Exploring Dark matter, Neutrino mass and $R_{K^{(*)}}$ anomalies in $L_\mu - L_\tau$ model

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Outline of Talk

1. $L_\mu - L_\tau$ model with Scalar Leptoquark
2. Symmetry breaking and mass spectrum
3. Dark Matter Phenomenology
4. Constraints from Flavour Sector
5. Implications
6. Conclusion

Motivation

- No direct evidence of NP either in Energy frontier or Intensity frontier (except Neutrino Oscillation)
- However, in last few years several anomalies are reported in in $b \to s\ell\ell$ FCNC transitions, which might possibly suggest the presence of New Physics
- Interesting one: Lepton Non-Universality Parameter Sizable discrepancies reported by the LHCb Collaboration in the ratio $R_{K^{(*)}}$ of

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

LNU parameters	SM predictions	Expt. values	Deviations
$R_K\vert_{q^2\in[1.0,6.0]}$	1.0003 ± 0.0001	$0.745^{+0.090}_{-0.074} \pm 0.036$	2.6σ
$R_{K^*}\vert_{q^2\in[0.045,1.1]}$	0.92 ± 0.02	$0.660^{+0.110}_{-0.070} \pm 0.024$	2.2σ
$R_{K^*}\vert_{q^2\in[1.1,6.0]}$	1.00 ± 0.01	$0.685^{+0.113}_{-0.007} \pm 0.047$	2.4σ

R. Aaij et al. [LHCb Collab], Phys. Rev. Lett. 113, 151601 (2014); JHEP 08, 055 (2017).

- Another famous anomaly observed in the angular analyses of $B \to K^* \mu\mu$ is in the FFI P_5' observable which has around 3σ deviation in the interval $4.3 < q^2 < 8.68~\mathrm{GeV}^2$
- Also the differential branching fraction $B_s \to \phi\mu\mu$ process, in the $1 < q^2 < 6~\mathrm{GeV}^2$ bin is more than 3σ below the SM predictions
- Interesting to note individual deviations in the observables mentioned above are in the same direction, i.e. destructive with the SM.
- The effective Hamiltonian describing $b \to s\ell\ell$ is given as

$$\mathcal{H}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \left(C_i^\ell O_i^\ell + C_i'^\ell O_i'^\ell \right), \quad C_i^{(\prime)\ell} = C_i^{(\prime)\mathrm{SM}} + C_i^{(\prime)\ell,\mathrm{NP}}$$

- Global fit shows that sizable NP contributions to $C_{9(10)}^\mu$ can accommodate the data
- Bottom Line: NP could couple primarily couple to muon sector

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

- The SM has accidental $U(1)$ global symmetries like B and L no. conservation, they become anomalous if converted into a local one
- The anomaly free situation can be obtained if instead of considering B and L separately, one uses 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, so free from any constraints coming from lepton and hadron colliders, such as LEP and LHC.
- 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	+
	$e_L \equiv (\nu_e, \ e)_L^T$	$(\mathbf{1}, \mathbf{2}, \ -1/2)$	0	+
	e_R	$(\mathbf{1}, \mathbf{1}, \ -1)$	0	+
	$\mu_L \equiv (\nu_\mu, \ \mu)_L^T$	$(\mathbf{1}, \mathbf{2}, \ -1/2)$	1	+
	μ_R	$(\mathbf{1}, \mathbf{1}, \ -1)$	1	+
	$\tau_L \equiv (\nu_\tau, \ \tau)_L^T$	$(\mathbf{1}, \mathbf{2}, \ -1/2)$	-1	+
	τ_R	$(\mathbf{1}, \mathbf{1}, \ -1)$	-1	+
	N_e	$(\mathbf{1}, \mathbf{1}, \ 0)$	0	$-$
	N_μ	$(\mathbf{1}, \mathbf{1}, \ 0)$	1	$-$
	N_τ	$(\mathbf{1}, \mathbf{1}, \ 0)$	-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	$-$

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

$$\begin{aligned}
\mathcal{L} &= \mathcal{L}_{\rm SM} - \frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu} - g_{\mu\tau} \overline{\mu}_L \gamma^\mu \mu_L Z'_\mu - g_{\mu\tau} \overline{\mu}_R \gamma^\mu \mu_R Z'_\mu \\
&+ g_{\mu\tau} \overline{\tau}_L \gamma^\mu \tau_L Z'_\mu + g_{\mu\tau} \overline{\tau}_R \gamma^\mu \tau_R Z'_\mu + \overline{N}_e i \partial\!\!\!/ \, N_e + \overline{N}_\mu \left(i \partial\!\!\!/ - g_{\mu\tau} Z'_\mu \gamma^\mu \right) N_\mu \\
&+ \overline{N}_\tau \left(i \partial\!\!\!/ + g_{\mu\tau} Z'_\mu \gamma^\mu \right) N_\tau - \frac{f_\mu}{2} \left(\overline{N^c_\mu} N_\mu \phi_2^\dagger + {\rm h.c.} \right) - \frac{f_\tau}{2} \left(\overline{N^c_\tau} N_\tau \phi_2 + {\rm h.c.} \right) \\
&- \frac{1}{2} M_{ee} \overline{N^c_e} N_e - \frac{1}{2} M_{\mu\tau} (\overline{N^c_\mu} N_\tau + \overline{N^c_\tau} N_\mu) - \sum_{q=d,s,b} (y_{qR} \, \overline{d^c_{qR}} S_1 N_\mu + {\rm h.c.}) \\
&- \sum_{i=e,\mu,\tau} Y_{\alpha i} \, (\overline{\ell_L})_\alpha \, \tilde{\eta} \, N_{iR} + \left| \left(i \partial_\mu - 2 g_{\mu\tau} Z'_\mu \right) \phi_2 \right|^2 \\
&+ \left| \left(i \partial_\mu - \frac{g}{2} \boldsymbol{\tau}^a \cdot \mathbf{W}^a_\mu - \frac{g'}{2} B_\mu \right) \eta \right|^2 + + \left| \left(i \partial_\mu - \frac{g'}{3} B_\mu + g_{\mu\tau} Z'_\mu \right) S_1 \right|^2 \\
&- V(H, \eta, \phi_2, S_1),
\end{aligned}$$

Scalar potential

The scalar potential V is expressed as

$$\begin{aligned}
V(H,\eta,\phi_2,S_1) &= \mu_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2 + \mu_\eta (\eta^\dagger \eta) + \lambda_{H\eta}(H^\dagger H)(\eta^\dagger \eta) \\
&+ \lambda_\eta (\eta^\dagger \eta)^2 + \lambda'_{H\eta}(H^\dagger \eta)(\eta^\dagger H) + \frac{\lambda''_{H\eta}}{2}\left[(H^\dagger \eta)^2 + \mathrm{h.c.}\right] \\
&+ \mu_2^2(\phi_2^\dagger \phi_2) + \lambda_2(\phi_2^\dagger \phi_2)^2 + \mu_S^2({S_1}^\dagger S_1) + \lambda_S({S_1}^\dagger S_1)^2 \\
&+ \left[\lambda_{H2}(\phi_2^\dagger \phi_2) + \lambda_{HS}(S_1^\dagger S_1)\right](H^\dagger H) + \lambda_{S2}(\phi_2^\dagger \phi_2)({S_1}^\dagger S_1) \\
&+ \lambda_{\eta 2}(\phi_2^\dagger \phi_2)(\eta^\dagger \eta) + \lambda_{S\eta}({S_1}^\dagger S_1)(\eta^\dagger \eta).
\end{aligned}$$

Mass Spectra

- Spontaneous symmetry breaking pattern:

$$SU(2)_L \times U(1)_Y \times U(1)_{L_\mu - L_\tau} \Longrightarrow SU(2)_L \times U(1)_Y \Longrightarrow SU(2)_L \times U(1)_{em}$$

$$\phi_2^0 = \frac{1}{\sqrt{2}}(v_2 + h_2) + \frac{i}{\sqrt{2}}A_2 \,, \quad H^0 = \frac{1}{\sqrt{2}}(v + h) + \frac{i}{\sqrt{2}}A^0 \,.$$

- Fermion and Scalar Mass Matrices

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

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

$$U^T_{\alpha(\zeta)} M_{N(S)} U_{\alpha(\zeta)} = \mathrm{diag}\, [M_{N_-(H_1)}, M_{N_+(H_2)}],$$

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

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

- Inert doublet components $(\eta^+, \eta^0)^T$ with $\eta^0 = (\eta_e + \eta_o)/\sqrt{2}$:

$$
\begin{aligned}
M^2_{\eta^+} &= \mu^2_\eta + \frac{\lambda_{H\eta}}{2} v^2 + \frac{\lambda_{\eta 2}}{2} v_2^2 , \\
M^2_{\eta_{e,o}} &= \mu^2_\eta + \frac{\lambda_{\eta 2}}{2} v_2^2 + \left(\lambda_{H\eta} + \lambda'_{H\eta} \pm \lambda''_{H\eta}\right) \frac{v^2}{2} .
\end{aligned}
$$

- Scalar Letpoquark: $M^2_{S_1} = 2\mu^2_S + \lambda_{HS} v^2 + \lambda_{S2} v_2^2$
- New $U(1)$ gauge boson: $M_{Z'} = 2 v_2 g_{\mu\tau}$.
- Benchmark values of scalar spectra: $(M_{S_1}, M_{\eta^+}, M_{\eta_{e,o}}) = (1.2, 2, 1.5)$ TeV

Light Neutrino mass generation (Scotogenic model)

- Scotogenic model presents an attractive example of the generation of light ν-mass via radiative mechanism in the dark sector
- The model enlarges the SM field content by: (a) 3 RHN fields N_k (b) a second $SU(2)_L$ scalar doublet η
- The scalar potential is

$$\begin{aligned} V(\phi,\eta) &= m_\phi^2 \phi^\dagger\phi + m_\eta^2 \eta^\dagger\eta + \frac{\lambda_1}{2}\left(\phi^\dagger\phi\right)^2 + \frac{\lambda_2}{2}\left(\eta^\dagger\eta\right)^2 \\ &+ \lambda_3(\phi^\dagger\phi)(\eta^\dagger\eta) + \lambda_4(\phi^\dagger\eta)(\eta^\dagger\phi) + \lambda_5\left((\phi^\dagger\eta)^2 + (\eta^\dagger\phi)^2\right) \end{aligned}$$

- Inert scalar sector : η^+, $\eta^0 = (\eta_R + i\eta_I)/\sqrt{2}$ with mass

$$m_{\eta^+}^2 = m_\eta^2 + \lambda_3\frac{v^2}{2}, \quad m_{\eta_{R(I)}}^2 = m_\eta^2 + (\lambda_3 + \lambda_4 \pm \lambda_5)\frac{v^2}{2}$$

$$\Longrightarrow m_{\eta_R}^2 - m_{\eta_I}^2 = \lambda_5 v^2$$

Radiative Neutrino mass generation

- The structure of light neutrino mass would be

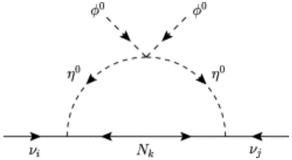
$$m_\nu \sim \frac{1}{16\pi^2}(\text{favour structure}) \times (\text{mass scale}) \times (\text{loop function})$$

- The active neutrino mass matrix obtained from the diagram (below)

$$(\mathcal{M}_\nu)_{\alpha\beta} = \sum_{k=1}^{3} \frac{h_{k\alpha} h_{k\beta}}{16\pi^2} M_k \left[\frac{m^2_{\eta R}}{m^2_{\eta R} - M_k^2} \ln\left(\frac{m^2_{\eta R}}{M_k^2}\right) - \frac{m^2_{\eta I}}{m^2_{\eta I} - M_k^2} \ln\left(\frac{m^2_{\eta I}}{M_k^2}\right)\right]$$

$$\simeq \sum_{k=1}^{3} \frac{\lambda_5 h_{k\alpha} h_{k\beta} v^2}{16\pi^2} M_k \left[1 - \frac{M_k^2}{(m_0^2 - M_k^2)} \ln\left(\frac{m_0^2}{M_k^2}\right)\right]$$

where $m^2_{\eta_R} - m^2_{\eta_I} = \lambda_5 v^2 \ll m_0^2 = (m^2_{\eta_R} + m^2_{\eta_I})/2.$



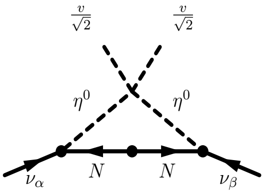
- Light neutrino mass : From the Yukawa interaction term

$$\sum_{i=e,\mu,\tau} Y_{\alpha i}\, (\overline{\ell_L})_\alpha\, \tilde{\eta}\, N_{iR}$$

one can obtain

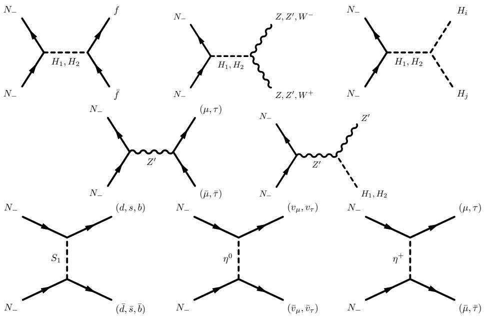
$$(\mathcal{M}_\nu)_{\alpha\beta} = \frac{\lambda''_{H\eta} v^2}{16\pi^2} \sum_{i=e,\mu,\tau} \frac{Y_{\alpha i} Y_{\beta i} M_{Di}}{m_0^2 - M_{Di}^2} \left[1 - \frac{M_{Di}^2}{m_0^2 - M_{Di}^2} \ln \frac{m_0^2}{M_{Di}^2} \right].$$

With sample parameter space $(Y_{\alpha i}, \lambda''_{H\eta}) \sim (10^{-2}, 10^{-5})$ and $(m_0, M_-, M_{ee}, M_+) \sim (1.5, 0.4, 3, 3)$ TeV, one can explain the light neutrino mass m_ν, near eV scale



Relic density

- (Scalar Leptoquark, η, H_1, H_2, Z') - portal



- 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.

Relic density

- Relevant parameters: $M_-, g_{\mu\tau}, M_{Z'}, Y_{\alpha i}, y_{qR})$
- $g_{\mu\tau}$ controls the s-channel contribution whereas $Y_{\alpha i}, y_{qR}$ relevant for t-channel

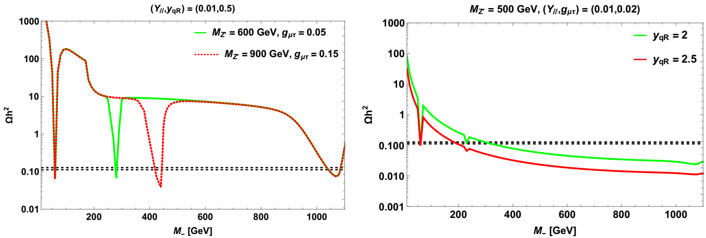


Figure: Behaviour of Relic density with DM mass

- Relic density for s-channel meet Planck limit near the resonance in propagator (H_1, H_2, Z') near $M_- = M_{\rm prop}/2$ $(80 < M_- < 1000)$GeV.

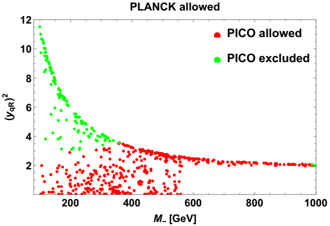
Direct Detection: Scalar LQ portal

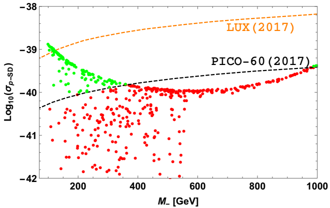
The effective interaction Lagrangian is given by

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

$$\implies \sigma_{S_1}^{SD} = \frac{M_-^2 M_n^2}{\pi(M_- + M_n)^2} \frac{\cos^4\alpha}{(M_{S_1}^2 - M_-^2)^2} \left[y_{dR}^2\Delta_d + y_{sR}^2\Delta_s\right]^2 J_N(J_N+1).$$

where the angular momentum $J_N = \frac{1}{2}$, $M_n \simeq 1$ GeV for nucleon.
* DM study has no significant impact on $M_{Z'} - g_{\mu\tau}$ parameters.





Constraints from Flavor Sector

A. $B \to K\ell^+\ell^-$:

We use $\mathrm{Br}(B^+ \to K^+\tau^+\tau^-)$ and R_K obsrvables, which will put constraint on all the four parameters, i.e., $(y_{qR})^2$, $g_{\mu\tau}$, $M_{Z'}$ and M_-.

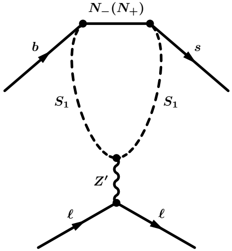


Figure: Penguin diagram of $b \to s\ell\ell$ processes, where $\ell = \mu, \tau$ with leptoquark in the loop.

- Computing the penguin loop and comparing with SM effective Hamiltonian gives

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

- Expt. data used to obtain the constrained parameters:

$$\mathrm{Br}(B^+ \to K^+ \tau^+ \tau^-)\Big|^{\mathrm{Expt}} < 2.5 \times 10^{-3},$$

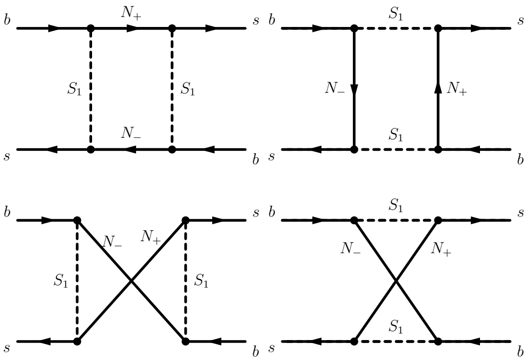
  whereas

$$\mathrm{Br}(B^+ \to K^+ \tau^+ \tau^-)\Big|^{\mathrm{SM}} = (1.486 \pm 0.12) \times 10^{-7}.$$

- Since Z' doesn't couple to electron, the branching ratio of $B^+ \to K^+ e^+ e^-$ process is considered to be SM like.
- The anomalies of $b \to s\ell\ell$ decay modes can put constraint on all the four parameters, i.e., $(y_{qR})^2$, $g_{\mu\tau}$, $M_{Z'}$ and M_-.

B. $B_s - \bar{B}_s$ mixing:

- $\Delta M_s^{\rm SM} = (17.426 \pm 1.057)\ {\rm ps}^{-1}$, $\Delta M_s^{\rm Expt} = 17.761 \pm 0.022\ {\rm ps}^{-1}$.
- $B_s - \bar{B}_s$ mixing will put bound on $(y_{qR})^2$ and M_- parameters.



$$\Delta M_s^{\rm NP} = \frac{(y_{sR} y_{bR})^2}{48\pi^2 M_{S_1}^2} \cos^2\alpha \sin^2\alpha\, C_{B_s}^{\rm NP} \eta_B \hat{B}_{B_s} f_{B_s}^2 M_{B_s}\ .$$

C. $B \to X_s\gamma$ and $\tau \to \mu\nu_\tau\bar{\nu}_\mu$:

- $B \to X_s\gamma$ will constrain the $(y_{qR})^2$ and M_- parameters
- $\mathrm{Br}(\tau \to \mu\nu_\tau\bar{\nu}_\mu)$ will put bounds on $M_{Z'} - g_{\mu\tau}$ parameter space.

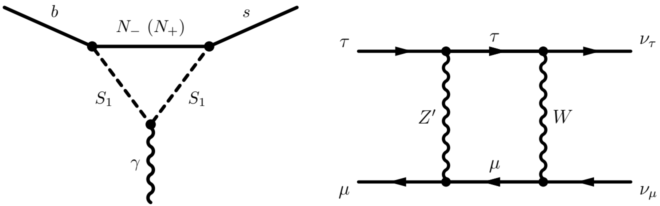
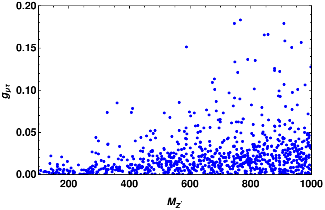
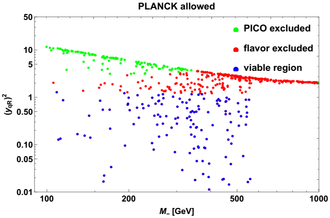


Figure: Feynman diagram of $b \to s\gamma$ (left panel) and $\tau \to \mu\nu_\tau\bar{\nu}_\mu$ (right panel) processes in the presence of scalar leptoquark.

Constraints on the parameter space from Flavor and Dark Matter sectors





Parameters	DM-I	DM-II	DM+Flavor
M_- [GeV]	103 – 560	561 – 988	103 – 560
$(y_{qR})^2$	0 – 3.51	1.94 – 2.56	0 – 1.26

Table: Predicted allowed range of parameters M_- and $(y_{qR})^2$.

Implication on $B_{(s)} \to K^*(\phi)\mu^+\mu^-$ Processes

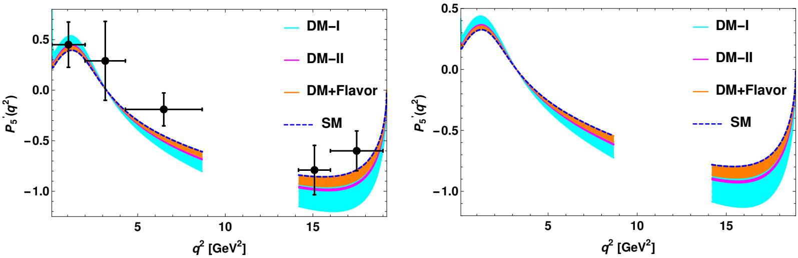


Figure: Left panel corresponds to P_5' observable of $B \to K^*\mu^+\mu^-$, and right panel corresponds to $B_s \to \phi\mu^+\mu^-$.

Implication on $B_{(s)} \to K^*(\phi)\mu^+\mu^-$ Processes

We have tested the LNU parameters (R_{K^*}, R_ϕ) and the optimized angular observables, $P'_{4,5}$.

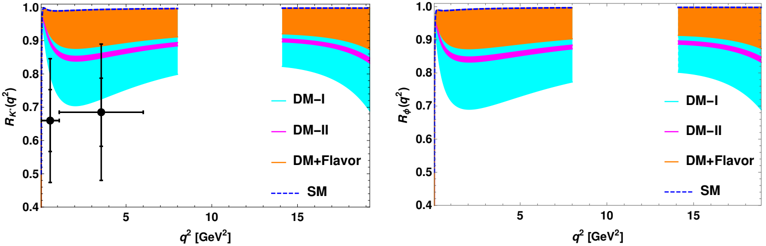


Figure: The q^2 variation of R_{K^*} (left panel) and R_ϕ (right panel) LNU parameters in the $L_\mu - L_\tau$ model.

Summary

- We explored Majorana dark matter 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 SLQ, Z' as well as scalar 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, $B \to K\tau^+\tau^-$, $B_s - \bar{B}_s$ mixing, $B \to X_s\gamma$ and $\tau \to \mu\nu_\tau\bar{\nu}_\mu$ processes.
- Using the allowed parameters space, the LNU parameters (R_{K^*}, R_ϕ), and the P_5' observables of $B_{(s)} \to K^*(\phi)\mu^+\mu^-$ decay modes are estimated.
- This simple gauge extension provides a platform to address dark matter, neutrino and flavor sectors in phenomenological perspective.

Thank You