics for $b \to s$ transition.
- η along with heavy fermions generates neutrino mass at one-loop.

- The relevant Lagrangian is given by

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

- 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

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

- One can diagonalize the above mass matrices by $U^T_{\delta(\zeta)} M_{N(S)} U_{\delta(\zeta)} = \text{diag}\,[M_{N_1(H_1)}, M_{N_2(H_2)}]$, where

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

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 $b \to s l^+ l^-$ transition is given by (8)

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

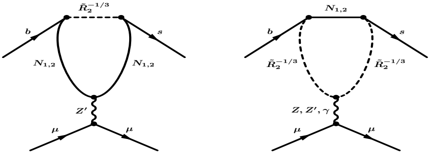
where G_F is the Fermi constant, $V_{tb} V_{ts}^*$ denote the CKM matrix elements.

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

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

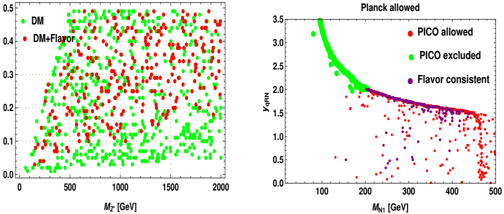
where α_{em} is the fine structure constant.

Constraints on NP coupling(s)



- The new Wilson coefficient is given as,

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



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

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

$$\begin{aligned} \frac{d\mathcal{B}}{dq^2} &= \frac{1}{3}\left[K_{1cc} + 2K_{1ss} + 2K_{2cc} + 4K_{2ss} + 2K_{3ss}\right], \\ R_{\Lambda^*} &= \frac{d\mathcal{B}/dq^2|_\mu}{d\mathcal{B}/dq^2|_e}, \end{aligned} \tag{7}$$

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

Contd...

Analysis:

- $g_{e\mu} = 0.3$, $y_{qRN} = 1.1$, $m_{Z'} = 671$ GeV, $m_N = 300$ GeV and $\delta = 30°$.

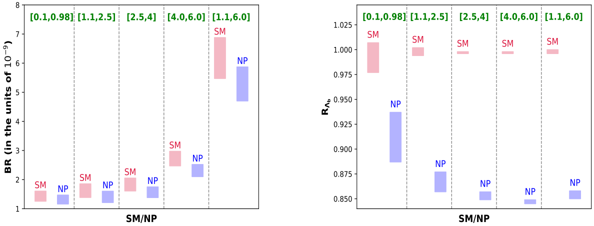


Figure: The q^2 dependency of branching ratio (left panel) and the lepton non-universal observable (right panel)in the SM and new physics.

- *BR*: The presence of NP coupling reduces the branching ratio. However, in the low q^2 region, it becomes consistent with the SM contribution.
- *R*: NP coupling reduces the lepton non-universality observable.

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 the 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 $q_1\overline{q_1'}$ with $q_1, q_1' = u, c, t$. Via $\tilde{R_2}^{-1/3}$ $N_1 N_1$ produce $q_2\overline{q_2'}$ 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

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

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

Analysis :

- $M_{Z'} = 671$ GeV, $M_{H1} = 125$ GeV, $M_{H2} = 800$ GeV (resonance at $M_{N_1} = M_{\rm prop}/2$)
- $\zeta \sim 10^{-3}$, $\delta = 30^\circ$

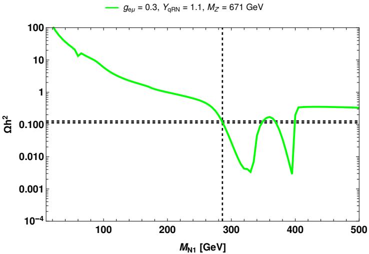


Figure: Figure projects relic density as a function of dark matter mass with horizontal dashed lines corresponding to Planck 3σ constraint on relic density.

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 $b \to s$ transition (penguin loop).
- We have studied the $\Lambda_b \to \Lambda^*(\to pK)\mu\mu$ process pertaining to $b \to s\mu\mu$ transition.
- The differential branching ratio deviates, and also quite distinguishable from the SM contributions.
- The relic density of the lightest Majorana fermion is obtained, consistent with Planck satellite data. The annihilation channels with fermion anti-fermion pair in the final state contribute maximally and are mediated by scalar Higgs boson, Z', and $\tilde{R}_2$ leptoquark.

Thank you!

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