RECEIVED: July 17, 2018

REVISED: November 7, 2018

ACCEPTED: November 14, 2018

PUBLISHED: November 26, 2018

A gauged horizontal SU(2) symmetry and $R_{K(*)}$

Diego Guadagnoli,^a Mril Reboud^a and Olcyr Sumensari^{b,c}

^a*Laboratoire d'Annecy-le-Vieux de Physique Thorique UMR5108,
Universit de Savoie Mont-Blanc et CNRS,
B.P. 110, F-74941, Annecy Cedex, France*

^b*Dipartimento di Fisica e Astronomia "G. Galilei", Universit di Padova,
Via Marzolo 8, I-35131 Padua, Italy*

^c*Istituto Nazionale Fisica Nucleare, Sezione di Padova,
Via Marzolo 8, I-35131 Padua, Italy*

E-mail: diego.guadagnoli@lapth.cnrs.fr, meril.reboud@lapth.cnrs.fr,
olcyr.sumensari@pd.infn.it

ABSTRACT: One of the greatest challenges for models of $b \rightarrow s$ anomalies is the necessity to produce a large contribution to a quark times a lepton current, $J_q \times J_\ell$, and to avoid accordingly large contributions to flavour-changing $J_q \times J_q$ and $J_\ell \times J_\ell$ amplitudes, which are severely constrained by data. We consider a gauged horizontal symmetry involving the two heaviest generations of all left-handed fermions. In the limit of degenerate masses for the horizontal bosons, and in the absence of mixing between the two heavier generations and the lighter one, such symmetry would make $J_q \times J_q$ and $J_\ell \times J_\ell$ amplitudes exactly flavour-diagonal. Mixing with the first generation is however inescapable due to the CKM matrix, and the above mechanism turns out to be challenged by constraints such as $D^0 - \bar{D}^0$ mixing. Nonetheless, we show that a simultaneous description of all data can be accomplished by simply allowing for non-degenerate masses for the horizontal bosons. Such scenario predicts modifications in several processes that can be tested at present and upcoming facilities. In particular, it implies a lower and upper bound for $\mathcal{B}(B \rightarrow K \mu^\pm \tau^\mp)$, an asymmetry between its two charge conjugated modes, and well-defined correlations with LFV in τ decays.

KEYWORDS: Beyond Standard Model, Heavy Quark Physics, Gauge Symmetry

ARXIV EPRINT: [1807.03285](https://arxiv.org/abs/1807.03285)

Contents

1	Introduction	1
2	Model	2
2.1	Low-energy theory and notation	5
3	Scenario 0	6
4	Scenario 1	8
4.1	$b \rightarrow s\ell\ell'$ and leptonic LFV	11
4.2	$\Delta M_s/\Delta M_d$	14
4.3	$B \rightarrow K\nu\bar{\nu}$	15
4.4	$\tau \rightarrow \mu\nu\bar{\nu}$	16
4.5	$D^0 \rightarrow \mu\mu$	16
4.6	Further constraints	17
5	Conclusions	18

1 Introduction

Data on $b \rightarrow s$ semi-leptonic transitions display persistent deviations with respect to Standard-Model (SM) predictions, hinting at a violation of lepton universality (LUV) [1, 2], namely at some new interaction that distinguishes among lepton species. Further hints of LUV exist for $b \rightarrow c$ semi-leptonic transitions [3–6]. At face value, the two sets of anomalies have similar significances of about 4σ [7–13], which justifies taking both datasets on an equal footing. From a theory point of view, such a stance is also motivated by the fact that the two sets of anomalies convey the same qualitative message (LUV), and that they concern currents that can be related by the SM $SU(2)_L$ symmetry, which is what one would expect of new effects arising above the electroweak symmetry-breaking (EWSB) scale [14–16]. However, seeking an explanation of both sets of anomalies turns out to be problematic at the *quantitative* level, if nothing else because $b \rightarrow c$ and $b \rightarrow s$ data hint at $\sim 10 - 20\%$ shifts in, respectively, a SM tree and a SM loop amplitude. If both shifts are to be explained through the same effective, $SU(2)_L$ -invariant structure, its flavour-dependent coupling must come with a mechanism allowing for more suppressed effects in $b \rightarrow s$ than in $b \rightarrow c$. Numerous proposals in this direction have already been made in the literature, for example [17], that implements a tree- vs. loop-suppression mechanism akin to the SM one (on this model, see also [18, 19]), or a broken flavour symmetry whereby $b \rightarrow c\tau\nu$ and $b \rightarrow s\mu\mu$ effects arise as respectively first and third order in the breaking parameter [20] (see

also [16, 21, 22]). Many more such proposals exist in the literature, including a few UV-complete models [23–30]. These models have to invariably withstand non-negligible constraints, in particular from certain low-energy precision observables [31–34] and/or direct searches [35]. The overall challenge thus boils down to the difficulty of writing down a calculable model that explains a (coherent) set of LUV anomalies in $b \rightarrow s$ and $b \rightarrow c$ currents, with no observed departures in other directly related sets of data. Perhaps this difficulty is indicating that data are still premature to be taken quantitatively. In these circumstances, we choose to focus on $b \rightarrow s$ anomalies alone. In this paper we propose a mechanism for these discrepancies, that rests on two main requirements that data seem to convey: (i) the new dynamics explaining the $b \rightarrow s$ measurements must, directly or indirectly, involve the second and the third generation of quarks and leptons; (ii) it must yield large enough effects in the product of a quark times a charged-lepton bilinear, $J_q \times J_\ell$, and small enough effects elsewhere, in particular in flavour-changing $J_q \times J_q$ and $J_\ell \times J_\ell$ amplitudes.

2 Model

Facts (i) and (ii) in the previous section suggest, for reasons that will be transparent shortly, the consideration of a ‘horizontal’ group, with SU(2) being the smallest one that may be at play.¹ In this paper we invoke the possibility of a gauged SU(2) horizontal symmetry. We consider the gauge group $G_{\text{SM}} \times G_h$, where G_{SM} is the SM gauge group $\text{SU}(3)_c \times \text{SU}(2)_L \times \text{U}(1)_Y$, acting ‘vertically’ in each generation, and $G_h = \text{SU}(2)_h$ is a horizontal group connecting the 2nd and 3rd generations as defined before EWSB. More generally, we may actually assume one $\text{SU}(2)_h$ symmetry for either chirality of fermions.² Anomaly cancellation is automatic for each chirality separately, and we will comment on it later.

In general, we can then augment the SM Lagrangian with the following terms

$$\delta\mathcal{L} = \sum_{\mathcal{F},a} \bar{\mathcal{F}} \left(g_L \gamma_\mu P_L G_L^{\mu a} + g_R \gamma_\mu P_R G_R^{\mu a} \right) \tau^a \mathcal{F}, \quad (2.1)$$

where $P_{L,R}$ are the usual chirality projectors, that we henceforth include in the gamma matrices for brevity, i.e. $\gamma^\mu P_{L,R} = \gamma_{L,R}^\mu$. Furthermore, $\tau^a = \sigma^a/2$, and $G_{L,R}^{\mu a}$ are the gauge bosons of the horizontal symmetry for either chirality, whose masses are assumed to be larger than the EWSB scale. The fields $\mathcal{F}$ are such that

$$\mathcal{F} \equiv \begin{pmatrix} f_2 \\ f_3 \end{pmatrix}, \quad (2.2)$$

with 2, 3 being generation indices in general not aligned with the mass eigenbasis. The symbol f runs over all SM fermion species $u_{L,R}, d_{L,R}, \nu_L, \ell_{L,R}$.

¹References on the topic of horizontal symmetries for B -decay discrepancies include [36–38], but respective lines of arguments are quite distant from the one pursued here. In a context predating LUV in B decays, the possibility of a fully gauged flavour group was discussed in refs. [39, 40].

²Our main line of argument was presented, in an entirely different context, in an old work by Cahn and Harari [41]. See also [42].

An interesting phenomenological feature of the above interaction becomes apparent after integrating out the G_L and G_R gauge bosons. One obtains the effective interactions

$$\delta\mathcal{L}_{\text{eff}} = - \sum_{\mathcal{F}, \mathcal{F}', a} \left\{ \frac{g_L^2}{2M_{G_{La}}^2} (\bar{\mathcal{F}} \gamma_L^\mu \tau^a \mathcal{F}) (\bar{\mathcal{F}}' \gamma_{\mu L} \tau^a \mathcal{F}') + \frac{g_R^2}{2M_{G_{Ra}}^2} (\bar{\mathcal{F}} \gamma_R^\mu \tau^a \mathcal{F}) (\bar{\mathcal{F}}' \gamma_{\mu R} \tau^a \mathcal{F}') \right\}, \quad (2.3)$$

where both $\mathcal{F}$ and $\mathcal{F}'$ are defined as in eq. (2.2). Below the EWSB scale, where SM fermions acquire masses, the fields $\mathcal{F}$ undergo chiral unitary³ transformations of the kind

$$\mathcal{F} = \mathcal{U}_{\mathcal{F}} \hat{\mathcal{F}} \quad (2.4)$$

where $\hat{\mathcal{F}}$ denotes the mass-eigenbasis fields. After such transformations, the four-fermion structures generated by integrating out the G_{La} horizontal bosons from eq. (2.3) become

$$\delta\mathcal{L}_{\text{eff}} \propto \frac{1}{2M_{G_{La}}^2} \left(\bar{\hat{\mathcal{F}}} \mathcal{U}_{\mathcal{F}}^\dagger \gamma_L^\mu \tau^a \mathcal{U}_{\mathcal{F}} \hat{\mathcal{F}} \right) \left(\bar{\hat{\mathcal{F}}}' \mathcal{U}_{\mathcal{F}'}^\dagger \gamma_{\mu L} \tau^a \mathcal{U}_{\mathcal{F}'} \hat{\mathcal{F}}' \right), \quad (2.5)$$

and analogous structures are generated by the G_{Ra} terms. Hence, in either the left- or right-handed sector, these effective interactions have the form $\sum_a J_{\mathcal{F}}^a \times J_{\mathcal{F}'}^a / M_{G_a}^2$. Then, from eq. (2.5) one sees that, *in the limit of mass degeneracy* across the horizontal bosons of either sector, products of currents involving the same fermions, $\mathcal{F} = \mathcal{F}'$ (for example, both equal to down-type quarks), are such that the rotations $\mathcal{U}_{\mathcal{F}}$ can be shuffled in the definition of the horizontal gauge-boson fields, and *the corresponding fermion bilinears can be taken as flavour diagonal in all generality* [41].

As advertised above, this property is welcome, because new off-diagonal contributions to products of currents with $\mathcal{F} = \mathcal{F}'$ are severely constrained by data, in particular meson mixings ($\mathcal{F} = \mathcal{F}' = d$) and respectively purely leptonic LFV decays such as $\tau \rightarrow 3\mu$ ($\mathcal{F} = \mathcal{F}' = \ell$). In the absence of such mechanism, these processes would pose the most formidable constraints, as they do in other SM extensions by gauge groups, in particular W', Z' ones (see in particular [21, 43–45]). In fact, these constraints are perhaps the most outstanding reason in favour of models with lepto-quark mediators, whereby $J_\ell \times J_\ell$ and $J_q \times J_q$ currents⁴ are generated only at loop level.

There is actually a subtlety, already mentioned in footnote 3. Although above the EWSB scale $SU(2)_h$ involves (by construction) only the 2nd and 3rd generations, mixing beneath this scale involves all the three generations. As a consequence, the $\mathcal{U}_{\mathcal{F}}$ matrices in eq. (2.4) are not exactly unitary, implying that the contributions to processes such as meson mixings, as well as to decays involving only leptons, are non-zero. It is true that these contributions will be parametrically suppressed by powers of the mixing between the two heavier and the light generation. However, a non-zero mixing onto the 1st generation translates into contributions to light-fermion processes like $K^0 - \bar{K}^0$ mixing and $\mu \rightarrow 3e$ for

³For two generations, as in eq. (2.2), these transformations are actually not unitary. Here we are sacrificing accuracy for the sake of presenting the main argument. We will make notation more precise afterwards.

⁴At least in lepto-quark models where di-quark couplings are absent [46].

example, which are well-known to be very constraining [47]. We will discuss such effects in detail in the analysis.

We need meanwhile to generalize the formalism in eqs. (2.1)–(2.5) to account for three-generation mixing. We then define

$$\mathcal{F} \equiv \begin{pmatrix} f_1 \\ f_2 \\ f_3 \end{pmatrix}. \quad (2.6)$$

The Lagrangian shift in eq. (2.1) becomes

$$\delta\mathcal{L} = \sum_{\mathcal{F}} \tilde{\mathcal{F}} \left(g_L \gamma_\mu L G_L^{\mu a} + g_R \gamma_\mu R G_R^{\mu a} \right) T^a \mathcal{F}, \quad (2.7)$$

with namely the replacement $\tau^a \rightarrow T^a$, where

$$T^a \equiv \begin{pmatrix} 0_{1 \times 1} & \\ & \tau^a \end{pmatrix}, \quad (2.8)$$

and eqs. (2.3) and (2.5) will change accordingly. It is this Lagrangian that we will use in the analysis.

We reiterate that the argument leading to flavour-diagonal $J_q \times J_q$ and $J_\ell \times J_\ell$ amplitudes holds for horizontal bosons with degenerate masses, which needn't be the case. In fact, a departure from the hypothesis of exact mass degeneracy will be instrumental for our framework to withstand the constraints from, in particular, $D^0 - \bar{D}^0$ mixing. Effects on this and other observables will thus be parametric in the mass splittings among the horizontal bosons. As concerns the performance of eq. (2.7) in explaining $R_{K^{(*)}}$, we note that the introduction of a sizeable contribution to the quark right-handed bilinear is expected to upset the relation $R_{K^*} \simeq R_K$ [48]. The bulk of our analysis will therefore assume $g_R = 0$.

Before concluding, two points deserve discussion. First, the question whether the enlarged gauge group may introduce anomalies, even with just the SM matter content. A simple horizontal gauge group G_h introduces two potentially worrisome anomaly diagrams: the one with G_h^3 and the one with $G_h^2 \times \text{U}(1)_Y$. Having chosen G_h to be an $\text{SU}(2)$ group, the first diagram vanishes — whereas it wouldn't for larger simple groups such as $\text{SU}(3)$. As concerns the second diagram, it likewise vanishes, and it does so for the same reason also at work within the SM, namely the rather magical compensation of the quark vs. lepton $\text{U}(1)_Y$ quantum numbers of either chirality. So this anomaly cancels separately for an $\text{SU}(2)_h$ coupled only to left-handed fermions or to right-handed ones.

A second outstanding question concerns the specification of the Yukawa sector, addressing for example how a horizontal symmetry involving the two heavier generations may be compatible with the observed fermion masses and mixing. A first possible scenario would be to invoke a Yukawa sector bilinear in SM fermion fields. Such scenario requires the introduction of new scalar representations that are charged under G_h , notably in Yukawa terms with products between 1st- and 2nd- or 3rd-generation SM fermions. The resulting construction resembles general models with extended Higgs sectors, that will reintroduce

tree-level contributions to the very FCNC processes that our initial symmetry argument is designed to guard against. A more promising possibility is to consider a scenario akin to partial compositeness [49], where the UV Yukawa terms involve the product between SM fermions, new vector-like fermions Ψ as well as suitable scalar representations Φ_i to break $SU(2)_h$ spontaneously. For definiteness, one could consider the following field content

$$\Psi_{L,R}^U \sim (\mathbf{3}, \mathbf{1}, 2/3; \mathbf{2}), \quad \Psi_{L,R}^D \sim (\mathbf{3}, \mathbf{1}, -1/3; \mathbf{2}), \quad \Phi_{1,2} \sim (\mathbf{1}, \mathbf{1}, 0; \mathbf{2}), \quad (2.9)$$

where transformation properties refer to $G_{\text{SM}} \times G_h$. This field content gives rise to the following renormalizable Lagrangian terms

$$\begin{aligned} \delta\mathcal{L}_Y \supset & m_U \bar{\Psi}_L^U \Psi_R^U + m_D \bar{\Psi}_L^D \Psi_R^D \\ & + \sum_{a=1,2} \sum_{i=1,\dots,3} \left((Y_U)_{ai} \bar{\Psi}_L^U \Phi_a (u_R)_i + (Y_D)_{ai} \bar{\Psi}_L^D \Phi_a (d_R)_i \right) \\ & + c_U \bar{F}_Q \tilde{H} \Psi_R^U + c_D \bar{F}_Q H \Psi_R^D + \text{H.c.}, \end{aligned} \quad (2.10)$$

where i is a flavour index, $F_Q = ((Q_L)_2, (Q_L)_3)^T$, with $2,3$ generation indices, and H is the SM Higgs doublet. SM Yukawa terms for quarks would then arise after integrating out the heavy Ψ and assigning vev's to the Φ 's. Two scalar fields are needed in eq. (2.9) in order to generate rank-3 effective Yukawa matrices. The number of dimensionless parameters and mass scales thus involved is sufficient to accommodate quark masses and mixing. An entirely similar construction allows to also address lepton masses and mixing. Gauge models for $b \rightarrow s$ anomalies implementing a similar mechanism are refs. [50–52].

2.1 Low-energy theory and notation

The most general dimension-six Hamiltonian describing the transition $b \rightarrow s \ell_1^- \ell_2^+$ with $\ell = e, \mu, \tau$ reads (we adopt the normalization in [53])

$$\begin{aligned} \mathcal{H}_{\text{eff}} = & -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left\{ \sum_{i=1}^6 C_i(\mu) \mathcal{O}_i(\mu) + \sum_{i=7,8} \left[C_i(\mu) \mathcal{O}_i(\mu) + (C_i(\mu))' (\mathcal{O}_i(\mu))' \right] \right. \\ & \left. + \sum_{i=9,10,S,P} \left[C_i^{\ell_1 \ell_2}(\mu) \mathcal{O}_i^{\ell_1 \ell_2}(\mu) + (C_i^{\ell_1 \ell_2}(\mu))' (\mathcal{O}_i^{\ell_1 \ell_2}(\mu))' \right] \right\} + \text{h.c.}, \end{aligned} \quad (2.11)$$

where $C_i(\mu)$ and $C_i^{\ell_1 \ell_2}(\mu)$ are the Wilson coefficients, while the effective operators relevant to our study are defined by

$$\mathcal{O}_9^{\ell_1 \ell_2} = \frac{e^2}{(4\pi)^2} (\bar{s} \gamma_\mu L b) (\bar{\ell}_1 \gamma^\mu \ell_2), \quad \mathcal{O}_{10}^{\ell_1 \ell_2} = \frac{e^2}{(4\pi)^2} (\bar{s} \gamma_\mu L b) (\bar{\ell}_1 \gamma^\mu \gamma^5 \ell_2), \quad (2.12)$$

in addition to the electromagnetic-dipole operator $\mathcal{O}_7 = e/(4\pi)^2 m_b (\bar{s} \sigma_{\mu\nu} P_R b) F^{\mu\nu}$. The chirality-flipped operators $\mathcal{O}'_i$ are obtained from $\mathcal{O}_i$ by the replacement $P_L \leftrightarrow P_R$. Henceforth we will split Wilson coefficients as $C_i = C_i^{\text{SM}} + \delta C_i$ so that the SM limit [54–56] for the Wilson coefficients is obtained by $\delta C_i^{(\prime)} = 0$. Using the Hamiltonian given above, it is straightforward to compute the decay rates of $B_s \rightarrow \ell_1^- \ell_2^+$, $B \rightarrow K^{(*)} \ell_1^- \ell_2^+$ [57, 58], and

other similar modes, including radiative ones, given that the effective Hamiltonian is the same [59, 60].

The pattern of observed departures of *all* $b \rightarrow s\ell\ell$ data from the SM finds a straightforward interpretation within the above EFT framework [8–13]. Interestingly, among the preferred operators to explain the anomalies is the product of two left-handed currents [61, 62], i.e. $\delta C_9^{\mu\mu} = -\delta C_{10}^{\mu\mu}$. Such solution is especially appealing theoretically, as it can naturally be expressed in terms of the $SU(2)_L$ -invariant fields Q_L and L_L [14, 15], which is what one would expect of new effects generated above the electroweak symmetry-breaking (EWSB) scale. In order to obtain a ‘conservative’ estimate of the allowed range for these Wilson coefficients, we use the results quoted in ref. [11] using only the ratios R_K and R_{K^*} , as well as the leptonic decay $\mathcal{B}(B_s \rightarrow \mu^+\mu^-)$. The result of the fit to 1σ accuracy is

$$\delta C_9^{(\mu)} = -\delta C_{10}^{(\mu)} \in [-0.85, -0.50]. \quad (2.13)$$

3 Scenario 0

We then start from the effective Lagrangian eq. (2.3), keeping henceforth only the left-handed interaction as motivated in the Introduction, and with mass-degenerate horizontal bosons. In order to simplify notation, we will in the rest of our paper remove the L subscript from the G_{La} fields (denoted simply as G_a) as well as from the quark and lepton multiplets in generation space. We will instead keep the subscript in g_L , in order that this coupling not be confused with SM ones.

Fermionic fields $\mathcal{F}$, eq. (2.6), are rotated to the mass eigenbasis through chiral transformations $\mathcal{U}_{\mathcal{F}}$. The most general parameterization compatible with the $SU(2)_h$ symmetry would be of the form

$$\mathcal{U}_{\mathcal{F}} = \text{diag}(\exp(i\phi_{\mathcal{F}}), \exp(i\Phi_{\mathcal{F}})\Sigma_{\mathcal{F}}), \quad (3.1)$$

where $\Sigma_{\mathcal{F}} = \exp(i\vec{\theta}_{\mathcal{F}} \cdot \vec{\sigma}/2)$ parameterizes a general $SU(2)$ transformation acting on the $f_{2,3}$ components of the fermion $\mathcal{F}$, see eq. (2.6). The dependence on the phases $\phi_{\mathcal{F}}$ and $\Phi_{\mathcal{F}}$ cancels in quark and lepton bilinears. The dependence on the $SU(2)$ transformation in turn cancels in effective-Lagrangian terms involving one single fermion species, i.e. terms of the form in eq. (2.5) with $\mathcal{F} = \mathcal{F}'$, because of the argument made below that equation. As noted there, this mechanism [41] makes $J_q \times J_q$ and $J_\ell \times J_\ell$ amplitudes flavour diagonal (at tree level), thus preventing dangerous contributions to processes such as $B_s - \bar{B}_s$ mixing and $\tau \rightarrow 3\mu$.

Let us focus on the interaction term involving down-type quarks and charged leptons, $\delta\mathcal{L}_{\text{eff}}^{DL}$, which is of direct interest to us. Eq. (2.3) implies

$$\delta\mathcal{L}_{\text{eff}}^{DL} = -\frac{g_L^2}{m_G^2} \left[\bar{\hat{D}} \left(\mathcal{U}_D^\dagger \gamma_L^\mu T^a \mathcal{U}_D \right) \hat{D} \right] \left[\bar{\hat{L}} \left(\mathcal{U}_L^\dagger \gamma_{\mu L} T^a \mathcal{U}_L \right) \hat{L} \right], \quad (3.2)$$

where $\hat{D} = (d_L, s_L, b_L)^T$ and $\hat{L} = (e_L, \mu_L, \tau_L)^T$ denote left-handed mass-eigenstate fermions and m_G is the common mass of the G_a horizontal bosons. Using the argument below

eq. (2.5), one can rewrite eq. (3.2) as

$$\delta\mathcal{L}_{\text{eff}}^{DL} = -\frac{g_L^2}{m_G^2} \left[\hat{D} \left(\gamma_L^\mu T^a \right) \hat{D} \right] \left[\hat{\bar{L}} \left(\mathcal{U}_{DL}^\dagger \gamma_{\mu L} T^a \mathcal{U}_{DL} \right) \hat{L} \right], \quad (3.3)$$

where $\mathcal{U}_{DL} \equiv \mathcal{U}_D^\dagger \mathcal{U}_L$ can be parameterized as in eq. (3.1). Again, phase terms disappear in the lepton bilinear. As concerns the SU(2) transformation Σ_{DL} , it is convenient to express it in terms of Euler angles:

$$\Sigma_{DL} = \exp(-i\alpha_{DL}\sigma_3) \exp(-i\beta_{DL}\sigma_2) \exp(-i\gamma_{DL}\sigma_3). \quad (3.4)$$

Neglecting neutrino masses, the γ_{DL} phase can be absorbed in the definition of the charged-lepton fields. A similar rephasing of the D component fields to absorb α_{DL} would shuffle this phase to the CKM matrix, so α_{DL} and β_{DL} are physical.⁵

We next discuss the most general effects within the parameterization in eq. (3.4), in particular whether scenario 0 explains $R_{K^{(*)}}$ and what are the relevant constraints. By matching the Lagrangian in eq. (3.3) with eq. (2.11), we obtain the following Wilson-coefficient shifts δC_9^{ij}

$$\delta C_9^{\mu\mu} = -\delta C_9^{\tau\tau} = e^{-2i\alpha_{DL}} \frac{\sin 2\beta_{DL} g_L^2}{8m_G^2} \cdot \frac{2\pi v^2}{\alpha_{\text{em}} V_{tb} V_{ts}^*}, \quad (3.5)$$

$$\delta C_9^{\tau\mu} = e^{-2i\alpha_{DL}} \frac{\cos^2 \beta_{DL} g_L^2}{4m_G^2} \cdot \frac{2\pi v^2}{\alpha_{\text{em}} V_{tb} V_{ts}^*}, \quad (3.6)$$

$$\delta C_9^{\mu\tau} = -e^{-2i\alpha_{DL}} \frac{\sin^2 \beta_{DL} g_L^2}{4m_G^2} \cdot \frac{2\pi v^2}{\alpha_{\text{em}} V_{tb} V_{ts}^*}, \quad (3.7)$$

and one has also $\delta C_{10}^{ij} = -\delta C_9^{ij}$. The last factor on the r.h.s. of either of eqs. (3.5)–(3.7) corresponds to an effective scale $\approx 34 \text{ TeV}$ [11]. From eqs. (3.5)–(3.7) we also see that largest (in magnitude) shifts to the considered Wilson coefficients are obtained for $\alpha_{DL} \approx 0$ because of the nearly real SM normalization in the usual CKM conventions. The bounds in eq. (2.13) then would amount to

$$\frac{m_G^2}{\sin 2\beta_{DL} g_L^2} \in ([13, 17] \text{ TeV})^2, \quad (3.8)$$

and the correlation between the rotation β_{DL} and the scale m_G/g_L is shown in the left panel of figure 1. Eqs. (3.5)–(3.7) instruct us that a nonzero value of β_{DL} is needed to successfully explain $R_{K^{(*)}}$. This requirement automatically implies a nonzero value of $\delta C_9^{\tau\mu}$ and $\delta C_9^{\mu\tau}$. Therefore, LFV in the $b \rightarrow s\mu^\pm\tau^\mp$ channel is a very distinctive signature of our scenario, that we will discuss more extensively in section 4.1. It is likewise noteworthy that our framework predicts an asymmetry between $b \rightarrow s\mu^-\tau^+$ and $b \rightarrow s\mu^+\tau^-$, controlled by the β_{DL} value.

⁵Note that, if one sets $\alpha_{DL} = 0$, eq. (3.4) amounts to a generic rotation between the second and third generations. One sees that in the small- β_{DL} limit, operators that violate generation number (either of the quark or lepton one, or both) by one or two units are proportional to one or two powers of β_{DL} , respectively, whereas only operators that conserve generation numbers are present in the limit of no mixing [41].

Figure 1. Two relevant projections of the model parameter space within scenario 0. Gray points fulfil all constraints except R_K and x_D . Light-blue points fulfil also R_K . The dashed line represents the 3σ upper bound on x_D from ref. [7].

There is, however, an important caveat around eq. (3.1). Below the EWSB scale, the rotations $\mathcal{U}_D$ and $\mathcal{U}_U$ cannot both have the form in eq. (3.1), because $\mathcal{U}_U^\dagger \mathcal{U}_D = V_{\text{CKM}}$. This implies that, although the $\text{SU}(2)_h$ symmetry prevents the occurrence of flavour-violating $J_q \times J_q$ and $J_\ell \times J_\ell$ effects for scales above the EWSB one, $J_q \times J_q$ effects will be induced for lower scales, because of V_{CKM} -induced mixing.⁶ The most constraining of these effects turns out to be the mass difference in the $D^0 - \bar{D}^0$ system, ΔM_D . We imposed that the latest global fit to the related parameter x_D [7] be saturated by our model's short-distance prediction for the same quantity, that we estimated using ref. [63].⁷ We believe that this approach be justified, given that the possible range for the SM contribution to ΔM_D encompasses several orders of magnitude [65].

At face value,⁸ and quite unexpectedly, the x_D constraint excludes our scenario 0. However our model is suited for straightforward, and actually plausible, generalizations. The latter fall in at least two categories: (i) mass splittings among the three vector bosons of the $\text{SU}(2)_h$ symmetry; (ii) (small) mixing terms between the first and the two heavier generations in the T^a matrices of eq. (2.8). As we will discuss in the rest of the paper, the first generalization turns out to be sufficient to pass all constraints.

4 Scenario 1

The most straightforward generalization of the scenario discussed so far is to allow for non-degenerate masses for the gauge bosons of the $\text{SU}(2)_h$ symmetry. The simplest mass

⁶On the other hand, $J_\ell \times J_\ell$ effect will remain tiny because of the very small neutrino masses.

⁷For all details on the implementation, see ref. [64].

⁸I.e. barring a tuning of order 10^{-2} between the SM and the new-physics contribution.

splitting is such that two masses stay degenerate. Such splitting can be achieved via the symmetry-breaking pattern advocated in ref. [66], i.e. through one spin-1/2 *and* one spin-1 fundamental scalar representation.

With split G_a masses, we are no more allowed to bundle the two unitary transformations $\mathcal{U}_D$ and $\mathcal{U}_L$ in one single transformation, as in eq. (3.3). Our effective interaction is thus

$$\delta\mathcal{L}_{\text{eff}}^{DL} = - \sum_a \frac{g_L^2}{m_{G_a}^2} \left[\hat{\bar{D}} \left(\mathcal{U}_D^\dagger \gamma_L^\mu T^a \mathcal{U}_D \right) \hat{D} \right] \left[\hat{\bar{L}} \left(\mathcal{U}_L^\dagger \gamma_{\mu L} T^a \mathcal{U}_L \right) \hat{L} \right], \quad (4.1)$$

i.e. akin to eq. (3.2) but for non-degenerate G_a masses. In a notation straightforwardly generalizing that in eq. (3.4), the matrices $\mathcal{U}_{D,L}$ will introduce the rotations β_D and β_L , as well as the phase parameters $\alpha_{D,L}$ and $\gamma_{D,L}$. To the extent that we do not consider CP -violating observables, non-zero values for these phase terms serve only to suppress the magnitude of the Wilson coefficients relevant to our analysis — see discussion around eqs. (3.5)–(3.7). We will therefore set $\alpha_{D,L} = \gamma_{D,L} = 0$ and focus on the rotations β_D and β_L . We note that, after EWSB, the above choice for the $\mathcal{U}_D$ matrix allows to subsequently set $\mathcal{U}_U = \mathcal{U}_D V_{\text{CKM}}^\dagger$. An important assumption concerns then the $\mathcal{U}_D$ parameterization. We assume, on phenomenological grounds, that $\mathcal{U}_D$ still fulfils the block-diagonal form in eq. (3.4), because this guarantees the absence of tree-level effects in $K^0 - \bar{K}^0$ mixing.

Quite remarkably a scenario with

$$m_{G_1} = m_{G_2} \ll m_{G_3} \quad \& \quad |\sin 2\beta_D| \ll |\sin 2\beta_L| \quad (4.2)$$

accounts at one stroke for new effects in $b \rightarrow s\mu\mu$ as large as measured and is compatible with the SM-like results in all other collider datasets. We remark from the outset that, allowing for a mass hierarchy between the horizontal gauge bosons amounts to completely forsaking the argument made below eq. (2.5). This makes scenarios 0 and 1 completely different at the level of the underlying mechanisms. Within scenario 0 (degenerate horizontal-boson masses) the flavour diagonality of $J_q \times J_q$ and $J_\ell \times J_\ell$ currents would be the result of an underlying global symmetry coming with the postulated $\text{SU}(2)_h$ group. However, off-diagonalities are inescapable because of the CKM matrix, and the result is too large a contribution to $D^0 - \bar{D}^0$ mixing. Within scenario 1, one allows for non-degenerate masses, and phenomenological viability chooses a hierarchical pattern, i.e. one of $\text{O}(1)$ breaking of the mentioned *global* symmetry.

The basic mechanism at work can be straightforwardly understood by inspection of the model's prediction of $D^0 - \bar{D}^0$ mixing and R_K , that scenario 0 fell short to describe simultaneously. We will see that, with these two phenomenological requirements fulfilled, all other constraints fall in place, either because of the pattern in eq. (4.2), or because of the underlying $\text{SU}(2)_h$ symmetry. We will next discuss all these requirements in turn.

Within scenario 1, the contribution to $D^0 - \bar{D}^0$ is due to

$$\delta\mathcal{L}_{\text{eff}}^{UU} = - \sum_a \frac{g_L^2}{2m_{G_a}^2} (\bar{U}' \gamma_L^\mu T^a U')^2 \supset C_{(uc)^2} (\bar{u} \gamma_L^\mu c)^2, \quad (4.3)$$

Figure 2. Color code henceforth: grey points fulfil all constraints except R_K and x_D ; light-blue points also fulfil R_K , but not x_D ; dark-blue points fulfil all constraints. Left panel: R_K vs. m_{G_1}/g_L as implied by eq. (4.5). Right panel: effective mass scale for the heavier among the G_a bosons, as required by the x_D constraint. The horizontal dashed line denotes the 3σ upper bound on x_D [7].

where, exploiting CKM hierarchies, we can write

$$C_{(uc)^2} = -(V_{us}V_{cs}^*)^2 \frac{g_L^2}{8} \left(\frac{\sin^2(2\beta_D)}{m_{G_1}^2} + \frac{\cos^2(2\beta_D)}{m_{G_3}^2} \right) + O(\lambda^4). \quad (4.4)$$

with λ the Wolfenstein parameter. While the approximate formula in eq. (4.4) is very convenient to exhibit the mechanism at work, the numerical analysis includes the exact CKM dependence. In turn, the model's contribution to $\delta C_{9,10}^{\mu\mu}$ reads

$$\delta C_9^{\mu\mu} = -\delta C_{10}^{\mu\mu} = \frac{g_L^2}{4} \frac{v^2 \pi}{\alpha_{\text{em}} V_{tb} V_{ts}^*} \left[\frac{\sin(2\beta_D) \cos(2\beta_L)}{m_{G_3}^2} - \frac{\sin(2\beta_L) \cos(2\beta_D)}{m_{G_1}^2} \right]. \quad (4.5)$$

Clearly, with the advocated pattern of G_a masses and rotation angles, the contribution in eq. (4.4) will be parametrically suppressed by the decoupling of G_3 plus the smallness of β_D , and this very pattern ensures a sizeable contribution to $\delta C_9^{\mu\mu}$ from the second, negative term in eq. (4.5). These features are displayed more quantitatively in figure 2. In particular, the effective scale for the lighter among the G_a bosons is shown versus R_K in the left panel, where dark blue denotes points that fulfil all other constraints to be described later, and including x_D . The effective mass scale pointed to by the x_D constraint, ruled by m_{G_3}/g_L ,⁹ is displayed in the right panel of figure 2. In figure 3 we also display the hierarchy in the second of eqs. (4.2) versus the lightest G_a mass. The left panel shows a quite strong correlation between the absolute scale of the effects and the actual size allowed

⁹It is clear that the requirement that x_D saturate the experimental result entails a strong correlation between m_{G_1} and β_D in eq. (4.4).

Figure 3. $\sin 2\beta_{L,R}$ vs. m_{G_1}/g_L as implied by eq. (4.2), see text for details. Color code as in figure 2.

to the large angle, namely β_L . This correlation arises from the measurement of $R_K^{(*)}$, in the limit of large m_{G_3} , as it can be seen from eq. (4.5). Conversely, the right panel confirms that, once all constraints are taken into account, $\sin 2\beta_D$ should be small regardless of the value of m_{G_1} , as discussed below eq. (4.2).

A few qualifications are now in order on the general setup of our numerical analysis. So far we focused on $D^0 - \bar{D}^0$ mixing because it turned out to be the most constraining observable within scenario 0. However, the pattern of parameters that we advocated in eq. (4.2) may generate large effects in other observables, to be discussed in the next sections. With the exception of $\tau \rightarrow \mu\gamma$, that we comment upon in section 4.6, all of our considered observables depend on the ratios m_{G_a}/g_L , rather than on masses and g_L separately. Our main numerical scan then assumes the ranges to follow

$$m_{G_a}/g_L \in [1, 500] \text{ TeV} \quad \& \quad \beta_D, \beta_L \in [0, 2\pi). \quad (4.6)$$

It goes without saying that the upper limit of 500 TeV in general corresponds to m_{G_a} values *well below* this mass scale, because g_L is in general well below unity. As concerns the hierarchies in eq. (4.2), we followed two alternative procedures: on the one side, we performed scans imposing such hierarchies from the outset; on the other side, we let the constraints choose them. We found no appreciable difference in the results obtained with these alternative procedures.

4.1 $b \rightarrow s\ell\ell'$ and leptonic LFV

A large β_L , combined with a value for m_{G_1} as low as required by $R_{K^{(*)}}$, may lead to troublesome effects in particular in $b \rightarrow s\tau^\pm\mu^\mp$ as well as in leptonic LFV decays such as $\tau \rightarrow 3\mu$. Quite interestingly, the effects are indeed sizeable, but below existing limits. Besides, the small number of parameters involved establishes clear-cut correlations between LUV and

LFV observables, as well as across different LFV observables. These correlations represent a prominent feature of our model, as can be qualitatively understood, again, from the basic formulae for the relevant Wilson coefficients. A first comment concerns $b \rightarrow s\tau\tau$. Since

$$\delta C_{9,10}^{\tau\tau} = -\delta C_{9,10}^{\mu\mu}, \quad (4.7)$$

the departure of $\mathcal{B}(B \rightarrow K\tau\tau)$ from its SM prediction can be written as a function of the departure of R_K from unity. As a consequence, modifications of branching ratios for $B \rightarrow K\tau\tau$ as well as $B_s \rightarrow \tau\tau$ will be of the order of 20% with respect to the respective SM expectations, which are sizeably below existing limits [67, 68].

We next turn to the predictions for $b \rightarrow s\tau\mu$ decays. The relevant Wilson coefficients read

$$\delta C_9^{\mu\tau} = -\frac{g_L^2}{4} \frac{v^2\pi}{\alpha_{\text{em}} V_{tb} V_{ts}^*} \left(\frac{\cos 2\beta_D \cos 2\beta_L}{m_{G_1}^2} + \frac{\sin 2\beta_D \sin 2\beta_L}{m_{G_3}^2} - \frac{1}{m_{G_2}^2} \right), \quad (4.8)$$

$$\delta C_9^{\tau\mu} = -\frac{g_L^2}{4} \frac{v^2\pi}{\alpha_{\text{em}} V_{tb} V_{ts}^*} \left(\frac{\cos 2\beta_D \cos 2\beta_L}{m_{G_1}^2} + \frac{\sin 2\beta_D \sin 2\beta_L}{m_{G_3}^2} + \frac{1}{m_{G_2}^2} \right). \quad (4.9)$$

Keeping in mind the main assumptions defining our scenario 1, eq. (4.2), it is clear that the dominant dependence is on $|\cos 2\beta_L \pm 1|/m_{G_{1,2}}^2$. Hence, a rather distinctive feature of this scenario is that $\mathcal{B}(B \rightarrow K\tau^+\mu^-) \neq \mathcal{B}(B \rightarrow K\tau^-\mu^+)$, although either can be larger than the other, depending on the choice of the β_L phase. The correlation between these two modes is displayed in figure 4. The dominant parametric dependence highlighted above translates into an approximate reflection symmetry of the plot around the diagonal.

Most importantly, our model predicts not only an upper bound, but also a lower bound on the LFV rates. We obtain (see also left panel of figure 5)

$$1.3 \times 10^{-8} \lesssim \mathcal{B}(B \rightarrow K\mu^+\tau^-) + \mathcal{B}(B \rightarrow K\mu^-\tau^+) \lesssim 5.2 \times 10^{-6}. \quad (4.10)$$

Interestingly, the maximal rate predicted by our scenario lies just one order of magnitude below the existing limits obtained by BaBar [69], $\mathcal{B}(B \rightarrow K\mu^+\tau^-)_{\text{exp}} < 4.5 \times 10^{-5}$ and $\mathcal{B}(B \rightarrow K\mu^-\tau^+)_{\text{exp}} < 2.8 \times 10^{-5}$.¹⁰ As discussed in ref. [58], the predictions given above can be translated into corresponding fiducial ranges on the other exclusive decays generated by the $b \rightarrow s\mu\tau$ current

$$\frac{\mathcal{B}(B_s \rightarrow \mu^\pm\tau^\mp)}{\mathcal{B}(B \rightarrow K\mu^\pm\tau^\mp)} \approx 0.9, \quad \frac{\mathcal{B}(B \rightarrow K^*\mu^\pm\tau^\mp)}{\mathcal{B}(B \rightarrow K\mu^\pm\tau^\mp)} \approx 1.8, \quad (4.11)$$

where we take central values for the hadronic parameters. These relations show that $B \rightarrow (K)\ell\ell'$ decays with a final-state τ are expected to be related with each other by $\mathcal{O}(1)$ factors [73], i.e. that *experimentally reaching one of them will possibly lead to reaching them all*. Existing experimental limits for these channels are not very constraining [74],¹¹ and yet this is a very characteristic prediction of models that interpret $b \rightarrow s\ell\ell$ discrepancies as due to a $(V-A) \times (V-A)$ interaction coupled, above the EWSB scale, to third-generation-only SM fermions [73].

¹⁰Also noteworthy, the lower bound is in good accord with the predictions obtained within approaches motivated by completely different considerations [18, 58, 70–72].

¹¹Strongest limits are on modes with final-state electrons and muons, e.g. ref. [75].

Figure 4. Correlation between the two $\mathcal{B}(B \rightarrow K\mu\tau)$ modes within scenario 1. Color code as in figure 2. Dashed lines denote the existing bounds on the respective modes [69], see text for details.

As anticipated, the above LFV predictions are in turn correlated with purely leptonic LFV, in particular in the processes $\tau \rightarrow 3\mu$ and $\tau \rightarrow \phi\mu$. From

$$\delta\mathcal{L}_{\text{eff}}^{LL} \supset +\frac{g_L^2}{8}\sin(4\beta_L)\left(\frac{1}{m_{G_3}^2}-\frac{1}{m_{G_1}^2}\right)(\bar{\tau}\gamma_L^\mu\mu)(\bar{\mu}\gamma_{\mu L}\mu), \quad (4.12)$$

one gets [76]

$$\mathcal{B}(\tau \rightarrow 3\mu) = \frac{m_\tau^5}{3072\pi^3\Gamma_\tau}\frac{g_L^4}{64}\sin^2(4\beta_L)\left(\frac{1}{m_{G_3}^2}-\frac{1}{m_{G_1}^2}\right)^2. \quad (4.13)$$

Besides, from

$$\delta\mathcal{L}_{\text{eff}}^{LD} \supset C_{ss}^{\mu\tau}(\bar{\mu}\gamma_L^\mu\tau)(\bar{s}\gamma_{\mu L}s) \quad (4.14)$$

with

$$C_{ss}^{\mu\tau} = -\frac{g_L^2}{4}\left[-\frac{\cos(2\beta_D)\sin(2\beta_L)}{m_{G_3}^2} + \frac{\sin(2\beta_D)\cos(2\beta_L)}{m_{G_1}^2}\right], \quad (4.15)$$

one likewise arrives at

$$\mathcal{B}(\tau \rightarrow \mu\phi) \simeq |C_{ss}^{\mu\tau}|^2 \frac{f_\phi^2 m_\phi^4}{64\pi m_\tau \Gamma_\tau} \left(1 - \frac{m_\phi^2}{m_\tau^2}\right) \left(-1 + \frac{m_\tau^2}{2m_\phi^2} + \frac{m_\tau^4}{2m_\phi^4}\right), \quad (4.16)$$

where $f_\phi = 241(18)$ MeV is the ϕ -meson decay constant [77], and we have neglected the m_μ mass dependence, which amounts to an approximation of few percent.

Similarly to the transition $b \rightarrow s\mu^+\mu^-$, this observable is only modified for nonzero values of β_L . From the current experimental limit [78, 79] (90% CL), and keeping in mind

Figure 5. Left panel: correlation between $\mathcal{B}(B \rightarrow K\tau^\pm\mu^\mp)$ and $\tau \rightarrow 3\mu$. Right panel: correlation between $\tau \rightarrow 3\mu$ and $\tau \rightarrow \mu\phi$. Color code as in figure 2.

eq. (4.2), we obtain

$$\frac{m_{G_{1,2}}^2}{g_L^2 \sin 2\beta_D \cos 2\beta_L} \geq (3.7 \text{ TeV})^2, \quad (4.17)$$

which is once again consistent with the constraint derived in eq. (3.8) from $R_{K^{(*)}}$. From the requirement that the $R_{K^{(*)}}$ discrepancies be reproduced at 1σ , we obtain $\mathcal{B}(\tau \rightarrow \mu\phi)$ as large as 1×10^{-10} and, in general, model points mostly populating the range between 10^{-14} and 10^{-10} (see right panel of figure 5). It is worth mentioning that the projected Belle-II sensitivity to this decay is around 10^{-9} .¹²

In the parameter space of eq. (4.2), the above formulae translate into a triple correlation between $\mathcal{B}(B \rightarrow K\mu^\pm\tau^\mp)$, $\mathcal{B}(\tau \rightarrow 3\mu)$ and $\mathcal{B}(\tau \rightarrow \mu\phi)$, illustrated in the two plots of figure 5.

4.2 $\Delta M_s/\Delta M_d$

Mixings in the $B_{d,s}$ sector, in particular the ratio $\Delta M_s/\Delta M_d$, represent a strong constraint (see ref. [81] for a recent discussion). Actually, it is mainly this constraint that selects the mass hierarchy in eq. (4.2), the angles' hierarchy being instead mostly the result of R_K and x_D . From the effective Hamiltonian

$$\mathcal{H}_{\text{eff}}^{\Delta M_q} = (C_1^{\text{SM}} + \delta C_1^q)(\bar{q}\gamma_L^\mu b)^2 + \text{h.c.} \quad (4.18)$$

with q either of d or s , and using ref. [56] to get C_1^{SM} in our normalization, we obtain

$$\delta C_1^s = \frac{g_L^2}{8} \left(\frac{\cos^2 2\beta_D}{m_{G_1}^2} + \frac{\sin^2 2\beta_D}{m_{G_3}^2} - \frac{1}{m_{G_2}^2} \right), \quad \delta C_1^d = 0. \quad (4.19)$$

¹²See e.g. ref. [80].

We can then write

$$\frac{\Delta M_s}{\Delta M_d} = \left| \frac{V_{ts}}{V_{td}} \right|^2 \xi^2 \frac{m_{B_s}}{m_{B_d}} \left| 1 + \frac{\delta C_1^s}{C_1^{\text{SM}}} \right|. \quad (4.20)$$

Taking $\xi = 1.239(46)$ [82] as well as $|V_{ts}/V_{td}| = 4.58(24)$ from a Unitarity-Triangle fit using only quantities not affected by new physics [83, 84],¹³ one would obtain the SM prediction $(\Delta M_s/\Delta M_d)_{\text{SM}} = 33(4)$, perfectly consistent with the value $(\Delta M_s/\Delta M_d)_{\text{exp}} = 35.06(14)$ obtained from the mass differences reported in ref. [74]. Our model's prediction for this ratio, normalized to the SM result, reads

$$\frac{\Delta M_s}{\Delta M_d} / \left(\frac{\Delta M_s}{\Delta M_d} \right)_{\text{SM}} \in [0.8, 1]. \quad (4.21)$$

In short, the model tends to predict a suppression of the order of 10-20%. However, such shift comes with an error of comparable size, about 12%, dominated by the CKM input, followed by the ξ input. This error at present prevents this observable from providing a stringent test of our framework. Such test will however be possible with improvements on fits to the unitarity triangle using only observables realistically unaffected by new physics, such as γ from $B \rightarrow DK^{(*)}$ (see in particular [86–88]). This highlights the well-known importance of improvements in such ‘standard-candle’ measurements.

4.3 $B \rightarrow K\nu\bar{\nu}$

Within our model, an explanation of $R_{K^{(*)}}$ implies new contributions to the $B \rightarrow K^{(*)}\nu\bar{\nu}$ decays. The only part of the $b \rightarrow s\nu\bar{\nu}$ Hamiltonian relevant to our discussion is (we adhere to the notation in [89])

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* C_L^{ij} \mathcal{O}_L^{ij} + \text{h.c.} \quad (4.22)$$

with

$$\mathcal{O}_L^{ij} = \frac{e^2}{(4\pi)^2} (\bar{s} \gamma_L^\mu b) (\bar{\nu}_i \gamma_\mu (1 - \gamma_5) \nu_j). \quad (4.23)$$

We define the ratio $R_{\nu\nu}^{(*)} \equiv \mathcal{B}(B \rightarrow K^{(*)}\nu\nu)/\mathcal{B}(B \rightarrow K^{(*)}\nu\nu)^{\text{SM}}$, where, as usual, a sum over the (undetected) neutrino species is understood. In our scenario this ratio is modified as follows

$$R_{\nu\nu}^{(*)} = \frac{\sum_{ij} |\delta_{ij} C_L^{\text{SM}} + \delta C_L^{ij}|^2}{3|C_L^{\text{SM}}|^2} = 1 + \frac{2C_L^{\text{SM}} \sum_i \delta C_L^{ii} + \sum_{ij} |\delta C_L^{ij}|^2}{3|C_L^{\text{SM}}|^2}, \quad (4.24)$$

where $C_L^{\text{SM}} = -6.38(6)$ is the SM Wilson coefficient as defined in ref. [89]. The contributions to $R_{\nu\nu}^{(*)}$ induced by new physics are encoded in the Wilson coefficients δC_L^{ij} , which satisfy $\delta C_L^{ij} = 2\delta C_9^{ij}$, cf. eq. (2.11). Note that $R_{\nu\nu} = R_{\nu\nu}^*$ in our framework because of the absence of contributions to the right-handed counterpart of the operator $\mathcal{O}_L^{ij}$ [48]. By replacing eqs. (3.5)–(3.7) in eq. (4.24), we obtain

$$R_{\nu\nu}^{(*)} = 1 + \frac{1}{3|C_L^{\text{SM}}|^2} \frac{v^4 \pi^2}{\alpha_{\text{em}}^2 |V_{tb} V_{ts}^*|^2} \frac{g_L^4}{8} \left(\frac{\cos^2 2\beta_D}{m_{G_1}^4} + \frac{\sin^2 2\beta_D}{m_{G_3}^4} + \frac{1}{m_{G_2}^4} \right). \quad (4.25)$$

¹³A similar prediction may be obtained using the CKMfitter code [85].

Interestingly, the flavour-diagonal contributions satisfy $\delta C_L^{\mu\mu} = -\delta C_L^{\tau\tau}$ (whereas C_L^{ee} is not modified), so that interference terms between the SM and NP *vanish*, and NP contributions only enter at second order in the small ratio $\delta C_L^{ij}/C_L^{\text{SM}}$. Because of this feature, which is a consequence of the underlying $\text{SU}(2)_h$ symmetry, the strong experimental constraints $R_{\nu\nu}^* < 2.7$ [89, 90] do not pose, within our model, a challenge in the description of $b \rightarrow s$ anomalies. More quantitatively, using eq. (4.2) the $R_{\nu\nu}^{\text{exp}}$ constraint can be translated into the bound

$$\frac{m_{G_{1,2}}^2}{g_L^2 \sqrt{1 + \cos^2 2\beta_D}} \geq (3.8 \text{ TeV})^2, \quad (4.26)$$

much weaker than the constraint derived in eq. (3.8). Note that the dependence on β_L disappears because of the sum over all neutrino species.

4.4 $\tau \rightarrow \mu\nu\bar{\nu}$

In spite of the horizontal gauge bosons G_a being electrically neutral, they can also contribute to processes that in the SM are generated by charged currents, for example $\ell \rightarrow \ell' \nu \bar{\nu}$ decays. More precisely, one can show that the following term appears in $\delta\mathcal{L}_{\text{eff}}$

$$\delta\mathcal{L}_{\text{eff}} \supset -\frac{g_L^2}{4} \left(\frac{\sin^2 2\beta_L}{m_{G_3}^2} + \frac{\cos^2 2\beta_L}{m_{G_1}^2} + \frac{1}{m_{G_2}^2} \right) (\bar{\nu}_\tau \gamma_L^\mu \nu_\mu) (\bar{\mu} \gamma_\mu L \tau). \quad (4.27)$$

This contribution entails the following modification of $\mathcal{B}(\tau \rightarrow \mu\nu\nu)$ with respect to its SM prediction

$$\frac{\mathcal{B}(\tau \rightarrow \mu\nu\nu)}{\mathcal{B}(\tau \rightarrow \mu\nu\nu)^{\text{SM}}} = 1 + \frac{g_L^2 v^2}{4} \left(\frac{\cos^2 2\beta_L}{m_{G_1}^2} + \frac{\sin^2 2\beta_L}{m_{G_3}^2} + \frac{1}{m_{G_2}^2} \right) + \dots, \quad (4.28)$$

where, for simplicity, we only show the dominant term coming from the interference, whereas in the numerics we include also the subleading (new-physics)² contributions. By using the experimental average $\mathcal{B}(\tau \rightarrow \mu\bar{\nu}_\mu\nu_\tau)_{\text{exp}} = 17.33(5)\%$ [74] and the SM prediction $\mathcal{B}(\tau \rightarrow \mu\bar{\nu}_\mu\nu_\tau)^{\text{SM}} = 17.29(3)\%$ [58], we obtain the following 2σ bound

$$\frac{m_{G_{1,2}}^2}{g_L^2 \sqrt{1 + \cos^2 2\beta_L}} \geq (1.6 \text{ TeV})^2, \quad (4.29)$$

which is weaker than the one derived in eq. (4.26) from the experimental limit on $\mathcal{B}(B \rightarrow K\nu\nu)$.

4.5 $D^0 \rightarrow \mu\mu$

Similarly to $D^0 - \bar{D}^0$ mixing, the CKM matrix induces a nonzero contribution to other charm-physics observables, most notably $D^0 \rightarrow \mu\mu$. We will show however that the induced modifications are too small to be observed with the sensitivity of the current experiments. The piece of eq. (2.5) describing four-fermion interactions of up-type quarks U' and charged leptons L' , the primes denoting as usual the ‘gauge’ basis, reads

$$\delta\mathcal{L}_{\text{eff}}^{UL} = -\sum_a \frac{g_L^2}{m_{G_a}^2} (\bar{U}' \gamma_L^\mu T^a U') (\bar{L}' \gamma_{\mu L} T^a L') \supset C_{uc}^{\mu\mu} (\bar{u} \gamma_L^\mu c) (\bar{\mu} \gamma_\mu L \mu). \quad (4.30)$$

After manipulations entirely analogous to those leading to eq. (4.4), we obtain

$$C_{uc}^{\mu\mu} = -V_{cs}^* V_{us} \frac{g_L^2}{4} \left(\frac{\cos 2\beta_D \cos 2\beta_L}{m_{G_3}^2} + \frac{\sin 2\beta_D \sin 2\beta_L}{m_{G_1}^2} \right) + O(\lambda^3). \quad (4.31)$$

We note again that the expansion in λ is only for illustrative purposes, and that in the numerics we use exact expressions. The corresponding branching ratio is then given by

$$\begin{aligned} \mathcal{B}(D^0 \rightarrow \mu^+ \mu^-) &= \frac{f_D^2 m_\mu^2 m_D}{32\pi \Gamma_D} \sqrt{1 - \frac{4m_\mu^2}{m_{D^0}^2}} \times \\ &\times \left[\frac{g_L^2}{4} |V_{cs}^* V_{us}| \left(\frac{\cos 2\beta_D \cos 2\beta_L}{m_{G_3}^2} + \frac{\sin 2\beta_D \sin 2\beta_L}{m_{G_1}^2} \right) \right]^2 + O(\lambda^4). \end{aligned} \quad (4.32)$$

where we have neglected the small SM contribution. This expression should be confronted with the current experimental limit $\mathcal{B}(D^0 \rightarrow \mu^+ \mu^-)_{\text{exp}} < 6.2 \times 10^{-9}$ [91]. However, by inspection of eq. (4.32) one sees that the relevant masses being bounded are a combination of $m_{G_1}^2 / \sin 2\beta_D$ and $m_{G_3}^2$. Keeping in mind the parameter space in eq. (4.2), one concludes that eq. (4.32) provides a bound on the heavier scale, not the lighter one, and is thus irrelevant.

4.6 Further constraints

Here we collect comments on further, potentially constraining, experimental information not discussed so far. A first comment deserves the decay $\tau \rightarrow \mu\gamma$, whose current experimental limit reads $\mathcal{B}(\tau \rightarrow \mu\gamma) \leq 4.4 \times 10^{-8}$ [92]. By construction, our model induces the required dipole interaction only at one loop. Therefore this decay is, at present, not very constraining within our model, as it suffers from a further loop and α_{em} suppression with respect to the other τ LFV decays discussed before, whose predictions are summarised in the right panel of figure 5.

Further consideration deserve possible bounds coming from direct searches. To our knowledge, the most relevant analysis for our case is ref. [93]. In particular, our model induces a contribution to $pp(s\bar{s}) \rightarrow \mu\mu$, which can be tested at the LHC by looking at the tails of dilepton distributions. Assuming that such distortions be the result of contact interactions of the kind

$$\mathcal{L}_{\text{eff}} \supset \frac{C_{ij}^{D\mu}}{v^2} (\bar{d}^i \gamma_L^\mu d^j) (\bar{\mu} \gamma_{\mu L} \mu), \quad (4.33)$$

with an effective scale well above the typical momentum exchange in the process, ref. [93] quotes a present-day limit on $|C_{ss}^{D\mu}|$ of around 1×10^{-2} . In our model, this coefficient is of order $g_L^2 \cdot v^2 / \min(m_{G_a}^2)$, that we can bound with $1 \times (0.246/5)^2 \simeq 2 \times 10^{-3}$, see e.g. x -axis scale on the left panel of figure 2. It is true that in some parts of our parameter space — with very low $\min(m_{G_a})$ and sizeable g_L — there may be distortions with respect to the effective-theory description in ref. [93]. While this aspect may warrant further investigation, we believe that the above argument provides a robust order-of-magnitude assessment of the constraint.

5 Conclusions

Semileptonic decays involving $b \rightarrow s$ and $b \rightarrow c$ quark currents display persistent deviations with respect to Standard-Model predictions, at present the only coherent array of departures from the Standard Model in collider data. The putative new dynamics must, directly or indirectly, involve the second and the third generation of quarks and leptons. Furthermore, it must produce sufficiently large effects in the product of a quark times a charged-lepton bilinear, $J_q \times J_\ell$, and sufficiently small effects in flavour-changing $J_q \times J_q$ and $J_\ell \times J_\ell$ amplitudes. Especially this second requirement has greatly oriented the model-building literature towards leptoquark models, that avoid the problem by construction, although they are not free of other shortcomings. In this paper we take a different approach. The two aforementioned requirements invite consideration of a ‘horizontal’ group, SU(2) being the smallest one that may be at play. We accordingly invoke the possibility of a gauged such symmetry, SU(2)_h, with all the left-handed 2nd- and 3rd-generation fermions universally charged under the corresponding group — in the ‘gauge’ basis.

After integrating out the heavy SU(2)_h bosons, one generates all sorts of $J_{q,\ell} \times J_{q,\ell}$ amplitudes. However, assuming degenerate masses for the horizontal bosons, and in the absence of mixing between the two heavier generations and the lighter one, the assumed symmetry would make $J_q \times J_q$ and $J_\ell \times J_\ell$ amplitudes exactly flavour-diagonal, in the fermion mass eigenstate basis. This property prevents dangerous tree-level contributions to processes such as meson mixings and purely leptonic flavour-violating transitions. In reality, such contributions are not exactly zero because of CKM-induced mixing across all the generations. The most constraining of these effects turns out to be the mass difference in the $D^0 - \bar{D}^0$ system, ΔM_D .

However, and quite remarkably in our view, one can accomplish a successful description of $b \rightarrow s$ deviations as well as of all constraints, by advocating a splitting of the horizontal-boson masses — per se a plausible possibility — in particular a configuration with two mass-degenerate gauge bosons hierarchically lighter than the third one.

Our scenario has, by construction, distinctive signatures in $b \rightarrow s \ell \ell'$ decays. In particular, $B \rightarrow K \tau^\pm \mu^\mp$ is predicted in the range

$$1.3 \times 10^{-8} \lesssim \mathcal{B}(B \rightarrow K \mu^+ \tau^-) + \mathcal{B}(B \rightarrow K \mu^- \tau^+) \lesssim 5.2 \times 10^{-6}, \quad (5.1)$$

with the $\tau^+ \mu^-$ and $\tau^- \mu^+$ modes in general differing by a sizeable amount that could have either sign. Besides, the small number of parameters involved establishes clear-cut correlations between semi-leptonic LFV decays of B mesons and LFV decays involving only leptons, in particular a triple correlation between $B(B \rightarrow K \mu^\pm \tau^\mp)$, $B(\tau \rightarrow 3\mu)$ and $B(\tau \rightarrow \mu\phi)$.

The framework we advocate opens several follow-up directions. First, and needless to say, in order to be fully calculable beyond tree level, the model still requires specification of the scalar sector that accomplishes the spontaneous breaking of the SU(2)_h symmetry. Addressing this question in full introduces a degree of model dependence, and probably requires more data. We believe that, for the sake of the present paper, the existence of such a scalar sector is just sufficient.

A central issue is whether an appropriate variation of the mechanism may also explain charged-current discrepancies in $b \rightarrow c\ell\nu$. We do not see how such an extension could avoid introducing relations between up-type and down-type fermion chiral rotations. Our main perplexity is in the fact that a quantitative change in the $R_{D^{(*)}}$ anomalies may change such relations *qualitatively*. Hence, as also commented upon in the Introduction, we refrained from attempting a unified description of all anomalies in this work.

Finally, another interesting question is whether a suitable extension of our framework may include a candidate for thermal Dark Matter. To this end, and although not required to cure anomalies in our framework, one may introduce additional matter, made stable by a Z_2 remnant of the spontaneously broken gauge symmetry, along the lines of, e.g., ref. [94].

Acknowledgments

We would like to thank Denis Derkach for important feedback on CKM-matrix input, as well as Luca Di Luzio and Marco Nardecchia for valuable comments. We also acknowledge useful exchanges with Damir Becirevic, Sjetlana Fajfer, Rabindra N. Mohapatra and Maurizio Pierini. The work of DG is partially supported by the CNRS grant PICS07229. This project has received support from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement N° 674896.

Open Access. This article is distributed under the terms of the Creative Commons Attribution License ([CC-BY 4.0](https://creativecommons.org/licenses/by/4.0/)), which permits any use, distribution and reproduction in any medium, provided the original author(s) and source are credited.

References

- [1] LHCb collaboration, *Test of lepton universality using $B^+ \rightarrow K^+\ell^+\ell^-$ decays*, *Phys. Rev. Lett.* **113** (2014) 151601 [[arXiv:1406.6482](https://arxiv.org/abs/1406.6482)] [[INSPIRE](#)].
- [2] LHCb collaboration, *Test of lepton universality with $B^0 \rightarrow K^{*0}\ell^+\ell^-$ decays*, *JHEP* **08** (2017) 055 [[arXiv:1705.05802](https://arxiv.org/abs/1705.05802)] [[INSPIRE](#)].
- [3] BABAR collaboration, J.P. Lees et al., *Measurement of an excess of $\bar{B} \rightarrow D^{(*)}\tau^-\bar{\nu}_\tau$ decays and implications for charged Higgs bosons*, *Phys. Rev. D* **88** (2013) 072012 [[arXiv:1303.0571](https://arxiv.org/abs/1303.0571)] [[INSPIRE](#)].
- [4] LHCb collaboration, *Measurement of the ratio of branching fractions $\mathcal{B}(\bar{B}^0 \rightarrow D^{*+}\tau^-\bar{\nu}_\tau)/\mathcal{B}(\bar{B}^0 \rightarrow D^{*+}\mu^-\bar{\nu}_\mu)$* , *Phys. Rev. Lett.* **115** (2015) 111803 [*Erratum ibid.* **115** (2015) 159901] [[arXiv:1506.08614](https://arxiv.org/abs/1506.08614)] [[INSPIRE](#)].
- [5] BELLE collaboration, S. Hirose et al., *Measurement of the τ lepton polarization and $R(D^*)$ in the decay $\bar{B} \rightarrow D^*\tau^-\bar{\nu}_\tau$* , *Phys. Rev. Lett.* **118** (2017) 211801 [[arXiv:1612.00529](https://arxiv.org/abs/1612.00529)] [[INSPIRE](#)].
- [6] LHCb collaboration, *Test of lepton flavor universality by the measurement of the $B^0 \rightarrow D^{*-}\tau^+\nu_\tau$ branching fraction using three-prong τ decays*, *Phys. Rev. D* **97** (2018) 072013 [[arXiv:1711.02505](https://arxiv.org/abs/1711.02505)] [[INSPIRE](#)].
- [7] HFLAV collaboration, Y. Amhis et al., *Averages of b -hadron, c -hadron and τ -lepton properties as of summer 2016*, *Eur. Phys. J. C* **77** (2017) 895 [[arXiv:1612.07233](https://arxiv.org/abs/1612.07233)] [[INSPIRE](#)].

- [8] W. Altmannshofer, P. Stangl and D.M. Straub, *Interpreting hints for lepton flavor universality violation*, *Phys. Rev. D* **96** (2017) 055008 [[arXiv:1704.05435](#)] [[INSPIRE](#)].
- [9] B. Capdevila, A. Crivellin, S. Descotes-Genon, J. Matias and J. Virto, *Patterns of new physics in $b \rightarrow s\ell^+\ell^-$ transitions in the light of recent data*, *JHEP* **01** (2018) 093 [[arXiv:1704.05340](#)] [[INSPIRE](#)].
- [10] M. Ciuchini et al., *On flavourful easter eggs for new physics hunger and lepton flavour universality violation*, *Eur. Phys. J. C* **77** (2017) 688 [[arXiv:1704.05447](#)] [[INSPIRE](#)].
- [11] G. D’Amico et al., *Flavour anomalies after the R_{K^*} measurement*, *JHEP* **09** (2017) 010 [[arXiv:1704.05438](#)] [[INSPIRE](#)].
- [12] G. Hiller and I. Nisandzic, *R_K and R_{K^*} beyond the Standard Model*, *Phys. Rev. D* **96** (2017) 035003 [[arXiv:1704.05444](#)] [[INSPIRE](#)].
- [13] L.-S. Geng, B. Grinstein, S. Jäger, J. Martin Camalich, X.-L. Ren and R.-X. Shi, *Towards the discovery of new physics with lepton-universality ratios of $b \rightarrow s\ell\ell$ decays*, *Phys. Rev. D* **96** (2017) 093006 [[arXiv:1704.05446](#)] [[INSPIRE](#)].
- [14] B. Bhattacharya, A. Datta, D. London and S. Shivashankara, *Simultaneous explanation of the R_K and $R(D^{(*)})$ puzzles*, *Phys. Lett. B* **742** (2015) 370 [[arXiv:1412.7164](#)] [[INSPIRE](#)].
- [15] R. Alonso, B. Grinstein and J. Martin Camalich, *$SU(2) \times U(1)$ gauge invariance and the shape of new physics in rare B decays*, *Phys. Rev. Lett.* **113** (2014) 241802 [[arXiv:1407.7044](#)] [[INSPIRE](#)].
- [16] D. Buttazzo, A. Greljo, G. Isidori and D. Marzocca, *B -physics anomalies: a guide to combined explanations*, *JHEP* **11** (2017) 044 [[arXiv:1706.07808](#)] [[INSPIRE](#)].
- [17] M. Bauer and M. Neubert, *Minimal leptoquark explanation for the $R_{D^{(*)}}$, R_K and $(g-2)_g$ anomalies*, *Phys. Rev. Lett.* **116** (2016) 141802 [[arXiv:1511.01900](#)] [[INSPIRE](#)].
- [18] D. Bečirević, N. Košnik, O. Sumensari and R. Zukanovich Funchal, *Palatable leptoquark scenarios for lepton flavor violation in exclusive $b \rightarrow s\ell_1\ell_2$ modes*, *JHEP* **11** (2016) 035 [[arXiv:1608.07583](#)] [[INSPIRE](#)].
- [19] Y. Cai, J. Gargalionis, M.A. Schmidt and R.R. Volkas, *Reconsidering the one leptoquark solution: flavor anomalies and neutrino mass*, *JHEP* **10** (2017) 047 [[arXiv:1704.05849](#)] [[INSPIRE](#)].
- [20] R. Barbieri, G. Isidori, A. Pattori and F. Senia, *Anomalies in B -decays and $U(2)$ flavour symmetry*, *Eur. Phys. J. C* **76** (2016) 67 [[arXiv:1512.01560](#)] [[INSPIRE](#)].
- [21] A. Greljo, G. Isidori and D. Marzocca, *On the breaking of lepton flavor universality in B decays*, *JHEP* **07** (2015) 142 [[arXiv:1506.01705](#)] [[INSPIRE](#)].
- [22] M. Bordone, G. Isidori and S. Trifinopoulos, *Semileptonic B -physics anomalies: a general EFT analysis within $U(2)^n$ flavor symmetry*, *Phys. Rev. D* **96** (2017) 015038 [[arXiv:1702.07238](#)] [[INSPIRE](#)].
- [23] N. Assad, B. Fornal and B. Grinstein, *Baryon number and lepton universality violation in leptoquark and diquark models*, *Phys. Lett. B* **777** (2018) 324 [[arXiv:1708.06350](#)] [[INSPIRE](#)].
- [24] L. Di Luzio, A. Greljo and M. Nardecchia, *Gauge leptoquark as the origin of B -physics anomalies*, *Phys. Rev. D* **96** (2017) 115011 [[arXiv:1708.08450](#)] [[INSPIRE](#)].
- [25] L. Calibbi, A. Crivellin and T. Li, *A model of vector leptoquarks in view of the B -physics anomalies*, [arXiv:1709.00692](#) [[INSPIRE](#)].

- [26] M. Bordone, C. Cornella, J. Fuentes-Martin and G. Isidori, *A three-site gauge model for flavor hierarchies and flavor anomalies*, *Phys. Lett. B* **779** (2018) 317 [[arXiv:1712.01368](#)] [[INSPIRE](#)].
- [27] R. Barbieri and A. Tesi, *B-decay anomalies in Pati-Salam SU(4)*, *Eur. Phys. J. C* **78** (2018) 193 [[arXiv:1712.06844](#)] [[INSPIRE](#)].
- [28] D. Bečirević, I. Doršner, S. Fajfer, N. Košnik, D.A. Faroughy and O. Sumensari, *Scalar leptoquarks from grand unified theories to accommodate the B-physics anomalies*, *Phys. Rev. D* **98** (2018) 055003 [[arXiv:1806.05689](#)] [[INSPIRE](#)].
- [29] S. Trifinopoulos, *Revisiting R-parity violating interactions as an explanation of the B-physics anomalies*, *Eur. Phys. J. C* **78** (2018) 803 [[arXiv:1807.01638](#)] [[INSPIRE](#)].
- [30] M. Blanke and A. Crivellin, *B meson anomalies in a Pati-Salam model within the Randall-Sundrum background*, *Phys. Rev. Lett.* **121** (2018) 011801 [[arXiv:1801.07256](#)] [[INSPIRE](#)].
- [31] F. Feruglio, P. Paradisi and A. Pattori, *Revisiting lepton flavor universality in B decays*, *Phys. Rev. Lett.* **118** (2017) 011801 [[arXiv:1606.00524](#)] [[INSPIRE](#)].
- [32] F. Feruglio, P. Paradisi and A. Pattori, *On the importance of electroweak corrections for B anomalies*, *JHEP* **09** (2017) 061 [[arXiv:1705.00929](#)] [[INSPIRE](#)].
- [33] C. Cornella, F. Feruglio and P. Paradisi, *Low-energy effects of lepton flavour universality violation*, *JHEP* **11** (2018) 012 [[arXiv:1803.00945](#)] [[INSPIRE](#)].
- [34] F. Feruglio, P. Paradisi and O. Sumensari, *Implications of scalar and tensor explanations of $R_{D^{(*)}}$* , [arXiv:1806.10155](#) [[INSPIRE](#)].
- [35] D.A. Faroughy, A. Greljo and J.F. Kamenik, *Confronting lepton flavor universality violation in B decays with high- p_T tau lepton searches at LHC*, *Phys. Lett. B* **764** (2017) 126 [[arXiv:1609.07138](#)] [[INSPIRE](#)].
- [36] A. Crivellin, G. D'Ambrosio and J. Heeck, *Addressing the LHC flavor anomalies with horizontal gauge symmetries*, *Phys. Rev. D* **91** (2015) 075006 [[arXiv:1503.03477](#)] [[INSPIRE](#)].
- [37] R. Alonso, P. Cox, C. Han and T.T. Yanagida, *Anomaly-free local horizontal symmetry and anomaly-full rare B-decays*, *Phys. Rev. D* **96** (2017) 071701 [[arXiv:1704.08158](#)] [[INSPIRE](#)].
- [38] J.M. Cline and J. Martin Camalich, *B decay anomalies from non-Abelian local horizontal symmetry*, *Phys. Rev. D* **96** (2017) 055036 [[arXiv:1706.08510](#)] [[INSPIRE](#)].
- [39] B. Grinstein, M. Redi and G. Villadoro, *Low scale flavor gauge symmetries*, *JHEP* **11** (2010) 067 [[arXiv:1009.2049](#)] [[INSPIRE](#)].
- [40] D. Guadagnoli, R.N. Mohapatra and I. Sung, *Gauged flavor group with left-right symmetry*, *JHEP* **04** (2011) 093 [[arXiv:1103.4170](#)] [[INSPIRE](#)].
- [41] R.N. Cahn and H. Harari, *Bounds on the masses of neutral generation changing gauge bosons*, *Nucl. Phys. B* **176** (1980) 135 [[INSPIRE](#)].
- [42] F. Wilczek and A. Zee, *Horizontal interaction and weak mixing angles*, *Phys. Rev. Lett.* **42** (1979) 421 [[INSPIRE](#)].
- [43] S.M. Boucenna, A. Celis, J. Fuentes-Martin, A. Vicente and J. Virto, *Non-Abelian gauge extensions for B-decay anomalies*, *Phys. Lett. B* **760** (2016) 214 [[arXiv:1604.03088](#)] [[INSPIRE](#)].

- [44] A.J. Buras, F. De Fazio and J. Girrbach, 331 models facing new $b \rightarrow s\mu^+\mu^-$ data, *JHEP* **02** (2014) 112 [[arXiv:1311.6729](#)] [[INSPIRE](#)].
- [45] S. Descotes-Genon, M. Moscati and G. Ricciardi, A non-minimal 331 model for lepton flavour universality violation in $b \rightarrow s\ell\ell$ decays, [arXiv:1711.03101](#) [[INSPIRE](#)].
- [46] I. Doršner, S. Fajfer, A. Greljo, J.F. Kamenik and N. Košnik, Physics of leptokuarks in precision experiments and at particle colliders, *Phys. Rept.* **641** (2016) 1 [[arXiv:1603.04993](#)] [[INSPIRE](#)].
- [47] G. Isidori, Y. Nir and G. Perez, Flavor physics constraints for physics beyond the Standard Model, *Ann. Rev. Nucl. Part. Sci.* **60** (2010) 355 [[arXiv:1002.0900](#)] [[INSPIRE](#)].
- [48] G. Hiller and M. Schmaltz, Diagnosing lepton-nonuniversality in $b \rightarrow s\ell\ell$, *JHEP* **02** (2015) 055 [[arXiv:1411.4773](#)] [[INSPIRE](#)].
- [49] D.B. Kaplan, Flavor at SSC energies: a new mechanism for dynamically generated fermion masses, *Nucl. Phys. B* **365** (1991) 259 [[INSPIRE](#)].
- [50] W. Altmannshofer, S. Gori, M. Pospelov and I. Yavin, Quark flavor transitions in L_μ - L_τ models, *Phys. Rev. D* **89** (2014) 095033 [[arXiv:1403.1269](#)] [[INSPIRE](#)].
- [51] D. Aristizabal Sierra, F. Staub and A. Vicente, Shedding light on the $b \rightarrow s$ anomalies with a dark sector, *Phys. Rev. D* **92** (2015) 015001 [[arXiv:1503.06077](#)] [[INSPIRE](#)].
- [52] A. Crivellin, G. D'Ambrosio and J. Heeck, Explaining $h \rightarrow \mu^\pm\tau^\mp$, $B \rightarrow K^*\mu^+\mu^-$ and $B \rightarrow K\mu^+\mu^-/B \rightarrow Ke^+e^-$ in a two-Higgs-doublet model with gauged L_μ - L_τ , *Phys. Rev. Lett.* **114** (2015) 151801 [[arXiv:1501.00993](#)] [[INSPIRE](#)].
- [53] C. Bobeth, T. Ewerth, F. Krüger and J. Urban, Analysis of neutral Higgs boson contributions to the decays $\bar{B}_s \rightarrow \ell^+\ell^-$ and $\bar{B} \rightarrow K\ell^+\ell^-$, *Phys. Rev. D* **64** (2001) 074014 [[hep-ph/0104284](#)] [[INSPIRE](#)].
- [54] A.J. Buras and M. Münz, Effective Hamiltonian for $B \rightarrow X_s e^+e^-$ beyond leading logarithms in the NDR and HV schemes, *Phys. Rev. D* **52** (1995) 186 [[hep-ph/9501281](#)] [[INSPIRE](#)].
- [55] M. Misiak, The $b \rightarrow se^+e^-$ and $b \rightarrow s\gamma$ decays with next-to-leading logarithmic QCD corrections, *Nucl. Phys. B* **393** (1993) 23 [*Erratum ibid.* **B 439** (1995) 461] [[INSPIRE](#)].
- [56] G. Buchalla, A.J. Buras and M.E. Lautenbacher, Weak decays beyond leading logarithms, *Rev. Mod. Phys.* **68** (1996) 1125 [[hep-ph/9512380](#)] [[INSPIRE](#)].
- [57] J. Gratrex, M. Hopfer and R. Zwicky, Generalised helicity formalism, higher moments and the $B \rightarrow K_{JK}(\rightarrow K\pi)\bar{\ell}_1\ell_2$ angular distributions, *Phys. Rev. D* **93** (2016) 054008 [[arXiv:1506.03970](#)] [[INSPIRE](#)].
- [58] D. Bečirević, O. Sumensari and R. Zukanovich Funchal, Lepton flavor violation in exclusive $b \rightarrow s$ decays, *Eur. Phys. J. C* **76** (2016) 134 [[arXiv:1602.00881](#)] [[INSPIRE](#)].
- [59] D. Guadagnoli, D. Melikhov and M. Reboud, More lepton flavor violating observables for $LHCb$'s run 2, *Phys. Lett. B* **760** (2016) 442 [[arXiv:1605.05718](#)] [[INSPIRE](#)].
- [60] D. Guadagnoli, M. Reboud and R. Zwicky, $B_s^0 \rightarrow \ell^+\ell^-\gamma$ as a test of lepton flavor universality, *JHEP* **11** (2017) 184 [[arXiv:1708.02649](#)] [[INSPIRE](#)].
- [61] G. Hiller and M. Schmaltz, R_K and future $b \rightarrow s\ell\ell$ physics beyond the Standard Model opportunities, *Phys. Rev. D* **90** (2014) 054014 [[arXiv:1408.1627](#)] [[INSPIRE](#)].
- [62] D. Ghosh, M. Nardecchia and S.A. Renner, Hint of lepton flavour non-universality in B meson decays, *JHEP* **12** (2014) 131 [[arXiv:1408.4097](#)] [[INSPIRE](#)].

- [63] E. Golowich, J. Hewett, S. Pakvasa and A.A. Petrov, *Implications of D^0 - $\bar{D}^0$ mixing for new physics*, *Phys. Rev. D* **76** (2007) 095009 [[arXiv:0705.3650](#)] [[INSPIRE](#)].
- [64] D. Guadagnoli and R.N. Mohapatra, *TeV scale left right symmetry and flavor changing neutral Higgs effects*, *Phys. Lett. B* **694** (2011) 386 [[arXiv:1008.1074](#)] [[INSPIRE](#)].
- [65] A.F. Falk, Y. Grossman, Z. Ligeti, Y. Nir and A.A. Petrov, *The D^0 - $\bar{D}^0$ mass difference from a dispersion relation*, *Phys. Rev. D* **69** (2004) 114021 [[hep-ph/0402204](#)] [[INSPIRE](#)].
- [66] V.A. Monich, B.V. Struminsky and G.G. Volkov, *Oscillation and CP violation in the ‘horizontal’ superweak gauge scheme*, *Phys. Lett. B* **104** (1981) 382 [[INSPIRE](#)].
- [67] BABAR collaboration, J.P. Lees et al., *Search for $B^+ \rightarrow K^+ \tau^+ \tau^-$ at the BaBar experiment*, *Phys. Rev. Lett.* **118** (2017) 031802 [[arXiv:1605.09637](#)] [[INSPIRE](#)].
- [68] LHCb collaboration, *Search for the decays $B_s^0 \rightarrow \tau^+ \tau^-$ and $B^0 \rightarrow \tau^+ \tau^-$* , *Phys. Rev. Lett.* **118** (2017) 251802 [[arXiv:1703.02508](#)] [[INSPIRE](#)].
- [69] BABAR collaboration, J.P. Lees et al., *A search for the decay modes $B^\pm \rightarrow h^\pm \tau \ell$* , *Phys. Rev. D* **86** (2012) 012004 [[arXiv:1204.2852](#)] [[INSPIRE](#)].
- [70] D. Guadagnoli and K. Lane, *Charged-lepton mixing and lepton flavor violation*, *Phys. Lett. B* **751** (2015) 54 [[arXiv:1507.01412](#)] [[INSPIRE](#)].
- [71] S.M. Boucenna, J.W.F. Valle and A. Vicente, *Are the B decay anomalies related to neutrino oscillations?*, *Phys. Lett. B* **750** (2015) 367 [[arXiv:1503.07099](#)] [[INSPIRE](#)].
- [72] M. Bordone, C. Cornella, J. Fuentes-Martín and G. Isidori, *Low-energy signatures of the PS^3 model: from B-physics anomalies to LFV*, *JHEP* **10** (2018) 148 [[arXiv:1805.09328](#)] [[INSPIRE](#)].
- [73] S.L. Glashow, D. Guadagnoli and K. Lane, *Lepton flavor violation in B decays?*, *Phys. Rev. Lett.* **114** (2015) 091801 [[arXiv:1411.0565](#)] [[INSPIRE](#)].
- [74] PARTICLE DATA GROUP collaboration, C. Patrignani et al., *Review of particle physics*, *Chin. Phys. C* **40** (2016) 100001 [[INSPIRE](#)].
- [75] LHCb collaboration, *Search for the lepton-flavour violating decays $B_{(s)}^0 \rightarrow e^\pm \mu^\mp$* , *JHEP* **03** (2018) 078 [[arXiv:1710.04111](#)] [[INSPIRE](#)].
- [76] E. Bertuzzo, Y.F. Perez G., O. Sumensari and R. Zukanovich Funchal, *Limits on neutrinophilic two-Higgs-doublet models from flavor physics*, *JHEP* **01** (2016) 018 [[arXiv:1510.04284](#)] [[INSPIRE](#)].
- [77] HPQCD collaboration, G.C. Donald, C.T.H. Davies, J. Koponen and G.P. Lepage, *V_{cs} from $D_s \rightarrow \phi \ell \nu$ semileptonic decay and full lattice QCD*, *Phys. Rev. D* **90** (2014) 074506 [[arXiv:1311.6669](#)] [[INSPIRE](#)].
- [78] BELLE collaboration, Y. Miyazaki et al., *Search for lepton-flavor-violating tau decays into a lepton and a vector meson*, *Phys. Lett. B* **699** (2011) 251 [[arXiv:1101.0755](#)] [[INSPIRE](#)].
- [79] BELLE-II collaboration, C. Schwanda, *Charged lepton flavour violation at Belle and Belle II*, *Nucl. Phys. Proc. Suppl.* **248-250** (2014) 67 [[INSPIRE](#)].
- [80] B. Golob, K. Trabelsi and P. Urquijo, *Impact of Belle II on flavour physics*, BELLE2-NOTE-PH-2015-002, (2015).
- [81] L. Di Luzio, M. Kirk and A. Lenz, *Updated B_s -mixing constraints on new physics models for $b \rightarrow s \ell^+ \ell^-$ anomalies*, *Phys. Rev. D* **97** (2018) 095035 [[arXiv:1712.06572](#)] [[INSPIRE](#)].

- [82] S. Aoki et al., *Review of lattice results concerning low-energy particle physics*, *Eur. Phys. J. C* **77** (2017) 112 [[arXiv:1607.00299](#)] [[INSPIRE](#)].
- [83] D. Derkach, private communication.
- [84] M. Ciuchini et al., 2000 *CKM triangle analysis: a critical review with updated experimental inputs and theoretical parameters*, *JHEP* **07** (2001) 013 [[hep-ph/0012308](#)] [[INSPIRE](#)].
- [85] CKMFITTER GROUP collaboration, J. Charles et al., *CP violation and the CKM matrix: assessing the impact of the asymmetric B factories*, *Eur. Phys. J. C* **41** (2005) 1 [[hep-ph/0406184](#)] [[INSPIRE](#)].
- [86] J. Brod and J. Zupan, *The ultimate theoretical error on γ from $B \rightarrow DK$ decays*, *JHEP* **01** (2014) 051 [[arXiv:1308.5663](#)] [[INSPIRE](#)].
- [87] LHCb collaboration, *Measurement of the CKM angle γ using $B^\pm \rightarrow DK^\pm$ with $D \rightarrow K_S^0 \pi^+ \pi^-$, $K_S^0 K^+ K^-$ decays*, *JHEP* **08** (2018) 176 [Erratum *ibid.* **10** (2018) 107] [[arXiv:1806.01202](#)] [[INSPIRE](#)].
- [88] D. Craik, T. Gershon and A. Poluektov, *Optimising sensitivity to γ with $B^0 \rightarrow DK^+ \pi^-$, $D \rightarrow K_S^0 \pi^+ \pi^-$ double Dalitz plot analysis*, *Phys. Rev. D* **97** (2018) 056002 [[arXiv:1712.07853](#)] [[INSPIRE](#)].
- [89] A.J. Buras, J. Girrbach-Noe, C. Niehoff and D.M. Straub, *$B \rightarrow K^{(*)} \nu \bar{\nu}$ decays in the Standard Model and beyond*, *JHEP* **02** (2015) 184 [[arXiv:1409.4557](#)] [[INSPIRE](#)].
- [90] BELLE collaboration, J. Grygier et al., *Search for $B \rightarrow h \nu \bar{\nu}$ decays with semileptonic tagging at Belle*, *Phys. Rev. D* **96** (2017) 091101 [Addendum *ibid.* **D 97** (2018) 099902] [[arXiv:1702.03224](#)] [[INSPIRE](#)].
- [91] LHCb collaboration, *Search for the rare decay $D^0 \rightarrow \mu^+ \mu^-$* , *Phys. Lett. B* **725** (2013) 15 [[arXiv:1305.5059](#)] [[INSPIRE](#)].
- [92] BABAR collaboration, B. Aubert et al., *Searches for lepton flavor violation in the decays $\tau^\pm \rightarrow e^\pm \gamma$ and $\tau^\pm \rightarrow \mu^\pm \gamma$* , *Phys. Rev. Lett.* **104** (2010) 021802 [[arXiv:0908.2381](#)] [[INSPIRE](#)].
- [93] A. Greljo and D. Marzocca, *High- p_T dilepton tails and flavor physics*, *Eur. Phys. J. C* **77** (2017) 548 [[arXiv:1704.09015](#)] [[INSPIRE](#)].
- [94] 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** (2017) 095015 [[arXiv:1702.00395](#)] [[INSPIRE](#)].