Vector like dark matter and flavor anomalies in leptoquark model

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Abstract

1. To resolve the neutral and charged current B anomalies, we consider a model where the standard model is extended by a pair of vector-like quark and lepton doublets, a new singlet scalar and a scalar leptoquark.
2. We investigate the phenomenology of vector-like dark matter in the leptoquark portal. We constrain the new parameter space by using the bounds on relic density and direct detection observables.
3. In the flavor sector, we use the bounds on $b \to sll(\nu\bar{\nu})$, $b \to s\gamma$ to constrain the model parameters.
4. We have further constrain the new parameters from the τ decay modes: $\tau \to \mu\gamma$, $\tau \to \mu\mu\mu$, $\tau \to \mu\bar{\nu}_\mu\nu_\tau$ and the $(g-2)_\mu$ anomalies.

Model description

Table 1: 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	$\psi_q \equiv (\psi_u, \psi_d)^T$	$(\mathbf{3},\mathbf{2},\ 1/6)$	−
	$\psi_\ell \equiv (\psi_\nu,\ \psi_l)^T$	$(\mathbf{1},\mathbf{2},\ -1/2)$	−
	χ	$(\mathbf{1},\mathbf{1},\ 0)$	−
Scalars	H	$(\mathbf{1},\mathbf{2},\ 1/2)$	+
	S_1	$(\bar{\mathbf{3}},\mathbf{1},\ 1/3)$	−

The Lagrangian of the present model can be written as

$$\begin{aligned}\mathcal{L} &= \mathcal{L}_{\rm SM} - M_q\overline{\psi_q}\psi_q - M_\psi\overline{\psi_\ell}\psi_\ell - M_\chi\overline{\chi_\ell}\chi_\ell - (y_D\overline{\psi_\ell}\tilde{H}\chi_\ell + {\rm H.c}) \\ &- y_{qL}^{S_1}\,\overline{Q_L}^C S_1\epsilon^{ab}\psi_{\ell L} - y_{\ell L}^{S_1}\,\overline{\psi_q}^C S_1\epsilon^{ab}\ell_L - y_{\ell R}^{S_1}\,\overline{d_R}^C S_1\chi_{\ell R} + {\rm h.c} \\ &+ \overline{\psi_\ell}\gamma^\mu\left(i\partial_\mu - \frac{g}{2}\boldsymbol{\tau}^a\cdot\mathbf{W}_\mu^a + \frac{g'}{2}B_\mu\right)\psi_\ell + \overline{\psi_q}\gamma^\mu\left(i\partial_\mu - \frac{g}{2}\boldsymbol{\tau}^a\cdot\mathbf{W}_\mu^a - \frac{g'}{6}B_\mu\right)\psi_q \\ &+ \overline{\chi_\ell}\gamma^\mu\left(i\partial_\mu\right)\chi_\ell + \left|\left(i\partial_\mu - \frac{g'}{3}B_\mu\right)S_1\right|^2 - V(H,S_1), \qquad (1)\end{aligned}$$

where the scalar potential V is

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

The new neutral fermions mixing takes the form

$$M_N = \begin{pmatrix} M_{\psi_\ell} & \frac{y_D}{\sqrt{2}} \\ \frac{y_D}{\sqrt{2}} & M_{\chi_\ell}\end{pmatrix}. \qquad (2)$$

One can diagonalize the above mass matrices by $U_\alpha^T M_N U_\alpha = {\rm diag}\,[M_1, M_2]$, with $\alpha = \frac{1}{2}\tan^{-1}\left(\frac{2y_D v}{\sqrt{2}(M_{\psi_\ell}-M_{\chi_\ell})}\right)$. The lightest mass eigenstate N_2 is a probable dark matter in the present model.

Relic density

Based on the mass splitting between N_1 and N_2, apart from annihilations several co-annihilation channels with leptons, quarks and gauge bosons in final state can contribute to relic density. The formula is given by

$$\Omega h^2 = \frac{2.14\times10^9\ {\rm GeV}^{-1}}{M_{\rm pl}\ {g_*}^{1/2}}\frac{1}{J(x_f)}, \quad J(x_f) = \int_{x_f}^\infty \frac{\langle\sigma v\rangle(x)}{x^2}dx. \qquad (3)$$

Here $M_{\rm Pl} = 1.22\times10^{19}$ GeV, $g_* = 106.75$ and the freeze out paramter $x_f = M_2/T_f \simeq 20$. The thermally averaged annihilation cross section is given by

$$\langle\sigma v\rangle(x) = \frac{x}{8M_2^5K_2^2(x)}\int_{4M_2^2}^\infty \hat{\sigma}\times(s-4M_2^2)\ \sqrt{s}\ K_1\left(\frac{x\sqrt{s}}{M_2}\right)ds, \qquad (4)$$

where K_1, K_2 denote the modified Bessel functions.

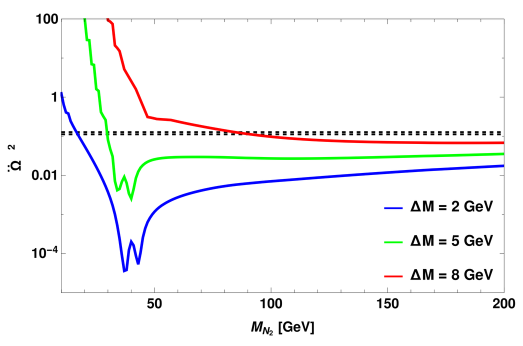


Figure 1: Relic density as a function of DM mass with horizontal dashed lines represent Planck 3σ range.

Direct Detection

The DM can provide direct detection signals from the following effective interactions

$$\begin{aligned}\mathcal{L}_Z^{\rm eff} &\sim \frac{1}{M_Z^2}(\overline{q}\gamma^\mu q)(\overline{N_2}\gamma_\mu N_2), \\ \mathcal{L}_h^{\rm eff} &\sim \frac{1}{M_h^2}(\overline{q}q)(\overline{N_2}N_2), \\ \mathcal{L}_{S_1}^{\rm eff} &\sim \frac{1}{M_{S_1}^2}\left[(\overline{q}\gamma^\mu q)(\overline{N_2}\gamma_\mu N_2) + (\overline{q}\gamma^\mu\gamma^5 q)(\overline{N_2}\gamma_\mu\gamma_5 N_2)\right]. \qquad (5)\end{aligned}$$

- XENON1T restricts the singlet-doublet mixing in Z-portal ($\sin\theta < 10^{-3}$) (spin-independent).
- XENON1T excludes couplings above 0.02 in SLQ portal (spin-independent).
- PICO-60 excludes couplings above 2 in SLQ portal (spin-dependent).

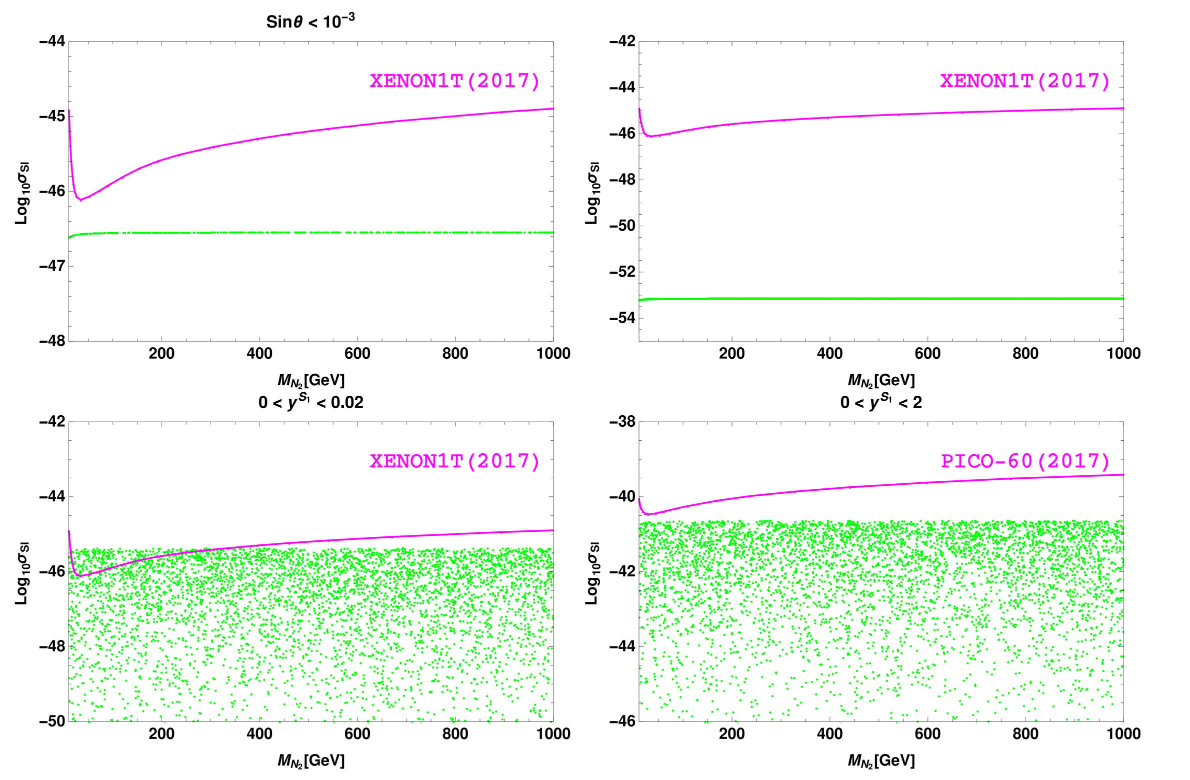


Figure 2: WIMP-nucleon cross section as a function of DM mass, included with current experimental upper limits.

Flavor sector

Using the full Run-I and Run-II data set, recently the LHCb Collaboration has updated the lepton non-universality R_K parameter in the $q^2 \in [1,6]$ GeV^2 [1]

$$R_K^{\rm LHCb21} = \frac{{\rm BR}(B^+\to K^+\mu^+\mu^-)}{{\rm BR}(B^+\to K^+e^+e^-)} = 0.846^{+0.042+0.013}_{-0.039-0.012} \qquad (6)$$

giving rise to the disagreement of 3.1σ from the SM prediction

$$R_K^{\rm SM} = 1.0003\pm0.0001\,. \qquad (7)$$

The recent measurements by the LHCb experiment on R_{K^*} ratio in two bins of low- and high-q^2 regions [2]:

$$R_{K^*}^{\rm LHCb} = \begin{cases}0.660^{+0.110}_{-0.070}\pm0.03 & q^2\in[0.045,1.1]\ {\rm GeV}^2, \\ 0.69^{+0.11}_{-0.07}\pm0.05 & q^2\in[1.1,6.0]\ {\rm GeV}^2.\end{cases} \qquad (8)$$

have respectively 2.1σ and 2.5σ deviations from their corresponding SM values:

$$R_{K^*}^{\rm SM} = \begin{cases}0.92\pm0.02 & q^2\in[0.045,1.1]\ {\rm GeV}^2, \\ 1.00\pm0.01 & q^2\in[1.1,6.0]\ {\rm GeV}^2.\end{cases} \qquad (9)$$

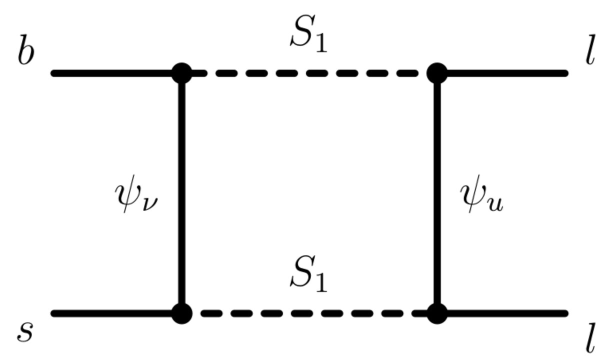
$b \to sll$:

The effective Hamiltonian describing the $b\to sl^+l^-$ quark level transition is given by

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}}\lambda_t\left[\sum_{i=1}^{6}C_i(\mu)\mathcal{O}_i + \sum_{i=7,9,10}(C_i(\mu)\mathcal{O}_i + C_i'(\mu)\mathcal{O}_i')\right], \qquad (10)$$

where

$$\begin{aligned}O_7^{(\prime)} &= \frac{e}{16\pi^2}\Big(\bar{s}\sigma_{\mu\nu}\left(m_sP_{L(R)} + m_bP_{R(L)}\right)b\Big)F^{\mu\nu}, \\ O_9^{(\prime)} &= \frac{\alpha_{\rm em}}{4\pi}(\bar{s}\gamma^\mu P_{L(R)}b)(\bar{l}\gamma_\mu l)\,, \qquad O_{10}^{(\prime)} = \frac{\alpha_{\rm em}}{4\pi}(\bar{s}\gamma^\mu P_{L(R)}b)(\bar{l}\gamma_\mu\gamma_5 l)\,, \qquad (11)\end{aligned}$$



New Wilson coefficients:

$$C_9^{\rm NP} = -C_{10}^{\rm NP} = -\frac{\sqrt{2}y_s^{S_1}y_b^{S_1}|y_l^{S_1}|^2}{512\pi G_F\alpha_{\rm em}\lambda_t M_{S_1}^2}\Big[F(x_u,x_{\psi_\nu}) + F(x_u,x_\chi)\Big]\ , \qquad (12)$$

with $x_i = M_i^2/M_{S_1}^2$, $\quad i = \psi_\nu, \psi_l, \chi, \zeta_u, \zeta_d$ and

$$F(x_i,x_j) = \frac{1}{(1-x_i)(1-x_j)} + \frac{x_i^2\log x_i}{(1-x_i)^2(x_i-x_j)} + \frac{x_j^2\log x_j}{(1-x_j)^2(x_j-x_i)}. \qquad (13)$$

The $b\to sll$ includes the following observables

- $R_{K^{(*)}}$ in observed bins
- ${\rm Br}(B_s\to ll$
- ${\rm Br}(B\to Kll)$
- ${\rm Br}(B\to K^*ll)$
- ${\rm Br}(B_s\to\phi ll)$
- $P_i^{(\prime)}$, $i = 1,2,3,4,5,6,8$

$b \to s\nu\bar{\nu}$:

The effective Hamiltonian of $b\to s\nu_i\bar{\nu}_j$ process is given by

$$\mathcal{H}_{\rm eff}^{\nu_i\nu_j} = -\frac{4G_F}{\sqrt{2}}\lambda_t\ \left(C_L^{\rm SM}\delta^{ij} + C_L^{ij}\right)\mathcal{O}_L^{ij}\,, \qquad (14)$$

where

$$\mathcal{O}_L^{ij} = \frac{\alpha_{\rm em}}{4\pi}[\bar{s}\gamma^\mu P_Lb][\bar{\nu}_i\gamma_\mu\left(1-\gamma^5\right)\nu_j]\,, \qquad (15)$$

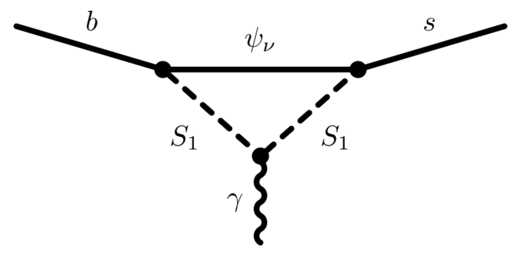
New Wilson Coefficients:

$$C_L^{ij} = -\frac{\sqrt{2}y_s^{S_1}y_b^{S_1}|y_l^{S_1}|^2}{512\pi G_F\alpha_{\rm em}\lambda_t M_{S_1}^2}F(x_d,x_{\psi_\nu})\ . \qquad (16)$$

The $b\to s\nu_l\bar{\nu}_l$ includes

- ${\rm Br}(B\to K\nu_l\bar{\nu}_l)$
- ${\rm Br}(B\to K^*\nu_l\bar{\nu}_l)$

$b \to s\gamma$:



New Wilson coefficients:

$$C_7^{\gamma\rm NP} = \frac{\sqrt{2}}{24G_FV_{tb}V_{ts}^*}\frac{y_b^{S_1}y_s^{S_1}}{M_{S_1}^2}\left(\tilde{F}_7(y_{\psi_l}) + 2F_7(y_{\psi_l})\right)\,, \qquad (17)$$

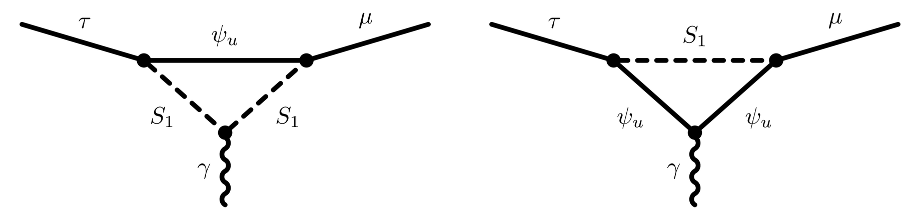
with

$$F_7(x) = \frac{x^3-6x^2+6x\log x+3x+2}{12(x-1)^4}, \qquad \tilde{F}_7(x) = x^{-1}F_7(x^{-1}). \qquad (18)$$

$\tau \to \mu\gamma$:

The effective Hamiltonian for $\tau^-\to\mu^-\gamma$ process is given by

$$\mathcal{H}_{\rm eff} = e\Big(C_L\bar{\mu}_R\sigma^{\mu\nu}F_{\mu\nu}\tau_L + C_R\bar{\mu}_L\sigma^{\mu\nu}F_{\mu\nu}\tau_R\Big), \qquad (19)$$



New Coefficients:

$$\begin{aligned}C_L &= \frac{N_c}{48\pi^2M_{S_1}^2}y_\tau^{S_1}y_\mu^{S_1*}\Big(2f_2(y_u) - \bar{f}_2(y_u)\Big), \\ C_R &= \frac{N_c}{48\pi^2M_{S_1}^2}y_\tau^{S_1}y_\mu^{S_1*}\Big(2f_1(y_u) - \bar{f}_1(y_u)\Big), \qquad (20)\end{aligned}$$

$(g-2)_\mu$:

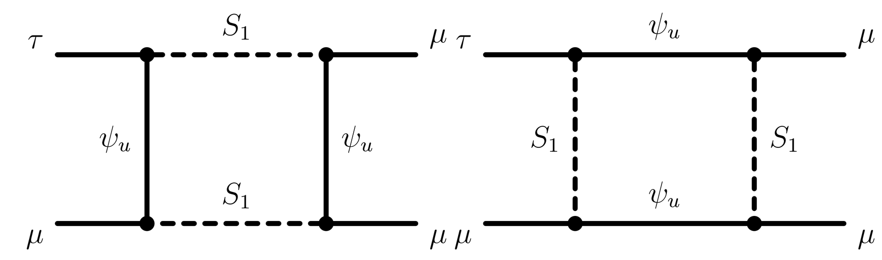
Recently, Fermilab's E989 experimenthas reported a discrepancy of 4.2σ

$$\Delta a_\mu^{\rm FNAL} = (25.1\pm5.9)\times10^{-10}. \qquad (21)$$

The scalar LQ contribution to a_μ is

$$\Delta a_\mu = -\frac{m_\mu^2(y_l^{S_1})^2}{16\pi^2M_{S_1}^2}\Big(2(f_1(x_u)+f_2(x_u)) - (\bar{f}_1(x_u)+\bar{f}_2(x_u))\Big), \qquad (22)$$

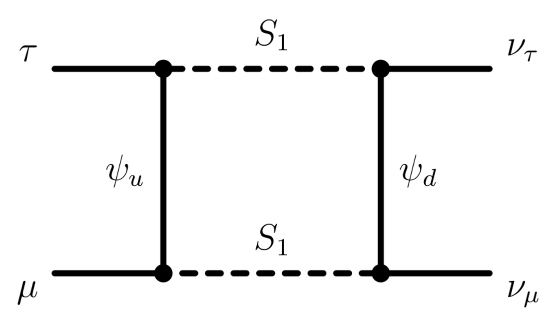
$\tau \to \mu\mu\mu$:



New Coefficients:

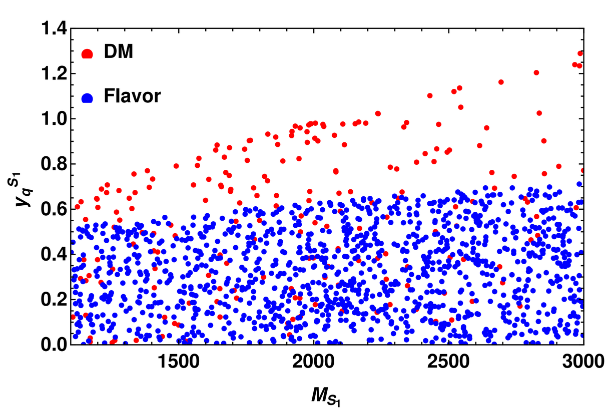
$$C_{\tau\to3\mu} = \frac{(y_\mu^{S_1})^3y_\tau^{S_1}}{2M_{S_1}^2}F(x_u,x_u)\,, \qquad (23)$$

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



New Coefficients:

$$C_{\tau\to3\mu} = \frac{y_\tau^{S_1}y_\mu^{S_1}y_{\nu_\mu}^{S_1}y_{\nu_\tau}^{S_1}}{2M_{S_1}^2}F(x_u,x_d)\,. \qquad (24)$$



Conclusion

- We have extended the standard model with additional vector-like fermion doublets and a scalar leptoquark, odd under under Z_2 symmetry.
- The lightest neutral fermion is the DM candidate.
- We constrain the new parameters from both the quark sector: $b\to sll\ (\nu\bar{\nu})$, $b\to s\gamma$, the tau sector: $\tau\to\mu\gamma$, $\tau\to\mu\mu\mu$, $\tau\to\mu\bar{\nu}_\mu\nu_\tau$ and by using the recent $(g-2)_\mu$ anomalies.

References

[1] **LHCb**, R. Aaij *et al.*, "*Test of lepton universality in beauty-quark decays*," arXiv:2103.11769.

[2] **LHCb**, R. Aaij *et al.*, "*Test of lepton universality with $B^0\to K^{*0}\ell^+\ell^-$ decays*," JHEP **08** (2017) 055, arXiv:1705.05802.