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

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Outline of the Talk

1. $L_\mu - L_\tau$ model with Scalar Leptoquark
2. Symmetry breaking and mass spectra
3. Dark Matter Phenomenology
4. Constraints from Flavour Sector
5. Implications on Rare B decays with $\not{E}$
6. Conclusion

Motivation

- There are a few open issues, which can not be addressed in the SM, e.g. Existence of Dark Matter, Non-zero neutrino masses & mixing, Observed Baryon Asymmetry of the Universe, etc
- SM must be extended. What is the underlying fundamental theory?
- No direct evidence of NP either in Energy frontier or Intensity frontier
- In last few years several anomalies are reported in in $b \to s\ell\ell$ FCNC transitions, which might possibly suggest the presence of NP
- Interesting one: Lepton Non-Universality Observable Sizable discrepancies ($\geq 2\sigma$) reported by the LHCb and Belle Collaborations in the ratio $R_{K^{(*)}}$

$$R_{K^{(*)}} = \frac{\mathrm{Br}(B \to K^{(*)}\mu\mu)}{\mathrm{Br}(B \to K^{(*)}ee)}$$

LNU observable	SM prediction	Expt. value	Deviation
$R_K\|_{q^2\in[1.0,6.0]}$	1.0003 ± 0.0001	$0.846^{+0.044}_{-0.041}$ (LHCb)	3.1σ
$R_{K^*}\|_{q^2\in[0.045,1.1]}$	0.92 ± 0.02	$0.660^{+0.110}_{-0.070} \pm 0.024$ (LHCb)	2.2σ
$R_{K^*}\|_{q^2\in[1.1,6.0]}$	1.00 ± 0.01	$0.685^{+0.113}_{-0.007} \pm 0.047$ (LHCb)	2.4σ

R. Aaij et al. [LHCb Collab], 2103.11769, JHEP 08, 055 (2017).

Model description (Gauged $L_\mu - L_\tau$)

- The SM has accidental $U(1)$ global symmetries like B and L no. conservation
- However, they become anomalous if promoted into a local one
- The anomaly free situation can be obtained if instead of considering B and L separately, some combinations between them, e.g., $B-L$, $L_e - L_\mu$, $L_e - L_\tau$ or $L_\mu - L_\tau$
- For the anomaly cancellation of local $B-L$ models, one requires 3 RHNs with appropriate $B-L$ charges
- Unlike $B-L$ case, the anomaly cancellation does not require any extra chiral fermionic degrees of freedom for $L_\alpha - L_\beta$, as anomalies cancel between different leptonic generations.
- $U(1))_{L_\mu - L_\tau}$ is less constrained, as the extra Z' does not couple to electrons and quarks, $\Rightarrow$ free from any constraints from lepton and hadron colliders
- Another theoretical motivation: it can explain the muon $(g-2)$ anomaly

Particle Content of $L_\mu - L_\tau$ model

	Field	$SU(3)_C \times SU(2)_L \times U(1)_Y$	$U(1)_{L_\mu - L_\tau}$	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	+
	$\ell_L \equiv e_L, \mu_L, \tau_L$	$(\mathbf{1}, \mathbf{2}, -1/2)$	$0, 1, -1$	+
	$\ell_R \equiv e_R, \mu_R, \tau_R$	$(\mathbf{1}, \mathbf{1}, -1)$	$0, 1, -1$	+
	N_e, N_μ, N_τ	$(\mathbf{1}, \mathbf{1}, 0)$	$0, 1, -1$	−
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	+
	S_1	$(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$	-1	−
Gauge bosons	$W_\mu^i \ (i = 1, 2, 3)$	$(\mathbf{1}, \mathbf{3}, 0)$	0	+
	B_μ	$(\mathbf{1}, \mathbf{1}, 0)$	0	+
	V_μ	$(\mathbf{1}, \mathbf{1}, 0)$	0	+

Table: Fields and their charges of the proposed $U(1)_{L_\mu - L_\tau}$ model.

Lagrangian of the Model

The Lagrangian of the present model can be written as

$$\mathcal{L}_G = -\frac{1}{4}\left(\hat{\mathbf{W}}_{\mu\nu}\hat{\mathbf{W}}^{\mu\nu} + \hat{B}_{\mu\nu}\hat{B}^{\mu\nu} + \hat{V}_{\mu\nu}\hat{V}^{\mu\nu} + 2\sin\chi\hat{B}_{\mu\nu}\hat{V}^{\mu\nu}\right),$$

$$\mathcal{L}_f = -\frac{1}{2}M_{ee}\overline{N_e^c}N_e - \frac{f_\mu}{2}\left(\overline{N_\mu^c}N_\mu\phi_2^\dagger + \mathrm{h.c.}\right) - \frac{f_\tau}{2}\left(\overline{N_\tau^c}N_\tau\phi_2 + \mathrm{h.c.}\right)$$
$$-\frac{1}{2}M_{\mu\tau}(\overline{N_\mu^c}N_\tau + \overline{N_\tau^c}N_\mu) - \sum_{l=e,\mu,\tau}(Y_{ll}(\overline{\ell_L})_l\tilde{\eta}N_{lR} + \mathrm{h.c})$$
$$-\sum_{q=d,s,b}(y_{qR}\,\overline{d_{qR}^c}S_1N_\mu + \mathrm{h.c.}),$$

$$\mathcal{L}_{G-f} = -g_{\mu\tau}\overline{\mu}\gamma^\mu\mu\hat{V}_\mu + g_{\mu\tau}\overline{\tau}\gamma^\mu\tau\hat{V}_\mu - g_{\mu\tau}\overline{\nu_\mu}\gamma^\mu(1-\gamma^5)\nu_\mu\hat{V}_\mu$$
$$+g_{\mu\tau}\overline{\nu_\tau}\gamma^\mu(1-\gamma^5)\nu_\tau\hat{V}_\mu - g_{\mu\tau}\overline{N_\mu}\hat{V}_\mu\gamma^\mu\gamma^5N_\mu + g_{\mu\tau}\overline{N_\tau}\hat{V}_\mu\gamma^\mu\gamma^5N_\tau,$$

$$\mathcal{L}_S = \left|\left(i\partial_\mu - \frac{g}{2}\boldsymbol{\tau}^a\cdot\hat{\mathbf{W}}_\mu^a - \frac{g'}{2}\hat{B}_\mu\right)\eta\right|^2 + \left|\left(i\partial_\mu - \frac{g'}{3}\hat{B}_\mu + g_{\mu\tau}\hat{V}_\mu\right)S_1\right|^2$$
$$+\left|\left(i\partial_\mu - 2g_{\mu\tau}\hat{V}_\mu\right)\phi_2\right|^2 - V(H,\eta,\phi_2,S_1).$$

Scalar potential

- The scalar potential V is expressed as

$$
\begin{aligned}
V(H,\eta,\phi_2,S_1) = {}& V(H) + \mu_\eta^2 \eta^\dagger \eta + \lambda_{H\eta}(H^\dagger H)(\eta^\dagger \eta) + \lambda_\eta (\eta^\dagger \eta)^2 \\
&+ \lambda'_{H\eta}(H^\dagger \eta)(\eta^\dagger H) + \frac{\lambda''_{H\eta}}{2}\left[(H^\dagger \eta)^2 + \mathrm{h.c.}\right] + \mu_\phi^2(\phi_2^\dagger \phi_2) + \lambda_\phi(\phi_2^\dagger \phi_2)^2 \\
&+ \mu_S^2({S_1}^\dagger S_1) + \lambda_S({S_1}^\dagger S_1)^2 + \left[\lambda_{H\phi}(\phi_2^\dagger \phi_2) + \lambda_{HS}(S_1^\dagger S_1)\right](H^\dagger H) \\
&+ \lambda_{S\phi}(\phi_2^\dagger \phi_2)({S_1}^\dagger S_1) + \lambda_{\eta\phi}(\phi_2^\dagger \phi_2)(\eta^\dagger \eta) + \lambda_{S\eta}({S_1}^\dagger S_1)(\eta^\dagger \eta).
\end{aligned}
$$

- SSB occurs when the scalars get their VEVs: $\langle \phi_2 \rangle = \frac{v_2}{\sqrt{2}}$, $\langle H \rangle = \frac{v}{\sqrt{2}}$, $SU(2)_L \times U(1)_Y \times U(1)_{L_\mu - L_\tau} \Longrightarrow SU(2)_L \times U(1)_Y \Longrightarrow U(1)_{em}$
- We have $\mu_\eta^2, \mu_S^2 > 0$ and the masses of the SLQ and inert doublet η are

$$
\begin{aligned}
M_{S_1}^2 &= 2\mu_S^2 + \lambda_{HS} v^2 + \lambda_{S\phi} v_2^2 \,, \\
M_{\eta_c}^2 &= \mu_\eta^2 + \lambda_{H\eta} v^2/2 + \lambda_{\eta\phi} v_2^2/2, \\
M_{\eta_{r,i}}^2 &= \mu_\eta^2 + \left(\lambda_{H\eta} + \lambda'_{H\eta} \pm \lambda''_{H\eta}\right) v^2/2 + \lambda_{\eta\phi} v_2^2/2.
\end{aligned}
$$

Gauge mixing

- For the mixing of $U(1)_Y$ and $U(1)_{L_\mu - L_\tau}$ gauge bosons, we consider the $GL(2,R)$ transformation

$$\begin{pmatrix} \bar{B}_\mu \\ \bar{V}_\mu \end{pmatrix} = \begin{pmatrix} 1 & \sin\chi \\ 0 & \cos\chi \end{pmatrix} \begin{pmatrix} \hat{B}_\mu \\ \hat{V}_\mu \end{pmatrix}.$$

- Thus, the mass matrix of gauge fields in the basis $\left(W_\mu^3, \bar{B}_\mu, \bar{V}_\mu\right)$ as

$$M_G^2 = \begin{pmatrix} \frac{1}{8}g^2v^2 & -\frac{1}{8}gg'v^2 & \frac{1}{8}gg'\tan\chi v^2 \\ -\frac{1}{8}gg'v^2 & \frac{1}{8}g'^2v^2 & -\frac{1}{8}g'^2\tan\chi v^2 \\ \frac{1}{8}gg'\tan\chi v^2 & -\frac{1}{8}g'^2\tan\chi v^2 & 2g_{\mu\tau}^2\sec\chi^2 v^2 \end{pmatrix}.$$

- Diagonalization of M_G^2 gives the masses of the physical gauge bosons

$$M_Z^2 = M_{Z_{SM}}^2\cos\alpha^2 - \delta M^2\sin 2\alpha + M_{\bar{V}}^2\sin\alpha^2,$$
$$M_{Z'}^2 = M_{Z_{SM}}^2\sin\alpha^2 + \delta M^2\sin 2\alpha + M_{\bar{V}}^2\cos\alpha^2,$$
$$\alpha = \frac{1}{2}\tan^{-1}\left[\frac{2\,\delta M^2}{M_{\bar{V}}^2 - M_{Z_{SM}}^2}\right].$$

Scalar and Fermion mixing

- The CP-even scalars h and h_2 as well as the heavy fermion states N_μ and N_τ mix with the mixing matrices given as

$$M_H^2 = \begin{pmatrix} 2\lambda_H v^2 & \lambda_{H\phi} v v_2 \\ \lambda_{H\phi} v v_2 & 2\lambda_\phi v_2^2 \end{pmatrix}, \quad M_N = \begin{pmatrix} \frac{1}{\sqrt{2}} f_\mu v_2 & M_{\mu\tau} \\ M_{\mu\tau} & \frac{1}{\sqrt{2}} f_\tau v_2 \end{pmatrix}.$$

One can diagonalize the above mass matrices using a 2×2 rotation matrix

$$U_\zeta^T M_H^2 U_\zeta = \mathrm{diag}\,[M_{H_1}^2, M_{H_2}^2], \qquad U_\beta^T M_N U_\beta = \mathrm{diag}\,[M_-, M_+],$$

with $\zeta = \frac{1}{2}\tan^{-1}\left(\frac{\lambda_{H\phi} v v_2}{\lambda_\phi v_2^2 - \lambda_H v^2}\right)$, $\beta = \frac{1}{2}\tan^{-1}\left(\frac{2M_{\mu\tau}}{(f_\tau - f_\mu)(v_2/\sqrt{2})}\right)$.

- The lightest fermion mass eigenstate N_- considered as probable DM candidate, and M_{H_1} as the SM Higgs

M_{S_1}	M_+	M_{H_1}	M_{H_2}	$\sin\beta$	$\sin\zeta$	χ	$\alpha \times 10^4$
1200	500	125	500	1/2	$10^{-3} - 10^{-2}$	10^{-3}	$4.83 - 4.85$

Table: Values of the model parameters used in the analysis (masses are in GeV).

Dark Matter Relic Abundance

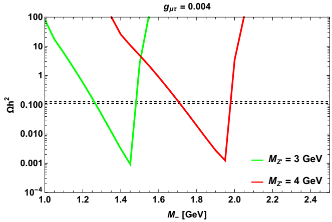
- The relic density of the light DM (N_-) is computed via freeze-out mechanism through the following decay channels:

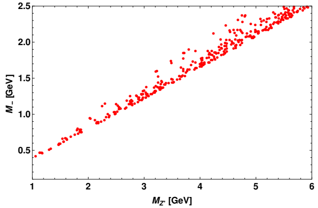
$$\begin{aligned} N_-\overline{N}_- &\to \mu\overline{\mu},\ \tau\overline{\tau},\ \nu_\mu\overline{\nu}_\mu,\ \nu_\tau\overline{\nu}_\tau \ \ (s \text{ channel } Z' \text{ and } \eta \text{ portal}) \\ &\to d\overline{d},\ s\overline{s} \ \ (t \text{ channel } SLQ(S_1) \text{ portal}) \end{aligned}$$

- DM relic density is computed by

$$\Omega h^2 = \frac{2.14 \times 10^9 \mathrm{GeV}^{-1}}{g*^{1/2}\, M_{Pl}} \frac{1}{J(x_f)}, \qquad J(x_f) = \int_{x_f}^{\infty} \frac{\langle \sigma v \rangle (x)}{x^2} dx.$$

where $x = M_-/T$ and x_f is the freeze out parameter.





Detection prospects

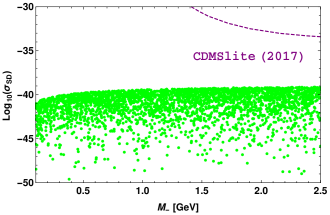
- SLQ portal spin-dependent (SD) cross section can arise from the effective interaction

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

and the computed cross section is given as

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

- The WIMP-nucleon cross section via $(Z,\, Z')$ portal and $(\,H_1,\, H_2)$ portal is found to be very small and insensitive to direct detection experiments.



Constraints from Flavour sector

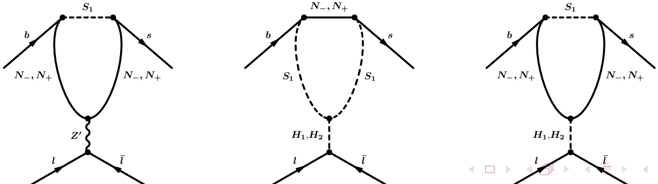
- Model parameters of LQ and Z' couplings can be constrained using $R_{K^{(*)}}$ and $\mathrm{Br}(B \to X_s \gamma)$.
- The effective Hamiltonian mediating $b \to s l^+ l^-$ is

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

$$O_7^{(\prime)} \;=\; \frac{e}{16\pi^2} \Big[\bar{s} \sigma_{\mu\nu} \left(m_s P_{L(R)} + m_b P_{R(L)} \right) b \Big] F^{\mu\nu} ,$$

$$O_9^{(\prime)} \;=\; \frac{\alpha_{\rm em}}{4\pi} (\bar{s} \gamma^\mu P_{L(R)} b)(\bar{l} \gamma_\mu l) \,, \qquad O_{10}^{(\prime)} = \frac{\alpha_{\rm em}}{4\pi} (\bar{s} \gamma^\mu P_{L(R)} b)(\bar{l} \gamma_\mu \gamma_5 l) \,,$$

- Following one loop diagrams provide non-zero contribution to the rare $b \to s l l$ processes (2nd and 3rd diagrams $\propto m_q M_\pm / M_{S_1}^2$)



- Z' exchange penguin diagram gives the transition amplitude of $b \to sll$ process

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

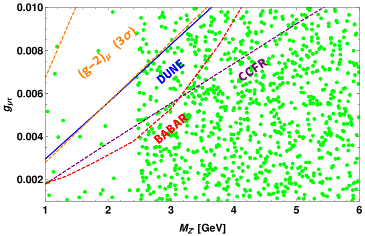
which provides additional primed Wilson coefficient

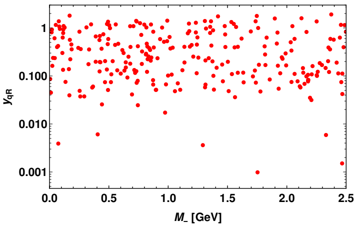
$$C_9'^{\rm NP} = \frac{\sqrt{2}}{2^4\pi G_F \alpha_{\rm em} V_{tb}V_{ts}^*}\frac{y_{qR}^2 g_{\mu\tau}^2}{(q^2 - {M_{Z'}}^2)}\mathcal{V}_{sb}\left(\chi_-, \chi_+\right) ,$$

$\mathcal{V}_{sb}\left(\chi_-, \chi_+\right)$ is the loop function and $\chi_\pm = M_\pm^2/M_{S_1}^2$.

- As only $C_9'^{\rm NP}$ involves, $B_s \to \mu\mu(\tau\tau)$ won't play any role in constraining the new parameters.
- Absence of $Z'\mu\tau$ coupling $\Rightarrow$ LFV decays like $B \to K^{(*)}\mu\tau$, $\tau \to \mu\gamma$ and $\tau \to 3\mu$ are not allowed

- Thus, using R_K/R_{K^*} and $\mathrm{Br}(B \to X_s\gamma)$ observables, the $g_{\mu\tau}$, $M_{Z'}$ and the y_{qR}, M_- allowed regions are shown below





- The allowed range of all the four new parameters consistent with flavor phenomenology

Parameters	y_{qR}	$g_{\mu\tau}$	M_- (GeV)	$M_{Z'}$ (GeV)
Allowed range	$0-2.0$	$0-0.01$	$0-2.5$	$1-6$

Table: The allowed regions of y_{qR}, $g_{\mu\tau}$, M_- and $M_{Z'}$ parameters.

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

- In SM, $b \to s+$ missing energy can be described by the $b \to s\nu\bar{\nu}$
- The effective Hamiltonian in SM

$$\mathcal{H}_{eff} = \frac{-4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left(C_L^\nu \mathcal{O}_L^\nu + C_R^\nu \mathcal{O}_R^\nu \right) + h.c.,$$

where

$$\mathcal{O}_L^\nu = \frac{\alpha_{\rm em}}{4\pi} \left(\bar{s}_R \gamma_\mu b_L \right) \left(\bar{\nu}\gamma^\mu \left(1-\gamma_5\right) \nu \right), \quad \mathcal{O}_R^\nu = \frac{\alpha_{\rm em}}{4\pi} \left(\bar{s}_L \gamma_\mu b_R \right) \left(\bar{\nu}\gamma^\mu \left(1-\gamma_5\right) \nu \right),$$

$$C_L^\nu = -X(x_t)/\sin^2\theta_w \,, \qquad X(x_t) = X_0(x_t) + \frac{\alpha_s}{4\pi} X_1(x_t),$$

- The branching ratios of $B_{(s)} \to K^*(\phi)\nu\bar{\nu}$ and their corresponding experimental limits are

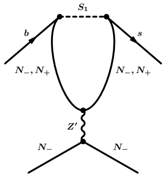
Decay process	BR in the SM	Experimental limit
$B^0 \to K^0 \nu_l \bar{\nu}_l$	$(4.53 \pm 0.267) \times 10^{-6}$	$<2.6 \times 10^{-5}$
$B^+ \to K^+ \nu_l \bar{\nu}_l$	$(4.9 \pm 0.288) \times 10^{-6}$	$<1.6 \times 10^{-5}$
$B^0 \to K^{*0} \nu_l \bar{\nu}_l$	$(9.48 \pm 0.752) \times 10^{-6}$	$<1.8 \times 10^{-5}$
$B^+ \to K^{*+} \nu_l \bar{\nu}_l$	$(1.03 \pm 0.06) \times 10^{-5}$	$<4.0 \times 10^{-5}$
$B_s \to \phi \nu_l \bar{\nu}_l$	$(1.2 \pm 0.07) \times 10^{-5}$	$<5.4 \times 10^{-3}$

- In this model, the additional process involved is

$$b \to s + \text{missing energy} = b \to s\nu\nu + b \to sN_- N_-$$

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

- The relevant one-loop diagram for $b \to sN_- N_-$ is



- Thus, e.g., the amplitude of $B \to KN_- N_-$ process from the Z' exchanging diagram is

$$\mathcal{M} = C^{\rm NP}(q^2)[\bar{u}(p_B)\gamma^\mu(1+\gamma_5)u(p_K))][\bar{v}(p_2)\gamma_\mu u(p_1))]$$

where

$$C^{\rm NP}(q^2) = \frac{1}{2^5\pi^2}\frac{y_{qR}^2 g_{\mu\tau}^2 \cos 2\beta \cos\alpha \sec\chi}{q^2 - M_{Z'}^2}\mathcal{V}_{sb}(\chi_-, \chi_+)\,,$$

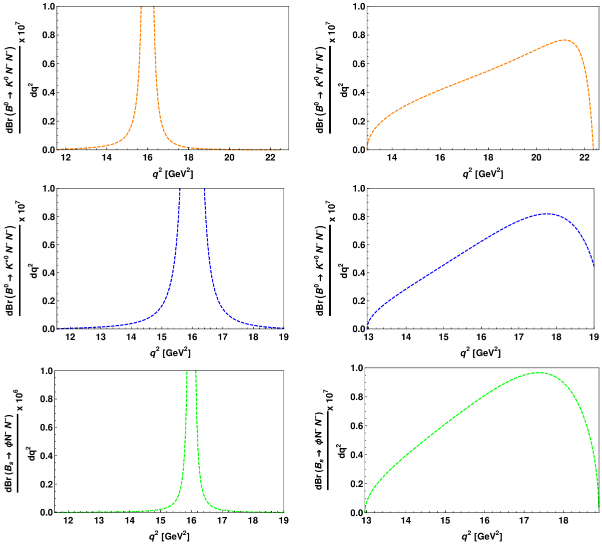
Predicted Results for $b \to s + \not{E}$ decay modes

- We use two sets of benchmark values of new parameters, allowed by both the DM and flavor phenomenology

Benchmark	y_{qR}	$g_{\mu\tau}$	M_- (GeV)	$M_{Z'}$ (GeV)
Benchmark-I	2.0	0.002	1.7	4
Benchmark-II	2.0	0.008	1.8	4.8

Table: Benchmark values of y_{qR}, M_-, $g_{\mu\tau}$ and $M_{Z'}$ parameters used in our analysis.

Predicted Results for $b \to s + \not{E}$ decay modes



Predicted Results for $b \to s + \not{E}$ decay modes

- For Benchmark-I, there is a singularity at $q^2 = M_{Z'}^2$, i.e., $q^2 = 16\ \mathrm{GeV}^2$. To avoid it, we use the cuts at $(M_{Z'} - 0.002)^2 \leq q^2 \leq (M_{Z'} + 0.002)^2$ GeV^2.

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

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

Conclusion

- We explored GeV scale dark matter and flavour anomalies in a $U(1)_{L_\mu - L_\tau}$ gauge extension of SM with an additional $(\bar{\mathbf{3}}, \mathbf{1}, \ 1/3)$ Scalar LQ.
- Relic density is investigated in Z' portal and the spin-dependent WIMP-nucleon cross section in SLQ-portal.
- In flavor sector, the model parameters are constrained from experimental limits on R_K/R_{K^*} and $B \to X_s \gamma$.
- We have shown the impact on rare B meson decays to missing energy, the observation of these modes would provide strong hints for the existence of light fermionic dark matter.
- This simple gauge extension provides an ideal platform to address the phenomenological perspectives of dark matter and flavor anomalies simultaneously.

Thank You