Vector-like dark matter and flavor anomalies with leptoquarks

Suchismita Sahoo, S. Shivaramakrishna, Rukmani Mohanta

Physical Research Laboratory

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Physical Research Laboratory

Outline

- Model description
- Dark matter sector
- Flavor sector
- Impact on $b \to c l \bar{\nu}_l$ decay modes
- Conclusion

Model

Table: Fields and their charges in the present model.

	Field	$SU(3)_C \times SU(2)_L \times U(1)_Y$	Z_2
Fermions	$Q_L \equiv (u, d)_L^T$	$(\mathbf{3}, \mathbf{2}, \ 1/6)$	$+$
	u_R	$(\mathbf{3}, \mathbf{1}, \ 2/3)$	$+$
	d_R	$(\mathbf{3}, \mathbf{1}, \ -1/3)$	$+$
	$\ell_L \equiv (\nu, \ e)_L^T$	$(\mathbf{1}, \mathbf{2}, \ -1/2)$	$+$
	e_R	$(\mathbf{1}, \mathbf{1}, \ -1)$	$+$
Vector-like fermions	$\psi_q \equiv (\psi_u, \psi_d)^T$	$(\mathbf{3}, \mathbf{2}, \ 1/6)$	$-$
	$\psi_\ell \equiv (\psi_\nu, \ \psi_l)^T$	$(\mathbf{1}, \mathbf{2}, \ -1/2)$	$-$
Scalars	H	$(\mathbf{1}, \mathbf{2}, \ 1/2)$	$+$
	S_1	$(\bar{\mathbf{3}}, \mathbf{1}, \ 1/3)$	$-$
Vector	V_1	$(\mathbf{3}, \mathbf{1}, \ 2/3)$	$-$

The Lagrangian of the present model can be written as

$$\mathcal{L} = \mathcal{L}_{\rm SM} - M_\ell \overline{\psi^\ell}\psi^\ell - M_q \overline{\psi^q}\psi^q - \sum_q (y_{qL}^{S_1}\ \overline{Q^C} S_1 i\sigma^2 \psi^\ell + {\rm h.c}) - \sum_\ell (y_{\ell L}^{S_1}\ \overline{\psi^{q\,C}} S_1 \ell + {\rm h.c})$$
$$- \sum_\ell (y_{\ell L}^{V_1}\ \overline{\psi^q}\gamma_\mu V_1^\mu \ell + {\rm h.c.}) - \sum_q (y_{qL}^{V_1}\ \overline{Q}\gamma_\mu V_1^\mu \psi^\ell + {\rm h.c.}) +$$
$$\overline{\psi^\ell}\gamma^\mu \left(i\partial_\mu - \frac{g}{2}\boldsymbol{\tau}^a \cdot \mathbf{W}_\mu^a + \frac{g'}{2} B_\mu \right) \psi^\ell + \overline{\psi^q}\gamma^\mu \left(i\partial_\mu - \frac{g}{2}\boldsymbol{\tau}^a \cdot \mathbf{W}_\mu^a - \frac{g'}{6} B_\mu \right) \psi^q$$
$$+ \left| \left(i\partial_\mu - \frac{g'}{3} B_\mu \right) S_1 \right|^2 - V(H, S_1), \quad (1)$$

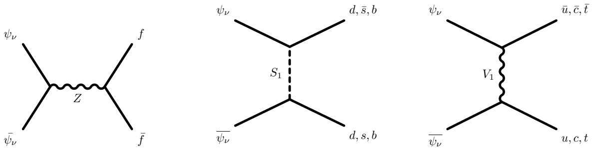
where the scalar potential V is

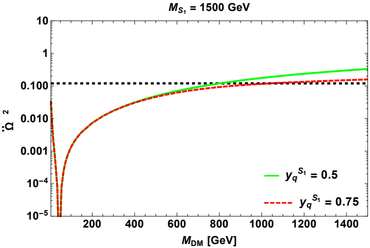
$$V(H, S_1) = \mu_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2 + \mu_S^2 ({S_1}^\dagger S_1) + \lambda_S ({S_1}^\dagger S_1)^2 + \quad \lambda_{HS} (H_2^\dagger H)({S_1}^\dagger S_1). \quad (2)$$

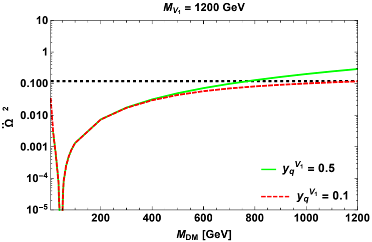
Dark Matter Sector

Relic abudance:

- DM annihilation channels are mediated by Z, S_1 and V_1.







Direct searches: The effective interaction lagrangian that signals in direct searches take the form

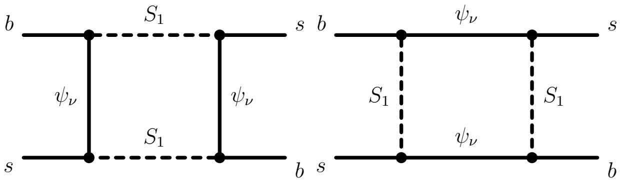
$$\mathcal{L}_{\rm eff} \simeq \frac{(y_q^a)^2}{4c_a(M_a^2 - M_\nu^2)} \left[\overline{\psi_\nu}\gamma^\mu\psi_\nu\overline{q}\gamma_\mu q + \overline{\psi_\nu}\gamma^\mu\gamma^5\psi_\nu\overline{q}\gamma_\mu\gamma^5 q\right]. \quad (3)$$

The corresponding SD (spin-dependent) and SI (spin-independent) contributions are

$$\begin{aligned}
\sigma_{S_1}^{\rm SD} &= \frac{3\mu_{\nu n}^2}{64\pi}\frac{(y_q^{S_1})^4(\Delta_d + \Delta_s)^2}{(M_{S_1}^2 - M_\nu^2)^2} J(J+1), \\
\sigma_{S_1}^{\rm SI} &= \frac{\mu_{\nu n}^2}{64\pi}\frac{(y_q^{S_1})^4}{(M_{S_1}^2 - M_\nu^2)^2}\left(2 - \frac{Z}{A}\right)^2, \\
\sigma_{V_1}^{\rm SD} &= \frac{3\mu_{\nu n}^2}{16\pi}\frac{(y_q^{V_1})^4\Delta_u^2}{(M_{V_1}^2 - M_\nu^2)^2} J(J+1), \\
\sigma_{V_1}^{\rm SI} &= \frac{\mu_{\nu n}^2}{16\pi}\frac{(y_q^{V_1})^4}{(M_{V_1}^2 - M_\nu^2)^2}\left(1 + \frac{Z}{A}\right)^2. \quad (4)
\end{aligned}$$

where $a = S_1, V_1$, $c_{S_1(V_1)} = 2(1)$ and (Z, A) represent the atomic and mass number of the target material. The angular momentum $J = \frac{1}{2}$ and $\mu_{\nu n} = \frac{M_\nu M_n}{M_\nu + M_n}$ denotes the reduced mass with $M_n \simeq 1$ GeV for nucleon. $\Delta_{u,d,s}$ are the quark spin functions.

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



New Wilson coefficient:

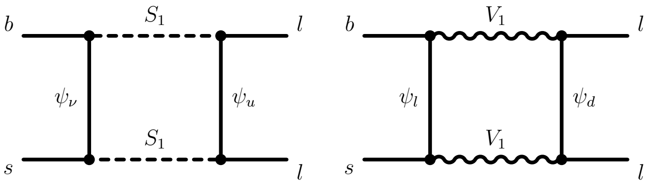
$$C_{B\bar{B}} = \frac{(y_s^{S_1} y_b^{S_1 *})^2}{512\pi^2 M_{S_1}^2} F(x_{\psi_\nu}, x_{\psi_\nu}), \quad \text{for} \quad S_1(\bar{3}, 1, 1/3)\,,$$

$$= \frac{(y_s^{V_1} y_b^{V_1 *})^2}{128\pi^2 M_{S_1}^2} F(y_{\psi_l}, y_{\psi_l}), \quad \text{for} \quad V_1(3, 1, 2/3)\,, \qquad (5)$$

with $x_i = M_i^2/M_{S_1}^2$, $y_i = M_i^2/M_{V_1}^2$ and

$$F(x_i, x_j) = \frac{1}{(1-x_i)(1-x_j)} + \frac{x_i^2 \log x_i}{(1-x_i)^2(x_i - x_j)} + \frac{x_j^2 \log x_j}{(1-x_j)^2(x_j - x_i)}. \qquad (6)$$

b $\to$ sll $(\nu\bar{\nu})$:

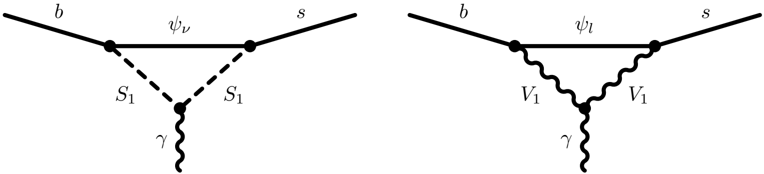


New Wilson coefficients:

$$C_9^{\mathrm{NP}} = -C_{10}^{\mathrm{NP}} = -\frac{\sqrt{2} y_s^{S_1} y_b^{S_1} |y_l^{S_1}|^2}{512\pi G_F \alpha_{\mathrm{em}} \lambda_t M_{S_1}^2} F(x_u, x_{\psi_\nu}) \quad \text{for} \quad S_1(\bar{3}, 1, 1/3)\,,$$

$$= -\frac{\sqrt{2} y_s^{V_1} y_b^{V_1} |y_l^{V_1}|^2}{128\pi G_F \alpha_{\mathrm{em}} \lambda_t M_{V_1}^2} F(y_d, y_{\psi_l}) \quad \text{for} \quad V_1(3, 1, 2/3)\,, \quad (7)$$

$b \to s\gamma$:



New Wilson coefficients for scalar leptoquark:

$$C_7^{\gamma \mathrm{NP}} = \frac{\sqrt{2}}{24 G_F V_{tb} V_{ts}^*} \frac{y_b^{S_1} y_s^{S_1}}{M_{S_1}^2} \left(\tilde{F}_7(y_{\psi_\nu}) + 2 F_7(y_{\psi_\nu}) \right) ,$$

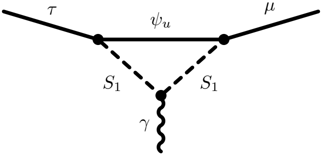
$$C_8^{\gamma \mathrm{NP}} = -\frac{\sqrt{2}}{24 G_F V_{tb} V_{ts}^*} \frac{y_b^{S_1} y_s^{S_1}}{M_{S_1}^2} F_7(y_{\psi_\nu}), \tag{8}$$

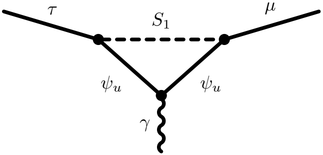
and for vector leptoquark

$$C_7^{\gamma \mathrm{NP}} = -\frac{\sqrt{2}}{12 G_F V_{tb} V_{ts}^*} \frac{y_b^{V_1} y_s^{V_1}}{M_{V_1}^2} \left(2\tilde{F}_7(y_{\psi_l}) + F_7(y_{\psi_l}) \right) ,$$

$$C_8^{\gamma \mathrm{NP}} = -\frac{\sqrt{2}}{12 G_F V_{tb} V_{ts}^*} \frac{y_b^{V_1} y_s^{V_1}}{M_{V_1}^2} F_7(y_{\psi_l}) . \tag{9}$$

$\tau \to \mu\gamma$ (muon anomalous moment):





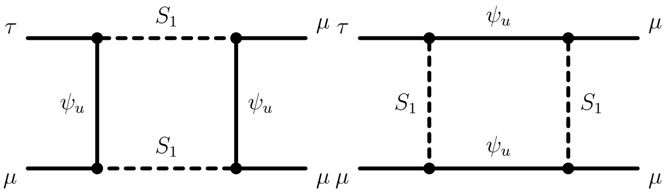
New coefficients for scalar leptoquark:

$$
\begin{aligned}
C_L &= \frac{N_c}{48\pi^2 M_{S_1}^2} y_\tau^{S_1} y_\mu^{S_1\,*} \Big(2 f_2(y_u) - \bar{f}_2(y_u)\Big), \\
C_R &= \frac{N_c}{48\pi^2 M_{S_1}^2} y_\tau^{S_1} y_\mu^{S_1\,*} \Big(2 f_1(y_u) - \bar{f}_1(y_u)\Big),
\end{aligned}
\tag{10}
$$

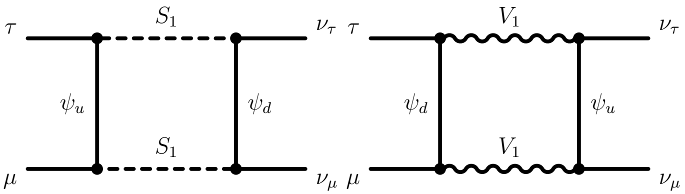
and for vector leptoquark

$$
\begin{aligned}
C_L &= \frac{N_c}{48\pi^2 M_{V_1}^2} y_\tau^{V_1} y_\mu^{V_1\,*} \Big(2 \bar{g}_2(x_d) - g_2(x_d)\Big), \\
C_R &= \frac{N_c}{48\pi^2 M_{V_1}^2} y_\tau^{V_1} y_\mu^{V_1\,*} \Big(2 \bar{g}_1(y_d) - g_1(y_d)\Big),
\end{aligned}
\tag{11}
$$

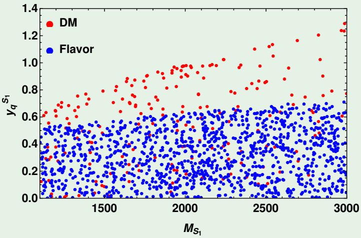
$\tau \to 3\mu$:

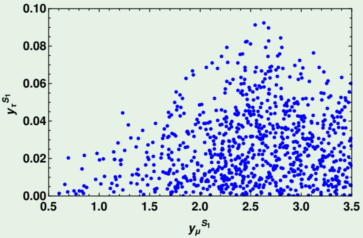


$\tau \to \mu\nu_\tau\bar{\nu}_\mu$:

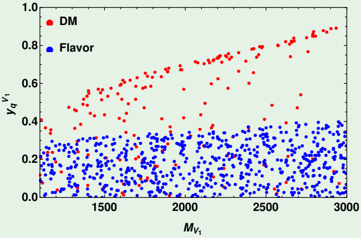


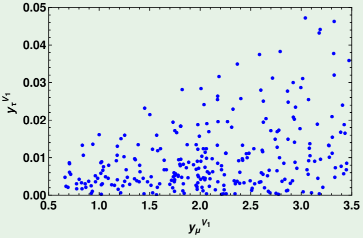
Scalar leptoquark



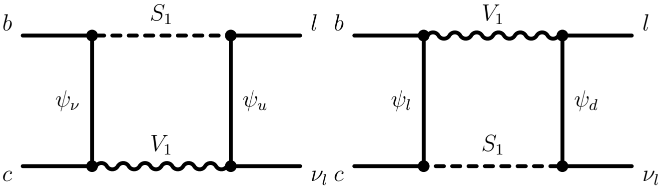


Vector leptoquark





Impact on $b \to c l \bar{\nu}_l$ decay modes



The general effective Lagrangian of $b \to c\tau\bar{\nu}_\tau$ transitions is given by

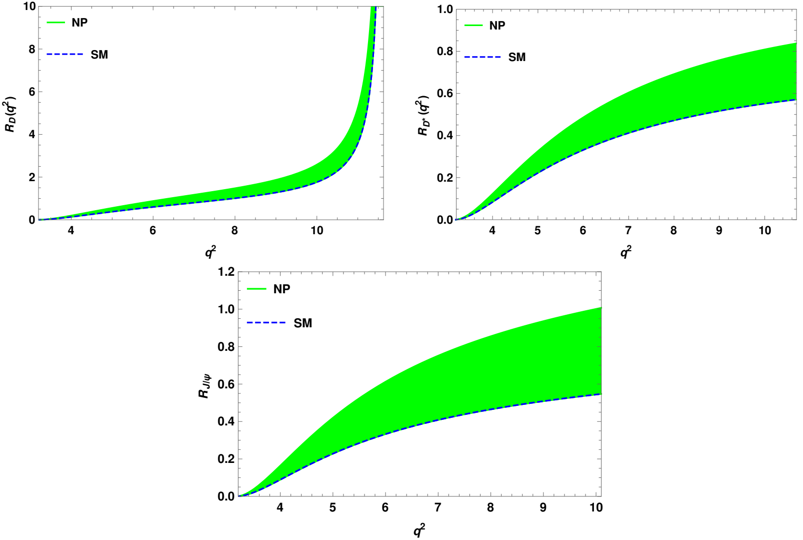
$$\mathcal{L}_{\rm eff} \quad = \quad -\frac{4\,G_F}{\sqrt{2}}\,V_{cb}\,(1+V_L)\,\bar{l}_L\,\gamma_\mu\,\nu_L\,\bar{q}_L\,\gamma^\mu\,b_L + \text{h.c.}\,, \qquad (12)$$

where the V_L new Wilson coefficient is given as

$$V_L = -\frac{\sqrt{2}}{64\pi\alpha_{\rm em}V_{cb}M_{\rm LQ}^2}\left[y_c^{V_1}y_b^{S_1}y_l^{S_1}y_{\nu_l}^{V_1}F(x_u,x_{\psi_\nu}) + y_b^{V_1}y_c^{S_1}y_l^{V_1}y_{\nu_l}^{S_1}F(x_d,x_{\psi_l})\right]. \quad (13)$$

The lepton nonuniversality parameters are defined as

$$R_{D(V)} = \frac{\mathrm{Br}(\bar{B} \to D(V)\tau\bar{\nu}_\tau)}{\mathrm{Br}(\bar{B} \to D(V)l\bar{\nu}_l)}, \qquad l = e, \mu, \quad V = D^*, J/\psi\,, \tag{14}$$



Conclusion

- We have extended the standard model by adding additional vector-like fermion doublets and a scalar and vector leptoquark singlets.
- All the new fermions and leptoquarks are assigned with charge -1 under Z_2 symmetry.
- Imposing PLANCK limit on relic density and well known PICO-60, LUX bounds on spin- dependent cross section, we have constrained the new parameters of the model.
- In the flavor sector, we have computed the allowed regions of new parameters by using $B_s - \bar{B}_s$ mixing, $b \to sll(\nu\bar{\nu})$, $b \to s\gamma$, $\tau \to 3\mu$, $\tau \to \mu\nu_\tau\bar{\nu}_\tau$ and $(g-2)\mu$ observables.
- We have shown the effects of both the dark matter and flavor observables on the anomalies associated with $b \to cl\bar{\nu}_l$ decay modes.

Thank you!!

Back up: Lepton non-universality

LNU parameters	Expt. Results	SM prediction	Deviation
$R_K\|_{q^2\in[1,6]\ \mathrm{GeV}^2}$	$0.745^{+0.090}_{-0.074} \pm 0.036$	1.003 ± 0.0001	2.6σ
$R_{K^*}\|_{q^2\in[0.045,1.1]\ \mathrm{GeV}^2}$	$0.66^{+0.11}_{-0.07} \pm 0.03$	0.92 ± 0.02	2.2σ
$R_{K^*}\|_{q^2\in[1.1,6]\ \mathrm{GeV}^2}$	$0.69^{+0.11}_{-0.07} \pm 0.05$	1.00 ± 0.01	2.4σ
R_D	$0.391 \pm 0.041 \pm 0.028$	0.300 ± 0.008	1.9σ
R_{D^*}	$0.316 \pm 0.016 \pm 0.010$	0.252 ± 0.003	3.3σ
$R_{J/\psi}$	$0.71 \pm 0.17 \pm 0.184$	0.289 ± 0.01	2σ