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# Framework for neutrino masses and flavor anomalies

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Scalar leptoquark (LQs) are the prime candidates for physics beyond the Standard Model (SM) to resolve tantalizing flavor anomalies in the beauty-quark decay for both neutral- and charged-current transitions, $R_{D^{(*)}}$ and $R_{K^{(*)}}$. These same LQs can also resolve long standing tension in the muon and electron $g-2$ anomalies. These lepton flavor universality violation (LFUV) have discrepancies in the range of $2.5\sigma - 4.2\sigma$. We propose a resolution to all these anomalies in a unified framework that naturally gives masses to neutrinos at the two-loop order while satisfying all the constraints from collider searches, including those from flavor physics.

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## 1. Introduction

Several precision observable experiments strongly suggests LFUV, hinting physics beyond the SM (BSM), among which lepton anomalous magnetic moments (AMMs) and LFU violating $B$-meson decays stands out with the discrepancies in the range of $2.5\sigma - 4.2\sigma$. The combined result from Fermilab [1] and Brookhaven [2] show a large $+4.2\sigma$ discrepancy with the SM prediction [3]. In addition to the muon $g-2$ anomaly, there is also $-2.4\sigma$ disagreement with the direct experimental measurement [4] in $(g-2)_e$ [1]. Moreover, LFU violating $B$-meson decays in the neutral current transitions $R_{K^{(*)}} = Br\left(B \to K^{(*)}\mu^+\mu^-\right)/Br\left(B \to K^{(*)}e^+e^-\right)$ as well as charged current $R_{D^{(*)}} = Br\left(B \to D^{(*)}\tau\overline{\nu}_\tau\right)/Br\left(B \to D^{(*)}\ell\overline{\nu}\right)$ show deviations from the SM prediction with a significance of about $3\sigma$ [7]. These processes have very small theoretical uncertainties since hadronic uncertainties cancel out in the above ratios, making it extremely sensitive to new physics probes.

Besides all these anomalies, SM also fails to incorporate the origin of neutrino masses, firmly confirmed by the oscillation experiments [8, 9]. Motivated by this drawbacks of the SM, we propose a new two loop neutrino mass model [10, 11] that gives a simultaneous solution to all four of the anomalies mentioned above. The model utilizes two scalar leptoquarks (LQs) $\{S_1(\overline{3},1,1/3)$ and $R_2(3,2,7/6)\}$ that are directly intertwined with the neutrino mass generation mechanism. These LQs are required to have mass at electroweak scale to address these anomalies, thus making the model fully testable.

## 2. Model

In addition to the SM particle content, the proposed model [10, 11] consists of two scalar LQs (SLQs), $S_1(\overline{3},1,+1/3)$, $R_2(3,2,7/6)$, and another BSM multiplet $\xi_3(3,3,2/3)$. We denote their component fields by

$$R_2 = \begin{pmatrix} R^{5/3} \\ R^{2/3} \end{pmatrix}, \qquad S_1 = S^{1/3}, \qquad \xi = \begin{pmatrix} \frac{\xi^{2/3}}{\sqrt{2}} & \xi^{5/3} \\ \xi^{-1/3} & -\frac{\xi^{2/3}}{\sqrt{2}} \end{pmatrix}.$$

The LQs coupling with the SM fermions read as

$$\mathcal{L}_Y^{\rm new} = f_{ij}^L \overline{u}_{Ri} R_2 \cdot L_j + f_{ij}^R \overline{Q}_i R_2 \ell_{Rj} + y_{ij}^L \overline{Q_i^c} \cdot L_j S_1 + y_{ij}^R \overline{u^c}_{Ri} S_1 \ell_{Rj}, \tag{1}$$

where $Q$ and $L$ respectively stand for left-handed quark and lepton doublets, $u_R$ and $\ell_R$ are right-handed up-type quark and lepton, and $i,j = 1-3$ are family indices. We also use "$\cdot$" to denote $SU(2)$ contraction so that $L \cdot Q \equiv L^\rho Q^\sigma \epsilon_{\rho\sigma}$ with $\epsilon$ being the Levi-Civita tensor and $\rho, \sigma =$ being $SU(2)$ indices. Here we turn off the diquark coupling of $S_1$ LQ, which guarantees baryon number conservation. Moreover, we have chosen to work in the so-called "up-quark mass diagonal basis". The relevant Higgs interaction

$$V_{sc} \supset \lambda\, S_1^\dagger H^T \epsilon \xi^\dagger H + \mu\, R_2^\dagger \xi H\,, \tag{2}$$

together with the Yukawa couplings break the lepton number by two units and generate non-zero Majorana neutrino masses as shown in Fig. 1. Note that to incorporate flavor anomalies, $\mathcal{O}(1)$

[1]Contrary to the 2018 result by Berkeley National Laboratory [5], this new 2020 result [6] finds $\Delta a_e$ to be positive ($+1.6\sigma$), indicating a $\sim 5\sigma$ disagreement between these two experiments.

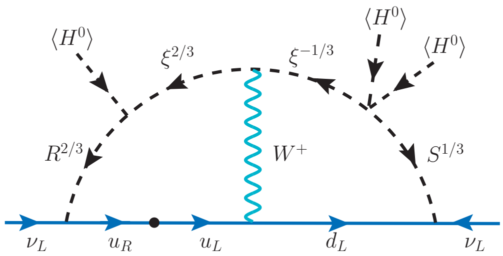


**Figure 1:** A typical two-loop diagram leading to non-zero neutrino mass. For full set of diagrams, see Ref. [10].

Yukawa couplings are required, compelling to have small mixing angles to generate neutrino masses of order 0.1 eV. We, therefore, identify gauge eigenstates $R^{2/3,5/3}$ and $S^{1/3}$ as their physical eigenstates. The neutrino mass then takes the following form:

$$\mathcal{M}_\nu = m_0 I_0 \left\{ 2(y^L)^T D_u f^L + \frac{m_\tau}{m_t} D_\ell (y^R)^T f^L - \frac{m_\tau}{m_t} D_\ell (f^R)^T y^L \right\} + \text{transpose}, \tag{3}$$

where $m_0 = 3g^2 m_t/\sqrt{2}(16\pi^2)^2$ with $g$ being the $SU(2)$ gauge coupling constant and $m_t$ being the top-quark mass. The normalized mass matrices of up-type quarks and charged leptons are $D_u = \text{diag.}\left(\frac{m_u}{m_t}, \frac{m_c}{m_t}, 1\right)$ and $D_\ell = \text{diag.}\left(\frac{m_e}{m_\tau}, \frac{m_\mu}{m_\tau}, 1\right)$. The loop integral $I_0$ in the asymptotic limit (i.e., when all fermion masses are zero) is given by

$$I_0 = \frac{1}{4} \sin 2\theta \sin 2\phi \sum_{a,b=1}^{2} (-1)^{a+b}\, 8 \left(1 - \frac{3}{4}\frac{M_{a+2}}{M_b}\right) - \frac{5}{6}\pi^2 \left(1 - \frac{2}{5}\frac{M_{a+2}}{M_b}\right) + \frac{M_b^2}{m_W^2}\left(\frac{M_{a+2}}{M_b} - 1\right)\left(2 - \tfrac{1}{3}\pi^2\right) + \left(\frac{2M_{a+2}}{M_b} - 1\right) \ln \frac{m_W^2}{M_b^2}. \tag{4}$$

Here $\theta$ and $\phi$ denote the mixing angles of LQ with charges $1/3$ and $2/3$, respectively, while $M_{1,2}$ are masses for $2/3$ charged LQs and $M_{3,4}$ are for $1/3$ charged LQ. For more detailed see Ref. [10].

## 3. Constraints

The flavor structure to resolve these four anomalies while incorporating neutrino oscillation data is highly non-trivial and leads the way to various flavor violating processes such as $\ell_i \to \ell_j \gamma$ [13]. Constraint from coherent $\mu - e$ conversion in nuclei also provides a strong constraint: $|\hat{f}^R_{ue} \hat{f}^{R*}_{u\mu}| \leq 8.58 \times 10^{-6} \left(\frac{M_{R_2}}{\text{TeV}}\right)^2$. Similarly, $R_2$ LQ in the up-quark diagonal basis leads to various kaon decay processes [12] for which numerous stringent bounds are listed in Table 1. Moreover, $Z$-boson decay to fermion pairs through one-loop radiative corrections leads to $|f^R_{b\tau}| \leq 1.21$ [14] for LQ mass of 1.0 TeV. At the LHC, $S_1$ and $R_2$ LQs can be pair produced [15, 16] through $gg$ and $q\bar{q}$ fusion processes or can be singly produced in association with charged leptons via $s$- and $t$- channel quark-gluon fusion processes. In both ATLAS and CMS, there are dedicated searches for the LQ pair production in different modes, LQ$^\dagger$ LQ $\to q\bar{q}\ell\bar{\ell}, q\bar{q}\nu\bar{\nu}$. Apart from the LQ-pair production bound, there are bounds on the couplings and mass on the LQ from the high-$p_T$ tails of $pp \to \ell\ell$ distributions [17, 18].



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| **Process** | **Constraints** [12] |
|---|---|
| $K_L \to e^+e^-$ | $\lvert\hat{f}^R_{de}\hat{f}^{R*}_{se}\rvert \leq 2.0\times 10^{-3}\left(\frac{M_{R_2}}{\text{TeV}}\right)^2$ |
| $K^0_L \to e^\pm\mu^\mp$ | $\lvert\hat{f}^R_{d\mu}\hat{f}^{R*}_{se} + \hat{f}^R_{s\mu}\hat{f}^{R*}_{de}\rvert \leq 1.9\times 10^{-5}\left(\frac{M_{R_2}}{\text{TeV}}\right)^2$ |
| $K^0_L \to \pi^0 e^\pm\mu^\mp$ | $\lvert\hat{f}^R_{d\mu}\hat{f}^{R*}_{se} - f^R_{s\mu}f^{R*}_{de}\rvert \leq 2.9\times 10^{-4}\left(\frac{M_{R_2}}{\text{TeV}}\right)^2$ |
| $K^+ \to \pi^+e^+e^-$ | $\lvert\hat{f}^R_{de}\hat{f}^{R*}_{s\mu}\rvert \leq 2.3\times 10^{-2}\left(\frac{M_{R_2}}{\text{TeV}}\right)^2$ |
| $K^+ \to \pi^+e^-\mu^+$ | $\lvert\hat{f}^R_{d\mu}\hat{f}^{R*}_{se}\rvert, \lvert\hat{f}^R_{de}\hat{f}^{R*}_{s\mu}\rvert \leq 1.9\times 10^{-4}\left(\frac{M_{R_2}}{\text{TeV}}\right)^2$ |
| $K - \bar{K}$ | $\lvert\hat{f}^{R*}_{d\alpha}\hat{f}^R_{s\alpha}\rvert \leq 0.0266\left(\frac{M_{R_2}}{\text{TeV}}\right)$ |
| $K^+ \to \pi^+\nu\nu$ | $\text{Re}[\hat{y}^L_{de}\hat{y}^L_{se}] = [-3.7, 8.3]\times 10^{-4}\left(\frac{M_{S_1}}{\text{TeV}}\right)^2$<br>$[\sum_{m\neq n}\lvert\hat{y}^L_{dm}\hat{y}^{L*}_{sn}\rvert^2]^{1/2} < 6.0\times 10^{-4}\left(\frac{M_{S_1}}{\text{TeV}}\right)^2$ |
| $B \to K^{(*)}\nu\nu$ | $\hat{y}^L_{b\alpha}\hat{y}^L_{s\beta} = [-0.036, 0.076]\left(\frac{M_{S_1}}{\text{TeV}}\right)^2, [R^{\nu\bar{\nu}}_{K^*} < 2.7]$<br>$\hat{y}^L_{b\alpha}\hat{y}^L_{s\beta} = [-0.047, 0.087]\left(\frac{M_{S_1}}{\text{TeV}}\right)^2, [R^{\nu\bar{\nu}}_{K} < 3.9]$ |

**Table 1:** Constraints on the relevant LQ couplings as a function of mass from kaon and $B$ meson decays.

## 4. Results and Discussion

We present numerical results and study the correlations among $R_{D^{(*)}}$, $R_{K^{(*)}}$, $\Delta a_\mu$, and $\Delta a_e$ anomalies within their $1\sigma$ measured values while consistently incorporating neutrino oscillations data. We provide a benchmark points as follows: with $m_0 I_0 = 1.73\times 10^{-6}$ GeV, $M_{R_2} = 1.5$ TeV and $M_{S_1} = 1.2$ TeV:

$$f^R = \begin{pmatrix} 0 & 0 & 0 \\ \mathbf{0.13} & 0 & -0.027 \\ \mathbf{0.036} & 0.01 & 0 \end{pmatrix}, \qquad f^L = \begin{pmatrix} 0 & 0 & \mathit{1.0} \\ 0 & 0 & 6.36\times 10^{-4} \\ 0 & 0 & -5.32\times 10^{-6} \end{pmatrix},$$

$$y^R = \begin{pmatrix} 0 & 0 & 0 \\ -0.3^{\star} & 0 & \boxed{1.0} \\ 0 & 0.0025^{\dagger} & 0 \end{pmatrix}, \qquad y^L = \begin{pmatrix} 0 & 0 & 0 \\ 0.02^{\star} & 0 & 0 \\ 0 & \boxed{1.2}^{\dagger} & 0 \end{pmatrix}. \tag{5}$$

This flavor structure explains $R_D - R_{D^*}$ ( $\square$ ), $(g-2)_\mu$ ( $\dagger$ ), and $(g-2)_e$ ( $\star$ ) utilizing $S_1$ LQ, and $R_K - R_{K^*}$ (**bold**) from $R_2$ LQ. Non-zero elements in black are the additional entries required to explain neutrino oscillation data. The only non-zero entry that induces observable NSI [19, 20] is shown in *italics*. With this benchmark points we find the following fit

$$\begin{aligned} &\sin^2\theta_{12} = 0.316, \qquad \sin^2\theta_{13} = 0.0218, \qquad \sin^2\theta_{23} = 0.506, \\ &\Delta m^2_{21} = 7.41\times 10^{-5}\text{eV}^2\,, \qquad \Delta m^2_{31} = 2.53\times 10^{-3}\text{eV}^2\,, \\ &C^{ee}_9 = C^{ee}_{10} = -1.39, \qquad (g-2)_e = -86\times 10^{-14}, \qquad (g-2)_e = -22.4\times 10^{-10} \end{aligned} \tag{6}$$

The allowed parameter space to explain $R_{D^{(*)}}$ and $R_{K^{(*)}}$ at $1\sigma$ (green shaded) and $2\sigma$ (yellow

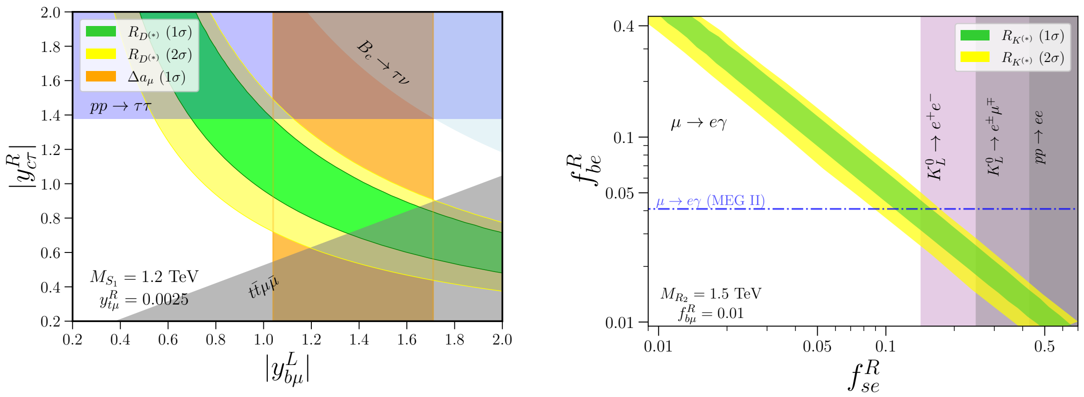


**Figure 2:** $1\sigma$ (green) and $2\sigma$ (yellow) allowed range for $R_{D^{(*)}}$ (top) and $R_{K^{(*)}}$ (bottom) in the relevant Yukawa coupling planes, with the $S_1$ ($R_2$) LQ mass fixed at 1.2 (1.5) TeV. Orange band on the top figure corresponds to $1\sigma$ allowed range of $\Delta a_\mu$.

shaded) CL in the relevant Yukawa coupling planes are illustrated in Fig. 2 by fixing $R_2$ ($S_1$) mass at 1.2 (1.5) TeV. In computing $R_{D^{(*)}}$ and $R_{K^{(*)}}$ observables, we utilized `Flavio package` [21]. By fixing $y^R_{t\mu} = 0.0025$ (cf. Eq. (5)), the allowed range to incorporate $\Delta a_\mu$ at $1\sigma$ is shown in orange band that corresponds to $y^R_{t\mu} y^L_{t\mu} \sim 10^{-3}$. We also show the exclusion regions obtained from resonant ($t\bar{t}\mu\bar{\mu}$) and non-resonant ($pp \to \tau\tau, ee$) production of LQs, along with flavor constraints such as $\mu \to e\gamma$ for a fixed $f^R_{b\mu}$, and kaon decays. Here the remaining anomaly $\Delta a_e$ is determined by the product $y^R_{ce} y^L_{ce}$.

As it is clear form this analysis, the valid parameter space addressing all the anomalies is very limited. Due to various collider and flavor violating constraints, and upcoming experiments searching for LFV, this model fully testable in the near future. Thus, the model of two-loop neutrino mass consisting of two scalars LQs $S_1(\bar{3}, 1, 1/3)$ and $R_2(3, 2, 7/6)$ and another BSM scalar $\xi(3, 3, 2/3)$ has close-knit connections with $R_{K^{(*)}}$, $R_{D^{(*)}}$, and $(g-2)_{\mu,e}$, while being fully consistent with all the relevant relevant flavor violating and collider constraints.

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