PROCEEDINGS OF SCIENCE

Addressing R_K and neutrino mixing in a class of $U(1)_X$ models

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We present a class of minimal $U(1)_X$ models as a plausible solution to the R_K anomaly that can also help reproduce the neutrino mixing pattern. The symmetries and the corresponding X-charges of the fields are determined in a bottom-up approach demanding both theoretical and experimental consistencies. The breaking of $U(1)_X$ symmetry results in a massive Z', whose couplings with leptons and quarks are necessarily non-universal to address the R_K anomaly. In the process, an additional Higgs doublet is introduced to generate quark mixings. The mixings in the neutrino sector are generated through Type-I seesaw mechanism by the addition of three right handed neutrinos and a scalar singlet. The Z' can be probed with a few hundred fb^{-1} of integrated luminosity at the 13 TeV LHC in the di-muon channel.

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1. Introduction

The flavour observable, $R_K \equiv \text{BR}(B \to K\mu\mu)/\text{BR}(B \to Kee)$, is predicted to be unity in the standard model (SM) to a very good accuracy [1, 2]. The experimentally measured value of R_K in the low dilepton mass squared bin [3] is $0.745^{+0.090}_{-0.074} \pm 0.036$, which deviates from the SM currently by 2.6σ and therefore hints towards lepton flavour universality violation. The angular observable P_5' [4] measured in $B \to K^*\mu\mu$ also shows a deviation from the SM [5, 6]. The $b \to s$ flavour anomalies in R_K and P_5' can be simultaneously addressed if the new physics (NP) effects are present in the Wilson coefficients (C_i) of the following operators ($\mathscr{O}_i$) [7]:

$$\begin{aligned} \mathscr{O}_9^\ell &= \left(\bar{b}\,\gamma_\mu P_L\, s\right)\,\left(\bar{\ell}\,\gamma^\mu \ell\right)\,, \quad \mathscr{O}_{10}^\ell = \left(\bar{b}\,\gamma_\mu P_L\, s\right)\,\left(\bar{\ell}\,\gamma^\mu \gamma_5 \ell\right)\,, \\ \mathscr{O}_9^{\ell\prime} &= \left(\bar{b}\,\gamma_\mu P_R\, s\right)\,\left(\bar{\ell}\,\gamma^\mu \ell\right)\,, \quad \mathscr{O}_{10}^{\ell\prime} = \left(\bar{b}\,\gamma_\mu P_R\, s\right)\,\left(\bar{\ell}\,\gamma^\mu \gamma_5 \ell\right)\,. \end{aligned} \tag{1.1}$$

Global fits [8, 9, 10, 11, 12] performed on $b \to s\ell\ell$ and $b \to s\gamma$ data prefer dominant NP effects in $\mathscr{O}_9^\mu$, with $C_9^{\text{NP},\mu} \sim -1$. Non-zero contributions to $C_9^{\text{NP},e}$ and $C_9^{\text{NP},\mu}$ simultaneously are consistent with global fits [9, 10, 11, 12] within 2σ. The two-dimensional fit performed by [12] favour NP effects in $\left(C_9^\mu, C_9^e\right)$ over others.

Motivated by above results, we build our model around the choice where NP effects are present in $\mathscr{O}_9^\ell$ operator in a bottom-up approach [13]. New physics contributions to C_9^ℓ can be generated in the presence of a Z' or leptoquarks. We choose to explain the anomaly using a Z' solution, and hence augment the SM with an additional gauge symmetry, $U(1)_X$ [13]. The SM fields i are assigned the charge X_i under $U(1)_X$. The explanation of the R_K anomaly necessarily requires the X-charges of the electron and muon to be different. Dominant NP contributions to $b \to s\ell\ell$ using a Z' also dictate non-universality of the X-charges for quarks.

The $U(1)_X$ extensions of the SM should also be able to explain neutrino masses and mixings. Thus it will be interesting to have a common origin for flavour anomalies and neutrino mass generation. We do not pre-assume any value for the X-charges, rather determine them in a bottom-up approach while satisfying all the current measurements and theoretical consistencies in a minimalist way. This also provides a framework which can be used for analyzing future data.

2. Constructing the $U(1)_X$ models

2.1 Theoretical considerations

The additional gauge symmetry, $U(1)_X$ should not introduce any gauge anomaly. A minimal addition of three right handed neutrinos with vector-like X-charge assignments, i.e., $X_{u_L} = X_{d_L} = X_{u_R} = X_{d_R} \equiv X_Q$,$X_{\ell_L} = X_{\nu_{\ell L}} = X_{\ell_R} = X_{\nu_{\ell R}} \equiv X_\ell$, will ensure our model to be gauge anomaly free, if the charges satisfy

$$\sum_i 3X_{Q_i} + X_{\ell_i} = 0\,, \tag{2.1}$$

where the sum is over the fermionic generation. With these charges, the Yuwaka interactions, given as

$$\mathscr{L}_{\text{Yuk}} = \overline{Q_L}\,\mathscr{Y}^d\,\Phi\, d_R + \overline{Q_L}\,\mathscr{Y}^u\,\Phi\, u_R + \overline{L_L}\,\mathscr{Y}^e\,\Phi\, e_R\,, \tag{2.2}$$

will consist of non-zero diagonal $\mathscr{Y}^d_{ii}$, $\mathscr{Y}^u_{ii}$ and $\mathscr{Y}^e_{ii}$ only if Φ_{SM} is a singlet under $U(1)_X$.

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2.2 Constraints on the quark sector from the SM predictions

The unequal X-charges for the quark generation leads to potential flavour changing neutral interactions at tree level, which can affect neutral meson mixings, in particular. The stringent constraints from K–$\overline{K}$ mixing [14] are accounted for by choosing $X_{Q_1} = X_{Q_2}$. Hence in our model, the non-universality appears in the third generation of the quark sector. Although this will generate appropriate NP contributions to explain R_K, it will be unable to generate the measured CKM matrix. This problem can be resolved with an additional doublet, $\Phi_{\rm NP}$, with X-charge, $d = X_{Q_1} - X_{Q_3}$ [13] (A similar choice has been considered in [15]). We also choose the left-handed quark rotation matrices $V_{d_L} = V_{\rm CKM}$ and $V_{u_L} = I$, which ensure no Z' contribution to the CP violating phases in B–$\overline{B}$ oscillations. With this choice, $[V_{d_R}]_{23} \approx A\lambda^2 m_s/m_b$, $[V_{d_R}]_{13} \approx -A\lambda^3 m_d/m_b$, $[V_{u_R}]_{23} = [V_{u_R}]_{13} = 0$, with unconstrained $[V_{d_R}]_{12}$ and $[V_{u_R}]_{12}$, which we choose to be vanishing. Thus, $V_{d_R} \approx I$ and $V_{u_R} = I$ in our model.

Following the results from global fits [9, 10, 11, 12], we require dominant new physics contributions only to $\mathscr{O}_9$. Therefore, the contributions to other operators — $\mathscr{O}'_9$, $\mathscr{O}_{10}$ and $\mathscr{O}'_{10}$ should vanish. The vector-like charge assignments automatically ensure the NP contributions to $\mathscr{O}_{10}$ and $\mathscr{O}'_{10}$ are absent. The contributions to the $\mathscr{O}'_9$ operator are also small in comparison to the $\mathscr{O}_9$ as $V_{d_R} \approx I$. Therefore our charge assignments generate significant NP contributions only to the $\mathscr{O}_9$ operator [13].

2.3 Neutrino masses and mixings

We generate neutrino masses and mixings using Type-I seesaw mechanism. The additional scalar S, with X-charge a, is included to obtain the observed neutrino mixings from the oscillation data. The Lagrangian describing the mass term of neutrinos (with X-charges y_e, y_μ and y_τ) is

$$\mathscr{L}_\nu^{\rm mass} = -\overline{\nu_L}\, m_D\, \nu_R - \frac{1}{2}\overline{\nu_R^c} M_R\, \nu_R - \frac{1}{2}\overline{\nu_R^c}\mathscr{Y}_R \nu_R\, S + h.c.\,. \tag{2.3}$$

Without loss of generality, we can always choose the basis for the charged leptons and left handed neutrinos ν_L such that m_D and m_ℓ (mass matrix for charged leptons) are diagonal. The X-charges dictate the texture of the right handed mass matrix, M_R^S:

$$[M_R^S]_{\alpha\beta} = [M_R]_{\alpha\beta} + \frac{v_S}{\sqrt{2}}[y_R]_{\alpha\beta} \neq 0 \quad \text{if } \; y_\alpha + y_\beta = 0\,, \pm a\,. \tag{2.4}$$

The allowed M_R^S textures [16, 17] can be used to infer the possible X-charges in the lepton sector using eq. (2.4). The allowed symmetry combinations hence obtained are listed in the left panel of fig. 1 and are clubbed according to y_e/y_μ. Note that the combinations obtained for the two-zero textures match with those derived in [18].

2.4 Scalar sector

We have three scalars, Φ, $\Phi_{\rm NP}$ and S, in our model, with X-charges 0, d and a, respectively. The doublet $\Phi_{\rm NP}$ and the scalar S break $U(1)_X$ symmetry spontaneously, thereby providing Z' a mass. The vacuum expectation value of S is $\mathscr{O}(\text{TeV})$ owing to stringent limits on Z' mass from colliders. With such a vev, S gets effectively decoupled and the effective scalar potential for the doublets, $\Phi \equiv \Phi_2$ and $\Phi_{\rm NP} \equiv \Phi_1$, is

Category	Symmetries
A	$L_\mu,\, L_\mu - L_\tau$
B	$L_e - 3L_\mu \pm L_\tau$
C	$L_e + 3L_\mu - L_\tau$
D	$L_e - L_\mu \pm L_\tau,\, L_e - L_\mu \pm 3L_\tau$
E	$L_e + L_\mu - L_\tau,\, L_e + L_\mu - 3L_\tau$
F	$3L_e - L_\mu - L_\tau$
G	L_e

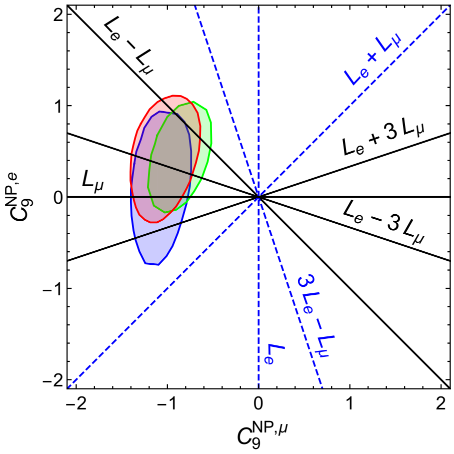

Figure 1: In the left panel, all the allowed leptonic symmetries consistent with the neutrino oscillation data are listed. They are categorized according to the ratio y_e/y_μ. In the right panel, the global fits obtained from [10] (red), [11] (blue) and [12] (green) are plotted together with the predictions for the symmetry combinations listed in the left panel, in the $\left(C_9^{\mathrm{NP},\mu}, C_9^{\mathrm{NP},e}\right)$ plane.

$$V_{\Phi_1\Phi_2} = -\left(m_{11}^2 - \frac{\lambda_{1S_1}}{2} v_S^2\right)\Phi_1^\dagger\Phi_1 + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 - \left(m_{22}^2 - \frac{\lambda_{2S}}{2} v_S^2\right)\Phi_2^\dagger\Phi_2$$
$$+\frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1). \tag{2.5}$$

The absence of $\Phi_1^\dagger\Phi_2 + h.c.$ term in the Lagrangian would render a massless boson in our theory. This problem can be avoided by equating $X_S = X_{\Phi_1}$, i.e. $a = d$, which admits

$$\Delta V_{\Phi_1\Phi_2 S} = -\widetilde{m}_{12}\left[S\,\Phi_1^\dagger\Phi_2 + S^\dagger\,\Phi_2^\dagger\Phi_1\right]\,. \tag{2.6}$$

This explicitly breaks the global $U(1)_A$ symmetry. We now summarize the charge assignments in the following table:

Fields	Q_1	Q_2	Q_3	L_1	L_2	L_3	Φ	Φ_{NP}	S
$U(1)_X$	x_1	x_1	$x_1 - a$	y_e	y_μ	y_τ	0	a	a

Table 1: Vector-like X-charge assignments. The fields Q_i and L_i refer to the i^{th} generations of quarks and leptons, respectively. The charges of fermions are related with eq. (2.1).

The X-charges of all particles are proportional to a [13], therefore we absorb a in the definition of $g_{Z'}$ and proceed our analysis further by assigning $a = 1$. Note that, for simplicity, we continue to label the full $U(1)_X$ symmetry in terms of the leptons as described in left panel of the fig. 1.

2.5 Selecting the plausible symmetry combinations

We now want to determine the desirable symmetry combinations which are compatible with the global fits to $b \to s\ell\ell$ and $b \to s\gamma$ data. We consider the allowed region in the $\left(C_9^{\mathrm{NP},\mu}, C_9^{\mathrm{NP},e}\right)$

plane from global fits [10, 11, 12] and plot the predictions for all the symmetries listed in left panel of fig. 1. The combinations in categories A, B, C and D pass through 1σ contours for all the global fits and hence are selected [13].

3. Experimental constraints

In this section, we consider one of the allowed symmetry combination, i.e. $L_e - 3L_\mu + L_\tau$ from category B for illustration, and subject it to constraints from neutral meson mixing data (K–$\overline{K}$, B_d–$\overline{B_d}$, B_s–$\overline{B_s}$) [14], global fits on $b \to s\ell\ell$ and $b \to s\gamma$ data [12], and direct detection limits on Z' searches from ATLAS in the di-muon channel [19]. The allowed parameter space in $(g_{Z'}, M_{Z'})$ plane is shown in the left panel of fig. 2. The analysis for all the symmetries may be seen in [13]. We also show the reach for detecting such a Z' with $g_{Z'} = 0.36$ at the 13 TeV LHC in the right panel of fig. 2.

4. Results

We have arrived at a class of $U(1)_X$ models which can explain flavour anomalies and neutrino oscillation data simultaneously in a bottom-up approach. A total of nine symmetry combinations are shortlisted demanding theoretical consistencies and experimental constraints. An additional Higgs doublet is introduced to generate the quark mixings. Three right handed neutrinos and an additional scalar singlet are introduced to explain neutrino mass and mixings in Type-I seesaw framework. The parameters may be chosen such that the additional scalars and the right handed neutrinos are decoupled from the theory. Hence effectively at TeV energies, our model is described by the SM and an additional Z'. We determine the allowed parameter space in the plane of ($g_{Z'}$, $M_{Z'}$) and also calculate the Z' detection reach at the 13 TeV LHC in the di-muon channel.

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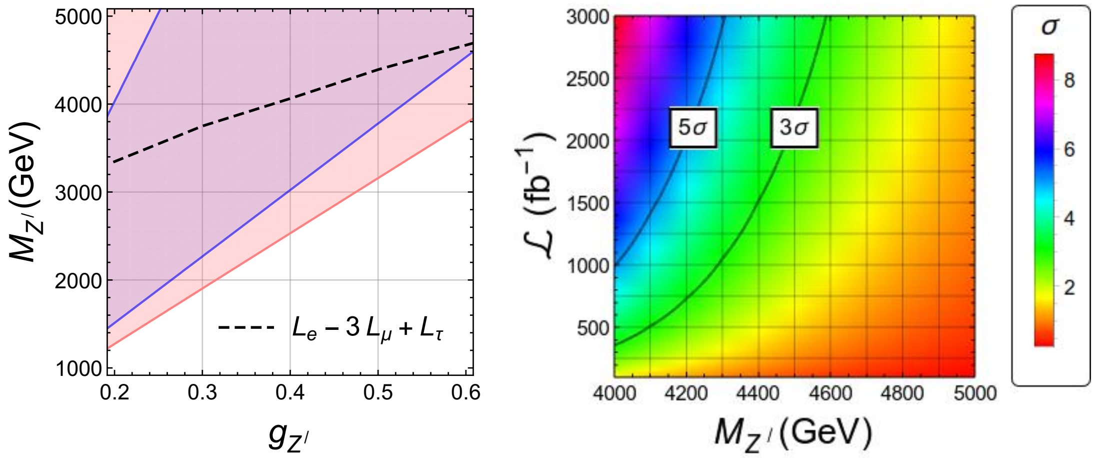

Figure 2: In the left panel, we plot the constraints obtained from neutral meson mixing, global fits on $b \to s\ell\ell$, $b \to s\gamma$ data and direct detection of Z' in the di-lepton channel. The regions in pink (blue) are allowed by the neutral meson mixings (global fits) at 2σ. The regions above the dotted line is consistent with direct detection limits at 95% C.L. In the right panel, we plot the significance of observing such a Z' (with $g_{Z'} = 0.36$) in the di-muon channel. The plots are shown for the symmetry combination $L_e - 3L_\mu + L_\tau$.

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