B meson anomalies within the triplet vector boson model to the light of recent measurements from LHCb

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(Received 2 May 2023; accepted 10 January 2024; published 30 January 2024)

The triplet vector boson (TVB) is a simplified new physics model involving massive vector bosons transforming as a weak triplet vector. Such a model has been proposed as a combined explanation of the anomalous $b \to s\mu^+\mu^-$ and $b \to c\tau\bar{\nu}_\tau$ data (the so-called B meson anomalies). In this work, we carry out a revamped view of the TVB model by incorporating the most recent 2022 and 2023 LHCb measurements on the lepton-flavor universality ratios $R(D^{(*)}) = \mathrm{BR}(B \to D^{(*)}\tau\bar{\nu}_\tau)/\mathrm{BR}(B \to D^{(*)}\ell'\bar{\nu}_{\ell'})$, $R(\Lambda_c) = \mathrm{BR}(\Lambda_b \to \Lambda_c\tau\bar{\nu}_\tau)/\mathrm{BR}(\Lambda_b \to \Lambda_c\mu\bar{\nu}_\mu)$, and $R_{K^{(*)}} = \mathrm{BR}(B \to K^{(*)}\mu^+\mu^-)/\mathrm{BR}(B \to K^{(*)}e^+e^-)$. We perform a global fit to explore the allowed parameter space by the new data and all relevant low-energy flavor observables including the recent experimental progress from Belle, Belle II, and LHCb. Our results are confronted with the recent high-mass dilepton searches at the LHC. We find that for a heavy TVB mass of 1 TeV a common explanation of the B meson anomalies is possible for all data with the recent LHCb measurements on $R(D^{(*)})$, consistent with LHC constraints. However, this framework is in strong tension with LHC bounds when one considers all data along with the world average values reported by the Heavy Flavor Averaging Group (*BABAR*, Belle, and LHCb) on $R(D^{(*)})$. Future measurements will be required in order to clarify such a situation.

DOI: 10.1103/PhysRevD.109.015029

I. INTRODUCTION

In the last ten years, approximately, the high-energy physics community has been a witness of discrepancies between experimental measurements and the Standard Model (SM) calculations in several observables involving $b \to s\mu^+\mu^-$ (neutral-current) and $b \to c\tau\bar{\nu}_\tau$ (charged-current) transitions, which provide an important test of lepton-flavor universality (LFU). Such inconsistencies indicate strong signals of LFU violation (for very recent interesting reviews, see Refs. [1–3]). For the neutral-current $b \to s\mu^+\mu^-$ transition, the ratio of semileptonic decay channels,

$$R_{K^{(*)}} = \frac{\mathrm{BR}(B \to K^{(*)}\mu^+\mu^-)}{\mathrm{BR}(B \to K^{(*)}e^+e^-)}, \tag{1}$$

provides a test of μ/e LFU for different dilepton mass-squared range q^2 (q^2 bins). From 2014 to 2021, the LHCb experiment reported the existence of discrepancies between the SM predictions and the experimental measurements (low and central q^2 bins) of R_K, R_{K^*}, R_{K_S}, and $R_{K^{*+}}$ [4–8], hinting toward LFU violation in the μ/e sector. However, at the end of 2022, an improved LHCb analysis of the ratios $R_{K^{(*)}}$, namely [9,10],

$$R_K = \begin{cases} 0.994^{+0.090+0.029}_{-0.082-0.027}, & q^2 \in [0.1, 1.1]\ \mathrm{GeV}^2, \\ 0.949^{+0.042+0.022}_{-0.041-0.022}, & q^2 \in [1.1, 6.0]\ \mathrm{GeV}^2, \end{cases} \tag{2}$$

and

$$R_{K^*} = \begin{cases} 0.927^{+0.093+0.036}_{-0.087-0.035}, & q^2 \in [0.1, 1.1]\ \mathrm{GeV}^2, \\ 1.027^{+0.072+0.027}_{-0.068-0.026}, & q^2 \in [1.1, 6.0]\ \mathrm{GeV}^2, \end{cases} \tag{3}$$

now shows good agreement with the SM [9,10]. In addition, the CMS experiment has presented a new measurement of

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TABLE I. Experimental status and SM predictions on observables related to the charged-current transitions $b \to c\ell\bar{\nu}_\ell$ ($\ell = \mu, \tau$).

Observable	Experimental measurement	SM prediction
$R(D)$	$0.441 \pm 0.060 \pm 0.066$ (LHCb22) [43,44]	0.298 ± 0.004 [47]
	0.356 ± 0.029 (HFLAV) [47]	
$R(D^*)$	$0.281 \pm 0.018 \pm 0.024$ (LHCb22) [43,44]	0.254 ± 0.005 [47]
	$0.257 \pm 0.012 \pm 0.018$ (LHCb23) [45]	
	0.284 ± 0.013 (HFLAV) [47]	
$R(J/\psi)$	$0.71 \pm 0.17 \pm 0.18$ [40]	0.2582 ± 0.0038 [48]
$P_\tau(D^*)$	$-0.38 \pm 0.51^{+0.21}_{-0.16}$ [38,39]	-0.497 ± 0.007 [49]
$F_L(D^*)$	$0.60 \pm 0.08 \pm 0.035$ [41]	0.464 ± 0.003 [49]
$R(X_c)$	0.223 ± 0.030 [52]	0.216 ± 0.003 [52]
$\mathrm{BR}(B_c^- \to \tau^-\bar{\nu}_\tau)$	$< 10\%$ [51], $< 30\%$ [50]	$(2.16 \pm 0.16)\%$ [53]
$R_D^{\mu/e}$	$0.995 \pm 0.022 \pm 0.039$ [54]	0.9960 ± 0.0002 [55]
$R_{D^*}^{\mu/e}$	0.961 ± 0.050 [56]	0.9974 ± 0.0001 [57]

the branching ratio of $B_s \to \mu^+\mu^-$ more consistent with the SM [11]. Despite that the tension on $R_{K^{(*)}}$ ratios and $\mathrm{BR}(B_s \to \mu^+\mu^-)$ has now disappeared, there are still some discrepancies in the measurements of additional $b \to s\mu^+\mu^-$ observables, such as angular observables and differential branching fractions related with $B \to K^*\mu^+\mu^-$ and $B_s \to \phi\mu^+\mu^-$ decays [12–17]. Within a model-independent effective Hamiltonian approach, different scenarios with New Physics (NP) operators (dimension 6) to $b \to s\ell^+\ell^-$ transitions have been surveyed in the literature [1,18–28]. Taking into account updated $b \to s\mu^+\mu^-$ data (including $R_{K^{(*)}}$ by LHCb [9,10] and $\mathrm{BR}(B_s \to \mu^+\mu^-)$ by CMS [11]), the most recent global fit analysis [26–28] show, in general, a different situation for the possible one-dimension NP scenarios compared to previous analyses [1,18–25]. Now, the so-called *lepton-flavor universal* (universal contributions to $b \to se^+e^-$ and $b \to s\mu^+\mu^-$) solution $C_9^{bs\ell\ell}$ ($\ell = e, \mu$) is favoured to explain the data.[1] Moreover, there is also a marked preference to the lepton-flavor universal solution $C_9^{bs\ell\ell} = -C_{10}^{bs\ell\ell}$. In addition, the scenario where only NP contribution to $b \to s\mu^+\mu^-$ is assumed ($C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$) remains as a feasible option.

On the other hand, the experimental measurements collected by the *BABAR*, Belle, and LHCb experiments on different charged-current $b \to c\tau\bar{\nu}_\tau$ observables indicate the existence of disagreement with respect to the SM predictions [29–47] (see Table I for a summary). Regarding the ratios of semileptonic B meson decays,

$$R(D^{(*)}) = \frac{\mathrm{BR}(B \to D^{(*)}\tau\bar{\nu}_\tau)}{\mathrm{BR}(B \to D^{(*)}\ell'\bar{\nu}_{\ell'})}, \tag{4}$$

with $\ell' = e$ or μ [the so-called $R(D^{(*)})$ *anomalies*], the LHCb has presented, very recently, the first combined measurement using Run 1 data (3 fb^{-1}) with muonic τ decay reconstruction [43,44],

$$R(D)_{\mathrm{LHCb22}} = 0.441 \pm 0.060 \pm 0.066, \tag{5}$$

$$R(D^*)_{\mathrm{LHCb22}} = 0.281 \pm 0.018 \pm 0.024, \tag{6}$$

which show a tension of 1.9σ with the SM predictions. Additionally, the LHCb also reported a preliminary measurement of $R(D^*)$ using partial Run 2 data (2 fb^{-1}), where the τ is hadronically reconstructed [45,46]. When combined with Run 1, the result is [45,46]

$$R(D^*)_{\mathrm{LHCb23}} = 0.257 \pm 0.012 \pm 0.018, \tag{7}$$

that is compatible with SM at the $\sim 1\sigma$ level. Incorporating these new LHCb results, the preliminary world average values reported by the Heavy Flavor Averaging Group (HFLAV) are [47]

$$R(D)_{\mathrm{HFLAV23}} = 0.356 \pm 0.029, \tag{8}$$

$$R(D^*)_{\mathrm{HFLAV23}} = 0.284 \pm 0.013, \tag{9}$$

that now exceed the SM by 3.2σ. Moreover, the LHCb measurement of the ratio $R(J/\psi) = \mathrm{BR}(B_c \to J/\psi\tau\bar{\nu}_\tau)/\mathrm{BR}(B_c \to J/\psi\mu\bar{\nu}_\mu)$ [40] also shows tension ($\sim 2\sigma$) with regard to the SM prediction [48]. Additional hints of LFU violation in the $b \to c\tau\bar{\nu}_\tau$ transition have been obtained in the Belle measurements of the τ lepton polarization $P_\tau(D^*)$ [38,39] and the longitudinal polarization of the D^* meson $F_L(D^*)$ [41] related with the channel $\bar{B} \to D^*\tau\bar{\nu}_\tau$, which also exhibit a deviation from the SM values [49]. The tauonic channel $B_c \to J/\psi\tau\bar{\nu}_\tau$ has not been measured yet, but indirect constraints on its branching ratio have been imposed $< 30\%$ [50] and $< 10\%$ [51]. In Table I, we summarize the current experimental measurements and their

[1] Some explicit model examples are shown in Ref. [26].

corresponding SM predictions. We also collect in Table I the experimental and theoretical values of the ratio of inclusive decays $R(X_c) \equiv \mathrm{BR}(B \to X_c \tau \bar{\nu}_\tau)/\mathrm{BR}(B \to X_c \mu \bar{\nu}_\mu)$, which is generated via the same $b \to c\tau\bar{\nu}_\tau$ transition [52]. The SM estimation on $R(X_c)$ is based on the $1S$ mass scheme and includes nonperturbative corrections of the order $\mathcal{O}(1/m_b^3)$, while the NP effects took into account the subleading $\mathcal{O}(1/m_b)$ corrections [52]. The $R(D^{(*)})$ anomalies still exhibit the largest deviation. The other $b \to c\tau\bar{\nu}_\tau$ observables also show tension (moderate) with the data, although some of them have large experimental uncertainties [such as $R(J/\psi)$ and $P_\tau(D^*)$], while the ratio $R(X_c)$ is in excellent agreement with the SM.

In addition, the LHCb Collaboration has recently released the first measurement of the ratio of semileptonic Λ_b baryon decays, namely [58],

$$R(\Lambda_c) \equiv \frac{\mathrm{BR}(\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau)}{\mathrm{BR}(\Lambda_b^0 \to \Lambda_c^+ \mu^- \bar{\nu}_\mu)} = 0.242 \pm 0.076, \qquad (10)$$

in agreement at the $\sim 1.2\sigma$ level with the most recent SM calculation, $R(\Lambda_c)_{\mathrm{SM}} = 0.324 \pm 0.004$ [59]. In Eq. (10), we have added in quadrature the statistical and systematic uncertainties and the external branching ratio uncertainty from the channel $\Lambda_b^0 \to \Lambda_c^+ \mu^- \bar{\nu}_\mu)$ [58]. It is interesting to highlight that this new measurement is below the SM value, pointing to an opposite direction than the current $b \to c\tau\bar{\nu}_\tau$ data (see Table I). Nevertheless, to provide an overall picture, all the anomalous $b \to c\tau\bar{\nu}_\tau$ data must be taken into account. To the best of our knowledge, the impact of the new LHCb measurement on $R(\Lambda_c)$ has been recently studied in a model-independent way (effective field theory approach) [60] and in the singlet vector leptoquark model [61].

Although the $b \to c\tau\bar{\nu}_\tau$ data are suggesting stronger signals of LFU violation than the $b \to s\mu^+\mu^-$ data, a combined explanation of the current data is still desirable. This simultaneous explanation can be generated by different tree-level heavy mediators with adequate couplings, for example, charged scalar bosons, extra gauge bosons, or leptoquarks (scalar and vector). For an extensive list of literature, see the theoretical status report presented in Ref. [1]. In this work, we will pay particular attention to the common explanation provides by the so-called triplet vector boson (TVB) model [62–71],[2] in which the SM is extended by including a color-neutral real $SU(2)_L$ triplet of massive vectors W' and Z' that coupled predominantly to left-handed (LH) fermions from the second and third generations [62–71]. The neutral boson Z' is responsible for the $b \to s\mu^+\mu^-$ data, while the charged boson W' generates the $b \to c\tau\bar{\nu}_\tau$ one. We adopt a phenomenological approach of the TVB model based on the minimal setup of couplings between the new gauge bosons Z', W' and LH fermions of the SM, without specifying the complete UV model. We present an updated analysis of the TVB model (parametric space) by including the new 2022 and 2023 LHCb data on $R_{K^{(*)}}$, $R(D^{(*)})$, and $R(\Lambda_c)$. We also incorporate in our study all relevant flavor observables that are also affected by this NP model, such as $B_s - \bar{B}_s$ mixing, neutrino trident production, lepton flavor violation decays ($B \to K^{(*)}\mu^\pm\tau^\mp$, $B_s \to \mu^\pm\tau^\mp$, $\tau \to \mu\phi$, $\Upsilon(nS) \to \mu^\pm\tau^\mp$), rare B decays ($B \to K^{(*)}\nu\bar{\nu}, B \to K\tau^+\tau^-, B_s \to \tau^+\tau^-$), and bottomonium LFU ratios. Furthermore, we study the consistency of the allowed TVB parameter space with the LHC bounds from searches of high-mass dilepton resonances at the ATLAS experiment.

Even though our focus will be phenomenological, regarding the UV-complete realization for the TVB model, the extension of the SM must allow for lepton-flavor nonuniversal (LFNU) couplings to the extra gauge bosons and LFV. In this direction in Ref. [71], there is a proposal in which an extra $SU(2)$ gauge group is added and where extra scalars, new vectorlike fermions, and some nontrivial transformations under the SM group are included. It is clear that the couplings of fermions to the extra gauge bosons of the particular UV realization will have model-dependent consequences that might relate different terms between them; however, since we emphasize that our approach is phenomenological, we will start from the most general Lagrangian for the TVB model as possible, and we will make comparisons to other approaches presented in Refs. [62,63,66,67], where the new physics is coupled predominantly to the second and third generations of left-handed quarks and leptons, ensuring LFNU and LFV through different mechanisms. Restricting our results to a particular UV model is out of our target.

This paper is structured as follows. In Sec. II, we discuss the main aspects of the TVB model to accommodate the B meson anomalies. As a next step in Sec. III, we consider the most relevant flavor observables and present the TVB model contributions to them. The LHC bounds are also studied. We then perform our phenomenological analysis of the allowed parametric space in Sec. IV, and our conclusions are presented in Sec. V.

II. TRIPLET VECTOR BOSON MODEL

In general, flavor anomalies have been boarded into the current literature as a motivation to build innovative models and to test well-established New Physics (NP) models. In this section, we focus in the previously mentioned TVB model [62–71] as a possible explanation of these anomalies, that might accommodate the observed flavor experimental results. One significant feature of this model is the inclusion of extra SM-like vector bosons with nonzero

[2]Let us notice that in a recent work [72] the TVB model was implemented as an explanation to the Cabibbo angle anomaly and $b \to s\ell^+\ell^-$ data.

couplings to the SM fermions, that allow us to include additional interactions.

In the fermion mass basis, the most general Lagrangian describing the dynamics of the fields can be written as

$$\Delta\mathcal{L}_V = g^q_{ij}(\bar{\Psi}^Q_{iL}\gamma^\mu\sigma^I\Psi^Q_{jL})V^I_\mu + g^\ell_{ij}(\bar{\Psi}^\ell_{iL}\gamma^\mu\sigma^I\Psi^\ell_{jL})V^I_\mu, \tag{11}$$

where V_μ stands for the extra or new vector bosons that transform as (1, 3, 0) under the $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ gauge symmetry and must be redefined as $W'^{\pm}, Z'$. On the other side, SM fermions are arranged into the doublets Ψ^Q_L and Ψ^ℓ_L given by

$$\Psi^Q_L = \begin{pmatrix} V^\dagger u_L \\ d_L \end{pmatrix}, \qquad \Psi^\ell_L = \begin{pmatrix} \nu_L \\ \ell_L \end{pmatrix}. \tag{12}$$

where V is the Cabbibo-Kobayashi-Maskawa (CKM) matrix.

To find the effective Lagrangian for this model, the heavy degrees of freedom corresponding to vector bosons introduced above must be integrated out. Introducing the definition for the currents $J_Q = \bar{\Psi}^Q_{iL}\gamma^\mu\sigma^I\Psi^Q_{jL}$ and $J_\ell = \bar{\Psi}^\ell_{iL}\gamma^\mu\sigma^I\Psi^\ell_{jL}$, the effective Lagrangian is therefore

$$\mathcal{L}_{\rm eff} = -\frac{(g^q_{ij}J_Q + g^\ell_{ij}J_\ell)^2}{2M_V^2} \tag{13}$$

$$= -\frac{(g^q_{ij}J_Q)^2}{2M_V^2} - \frac{g^q_{ij}g^\ell_{kl}J_QJ_\ell}{M_V^2} - \frac{(g^\ell_{ij}J_\ell)^2}{2M_V^2}. \tag{14}$$

The middle term of the right-hand side of the above equation corresponds to

$$\frac{g^q_{ij}g^\ell_{kl}J_QJ_\ell}{M_V^2} = \frac{g^q_{ij}g^\ell_{kl}}{M_V^2}(\bar{\Psi}^Q_{iL}\gamma_\mu\sigma^I\Psi^Q_{jL})(\bar{\Psi}^\ell_{kL}\gamma^\mu\sigma^I\Psi^\ell_{lL}). \tag{15}$$

Substituting Eq. (12) in the last expression, it leads us to

$$\begin{aligned}\frac{g^q_{ij}g^\ell_{kl}J_QJ_\ell}{M_V^2} = {}& 2\frac{g^\ell_{kl}}{M_V^2}[(Vg^d)_{ij}(\bar{u}_{iL}\gamma_\mu d_{jL})(\bar{\ell}_k\gamma^\mu\nu_{lL}) + \text{H.c.}] \\ &+ \frac{g^\ell_{kl}}{M_V^2}[(Vg^dV^\dagger)_{ij}(\bar{u}_{iL}\gamma_\mu u_{jL})(\bar{\nu}_{kL}\gamma^\mu\nu_{lL}) \\ &+ g^d_{ij}(\bar{d}_{iL}\gamma_\mu d_{jL})(\bar{\ell}_{kL}\gamma^\mu\ell_{lL})] \\ &- \frac{g^\ell_{kl}}{M_V^2}[(Vg^dV^\dagger)_{ij}(\bar{u}_{iL}\gamma_\mu u_{jL})(\bar{\ell}_{kL}\gamma^\mu\ell_{lL}) \\ &+ g^d_{ij}(\bar{d}_{iL}\gamma_\mu d_{jL})(\bar{\nu}_{kL}\gamma^\mu\nu_{lL})];\end{aligned} \tag{16}$$

in this expression, we can identify that the first term expresses an effective interaction of the SM fields that should be mediated by extra bosonic charged fields, while the remaining terms are mediated by an extra neutral bosonic field. These extra fields are precisely the vector boson fields W' and Z' introduced in this model and which masses can naively be considered to be (almost) degenerated which is required by electroweak precision data [65]. For simplicity, and without losing generality, we are going to consider that the couplings $g^{q,\ell}$ are real to avoid CP-violation effects. Additionally, it is important to notice that we can write compactly the couplings of quarks to the vector boson fields with an explicit dependence in the couplings of the down sector and also keep in mind that the CKM matrix couples into the doublets to up-type quarks and that we should restrict the significant contributions for the second and third families. For this purpose, we restrict the relevant couplings of the down sector to g_{bb}, g_{ss}, and $g_{sb} = g_{bs}$, while other terms remain zero. This hypothesis that the couplings to the first generation of fermions (also in the leptonic sector) can be neglected has been widely accepted in the literature in the context of flavor anomaly explanations [62–69]. Lastly, the resultant compact form for the couplings of the quark sector to the W' that we obtained are

$$\begin{aligned} g_{\alpha b} &= g_{bb}V_{\alpha b} + g_{sb}V_{\alpha s}, \\ g_{\alpha s} &= g_{ss}V_{\alpha s} + g_{sb}V_{\alpha b}, \end{aligned} \tag{17}$$

where α stands for u, c, or t quark flavors. The same procedure described above must be implemented for a compact form of the couplings of up-type quarks to the Z' boson. In this case, we find two possibilities: one on flavor-conserving interaction given by

$$g_{\alpha\alpha} = g_{bb}V^2_{\alpha b} + 2g_{\alpha b}V_{\alpha s}V_{\alpha b} + g_{ss}V^2_{\alpha s} \tag{18}$$

and the other related to flavor-changing Z' couplings mediated by

$$g_{\alpha\beta} = g_{bb}V_{\beta b}V_{\alpha b} + g_{sb}V_{\beta s}V_{\alpha b} + g_{sb}V_{\beta b}V_{\alpha s} + g_{ss}V_{\beta s}V_{\alpha s}, \tag{19}$$

where $\alpha \neq \beta$ labels u, c, or t quark flavors.

Regarding the leptonic sector, we will assume that the couplings will follow the structure

$$g^\ell_{kl} = \begin{pmatrix} g_{ee} & 0 & 0 \\ 0 & g_{\mu\mu} & g_{\mu\tau} \\ 0 & g_{\mu\tau} & g_{\tau\tau} \end{pmatrix}; \tag{20}$$

this assumption is motivated through different flavor observables as well as possible theoretical flavor symmetries such as those sketched in Refs. [62,67], where the mixing pattern for different fermions is enriched by the inclusion of mixing matrices that will rotate the fields from the gauge basis to the mass basis, thus privileging second and third families of leptons. In this way, we will only consider possible flavor change (lepton-flavor violation) from μ to τ and vice versa.

To close this kind of parametrization, we mention that the terms of the rhs of Eq. (15) are responsible for and will be important to $4q$ and 4ℓ interactions ruled by the Lagrangian

$$\mathcal{L}_{NP}^{4q,4\ell} = -\frac{g_{ij}^q g_{kl}^q}{2M_V^2}(\bar{\Psi}_{iL}^Q \gamma_\mu \sigma^I \Psi_{jL}^Q)(\bar{\Psi}_{kL}^Q \gamma^\mu \sigma^I \Psi_{lL}^Q) - \frac{g_{ij}^\ell g_{kl}^\ell}{2M_V^2}(\bar{\Psi}_{iL}^\ell \gamma_\mu \sigma^I \Psi_{jL}^\ell)(\bar{\Psi}_{kL}^\ell \gamma^\mu \sigma^I \Psi_{lL}^\ell). \quad (21)$$

A. Other parametrizations

In this subsection, we compare the previous parametrization explained above with others used in some representative references studied widely in the TVB model.

In the TVB model presented in Refs [62,67], the mixing pattern for quarks is enriched by the inclusion of mixing matrices that will rotate the fields from the gauge basis to the mass basis and a projector (X, Y) that will ensure the dominance of the second and third families to explain anomalies. Particularly, the explicit form of these matrices for the down-type quarks and charged leptons and projectors is

$$D = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_D & \sin\theta_D \\ 0 & -\sin\theta_D & \cos\theta_D \end{pmatrix}, \quad L = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_L & \sin\theta_L \\ 0 & -\sin\theta_L & \cos\theta_L \end{pmatrix},$$
$$X = Y = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}. \quad (22)$$

These matrices will leave an explicit dependence of these mixing angles $(\theta_{D,L})$ into the couplings to the extra fields, which by the experimental results coming from different observables can be constrained. The assumptions made in the introduction of these matrices were previously introduced in Ref. [62], and we can establish the full equivalence between the notations of the angles by the relations $\theta_D = \alpha_{sb}$ and $\theta_L = \alpha_{\mu\tau}$. We have also found that these couplings can be translated into the generic parametrization introduced at the beginning of this section; for this purpose, as explained earlier, the couplings of the whole quark sector will depend on the couplings of the down-type quarks, especially in this kind of parametrization. We can show the way in which the couplings are obtained by the effective charged Lagrangian, given as

$$\mathcal{L}_{\text{eff}}^{W'} = 2\frac{g_2^q g_2^\ell}{M_V^2}[(VD^\dagger XD)_{ij}(\bar{u}_{iL}\gamma_\mu d_{jL}) \times (L^\dagger YL)_{kl}(\overline{\ell}_k \gamma^\mu \nu_{lL}) + \text{H.c.}]; \quad (23)$$

thus, we obtain the equivalence

$$g_{bb} \to g_2^q \cos^2\theta_D$$
$$g_{sb} \to -g_2^q \sin\theta_D \cos\theta_D$$
$$g_{ss} \to g_2^q \sin^2\theta_D \quad (24)$$

and for the leptonic sector

$$g_{\tau\tau} \to g_2^\ell \cos^2\theta_L$$
$$g_{\mu\tau} \to -g_2^\ell \sin\theta_L \cos\theta_L$$
$$g_{\mu\mu} \to g_2^\ell \sin^2\theta_L. \quad (25)$$

The comparison and equivalence among parametrizations of different influential references can be found in Tables II–V.

For our last comparison, we considered the parametrization given in Refs. [63,66] where the couplings to the vector bosons have almost the same structure of the initial parametrization presented here, but its major difference consists in the dependence on flavor matrices denoted by the authors as $\lambda_{ij}^{(q,\ell)}$. This incidence of the flavor structure into the model can be shown using the charged effective Lagrangian as we did before,

$$\mathcal{L}_{\text{eff}}^{W'} = \frac{g_q g_\ell}{2M_V^2}[(V\lambda)_{ij}(\bar{u}_{iL}\gamma_\mu d_{jL})(\overline{\ell}_k \gamma^\mu \nu_{lL}) + \text{H.c.}], \quad (26)$$

to obtain the desired dominance of couplings to the second and third families using the flavor matrices mentioned

TABLE II. Couplings to W' boson in different parametrizations of the TVB model.

Coupling	Parametrization in Ref. [68]	Parametrization in Refs. [62,67]	Parametrization in Refs. [63,66]
g_{ub}^q	$g_{bb}V_{ub} + g_{sb}V_{us}$	$g_2^q(V_{ub}\cos^2\theta_d - V_{us}\cos\theta_d\sin\theta_d)$	$g_q(V_{ub} + V_{ud}\lambda_{db} + V_{us}\lambda_{sb})/\sqrt{2}$
g_{cb}^q	$g_{bb}V_{cb} + g_{sb}V_{cs}$	$g_2^q(V_{cb}\cos^2\theta_d - V_{cs}\cos\theta_d\sin\theta_d)$	$g_q(V_{cb} + V_{cd}\lambda_{db} + V_{cs}\lambda_{sb})/\sqrt{2}$
g_{tb}^q	$g_{bb}V_{tb} + g_{sb}V_{ts}$	$g_2^q(V_{tb}\cos^2\theta_d - V_{ts}\cos\theta_d\sin\theta_d)$	$g_q(V_{tb} + V_{ud}\lambda_{tb} + V_{us}\lambda_{sb})/\sqrt{2}$
g_{us}^q	$g_{ss}V_{us} + g_{sb}V_{ub}$	$g_2^q(V_{us}\sin^2\theta_d - V_{ub}\cos\theta_d\sin\theta_d)$	$g_q(V_{ud}\lambda_{ds} + V_{ub}\lambda_{sb} + V_{us}\lambda_{ss})/\sqrt{2}$
g_{cs}^q	$g_{ss}V_{cs} + g_{sb}V_{ucb}$	$g_2^q(V_{cs}\sin^2\theta_d - V_{cb}\cos\theta_d\sin\theta_d)$	$g_q(V_{cd}\lambda_{ds} + V_{cb}\lambda_{sb} + V_{cs}\lambda_{ss})/\sqrt{2}$
g_{ts}^q	$g_{ss}V_{ts} + g_{sb}V_{tb}$	$g_2^q(V_{ts}\sin^2\theta_d - V_{tb}\cos\theta_d\sin\theta_d)$	$g_q(V_{td}\lambda_{ds} + V_{tb}\lambda_{sb} + V_{ts}\lambda_{ss})/\sqrt{2}$

TABLE III. Flavor-conserving couplings to Z' boson in different parametrizations of the TVB model.

Coupling	Parametrization in Ref. [68]	Parametrization in Refs. [62,67]	Parametrization in Refs. [63,66]
g^q_{uu}	$g_{bb}V^2_{ub} + 2g_{sb}V_{us}V_{ub} + g_{ss}V^2_{us}$	$g^q_2(V^2_{ub}\cos^2\theta_d - 2V_{us}V_{ub}\cos\theta_d\sin\theta_d + V^2_{us}\sin^2\theta_d)$	$g_q\lambda_{uu}/\sqrt{2}$
g^q_{cc}	$g_{bb}V^2_{cb} + 2g_{sb}V_{cs}V_{cb} + g_{ss}V^2_{cs}$	$g^q_2(V^2_{cb}\cos^2\theta_d - 2V_{cs}V_{cb}\cos\theta_d\sin\theta_d + V^2_{cs}\sin^2\theta_d)$	$g_q\lambda_{cc}/\sqrt{2}$
g^q_{tt}	$g_{bb}V^2_{tb} + 2g_{sb}V_{ts}V_{tb} + g_{ss}V^2_{ts}$	$g^q_2(V^2_{tb}\cos^2\theta_d - 2V_{ts}V_{tb}\cos\theta_d\sin\theta_d + V^2_{ts}\sin^2\theta_d)$	$g_q\lambda_{tt}/\sqrt{2}$

before; the λ_{ij} belonging to the first family must be set to zero. Additionally, the values for $\lambda_{bb} = \lambda_{\tau\tau} = 1$ in order to maximize its contribution. However, as an illustration, we can make a complete relation of the implementation of the flavor matrices to the construction of couplings for the quark sector without any assumption in Tables II–V.

We emphasize that the results presented in Tables II–V allow us to understand the differences and similarities for the parametrizations presented above in the context of the TVB model; additionally, it gives us a complete interpretation of the variables present on each one and the possibilities to find adjustments to explain flavor anomalies.

III. RELEVANT OBSERVABLES

In this section, we discuss the constraints from the most relevant flavor observables on the TVB model couplings to simultaneously accommodate the B meson anomalies. We will include the recent experimental progress from Belle and LHCb on different LFV decays [such as $\Upsilon(1S) \to \mu^\pm\tau^\mp$, $B \to K^{(*)}\mu^\pm\tau^\mp$, and $\tau \to \mu\phi$], and the first evidence reported by Belle II of $B^+ \to K^+\nu\bar{\nu}$.

A. $b \to s\ell^+\ell^-$ data

The NP effective Lagrangian responsible for the semileptonic transition $b \to s\ell^+\ell^-$ ($\ell = e, \mu$) can be expressed as

$$\mathcal{L}(b \to s\ell^+\ell^-)_{\rm NP} = \frac{4G_F}{\sqrt{2}} V_{tb}V^*_{ts}(C^{bs\ell\ell}_9 \mathcal{O}^{bs\ell\ell}_9 + C^{bs\ell\ell}_{10}\mathcal{O}^{bs\ell\ell}_{10}) + \text{H.c.}, \tag{27}$$

where the NP is encoded in the Wilson coefficient (WCs) $C^{bs\ell\ell}_9$ and $C^{bs\ell\ell}_{10}$ of the four-fermion operators

$$\mathcal{O}^{bs\ell\ell}_9 = \frac{\alpha_{\rm em}}{4\pi}(\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu\ell), \tag{28}$$

$$\mathcal{O}^{bs\ell\ell}_{10} = \frac{\alpha_{\rm em}}{4\pi}(\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu\gamma_5\ell), \tag{29}$$

respectively, with $\alpha_{\rm em}$ being the fine-constant structure. As stated above in the Introduction, global analysis of $b \to s\ell^+\ell^-$ data have been recently performed in Refs. [26–28]. In general, despite that these analyses employed different methodologies (such as statistical methods, form factors

TABLE IV. Flavor-changing couplings to Z' boson in different parametrizations of the TVB model.

Coupling	Parametrization in Ref. [68]	Parametrization in Refs. [62,67]	Parametrization in Refs. [63,66]
g^q_{uc}	$g_{bb}V_{cb}V_{ub} + g_{sb}V_{cs}V_{ub}$ $+g_{sb}V_{cb}V_{us} + g_{ss}V_{cs}V_{us}$	$g^q_2V_{cb}V_{ub}\cos^2\theta_d - g^q_2V_{cs}V_{ub}\cos\theta_d\sin\theta_d$ $-g^q_2V_{cb}V_{us}\cos\theta_d\sin\theta_d + g^q_2V_{cs}V_{us}\sin^2\theta_d$	$g_q\lambda_{uc}/\sqrt{2}$
g^q_{ut}	$g_{bb}V_{tb}V_{ub} + g_{sb}V_{ts}V_{ub}$ $+g_{sb}V_{tb}V_{us} + g_{ss}V_{ts}V_{us}$	$g^q_2V_{tb}V_{ub}\cos^2\theta_d - g^q_2V_{ts}V_{ub}\cos\theta_d\sin\theta_d$ $-g^q_2V_{tb}V_{us}\cos\theta_d\sin\theta_d + g^q_2V_{ts}V_{us}\sin^2\theta_d$	$g_q\lambda_{ut}/\sqrt{2}$
g^q_{ct}	$g_{bb}V_{cb}V_{tb} + g_{sb}V_{cs}V_{tb}$ $+g_{sb}V_{cb}V_{ts} + g_{ss}V_{cs}V_{ts}$	$g^q_2V_{cb}V_{tb}\cos^2\theta_d - g^q_2V_{cs}V_{tb}\cos\theta_d\sin\theta_d$ $-g^q_2V_{cb}V_{ts}\cos\theta_d\sin\theta_d + g^q_2V_{cs}V_{ts}\sin^2\theta_d$	$g_q\lambda_{ct}/\sqrt{2}$

TABLE V. Couplings of leptons to Z' boson in different parametrizations of the TVB model.

Coupling	Parametrization in Ref. [68]	Parametrization in Refs. [62,67]	Parametrization in Refs. [63,66]
$g_{\mu\mu}$	$g_{\mu\mu}$	$g^\ell_2\sin^2\theta_L$	$g_q(\lambda_{\mu\mu})/\sqrt{2}$
$g_{\mu\tau}$	$g_{\mu\tau}$	$-g^\ell_2\sin\theta_L\cos\theta_L$	$2g_q(\lambda_{\mu\tau})/\sqrt{2}$
$g_{\tau\tau}$	$g_{\tau\tau}$	$g^\ell_2\cos^2\theta_L$	$g_q/\sqrt{2}$

choices, assumptions about nonperturbative effects, among others), there is a notable level of agreement. Therefore, for simplicity, in our study, we will consider the results obtained in Ref. [26]. In the one-dimensional NP scenarios (see Table 6 of Ref. [26]), the 1σ solution of the WC $C_9^{bs\ell\ell} \in [-0.99, -0.57]$ with a pull $= 3.7\sigma$ is notably preferred by the data, thus favoring solutions in which the NP contributes equally to electrons and muons ($\ell = e, \mu$). The analysis also leaves open the possibility of different NP scenarios, such as the one generated by the $C_9^{bs\ell\ell} = -C_{10}^{bs\ell\ell}$ solution, which is associated with the dimension-6 operator $(\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu P_L \ell)$. In the context of the TVB model, the Z' boson couples only to left-handed fermions, allowing it to induce this operator at the tree level. Keeping this in mind, we consider the following two 1σ solutions [26]:

(1) lepton-universal: universal contributions to $b \to s e^+ e^-$ and $b \to s\mu^+\mu^-$ (but not $b \to s\tau^+\tau^-$),

$$C_9^{bs\ell\ell} = -C_{10}^{bs\ell\ell} \in [-0.51, -0.29] \qquad (\text{pull} = 3.5\sigma), \tag{30}$$

(2) muon specific: purely muonic contribution to $b \to s\mu^+\mu^-$,

$$C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu} \in [-0.23, -0.11] \qquad (\text{pull} = 2.7\sigma). \tag{31}$$

The pull for the lepton-universal solution is considerably larger than that for the muon-specific one. However, the muon-specific solution still stands as a viable choice. In further analysis, we will use these two different scenarios. The corresponding WC read as follows:

$$C_9^{bs\ell\ell} = -C_{10}^{bs\ell\ell} = -\frac{\pi}{\sqrt{2} G_F \alpha_{\rm em} V_{tb} V_{ts}^*} \frac{g_{sb}^q g_{\ell\ell}^\ell}{M_V^2}. \tag{32}$$

Using the above results of the global fit [26], these correspond to

$$-\frac{g_{sb}^q g_{\ell\ell}^\ell}{M_V^2} \in [4.4, 7.7] \times 10^{-4}\ \text{TeV}^{-2}, \tag{33}$$

$$-\frac{g_{sb}^q g_{\mu\mu}^\ell}{M_V^2} \in [1.7, 3.5] \times 10^{-4}\ \text{TeV}^{-2} \tag{34}$$

for the lepton-universal and muon-specific solutions, respectively.

B. $b \to c\ell^-\bar{\nu}_\ell$ data

The W' boson leads to additional tree-level contribution to $b \to c\ell^-\bar{\nu}_\ell$ transitions involving all lepton generations ($\ell = e, \mu, \tau$). The total low-energy effective Lagrangian has the form [53]

$$-\mathcal{L}_{\rm eff}(b \to c\ell\bar{\nu}_\ell)_{\rm SM+W'} = \frac{4G_F}{\sqrt{2}} V_{cb}[(1 + C_V^{bc\ell\nu_\ell}) \times (\bar{c}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu P_L \nu_\ell)], \tag{35}$$

where G_F is the Fermi coupling constant, V_{cb} is the charm-bottom CKM matrix element, and $C_V^{bc\ell\nu_\ell}$ is the WC associated with the NP vector (left-left) operator. This WC is defined as

$$C_V^{bc\ell\nu_\ell} = \frac{\sqrt{2}}{4G_F V_{cb}} \frac{2(V_{cs} g_{sb}^q + V_{cb} g_{bb}^q) g_{\ell\ell}^\ell}{M_V^2}, \tag{36}$$

with $g_{\ell\ell}^\ell = g_{ee}^\ell, g_{\mu\mu}^\ell, g_{\tau\tau}^\ell$, and M_V the heavy boson mass. Let us notice that in the lepton-universal scenario $C_9^{bs\ell\ell} = -C_{10}^{bs\ell\ell}$ ($\ell = e,\ \mu$) we have $C_V^{bc\mu\nu_\mu} = C_V^{bce\nu_e} \neq 0$ owing to $g_{\mu\mu}^\ell = g_{ee}^\ell$, while in the muon-specific scenario $C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$, we have $C_V^{bc\mu\nu_\mu} \neq 0$ and $C_V^{bce\nu_e} = 0$, because of $g_{\mu\mu}^\ell \neq 0$ and $g_{ee}^\ell = 0$, respectively. The NP effects on the LFU ratios $R(X)$ ($X = D^{(*)}, J/\psi, \Lambda_c$) can be easily parametrized as

$$R(D^{(*)}) = R(D^{(*)})_{\rm SM} \frac{2|1 + C_V^{bc\tau\nu_\tau}|^2}{|1 + C_V^{bc\mu\nu_\mu}|^2 + |1 + C_V^{bce\nu_e}|^2} \tag{37}$$

$$R(J/\psi) = R(J/\psi)_{\rm SM} \frac{|1 + C_V^{bc\tau\nu_\tau}|^2}{|1 + C_V^{bc\mu\nu_\mu}|^2}, \tag{38}$$

$$R(\Lambda_c) = R(\Lambda_c)_{\rm SM} \frac{|1 + C_V^{bc\tau\nu_\tau}|^2}{|1 + C_V^{bc\mu\nu_\mu}|^2}. \tag{39}$$

The D^* and τ longitudinal polarizations related with the channel $\bar{B} \to D^*\tau\bar{\nu}_\tau$ and the tauonic decay $B_c^- \to \tau^-\bar{\nu}_\tau$ are only affected by NP contributions to the third lepton generation. These observables are modified as

$$F_L(D^*) = F_L(D^*)_{\rm SM} r_{D^*}^{-1} |1 + C_V^{bc\tau\nu_\tau}|^2, \tag{40}$$

$$P_\tau(D^*) = P_\tau(D^*)_{\rm SM} r_{D^*}^{-1} |1 + C_V^{bc\tau\nu_\tau}|^2, \tag{41}$$

$$\text{BR}(B_c^- \to \tau^-\bar{\nu}_\tau) = \text{BR}(B_c^- \to \tau^-\bar{\nu}_\tau)_{\rm SM} |1 + C_V^{bc\tau\nu_\tau}|^2, \tag{42}$$

respectively, where $r_{D^*} = R(D^*)/R(D^*)_{\rm SM}$. For BR $\times$ $(B_c^- \to \tau^-\bar{\nu}_\tau)$, we will use the bound $< 10\%$ [51].

With regard to the transition $b \to c\mu\bar{\nu}_\mu$, the μ/e LFU ratios $R_{D^{(*)}}^{\mu/e} \equiv \text{BR}(B \to D^{(*)}\mu\bar{\nu}_\mu)/\text{BR}(B \to D^{(*)} e\bar{\nu}_e)$ have to be taken into account. The experimental values obtained by Belle [54,56] are in great accordance with the SM estimations [55,57] (see Table I). The NP effects on this ratio read as

$$R^{\mu/e}_{D^{(*)}} = [R^{\mu/e}_{D^{(*)}}]_{\rm SM} \frac{|1 + C_V^{bc\mu\nu_\mu}|^2}{|1 + C_V^{bce\nu_e}|^2}. \quad (43)$$

C. $b \to u\ell^- \bar{\nu}_\ell$ ($\ell = \mu, \tau$) data

The TVB model can also induce NP contributions in the leptonic decay $B \to \ell\bar{\nu}_\ell$ induced via the charged-current transition $b \to u\ell^-\bar{\nu}_\ell$ ($\ell = \mu, \tau$). The ratio

$$R_B^{\tau/\mu} \equiv \frac{{\rm BR}(B^- \to \tau^-\bar{\nu}_\tau)}{{\rm BR}(B^- \to \mu^-\bar{\nu}_\mu)} \quad (44)$$

provides a clean LFU test [55]. Through this ratio, the uncertainties on the decay constant f_B and CKM element V_{ub} cancel out (circumventing the tension between the exclusive and inclusive values of V_{ub} [73]). The NP effects on this ratio can be expressed as

$$R_B^{\tau/\mu} = [R_B^{\tau/\mu}]_{\rm SM} \left| \frac{1 + C_V^{bu\tau\nu_\tau}}{1 + C_V^{bu\mu\nu_\mu}} \right|^2, \quad (45)$$

where

$$C_V^{bu\ell\nu_\ell} = \frac{\sqrt{2}}{4G_F V_{ub}} \frac{2(V_{us} g^q_{sb} + V_{ub} g^q_{bb}) g^\ell_{\ell\ell}}{M_V^2}, \quad (46)$$

and

$$[R_B^{\tau/\mu}]_{\rm SM} = \left(\frac{m_\tau}{m_\mu}\right)^2 \left(\frac{m_B^2 - m_\tau^2}{m_B^2 - m_\mu^2}\right)^2 = 222.5 \pm 3.0. \quad (47)$$

The experimental value is $[R_B^{\tau/\mu}]_{\rm Exp} = 205.7 \pm 96.6$, which was obtained from the values reported by the Particle Data Group (PDG) on ${\rm BR}(B^- \to \tau^-\bar{\nu}_\tau)$ [74] and the Belle experiment on ${\rm BR}(B^- \to \mu^-\bar{\nu}_\mu)$ [75].

D. Bottomonium processes: $R_{\Upsilon(nS)}$ and $\Upsilon(nS) \to \mu^\pm\tau^\mp$

A test of LFU has also been studied in the leptonic ratio $R_{\Upsilon(nS)}$ (with $n = 1, 2, 3$) [76],

$$R_{\Upsilon(nS)} = \frac{\Gamma(\Upsilon(nS) \to \tau^+\tau^-)}{\Gamma(\Upsilon(nS) \to \ell^+\ell^-)} \quad (\ell = e, \mu), \quad (48)$$

in connection with the reported hints of LFU violation in the charged-current transition $b \to c\tau\bar{\nu}_\tau$ [76,77].[3] It is known that NP scenarios aiming to provide an explanation to the anomalous $b \to c\tau\bar{\nu}_\tau$ data also induce effects in the neutral-current transition $b\bar{b} \to \tau^+\tau^-$ [76,77]. Experimentally, the *BABAR* and CLEO Collaborations have reported the values [79–81]

$$R_{\Upsilon(1S)} = \begin{cases} BABAR\text{-}10: 1.005 \pm 0.013 \pm 0.022\,[81], \\ \text{SM}: 0.9924\,[79], \end{cases} \quad (49)$$

$$R_{\Upsilon(2S)} = \begin{cases} \text{CLEO-07}: 1.04 \pm 0.04 \pm 0.05\,[82], \\ \text{SM}: 0.9940\,[79], \end{cases} \quad (50)$$

$$R_{\Upsilon(3S)} = \begin{cases} \text{CLEO-07}: 1.05 \pm 0.08 \pm 0.05\,[82], \\ BABAR\text{-}20: 0.966 \pm 0.008 \pm 0.014\,[83], \\ \text{SM}: 0.9948\,[79], \end{cases} \quad (51)$$

where the theoretical uncertainty is typically of the order $\pm\mathcal{O}(10^{-5})$ [76]. These measurements are in good accordance with the SM estimations, except for the 2020 measurement on $R_{\Upsilon(3S)}$ that shows an agreement at the 1.8σ level [81]. By averaging the CLEO-07 [80] and *BABAR*-20 [81] measurements, we obtain $R^{\rm Ave}_{\Upsilon(3S)} = 0.968 \pm 0.016$, which deviates at the 1.7σ level with respect to the SM prediction [77].

The NP effects of the TVB model on the leptonic ratio can be expressed as [76]

$$R_{\Upsilon(nS)} = (1 - 4x_\tau^2)^{1/2} \left[\frac{|A_V^{b\tau}|^2(1 + 2x_\tau^2) + |B_V^{b\tau}|^2(1 - 4x_\tau^2)}{|A_V^{b\mu}|^2 + |B_V^{b\mu}|^2} \right], \quad (52)$$

with $x_\tau = m_\tau/m_{\Upsilon(nS)}$ and

$$A_V^{b\ell} = -4\pi\alpha Q_b + \frac{m^2_{\Upsilon(nS)}}{4} \frac{g^q_{bb} g^\ell_{\ell\ell}}{4M_V^2}, \quad (53)$$

$$B_V^{b\ell} = -\frac{m^2_{\Upsilon(nS)}}{2} \frac{g^q_{bb} g^\ell_{\ell\ell}}{4M_V^2}. \quad (54)$$

This ratio is modified because $\Upsilon(nS) \to \tau^+\tau^-$ and $\Upsilon(nS) \to \mu^+\mu^-$ are affected.

The neutral gauge boson also generates the LFV processes $\Upsilon \to \mu^\pm\tau^\mp$ ($\Upsilon \equiv \Upsilon(nS)$). The branching fraction is given by [67,68]

$$\begin{aligned} {\rm BR}(\Upsilon \to \mu^\pm\tau^\mp) = & \frac{f_\Upsilon^2 m_\Upsilon^3}{48\pi\Gamma_\Upsilon} \left(2 + \frac{m_\tau^2}{m_\Upsilon^2}\right) \\ & \times \left(1 - \frac{m_\tau^2}{m_\Upsilon^2}\right)^2 \left| \frac{g^q_{bb}(g^\ell_{\mu\tau})^*}{M_V^2} \right|^2, \end{aligned} \quad (55)$$

where f_Υ and m_Υ are the Upsilon decay constant and mass, respectively. The decay constant values can be extracted from the experimental branching ratio

[3] Recently, in Ref. [78] has been proposed a new method to test LFU through inclusive dileptonic $\Upsilon(4S)$ decays.

measurements of the processes $\Upsilon \to e^- e^+$. Using current data from PDG [74], one obtains $f_{\Upsilon(1S)} = (659 \pm 17)$ MeV, $f_{\Upsilon(2S)} = (468 \pm 27)$ MeV, and $f_{\Upsilon(3S)} = (405 \pm 26)$ MeV. Experimentally, the reported upper limits (ULs) are $\mathrm{BR}(\Upsilon(1S) \to \mu^\pm \tau^\mp) < 2.7 \times 10^{-6}$ from Belle [82] and $\mathrm{BR}(\Upsilon(2S) \to \mu^\pm \tau^\mp) < 3.3 \times 10^{-6}$, $\mathrm{BR}(\Upsilon(3S) \to \mu^\pm \tau^\mp) < 3.1 \times 10^{-6}$ from PDG [74]. From these ULs, we get

$$\Upsilon(1S) \to \mu^\pm \tau^\mp: \frac{|g_{bb}^q (g_{\mu\tau}^\ell)^*|}{M_V^2} < 5.7\ \mathrm{TeV}^{-2}, \tag{56a}$$

$$\Upsilon(2S) \to \mu^\pm \tau^\mp: \frac{|g_{bb}^q (g_{\tau\mu}^\ell)^*|}{M_V^2} < 6.2\ \mathrm{TeV}^{-2}, \tag{56b}$$

$$\Upsilon(3S) \to \mu^\pm \tau^\mp: \frac{|g_{bb}^q (g_{\mu\tau}^\ell)^*|}{M_V^2} < 5.2\ \mathrm{TeV}^{-2}. \tag{56c}$$

E. $\Delta F = 2$ processes: $B_s - \bar{B}_s$ and $D^0 - \bar{D}^0$ mixing

The interactions of a Z' boson to quarks $s\bar{b}$ relevant for $b \to s\mu^+\mu^-$ processes also generate a contribution to $B_s - \bar{B}_s$ mixing [83,84]. The NP effects to the $B_s - \bar{B}_s$ mixing can be described by the effective Lagrangian

$$\mathcal{L}_{\Delta B=2}^{Z'} = -\frac{4G_F}{\sqrt{2}} |V_{tb} V_{ts}^*|^2 C_{sb}^{LL} (\bar{s}\gamma_\mu P_L b)(\bar{s}\gamma^\mu P_L b) + \mathrm{H.c.}, \tag{57}$$

where

$$C_{sb}^{LL} = \frac{1}{4\sqrt{2} G_F |V_{tb} V_{ts}^*|^2} \frac{|g_{sb}^q|^2}{M_{Z'}^2}. \tag{58}$$

Thus, the NP contributions to the mass difference ΔM_s of the neutral B_s meson can be expressed as [83]

$$\frac{\Delta M_s^{\mathrm{SM+NP}}}{\Delta M_s^{\mathrm{SM}}} = \left(1 + \frac{\eta^{6/23}}{R_{\mathrm{SM}}^{\mathrm{loop}}} C_{sb}^{LL}\right), \tag{59}$$

where $\eta = \alpha_s(M_{Z'})/\alpha_s(m_b)$ accounts for running from the $M_{Z'}$ scale down to the b-quark mass scale and the SM loop function is $R_{\mathrm{SM}}^{\mathrm{loop}} = (1.310 \pm 0.010) \times 10^{-3}$ [83]. At present, ΔM_s has been experimentally measured with great precision $\Delta M_s^{\mathrm{Exp}} = (17.757 \pm 0.021)\ \mathrm{ps}^{-1}$ [42,83]. On the theoretical side, the average is $\Delta M_s^{\mathrm{SM}} = (18.4^{+0.7}_{-1.2})\ \mathrm{ps}^{-1}$, implying that $\Delta M_s^{\mathrm{SM}}/\Delta M_s^{\mathrm{Exp}} = 1.04^{+0.04}_{-0.07}$ [83]. This value results in to

$$0.89 \leq \left| 1 + \frac{\eta^{6/23}}{R_{\mathrm{loop}}^{\mathrm{SM}}} C_{sb}^{LL} \right| \leq 1.11, \tag{60}$$

which in the TVB model translates into the important 2σ bound

$$\frac{|g_{sb}^q|}{M_V} \geq 3.9 \times 10^{-3}\ \mathrm{TeV}^{-1}. \tag{61}$$

In addition, the Z' boson can also admit $c \to u$ transitions, consequently generating tree-level effects on $D^0 - \bar{D}^0$ mixing [68,85]. The effective Lagrangian describing the Z' contribution to $D^0 - \bar{D}^0$ mixing can be expressed as [68,85]

$$\mathcal{L}_{\Delta C=2}^{Z'} = -\frac{|g_{uc}|^2}{2M_{Z'}^2} (\bar{c}\gamma_\mu P_L u)(\bar{c}\gamma^\mu P_L u) + \mathrm{H.c.}, \tag{62}$$

where $g_{uc} = g_{bb}^q V_{cb} V_{ub}^* + g_{sb}^q (V_{cs} V_{ub}^* + V_{cb} V_{us}^*) + g_{ss}^q V_{cs} V_{us}^*$ [68] (see also Table IV). Such NP contributions are constrained by the results of the mass difference ΔM_D of neutral D mesons. The theoretical determination of this mass difference is limited by our understanding of the short- and long-distance contributions [68,85]. Here, we follow the recent analysis of Ref. [68] focused on short-distance SM contribution that sets the conservative (strong) bound

$$\frac{|g_{ss}^q|}{M_V} \leq 3 \times 10^{-3}\ \mathrm{TeV}^{-1}. \tag{63}$$

The couplings g_{bb}^q and g_{sb}^q are less constrained by ΔM_D [68]; therefore, we will skip them in our study.

F. Neutrino trident production

The Z' couplings to leptons from second generation ($g_{\mu\mu} = g_{\nu_\mu \nu_\mu}$) also generate a contribution to the cross section of neutrino trident production (NTP), $\nu_\mu N \to \nu_\mu N \mu^+ \mu^-$ [86]. The cross section is given by [86]

$$\frac{\sigma_{\mathrm{SM+NP}}}{\sigma_{\mathrm{SM}}} = \frac{1}{1 + (1 + 4s_W^2)^2} \left[\left(1 + \frac{v^2 g_{\mu\mu}^2}{M_V^2}\right)^2 + \left(1 + 4s_W^2 + \frac{v^2 g_{\mu\mu}^2}{M_V^2}\right)^2 \right], \tag{64}$$

where $v = (\sqrt{2} G_F)^{-1/2}$ and $s_W \equiv \sin\theta_W$ (with θ_W the Weinberg angle). The existing Chicago-Columbia-Fermilab-Rochester (CCFR) trident measurement $\sigma_{\mathrm{CCFR}}/\sigma_{\mathrm{SM}} = 0.82 \pm 0.28$ provides the upper bound

$$\frac{|g_{\mu\mu}^\ell|}{M_{Z'}} \leq 1.13\ \mathrm{TeV}^{-1}. \tag{65}$$

G. LFV B decays: $B \to K^{(*)} \mu^\pm \tau^\mp$ and $B_s \to \mu^\pm \tau^\mp$

The Z' boson mediates LFV transitions $b \to s\mu^\pm \tau^\mp$ ($B \to K^{(*)} \mu^\pm \tau^\mp$ and $B_s^0 \to \mu^\pm \tau^\mp$) at tree level via the WCs [62]:

$$C_9^{bs\mu\tau} = -C_{10}^{bs\mu\tau} = -\frac{\pi}{\sqrt{2}G_F\alpha_{\rm em}V_{tb}V_{ts}^*}\frac{g_{sb}^q(g_{\mu\tau}^\ell)^*}{M_V^2}. \quad (66)$$

The current experimental limits (90% C.L.) on the branching ratios of $B^+ \to K^+\mu^\pm\tau^\mp$ are [74]

$$\mathrm{BR}(B^+ \to K^+\mu^+\tau^-)_{\rm exp} < 4.5\times 10^{-5}, \quad (67)$$

$$\mathrm{BR}(B^+ \to K^+\mu^-\tau^+)_{\rm exp} < 2.8\times 10^{-5}. \quad (68)$$

Let us notice that LHCb Collaboration obtained a limit of $\mathrm{BR}(B^+ \to K^+\mu^-\tau^+)_{\rm LHCb} < 3.9\times 10^{-5}$ [87] that is comparable with the one quoted above from the PDG. On the other hand, the LHCb has recently presented the first search of $B^0 \to K^{*0}\mu^\pm\tau^\mp$ [88]. The obtained UL on this LFV decay is [88]

$$\mathrm{BR}(B^0 \to K^{*0}\mu^\pm\tau^\mp)_{\rm exp} < 1.0\times 10^{-5}. \quad (69)$$

From the theoretical side, the branching ratio of $B^+ \to K^+\mu^+\tau^-$ [89] and $B^0 \to K^{*0}\mu^+\tau^-$ [62] can be written as

$$\mathrm{BR}(B^+ \to K^+\mu^+\tau^-) = (a_K|C_9^{bs\mu\tau}|^2 + b_K|C_{10}^{bs\mu\tau}|^2)\times 10^{-9}, \quad (70)$$

$$\mathrm{BR}(B^0 \to K^{*0}\mu^+\tau^-) = ((a_{K^*}+c_{K^*})|C_9^{bs\mu\tau}|^2 + (b_{K^*}+d_{K^*})|C_{10}^{bs\mu\tau}|^2)\times 10^{-9}, \quad (71)$$

respectively, where $(a_K, b_K) = (12.72\pm 0.81, 13.21\pm 0.81)$ [89] and $(a_{K^*}, b_{K^*}, c_{K^*}, d_{K^*}) = (3.0\pm 0.8, 2.7\pm 0.7, 16.4\pm 2.1, 15.4\pm 1.9)$ [62] are the numerical coefficients that have been calculated using the $B\to K^{(*)}$ transitions form factors obtained from lattice QCD [62,89]. The decay channel with final state $\mu^-\tau^+$ can be easily obtained by replacing $\mu\leftrightarrows\tau$. The current ULs can be translated into the bounds

$$B^+ \to K^+\mu^+\tau^-: \frac{|g_{sb}^q(g_{\mu\tau}^\ell)^*|}{M_V^2} < 6.2\times 10^{-2}\ \mathrm{TeV}^{-2}, \quad (72a)$$

$$B^+ \to K^+\mu^-\tau^+: \frac{|g_{sb}^q(g_{\tau\mu}^\ell)^*|}{M_V^2} < 4.9\times 10^{-2}\ \mathrm{TeV}^{-2}, \quad (72b)$$

$$B^0 \to K^{*0}\mu^+\tau^-: \frac{|g_{sb}^q(g_{\mu\tau}^\ell)^*|}{M_V^2} < 2.5\times 10^{-2}\ \mathrm{TeV}^{-2}. \quad (72c)$$

As for the LFV leptonic decay $B_s \to \mu^\pm\tau^\mp$, the branching ratio is [62]

$$\mathrm{BR}(B_s^0 \to \mu^\pm\tau^\mp) = \tau_{B_s}\frac{f_{B_s}^2 m_{B_s} m_\tau^2}{32\pi^3}\alpha^2 G_F^2|V_{tb}V_{ts}^*|^2 \times\left(1-\frac{m_\tau^2}{m_{B_s}^2}\right)^2(|C_9^{bs\mu\tau}|^2+|C_{10}^{bs\mu\tau}|^2), \quad (73)$$

where $f_{B_s} = (230.3\pm 1.3)$ MeV is the B_s decay constant [42] and we have used the limit $m_\tau \gg m_\mu$. Recently, the LHCb experiment has reported the first upper limit of $\mathrm{BR}(B_s\to\mu^\pm\tau^\mp) < 4.2\times 10^{-5}$ at 95% C.L. [90]. Thus, one gets the following limit:

$$\frac{|g_{sb}^q(g_{\mu\tau}^\ell)^*|}{M_V^2} < 5.1\times 10^{-2}\ \mathrm{TeV}^{-2}. \quad (74)$$

H. Rare B decays: $B\to K^{(*)}\nu\bar\nu$, $B\to K\tau^+\tau^-$ and $B_s\to\tau^+\tau^-$

Recently, the interplay between the dineutrino channel $B\to K^{(*)}\nu\bar\nu$ and the B meson anomalies has been studied by several works [85,91–94]. In the NP scenario under study, the Z' boson can give rise to $B\to K^{(*)}\nu\bar\nu$ at tree level. The effective Hamiltonian for the $b\to s\nu\bar\nu$ transition is given by [95]

$$\mathcal{H}_{\rm eff}(b\to s\nu\bar\nu) = -\frac{\alpha_{\rm em}G_F}{\sqrt{2}\pi}V_{tb}V_{ts}^*C_L^{ij}(\bar s\gamma^\mu P_L b)\times(\bar\nu_i\gamma_\mu(1-\gamma_5)\nu_j), \quad (75)$$

where $C_L^{ij} = C_L^{\rm SM} + \Delta C_L^{ij}$ is the aggregate of the SM contribution $C_L^{\rm SM}\approx -6.4$ and the NP effects ΔC_L^{ij}, that in the TVB framework read as

$$\Delta C_L^{ij} = \frac{\pi}{\sqrt{2}G_F\alpha_{\rm em}V_{tb}V_{ts}^*}\frac{g_{sb}^q g_{ij}^\ell}{M_V^2}, \quad (76)$$

with $i, j = e, \mu, \tau$. By defining the ratio [95]

$$R_{K^{(*)}}^{\nu\bar\nu} \equiv \frac{\mathrm{BR}(B\to K^{(*)}\nu\bar\nu)}{\mathrm{BR}(B\to K^{(*)}\nu\bar\nu)_{\rm SM}}, \quad (77)$$

the NP contributions can be constrained. In the TVB model, this ratio is modified as

$$R_{K^{(*)}}^{\nu\bar\nu} = \frac{\sum_{ij}|\delta_{ij}C_L^{\rm SM}+\Delta C_L^{ij}|^2}{3|C_L^{\rm SM}|^2}, \quad (78)$$

$$= 1 + \frac{2\sum_i C_L^{\rm SM}\Delta C_L^{ii} + \sum_{ij}|\Delta C_L^{ij}|^2}{3|C_L^{\rm SM}|^2}. \quad (79)$$

From this expression, we can observe that diagonal leptonic couplings $g_{\mu\mu(ee)}^\ell$ contribute to $b\to s\nu_\mu\bar\nu_\mu(\nu_e\bar\nu_e)$

which are relevant for $b \to s\ell^+\ell^-$ data, while $g^{\ell}_{\tau\tau}$ contributes to $b \to s\nu_\tau\bar{\nu}_\tau$, which is relevant for $b \to c\tau\bar{\nu}_\tau$ data. In addition, since the neutrino flavor is experimentally unobservable in heavy meson experiments, it is also possible to induce the LFV transitions $b \to s\nu_\mu\bar{\nu}_\tau$ (and $\nu_\tau\bar{\nu}_\mu$) through the off-diagonal coupling $g^{\ell}_{\mu\tau}$.

Experimentally, the Belle II Collaboration (using 326 fb^{-1} data) has recently presented the first evidence of the $B^+ \to K^+\nu\bar{\nu}$ decay with a branching ratio [96,97],

$$\mathrm{BR}(B^+ \to K^+\nu\bar{\nu})_{\text{Belle II}} = (2.4 \pm 0.7) \times 10^{-5}, \quad (80)$$

which is in tension with the SM expectation $\mathrm{BR}(B^+ \to K^+\nu\bar{\nu})_{\mathrm{SM}} = (5.58 \pm 0.38) \times 10^{-6}$ [89] by about 2.8σ. Moreover, this new result is consistent within errors, but about twice larger, with a previous Belle II weighted average $(1.1 \pm 0.4) \times 10^{-5}$ [98,99]. In turn, with the new Belle II measurement, the ratio $R^{\nu\bar{\nu}}_{K^+}$ has been calculated to be

$$R^{\nu\bar{\nu}}_{K^+} = 4.3 \pm 1.3. \quad (81)$$

Given this enhance ratio, it is interesting to study its implication for the TVB model phenomenology. On the other hand, for the $B \to K^*\nu\bar{\nu}$ decay, the Belle experiment in 2017 obtained the following UL on its branching fraction $\mathrm{BR}(B \to K^*\nu\bar{\nu}) < 2.7 \times 10^{-5}$ (90% C.L.) [100], resulting in a limit on the ratio $R^{\nu\bar{\nu}}_{K^*}$ of [100]

$$R^{\nu\bar{\nu}}_{K^*} < 2.7. \quad (82)$$

The rare B processes $B_s \to \tau^+\tau^-$ and $B \to K\tau^+\tau^-$ (induced via $b \to s\tau^+\tau^-$ transition) are expected to receive significant NP impact. For the leptonic process $B_s \to \tau^+\tau^-$, the SM branching ratio is shifted by the factor

$$\mathrm{BR}(B_s \to \tau^+\tau^-) = \mathrm{BR}(B_s \to \tau^+\tau^-)_{\mathrm{SM}} \times \left| 1 + \frac{\pi}{\sqrt{2} G_F \alpha_{\mathrm{em}} V_{tb} V^*_{ts} C^{\mathrm{SM}}_{10}} \frac{g^q_{sb}(g^{\ell}_{\tau\tau})^*}{M_V^2} \right|^2, \quad (83)$$

where $C^{\mathrm{SM}}_{10} \simeq -4.3$. The strongest experimental bound on its branching ratio has been obtained by the LHCb, $\mathrm{BR}(B_s \to \tau^+\tau^-) < 6.8 \times 10^{-3}$ at 95% confidence level [101], while its SM prediction is $\mathrm{BR}(B^0_s \to \tau^+\tau^-)_{\mathrm{SM}} = (7.73 \pm 0.49) \times 10^{-7}$ [102]. The bound is

$$\frac{|g^q_{sb}(g^{\ell}_{\tau\tau})^*|}{M_V^2} < 0.56\ \mathrm{TeV}^{-2}. \quad (84)$$

As concerns the semileptonic decay $B \to K\tau^+\tau^-$, an easily handled numerical formula for the branching ratio (over the whole kinematic range for the lepton pair invariant mass) has been obtained in Ref. [103], for the case of a singlet vector leptoquark explanation of the B meson anomalies. Since the NP contribution is generated via the same operator, this expression can be easily (but properly) translated to the TVB model, namely,

$$\mathrm{BR}(B \to K\tau^+\tau^-) \simeq 1.5 \times 10^{-7} + 1.4 \times 10^{-3} \left(\frac{1}{2\sqrt{2}G_F}\right) \times \frac{\mathrm{Re}[g^q_{sb}(g^{\ell}_{\tau\tau})^*]}{M_V^2} + 3.5 \left(\frac{1}{2\sqrt{2}G_F}\right)^2 \times \frac{|g^q_{sb}(g^{\ell}_{\tau\tau})^*|^2}{M_V^4}. \quad (85)$$

This decay channel has not been observed so far, and the present reported bound is $\mathrm{BR}(B \to K\tau^+\tau^-) < 2.25 \times 10^{-3}$ [74]. We obtained the following bound

$$\frac{|g^q_{sb}(g^{\ell}_{\tau\tau})^*|}{M_V^2} < 0.83\ \mathrm{TeV}^{-2}, \quad (86)$$

that is weaker than the one get from $B_s \to \tau^+\tau^-$.

I. τ decays: $\tau \to \mu\bar{\mu}\mu$, $\tau \to \mu\bar{e}e$, $\tau \to \mu\bar{\nu}_\mu\nu_\tau$, and $\tau \to \mu\phi$

It is known that the TVB model generates four-lepton operators $(\bar{\mu}\gamma^\alpha P_L\tau)(\bar{\ell}\gamma_\alpha P_L\ell)$ and $(\bar{\mu}\gamma^\alpha P_L\tau)(\bar{\nu}_\tau\gamma_\alpha P_L\nu_\mu)$, thus yielding tree-level contributions to the leptonic τ decays, $\tau^- \to \mu^-\ell^+\ell^-$ $(\ell = e, \mu)$ and $\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$, respectively [67,68]. For the LFV decay $\tau^- \to \mu^-\ell^+\ell^-$, the expression for the branching ratio can be written as

$$\mathrm{BR}(\tau^- \to \mu^-\ell^+\ell^-) = \frac{m_\tau^5}{1536\pi^3\Gamma_\tau} \frac{|g^{\ell}_{\ell\ell} g^{\ell}_{\mu\tau}|^2}{M_V^4} \quad (\ell = e, \mu), \quad (87)$$

where Γ_τ is the total decay width of the τ lepton. The current experimental ULs reported by PDG (at 90% C.L.) are $\mathrm{BR}(\tau^- \to \mu^-\mu^+\mu^-) < 2.1 \times 10^{-8}$ and $\mathrm{BR}(\tau^- \to \mu^-e^+e^-) < 1.8 \times 10^{-8}$ [74]. These correspond to

$$\frac{|g^{\ell}_{\mu\mu} g^{\ell}_{\mu\tau}|}{M_V^2} < 1.13 \times 10^{-2}\ \mathrm{TeV}^{-2}, \quad (88)$$

$$\frac{|g^{\ell}_{ee} g^{\ell}_{\mu\tau}|}{M_V^2} < 1.05 \times 10^{-2}\ \mathrm{TeV}^{-2}. \quad (89)$$

The leptonic decay $\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$ is a lepton-flavor-conserving and SM allowed process that receives tree-level contribution from both W' (via lepton-flavor-conserving couplings) and Z' (via LFV couplings) bosons [68]. The branching ratio is given by [68]

$$\mathrm{BR}(\tau\to\mu\bar{\nu}_\mu\nu_\tau)=\mathrm{BR}(\tau\to\mu\bar{\nu}_\mu\nu_\tau)_{\mathrm{SM}}\left(\left|1+\frac{1}{2\sqrt{2}G_FM_V^2}\times(2g^{\ell}_{\mu\mu}g^{\ell}_{\tau\tau}-|g^{\ell}_{\mu\tau}|^2)\right|^2+\left|\frac{1}{2\sqrt{2}G_FM_V^2}|g^{\ell}_{\mu\tau}|^2\right|^2\right), \quad (90)$$

where $\mathrm{BR}(\tau\to\mu\bar{\nu}_\mu\nu_\tau)_{\mathrm{SM}}=(17.29\pm0.03)\%$ [104]. The Z' boson can also generates one-loop corrections, which can be safely ignored. This value has to be compared with the experimental value reported by PDG $\mathrm{BR}(\tau\to\mu\bar{\nu}_\mu\nu_\tau)=(17.39\pm0.04)\%$ [74].

Finally, the branching ratio of the LFV hadronic τ decay $\tau\to\mu\phi$ ($\tau\to\mu s\bar{s}$ transition) can be expressed as [67]

$$\mathrm{BR}(\tau^-\to\mu^-\phi)=\frac{f_\phi^2m_\tau^3}{128\pi\Gamma_\tau}\left(1+2\frac{m_\phi^2}{m_\tau^2}\right)\left(1-\frac{m_\phi^2}{m_\tau^2}\right)^2\frac{|g^{\ell}_{\mu\tau}g^{q}_{ss}|^2}{M_V^4}, \quad (91)$$

where m_ϕ and $f_\phi=(238\pm3)$ MeV [68] are the ϕ meson mass and decay constant, respectively. Currently, the UL reported by Belle on the branching ratio is $\mathrm{BR}(\tau^-\to\mu^-\phi)<2.3\times10^{-8}$ [105]. The current UL produces the bound

$$\frac{|g^{\ell}_{\mu\tau}g^{q}_{ss}|}{M_V^2}<9.4\times10^{-3}\ \mathrm{TeV}^{-2}. \quad (92)$$

Since the $D^0-\bar{D}^0$ mixing imposes that $|g^q_{ss}|/M_V\leq 3.3\times10^{-3}\mathrm{Te\,V}^{-1}$ (see Sec. III E), the constraint from $\tau\to\mu\phi$ can be easily fulfilled. We will not take into account this LFV process in further TVB model analysis.

J. LHC bounds

LHC constraints are always important for models with nonzero Z' couplings to the SM particles [106]. In particular, in our study, it will set important constraints on the parametric space conformed by the TVB couplings $(g^q_{bb},g^{\ell}_{\mu\mu})$ and $(g^q_{bb},g^{\ell}_{\tau\tau})$. We consider the ATLAS search for high-mass dilepton resonances in the mass range of 250 GeV to 6 TeV, in proton-proton collisions at a center-of-mass energy of $\sqrt{s}=13$ TeV during Run 2 of the LHC with an integrated luminosity of 139 fb^{-1} [107] (recently, the CMS Collaboration has also reported constraints for similar luminosities [108], basically identical to ATLAS [107]), and the data from searches of Z' bosons decaying to tau pairs with an integrated luminosity of 36.1 fb^{-1} from proton-proton collisions at $\sqrt{s}=13$ TeV [109]. There are also searches for high-mass resonances in the monolepton channels ($pp\to\ell\nu$) carried out by the ATLAS and CMS [110–112]. However, they provide weaker bounds than those obtained from dilepton searches, and we will not take them into account.

We obtain for benchmark mass value $M_V=1$ TeV the lower limit on the parameter space from the intersection of the 95% C.L. upper limit on the cross section from the ATLAS experiment [107,109] with the theoretical cross section given in Ref. [113]. Lower limits above 4.5 TeV apply to models with couplings to the first family, which is not our case. The strongest restrictions come from Z' production processes in the $b\bar{b}$ annihilation and the subsequent Z' decay into muons ($\mu^+\mu^-$) and taus ($\tau^+\tau^-$). Further details are shown in Refs. [113–115]. Let us remark that within the TVB framework it is also possible to consider the annihilation between quarks with different flavors (namely, g^q_{bs}); however, we anticipate that according to our phenomenological analysis in Sec. IV this coupling is very small. Therefore, we only consider production processes without flavor-changing neutral currents. In the next section, we will show that the TVB parameter space is limited by LHC constraints to regions where the couplings of the leptons or the quarks are close to zero, excluding the regions preferred by the B meson anomalies and low-energy flavor observables.

IV. ANALYSIS ON THE TVB PARAMETRIC SPACE

In this section, we present the parametric space analysis of the TVB model addressing a simultaneous explanation of the $b\to s\mu^+\mu^-$ and $b\to c\tau\bar{\nu}_\tau$ data. We define the pull for the ith observable as

$$\mathrm{pull}_i=\frac{\mathcal{O}_i^{\mathrm{exp}}-\mathcal{O}_i^{\mathrm{th}}}{\Delta\mathcal{O}_i}, \quad (93)$$

where $\mathcal{O}_i^{\mathrm{exp}}$ is the experimental measurement, $\mathcal{O}_i^{\mathrm{th}}\equiv\mathcal{O}_i^{\mathrm{th}}(g^q_{bs},g^q_{bb},g^{\ell}_{\mu\mu},g^{\ell}_{\tau\tau},g^{\ell}_{\mu\tau})$ is the theoretical prediction that include the NP contributions, and $\Delta\mathcal{O}_i=((\sigma_i^{\mathrm{exp}})^2+(\sigma_i^{\mathrm{th}})^2)^{1/2}$ corresponds to the combined experimental and theoretical uncertainties. By means of the pull, we can compare the fitted values of each observable to their measured values. The χ^2 function is written as the sum of squared pulls, i.e.,

$$\chi^2=\sum_i^{N_{\mathrm{obs}}}(\mathrm{pull}_i)^2, \quad (94)$$

where the sum extends over the number of observables (N_{obs}) to be fitted. Our phenomenological analysis is based on the flavor observables presented in the previous section (Sec. III). This all-data set includes $b\to c\tau\bar{\nu}_\tau$ and $b\to s\mu^+\mu^-$ data, bottomonium ratios $R_{\Upsilon(nS)}$, LFV decays $[B^+\to K^+\mu^\pm\tau^\mp,\ B^0\to K^{*0}\mu^\pm\tau^\mp,\ B_s\to\mu^\pm\tau^\mp,\ \Upsilon(nS)\to$

$\mu^\pm\tau^\mp$], rare B decays ($B \to K^{(*)}\nu\bar{\nu}, B \to K\tau^+\tau^-, B_s \to \tau^+\tau^-$), τ decays ($\tau \to 3\mu$, $\tau \to \mu\bar{\nu}_\mu\nu_\tau$), $\Delta F = 2$ processes, and neutrino trident production. We will study the impact of the most recent LHCb measurements on the ratios $R(D^{(*)})$ [43–45]. For such a purpose, we will consider in our analysis the following three different sets of observables:

(i) All data with $R(D)_{\mathrm{LHCb22}} + R(D^*)_{\mathrm{LHCb23}}$,
(ii) All data with $R(D^{(*)})_{\mathrm{LHCb22}}$,
(iii) All data with $R(D^{(*)})_{\mathrm{HFLAV23}}$.

Moreover, as it was pointed out in the Introduction and Sec. III A, the preferred solutions to describe the $R_{K^{(*)}}$ data are the one-dimension NP scenarios involving universal contributions to $b \to se^+e^-$ and $b \to s\mu^+\mu^-$ (lepton universal) and NP contributions only to $b \to s\mu^+\mu^-$ (muon specific). Keeping this in mind, we present an updated status of the TVB model as an explanation to the B meson anomalies and explore whether the TVB framework can account for these NP solutions. In both NP scenarios, muon specific and lepton universal, we have that all the three datasets contain a total number of observables $N_{\mathrm{obs}} = 31$ and five free TVB parameters (g^q_{bs}, g^q_{bb}, $g^\ell_{\mu\mu}$, $g^\ell_{\tau\tau}$, $g^\ell_{\mu\tau}$) to be fitted. The heavy TVB mass will be fixed to the benchmark value $M_V = 1$ TeV. Therefore, the number of degrees of freedom is $N_{\mathrm{dof}} = 26$.

For the three sets of observables, we find the best-fit point (BFP) values by minimizing the χ^2 function (χ^2_{min}). In

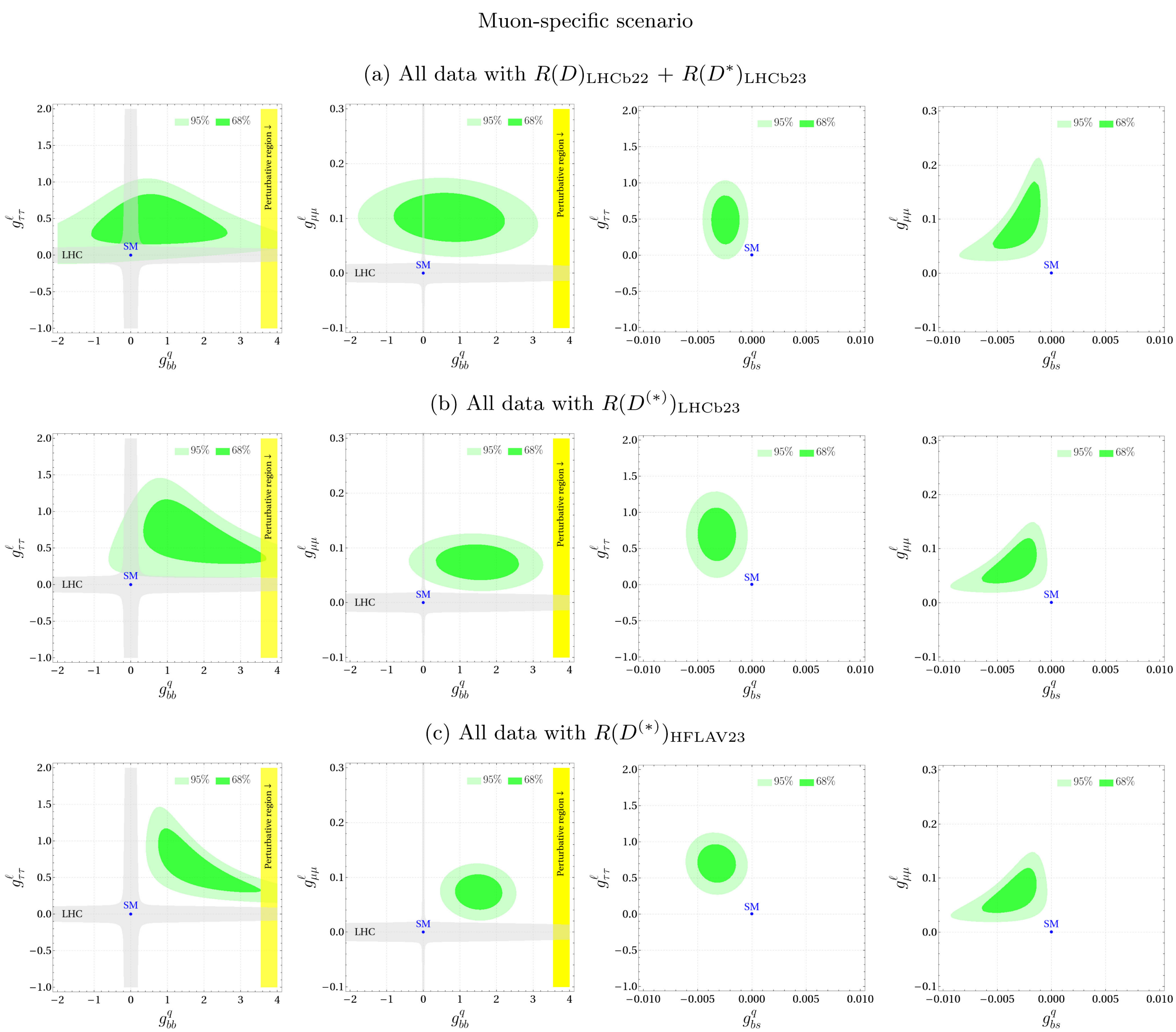

FIG. 1. Muon-specific scenario: 68% (green) and 95% (light-green) C.L. allowed regions for the most relevant 2D parametric space of (a) all data with $R(D)_{\mathrm{LHCb22}} + R(D^*)_{\mathrm{LHCb23}}$, (b) all data with $R(D^{(*)})_{\mathrm{LHCb22}}$, and (c) all data with $R(D^{(*)})_{\mathrm{HFLAV23}}$, respectively, for $M_V = 1$ TeV. In each plot, we are marginalizing over the rest of the parameters. The SM value is represented by the blue dot. The light-gray region corresponds to LHC bounds at the 95% C.L. The perturbative region ($g^q_{bb} \geq \sqrt{4\pi}$) is represented by the yellow color.

Table VI, we report our results of the BFP values and 1σ intervals of TVB couplings for the muon-specific and lepton-universal scenarios, respectively. For each fit, we also present in Table VI the values of $\chi^2_{\rm min}/N_{\rm dof}$ and its corresponding p value to evaluate the fit quality. The most significant observations are as follows:

(i) *Muon-specific scenario*. It is found (in general) that the three sets of observables provide an excellent fit of the data. In the quark sector, the TVB model requires small g_{bs}^q coupling, $|g_{bs}^q| \sim \mathcal{O}(10^{-3})$, and opposite sign to $g_{\mu\mu}^\ell$ to be consistent with $C_9^{\mu\mu} = -C_{10}^{\mu\mu}$ solution to $b \to s\mu^+\mu^-$ data and $B_s - \bar{B}_s$ mixing. On the other hand, large values for the bottom-bottom coupling $g_{bb}^q \sim \mathcal{O}(1)$ are preferred but safe from the perturbative regime ($< \sqrt{4\pi}$). The lower value on g_{bb}^q is obtained for all data with $R(D)_{\rm LHCb22} + R(D^*)_{\rm LHCb23}$. As for the leptonic couplings, it is found that the lepton-flavor-conserving ones have a similar size $g_{\mu\mu}^\ell \approx g_{\tau\tau}^\ell \sim \mathcal{O}(10^{-1})$ for all data with $R(D)_{\rm LHCb22} + R(D^*)_{\rm LHCb23}$, suggesting a nonhierarchy pattern. While for all data with $R(D^{(*)})_{\rm LHCb23}$ [with $R(D^{(*)})_{\rm HFLAV23}$], these couplings exhibit a hierarchy $g_{\tau\tau}^\ell > g_{\mu\mu}^\ell$. As LFV coupling is concerned, the obtained best-fit point values

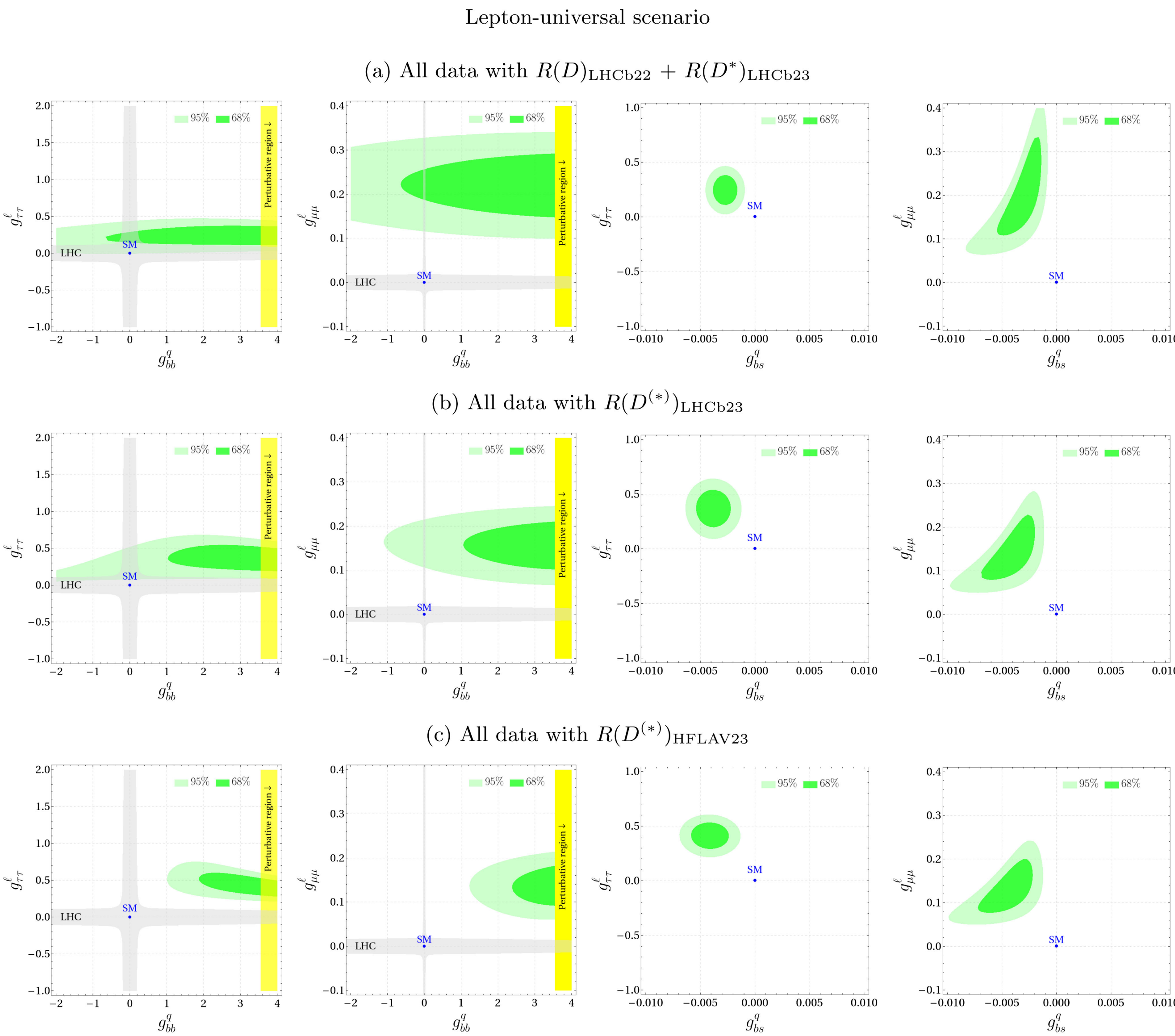

FIG. 2. Lepton-universal scenario: 68% (green) and 95% (light-green) C.L. allowed regions for the most relevant 2D parametric space of (a) all data with $R(D)_{\rm LHCb22} + R(D^*)_{\rm LHCb23}$, (b) all data with $R(D^{(*)})_{\rm LHCb22}$, and (c) all data with $R(D^{(*)})_{\rm HFLAV23}$, respectively, for $M_V = 1$ TeV. In each plot, we are marginalizing over the rest of the parameters. The SM value is represented by the blue dot. The light-gray region corresponds to LHC bounds at the 95% C.L. The perturbative region ($g_{bb}^q \geq \sqrt{4\pi}$) is represented by the yellow color.

on $g^{\ell}_{\mu\tau}$ are negligible. Thus, the TVB model does not lead to appreciable LFV effects.

(ii) *Lepton-universal scenario*. We obtained that this solution provides larger p values when compared with those from the muon-specific scenario. However, the BFP value and 1σ interval for the quark coupling g^{q}_{bb} are very large $g^{q}_{bb} \sim \sqrt{4\pi}$, thus putting the perturbativity of the TVB model into question. Such large coupling values can be understood because they are related to the NP solution size [26], the lepton-universal solution (-0.40 ± 0.11) is quite a bit larger the muon-specific one (-0.17 ± 0.11). Then, since $B_s - \bar{B}_s$ mixing demands $|g^{q}_{bs}| \sim \mathcal{O}(10^{-3})$, $g^{\ell}_{\mu\mu}$ must be in the range $\sim[0.01, 0.1]$, and $g^{\ell}_{\tau\tau} \sim \mathcal{O}(10^{-1})$ (due to $b \to s\tau^+\tau^-$ data). This in turns allows for very large values for g^{q}_{bb} to explain $R(D^{(*)})$. While for the muon-specific solution, smaller values for g^{q}_{bb} are obtained. In view of this situation, the lepton-universal solution could generate some difficulties to the phenomenology of the TVB model.

For the muon-specific and lepton-universal scenarios, in Figs. 1 and 2. we show the allowed regions of the most relevant two-dimensional (2D) parametric space of (a) all data with $R(D)_{\mathrm{LHCb22}} + R(D^*)_{\mathrm{LHCb23}}$, (b) all data with $R(D^{(*)})_{\mathrm{LHCb22}}$, and (c) all data with $R(D^{(*)})_{\mathrm{HFLAV23}}$; respectively, for a benchmark TVB mass $M_V = 1$ TeV. The 68% and 95% C.L. regions are shown in green and light-green colors, respectively. In each plot, we are marginalizing over the rest of the parameters. Furthermore, we include the LHC bounds (light-gray regions) obtained from searches of high-mass dilepton

TABLE VI. BFP values and 1σ intervals of the TVB couplings ($M_V = 1$ TeV) for the three different sets of observables in the muon-specific and lepton-universal scenarios.

	All data with $R(D)_{\mathrm{LHCb22}} + R(D^*)_{\mathrm{LHCb23}}$			
	Muon specific		Lepton universal	
TVB couplings	BFP	1σ intervals	BFP	1σ intervals
g^{q}_{bs}	-2.5×10^{-3}	$[-3.4, -1.6] \times 10^{-3}$	-2.7×10^{-3}	$[-3.4, -2.0] \times 10^{-3}$
g^{q}_{bb}	0.87	$[-0.24, 1.96]$	3.54	[1.08, 8.82]
$g^{\ell}_{\mu\mu}$	0.10	[0.070, 0.128]	0.21	[0.16, 0.26]
$g^{\ell}_{\tau\tau}$	0.50	[0.28, 0.73]	0.25	[0.16, 0.34]
$g^{\ell}_{\mu\tau}$	~ 0	$[-0.11, 0.11]$	~ 0	$[-0.04, 0.04]$
	$\chi^2_{\min}/N_{\mathrm{dof}} = 0.63$, p-value $= 92.9\%$		$\chi^2_{\min}/N_{\mathrm{dof}} = 0.57$, p-value $= 96.4\%$	

	All data with $R(D^{(*)})_{\mathrm{LHCb22}}$			
	Muon-specific		Lepton-universal	
TVB couplings	BFP	1σ intervals	BFP	1σ intervals
g^{q}_{bs}	-3.3×10^{-3}	$[-4.5, -2.1] \times 10^{-3}$	-3.7×10^{-3}	$[-4.8, -2.7] \times 10^{-3}$
g^{q}_{bb}	1.54	[0.76, 2.30]	3.54	[1.95, 5.79]
$g^{\ell}_{\mu\mu}$	0.071	[0.050, 0.092]	0.15	[0.11, 0.18]
$g^{\ell}_{\tau\tau}$	0.73	[0.47, 0.97]	0.37	[0.26, 0.48]
$g^{\ell}_{\mu\tau}$	~ 0	$[-0.15, 0.15]$	~ 0	$[-0.05, 0.05]$
	$\chi^2_{\min}/N_{\mathrm{dof}} = 0.63$, p-value $= 93\%$		$\chi^2_{\min}/N_{\mathrm{dof}} = 0.60$, p-value $= 95\%$	

	All data with $R(D^{(*)})_{\mathrm{HFLAV23}}$			
	Muon specific		Lepton universal	
TVB couplings	BFP	1σ intervals	BFP	1σ intervals
g^{q}_{bs}	-3.4×10^{-3}	$[-4.6, -2.1] \times 10^{-3}$	-4.1×10^{-3}	$[-5.3, -3.0] \times 10^{-3}$
g^{q}_{bb}	1.58	[1.13, 2.02]	3.54	[2.59, 4.71]
$g^{\ell}_{\mu\mu}$	0.070	[0.049, 0.090]	0.13	[0.10, 0.16]
$g^{\ell}_{\tau\tau}$	0.74	[0.57, 0.91]	0.41	[0.33, 0.49]
$g^{\ell}_{\mu\tau}$	~ 0	$[-0.15, 0.15]$	~ 0	$[-0.06, 0.06]$
	$\chi^2_{\min}/N_{\mathrm{dof}} = 0.59$, p-value $= 95.1\%$		$\chi^2_{\min}/N_{\mathrm{dof}} = 0.57$, p-value $= 96.4\%$	

(dimuon and ditau) resonances at the ATLAS experiment [107,109], as discussed in Sec. III J. The perturbative region ($g^q_{bb} \geq \sqrt{4\pi}$) is represented by the yellow color. In regard to the muon-specific solution (Fig. 1), it is observed in the planes ($g^q_{bb}, g^\ell_{\tau\tau}$) and ($g^q_{bb}, g^\ell_{\mu\mu}$) that for ll data with $R(D^{(*)})_{\rm HFLAV23}$ the TVB model seems to be strongly ruled out by the LHC bounds. However, for all data with $R(D)_{\rm LHCb22} + R(D^*)_{\rm LHCb23}$ [and with $R(D^{(*)})_{\rm LHCb22}$] that include the very recent LHCb measurements [43–45], the TVB model can provide a combined explanation of the $b \to c\tau\bar{\nu}_\tau$ and $b \to s\mu^+\mu^-$ anomalies, in consistency with LHC bounds. Our analysis shows that, given the current experimental situation, particularly with LHCb, it is premature to exclude the TVB model to address the B meson anomalies. Future improvements and new measurements on $b \to c\tau\bar{\nu}_\tau$ data at the Belle II and LHCb experiments will be a matter of importance to test the TVB model. As far as the lepton-universal scenario is concerned (Fig. 2), in general, a large part of the allowed parametric space of ($g^q_{bb}, g^\ell_{\tau\tau}$) and ($g^q_{bb}, g^\ell_{\mu\mu}$) lies within the perturbative region, which is in accordance with our results previously shown in Table VI. Again, we emphasize that the TVB model cannot generate this solution.

We close by mentioning that an analysis of the TVB model was previously reported by Kumar, London, and Watanabe (KLW) by implementing the 2018$b \to c\tau\bar{\nu}_\tau$ and $b \to s\mu^+\mu^-$ data [68]. At that time, the anomalous $R_{K^{(*)}}$ data can all be explained if there was NP that couples selectively to muons (muon specific), with a global fit solution of $C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu} = -0.68 \pm 0.12$ [68]. Using this solution, KLW found that the TVB model is not viable as a possible explanation of the B meson anomalies due to the bound from LHC dimuon search (3.2 fb^{-1}) [68]. At present, the recent LHCb measurements on $R_{K^{(*)}}$ showed that the tension has disappeared. Then, the muon-specific solution was narrowed to $C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu} = -0.17 \pm 0.11$ [26], and as it was explained above for the lepton-universal scenario, making now the TVB model allowed as shown above. This shows that the global analysis is strongly affected by the size of the $C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$ solution. Unlike to KLW analysis, we have incorporated several new observables and considered the recent available experimental measurements reported by Belle, Belle II, and LHCb and recent LHC dimuon (139 fb^{-1}) and ditau (36.1 fb^{-1}) searches. Thus, our present study is not only an update of the previous analysis performed by KLW but also extends and complements it. We also extend the recent analysis [77] where only the charged-current $b \to c\tau\bar{\nu}_\tau$ anomaly was addressed within this framework.

V. CONCLUSIONS

We have presented a revamped view of the TVB model as a simultaneous explanation of the B meson anomalies ($b \to c\tau\bar{\nu}_\tau$ and $b \to s\mu^+\mu^-$ data). We performed a global fit of the TVB parameter space with the most recent 2022 and 2023 data, including the LHCb measurements on the charged-current LFU ratios $R(D^{(*)})$ and $R(\Lambda_c)$ and the recent results on $R_{K^{(*)}}$ by LHCb and $\text{BR}(B_s \to \mu^+\mu^-)$ by CMS. For the latter, the new data preferred solutions in which the NP contributes equally to electrons and muons (*lepton universal*) and only muons (*muon specific*). We have explored whether the TVB framework can account for both NP scenarios. In addition, we have also included several important flavor observables: bottomonium LFU ratios, $B_s - \bar{B}_s$ mixing, neutrino trident production, recent experimental progress from Belle and LHCb on different LFV decays (such as $\Upsilon(1S) \to \mu^\pm\tau^\mp$, $B \to K^{(*)}\mu^\pm\tau^\mp$, and $\tau \to \mu\phi$), and the first evidence reported by Belle II of $B^+ \to K^+\nu\bar{\nu}$, as well as other rare B decays $B \to K^*\nu\bar{\nu}, B \to K\tau^+\tau^-$, and $B_s \to \tau^+\tau^-$. We have confronted the allowed paramater space with the LHC bounds from searches of high-mass dilepton resonances at the ATLAS experiment.

In the muon-specific scenario, our analysis has shown that for a heavy TVB mass of 1 TeV and using all data along with world average values on $R(D^{(*)})$ reported by HFLAV the TVB model can accommodate the $b \to c\tau\bar{\nu}_\tau$ and $b \to s\mu^+\mu^-$ anomalies (in consistency with other flavor observables), but it seems to be strongly disfavored by the LHC bounds. However, we obtained a different situation when all data are combined with the very recent LHCb measurements on $R(D^{(*)})$. The B meson anomalies can be addressed within the TVB model in consistency with LHC constraints. We concluded that new and improved $b \to c\tau\bar{\nu}_\tau$ data by LHCb and Belle II will be required to really establish the viability of the TVB model.

On the other hand, with regard to the lepton-universal case, we found that very large values for g^q_{bb} coupling ($\gtrsim \sqrt{4\pi}$) cannot be avoided, casting doubt on the perturbativity of the TVB model. In general, such a solution is very troublesome for the phenomenology of the TVB model.

ACKNOWLEDGMENTS

J. H. M. is grateful to Vicerrectoría de Investigación-Creación of Universidad del Tolima for financial support of Project No. 290130517. E. R. acknowledges financial support from the "Vicerrectoría de Investigaciones e Interacción Social VIIS de la Universidad de Nariño," Projects No. 1928 and No. 2172. We are grateful to Hector Gisbert for his comments on LFV effects in the dineutrino channels $B \to K^{(*)}\nu\bar{\nu}$.

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