Extra gauge bosons and lepton flavor universality violation in Υ and B meson decays

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(Received 15 March 2021; accepted 2 April 2021; published 20 April 2021)

Lepton flavor universality can be tested through the ratio of semileptonic B meson decays and leptonic Υ meson decays, with $\Upsilon \equiv \Upsilon(nS)$ ($n = 1, 2, 3$). For the charged-current transitions $b \to c\tau\bar{\nu}_\tau$, discrepancies between the experiment and the Standard Model (SM) have been observed in recent years by different flavor facilities such as *BABAR*, Belle, and LHCb. While for the neutral-current transitions $b\bar{b} \to \tau\bar{\tau}$, the *BABAR* experiment reported recently a new measurement of leptonic decay ratio $R_{\Upsilon(3S)} = \mathrm{BR}(\Upsilon(3S) \to \tau^+\tau^-)/\mathrm{BR}(\Upsilon(3S) \to \mu^+\mu^-)$, showing an agreement with the SM at the 1.8σ level. In light of this new *BABAR* result and regarding the connection between new physics (NP) interpretations to the charged-current $b \to c\tau\bar{\nu}_\tau$ anomalies and neutral-current $b\bar{b} \to \tau\bar{\tau}$ processes, in this study, we revisit the NP consequences of this measurement within a simplified model with extra massive gauge bosons that coupled predominantly to left-handed leptons of the third generation. We show that the *BABAR* measurement of $R_{\Upsilon(3S)}$ cannot easily be accommodated (within its experimental 1σ range) together with the other $b \to c\tau\bar{\nu}_\tau$ data, hinting toward a new anomalous observable.

DOI: 10.1103/PhysRevD.103.073003

I. INTRODUCTION

In recent years, tantalizing hints of lepton flavor universality (LFU) violation have been suggested by the experiments *BABAR*, Belle, and LHCb in the measurements of the ratio of semileptonic B meson decays [1–14]

$$R(D^{(*)}) = \frac{\mathrm{BR}(B \to D^{(*)}\tau\bar{\nu}_\tau)}{\mathrm{BR}(B \to D^{(*)}\ell'\bar{\nu}_{\ell'})} \quad (\ell' = e\,\mathrm{or}\,\mu), \tag{1}$$

$$R(J/\psi) = \frac{\mathrm{BR}(B_c \to J/\psi\tau\bar{\nu}_\tau)}{\mathrm{BR}(B_c \to J/\psi\mu\bar{\nu}_\mu)}. \tag{2}$$

The latest 2019 world averages values reported by the Heavy Flavor Averaging Group (HFLAV) on the measurements of $R(D^{(*)})$ [12,13] and the LHCb results on $R(J/\psi)$ [14–16],

$$R(D) = \begin{cases} \mathrm{HFLAV:}\ 0.340 \pm 0.027 \pm 0.013\,[12,13], \\ \mathrm{SM:}\ 0.299 \pm 0.003\,[12,13], \end{cases} \tag{3}$$

$$R(D^*) = \begin{cases} \mathrm{HFLAV:}\ 0.295 \pm 0.011 \pm 0.008\,[12,13], \\ \mathrm{SM:}\ 0.258 \pm 0.005\,[12,13], \end{cases} \tag{4}$$

$$R(J/\psi) = \begin{cases} \mathrm{LHCb:}\ 0.71 \pm 0.17 \pm 0.18\,[14], \\ \mathrm{SM:}\ 0.283 \pm 0.048\,[15,16], \end{cases} \tag{5}$$

exhibit a deviation with respect to the Standard Model (SM) expectations by 1.4σ, 2.5σ, and 1.8σ, respectively. SM predictions for $R(D^{(*)})$ are taken from the average values obtained by HFLAV [13], while for $R(J/\psi)$ we consider the recent lattice QCD calculations [15,16]. Furthermore, polarization observables such as the τ lepton polarization $P_\tau(D^*)$ and the longitudinal polarization of the D^* meson

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$F_L(D^*)$ related with the channel $\bar{B} \to D^* \tau \bar{\nu}_\tau$ have been observed in the Belle experiment [10,11,17],

$$P_\tau(D^*) = \begin{cases} \text{Belle:} \ -0.38 \pm 0.51^{+0.21}_{-0.16} \, [10, 11], \\ \text{SM:} \ -0.497 \pm 0.013 \, [18], \end{cases} \tag{6}$$

$$F_L(D^*) = \begin{cases} \text{Belle:} \ 0.60 \pm 0.08 \pm 0.035 \, [17], \\ \text{SM:} \ 0.46 \pm 0.04 \, [19], \end{cases} \tag{7}$$

and also present a disagreement respect with the corresponding SM predictions [18,19]. Additionally, strong constraints from the upper limits on the branching ratio of the tauonic B_c decay, $\mathrm{BR}(B_c^- \to \tau^- \bar{\nu}_\tau) \lesssim 30\%$ and 10%, imposed by the lifetime of B_c meson [20] and the LEP data taken at the Z peak [21], respectively, have to be taken into account.

All these measurements on $b \to c\tau\bar{\nu}_\tau$ data point toward LFU violation, and they are generally referred to as $b \to c\tau\bar{\nu}_\tau$ anomalies. Several model-independent studies of the effect of new physics (NP) operators regarding the most general dimension-six effective Lagrangian with the most recent $b \to c\tau\bar{\nu}_\tau$ data have been explored [22–39]. Sharing the same Lorentz structure as the SM, NP arising from left-handed vector operator $(\bar{c}\gamma_\mu P_L b)(\bar{\tau}\gamma^\mu P_L \nu_\tau)$ is still a preferred and feasible solution to address the anomalies, providing a good fit to the data [22–39]. Different NP scenarios can be generated via this semi-tauonic operator. One interesting possibility to accommodate the anomalies consists in considering an extra left-handed gauge boson W' [40–52]. The opening works suggesting in the literature a $SU(2)_L$ triplet of massive vectors mostly coupled to the left-handed fermions of the third generation (referred to as vector triplet model or vector boson model) were presented in Refs. [40–42].[1] It was found that although the model can accommodate the $R(D^{(*)})$ anomalies, the framework is severely constrained by the direct searches of neutral resonances decaying into $\tau^+\tau^-$ pairs at ATLAS and CMS [41,42]. Different W' boson scenarios (either UV completions and simplified models) have also been studied [43–52], and complementary tests of these models with the searches for heavy $\tau\nu$ resonances performed at the LHC, showed an agreement with the constraints from ATLAS and CMS data (see, for instance, Refs. [43,44,52,53]).

Additionally, alternative approaches regarding W' bosons associated with pure right-handed currents (involving a right-handed neutrino) have been discussed recently in the literature within different NP realizations [44,51,52, 54–64]. Nevertheless, some recent analyses have shown that this right-handed neutrino interpretation seems to be disfavored by the LHC data [29,44].

On the other hand, LFU can also be tested through the ratio of leptonic decays of bottomonium meson $\Upsilon(nS)$ [65]

$$R_{\Upsilon(nS)} \equiv \frac{\mathrm{BR}(\Upsilon(nS) \to \tau^+\tau^-)}{\mathrm{BR}(\Upsilon(nS) \to \ell^+\ell^-)}, \tag{8}$$

with $n = 1, 2, 3$ and $\ell = \mu, e$, providing a clean theoretical environment. Experimentally, the *BABAR* and CLEO Collaborations have reported the values [66,67]

$$R_{\Upsilon(1S)} = \begin{cases} \textit{BABAR}\text{-10:} \ 1.005 \pm 0.013 \pm 0.022 \, [66], \\ \text{SM:} \ 0.9924 \, [65], \end{cases} \tag{9}$$

$$R_{\Upsilon(2S)} = \begin{cases} \text{CLEO-07:} \ 1.04 \pm 0.04 \pm 0.05 \ \ [67], \\ \text{SM:} \ 0.9940 \, [65], \end{cases} \tag{10}$$

$$R_{\Upsilon(3S)} = \begin{cases} \text{CLEO-07:} \ 1.05 \pm 0.08 \pm 0.05 \ \ [67], \\ \text{SM:} \ 0.9948 \, [65], \end{cases} \tag{11}$$

where the theoretical uncertainty is typically of the order $\pm\mathcal{O}(10^{-5})$ [65]. These measurements are in good accordance with the SM by 0.5σ, 0.8σ, and 0.6σ, respectively. Recently, in 2020 the *BABAR* experiment has released a new measurement on the ratio $R_{\Upsilon(3S)}$ [68], whose value is

$$R_{\Upsilon(3S)}^{BABAR-20} = 0.966 \pm 0.008 \pm 0.014, \tag{12}$$

which improves the precision of the experimental value previously obtained by CLEO [67]. Despite this improvement, the new value is below the SM expectation and shows an agreement at the 1.8σ level [68], in higher tension than CLEO. Moreover, averaging the CLEO-07 [67] and *BABAR*-20 [68] measurements we obtain

$$R_{\Upsilon(3S)}^{\mathrm{Ave}} = 0.968 \pm 0.016, \tag{13}$$

which deviates at the 1.7σ level with respect to the SM prediction (uncertainties were taken in quadrature). Motivated by the tension generated by the new *BABAR* measurement on $R_{\Upsilon(3S)}$, it is intriguing to study its possible NP implications. As additional motivation, it is known that new physics scenarios (with left-handed neutrinos) aiming to provide an explanation to the $R(D^{(*)})$ anomalies also induce inevitable effects in the leptonic decay ratio $R_{\Upsilon(nS)}$ [65]. The connection between charged-current $b \to c\tau\bar{\nu}_\tau$ and neutral-current $b\bar{b} \to \tau\bar{\tau}$ processes was first pointed out by the authors of Ref. [42], in which they performed a recast of existing $\tau^+\tau^-$ resonance searches at the CMS and ATLAS experiments, allowing one to set constraints on different simplified models addressing the $R(D^{(*)})$ anomalies.

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[1] Let us notice that a simultaneous explanation of both the $b \to c\tau\bar{\nu}_\tau$ and $b \to s\mu^+\mu^-$ anomalies have also been discussed within the vector boson model in Refs. [40,41,49,50]; however, this approach is beyond the scope of the present work.

Keeping in mind the correlation between NP solutions to the charged-current $b \to c\tau\bar{\nu}_\tau$ anomalies and neutral-current $b\bar{b} \to \tau\bar{\tau}$ processes [42,65], and to the light of the very recent *BABAR* result on $R_{\Upsilon(3S)}$ [68], in this work we present a reanalysis of the extra gauge bosons within the vector triplet model that preferentially couples to third-generation fermions [41,42]. A previous analysis addressing the $R(D^{(*)})$ anomalies and the complementary $R_{\Upsilon(nS)}$ in this model was presented in Ref. [65], in which the authors found within 95% confidence level the numerical values for the Wilson coefficients that minimize the observed anomaly in $R(D^{(*)})$ and the corresponding predictions for $R_{\Upsilon(nS)}$. This study was implemented by considering the 2016 HFLAV averages [69], which differ from the most recent 2019 HFLAV ones [12,13]. Here, by means of a different approach we carry out a robust phenomenological analysis of the parametric space of gauge couplings allowed by charged-current $b \to c\tau\bar{\nu}_\tau$ and $R_{\Upsilon(nS)}$ data. Particularly, for the $b \to c\tau\bar{\nu}_\tau$ data, we include the polarizations of D^* and the tau lepton associated with $\bar{B} \to D^*\tau\bar{\nu}_\tau$, the ratio $R(J/\psi)$, and the upper limit on $\mathrm{BR}(B_c^- \to \tau^-\bar{\nu}_\tau)$, and we incorporate the forthcoming sensitivity of Belle II on $R(D^{(*)})$ measurements. In that sense, our work complements and extends the previous analysis performed in [65]. We will show that the vector triplet model is in conflict with the *BABAR* measurement of $R_{\Upsilon(3S)}$, and the 1σ range uncertainties cannot be explained in simultaneity with $b \to c\tau\bar{\nu}_\tau$ data.

The outline of this paper is organized as follows. In Sec. II, we briefly present the main features of the left-handed vector bosons model. A phenomenological analysis of the parametric space of gauge couplings allowed by charged-current and neutral-current data is presented in Sec. III. The main concluding remarks of this work are given in Sec. IV.

II. LEFT-HANDED VECTOR BOSONS MODEL

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 third generation [41,42]. The Lagrangian describing the interactions between fermions and vector bosons is [41,42]

$$\mathcal{L}^{\mathrm{LH-VB}} = g_b \bar{Q}_3 \frac{\sigma_a}{2} \gamma^\mu W^a_\mu Q_3 + g_\tau \bar{L}_3 \frac{\sigma_a}{2} \gamma^\mu W^a_\mu L_3, \tag{14}$$

where $Q_3 = (V_{cb} c_L, b_L)^T$ and $L_3 = (\nu_{\tau L}, \tau_L)^T$ are the LH quark and lepton doublets, $\sigma_a (a = 1,2,3)$ are the Pauli matrices, V_{cb} is the associated Cabibbo-Kobayashi-Maskawa (CKM) matrix element, and g_b and g_τ are the corresponding couplings of LH quarks and leptons to vector bosons, respectively. The down-type quark and charged-lepton mass eigenstate basis have been adopted for the LH fermion multiplets. After the heavy vector bosons are integrating out, the relevant charged-current $b \to c\tau\bar{\nu}_\tau$ and neutral-current $b\bar{b} \to \tau\bar{\tau}$ operators are given by [41]

$$\mathcal{L}_{\mathrm{CC}} = -\frac{g_b g_\tau}{2M_{W'}^2} V_{cb} (\bar{c}\gamma_\mu P_L b)(\bar{\tau}\gamma^\mu P_L \nu_\tau) + \mathrm{H.c.}, \tag{15}$$

$$\mathcal{L}_{\mathrm{NC}} = -\frac{g_b g_\tau}{4M_{Z'}^2} (\bar{b}\gamma_\mu P_L b)(\bar{\tau}\gamma^\mu P_L \tau), \tag{16}$$

respectively, where $M_V (V = W', Z')$ is the gauge boson mass. We are not assuming the existence of right-handed neutrinos within the model. Since the W' and Z' bosons couple primarily to the fermions from the third-generation, bounds coming from flavor-changing neutral currents are avoided. According to electroweak precision data, it is required that gauge bosons are (almost) degenerate $M_{W'} \simeq M_{Z'}$ [42]. The NP effects are driven by the mass scale of the heavy mediators and the size of couplings to the third generation of fermions g_b and g_τ. For simplicity, in further numerical analysis we will take these couplings to be real.

As it was mentioned above, an important caveat of the vector triplet model is that the parametric space required for the resolution of the $R(D^{(*)})$ anomalies and consistency with $\tau^+\tau^-$ resonance searches at the LHC (ATLAS and CMS) necessarily implies a very large Z' total decay width, $\Gamma_{Z'}/M_{Z'} = (g_\tau + 3g_b)/(48\pi) \gtrsim 30\%$ [41,42]. In Sec. III we will show that current $b \to c\tau\bar{\nu}_\tau$ data suggest that tension with constraints from ATLAS and CMS is now reduced.

A. Contribution to the charged-current $b \to c\tau\bar{\nu}_\tau$ and neutral-current $b\bar{b} \to \tau\bar{\tau}$ observables

In the SM framework, the $b \to c\tau\bar{\nu}_\tau$ quark level processes are mediated by a virtual W boson exchange. Within the NP scenarios discussed above, an extra W' boson leads to additional tree-level effective interactions, therefore, modifying the theoretical predictions for the observables associated with this charged-current transition. The ratios $R(M)$ $(M = D, D^*, J/\psi)$, and the D^* and τ longitudinal polarizations related with the channel $\bar{B} \to D^*\tau\bar{\nu}_\tau$ can be parametrized as [51]

$$R(M) = R(M)_{\mathrm{SM}} (|1 + C_{\mathrm{VLL}}^{bc\tau\nu_\tau}|^2), \tag{17}$$

$$F_L(D^*) = F_L(D^*)_{\mathrm{SM}} r_{D^*}^{-1} (|1 + C_{\mathrm{VLL}}^{bc\tau\nu_\tau}|^2), \tag{18}$$

$$P_\tau(D^*) = P_\tau(D^*)_{\mathrm{SM}} r_{D^*}^{-1} (|1 + C_{\mathrm{VLL}}^{bc\tau\nu_\tau}|^2), \tag{19}$$

respectively, where $r_{D^*} = R(D^*)/R(D^*)_{\mathrm{SM}}$ and $C_{\mathrm{VLL}}^{bc\tau\nu_\tau}$ is the vector left-left (VLL) Wilson coefficient associated with the NP vector operators given by

TABLE I. BFP values of gauge couplings, $\chi^2_{\rm min}/N_{\rm dof}$, p-value, and pull$_{\rm SM}$ for different datasets of observables.

Dataset	$(g_b,\, g_\tau)$	$\chi^2_{\rm min}/N_{\rm dof}$	p-value [%]	Pull$_{\rm SM}$
$b\to c\tau\bar{\nu}_\tau$	(2.99, 1.54)	1.04	39.0	3.72
$b\to c\tau\bar{\nu}_\tau + R_\Upsilon$ old	(3.05, 1.52)	0.79	61.3	3.75
$b\to c\tau\bar{\nu}_\tau + R_\Upsilon$ with *BABAR*-20	(3.27, 1.39)	1.20	29.3	3.68
$b\to c\tau\bar{\nu}_\tau + R_\Upsilon$ combined	(3.05, 1.52)	1.11	35.3	3.68

$$C_{\rm VLL}^{bc\tau\nu_\tau} = \frac{\sqrt{2}}{4G_F}\frac{g_b g_\tau}{M_{W'}^2}, \tag{20}$$

with G_F the Fermi coupling constant. Similarly, the tauonic decay $B_c^- \to \tau^-\bar{\nu}_\tau$ and the ratio $R(X_c)$ of inclusive semileptonic B decays are also modified as [51,70]

$$\mathrm{BR}(B_c^- \to \tau^-\bar{\nu}_\tau) = \mathrm{BR}(B_c^- \to \tau^-\bar{\nu}_\tau)_{\rm SM}(|1 + C_{\rm VLL}^{bc\tau\nu_\tau}|^2), \tag{21}$$

$$R(X_c) = R(X_c)_{\rm SM}(1 + 1.147|C_{\rm VLL}^{bc\tau\nu_\tau}|^2), \tag{22}$$

respectively.

As concerns neutral-current process $b\bar{b}\to\tau\bar{\tau}$, the leptonic decay ratio $R_{\Upsilon(nS)}$, Eq. (8), is altered by the vector triplet model [65]. This ratio can be expressed as [65]

$$R_{\Upsilon(nS)} = \frac{(1-4x_\tau^2)^{1/2}}{|A_V^{\rm SM}|^2}[|A_V^{b\tau}|^2(1+2x_\tau^2) + |B_V^{b\tau}|^2(1-4x_\tau^2)], \tag{23}$$

with $x_\tau = m_\tau/m_{\Upsilon(nS)}$, $|A_V^{\rm SM}| = -4\pi\alpha Q_b$, and

$$A_V^{b\tau} = -4\pi\alpha Q_b + \frac{m_{\Upsilon(nS)}^2}{4}C_{\rm VLL}^{bb\tau\tau}, \tag{24}$$

$$B_V^{b\tau} = -\frac{m_{\Upsilon(nS)}^2}{2}C_{\rm VLL}^{bb\tau\tau}, \tag{25}$$

where

$$C_{\rm VLL}^{bb\tau\tau} = \frac{g_b g_\tau}{4M_{W'}^2}. \tag{26}$$

It is straightforward to see the relation between charged and neutral coefficients, $C_{\rm VLL}^{bc\tau\nu_\tau} = (\sqrt{2}/G_F)C_{\rm VLL}^{bb\tau\tau}$. In the next section, we will present a phenomenological analysis of the parametric space of gauge couplings allowed by $b\to c\tau\bar{\nu}_\tau$ and $b\bar{b}\to\tau\bar{\tau}$ data.

III. PHENOMENOLOGICAL STUDY

To provide a robust phenomenological study we consider all of the charged-current transition $b\to c\tau\bar{\nu}_\tau$ observables, namely, the ratios $R(D^{(*)})$ (HFLAV 2019 averages), $R(J/\psi)$, $R(X_c)$; the polarizations $P_\tau(D^*)$, $F_L(D^*)$; and the upper limit $\mathrm{BR}(B_c^-\to\tau^-\bar{\nu}_\tau) < 10\%$. We will refer to this set as the $b\to c\tau\bar{\nu}_\tau$ data. On the other hand, regarding the neutral-current observables $R_{\Upsilon(nS)}$, we will take into account three different datasets:

1. R_Υ old data: $R_{\Upsilon(1S)}$ *BABAR*-10 [66], $R_{\Upsilon(2S)}$ CLEO-07 [67], and $R_{\Upsilon(3S)}$ CLEO-07 [67].
2. R_Υ with *BABAR*-20 data: $R_{\Upsilon(1S)}$ *BABAR*-10 [66], $R_{\Upsilon(2S)}$ CLEO-07 [67], and $R_{\Upsilon(3S)}$ *BABAR*-20 [68].
3. R_Υ combined data: $R_{\Upsilon(1S)}$ *BABAR*-10 [66], $R_{\Upsilon(2S)}$ CLEO-07 [67], and $R_{\Upsilon(3S)}$ average of CLEO-07 [67] and *BABAR*-20 [68],

with $\Upsilon \equiv \Upsilon(nS)$ for simplicity. The purpose of these sets is to estimate the impact of the very recent *BABAR* measurement on $R_{\Upsilon(3S)}$ [68]. Furthermore, we complement this analysis by exploring two plausible scenarios on the $R(D^{(*)})$ future measurements in the ongoing Belle II experiment [71]. The two projected scenarios are as follows [72], Belle II-P1: Belle II measurements on $R(D^{(*)})$ keep the central values of Belle combination averages with the projected Belle II sensitivities for 50 ab^{-1} [71]; and Belle II-P2: Belle II measurements on $R(D^{(*)})$ are in agreement with the current SM predictions at the 0.1σ level with the projected Belle II sensitivities for 50 ab^{-1} [71]. These Belle II future implications on a W' boson scenario have not been explored so far in previous works.

Bearing in mind the above-mentioned observables, we perform a standard $\chi^2 \equiv \chi^2(g_b, g_\tau)$ function analysis in order to prove whether it is possible to adjust the deviations of the SM predictions in the simplified extra gauge bosons model described in Sec. II. We consider the experimental correlation value -0.38 between $R(D)$ and $R(D^*)$ from HFLAV [12,13]. We determine the regions in the parameter space favored by the experimental data.

A. Parametric space (g_b, g_τ)

After fitting different sets of observables, we display in Table I our results of the best-fit point (BFP) values on the gauge couplings $(g_b,\, g_\tau)$, the ratio of the minimum of the χ^2 function and number of degrees of freedom $(\chi^2_{\rm min}/N_{\rm dof})$,

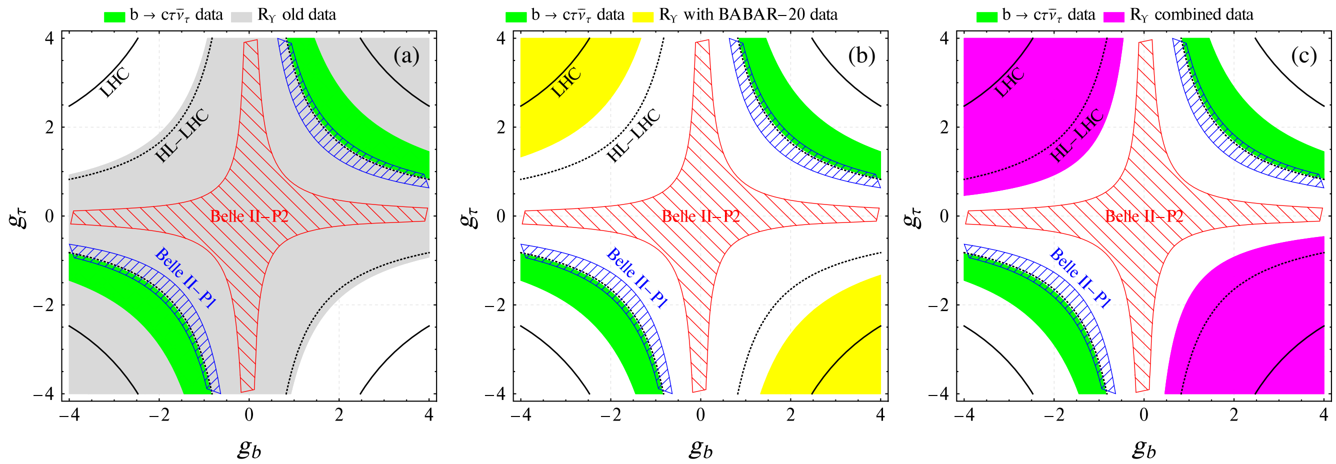

FIG. 1. The 1σ allowed parameter space in the (g_b, g_τ) plane for the current $b \to c\tau\bar{\nu}_\tau$ data [green region] and (a) R_Υ old data [gray region], (b) R_Υ with *BABAR*-20 data [yellow region], and (c) R_Υ combined data [magenta region], for $M_{W'} = 1$ TeV. The projection Belle II-P1 (Belle II-P2) for an integrated luminosity of 50 ab^{-1} is represented by the blue (red) hatched region. The inner black contour lines illustrate the permitted regions from LHC bounds (solid line) and HL-LHC prospects (dotted line).

the p-value, and the pull of the SM $\mathrm{pul}_{\mathrm{lSM}} = \sqrt{\chi^2_{\rm SM} - \chi^2_{\rm min}}$, with $\chi^2_{\rm SM} = \chi^2(0)$. In order to keep the couplings in the perturbative regime $(\sim\sqrt{4\pi})$, we took a benchmark W' mass value of $M_{W'} = 1$ TeV in our analysis. There is no tension with the current LHC constraints for the $M_{W'}$ (which are above 4 TeV) since we are assuming zero couplings to the first and second families. For a W' dominantly coupled to a third family, a W' mass value of ∼1 TeV is compatible with LHC bounds (see, for instance, Refs. [22,53,54].) From Table I, it is observed that with only $b \to c\tau\bar{\nu}_\tau$ data is a good fit obtained, as expected, with a p-value = 39%. When $b \to c\tau\bar{\nu}_\tau$ and R_Υ old data are joined together, a better fit is obtained with a larger p-value of 61.3%. This indicates that the extra gauge bosons model can simultaneously explain both charged-current and neutral-current data of b-flavored mesons. However, once the *BABAR* measurement on $R_{\Upsilon(3S)}$ [68] is incorporated into the fit, through either R_Υ with *BABAR*-20 or R_Υ combined data, it induces tension in the analysis, causing the quality of the fit to decrease (smaller p-value), but maintaining almost the same value of BFP and $\mathrm{pull}_{\rm SM}$. In turn, *BABAR*'s result [68] seems to challenge this NP explanation.

In Figs. 1(a), 1(b), and 1(c) we show the 1σ allowed parameter space in the (g_b, g_τ) plane, where the gray, yellow, and magenta regions are obtained by considering R_Υ old data, R_Υ with *BABAR*-20 data, and R_Υ combined data, respectively. In all of the panels, the green region represents the allowed region by the charged-current transition $b \to c\tau\bar{\nu}_\tau$ data, and the projection Belle II-P1 (Belle II-P2) for an integrated luminosity of 50 ab^{-1} is represented by the blue (red) hatched region. To further extend our analysis, the inner black contour lines illustrate the permitted regions from LHC bounds (solid line) and the prospects at the high-luminosity (HL)-LHC (dotted line) [22,53].[2] From Fig. 1(a) one can note that it is possible to get an allowed region on the parameter space to account for a joint explanation to the $b \to c\tau\bar{\nu}_\tau$ and R_Υ old data, in consistency with LHC and HL-LHC bounds. As for Figs. 1(b) and 1(c), the datasets R_Υ with *BABAR*-20 and R_Υ combined prove a different parametric space not compatible with $b \to c\tau\bar{\nu}_\tau$ data. Thus, we confirm that the recent *BABAR* results on $R_{\Upsilon(3S)}$ generates tension; therefore, charged-current and neutral-current data of b-flavored mesons cannot be addressed simultaneously in this model. Only relaxing the $R_{\Upsilon(3S)}$ experimental uncertainties to the 2σ level can a common allowed region be obtained. Regarding the Belle II experiment, the projection Belle II-P2 indicates that the parametric space would be severely constrained, but still allow a window for significant NP contributions. Remarkably, the Belle II-P2 scenario would provide stronger bounds on the (g_b, g_τ) plane than prospects at the HL-LHC.

On the other hand, as concerns the vector triplet model interpretation to the most recent $b \to c\tau\bar{\nu}_\tau$ data and its consistency with LHC searches for Z' resonances decaying to $\tau^+\tau^-$ [41,42], it is observed that using the BFP gauge couplings values we get $\Gamma_{Z'}/M_{Z'} \simeq 20\%$ for $M_{Z'} = 1$ TeV, implying a decrease in the tension. In addition, future Belle II sensitivity on $R(D^{(*)})$ would point to smaller widths $\Gamma_{Z'}/M_{Z'} \simeq (1-5)\%$ within the allowed regions by LHC bounds [41,42].

In summary, the recent *BABAR* results on $R_{\Upsilon(3S)}$ hint toward a new anomalous measurement. Here, we

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[2] These contours have been obtained by taking into account the LHC bounds on the left-handed vector WC of $|C^{cb\tau\nu_\tau}_{\rm VLL}| \simeq 0.3$ and the future prospects values at HL-LHC of $|C^{cb\tau\nu_\tau}_{\rm VLL}| \simeq 0.1$, evaluated at 1 TeV scale [22,53].

exemplified its implications on the vector triplet model. Because in a typical electroweak extension of the SM the charged current parameters and the corresponding ones in the neutral sector are related, this analysis can be carried out in most of the models involving the structure $(\bar{c}\gamma_\mu P_L b)(\bar{\tau}\gamma^\mu P_L \nu_\tau)$. Thus, our conclusions can be extrapolated to those models. Alternative NP scenarios can give rise to the same left-left vector operator such as vector leptoquark models; therefore, it is interesting to explore the possible effects of $R_{\Upsilon(3S)}$ on these scenarios [73].

IV. CONCLUDING REMARKS

New physics scenarios aiming to provide an explanation to the LFU violation anomalies reported in the charged-current observables of semileptonic B meson decays also induce effects in the neutral-current observables of bottomonium mesons $R_{\Upsilon(nS)}$, with $n = 1, 2, 3$. Motivated by the very recent *BABAR* measurement on $R_{\Upsilon(3S)}$, we revisited the simplified scenario of extra massive gauge bosons (W' and Z') that coupled predominantly to leptons of the third generation (involving LH neutrinos), proposed as a viable solution to the $b \to c\tau\bar{\nu}_\tau$ anomalies. We performed a robust phenomenological analysis of the parametric space of gauge couplings allowed by the most recent charged-current $b \to c\tau\bar{\nu}_\tau$ and neutral-current $b\bar{b} \to \tau\bar{\tau}$ data. As the main result of our analysis, it is found that the *BABAR* measurement of $R_{\Upsilon(3S)}$ is particularly challenging and the 1σ range uncertainties cannot be explained simultaneously with charged-current $b \to c\tau\bar{\nu}_\tau$ data within the LH vector bosons model. Therefore, this NP scenario seems to be disfavored by *BABAR* data. In order to clarify this situation, future $R_{\Upsilon(3S)}$ measurements in the ongoing experiments Belle II and LHCb will be a matter of importance to confirm or refute the discrepancy.

ACKNOWLEDGMENTS

J. H. M. is grateful to Oficina de Investigaciones of Universidad del Tolima for financial support of Project No. 290130517. The work of N. Q. has been financially supported by MINCIENCIAS and Universidad del Tolima through Convocatoria Estancias Postdoctorales No. 848-2019 (Contract No. 834-2020). 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.

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