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Majorana dark matter, neutrino mass and flavor anomalies in $L_\mu - L_\tau$ model

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Outline of talk

1. $L_\mu - L_\tau$ model with a SLQ
2. Symmetry breaking and mass spectrum
3. Dark Matter phenomenology
4. Constraints from flavor anomalies
5. Implications in flavor sector
6. Conclusion

$L_\mu - L_\tau$ model with a SLQ

	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	−

The Lagrangian of the present model can be written as

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

where the scalar potential V is

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

Mass spectrum

Spontaneous symmetry breaking :

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

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

- Fermion and scalar mass matrices

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

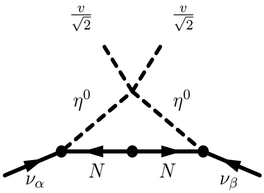
One can diagonalize the above mass matrices using a 2×2 rotation matrix as $U^T_{\alpha(\zeta)} M_{N(S)} U_{\alpha(\zeta)} = \text{diag}\,[M_{N_-(H_1)}, M_{N_+(H_2)}]$, with $\zeta = \frac{1}{2}\tan^{-1}\left(\frac{\lambda_{H2} v v_2}{\lambda_2 v_2^2 - \lambda_H v^2}\right)$, $\alpha = \frac{1}{2}\tan^{-1}\left(\frac{M_{\mu\tau}}{(f_\tau - f_\mu)(v/\sqrt{2})}\right)$.

- Inert doublet components :

$$M^2_{\eta_c} = \mu^2_\eta + \frac{\lambda_{H\eta}}{2}v^2 + \frac{\lambda_{\eta 2}}{2}v_2^2,$$
$$M^2_{\eta_{e,0}} = \mu^2_\eta + \frac{\lambda_{\eta 2}}{2}v_2^2 + \left(\lambda_{H\eta} + \lambda'_{H\eta} \pm \lambda''_{H\eta}\right)\frac{v^2}{2}.$$

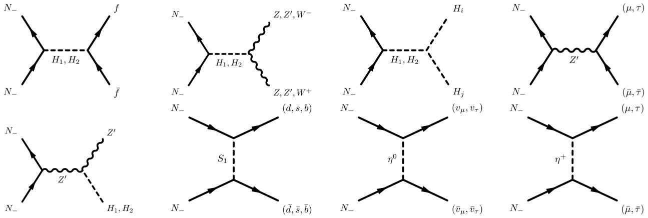
- Scalar letpoquark : $M^2_{S_1} = 2\mu^2_S + \lambda_{HS}v^2 + \lambda_{S2}v_2^2$
- New $U(1)$ gauge boson : $M_{Z'} = 2v_2 g_{\mu\tau}$.
- Light neutrino mass : $\sum_{i=e,\mu,\tau} Y_{\alpha i}\ (\overline{\ell_L})_\alpha\ \tilde{\eta}\ N_{iR}$

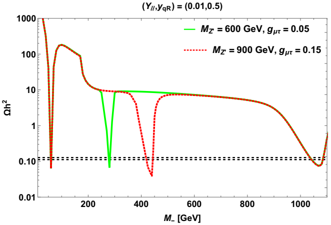
$$\implies (\mathcal{M}_\nu)_{\alpha\beta} = \frac{\lambda''_{H\eta}v^2}{16\pi^2}\sum_{i=e,\mu,\tau}\frac{Y_{\alpha i}Y_{\beta i}M_{Di}}{m_0^2 - M^2_{Di}}\left[1 - \frac{M^2_{Di}}{m_0^2 - M^2_{Di}}\ln\frac{m_0^2}{M^2_{Di}}\right].$$

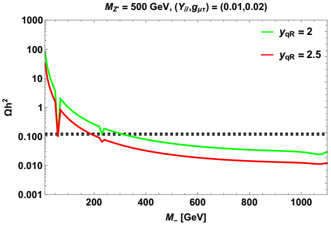


Relic density

- (S_1, η, H_i, Z') - portal







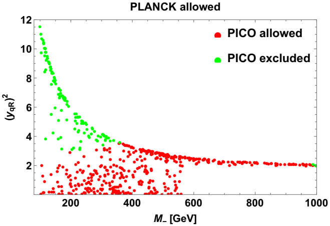
The effective interaction Lagrangian is given by

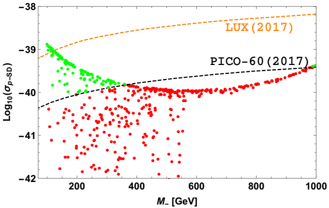
$$\mathcal{L}_{\rm eff} \simeq \frac{y_{qR}^2 \cos^2\alpha}{4(M_{S_1}^2 - M_-^2)} \overline{N_-}\gamma^\mu\gamma^5 N_- \bar{q}\gamma_\mu\gamma^5 q\,.$$

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

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.





Lepton non-universality

The lepton non-universality parameter ($R_{K^{(*)}}$) in $\bar{B} \to \bar{K}^{(*)} l^+ l^-$ is defined as

$$R_{K^{(*)}} = \frac{\text{Br}(B \to K^{(*)} \mu^+ \mu^-)}{\text{Br}(B \to K^{(*)} e^+ e^-)} \,. \qquad (3)$$

Table: Observed lepton non-universality in $b \to sll$ decay modes

LNU parameters	SM predictions	Expt. result [1,2]	Deviation
$R_K\|_{q^2 \in [1.0,6.0]}$	1.0003 ± 0.0001	$0.745^{+0.090}_{-0.074} \pm 0.036$	2.6σ
$R_{K^*}\|_{q^2 \in [0.045,1.1]}$	0.92 ± 0.02	$0.660^{+0.110}_{-0.070} \pm 0.024$	2.2σ
$R_{K^*}\|_{q^2 \in [1.1,6.0]}$	1.00 ± 0.01	$0.685^{+0.113}_{-0.0069} \pm 0.047$	2.4σ

1. R. Aaij et al. (LHCb), JHEP 08, 055 (2017).

2. R. Aaij et al. (LHCb), Phys. Rev. Lett. 113, 151601 (2014).

Constraint from flavor anomalies

$b \to sl^+l^-$:

This will put constraint on all the four parameters, i.e., $(y_{qR})^2$, $g_{\mu\tau}$, $M_{Z'}$ and M_-.

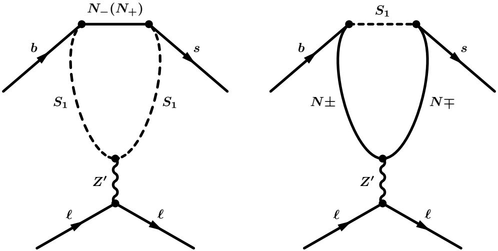


Figure: Penguin diagram of $b \to sll$ processes, where $l = \mu, \tau$ with leptoquark in the loop.

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

$B_s - \bar{B}_s$ mixing will put bound on $(y_{qR})^2$ and M_- parameters.

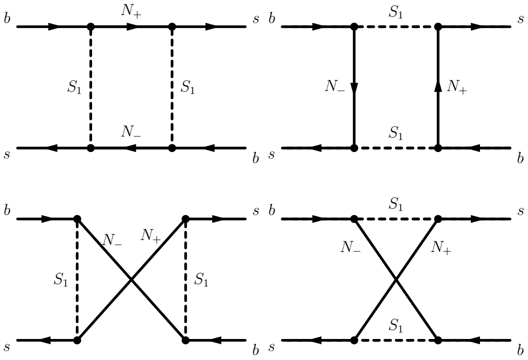
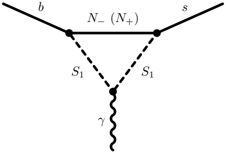
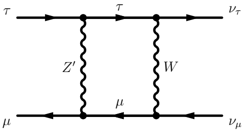


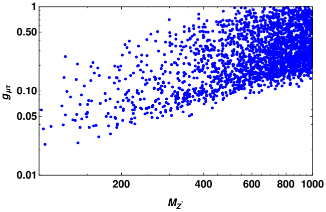
Figure: Box diagrams of $B_s - \bar{B}_s$ mixing with leptoquark in the loop.

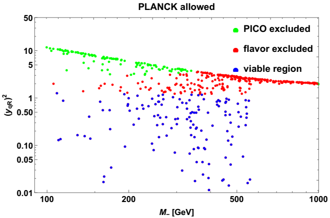
$B \to X_s\gamma$ and $\tau \to \mu\nu_\tau\bar{\nu}_\mu$:

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









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

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

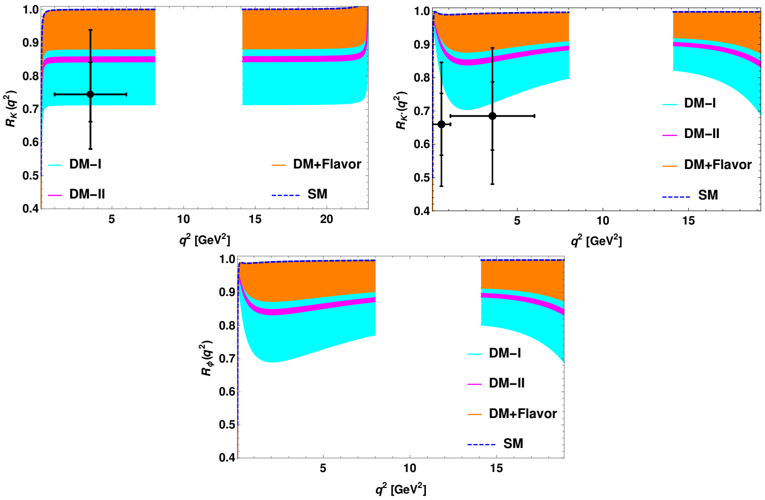


Figure: The q^2 variation of R_K (top-left panel), R_{K^*} (top-right panel) and R_ϕ (bottom panel) LNU parameters in the $L_\mu - L_\tau$ model.

Conclusion

- We have explored Majorana dark matter in a $U(1)_{L_\mu - L_\tau}$ gauge extension of SM with an $(\bar{\mathbf{3}}, \mathbf{1}, \ 1/3)$ SLQ.
- We have investigated relic density in SLQ, Z' and scalar portal, spin-dependent WIMP-nucleon cross section in SLQ-portal.
- In flavor sector, we have constrained the model parameters from experimental limits on $b \to s\ell^+\ell^-$, $B_s - \bar{B}_s$ mixing, $B \to X_s\gamma$ and $\tau \to \mu\nu_\tau\bar{\nu}_\mu$ processes.
- Using the allowed parameters space, we have investigated the $R_{K^{(*)}}$ and R_ϕ observables of $B_{(s)} \to K^{(*)}(\phi)\mu^+\mu^-$ decay modes.
- The parameter region satisfying only dark matter observables for $M_- \leq 560$ GeV have a good impact on the flavor anomalies.
- Finally, this simple gauge extension provides a platform to address dark matter, neutrino and flavor sectors in phenomenological perspective.

Thank you

Back up

- Since Z' does not couple to quarks, these gauge parameters couldn't be constrained from $b \to s\gamma$ decay modes and $B_s - \bar{B}_s$ oscillation data.
- Though the proposed model can allow $b \to s\nu_l\bar{\nu}_l$ decay modes, but the contributions of μ and τ leptons cancel with each other in the leading order of NP due to their equal and opposite $L_\mu - L_\tau$ charges.
- Since there is no $Z'\mu\tau$ coupling, the neutral and charged lepton flavor violating decay processes like $B \to K^{(*)}\mu^\mp\tau^\pm$, $\tau^- \to \mu^-\gamma$, $\tau \to \mu\mu\mu$ do not play any role.