$U(1)_{B_3-3L_2}$ gauge symmetry as a simple description of $b \to s$ anomalies

Cesar Bonilla,[1,*] Tanmoy Modak,[2,†] Rahul Srivastava,[3,‡] and José W. F. Valle[3,§]

[1]*Physik-Department T30d, Technische Universität München, James-Franck-Strasse, 85748 Garching, Germany*

[2]*Department of Physics, National Taiwan University, Taipei 10617, Taiwan*

[3]*AHEP Group, Institut de Física Corpuscular—C.S.I.C./Universitat de València, Parc Científic de Paterna. C/ Catedrático José Beltrán, 2 E-46980 Paterna (Valencia)—SPAIN*

(Received 29 September 2018; published 1 November 2018)

We present a simple $U(1)_{B_3-3L_2}$ gauge standard model extension that can easily account for the anomalies in $R(K)$ and $R(K^*)$ reported by LHCb. The model is economical in its setup and particle content. Among the standard model fermions, only the third generation quark family and the second generation leptons transform nontrivially under the new $U(1)_{B_3-3L_2}$ symmetry. This leads to lepton nonuniversality and flavor changing neutral currents involving the second and third quark families. We discuss the relevant experimental constraints and some implications.

DOI: 10.1103/PhysRevD.98.095002

I. INTRODUCTION

A host of increasingly sophisticated experiments over several decades has been able to thoroughly verify various predictions of the standard model of particle physics. These culminated with the discovery of the 125 GeV Higgs boson at the Large Hadron Collider (LHC) in 2012. Despite its amazing success, there are good reasons to think that the standard model may not be the ultimate theory. Apart from many theoretical shortcomings, the existence of neutrino mass suggests the existence of new physics, possibly in the electroweak-TeV range. By making very precise measurements of decay rates and angular observables, the LHCb Collaboration looks for the effect of new particles in various hadronic processes. Of particular interest to LHCb are the processes which are either forbidden or are extremely rare within the standard model. Since such processes may be allowed in new physics models, these searches can probe new physics models with good sensitivity, sometimes higher than attainable at the ATLAS and CMS experiments.

LHCb has recently announced anomalous measurements of $b \to s\mu^+\mu^-$ transitions [1]. They measured the ratio $R_{K^*} \equiv \mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)/\mathcal{B}(B^0 \to K^{*0}e^+e^-)$ as

$$R_{K^*}^{\rm expt} = \begin{cases} 0.660^{+0.110}_{-0.070}\ ({\rm stat}) \pm 0.024\ ({\rm syst}), & 0.045 \le q^2 \le 1.1\ {\rm GeV}^2, \\ 0.685^{+0.113}_{-0.069}\ ({\rm stat}) \pm 0.047\ ({\rm syst}), & 1.1 \le q^2 \le 6.0\ {\rm GeV}^2. \end{cases} \quad (1)$$

These measurements involve two ranges of q^2, the dilepton invariant squared mass. These numbers are very similar to the previous LHCb measurement of the ratio $R_K \equiv \mathcal{B}(B^+ \to K^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+e^+e^-)$ [2],

$$R_K^{\rm expt} = 0.745^{+0.090}_{-0.074}\ ({\rm stat}) \pm 0.036\ ({\rm syst}), \quad 1 \le q^2 \le 6.0\ {\rm GeV}^2, \quad (2)$$

These observations are also in tune with the so called P_5' anomaly observed in the angular variable P_5' of $B \to K^*\mu^+\mu^-$ decays [3–6]. In addition to these, LHCb has also observed several other anomalies all involving $b \to s$ transitions, such as $B_s \to \phi\mu^+\mu^-$ [7]. Specially remarkable is the fact that, although each individual result is not specially significant, all of the anomalies observed in $b \to s\mu^+\mu^-$ transitions form a coherent global picture [8–16].

At a basic level such rare transitions may be described by the effective Hamiltonian,

*cesar.bonilla@tum.de
†tanmoyy@hep1.phys.ntu.edu.tw
‡rahulsri@ific.uv.es
§valle@ific.uv.es

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}}\frac{e^2}{16\pi^2}V_{tb}V_{ts}^*\sum_i(\mathcal{C}_i(\Lambda)O_i(\Lambda)+\mathcal{C}_i'(\Lambda)O_i'(\Lambda)) \quad (3)$$

where $\mathcal{C}_i^{(\prime)} = C_i^{(\prime)\rm SM} + C_i^{(\prime)\rm NP}$. Here each coefficient is separated into a standard model (SM) part and a new physics contribution (NP). The relevant semileptonic operators required to account for the observed $b \to s\mu^+\mu^-$ anomalies are of the restricted type [17],

$$\mathcal{O}_9 = (\bar{s}\gamma_\alpha P_L b)(\bar{\ell}\gamma^\alpha \ell), \qquad \mathcal{O}_9' = (\bar{s}\gamma_\alpha P_R b)(\bar{\ell}\gamma^\alpha \ell)$$
$$\mathcal{O}_{10} = (\bar{s}\gamma_\alpha P_L b)(\bar{\ell}\gamma^\alpha\gamma_5 \ell), \qquad \mathcal{O}_{10}' = (\bar{s}\gamma_\alpha P_R b)(\bar{\ell}\gamma^\alpha\gamma_5 \ell).$$

In this paper we propose a consistent gauge model, constructed from first principles, that induces just one of the Wilson operators, $\mathcal{O}_9$. Its strength parameter can describe the observed $b \to s\mu^+\mu^-$ anomalies in agreement with all existing experimental restrictions. It provides a minimal way to account for the $b \to s\mu^+\mu^-$ discrepancies, while adding as few new particles and symmetries as possible: just a new $U(1)_{B_3-3L_2}$ gauge symmetry. In contrast to other alternative schemes, which typically require the addition of several new charged fermions[1] [20–41] or leptoquarks [42–52], all the anomalies induced by our $U(1)_{B_3-3L_2}$ gauge symmetry, including the gravitational ones, cancel without need for adding any new charged states. The only new fermions present are a pair of heavy vectorlike quarks $Q'_{L,R}$ and right handed neutrinos ν_R required in order to generate small neutrino masses through the type-I seesaw mechanism [53]. The only other new particles required are the Z' boson associated to the new gauge symmetry and new scalars involved in symmetry breaking, so as to generate mass for the Z' boson and neutrinos. The Z' boson mediates the anomalous $b \to s\mu^+\mu^-$ transitions.

The plan of the paper is as follows. In Sec. II we discuss the basics of the $U(1)_{B_3-3L_2}$ gauge model including the gauge and gauge-gravity anomaly cancellation conditions. We show that the model is free from anomalies. In Sec. III we summarize the main properties of the model and show that the flavor changing neutral currents (FCNC) mediated by the Z' boson have all the essential features required in order to account for the observed $b \to s\mu^+\mu^-$ discrepancies. In Sec. IV we discuss the various constraints on our model coming from flavor, collider and precision physics. We show that, after taking the relevant constraints into account, the model still has enough freedom to account for the observed anomalies in the B-system. Finally, our results are given in Fig. 1 and Sec. V and are summarized in Sec. VI.

[1]For Z' models without need of additional vector like quarks, see Refs. [18,19].

II. GAUGING THE $U(1)_{B_3-3L_2}$ SYMMETRY

In this section we discuss the details of the model. The $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ and $U(1)_{B_3-3L_2}$ charge assignments for the fermions and scalars are given in Table I, where $i = 1, 2$ labels the first two generations of quarks. Notice that apart from the "standard model-like" $SU(2)_L$ doublet scalar Φ_2, we also have added another $SU(2)_L$ doublet scalar Φ_1 which is also charged under the new $U(1)_{B_3-3L_2}$ symmetry. Notice that we have also included two $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ singlet scalars χ and σ which are also charged under the $U(1)_{B_3-3L_2}$ symmetry. As we will discuss shortly, the scalar χ is required to ensure that the model does not have a massless Nambu-Goldstone boson left after symmetry breaking. The scalar σ is needed in order to ensure a realistic pattern of neutrino masses and mixing that can describe oscillations. To induce the latter we also include, apart from the standard model fermions, three right handed neutrinos ν_{R_i} ($i = e, \mu, \tau$). Finally, we need the vector-like quarks Q'_L and Q'_R, transforming as $SU(2)_L$ doublets, and also carrying $U(1)_{B_3-3L_2}$ charges as shown in Tab. I.

In order for $U(1)_{B_3-3L_2}$ to be a consistent gauge symmetry it is important to ensure that the model is anomaly free. The $U(1)_{B_3-3L_2}$ symmetry can potentially induce the following triangular anomalies:

$$[SU(3)_c]^2U(1)_X \to \sum_q (X)_{q_L} - \sum_q (X)_{q_R} \quad (4)$$

$$[SU(2)_L]^2U(1)_X \to \sum_l (X)_{l_L} + 3\sum_q (X)_{q_L} \quad (5)$$

$$[U(1)_Y]^2U(1)_X \to \sum_{l,q}[Y_{l_L}^2(X)_{l_L} + 3Y_{q_L}^2(X)_{q_L}] - \sum_{l,q}[Y_{l_R}^2(X)_{l_R} + 3Yx_{q_R}^2(X)_{q_R}] \quad (6)$$

$$U(1)_Y[U(1)_X]^2 \to \sum_{l,q}[Y_{l_L}(X)_{l_L}^2 + 3Y_{q_L}(X)_{q_L}^2] - \sum_{l,q}[Y_{l_R}(X)_{l_R}^2 + 3Y_{q_R}(X)_{q_R}^2] \quad (7)$$

In addition we have anomaly conditions involving the $U(1)_{B_3-3L_2}$ just with itself and with gravity,

$$[U(1)_X]^3 \to \sum_{l,q}[(X)_{l_L}^3 + 3(X)_{q_L}^3] - \sum_{l,q}[(X)_{l_R}^3 + 3(X)_{q_R}^3] \quad (8)$$

$$[\text{Gravity}]^2[U(1)_X] \to \sum_{l,q}[(X)_{l_L} + 3(X)_{q_L}] - \sum_{l,q}[(X)_{l_R} + 3(X)_{q_R}] \quad (9)$$

TABLE I. Particle content and assignments. The singlet σ ensures a realistic pattern of neutrino oscillations [54].

Fields	$SU(3)_c\times SU(2)_L\times U(1)_Y$	$U(1)_{B_3-3L_2}$	Fields	$SU(3)_c\times SU(2)_L\times U(1)_Y$	$U(1)_{B_3-3L_2}$
Q_i	$(3,2,\frac{1}{3})$	0	L_e	$(1,2,-1)$	0
u_{R_i}	$(3,1,\frac{4}{3})$	0	e_R	$(1,1,-2)$	0
d_{R_i}	$(3,1,-\frac{2}{3})$	0	ν_{R_e}	(1,1,0)	x_1
Q_3	$(3,2,\frac{1}{3})$	1	L_μ	$(1,2,-1)$	-3
t_R	$(3,1,\frac{4}{3})$	1	μ_R	$(1,2,-1)$	-3
b_R	$(3,1,-\frac{2}{3})$	1	ν_{R_μ}	(1,1,0)	x_2
Q'_L	$(3,2,\frac{1}{3})$	1	L_τ	$(1,2,-1)$	0
Q'_R	$(3,2,\frac{1}{3})$	1	τ_R	$(1,1,-2)$	0
			ν_{R_τ}	(1,1,0)	x_3
Φ_1	$(1,2,-1)$	1	χ	(1,1,0)	y_1
Φ_2	(1,2,1)	0	σ	(1,1,0)	y_2

where $(X)_i$ denote the $U(1)_{B_3-3L_2}$ fermion charges. Using the assignments in Table. I, we find that the first four anomalies, i.e., Eqs. (4)–(7), cancel, irrespective of the charges of the right handed neutrinos. The anomaly cancellation conditions Eqs. (8) and (9) give the following two conditions on the $U(1)_{B_3-3L_2}$ charge of the right handed neutrinos

$$x_1^3+x_2^3+x_3^3=-27 \tag{10}$$

$$x_1+x_2+x_3=-3 \tag{11}$$

The only solution for Eq. (11) is given by

$$x_i=-3,\qquad x_j=-x_k. \tag{12}$$

This implies that under the $U(1)_{B_3-3L_2}$ symmetry, one of the right handed neutrinos should transform as -3 while the others can carry any arbitrary equal and opposite charge. For definiteness and keeping in mind simple scenarios of neutrino mass generation, we choose to assign the following charges to the right handed neutrinos:

$$\nu_{R_e}=\nu_{R_\tau}\sim 0,\qquad \nu_{R_\mu}\sim -3. \tag{13}$$

Also, we like to remark that the vectorlike nature of the additional quarks $Q'_{L,R}$ implies that the anomaly cancellation conditions do not fix their charges. Thus, they can have any charge under $U(1)_{B_3-3L_2}$ symmetry. However, for the sake of simplicity and keeping minimality in mind (see Goldstone boson discussion below) we set their charges to be 1, the same as the charges of the third generation of quarks.

Once the scalars get vacuum expectation values (vevs) the $SU(3)_C\otimes SU(2)_L\otimes U(1)_Y\otimes U(1)_{B_3-3L_2}$ symmetry is broken down to $U(1)_{\rm EM}$. Notice that, since only Φ_1,χ and σ are charged under the $U(1)_{B_3-3L_2}$ symmetry, the latter is broken only by the vevs of these scalars. Notice also that both standard model doublet scalars Φ_1 and Φ_2 contribute to the breaking of the $SU(3)_C\otimes SU(2)_L\otimes U(1)_Y$ symmetry.

The $U(1)_{B_3-3L_2}$ charges of the scalars are not fixed by anomaly cancellation conditions. But given the $U(1)_{B_3-3L_2}$ charges of all the fermions in the model, the charges of scalars can also be restricted by other considerations. The $U(1)_{B_3-3L_2}$ charge of the doublet scalar Φ_1 is fixed by requiring an adequate pattern of quark mixing consistent with experiments. The charge of singlet scalar χ is fixed by the requirement that if the $U(1)_{B_3-3L_2}$ charge of χ is not the same as the charge difference between Φ_1 and Φ_2, then the scalar potential will have a residual global $U(1)$ symmetry leading to a massless Goldstone boson. This can be avoided by taking

$$\chi\sim +1 \tag{14}$$

which provides a term in the scalar potential like $V\supset\kappa(\Phi_1^\dagger\Phi_2\chi+\text{H.c.})$, where κ is a dimensionful parameter. With these assignments for ν_{R_i}, Φ_1, Φ_2 and χ plus a scalar singlet σ, transforming as $\sigma\sim 3$, one also has a realistic pattern of neutrino mass and mixing.[2]

III. THE MODEL

Having satisfied the anomaly cancellation conditions we now turn to the scalar and Yukawa sectors of the model. As shown in Table I, except for the standard model-like Higgs scalar Φ_2, all other scalars are charged under the $U(1)_{B_3-3L_2}$ symmetry. Here our main focus is on explaining the anomaly, so we will skip the details of the scalar sector (fairly standard) in this work, and focus on the Lagrangian characterizing the Yukawa sector, which can be written as follows

[2] We stress that the above choice of ν_{R_i} charges under the $U(1)_{B_3-3L_2}$ symmetry is just the simplest one consistent with current neutrino oscillation data [54]. A detailed treatment of neutrino properties is outside the scope of this paper and will be addressed separately.

$$-\mathcal{L}_Y = y^u_{3j}\bar{Q}_3 u_j \Phi_1 + y^u_{4j}\bar{Q}'_L u_j \Phi_1 + y^u_{ij}\bar{Q}_i u_j \tilde{\Phi}_2 + y^u_{33}\bar{Q}_3 u_3 \tilde{\Phi}_2 + y^u_{43}\bar{Q}'_L u_3 \tilde{\Phi}_2 + y^d_{i3}\bar{Q}_i b_R \tilde{\Phi}_1 + y^d_{ij}\bar{Q}_i d_j \Phi_2 \\ + y^d_{33}\bar{Q}_3 d_3 \Phi_2 + y^d_{43}\bar{Q}'_L b_R \Phi_2 + y_{14}\bar{Q}_1 Q'_R \chi^* + y_{24}\bar{Q}_2 Q'_R \chi^* + \mu \bar{Q}_3 Q'_R + M_{Q'}\bar{Q}'_L Q'_R + \text{H.c.} \tag{15}$$

where $\tilde{\Phi} = i\tau_2 \Phi^*$ and $i,\ j = 1,\ 2$ represent the first two families. After spontaneous symmetry breaking the scalars acquire vevs $\langle \Phi_i \rangle = v_i;\ i = 1,\ 2,\ \langle \chi \rangle = v_\chi$ and $\langle \sigma \rangle = v_\sigma$. The resulting quark mass matrices in the basis $(\bar{Q}_1, \bar{Q}_2, \bar{Q}_3, \bar{Q}'_L)^T$ and (q_1, q_2, q_3, Q'_R) are given by

$$\mathcal{M}_d = \begin{pmatrix} y^d_{11}v_2 & y^d_{12}v_2 & y^d_{13}v_1 & y_{14}v_\chi \\ y^d_{21}v_2 & y^d_{22}v_2 & y^d_{23}v_1 & y_{24}v_\chi \\ 0 & 0 & y^d_{33}v_2 & \mu \\ 0 & 0 & y^d_{43}v_2 & M_{Q'} \end{pmatrix} \quad \text{and}$$

$$\mathcal{M}_u = \begin{pmatrix} y^u_{11}v_2 & y^u_{12}v_2 & 0 & y_{14}v_\chi \\ y^u_{21}v_2 & y^u_{22}v_2 & 0 & y_{24}v_\chi \\ y^u_{31}v_1 & y^u_{32}v_1 & y^u_{33}v_2 & \mu \\ y^u_{41}v_1 & y^u_{42}v_1 & y^u_{43}v_2 & M_{Q'} \end{pmatrix} \tag{16}$$

The resulting charged current weak interactions of quarks and leptons can be easily generated taking into account the mixing of standard model quarks with the new vectorlike quarks. The mass matrices of (16) have enough freedom to be able to generate the required Cabibbo-Kobayashi-Maskawa (CKM) mixing matrix of charged current interactions. However, the presence of vectorlike quarks charged under the $U(1)_{B_3-3L_2}$ symmetry leads to interesting implications for the neutral currents. Hence we focus here on the weak neutral current, mediated both by the standard model Z boson as well as the new Z'. Since the scalars Φ_1, χ and σ are all charged under $U(1)_{B_3-3L_2}$, their vevs break the $U(1)_{B_3-3L_2}$ symmetry and contribute to the Z' mass. Thus, in the limit in which $\langle \chi \rangle, \langle \sigma \rangle \gg v_1$ and taking negligible Z-Z' mixing, the neutral gauge boson masses are given by,

$$m^2_{Z'} \propto g'^2 u^2 \quad \text{and} \quad m^2_Z \propto (g^2_1 + g^2_2) v^2 \tag{17}$$

where g', g_1 and g_2 are the coupling constants of the $U(1)_{B_3-3L_2}$, $U(1)_Y$ and $SU(2)_L$ symmetries, respectively. The vevs of the doublet scalars $\langle \Phi_i \rangle = v_i$ $(i = 1, 2)$ satisfy $v^2 \equiv (174\ \text{GeV})^2 = v^2_1 + v^2_2$, whereas $u^2 \equiv v^2_\chi + 9v^2_\sigma + v^2_1$.

The key part of the theory in order to account for the B-decay anomaly is the neutral current. One can easily see that the standard model part of the neutral current, involving only Z boson interactions, is canonical, obeying the Glashow-Iliopoulos-Maiani mechanism. In contrast however, by construction, the neutral current Lagrangian associated with the Z' boson will give rise to flavor changing transitions, that is

$$-\mathcal{L}_{Z'} = g' Z'^\alpha J'^0_\alpha \\ = g' Z'^\alpha [-3\bar{\mu}\gamma_\alpha \mu + \bar{b}\gamma_\alpha b + \bar{t}\gamma_\alpha t - 3\bar{\nu}\gamma_\alpha \nu + \bar{Q}'\gamma_\alpha Q']. \tag{18}$$

From Eq. (18) it is clear that in our model, in the gauge basis, the Z' couples vectorially to the third generation standard model quarks and the second generation leptons. A chiral variant of this feature can also be obtained as in [55]. After spontaneous symmetry breaking the part associated to down-type quarks becomes

$$J'^0_\alpha \supset (\bar{d}\ \ \bar{s}\ \ \bar{b}\ \ \bar{Q}') D_L \gamma_\alpha \begin{pmatrix} 0&0&0&0 \\ 0&0&0&0 \\ 0&0&1&0 \\ 0&0&0&1 \end{pmatrix} D^\dagger_L \begin{pmatrix} d \\ s \\ b \\ Q' \end{pmatrix} \\ + (\bar{d}_R\ \ \bar{s}_R\ \ \bar{b}_R\ \ \bar{Q}') D_R \gamma_\alpha \begin{pmatrix} 0&0&0&0 \\ 0&0&0&0 \\ 0&0&1&0 \\ 0&0&0&1 \end{pmatrix} D^\dagger_R \begin{pmatrix} d_R \\ s_R \\ b_R \\ Q' \end{pmatrix},$$

where D_L is the rotation matrix that diagonalizes $\mathcal{M}^2_d = \mathcal{M}_d \mathcal{M}^\dagger_d$ (namely, $\text{diag}(m^2_d, m^2_s, m^2_b, M^2_{Q'}) = D_L \mathcal{M}^2_d D^\dagger_L$) and $D_R = \mathbb{I}$. The squared mass matrix for down-type quarks can be taken of the form,

$$\mathcal{M}^2_d \sim \begin{pmatrix} \times & 0 & 0 & \times \\ 0 & \times & 0 & \times \\ 0 & 0 & \times & \times \\ \times & \times & \times & \times \end{pmatrix} \quad \text{and hence}$$

$$D_L \sim \begin{pmatrix} 1 & 0 & 0 & V_{d4} \\ 0 & 1 & 0 & V_{s4} \\ 0 & 0 & 1 & V_{b4} \\ V_{4d} & V_{4s} & V_{4b} & 1 \end{pmatrix} \tag{19}$$

As a result, the interactions between Z' and the down-type quarks in the mass basis can be rewritten as follows

$$-\mathcal{L}'_{Z'} \supset g' Z'_\mu [\bar{d}'_a \gamma^\mu ((\Gamma_L)_{ab} P_L + (\Gamma_R)_{ab} P_R) d'_b] \tag{20}$$

where $d' = (d, s, b, Q')$,

$$\Gamma_L = \begin{pmatrix} |V_{4d}|^2 & V_{4d}V_{4s}^* & V_{4d}V_{4b}^* & V_{4d}V_{44}^* \\ V_{4s}V_{4d}^* & |V_{4s}|^2 & V_{4s}V_{4b}^* & V_{4s}V_{44}^* \\ V_{4b}V_{4d}^* & V_{4b}V_{4s}^* & 1-|V_{4b}|^2 & V_{4b}V_{44}^* \\ V_{44}V_{4d}^* & V_{44}V_{4s}^* & V_{44}V_{4b}^* & 1-|V_{44}|^2 \end{pmatrix} \quad \text{and}$$

$$\Gamma_R = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \tag{21}$$

One can see that our model implies that the $R(K)$ and $R(K^*)$ get modified only by the operator $\mathcal{O}_9$. Hence, $C_9'^{\rm NP} = C_{10}^{\rm NP} = C_{10}'^{\rm NP} = 0$. The associated strength parameter is given as

$$C_9^{\rm NP} = \left(\frac{8\pi^2 v^2}{e^2 \lambda_{bs}}\right)\left(\frac{3g'^2 \hat{\lambda}_{bs}}{m_{Z'}^2}\right) = -\frac{3\hat{\lambda}_{bs}}{\hat{\alpha}\lambda_{bs}}\left(\frac{g'}{m_{Z'}}\right)^2$$

where $\lambda_{bs} \equiv V_{tb}V_{ts}^*$, $\hat{\lambda}_{bs} \equiv V_{4b}V_{4s}^*$ and $\hat{\alpha} = e^2/(8\pi^2 v^2) \approx 1.9 \times 10^{-8}\ \text{GeV}^{-2}$. In what follows we show that our model not only qualitatively satisfies all requirements to explain the observed anomalies, but can also quantitatively explain them, satisfying all relevant experimental constraints. In our numerical computations in the next section we will work in the limit $|\hat{\lambda}_{bs}| \simeq |\lambda_{bs}| \sim \lambda_C^2$. Also, for a concrete benchmark we take V_{44}, $V_{4b} \sim 1$ and $V_{4s} \sim \lambda_C^2$. Furthermore, in order to avoid generating unacceptable K^0-$\bar{K}^0$ mixing we take $V_{4d} \sim 0$. In this limit Eq. (21) becomes

$$\Gamma_L \sim \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & \lambda_C^4 & \lambda_C^2 & \lambda_C^2 \\ 0 & \lambda_C^2 & 0 & 1 \\ 0 & \lambda_C^2 & 1 & 0 \end{pmatrix}. \tag{22}$$

In this approximation the Wilson coefficient turns out to be

$$C_9^{\rm NP} = -\frac{3}{\hat{\alpha}}\left(\frac{g'}{m_{Z'}}\right)^2. \tag{23}$$

Notice that the above choice constitutes just a simple benchmark of our model. The result in the last equation serves to illustrate in a simple manner that our model provides a successful way to account for the b-anomalies from first principles.

IV. EXPERIMENTAL CONSTRAINTS

Having shown that the flavor changing neutral current (FCNC) mediated by the Z' boson has the right form, we now turn to the experimental constraints on the two parameters, the Z' mass and coupling strength, relevant for describing in our model the anomalies recently observed in rare B decays.

A. B meson mixing

The existence of a nonzero $Z'bs$ coupling induces B_s-$\bar{B}_s$ mixing at the tree-level, resulting in very stringent limits on g' and $m_{Z'}$. Such a tree level Z' exchange modifies the B_s-$\bar{B}_s$ meson mixing amplitude M_{12}, which can be quantified as [56]

$$\frac{M_{12}}{M_{12}^{\rm SM}} = 1 + \frac{g'^2}{m_{Z'}^2}\left(\frac{g_2^2}{16\pi^2 v^2}(V_{ts}V_{tb}^*)^2 S_0\right)^{-1} \tag{24}$$

where g_2 is the $SU(2)_L$ gauge coupling and S_0 is Inami-Lim function with value $\simeq 2.3$ [57,58]. The mixing amplitude M_{12}, related to the mass difference by $\Delta m_{B_s^0} = 2|M_{12}|$ is measured precisely at per mill level [59], while the calculation of M_{12} suffers from several uncertainties. The two dominant sources of uncertainties are hadronic matrix element and CKM factor; the former is estimated by FLAG 2016 [60] as ~12%, while the latter is ~5% [61,62]. However, a recent accurate estimate provided by the Fermilab Lattice and MILC collaborations [63] has improved the hadronic uncertainty and pushed the FLAG average down to ~6%. Including such sources of uncertainties, CKMfitter constrains $|\frac{M_{12}}{M_{12}^{\rm SM}}| < 1.32$ [62] while UTfit $|\frac{M_{12}}{M_{12}^{\rm SM}}| < 1.28$ [61] at 2-standard-deviation (2σ). Note that the summer 2016 result [61] of UTfit includes the result of Ref. [63]. In order to constrain the parameter space of g' and $m_{Z'}$, we allow new physics contribution in $|\frac{M_{12}}{M_{12}^{\rm SM}}|$ up to 30% and 15%, which are displayed by the purple shaded region and purple dashed line in Fig. 1 respectively.[3]

B. Neutrino trident production

The production of a $\mu^+\mu^-$ pair in the scattering of a muon neutrino in the Coulomb field of a heavy nucleus, i.e., $\nu_\mu N \to \nu_\mu N \mu^+\mu^-$, provides a sensitive probe for g'. In our model the correction to the trident cross section can be expressed as [20]

$$\frac{\sigma^{\rm NP}}{\sigma^{\rm SM}} = \frac{1 + (4s_W^2 + 18v^2 g'^2/m_{Z'}^2)^2}{1 + (1 + 4s_W^2)^2} \tag{25}$$

where $v = 246$ GeV and $s_W = \sin\theta_W$. The measurement of the trident cross section by the CCFR collaboration is [65]

$$\frac{\sigma^{\rm CCFR}}{\sigma^{\rm SM}} = 0.82 \pm 0.28. \tag{26}$$

[3] See Ref. [64] for a more detailed discussion on the new physics contribution in $|\frac{M_{12}}{M_{12}^{\rm SM}}|$.

Utilizing Eqs. (25) and allowing 2σ error in $\frac{\sigma^{\rm CCFR}}{\sigma^{\rm SM}}$, we find the excluded region shown by the blue solid line in Fig. 1.

C. Lepton flavor universality in Z boson decay

The presence of $Z'\mu\mu$ and $Z'\nu_\mu\nu_\mu$ couplings will break lepton flavor universality (LFU) in Z boson decay. This is manifest in the Z boson couplings to muons and muon neutrinos through loop effects. The corrections to the vector and axial vector couplings of $Z\mu\mu$ coupling relative to the standard model-like Zee can be expressed as [20,66]

$$\frac{g_{V\mu}}{g_{Ve}} \simeq \frac{g_{A\mu}}{g_{Ae}} \simeq \left|1 + \frac{9g'^2}{(4\pi)^2}\kappa(m_{Z'})\right|; \tag{27}$$

and similarly for $Z\nu\nu$

$$\frac{g_{V\nu}}{g_{Ae}} = \frac{g_{A\nu}}{g_{Ae}} \simeq \left|1 + \frac{1}{3}\frac{9g'^2}{(4\pi)^2}\kappa(m_{Z'})\right| \tag{28}$$

where $\kappa(m_{Z'})$ is the loop factor associated with the Z' loop [67], whose real part is taken to match the convention of Ref. [68]. The factor $1/3$ in Eq. (28) accounts for the fact that out of three neutrino flavors only $Z \to \nu_\mu\bar{\nu}_\mu$ is affected by the Z'. The vector and axial vector couplings of Z boson in Eqs. (27) and (28) can be found from the average of 14 electroweak measurements in Ref. [68]. The relevant ones are: $g_{Ve} = -0.03816 \pm 0.00047$, $g_{Ae} = -0.50111 \pm 0.00035$, $g_{V\mu} = -0.0367 \pm 0.0023$, $g_{A\mu} = -0.50120 \pm 0.00054$ and $g_{V\nu} = g_{A\nu} = 0.5003 \pm 0.0012$. We find that $g_{A\mu}/g_{Ae} = 1.00018 \pm 0.00128$ provides the most stringent constraint, where the uncertainties are added in quadrature. The resulting 2σ upper limit on g' is shown by the red dashed line in Fig. 1.

D. Constraint from $Z \to 4\ell$

The ATLAS [69] and CMS [70] collaborations both have set upper limits on the branching ratio of the Z boson decay to four charged leptons. The ATLAS [69] analysis was performed with Run 1 data (7 TeV + 8 TeV), while CMS [70] utilized 13 TeV 35.9 fb^{-1} data to set the limit on $\mathcal{B}r(Z \to 4\ell)$. In particular, the observed value reported by Ref. [70] is $\mathcal{B}r(Z \to 4\mu) = (4.83^{+0.23}_{-0.22}\ (\text{stat})^{+0.32}_{-0.29}\ (\text{syst}) \pm 0.08\ (\text{theo}) \pm 0.12\ (\text{lumi})) \times 10^{-6}$, while the SM prediction is $(4.37 \pm 0.03) \times 10^{-6}$ [70].

In our model the $Z \to 4\ell$ decay will receive contributions from processes involving the Z' as the intermediate state, such as contribution from $Z \to \mu^+\mu^- Z'$ followed by $Z' \to \mu^+\mu^-$, resulting in stringent bound on g' for $m_{Z'} < m_Z$.

In order to determine the upper limit on g' from $\mathcal{B}r(Z \to 4\mu)$, we utilized the $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ prediction and observed value of Ref. [70], with the errors in the latter symmetrized and added in quadrature. The cross sections are generated in the Monte Carlo event generator MadGraph5_aMC@NLO [71], interfaced to PYTHIA 6.4 [72] for hadronization and showering and finally fed into fast detector simulator Delphes 3.3.3 [73] so as to incorporate detector effects. In our analysis we adopt the PDF set NN23LO1 PDF [74]. The effective Lagrangians written in Eqs. (18) and (20) are implemented in FEYNRULES 2.0 [75]. Following the analysis of Ref. [70], we select events with four isolated muons with two opposite sign same flavor dimuon pairs. The muons in the quadruplet are required to be separated by $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} > 0.02$, with each of them having maximum pseudorapidity $|\eta| < 2.5$. The two leading muons in an event should have transverse momenta $p_T > 20$ GeV and 15 GeV respectively, while the other two muons are required to have $p_T > 5$ GeV. The four muons will constitute two same flavor oppositely charged muon pairs in an event. The pair closest to the Z boson mass should have invariant mass > 40 GeV and both pairs should have invariant mass < 120 GeV. All pairs of oppositely charged muons must have invariant mass > 4 GeV. We finally impose an invariant mass cut 80 GeV $< m_{4\mu} <$ 100 GeV on the four muons in the event. Finally, demanding the SM plus NP contribution i.e., the total contribution from $Z' \to \mu^+\mu^-$ not to exceed the 2σ error, we overlay the solid red line (2σ upper limit) in the left panel of Fig. 1. The limits from Ref. [69] are weaker than those of Ref. [70], which we do not show in Fig. 1.

E. Constraint from $pp \to Z' + X \to \mu^+\mu^- + X$

The Z' boson will be produced at LHC predominantly by the flavor conserving $b\bar{b} \to Z'$ processes with a correction from flavor violating $s\bar{b} \to Z'$ (and its conjugate process). Hence, the search for heavy resonances in the dimuon final state by the ATLAS and CMS collaborations will constrain the parameter space of our model. In particular ATLAS [76] has set a 95% CL (confidence level) upper limit on $\sigma(pp \to Z' + X)\mathcal{B}r(Z' \to \mu^+\mu^-)$ in the 150 GeV $\lesssim m_{Z'} \lesssim$ 5 TeV mass range with the 13 TeV and 36.1 fb^{-1} data set, where X conforms inclusive activity. CMS [77] has also searched for heavy resonances decaying to dimuon pair in the mass range 200 GeV $\lesssim m_{Z'} \lesssim$ 5.5 TeV with 13 TeV, also with $\sim$36 fb^{-1} data set, setting a 95% CL upper limit on R_σ defined as:

$$R_\sigma = \frac{\sigma(pp \to Z' + X \to \mu^+\mu^- + X)}{\sigma(pp \to Z + X \to \mu^+\mu^- + X)}. \tag{29}$$

We reinterpret R_σ and extract $\sigma(pp \to Z' + X)\mathcal{B}r(Z' \to \mu^+\mu^-)$ by multiplying with the standard model prediction of $\sigma(pp \to Z + X)\mathcal{B}r(Z \to \mu^+\mu^-) = 1928.0$ pb [78].

In order to determine the upper limit, we generate matrix element (ME) of the $pp \to Z'$ process up to two additional jets in the final state to include inclusive contributions. The ME is then merged and matched with parton shower (PS)

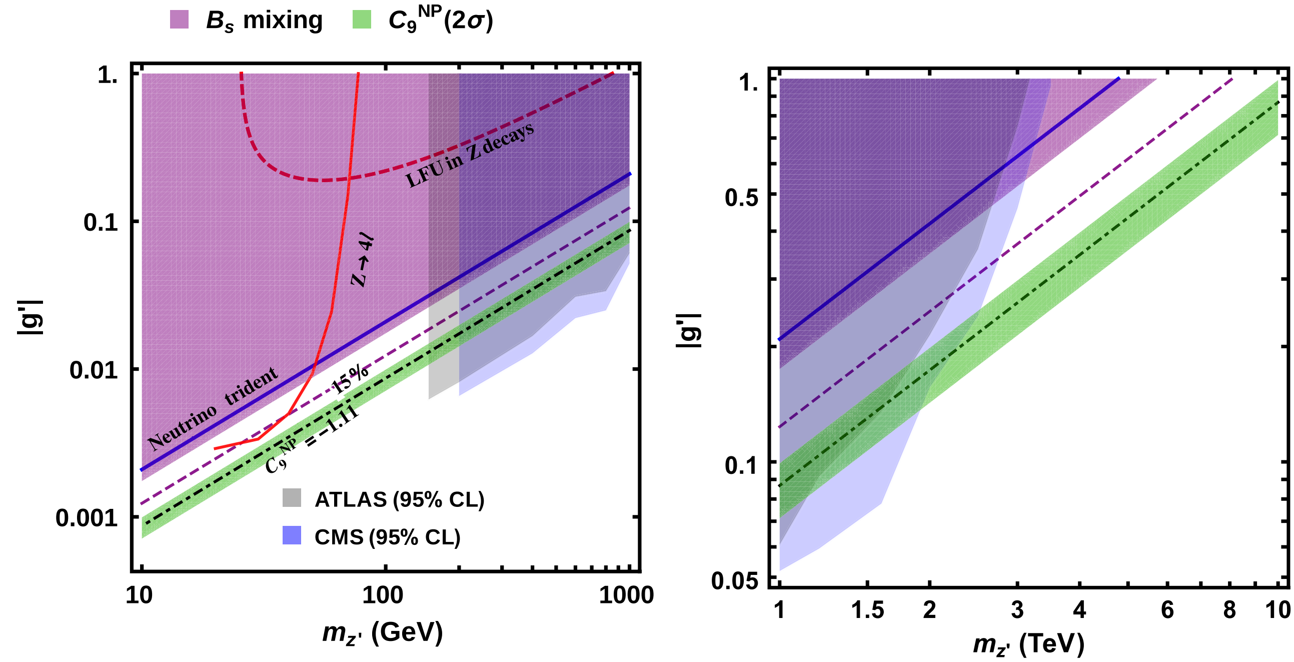

FIG. 1. Allowed region in g' vs $m_{Z'}$ obtained from the simplified parameter benchmark choice made in Eqs. (19)–(22). See text for detailed explanation of the constraints as well as their color code description.

following the MLM [79] matching prescription. We restrict ourselves up to two additional jets due to computational limitations. It should be noted that we have not used any K factor in our analysis. We finally convert the observed ATLAS (CMS) 95% CL upper limit on $\sigma(pp\to Z'+X)$ $\mathcal{B}r(Z'\to\mu^+\mu^-)$ to constraint g' and $m_{Z'}$ in the mass range $150\,\mathrm{GeV}<m_{Z'}<5\,\mathrm{TeV}$ $(200\,\mathrm{GeV}<m_{Z'}<5.5\,\mathrm{TeV})$ which is shown by the black (light-blue) shaded region in Fig. 1.

V. RESULTS

We now discuss the constraints on the coupling g' and mass $m_{Z'}$ in our model, which is summarized in Fig. 1.

The region of coupling-mass ($g'-m_{Z'}$) allowed by the various flavour and collider physics constraints are divided into two ranges indicated in Fig. 1. The left panel corresponds to the case of light ($m_{Z'}<1$ TeV) masses, while the heavy mass range (1 TeV $<m_{Z'}<10$ TeV) Z' is shown in the right panel. In order to find the allowed parameter space which describes the observed anomalies in $b\to s\ell\ell$ transition, we follow the global-fit analysis presented in Ref. [8]. The analysis uses all available $b\to s\ell\ell$ data from LHCb, ATLAS, CMS and Belle, with the best fit value $\mathrm{Re}C_9^{\mathrm{NP}}=-1.11$, and 2σ range

$$-1.45\le \mathrm{Re}C_9^{\mathrm{NP}}\le -0.75. \tag{30}$$

Utilizing Eq. (23), the 2σ allowed region of $\mathrm{Re}C_9$ is translated into g' vs $m_{Z'}$ plane, and shown by the green shaded region in Fig. 1, while the central value $\mathrm{Re}C_9^{\mathrm{NP}}=-1.11$ is shown by black dot-dashed line. Note that the authors of Ref. [8] also present results taking into account only lepton-flavor universality observables, such as $R_{K^{(*)}}$ etc., which we do not display in Fig. 1 for simplicity. Although in our analysis we have only utilized the global fit values from Ref. [8], there exist other global-fit analyses based on the effective Hamiltonian formalism (see e.g., Refs. [9–15]), which can also be used with similar results as displayed in Fig. 1. The resulting allowed regions are indeed very similar, with a significant overlap region.[4]

We have also studied all relevant constraints from flavor physics as well as from LEP precision observables [68] and direct searches at the LHC [70,76,77]. The most relevant LEP constraint from these decays is shown by red dashed line in Fig. 1. The region above the red dashed line is excluded by LFU in Z boson decay. The ATLAS collaboration [69] has also looked for the decay $Z\to 4\mu$ which in our model is mediated by the Z'. This places a constraint on our model parameter space, shown by the solid red line (the region above the line is ruled out). The most stringent limits for $m_{Z'}<150$ GeV come from B_s mixing [62,81], which is shown by the purple shaded region in both figures; except for 25 GeV $\lesssim m_{Z'}\lesssim$ 40 GeV where constraint from $Z\to 4\mu$ becomes strongest.

In the region 150 GeV $\lesssim m_{Z'}\lesssim$ 2.2 TeV the constraint from B_s mixing is superseded by the search for heavy Z' boson in the dimuon final state by the ATLAS [76] and

[4]There are other observables like P_5', derived in a model independent way from $B\to K^*\mu^+\mu^-$ decay [80], which indicate new physics contribution in the right handed current.

CMS collaborations [77]. The black shaded region in Fig. 1 is excluded by ATLAS, while the light-blue shaded region is ruled out by CMS. In general, limits from CMS [77] are a bit stronger than those of ATLAS [76]; except for 150 GeV $\lesssim m_{Z'} \lesssim 200$ GeV, where CMS provides no result. One sees that the direct search limits from ATLAS and CMS rule out a simultaneous explanation of all $b \to s$ transition anomalies for Z' masses in the range from 150 GeV $\lesssim m_{Z'} \lesssim 2.2$ TeV, leaving however the possibility for discovery in the range $m_{Z'} \lesssim 150$ GeV and $m_{Z'} \gtrsim 2.2$ TeV.[5] We also mention that low-energy experiments also set severe constraints on the model. For example, the constraint from neutrino trident production is shown by the solid blue line, with region above it excluded [20,65]. In addition, the decay $B \to K^{(*)}\nu\bar{\nu}$ [82] can also constrain the model parameters, though we find that the limits on g' are weaker and we do not display them in Fig. 1. Finally, another potentially strong constraint can come from D^0-$\bar{D}^0$ mixing [83]. However, we have checked that for our choice of benchmark point the limits coming from this constraint are weaker and hence not displayed in Fig. 1.

VI. CONCLUSIONS

In this paper we have presented a rather simple anomaly free $U(1)_{B_3-3L_2}$ standard model extension that can account for the recent anomalies in $b \to s\ell\ell$ transitions reported by the LHCb collaboration. The model is minimalistic both in its setup as well as particle content. Amongst the standard model quarks and leptons, only the third generation quark family and the second generation leptons transform nontrivially under our new postulated $U(1)_{B_3-3L_2}$ symmetry. This leads to a very simple pattern for lepton nonuniversality and flavor changing neutral currents involving the second and third families which reproduces the LHCb findings in a way consistent with all the relevant experimental constraints, except for the range from 150 GeV up to ~2.2 TeV, where the understanding of the $B \to K^{(*)}$ anomaly reported by LHCb would clash with the direct searches in the dimuon channel by the ATLAS and CMS collaborations. One should also stress, as seen in left panel of Figs. 1, that the Z' associated to our $U(1)_{B_3-3L_2}$ symmetry can be as light as 10 GeV, in contrast to Z's associated to other gauge extensions based on B-L [84,85] or 331 theories [86,87]. As a last comment, we mention that, throughout the paper, we have assumed dominance of the vector boson mediated neutral current contribution, neglecting all the scalars. We checked that, indeed, there is a realistic limit in parameters space where this can be achieved.

[5]See Ref. [64] for the details on how a Z', if it were confirmed in the near future, could be associated to $b \to s\ell\ell$ anomalies.

ACKNOWLEDGMENTS

We thank Avelino Vicente, Masaya Kohda and Amol Dighe for useful comments and discussions. Work supported by the Spanish Grants No. SEV-2014-0398 and No. FPA2017-85216-P (AEI/FEDER, UE), PROMETEO/2018/165 (Generalitat Valenciana) and the Spanish Red Consolider MultiDark FPA201790566REDC. C. B. acknowledges financial support from the Collaborative Research Center SFB1258. The work of T. M. is supported by MOST-104-2112-M-002-017-MY2.

[1] R. Aaij *et al.* (LHCb Collaboration), Test of lepton universality with $B^0 \to K^{*0}\ell^+\ell^-$ decays, J. High Energy Phys. 08 (2017) 055.

[2] R. Aaij *et al.* (LHCb Collaboration), Test of Lepton Universality Using $B^+ \to K^+\ell^+\ell^-$ Decays, Phys. Rev. Lett. **113**, 151601 (2014).

[3] S. Descotes-Genon, J. Matias, M. Ramon, and J. Virto, Implications from clean observables for the binned analysis of $B-> K*\mu^+\mu^-$ at large recoil, J. High Energy Phys. 01 (2013) 048.

[4] R. Aaij *et al.* (LHCb Collaboration), Measurement of Form-Factor-Independent Observables in the Decay $B^0 \to K^{*0}\mu^+\mu^-$, Phys. Rev. Lett. **111**, 191801 (2013).

[5] A. Abdesselam *et al.* (Belle Collaboration), Angular analysis of $B^0 \to K^*(892)^0\ell^+\ell^-$, in *Proceedings, LHCSki 2016-A First Discussion of 13 TeV Results: Obergurgl, Austria, 2016* (2016), https://inspirehep.net/record/1446979/files/arXiv:1604.04042.pdf.

[6] S. Wehle *et al.* (Belle Collaboration), Lepton-Flavor-Dependent Angular Analysis of $B \to K^*\ell^+\ell^-$, Phys. Rev. Lett. **118**, 111801 (2017).

[7] R. Aaij *et al.* (LHCb Collaboration), Angular analysis and differential branching fraction of the decay $B_s^0 \to \phi\mu^+\mu^-$, J. High Energy Phys. 09 (2015) 179.

[8] B. Capdevila, A. Crivellin, S. Descotes-Genon, J. Matias, and J. Virto, Patterns of new physics in $b \to s\ell^+\ell^-$ transitions in the light of recent data, J. High Energy Phys. 01 (2018) 093.

[9] W. Altmannshofer, P. Stangl, and D. M. Straub, Interpreting Hints for Lepton Flavor Universality Violation, Phys. Rev. D **96**, 055008 (2017).

[10] G. D'Amico, M. Nardecchia, P. Panci, F. Sannino, A. Strumia, R. Torre, and A. Urbano, Flavour anomalies after the R_{K^*} measurement, J. High Energy Phys. 09 (2017) 010.

[11] G. Hiller and I. Nisandzic, R_K and R_{K^*} beyond the standard model, Phys. Rev. D **96**, 035003 (2017).
[12] L.-S. Geng, B. Grinstein, S. Jäger, J. M. Camalich, X.-L. Ren, and R.-X. Shi, Towards the discovery of new physics with lepton-universality ratios of $b \to s\ell\ell$ decays, Phys. Rev. D **96**, 093006 (2017).
[13] M. Ciuchini, A. M. Coutinho, M. Fedele, E. Franco, A. Paul, L. Silvestrini, and M. Valli, On flavourful easter eggs for new physics hunger and lepton flavour universality violation, Eur. Phys. J. C **77**, 688 (2017).
[14] A. Celis, J. Fuentes-Martin, A. Vicente, and J. Virto, Gauge-invariant implications of the LHCb measurements on lepton-flavor nonuniversality, Phys. Rev. D **96**, 035026 (2017).
[15] T. Hurth, F. Mahmoudi, D. Martinez Santos, and S. Neshatpour, Lepton nonuniversality in exclusive $b \to s\ell\ell$ decays, Phys. Rev. D **96**, 095034 (2017).
[16] A. K. Alok, B. Bhattacharya, A. Datta, D. Kumar, J. Kumar, and D. London, New physics in $b \to s\mu^+\mu^-$ after the measurement of R_{K^*}, Phys. Rev. D **96**, 095009 (2017).
[17] S. Descotes-Genon, J. Matias, and J. Virto, Understanding the $B \to K^*\mu^+\mu^-$ anomaly, Phys. Rev. D **88**, 074002 (2013).
[18] A. Crivellin, G. D'Ambrosio, and J. Heeck, Addressing the LHC flavor anomalies with horizontal gauge symmetries, Phys. Rev. D **91**, 075006 (2015).
[19] D. Bhatia, S. Chakraborty, and A. Dighe, Neutrino mixing and R_K anomaly in $U(1)_X$ models: A bottom-up approach, J. High Energy Phys. 03 (2017) 117.
[20] W. Altmannshofer, S. Gori, M. Pospelov, and I. Yavin, Quark flavor transitions in $L_\mu - L_\tau$ models, Phys. Rev. D **89**, 095033 (2014).
[21] W. Altmannshofer, S. Gori, S. Profumo, and F. S. Queiroz, Explaining dark matter and B decay anomalies with an $L_\mu - L_\tau$ model, J. High Energy Phys. 12 (2016) 106.
[22] A. Crivellin, L. Hofer, J. Matias, U. Nierste, S. Pokorski, and J. Rosiek, Lepton-flavour violating B decays in generic Z' models, Phys. Rev. D **92**, 054013 (2015).
[23] D. A. Sierra, F. Staub, and A. Vicente, Shedding light on the $b \to s$ anomalies with a dark sector, Phys. Rev. D **92**, 015001 (2015).
[24] A. Carmona and F. Goertz, Lepton Flavor and Nonuniversality from Minimal Composite Higgs Setups, Phys. Rev. Lett. **116**, 251801 (2016).
[25] P. Ko, T. Nomura, and H. Okada, A flavor dependent gauge symmetry, Predictive radiative seesaw and LHCb anomalies, Phys. Lett. B **772**, 547 (2017).
[26] R. Gauld, F. Goertz, and U. Haisch, An explicit Z'-boson explanation of the $B \to K^*\mu^+\mu^-$ anomaly, J. High Energy Phys. 01 (2014) 069.
[27] J. F. Kamenik, Y. Soreq, and J. Zupan, Lepton flavor universality violation without new sources of quark flavor violation, Phys. Rev. D **97**, 035002 (2018).
[28] R. Gauld, F. Goertz, and U. Haisch, On minimal Z' explanations of the $B \to K^*\mu^+\mu^-$ anomaly, Phys. Rev. D **89**, 015005 (2014).
[29] A. Crivellin, G. D'Ambrosio, and J. Heeck, Explaining $h \to \mu^\pm\tau^\mp$, $B \to K^*\mu^+\mu^-$ and $B \to K\mu^+\mu^-/B \to Ke^+e^-$ in a Two-Higgs-Doublet Model with Gauged $L_\mu - L_\tau$, Phys. Rev. Lett. **114**, 151801 (2015).
[30] W.-S. Hou, M. Kohda, and T. Modak, Search for tZ' associated production induced by tcZ' couplings at the LHC, Phys. Rev. D **96**, 015037 (2017).
[31] K. Fuyuto, W.-S. Hou, and M. Kohda, Z-induced FCNC decays of top, beauty, and strange quarks, Phys. Rev. D **93**, 054021 (2016).
[32] B. Allanach, F. S. Queiroz, A. Strumia, and S. Sun, Z models for the LHCb and $g - 2$ muon anomalies, Phys. Rev. D **93**, 055045 (2016).
[33] A. Celis, W.-Z. Feng, and M. Vollmann, Dirac dark matter and $b \to s\ell^+\ell^-$ with U(1) gauge symmetry, Phys. Rev. D **95**, 035018 (2017).
[34] S. M. Boucenna, A. Celis, J. Fuentes-Martín, A. Vicente, and J. Virto, Non-abelian gauge extensions for B-decay anomalies, Phys. Lett. B **760**, 214 (2016).
[35] S. M. Boucenna, A. Celis, J. Fuentes-Martín, A. Vicente, and J. Virto, Phenomenology of an $SU(2) \times SU(2) \times U(1)$ model with lepton-flavour non-universality, J. High Energy Phys. 12 (2016) 059.
[36] A. Falkowski, M. Nardecchia, and R. Ziegler, Lepton flavor non-universality in B-meson decays from a U(2) flavor model, J. High Energy Phys. 11 (2015) 173.
[37] A. Celis, J. Fuentes-Martin, M. Jung, and H. Serodio, Family nonuniversal Z models with protected flavor-changing interactions, Phys. Rev. D **92**, 015007 (2015).
[38] G. Belanger, C. Delaunay, and S. Westhoff, A dark matter relic from muon anomalies, Phys. Rev. D **92**, 055021 (2015).
[39] C.-W. Chiang, X.-G. He, and G. Valencia, Z model for bs flavor anomalies, Phys. Rev. D **93**, 074003 (2016).
[40] E. Megias, G. Panico, O. Pujolas, and M. Quiros, A natural origin for the LHCb anomalies, J. High Energy Phys. 09 (2016) 118.
[41] W. S. Hou, M. Kohda, and T. Modak, Unraveling the couplings of a Drell-Yan produced Z' with heavy-flavor tagging, Phys. Rev. D **98**, 015002 (2018).
[42] R. Alonso, B. Grinstein, and J. Martin Camalich, Lepton universality violation and lepton flavor conservation in B-meson decays, J. High Energy Phys. 10 (2015) 184.
[43] D. Beirevi, S. Fajfer, N. Konik, and O. Sumensari, Leptoquark model to explain the B-physics anomalies, R_K and R_D, Phys. Rev. D **94**, 115021 (2016).
[44] S. Fajfer and N. Konik, Vector leptoquark resolution of R_K and $R_{D^{(*)}}$ puzzles, Phys. Lett. B **755**, 270 (2016).
[45] D. Beirevi and O. Sumensari, A leptoquark model to accommodate $R_K^{\rm exp} < R_K^{\rm SM}$ and $R_{K^*}^{\rm exp} < R_{K^*}^{\rm SM}$, J. High Energy Phys. 08 (2017) 104.
[46] B. Gripaios, M. Nardecchia, and S. A. Renner, Composite leptoquarks and anomalies in B-meson decays, J. High Energy Phys. 05 (2015) 006.
[47] S. Sahoo and R. Mohanta, Scalar leptoquarks and the rare B meson decays, Phys. Rev. D **91**, 094019 (2015).
[48] Y. Cai, J. Gargalionis, M. A. Schmidt, and R. R. Volkas, Reconsidering the one Leptoquark solution: Flavor anomalies and neutrino mass, J. High Energy Phys. 10 (2017) 047.
[49] A. Crivellin, D. Mller, and T. Ota, Simultaneous explanation of $R(D^{(*)})$ and $b \to s\mu^+\mu^-$: The last scalar leptoquarks standing, J. High Energy Phys. 09 (2017) 040.

[50] C.-H. Chen, T. Nomura, and H. Okada, Excesses of muon $g-2$, $R_{D^{(*)}}$, and R_K in a leptoquark model, Phys. Lett. B **774**, 456 (2017).

[51] C.-H. Chen, T. Nomura, and H. Okada, Explanation of $B \to K^{(*)}\ell^+\ell^-$ and muon $g-2$, and implications at the LHC, Phys. Rev. D **94**, 115005 (2016).

[52] G. Hiller, D. Loose, and K. Schnwald, Leptoquark flavor patterns & B decay anomalies, J. High Energy Phys. 12 (2016) 027.

[53] J. W. F. Valle and J. C. Romao, *Neutrinos in High Energy and Astroparticle Physics*, 1st ed. (Wiley-VCH, Berlin 2015).

[54] D. Forero, M. Tortola, and J. W. F. Valle, Neutrino oscillations refitted, Phys. Rev. D **90**, 093006 (2014); P. F. de Salas, D. V. Forero, C. A. Ternes, M. Tórtola, and J. W. F. Valle, Status of neutrino oscillations 2018: 3σ hint for normal mass ordering and improved CP sensitivity, Phys. Lett. B **782**, 633 (2018).

[55] J. M. Cline, J. M. Cornell, D. London, and R. Watanabe, Hidden sector explanation of B-decay and cosmic ray anomalies, Phys. Rev. D **95**, 095015 (2017).

[56] A. J. Buras, F. De Fazio, and J. Girrbach-Noe, Z-Z' mixing and Z-mediated FCNCs in $SU(3)_C \times SU(3)_L \times U(1)_X$ models, J. High Energy Phys. 08 (2014) 039.

[57] A. Lenz, U. Nierste, J. Charles, S. Descotes-Genon, A. Jantsch, C. Kaufhold, H. Lacker, S. Monteil, V. Niess, and S. T'Jampens, Anatomy of new physics in B-$\bar{B}$ mixing, Phys. Rev. D **83**, 036004 (2011).

[58] A. J. Buras, F. De Fazio, and J. Girrbach, The anatomy of Z' and Z with flavour changing neutral currents in the flavour precision era, J. High Energy Phys. 02 (2013) 116.

[59] C. Patrignani *et al.* (Particle Data Group), Review of particle physics, Chin. Phys. C **40**, 100001 (2016).

[60] S. Aoki *et al.*, Review of lattice results concerning low-energy particle physics, Eur. Phys. J. C **77**, 112 (2017).

[61] M. Bona *et al.* (UTfit Collaboration), Constraints on New Physics from the Quark Mixing Unitarity Triangle, Phys. Rev. Lett. **97**, 151803 (2006); Model-independent constraints on $\Delta F = 2$ operators and the scale of new physics, J. High Energy Phys. 03 (2008) 049.

[62] J. Charles *et al.*, Current status of the Standard Model CKM fit and constraints on $\Delta F = 2$ new physics, Phys. Rev. D **91**, 073007 (2015).

[63] A. Bazavov *et al.* (Fermilab Lattice and MILC Collaborations), $B^0_{(s)}$-mixing matrix elements from lattice QCD for the Standard Model and beyond, Phys. Rev. D **93**, 113016 (2016).

[64] M. Kohda, T. Modak, and A. Soffer, Identifying a Z' behind $b \to s\ell\ell$ anomalies at the LHC, Phys. Rev. D **97**, 115019 (2018).

[65] S. R. Mishra *et al.* (CCFR Collaboration), Neutrino Tridents and W Z Interference, Phys. Rev. Lett. **66**, 3117 (1991).

[66] W. Altmannshofer, C.-Y. Chen, P. S. Bhupal Dev, and A. Soni, Lepton flavor violating Z' explanation of the muon anomalous magnetic moment, Phys. Lett. B **762**, 389 (2016).

[67] U. Haisch and S. Westhoff, Massive color-octet bosons: Bounds on effects in top-quark pair production, J. High Energy Phys. 08 (2011) 088.

[68] S. Schael *et al.* (ALEPH, DELPHI, L3, OPAL, SLD Collaborations, LEP Electroweak Working Group, SLD Electroweak and Heavy Flavour Groups), Precision electroweak measurements on the Z resonance, Phys. Rep. **427**, 257 (2006).

[69] ATLAS collaboration, ATLAS measurements of the 7 and 8 TeV cross sections for $Z \to 4\ell$ in pp collisions, CERN Report No. ATLAS-CONF-2013-055, 2013.

[70] A. M. Sirunyan *et al.* (CMS Collaboration), Measurements of the $pp \to ZZ$ production cross section and the $Z \to 4\ell$ branching fraction, and constraints on anomalous triple gauge couplings at $\sqrt{s} = 13$ TeV, Eur. Phys. J. C **78**, 165 (2018); Erratum, Eur. Phys. J. C**78**, 515(E) (2018).

[71] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H.-S. Shao, T. Stelzer, P. Torrielli, and M. Zaro, The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations, J. High Energy Phys. 07 (2014) 079.

[72] T. Sjöstrand, S. Mrenna, and P. Z. Skands, Pythia 6.4 physics and manual, J. High Energy Phys. 05 (2006) 026.

[73] J. de Favereau, C. Delaere, P. Demin, A. Giammanco, V. Lemaître, A. Mertens, and M. Selvaggi (DELPHES 3 Collaboration), DELPHES 3, A modular framework for fast simulation of a generic collider experiment, J. High Energy Phys. 02 (2014) 057.

[74] R. D. Ball, V. Bertone, S. Carrazza, L. Del Debbio, S. Forte, A. Guffanti, N. P. Hartland, and J. Rojo (NNPDF Collaboration), Parton distributions with QED corrections, Nucl. Phys. **B877**, 290 (2013).

[75] A. Alloul, N. D. Christensen, C. Degrande, C. Duhr, and B. Fuks, FeynRules 2.0–A complete toolbox for tree-level phenomenology, Comput. Phys. Commun. **185**, 2250 (2014).

[76] M. Aaboud *et al.* (ATLAS Collaboration), Search for new high-mass phenomena in the dilepton final state using 36 fb?1 of proton-proton collision data at ($\sqrt{s} = 13$ TeV with the ATLAS detector, J. High Energy Phys. 10 (2017) 182.

[77] A. M. Sirunyan *et al.* (CMS Collaboration), Search for high-mass resonances in dilepton final states in proton-proton collisions at $\sqrt{s} = 13$ TeV, J. High Energy Phys. 06 (2018) 120.

[78] CMS Collaboration, Search for a narrow resonance produced in 13 TeV pp collisions decaying to electron pair or Muon pair final states, CERN, Report No. CMS-PAS-EXO-15-005, 2015.

[79] J. Alwall *et al.*, Comparative study of various algorithms for the merging of parton showers and matrix elements in hadronic collisions, Eur. Phys. J. C **53**, 473 (2008).

[80] R. Mandal and R. Sinha, Implications from $B \to K^*\ell^+\ell^-$ observables using 3 fb^{-1} of LHCb data, Phys. Rev. D **95**, 014026 (2017).

[81] Y. Amhis *et al.* (Heavy Flavor Averaging Group), Averages of b-hadron, c-hadron, and τ-lepton properties as of summer 2014, arXiv:1412.7515.

[82] A. J. Buras, J. Girrbach-Noe, C. Niehoff, and D. M. Straub, $B \to K^{(*)}\nu\bar{\nu}$ decays in the standard model and beyond, J. High Energy Phys. 02 (2015) 184.
[83] J. Kumar, D. London, and R. Watanabe, Combined explanations of the $b \to s\mu^+\mu^-$ and $b \to c\tau^-\bar{\nu}$ anomalies: A general model analysis, arXiv:1806.07403.
[84] S. Das, F. Deppisch, O. Kittel, and J. W. F. Valle, Heavy neutrinos and lepton flavour violation in left-right symmetric models at the LHC, Phys. Rev. D **86**, 055006 (2012).
[85] E. Ma, N. Pollard, R. Srivastava, and M. Zakeri, Gauge *B-L* model with residual Z_3 symmetry, Phys. Lett. B **750**, 135 (2015).
[86] F. F. Deppisch, N. Desai, and J. W. F. Valle, Is charged lepton flavour violation a high energy phenomenon?, Phys. Rev. D **89**, 051302(R) (2014).
[87] F. S. Queiroz, C. Siqueira, and J. W. F. Valle, Constraining flavor changing interactions from LHC Run-2 dilepton bounds with vector mediators, Phys. Lett. B **763**, 269 (2016).