Unraveling Light Dark Matter and Rare B Decays: $L_\mu - L_\tau$ Model Enhanced by Leptoquark

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Model Description

	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	+
	ϕ_2	$(\mathbf{1}, \mathbf{1}, 0)$	2	+
	S_1	$(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$	−1	−
Gauge bosons	W_μ^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	+

Fields in the chosen $U(1)_{L_\mu - L_\tau}$ model

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

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

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

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

where, the scalar potential is expressed as

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

Scalar and Fermion mixing

The CP-even scalars h and h_2 mix, so as heavy fermion states N_μ and N_τ. The mixing matrices of both scalar and fermion sectors is given by

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

The couplings and mass eigenvalues are related as

$$f_\mu = \frac{\sqrt{2}}{v_2}\left(M_- \cos^2\beta + M_+ \sin^2\beta\right),$$

$$f_\tau = \frac{\sqrt{2}}{v_2}\left(M_- \sin^2\beta + M_+ \cos^2\beta\right),$$

$$M_{\mu\tau} = \cos\beta \sin\beta \left(M_+ - M_-\right),$$

$$\lambda_H = \frac{1}{2v^2}\left(M_{H_1}^2 \cos^2\zeta + M_{H_2}^2 \sin^2\zeta\right),$$

$$\lambda_\phi = \frac{1}{2v_2^2}\left(M_{H_1}^2 \sin^2\zeta + M_{H_2}^2 \cos^2\zeta\right),$$

$$\lambda_{H\phi} = \frac{1}{v v_2} \cos\zeta \sin\zeta \left(M_{H_2}^2 - M_{H_1}^2\right).$$

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

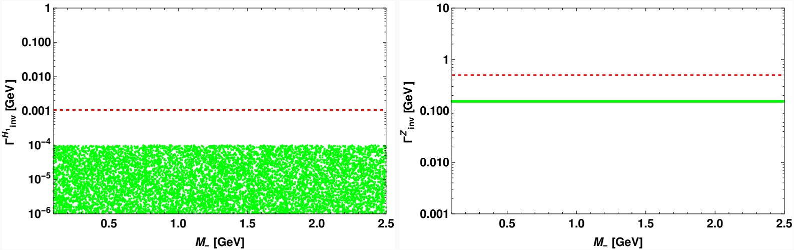
Higgs (H_1) and Z boson can decay to $N_- N_-$ whose expressions for invisible widths:

$$\Gamma^{H_1}_{\rm inv} = \frac{(f_\mu \cos^2\beta + f_\tau \sin^2\beta)^2 \sin^2\zeta}{8\pi} M_{H_1} \left(1 - \frac{4M_-^2}{M_{H_1}^2}\right)^{\frac{3}{2}} .$$

$\Gamma^Z_{\rm inv} = \Gamma^Z_{\nu\bar{\nu}} + \Gamma^Z_{N_- N_-}$, where

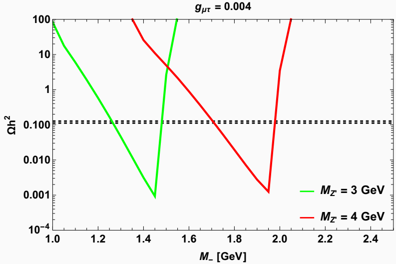
$$\Gamma^Z_{\nu\bar{\nu}} = \frac{g^2(\cos\alpha - \sin\alpha\tan\chi\sin\theta_W)^2}{96\pi\cos^2\theta_W} M_Z,$$

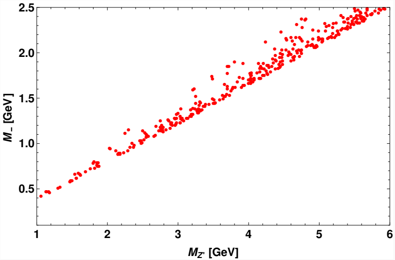
$$\Gamma^Z_{N_- N_-} = \frac{(g_{\mu\tau}\cos 2\beta\sec\chi\sin\alpha)^2}{24\pi} M_Z \left(1 - \frac{4M_-^2}{M_Z^2}\right)^{\frac{3}{2}} .$$



Left panel projects invisible width of Higgs (H_1) for $\sin\zeta < 10^{-2}$ and right panel projects the same for Z boson.

- The channels with lepton-anti lepton pair in final state ($\mu\overline{\mu}$, $\tau\overline{\tau}$, $\nu_\mu\overline{\nu_\mu}$, $\nu_\tau\overline{\nu_\tau}$) via Z' portal contribute to relic density.
- Furthermore, SLQ portal t-channel processes with $d\overline{d}$, $s\overline{s}$ in the final state are also kinematically allowed.





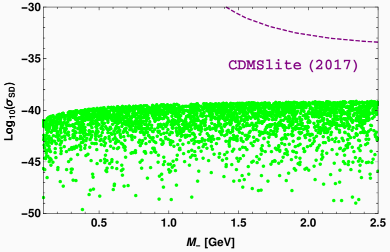
SLQ portal spin-dependent (SD) cross section can arise from the effective interaction

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

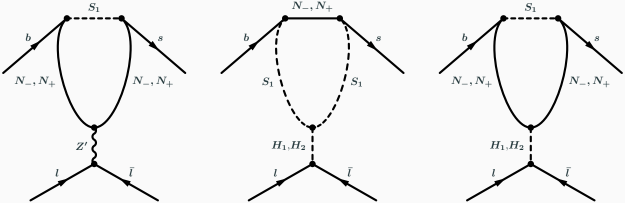
The computed cross section is given by

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

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



$b \to sll$

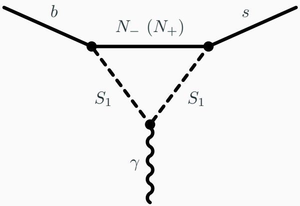


New Wilson coefficient to $b \to sll$ process:

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

- **Observables**: BR($B \to K^{(*)} \mu\mu$), $R_{K^{(*)}}$

$b \to s\gamma$



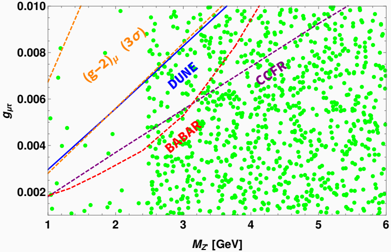
New Wilson coefficient to $b \to s\gamma$ process:

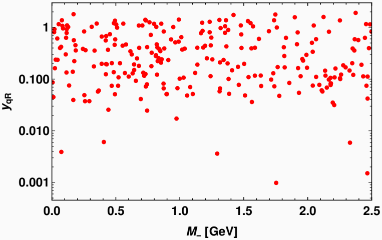
$$C_7^{\gamma\prime\mathrm{NP}} = -\frac{\sqrt{2}/3}{8G_F V_{tb} V_{ts}^*} \frac{y_{qR}^2}{M_{S_1}^2} \Big(J_1(\chi_-) \cos^2\alpha + J_1(\chi_+) \sin^2\alpha \Big),$$

with the loop functions $J_1(\chi_\pm)$

$$J_1(\chi_\pm) = \frac{1 - 6\chi_\pm + 3\chi_\pm^2 + 2\chi_\pm^3 - 6\chi_\pm^2 \log\chi_\pm}{12(1-\chi_\pm)^4}\,.$$

- **Observables**: $\mathrm{BR}(B \to X_s\gamma)$





Allowed regions of y_{qR}, $g_{\mu\tau}$, M_- and $M_{Z'}$ parameters

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

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

- The Belle II experiment has just reported the first measurement of $B^+ \to K^+ \nu \bar{\nu}$, revealing a branching ratio

$$\mathcal{BR}(B^+ \to K^+ + \not{E})\big|^{Exp.} = (2.4 \pm 0.7) \times 10^{-5}$$

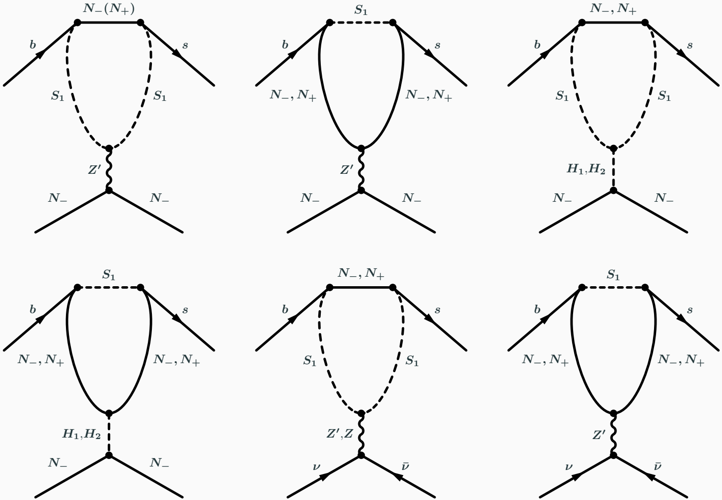
  This result deviates from the SM prediction $\mathcal{BR}(B^+ \to K^+ \nu_l \bar{\nu}_l)^{SM} = (5.06 \pm 0.14 \pm 0.28) \times 10^{-6}$ by 2.8σ.

- The general effective Hamiltonian responsible for the $b \to s \nu_l \bar{\nu}_l$ transition is given by

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

  where the dimension-6 current-current operators are

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


$N_-(N_+)$
b
s
S_1
S_1
Z'
N_-
N_-
S_1
b
s
N_-, N_+
N_-, N_+
Z'
N_-
N_-
N_-, N_+
b
s
S_1
S_1
H_1,H_2
N_-
N_-
S_1
b
s
N_-, N_+
N_-, N_+
H_1,H_2
N_-
N_-
N_-, N_+
b
s
S_1
S_1
Z',Z
ν
$\bar{\nu}$
S_1
b
s
N_-, N_+
N_-, N_+
Z'
ν
$\bar{\nu}$

$B \to K + \not{E}$

The total branching ratio of $B \to K + \not{E}$ is

$$\mathrm{Br}(B \to K + \not{E}) = \mathrm{Br}(B \to K\nu\bar{\nu}) + \mathrm{Br}(B \to KN_-N_-).$$

The transition amplitude of $B \to KN_-N_-$ process from the Z' exchanging one loop penguin diagram is

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

where

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

and $p_B(p_K)$ is the four momenta of $B(K)$ meson, $p_{1,2}$ are the momenta of N_- fermion.

The branching ratio of $B \to KN_-N_-$ decay mode is given by

$$\frac{d\mathrm{Br}}{dq^2} = \tau_B \frac{1}{2^7\pi^3 M_B^3}\sqrt{\lambda(M_B^2, M_K^2, q^2)}\beta_N f_+^2 \left(a_l(q^2) + \frac{c_l(q^2)}{3}\right) ,$$

where

$$a_l(q^2) = q^2|F_P|^2 + \left(\frac{\lambda(M_B^2, M_K^2, q^2)}{4} + 4M_-^2 M_B^2\right)|F_A|^2 + 2M_-(M_B^2 - M_K^2 + q^2)\mathrm{Re}(F_P F_A^*) ,$$

$$c_l(q^2) = -\frac{\lambda(M_B^2, M_K^2, q^2)}{4}\beta_N^2|F_A|^2,$$

with

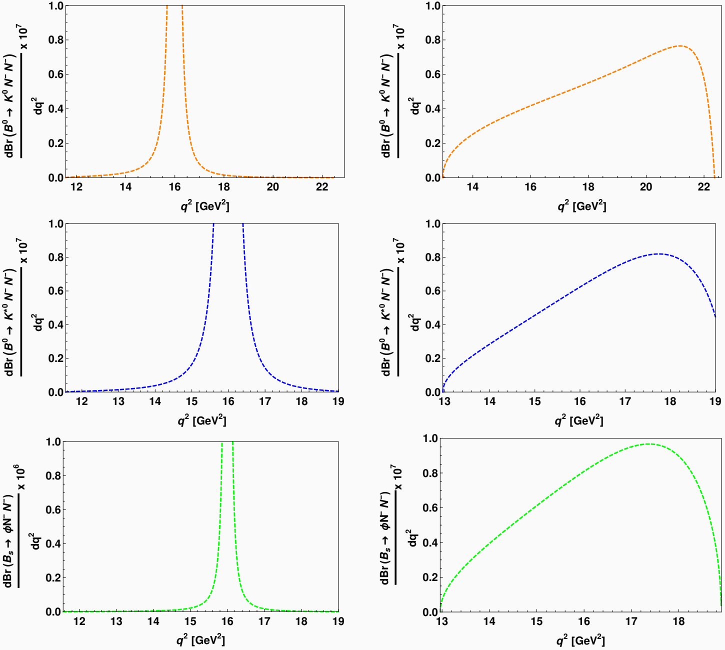
$$F_A = C^{\mathrm{NP}}(q^2), \;\; F_P = M_- C^{\mathrm{NP}}(q^2)\Big[\frac{M_B^2 - M_K^2}{q^2}\Big(\frac{f_0(q^2)}{f_+(q^2)} - 1\Big) - 1\Big], \;\; \beta_N = \sqrt{1 - 4M_-^2/q^2} .$$

Results

We have taken two different benchmark values of all the four new parameters, which are 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

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


dBr(B⁰ → K⁰ N⁻ N⁻) / dq² x 10⁷
q² [GeV²]
dBr(B⁰ → K*⁰ N⁻ N⁻) / dq² x 10⁷
q² [GeV²]
dBr(Bₛ → φN⁻ N⁻) / dq² x 10⁶
q² [GeV²]
dBr(Bₛ → φN⁻ N⁻) / dq² x 10⁷
q² [GeV²]

Conclusion

- Unification of flavor sector and dark matter in a single theoretical framework.
- Missing energy could be a pair of light dark matter.
- Leptoquark: bridge between different physics sectors: a superlative particle to probe new physics

Thank You !!!