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Non-abelian gauge extensions for B-decay anomalies

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ABSTRACT

We study the generic features of minimal gauge extensions of the Standard Model in view of recent hints of lepton-flavor non-universality in semi-leptonic $b \to s\ell^+\ell^-$ and $b \to c\ell\nu$ decays. We classify the possible models according to the symmetry-breaking pattern and the source of flavor non-universality. We find that in viable models the $SU(2)_L$ factor is embedded non-trivially in the extended gauge group, and that gauge couplings should be universal, hinting to the presence of new degrees of freedom sourcing non-universality. Finally, we provide an explicit model that can explain the B-decay anomalies in a coherent way and confront it with the relevant phenomenological constraints.

1. Introduction

Low-energy experiments have been crucial in the development of the current Standard Model (SM) of electroweak interactions, based on the gauge group $SU(2)_L \otimes U(1)_Y$. The structure of the SM electroweak theory was beautifully revealed by a large variety of experimental observations at low energy, together with requirements of a proper high-energy behavior of the theory. In particular, the intermediate vector bosons $W^\pm$, Z were predicted theoretically before their experimental discovery. Precision experiments at low energies continue providing important information about the possible ultraviolet (UV) completions of the SM, and New Physics (NP) might be revealed again first through the precision frontier.

Currently there are two sets of interesting tensions in B-physics data:

1. In 2012 the BaBar Collaboration reported deviations from lepton universality at the 25% level in the exclusive semileptonic $b \to c$ decays, through a measurement of the ratios

$$R(D) = \frac{\Gamma(B \to D\tau\nu)}{\Gamma(B \to D\ell\nu)} \overset{\text{SM}}{=} 0.297 \pm 0.017\,, \tag{1}$$

$$R(D^*) = \frac{\Gamma(B \to D^*\tau\nu)}{\Gamma(B \to D^*\ell\nu)} \overset{\text{SM}}{=} 0.252 \pm 0.003\,, \tag{2}$$

with $\ell = e$ or μ. The measured values by BaBar [1], $R(D) = 0.440 \pm 0.072$ and $R(D^*) = 0.332 \pm 0.030$, show an excess with respect to the SM of 2.0σ and 2.7σ respectively [1–3]. The Belle Collaboration reported a measurement of these ratios in 2015 which showed a slight enhancement with respect to the SM, $R(D) = 0.375 \pm 0.069$ and $R(D^*) = 0.293 \pm 0.041$ [4]. The LHCb Collaboration also measured $R(D^*) = 0.336 \pm 0.040$ [5], representing a deviation from the SM at the $\sim 2\sigma$ level. Very recently, the Belle Collaboration has presented a new independent determination of $R(D^*)$ [6] which is 1.6σ above the SM and is compatible with all the previous measurements: $R(D^*) = 0.302 \pm 0.032$.

2. The LHCb Collaboration has provided as well hints for flavor non-universality (FNU) in $b \to s\ell^+\ell^-$ transitions. The ratio [7][1]

$$R_K = \frac{\Gamma(B \to K\mu^+\mu^-)}{\Gamma(B \to Ke^+e^-)} \overset{\text{SM}}{=} 1 + \mathcal{O}(m_\mu^2/m_b^2)\,, \tag{3}$$

was measured in the low-q^2 region $q^2 \in [1,6]$ GeV^2 obtaining $R_K = 0.745^{+0.090}_{-0.074} \pm 0.036$ [8], which represents a 2.6σ devia-

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[1] We note that electromagnetic corrections to this ratio are expected to be of order $\alpha \log(m_e^2/m_\mu^2) \sim 8\%$. These logarithmic terms could also be enhanced by non-perturbative effects of order $\log(\Lambda/m_B)$, and/or large "accidental" numerical factors. The experimental analysis takes into account part of the final-state radiation, but a consistent study of electromagnetic effects is still lacking. In addition, in the presence of flavor-non-universal new physics, hadronic uncertainties in R_K are not suppressed by m_μ^2/m_b^2, but only by $(1 - R_K^{\text{NP}})$.

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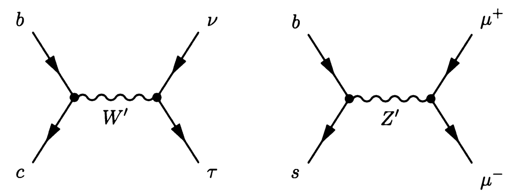

Fig. 1. Tree-level contributions to $b \to c\tau\nu$ and $b \to s\mu^+\mu^-$ transitions from hypothetical heavy W', Z' gauge bosons.

tion from the SM. Other anomalies have also been observed in $B \to K^{(*)}\mu^+\mu^-$ [9,10], and $B_s \to \phi\mu^+\mu^-$ [11]. The exact significance of the discrepancy with the SM in the latter modes depends on the treatment of hadronic uncertainties [12–15], but there is general consensus that sizable NP contributions ($\sim -25\%$ of the SM) to the effective operator $(\bar{s}\gamma^\alpha P_L b)(\bar{\mu}\gamma_\alpha\mu)$ improve the agreement with current data considerably [16–22]. One key observation is that the $b \to s\mu^+\mu^-$ and R_K anomalies are exactly consistent with each other if one assumes no NP in $b \to se^+e^-$ [21].

A simultaneous explanation of the $b \to c\tau\nu$ and $b \to s\ell^+\ell^-$ anomalies has been initially discussed in Ref. [23] within an effective theory (EFT) point of view, building on the idea of Ref. [24] that non-universality in R_K could be due to NP coupling predominantly to the third generation. This EFT approach was followed later in a series of works [25–27]. Scalar and/or vector leptoquarks as well as a $SU(2)_L$ triplet of massive vector bosons coupled predominantly to the third fermion generation were considered in these works as possible dynamical realizations [25,26]. The possibility of a leptoquark origin for these anomalies was subsequently explored in more detail in Refs. [28–33], making also interesting connections to other possible phenomena such as neutrino masses.

In this work we assume that the $b \to c\tau\nu$ and $b \to s\ell^+\ell^-$ anomalies arise from tree-level exchange of massive vector bosons (see Fig. 1). Such states could appear as heavy resonances associated to a strongly coupled dynamics [34]. One could also consider a scenario where these heavy vectors arise as mediators of a perturbative short-range force.

Thus, in this work we discuss possible realizations of this idea in a minimal setting, by extending the SM gauge group with an additional SU(2) factor. The spontaneous breaking of the enlarged gauge symmetry down to the electroweak group is supposed to occur around the TeV scale, giving rise to heavy W' and Z' gauge bosons that can mediate $b \to c\tau\nu$ and $b \to s\mu^+\mu^-$ transitions as in Fig. 1. By searching for viable models of this sort, we will see that these are restricted to be of a particular type (see Section 3). In Section 4 we construct an explicit model of this type. We identify gauge-mixing as a relevant issue for gauge models addressing the B-decay anomalies. This is discussed in Section 5.

2. Interpretation of B-decay anomalies

Measurements of decay rates as well as differential distributions in the transferred momenta and angular variables can be used to gain information about the underlying dynamics responsible for these flavor anomalies. We make the following observations based on current data:

- An analysis of the $q^2 = (p_B - p_{D^{(*)}})^2$ differential distribution in $b \to c\tau\nu$ decays by BaBar is compatible with an electrically charged spin-1 mediator as an explanation of the $R(D^{(*)})$ excess [35].
- Current data is compatible with the hypothesis of a universal scaling for $R(D)$ and $R(D^*)$. This dynamical feature appears automatically for a left-handed charged current interaction [23].
- Anomalies in $b \to s\mu^+\mu^-$ transitions together with R_K can be explained by the presence of a heavy neutral vector boson mediator with flavor changing couplings of the form $(\bar{s}\gamma^\alpha P_L b)Z'_\alpha$, with either vectorial or left-handed coupling to muons [14, 16–19,21,22].

Non-abelian gauge extensions of the SM often introduce mass mixing in the gauge sector. The latter typically appears when scalars fields responsible for the breaking of the electroweak symmetry are also charged under the extended group. In the presence of such mixing the W and Z couplings receive corrections of order $v^2/M^2_{W',Z'}$, with additional parametric suppressions possible but model dependent. This implies that new physics contributions from the tree-level exchange of a heavy vector boson and those due to gauge mixing effects (W and Z mediation) are potentially of the same size. This is the case for $\Delta F = 1$ transitions and charged-current processes which arise at tree level in the SM. For $\Delta F = 2$ transitions, gauge mixing effects will enter with a relative $v^2/M^2_{Z'}$ suppression at the amplitude level compared to the tree-level exchange of a heavy Z'.

Another important aspect to note is that $\Delta F = 1$ ratios probing LFU violation such as R_K have a small sensitivity to gauge mixing effects, contrary to their charged-current counterparts, $R(D^{(*)})$ or $\Gamma(\tau \to \mu\nu\bar{\nu})/\Gamma(\tau \to e\nu\bar{\nu})$. The underlying reason being that the required gauge boson couplings are already present in the SM for the case of charged-current processes.

3. Gauge extensions with lepton non-universality

3.1. General considerations on model-building

A common explanation of universality-violating hints in the decays $b \to c\tau\nu$ and $b \to s\ell^+\ell^-$ poses serious challenges for model building. This is mostly because the NP mediators responsible for such processes would have to act at tree level. Indeed, the semileptonic decays $B \to D^{(*)}\tau\nu$ are charged current processes which arise at tree level in the SM. Since the observed deviation from the SM prediction is quite sizable, $\mathcal{O}(25\%)$, this strongly suggests the presence of tree-level charged mediators. The same applies to the decays $B \to K^{(*)}\ell^+\ell^-$ even though they are due, in the SM, to neutral current processes arising at one-loop level. The large deviation from the SM, again $\mathcal{O}(25\%)$, would imply a very light mediator if the new interactions followed the SM pattern. Such a light mediator, $\mathcal{O}(M_Z)$, would be hard to hide from other flavor observables which are in perfect agreement with the SM as well as from direct searches for new states at high energy colliders such as the LHC.

We assume from now on that the anomalies R_K and $R(D^{(*)})$ are genuine and due to new gauge bosons entering at tree level. We are therefore looking for a non-universal gauge extension of the SM which could explain both anomalies at the same time. We will be interested in scenarios where new physics effects in the lepton sector affect mainly the muon and tau leptons.

There are essentially two strategies to follow in constructing non-universal gauge extensions of the SM:

▷ **Non-Universality from gauge couplings (g-NU)**:

via a non-universal embedding of SM fermions into a larger gauge group, or

▷ **Non-Universality from Yukawas (y-NU)**:

through non-universal interactions between SM fermions and extra particles which are universally coupled to new vector bosons.

This means that, in general, non-universality is either controlled by Yukawa couplings or by gauge couplings. Of course, one can always mix these two approaches, however we keep them separated for the sake of clarity and to gain insights based on generic considerations.

For simplicity and definiteness, we will focus on implementations where the gauge extensions consist of SU(2) and U(1) factors only. The minimal possibilities are denoted generically as $G(221)$ models. In addition to the source of non-universality, $G(221)$ models can be classified according to the gauge symmetry-breaking pattern. We distinguish two broad categories:

▹ **L-Breaking Pattern (L-BP)**:

For this breaking pattern the $\mathrm{U}(1)_Y$ group appears from a non-trivial breaking of the extended group:

$$\mathrm{SU}(2)_L \otimes \mathrm{SU}(2)_H \otimes \mathrm{U}(1)_H \to \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y$$

▹ **Y-Breaking Pattern (Y-BP)**:

The $\mathrm{SU}(2)_L$ factor is non-trivially embedded in the extended gauge group and arises from the breaking pattern:

$$\mathrm{SU}(2)_1 \otimes \mathrm{SU}(2)_2 \otimes \mathrm{U}(1)_Y \to \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y$$

We now proceed to reviewing the viability of the different possibilities that are available in our classification.

3.2. Non-universality from gauge couplings

▹ **Breaking chain L-BP**: A model within this scenario was already presented in Ref. [36] to explain the $R(D^{(*)})$ anomalies. However, just with the SM particle content one can only couple right-handed fermions to the extra gauge group, making it unable to accommodate R_K.

▹ **Breaking chain Y-BP**: This model has been studied in Refs. [37–39]. In this scenario it is only possible to reproduce the desired non-universal Z' and W' couplings to leptons if the gauge coupling hierarchy $g_2 \gg g_1 \sim g$ is enforced, with a single SM family coupling to $\mathrm{SU}(2)_2$. However the large g_2 limit has to face constraints from rapid proton decay and perturbativity. Instanton mediated processes will, in general, induce proton decay when a single SM family is coupled to a non-abelian gauge group, setting a bound on the gauge coupling: $g_2\left(M_{Z'}^2\right) \lesssim 1.3$–$1.6$, depending on the parameters of the model [40,41]. This bound can be circumvented by introducing extra fermions that couple to this gauge group, such as vector-like fermions. However, even in this case perturbativity sets an upper bound on the gauge coupling of $g_2\left(M_{Z'}^2\right) < \sqrt{4\pi} \simeq 3.5$. Given these limits, it is not possible to reproduce the requested hierarchy on the lepton couplings, making this framework disfavored for the simultaneous explanation of R_K and $R(D^{(*)})$.

3.3. Non-universality from Yukawa couplings

Here new vector-like (VL) fermions, charged universally under a new force to which the SM fermions are neutral, are Yukawa-coupled to the SM quarks and leptons. The effective coupling of the SM with the new bosons is achieved via mixings with the VL fermions and is hence controlled by the Yukawas, which can be in principle adjusted to get the desired flavor textures. In general these mixings will also modify the SM gauge and Higgs couplings. However one can charge the VL fermions under the gauge group in such a way that GIM protection is enforced at the scale of the first symmetry breaking, making these deviations sufficiently small to avoid experimental constraints.

Table 1
Summary of model building possibilities for $G(221)$ models: source of flavor non-universality (NU) versus symmetry-breaking patterns (BP). Blocks denote scenarios which are disfavored as an explanation of the B-decay anomalies while a star denotes a viable framework.

	L-BP	Y-BP
g-NU	■ No left-handed currents	■ perturbativity
y-NU	■ No GIM	★

This translates in the two breaking patterns we are considering as follows:

▹ **Breaking chain L-BP**: In order to obtain an effective coupling $W'^{\pm}$ to left-handed quarks, it is necessary to add VL quarks which mix with the SM weak quark doublet. The electric charge formula of this breaking chain is:

$$Q = T_{3_L} + (T_{3_H} + H)\,, \tag{4}$$

where T_{3_L} (T_{3_H}) and H are respectively the isospin under $\mathrm{SU}(2)_L$ ($\mathrm{SU}(2)_H$) and the $\mathrm{U}(1)_H$ charge. Since the SM fields are neutral under the new $\mathrm{SU}(2)_H$ interactions, $\mathrm{U}(1)_H$ charges coincide with the standard hypercharges. In order for two new quarks, Q_b and Q_c to couple to $W'^{\pm}$ they must belong to the same $\mathrm{SU}(2)_H$ multiplet and their isospin must satisfy $|T_{3_H}(Q_b) - T_{3_H}(Q_c)| = 1$. On the other hand, to preserve the GIM mechanism in the presence of the new mixings the new quarks must have the same SM quantum numbers (T_{3_L} and $Y \equiv T_{3_H} + H$) as the SM quarks with which they mix [42]. These two requirements are in conflict with each other and so we conclude that models of type L-BP cannot account for a unified description of R_K and $R(D^{(*)})$.

▹ **Breaking chain Y-BP**: The product $\mathrm{SU}(2)_1 \otimes \mathrm{SU}(2)_2$ can be broken to the diagonal $\mathrm{SU}(2)_L$ by a Higgs bi-doublet. This specific type of breaking allows for both couplings to W' and GIM suppression. It is enough to charge SM fermions under one of the two SU(2)'s, say $\mathrm{SU}(2)_2$, and copy the exact same assignments for the vector-like fermions. This is the scenario we deem more promising for the simultaneous explanation of $b \to s\ell^+\ell^-$ and $b \to c\tau\nu$ anomalies.

3.4. Summary

In summary, restricted to minimal gauge extensions we have found four broad classes of models that lead to flavor non-universality and can potentially address the flavor anomalies. These classes depend on the breaking pattern (L-BP or Y-BP) and the source of flavor non-universality (g-NU or y-NU). Table 1 summarizes our main conclusion: that the most promising candidates are gauge extensions where gauge couplings are universal and non-universality arises from Yukawa couplings of the SM fermions with a set of new vector-like fermions.

4. A model example

In this section we construct, as an explicit example, a model of the type y-NU/Y-BP. We consider the gauge group $\mathrm{SU}(3)_C \otimes \mathrm{SU}(2)_1 \otimes \mathrm{SU}(2)_2 \otimes \mathrm{U}(1)_Y$, with coupling constants denoted by (g_s, g_1, g_2, g') respectively. We consider also two scalar fields transforming as:

$$\phi = (\mathbf{1}, \mathbf{1}, \mathbf{2})_{1/2}\,, \qquad \Phi = \left(\mathbf{1}, \mathbf{2}, \bar{\mathbf{2}}\right)_0\,. \tag{5}$$

We assume a scalar potential leading to the following vacuum-expectation values:

$$\langle\phi\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v\end{pmatrix}, \qquad \langle\Phi\rangle = \frac{1}{2}\begin{pmatrix}u & 0\\ 0 & u\end{pmatrix}, \tag{6}$$

Table 2
Particle content of the model, added fields to the SM are shown in gray.

	generations	$SU(3)_C$	$SU(2)_1$	$SU(2)_2$	$U(1)_Y$
ϕ	1	**1**	**1**	**2**	1/2
Φ	1	**1**	**2**	$\bar{\mathbf{2}}$	0
q_L	3	**3**	**1**	**2**	1/6
u_R	3	**3**	**1**	**1**	2/3
d_R	3	**3**	**1**	**1**	−1/3
ℓ_L	3	**1**	**1**	**2**	−1/2
e_R	3	**1**	**1**	**1**	−1
$Q_{L,R}$	$n_{\rm VL}$	**3**	**2**	**1**	1/6
$L_{L,R}$	$n_{\rm VL}$	**1**	**2**	**1**	−1/2

with $v \simeq 246$ GeV and $\epsilon \equiv v/u \ll 1$ (typically $u \sim$ TeV). The resulting symmetry-breaking pattern is given by

$$SU(2)_1 \otimes SU(2)_2 \otimes U(1)_Y \xrightarrow{u} SU(2)_L \otimes U(1)_Y \xrightarrow{v} U(1)_{\rm em}$$

This breaking leads to a spectrum with a massless photon, two neutral Z, Z' bosons with masses $M_Z^2 \simeq v^2(g^2+g'^2)^2/4$ and $M_{Z'}^2 \simeq u^2(g_1^2+g_2^2)/4$, and two pairs of charged bosons $W^\pm$, $W'^\pm$ with masses $M_W^2 \simeq v^2g^2/4$ and $M_{W'}^2 \simeq M_{Z'}^2$. Here $g \equiv g_1g_2/\sqrt{g_1^2+g_2^2}$.

In order to source FNU from Yukawa couplings, we introduce, in addition to the SM fermion content, $n_{\rm VL}$ generations of VL fermions transforming as

$$Q_{L,R} = (\mathbf{3},\mathbf{2},\mathbf{1})_{1/6}\,, \qquad L_{L,R} = (\mathbf{1},\mathbf{2},\mathbf{1})_{-1/2}\,. \tag{7}$$

It can be shown that the requirements of *(i)* no W'/Z' couplings to electrons, and *(ii)* lepton non-universality between μ and τ, imply that $n_{\rm VL} \geq 2$. Indeed, the first requirement introduces three non-trivial conditions on the Yukawa couplings between the chiral leptons and the vector-like leptons which fix these completely and leave no room to satisfy the second condition. In what follows, we take the minimal possibility and fix $n_{\rm VL} = 2$. The complete particle content of the model is summarized in Table 2.

The Dirac masses of the VL fermions are assumed to be around the symmetry breaking scale $u \sim$ TeV. In this scenario, the couplings of Z', W' bosons to right-handed SM fermions are suppressed by $\sim m_f^2/v^2$, with m_f the mass of a SM fermion, and can be neglected for the couplings we are considering. Left-handed SM fermions have anomalous flavor-changing couplings to Z, W of $\mathcal{O}(\epsilon^2)$ due to gauge mixing effects, and $\mathcal{O}(1)$ couplings to Z', W'. The part of the Lagrangian describing these interactions is:

$$\begin{aligned}
\delta\mathcal{L} = &-\epsilon^2\frac{gg_2^4}{\sqrt{2}n_1^4}\Big[(V\Delta_L^q)_{ij}W_\mu^+\bar{u}_L^i\gamma^\mu d_L^j + (\Delta_L^\ell)_{ij}W_\mu^+\bar{\nu}_L^i\gamma^\mu\ell_L^j\Big] + \text{h.c.}\\
&-\frac{gg_2}{\sqrt{2}g_1}\Big[(V\Delta_L^q)_{ij}W_\mu'^+\bar{u}_L^i\gamma^\mu d_L^j + (\Delta_L^\ell)_{ij}W_\mu'^+\bar{\nu}_L^i\gamma^\mu\ell_L^j\Big] + \text{h.c.}\\
&-\epsilon^2\frac{n_2g_2^4}{2n_1^4}\Big[(V\Delta_L^qV^\dagger)_{ij}Z_\mu\bar{u}_L^i\gamma^\mu u_L^j - (\Delta_L^q)_{ij}Z_\mu\bar{d}_L^i\gamma^\mu d_L^j\\
&-(\Delta_L^\ell)_{ij}Z_\mu(\bar{\ell}_L^i\gamma^\mu\ell_L^j - \bar{\nu}_L^i\gamma^\mu\nu_L^j)\Big]\\
&-\frac{gg_2}{2g_1}\Big[(V\Delta_L^qV^\dagger)_{ij}Z'_\mu\bar{u}_L^i\gamma^\mu u_L^j - (\Delta_L^q)_{ij}Z'_\mu\bar{d}_L^i\gamma^\mu d_L^j\\
&-(\Delta_L^\ell)_{ij}Z'_\mu(\bar{\ell}_L^i\gamma^\mu\ell_L^j - \bar{\nu}_L^i\gamma^\mu\nu_L^j)\Big]\,,
\end{aligned}\tag{8}$$

where $n_1^2 \equiv g_1^2+g_2^2$ and $n_2^2 \equiv g^2+g'^2$. V is the CKM matrix, and $(1-\Delta_L^{q,\ell}) \sim (\lambda u/M)^2$ are hermitian matrices in flavor space, with λ the Yukawas that couple SM and VL fermions, and M the masses of the VL fermions. The NP contributions to the relevant four-fermion operators are given by:

$$\mathcal{L}_{c.c.}^{W'} = -\frac{\hat{g}^2}{2M_{W'}^2}(V\Delta_L^q)_{ij}(\Delta_L^\ell)_{ab}\,(\bar{u}_L^i\gamma_\mu d_L^j)(\bar{\ell}_L^a\gamma^\mu\nu_L^b) + \text{h.c.}\,, \tag{9}$$

$$\begin{aligned}
\mathcal{L}_{c.c.}^{\rm GM} = &-\frac{\hat{g}^2}{2M_{W'}^2}\Big[-(V\Delta_L^q)_{ij}\delta_{ab} - V_{ij}(\Delta_L^\ell)_{ab}\Big]\\
&\times(\bar{u}_L^i\gamma_\mu d_L^j)(\bar{\ell}_L^a\gamma^\mu\nu_L^b) + \text{h.c.}\,,
\end{aligned}\tag{10}$$

$$\begin{aligned}
\mathcal{L}_{\rm FCNC}^{Z'} = &-\frac{\hat{g}^2}{4M_{W'}^2}(\Delta_L^\ell)_{ab}\Big[(\Delta_L^q)_{ij}\,(\bar{d}_L^i\gamma_\mu d_L^j)\\
&-(V\Delta_L^qV^\dagger)_{ij}\,(\bar{u}_L^i\gamma_\mu u_L^j)\Big]\Big(\bar{\ell}_L^a\gamma^\mu\ell_L^b - \bar{\nu}_L^a\gamma^\mu\nu_L^b\Big)\,,
\end{aligned}\tag{11}$$

$$\begin{aligned}
\mathcal{L}_{\rm FCNC}^{\rm GM} = &-\frac{\hat{g}^2}{4M_{W'}^2}\delta_{ab}\Big[(\Delta_L^q)_{ij}\,(\bar{d}_L^i\gamma_\mu d_L^j) - (V\Delta_L^qV^\dagger)_{ij}\,(\bar{u}_L^i\gamma_\mu u_L^j)\Big]\\
&\times\Big(2s_W^2\,\bar{\ell}^a\gamma^\mu\ell^b - \bar{\ell}_L^a\gamma^\mu\ell_L^b + \bar{\nu}_L^a\gamma^\mu\nu_L^b\Big)\,,
\end{aligned}\tag{12}$$

$$\begin{aligned}
\mathcal{L}_{\Delta F=2}^{Z'} = &-\frac{\hat{g}^2}{8M_{W'}^2}\Big[\big[(\Delta_L^q)_{ij}(\bar{d}_L^i\gamma_\mu d_L^j)\big]^2\\
&+\big[(V\Delta_L^qV^\dagger)_{ij}(\bar{u}_L^i\gamma_\mu u_L^j)\big]^2\Big]\,,
\end{aligned}\tag{13}$$

where $\hat{g} \equiv gg_2/g_1$. Here we have separated explicitly the direct contributions from W'/Z' exchange from those due to gauge mixing (GM) effects. There are no contributions to $\mathcal{L}_{\Delta F=2}$ from gauge mixing at order ϵ^2. This is also true for lepton-flavor non-universal ratios of FCNCs, such as R_K, as can be seen from the δ_{ab} prefactor in Eq. (12). However, in the case of lepton-flavor non-universal ratios in charged-current processes, such as $R(D^{(*)})$, additional contributions from W-W' mixing encoded in Eq. (10) are present. The effective Lagrangian for leptonic decays is given in the Appendix.

The conclusion of this section is that the model-building guidelines discussed in Section 3 result in models with the structure needed to address the anomalies. However, we find additional effects from gauge mixing that are typically of the same order as the direct contributions from heavy-boson exchange. These contributions have the potential to spoil the flavor patterns needed to explain the B-decay anomalies.

5. Relevance of gauge mixing

When present, the size of mass mixing effects in the gauge sector is intrinsically connected to the hierarchy between the electroweak scale and the scale of breaking of the extended gauge group "u". The gauge boson mass matrix receives contributions of order $u^2W'^2$, v^2W^2, v^2WW' giving rise to corrections of the electroweak gauge boson couplings of order v^2/u^2. This is what occurs for example in the model presented in Sec. 4. Parametrical suppressions of the mass mixing term can be engineered in principle by considering a more involved symmetry breaking sector.

In this section we discuss the most relevant issues associated with gauge mixing effects when trying to account for the B-decay anomalies in the gauge framework of Sec. 4.

▷**Bounds from Z and W-pole observables:** Corrections to the electroweak gauge boson couplings to fermions are constrained at the per-mille/few percent from electroweak precision data collected at the Z and W-pole in the LEP experiment [43,44]. Note that when the symmetry breaking scale of the extended gauge group is of the order of the TeV scale, the natural suppression provided by the hierarchy of scales v^2/u^2 is typically enough to satisfy such strong bounds.

▹ **Flavor structure/patterns:** The main idea behind the explanation of B-decay anomalies in this setting is that flavor patterns of the UV dynamics are imprinted on the low energy effective Lagrangian describing flavor transitions. This amounts to the idea that flavor textures and/or hierarchies in the $\Delta_L^{q,\ell}$ couplings of Eq. (8) can be linked to information gathered in low-energy experiments. Gauge mixing effects however make the connection non-trivial. The low-energy effective Lagrangian in Eqs. (9)–(12) contains contributions due to gauge mixing which alter the flavor structure of the NP effects at low energies. We illustrate this feature with two examples:

(i) Fixing $\Delta_L^{q,\ell}$ to be non-vanishing only for the second and third generations can be motivated by: the strong constraints on light-quark meson systems and electrons, and, the fact that the observed B-decay anomalies only requires NP affecting these fermions. One would have then vanishing NP contributions at tree level to $\Gamma(P \to \mu\nu)/\Gamma(P \to e\nu)$ (with $P = \pi, K$) from the W' exchange. Gauge mixing effects would however introduce NP corrections to these observables via W-boson mediation. The same occurs for $\mu \to e\nu\bar{\nu}$.

(ii) The usual relation $\delta\mathcal{C}_9^{\rm NP} = -\delta\mathcal{C}_{10}^{\rm NP}$ associated to purely left-handed Z'-mediated FCNCs can receive significant corrections. Tree-level contributions from the Z-boson give corrections of order $v^2/M_{Z'}^2$ to these Wilson coefficients with $|\delta\mathcal{C}_9^{\rm NP}| \ll |\delta\mathcal{C}_{10}^{\rm NP}|$ due to the accidental suppression of the vectorial Z coupling to leptons.

▹ **Suppression of gauge mixing effects:** In the model of Sec. 4, such suppression could appear in certain regions of the parameter space if the scalar sector is extended by a complex scalar field with the following $\mathrm{SU}(3)_C \otimes \mathrm{SU}(2)_1 \otimes \mathrm{SU}(2)_2 \otimes \mathrm{U}(1)_Y$ quantum numbers $\phi'(\mathbf{1},\mathbf{2},\mathbf{1})_{1/2}$. Gauge mixing effects at low energy will depend on the ratio between the vacuum expectation values of ϕ and ϕ', here denoted as $\tan\beta = v_\phi/v_{\phi'}$. Effectively, one can account for these changes by multiplying the right-hand side of Eq. (10) and Eq. (12) by the factor

$$\zeta \equiv \left(\sin^2(\beta) - \frac{g_1^2}{g_2^2}\cos^2(\beta)\right). \tag{14}$$

The effects of gauge mixing in flavor transitions are then suppressed in this scenario for $\tan(\beta) \simeq g_1/g_2$. In the limit of vanishing mass mixing in the gauge sector, the structure of the low-energy effective Lagrangian relevant for flavor transitions reduces to Eq. (9) and Eq. (11).

To evaluate the impact of gauge mixing effects on flavor transitions, we perform a global fit of electroweak precision and flavor data, including:

- Bounds from Z and W pole observables, using the results provided in Ref. [45].
- Tests of lepton universality violation in tree-level charged current processes: $\ell \to \ell'\nu\bar{\nu}$, $\pi/K \to \ell\nu$, $\tau \to \pi/K\nu$, $K^+ \to \pi\ell\nu$, $D \to K\ell\nu$, $D_s \to \ell\nu$, $B \to D^{(*)}\ell\nu$ and $B \to X_c\ell\nu$ [46,47].
- $|\Delta F| = 1, 2$ transitions in the $b \to s$ sector receiving NP contributions at tree level in our model from the exchange of the massive neutral vector bosons. We treat $b \to s\ell^+\ell^-$ decays using the results of Ref. [17] and we use inputs from Ref. [48] for B-meson mixing.
- CKM inputs from a fit by the CKMfitter group with only tree-level processes [49], as used in Ref. [48].
- Bounds from the lepton flavor violating decays $\tau \to 3\mu$ and $Z \to \tau\mu$ [46,47].

We have fixed $\Delta_L^{q,\ell}$ to be non-vanishing only for the second and third generations in the fit. Our best fit regions in the $R(D^*) - R_K$ plane are shown in Fig. 2 for the two benchmark values $\zeta = 0, 1$ of the parameter that controls the size of gauge mixing effects. Allowed regions at 68% and 95% CL in the case of $\zeta = 1$ do not show any significant deviation from the SM in $R(D^*)$ while R_K is compatible with the LHCb measurement. In the case of vanishing gauge mixing, $\zeta = 0$, a joint explanation of the B-decay anomalies becomes possible as $R(D^*)$ can receive a significant enhancement compared to the SM. Note that in our model $R(D^*)$ and $R(D)$ have the same NP scaling since the W' has left-handed couplings to fermions.

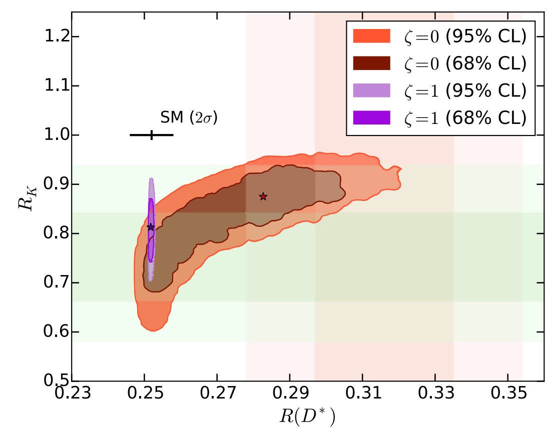

Fig. 2. Preferred allowed regions in the $R(D^*) - R_K$ plane at 68% and 95% CL from the global fit. Experimental values for these observables are also shown at 1σ (dark-band) and 2σ (light-band). The best fit points are illustrated with a star. The SM prediction is also shown at the 2σ level.

6. Conclusions

New Physics models with vector-boson triplets are potential candidates to accommodate the anomalies in $b \to c\ell\nu$ and $b \to s\ell\ell$. It has been shown that effective models with generic contributions to dimension-six operators, as well as more concrete dynamical models, can fit the anomalies while satisfying stringent constraints from flavor-universality. The question is whether one can build concrete gauge models of this sort.

We find that minimal gauge extensions of the SM leading to heavy gauge-boson triplets must be of a very particular type in order to address the B-decay anomalies and at the same time satisfy other constraints such as perturbativity, GIM suppression, or proton decay. We identify a viable class of gauge extensions in which the $\mathrm{SU}(2)_L$ factor is embedded non-trivially in the extended gauge group. Flavor non-universality is sourced by Yukawa couplings to additional matter fields, such as VL fermions.

We have built a concrete model and checked that it reproduces the correct patterns for the dimension-six operators related to the anomalies. We have identified the issue of gauge mixing as a relevant obstacle towards a joint explanation of the B-decay anomalies in the context of gauge extensions of the SM. The impact of these mixing effects on the explanation of the B-decay anomalies is illustrated in Fig. 2.

We find that a joint explanation of the B-decay anomalies is only possible within the proposed gauge framework when gauge mixing effects are suppressed. This is achieved via a non-trivial tuning between parameters of the scalar and gauge sector.

If lepton-flavor non-universality is established through more precise measurements in B decays and a more thorough examination of theoretical uncertainties, this could be the first indication of an extended gauge symmetry, such as the one presented here.

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Appendix A. Effective Lagrangian for leptonic decays

The effective Lagrangian for lepton flavor violating decays $\ell_b \to \ell_a \bar{\ell}_c \ell_c$ is given by

$$\begin{aligned}\mathcal{L}_{\rm LFV} = &-\frac{\hat{g}^2}{4M_{W'}^2}(\Delta_L^\ell)_{ab}(\Delta_L^\ell)_{cc}\left(\bar{\ell}_L^a\gamma_\mu\ell_L^b\right)\left(\bar{\ell}_L^c\gamma^\mu\ell_L^c\right)\\ &-\frac{\hat{g}^2}{4M_{W'}^2}\zeta(2s_W^2-1)(\Delta_L^\ell)_{ab}\left(\bar{\ell}_L^a\gamma_\mu\ell_L^b\right)\left(\bar{\ell}_L^c\gamma^\mu\ell_L^c\right)\\ &-\frac{\hat{g}^2}{2M_{W'}^2}\zeta s_W^2(\Delta_L^\ell)_{ab}\left(\bar{\ell}_L^a\gamma_\mu\ell_L^b\right)\left(\bar{\ell}_R^c\gamma^\mu\ell_R^c\right). \qquad \text{(A.1)}\end{aligned}$$

Here we have included the effect of the doublet ϕ' on the gauge mixing through the parameter ζ, see Eq. (14). For leptonic decays conserving lepton flavor $\ell \to \ell' \bar{\nu}_{\ell'} \nu_\ell$ the effective Lagrangian is

$$\begin{aligned}\mathcal{L}_{\rm LFNU} = &-\frac{\hat{g}^2}{4M_{W'}^2}\left\{\left[2(\Delta_L^\ell)_{ad}(\Delta_L^\ell)_{cb}-(\Delta_L^\ell)_{ab}(\Delta_L^\ell)_{cd}\right]\right.\\ &\left.-2\zeta\left[\delta_{ad}(\Delta_L^\ell)_{cb}+\delta_{cb}(\Delta_L^\ell)_{ad}\right]\right\}\left(\bar{\ell}_L^a\gamma_\mu\ell_L^b\right)\left(\bar{\nu}_L^c\gamma^\mu\nu_L^d\right). \qquad \text{(A.2)}\end{aligned}$$

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