

## Charged current $b \rightarrow c\tau\bar{\nu}_\tau$ anomalies in a general $W'$ boson scenario

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(Received 16 August 2019; published 20 November 2019)

Very recent experimental information obtained from the Belle experiment, along with that accumulated by the BABAR and LHCb experiments, has shown the existence of anomalies in the ratios  $R(D)$  and  $R(D^*)$  associated with the charged-current transition  $b \rightarrow c\tau\bar{\nu}_\tau$ . Although the Belle measurements are in agreement with standard model (SM) predictions, the new experimental world averages still exhibit a tension. In addition, the  $D^*$  longitudinal polarization  $F_L(D^*)$  related with the channel  $B \rightarrow D^*\tau\bar{\nu}_\tau$  observed by the Belle Collaboration and the ratio  $R(J/\psi)$  measured by the LHCb Collaboration also show discrepancies with their corresponding SM estimations. We present a model-independent study based on the most general effective Lagrangian that yields a tree-level effective contribution to the transition  $b \rightarrow c\tau\bar{\nu}_\tau$  induced by a general  $W'$  boson. Instead of considering any specific new physics (NP) realization, we perform an analysis by considering all of the different chiral charges to the charm-bottom and  $\tau - \nu_\tau$  interaction terms with a charged  $W'$  boson that explain the anomalies. We present a phenomenological study of parameter space allowed by the new experimental  $b \rightarrow c\tau\bar{\nu}_\tau$  data and with the mono-tau signature  $pp \rightarrow \tau_n X + \text{MET}$  at the LHC. For comparison, we include some of the  $W'$  boson NP realizations that have already been studied in the literature.

DOI: 10.1103/PhysRevD.100.093003

### I. INTRODUCTION

The  $B$  meson system has constituted a good scenario for studying, on both theoretical and experimental levels, the standard model (SM) as well as for exploring new physics (NP) effects at low-energy scales. Particularly, semileptonic and leptonic  $B$  meson decays offer an excellent place to test lepton universality (LU), so far one of the cornerstones of the SM. Any mismatch between the theoretical and experimental predictions may be an indication of LU violation, and therefore a hint of NP beyond the SM [1,2].

The BABAR Collaboration in 2012 was the first experiment that reported disagreement on the measurements of the ratio of semileptonic  $B$  decays ( $b \rightarrow c$  transition processes) [3,4]

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

compared with the SM predictions [5–7]. These discrepancies were later confirmed by Belle [8–11] and LHCb [12–14] experiments by means of different techniques. Theoretical progress on the SM calculations of  $R(D^{(*)})$  has been made recently [17–21], with average values [15,16] shown in Table I. Despite all of these advancements, the experimental measurements on  $R(D^{(*)})$  still exhibit a deviation from the SM expectations. Nevertheless, things seem to have changed, and the tension has been reduced with the new results on  $R(D^{(*)})$  that the Belle Collaboration has recently released [22] (as presented in Table I), which are now in agreement with the SM predictions within  $0.2\sigma$  and  $1.1\sigma$ , respectively. Incorporating these Belle results, in Table I we display the new 2019 world averages values reported by the Heavy Flavor Averaging Group (HFLAV) on the measurements of  $R(D)$  and  $R(D^*)$  [15,16], which now exceed the SM predictions by  $1.4\sigma$  and  $2.5\sigma$ , respectively. To see the incidence of the very recent Belle results, in Figure 1, we plot the  $R(D)$  vs  $R(D^*)$  plane by showing the HFLAV 2018 average (green region) and the new HFLAV 2019 average (blue region) [15,16], at both  $1\sigma$  and

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TABLE I. Experimental status on observables related to the charged transition  $b \rightarrow c\tau\bar{\nu}_\tau$ .

Observable	Expt. measurement	SM prediction
$R(D)$	$0.307 \pm 0.037 \pm 0.016$ Belle-2019 [22] $0.340 \pm 0.027 \pm 0.013$ HFLAV [15]	$0.299 \pm 0.003$ [15,16]
$R(D^*)$	$0.283 \pm 0.018 \pm 0.014$ Belle-2019 [22] $0.295 \pm 0.011 \pm 0.008$ HFLAV [15]	$0.258 \pm 0.005$ [15,16]
$R(J/\psi)$	$0.71 \pm 0.17 \pm 0.18$ [23]	$0.283 \pm 0.048$ [24]
$P_\tau(D^*)$	$-0.38 \pm 0.51^{+0.21}_{-0.16}$ [10,11]	$-0.497 \pm 0.013$ [25]
$F_L(D^*)$	$0.60 \pm 0.08 \pm 0.035$ [26]	$0.46 \pm 0.04$ [27]
$R(X_c)$	$0.223 \pm 0.030$ [28]	$0.216 \pm 0.003$ [28]

$2\sigma$ . The black (solid  $1\sigma$  and dotted  $2\sigma$ ) and red (dashed) contours show the SM predictions and the recent Belle measurements, respectively. This  $R(D)$  vs  $R(D^*)$  plot illustrates how the anomalies have been significantly narrowed due to the new Belle data.

Further hints of lepton flavor universality violation in the charged current  $b \rightarrow c\tau\bar{\nu}_\tau$  have recently been obtained by LHCb in the measurement of the ratio [23]

$$R(J/\psi) = \frac{\text{BR}(B_c \rightarrow J/\psi\tau\bar{\nu}_\tau)}{\text{BR}(B_c \rightarrow J/\psi\mu\bar{\nu}_\mu)}, \quad (2)$$

which also shows tension with regard to the SM prediction (around  $2\sigma$ ) [24,29–33]. In further calculations, we will use the theoretical prediction of Ref. [24] (see Table I), which is in agreement with other estimations [29–33]. Additionally, polarization observables associated with the channel  $B \rightarrow D^*\tau\bar{\nu}_\tau$  have been observed in the Belle experiment—namely, the  $\tau$  lepton polarization  $P_\tau(D^*)$  [10,11] and the  $D^*$  longitudinal polarization  $F_L(D^*)$  [26]. We present in Table I these measurements, as well as their corresponding SM values [25,27], which also exhibit a deviation from the experimental data.

The incompatibility of these measurements with the SM could be evidence of LU violation in  $B$  decays and, therefore, an indication of NP sensitive to the third generation of leptons. In order to understand these discrepancies, an enormous number of theoretical studies have been proposed. On the one hand, model-independent analyses of the impact of NP effective operators have been extensively studied (for the most recent ones that include the new Belle measurements, see Refs. [34–38]).<sup>1</sup> On the other hand, particular NP scenarios such as charged scalars [47–63], leptoquarks (both scalar and vector) [64–66,68–98], extra gauge bosons [48,95,99–112], right-handed neutrinos [63,107–114], R-parity-violating supersymmetric couplings [25,115–121] have been studied as well. Complementary tests at the LHC searches of some of these scenarios have been also explored [45,48,53,105,106,110,115]. Furthermore, the polarizations of the  $\tau$  lepton and  $D^*$  are also useful

observables to potentially distinguish the underlying NP [25,27,45,46].

The potential NP scenarios that could explain the  $R(D^{(*)})$  and  $R(J/\psi)$  anomalies would also affect the branching ratio associated with the leptonic decay  $B_c^- \rightarrow \tau^-\bar{\nu}_\tau$  [122,123] since all of them are generated by the same quark level transition,  $b \rightarrow c\tau\bar{\nu}_\tau$ . In Ref. [122], a constraint of  $\text{BR}(B_c^- \rightarrow \tau^-\bar{\nu}_\tau) \lesssim 30\%$  is imposed by considering the lifetime of  $B_c$ , while a stronger bound of  $\text{BR}(B_c^- \rightarrow \tau^-\bar{\nu}_\tau) \lesssim 10\%$  has been obtained in Ref. [123] from the LEP data taken at the  $Z$  peak. In the SM, the branching fraction of this tauonic decay is given by the expression [122,123]

$$\text{BR}(B_c^- \rightarrow \tau^-\bar{\nu}_\tau)_{\text{SM}} = \tau_{B_c} \frac{G_F^2}{8\pi} |V_{cb}|^2 f_{B_c}^2 m_{B_c} m_\tau^2 \left(1 - \frac{m_\tau^2}{m_{B_c}^2}\right)^2, \quad (3)$$

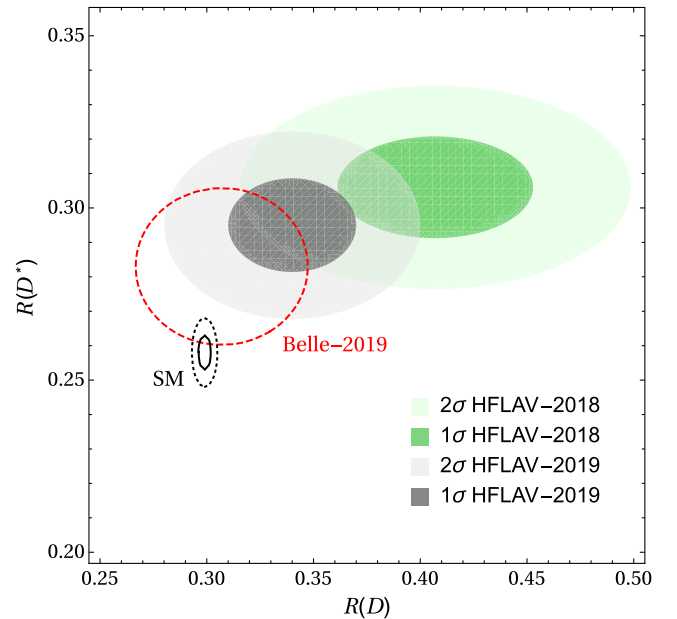


FIG. 1. The HFLAV 2018 and HFLAV 2019 averages (green and gray regions, respectively) [15,16] in the  $R(D)$  vs  $R(D^*)$  plane. The black ( $1\sigma$  solid and  $2\sigma$  dotted) and red (dashed) contours show the SM predictions and the recent Belle measurements [22], respectively.

<sup>1</sup>For previous works, see, for instance, Refs. [24,39–47].

where  $G_F$  is the Fermi constant,  $V_{cb}$  denotes the Cabbibo-Kobayashi-Maskawa (CKM) matrix element involved, and  $f_{B_c}$  and  $\tau_{B_c}$  are the  $B_c^-$  meson decay constant and lifetime, respectively. By using the following input values,  $\tau_{B_c} = (0.507 \pm 0.009)$  ps,  $m_{B_c} = 6.2749$  GeV, and  $|V_{cb}| = (40.5 \pm 1.5) \times 10^{-3}$  from the Particle Data Group (PDG) [124] and  $f_{B_c} = (434 \pm 15)$  MeV from lattice QCD [125], we get a value of

$$\text{BR}(B_c^- \rightarrow \tau^- \bar{\nu}_\tau)_{\text{SM}} = (2.16 \pm 0.16)\%. \quad (4)$$

It is worth mentioning that by taking the value for  $|V_{cb}| = (39.18 \pm 0.94 \pm 0.36) \times 10^{-3}$  reported by HFLAV [15], a value of  $\text{BR}(B_c^- \rightarrow \tau^- \bar{\nu}_\tau)_{\text{SM}} = (2.02 \pm 0.11)\%$  is obtained, which is consistent with Eq. (4). For later use in our phenomenological analysis, we will take Eq. (4) and the upper limit  $\text{BR}(B_c^- \rightarrow \tau^- \bar{\nu}_\tau) \lesssim 10\%$ . Moreover, we will consider the inclusive semileptonic decay  $B \rightarrow X_c \tau^- \bar{\nu}_\tau$  that is generated via the same transition,  $b \rightarrow c\tau^- \bar{\nu}_\tau$ . Including nonperturbative corrections of the order  $\mathcal{O}(1/m_b^2)$  and using the  $1S$  mass scheme, in Ref. [28], a very recent estimation has been calculated,  $R(X_c)_{\text{SM}} = 0.228 \pm 0.030$ , that is in agreement ( $0.2\sigma$ ) with the experimental value  $R(X_c)_{\text{exp}} = 0.223 \pm 0.030$  [28] (these values are also collected in Table I).

In light of the new HFLAV world average values  $R(D^{(*)})$  [15,16] (due to the very recent Belle measurements [22]) and the polarization observables  $P_\tau(D^*)$ ,  $F_L(D^*)$  measured by Belle [10,11,26], in this work, we look into the interpretation of these charged-current  $B$  anomalies driven by a general  $W'$  gauge boson scenario. Without invoking any particular NP model, we provide a model-independent study based on the most general effective Lagrangian given in terms of the flavor-dependent couplings  $\epsilon_{cb}^{L,R}$  and  $\epsilon_{\ell\nu}^{L,R}$  of the currents  $(\bar{c}\gamma_\mu P_{L,R}b)$  and  $(\bar{\ell}\gamma^\mu P_{L,R}\nu_\tau)$ , respectively (see Sec. II for details), which yields a tree-level effective contribution to the  $b \rightarrow c\tau\bar{\nu}_\tau$  transition. We implement a  $\chi^2$  analysis by considering all of the scenarios with different chiral charges that explain the  $R(D^{(*)})$  discrepancies. We also analyze the effect of taking into account all of the charged transition  $b \rightarrow c\tau\bar{\nu}_\tau$  observables—namely,  $R(J/\psi)$ ,  $P_\tau(D^*)$ ,  $F_L(D^*)$ ,  $R(X_c)$  and  $\text{BR}(B_c^- \rightarrow \tau^- \bar{\nu}_\tau)$ . We present a phenomenological analysis of parameter space allowed by the experimental data, and for comparison, we include some of the  $W'$  boson NP realizations that have already been studied in the literature [95,100,101,104–106,108–110]. Most of these models were implemented by considering the previous HFLAV averages and, in addition, not all of them considered the polarization observables  $P_\tau(D^*)$  and  $F_L(D^*)$ ; therefore, we explore which of these benchmark models are still favored (or disfavored) by the new  $b \rightarrow c\tau\bar{\nu}_\tau$  data.

It is important to remark that, since we are not implementing any NP realizations in our analysis, we will get out

of our discussion the possible connection with a  $Z'$  boson that appears in particular UV completions, as done, for instance, in Refs. [95,101,102,104,106,109–112].

This work is organized as follows. In Sec. II, we briefly present the most general charged-current effective Lagrangian for a general  $W'$  gauge boson; then, we study its tree-level effective contribution to the observables associated with the semileptonic transition  $b \rightarrow c\tau\bar{\nu}_\tau$ . In order to provide an explanation to the charged-current  $B$  anomalies, in Sec. III, we study different parametric models that depend on the choices of the chiral charges and carry out a  $\chi^2$  analysis to get the best candidates to adjust the experimental data. Based on this analysis, we explore the two parametric model to determine the regions in parameter space favored by two different datasets,  $R(D)$  and  $R(D^*)$ , and all of the  $b \rightarrow c\tau\bar{\nu}_\tau$  observables, and we make a comparison with some benchmark models studied in the literature. Our main conclusions are given in Sec. IV.

## II. A GENERAL $W'$ BOSON SCENARIO

The most general Lorentz invariant Lagrangian describing the couplings of a general  $W'$  boson to quarks and leptons may be written as<sup>2</sup>

$$\begin{aligned} \mathcal{L}_{\text{eff}}^{W'} = & \frac{W'_\mu}{\sqrt{2}} [\bar{u}_i (\epsilon_{u_i d_j}^L P_L + \epsilon_{u_i d_j}^R P_R) \gamma^\mu d_j \\ & + \bar{\ell}_i (\epsilon_{\ell_i \nu_j}^L P_L + \epsilon_{\ell_i \nu_j}^R P_R) \gamma^\mu \nu_j] + \text{H.c.}, \end{aligned} \quad (5)$$

where  $P_{R/L} = (1 \pm \gamma_5)/2$  are the right-handed (RH) and left-handed (LH) chirality projectors, respectively; and the coefficients  $\epsilon_{u_i d_j}^L$ ,  $\epsilon_{u_i d_j}^R$ ,  $\epsilon_{\ell_i \nu_j}^L$ , and  $\epsilon_{\ell_i \nu_j}^R$  are arbitrary dimensionless parameters that codify the NP flavor effects, with  $u_i \in (u, c, t)$ ,  $d_j \in (d, s, b)$ , and  $\ell_i, \ell_j \in (e, \mu, \tau)$ . For simplicity, we consider leptonic flavor-diagonal interactions ( $i = j$ ). In the SM, only the LH couplings  $\epsilon_{u_i d_j}^L = g_L V_{u_i d_j}$  and  $\epsilon_{\ell_i \nu_j}^L = g_L$  are present, with  $g_L$  being the  $SU(2)_L$  gauge coupling constant, and  $V_{u_i d_j}$  the corresponding CKM quark matrix element.

In the SM framework, the  $b \rightarrow c\tau\bar{\nu}_\tau$  quark level processes are mediated by a virtual  $W$  boson exchange, which is described by the effective Lagrangian

$$-\mathcal{L}_{\text{eff}}(b \rightarrow c\tau\bar{\nu}_\tau)_{\text{SM}} = \frac{4G_F}{\sqrt{2}} V_{cb} (\bar{c}\gamma_\mu P_L b) (\bar{\tau}\gamma^\mu P_L \nu_\tau), \quad (6)$$

where  $G_F$  is the Fermi coupling constant and  $V_{cb}$  is the associated CKM matrix element. According to Eq. (5), a general  $W'$  boson exchange leads to additional tree-level effective interactions to the  $b \rightarrow c\tau\bar{\nu}_\tau$  transition; thus, the total low-energy effective Lagrangian has the following form,

<sup>2</sup>See the review “ $W'$ -boson searches” in the PDG [124].

$$\begin{aligned}
& -\mathcal{L}_{\text{eff}}(b \rightarrow c\tau\bar{\nu}_\tau)_{\text{SM}+W'} \\
& = \frac{4G_F}{\sqrt{2}} V_{cb} [(1 + C_V^{LL})(\bar{c}\gamma_\mu P_L b)(\bar{\tau}\gamma^\mu P_L \nu_\tau) \\
& \quad + C_V^{RL}(\bar{c}\gamma_\mu P_R b)(\bar{\tau}\gamma^\mu P_L \nu_\tau) + C_V^{LR}(\bar{c}\gamma_\mu P_L b)(\bar{\tau}\gamma^\mu P_R \nu_\tau) \\
& \quad + C_V^{RR}(\bar{c}\gamma_\mu P_R b)(\bar{\tau}\gamma^\mu P_R \nu_\tau)], \tag{7}
\end{aligned}$$

where  $C_V^{LL}$ ,  $C_V^{RL}$ ,  $C_V^{LR}$ , and  $C_V^{RR}$  are the Wilson coefficients associated with the NP operators, particularly the LH and RH vector operator contributions, respectively. These Wilson coefficients depend on the choices of the chiral charges and are defined as

$$C_V^{LL} \equiv \frac{\sqrt{2}}{4G_F V_{cb}} \frac{\epsilon_{cb}^L \epsilon_{\tau\nu_\tau}^L}{M_{W'}^2}, \tag{8}$$

$$C_V^{RL} \equiv \frac{\sqrt{2}}{4G_F V_{cb}} \frac{\epsilon_{cb}^R \epsilon_{\tau\nu_\tau}^L}{M_{W'}^2}, \tag{9}$$

$$C_V^{LR} \equiv \frac{\sqrt{2}}{4G_F V_{cb}} \frac{\epsilon_{cb}^L \epsilon_{\tau\nu_\tau}^R}{M_{W'}^2}, \tag{10}$$

$$C_V^{RR} \equiv \frac{\sqrt{2}}{4G_F V_{cb}} \frac{\epsilon_{cb}^R \epsilon_{\tau\nu_\tau}^R}{M_{W'}^2}, \tag{11}$$

with  $M_{W'}$  being the  $W'$  boson mass, and  $\epsilon_{cb}^{L,R}$  and  $\epsilon_{\tau\nu_\tau}^{L,R}$  the effective flavor-dependent couplings given in Eq. (5). To accommodate the  $b \rightarrow c\tau\bar{\nu}_\tau$  anomalies, we will adopt the phenomenological assumption in which the  $W'$  boson couples only to the bottom-charm quarks and the third generation of leptons, i.e., the effective couplings  $\epsilon_{cb}^{L,R} \neq 0$  and  $\epsilon_{\tau\nu_\tau}^{L,R} \neq 0$  are other from zero, while the other ones are taken to be zero. Therefore, NP effects are negligible for light lepton modes ( $e$  or  $\mu$ ),  $\epsilon_{e\nu_e}^{L,R} = \epsilon_{\mu\nu_\mu}^{L,R} = 0$ . For simplicity, we take these effective couplings to be real. These are the minimal assumptions in order to provide an explanation to the discrepancies and not to get in conflict or tension with another low-energy LU test; for instance, there is no problem with LU constraints from the bottom-charm loop (mediated by a  $W'$  boson) contribution to the  $\tau$  lepton decay  $\tau \rightarrow \ell\nu_\tau\bar{\nu}_\ell$  [126].

As a final remark, let us notice that such a flavor texture assumption for the gauge interactions can be obtained by an approximated  $U(2)_q \times U(2)_\ell$  flavor symmetry [95,104] or in SM gauge extensions with additional exotic fermions [102].

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

According to the above effective Lagrangian (7), a general  $W'$  charged boson exchange will modify the observables associated with the semileptonic transition  $b \rightarrow c\tau\bar{\nu}_\tau$ . The ratios  $R(M)$  ( $M = D, D^*, J/\psi$ ) and the  $D^*$  and  $\tau$

longitudinal polarizations can be parametrized in terms of the effective Wilson coefficients  $C_V^{LL}$ ,  $C_V^{RL}$ ,  $C_V^{LR}$ , and  $C_V^{RR}$  as follows [45,109,112]

$$R(D) = R(D)_{\text{SM}} (|1 + C_V^{LL} + C_V^{RL}|^2 + |C_V^{LR} + C_V^{RR}|^2), \tag{12}$$

$$\begin{aligned}
R(D^*) & = R(D^*)_{\text{SM}} (|1 + C_V^{LL}|^2 + |C_V^{RL}|^2 + |C_V^{LR}|^2 + |C_V^{RR}|^2 \\
& \quad - 1.81 \text{Re}[(1 + C_V^{LL})C_V^{RL*} + (C_V^{RR})C_V^{LR*}]), \tag{13}
\end{aligned}$$

$$\begin{aligned}
R(J/\psi) & = R(J/\psi)_{\text{SM}} (|1 + C_V^{LL}|^2 + |C_V^{RL}|^2 + |C_V^{LR}|^2 + |C_V^{RR}|^2 \\
& \quad - 1.92 \text{Re}[(1 + C_V^{LL})C_V^{RL*} + (C_V^{RR})C_V^{LR*}]), \tag{14}
\end{aligned}$$

$$\begin{aligned}
F_L(D^*) & = F_L(D^*)_{\text{SM}} r_{D^*}^{-1} (|1 + C_V^{LL} - C_V^{RL}|^2 \\
& \quad + |C_V^{RR} - C_V^{LR}|^2), \tag{15}
\end{aligned}$$

$$\begin{aligned}
P_\tau(D^*) & = P_\tau(D^*)_{\text{SM}} r_{D^*}^{-1} (|1 + C_V^{LL}|^2 + |C_V^{RL}|^2 - |C_V^{RR}|^2 \\
& \quad - |C_V^{LR}|^2 - 1.77 \text{Re}[(1 + C_V^{LL})C_V^{RL*} \\
& \quad - (C_V^{RR})C_V^{LR*}]), \tag{16}
\end{aligned}$$

respectively, with  $r_{D^*} = R(D^*)/R(D^*)_{\text{SM}}$ . The numerical formula for  $R(J/\psi)$  have been obtained by using the analytic expressions and form factors given in Ref. [24]. Similarly, the leptonic decay  $B_c^- \rightarrow \tau^- \bar{\nu}_\tau$  will also be modified [45,112]

$$\begin{aligned}
\text{BR}(B_c^- \rightarrow \tau^- \bar{\nu}_\tau) & = \text{BR}(B_c^- \rightarrow \tau^- \bar{\nu}_\tau)_{\text{SM}} (|1 + C_V^{LL} - C_V^{RL}|^2 \\
& \quad + |C_V^{RR} - C_V^{LR}|^2), \tag{17}
\end{aligned}$$

as well as the ratio  $R(X_c)$  of inclusive semileptonic  $B$  decays<sup>3</sup> [28],

$$\begin{aligned}
R(X_c) & = R(X_c)_{\text{SM}} (1 + 1.147[|C_V^{LL}|^2 + |C_V^{RR}|^2 \\
& \quad + 2\text{Re}(C_V^{LL}) + |C_V^{LR}|^2 + |C_V^{RL}|^2] \\
& \quad - 0.714 \text{Re}[(1 + C_V^{LL})C_V^{RL*} + (C_V^{RR})C_V^{LR*}]). \tag{18}
\end{aligned}$$

In the next section, we will pay attention to the Wilson coefficients  $C_V^{LL}$ ,  $C_V^{RL}$ ,  $C_V^{LR}$ , and  $C_V^{RR}$ , given in terms of the effective couplings  $\epsilon_{cb}^{L,R}$  and  $\epsilon_{\tau\nu_\tau}^{L,R}$  and the  $W'$  boson mass, which can provide an explanation for the  $b \rightarrow c\tau\bar{\nu}_\tau$  anomalies.

## III. PHENOMENOLOGICAL ANALYSIS

Table I shows the most recent measurements for several flavor observables. In what follows, we will denote these values as  $\mathcal{O}_{\text{exp}}$ , and the corresponding theoretical expressions  $\mathcal{O}_{\text{th}}$  are shown in Eqs. (12)–(18). When there are no correlations or they are negligible, the  $\chi^2$  function is given by the sum of the squared pulls, i.e.,  $\chi^2 = \sum_i \text{pull}_i^2$ , where

<sup>3</sup>We thank Saeed Kamali for the useful conversations.

TABLE II. SM pulls of the all  $b \rightarrow c\tau\bar{\nu}_\tau$  observables.

$R(D)$	$R(D^*)$	$R(J/\psi)$	$P_\tau(D^*)$	$F_L(D^*)$	$R(X_c)$
1.36	2.55	1.69	0.21	1.46	0.23

$\text{pull}_i = (\mathcal{O}_{\text{exp}}^i - \mathcal{O}_{\text{th}}^i) / \sqrt{\sigma_{\text{exp}}^2 + \sigma_{\text{th}}^2}$ . Here  $\sigma_{\text{exp,th}}^i$  corresponds to the experimental (theoretical) error. In order to account for the  $R(D)$  and  $R(D^*)$  correlation, the contribution of these observables to the  $\chi^2$  function should be written as

$$\chi_{R(D)-R(D^*)}^2 = \frac{\text{pull}(D) + \text{pull}(D^*)^2 - 2\rho \text{pull}(D)\text{pull}(D^*)}{\sqrt{1 - \rho^2}}, \quad (19)$$

where  $\rho = -0.203$  is the  $R(D)-R(D^*)$  correlation reported by HFLAV [15,16]. This effect is important since the experimental methodology and the theoretical expressions are quite similar for these observables. This correlation does not significantly modify the best-fit point for all models presented here. We neglected the remaining correlations. From Eq. (5), it is possible to obtain several models by turning on some of the couplings, while the remaining ones are set equal to zero. In order to adjust the experimental anomalies, any model must contain a charm-bottom interaction term in the quark sector and the corresponding  $\tau\text{-}\nu_\tau$  interaction term in the lepton sector; this means that it is necessary to have at least two nonzero couplings in the Lagrangian (5). These models will be referred to as 2P models, and the corresponding models with three and four nonzero couplings will be referred to as 3P and 4P, respectively. Depending on the choices for the

chiral charges ( $\epsilon_{cb}^{L,R}, \epsilon_{\tau\nu}^{L,R}$ ), there are four different 2P models,  $LL, LR, RL$ , and  $RR$ . As we will see in the next section, two of them ( $LL$  and  $RR$ ) have already been studied in the literature; however, the  $LR$  and  $RL$  models, as far as we know, have not been reported on yet. The same is true for the 3P and 4P models.

In order to check whether it is possible to adjust the deviations of the standard model predictions in these models, we carried out a  $\chi^2$  analysis with the seven experimental observables mentioned above. Owing to the absence of the experimental measurement on  $B_c^- \rightarrow \tau^-\bar{\nu}_\tau$ , we used the SM estimation given in Eq. (4), which is consistent with the strongest upper limit  $\text{BR}(B_c^- \rightarrow \tau^-\bar{\nu}_\tau) < 10\%$  [123]. In Table II, we display the SM pulls of all of the  $b \rightarrow c\tau\bar{\nu}_\tau$  observables. The fit results are shown in Table III. In this fit, the number of degrees of freedom is given by  $\text{dof} = 7 - p$ , where  $p$  is the number of parameters. The goodness of fit  $\chi_{\text{min}}^2/\text{dof}$  is of order 1 for 2P models (except for the RL model); for the 3P and the 4P models,  $\chi_{\text{min}}^2/\text{dof} \sim 1.4$  and 1.8, respectively. So, the 2P models represent the best candidates to adjust the experimental anomalies. It is important to note that the observables that generate more tension are  $R(J/\psi)$  and  $F_L(D^*)$ , even though these experiments have large uncertainties. By comparing Tables II and III, we can see that, with respect to the SM, the models with an additional  $W'$  decrease the pulls for  $R(D)$  and  $R(D^*)$  without increasing the pulls of the other observables. In order to keep the couplings in the perturbative regime, we took the mass of the  $W'$  boson as  $M_{W'} = 1$  TeV. 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 SM fermions of the first family.

TABLE III. By turning on the parameters of the second column [keeping the remaining parameters of Lagrangian (7) equal to zero], we obtain several effective models at low energies. The models in rows 3–6 have two free parameters (the chiral couplings), and in the following, they will be referred to as 2P models. In the same sense, we will refer to the models in rows 7–9 as 3P models. In the last row, the model with all the parameters turned on is shown. The pulls for each observable are shown in columns 3–8, the minimum value for the  $\chi^2$  is shown in column 9, and the best-fit point for the chiral charges is shown for each model in the last four columns, for a gauge boson mass  $M_{W'} = 1$  TeV. All 2P models have an acceptable value for  $\chi_{\text{min}}^2/\text{dof} \sim 1$ , except the model with RH coupling to quarks and LH coupling to leptons. The goodness of fit decreases for the 3P and 4P models since, for them, the number of parameters increases while  $\chi_{\text{min}}^2$  stays at nearly the same value.

Parameters on	Pull <sub><i>i</i></sub>							$\chi_{\text{min}}^2$	Best-fit point				
	$R(D)$	$R(D^*)$	$R(J/\psi)$	$P_\tau(D^*)$	$F_L(D^*)$	$R(X_c)$	$\text{BR}(B_c \rightarrow \tau\bar{\nu})$		$\epsilon_{cb}^L$	$\epsilon_{cb}^R$	$\epsilon_{\tau\nu}^L$	$\epsilon_{\tau\nu}^R$	
2P	$(\epsilon_{cb}^L, \epsilon_{\tau\nu}^L)$	-0.045	0.032	1.53	0.21	1.46	-0.93	-0.27	5.49	-0.345	...	-0.276	...
	$(\epsilon_{cb}^L, \epsilon_{\tau\nu}^R)$	-0.047	0.027	1.53	-0.013	1.46	-0.94	-0.27	5.44	0.584	...	...	0.897
	$(\epsilon_{cb}^R, \epsilon_{\tau\nu}^L)$	2.57	0.46	1.55	0.19	1.52	-0.059	-0.26	12.28	...	-0.322	0.271	...
	$(\epsilon_{cb}^R, \epsilon_{\tau\nu}^R)$	-0.047	0.027	1.53	-0.013	1.46	-0.121	-0.27	5.44	...	0.584	...	0.897
3P	$(\epsilon_{cb}^L, \epsilon_{cb}^R, \epsilon_{\tau\nu}^L)$	0.31	-0.20	1.52	0.22	1.41	-0.91	-0.27	5.34	0.272	-0.051	0.326	...
	$(\epsilon_{cb}^R, \epsilon_{\tau\nu}^L, \epsilon_{\tau\nu}^R)$	0.31	-0.21	1.52	0.011	1.41	-0.91	-0.27	5.29	...	0.466	-0.038	1.082
	$(\epsilon_{cb}^L, \epsilon_{\tau\nu}^L, \epsilon_{\tau\nu}^R)$	-0.048	0.027	1.53	$-7.4 \times 10^{-7}$	1.46	-0.94	-0.27	5.44	0.666	...	0.008	0.764
4P	$(\epsilon_{cb}^L, \epsilon_{cb}^R, \epsilon_{\tau\nu}^L, \epsilon_{\tau\nu}^R)$	0.31	-0.21	1.52	$-4.1 \times 10^{-6}$	1.41	-0.91	-0.27	5.29	1.016	-0.105	0.009	-0.469

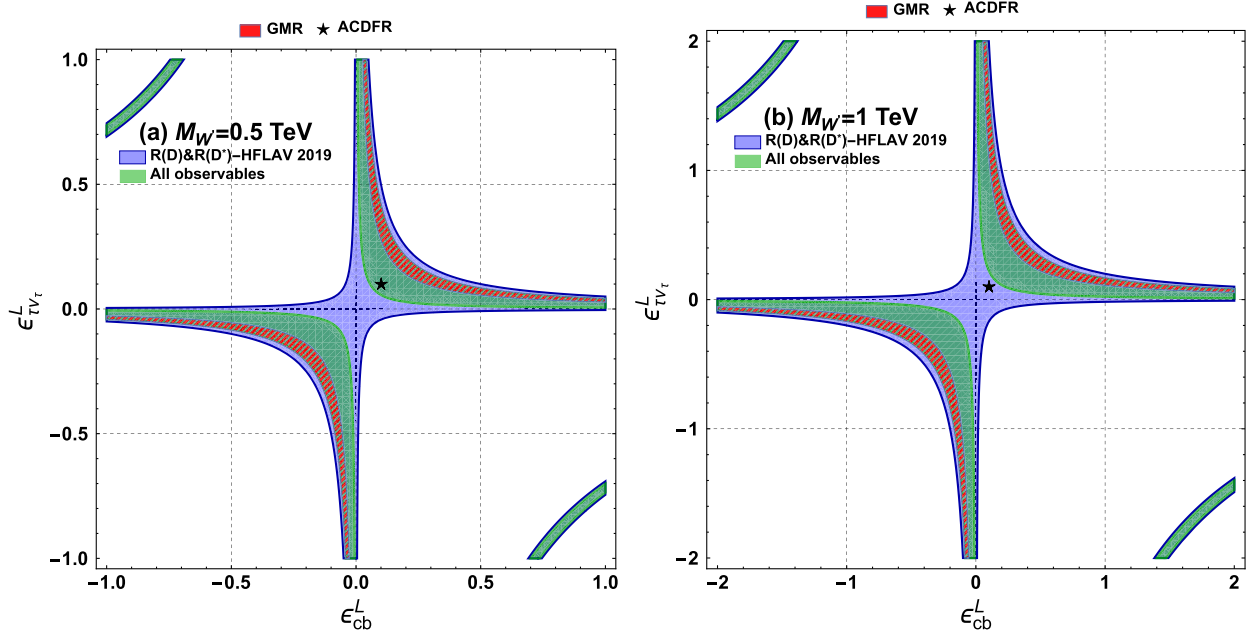


FIG. 2. The 95% C.L. allowed parameter space in the  $(\epsilon_{cb}^L, \epsilon_{\tau\nu_\tau}^L)$  plane for (a)  $M_{W'} = 0.5$  TeV and (b)  $M_{W'} = 1$  TeV. The purple region is obtained by considering only  $R(D^{(*)})$  from the HFLAV 2019 average, while the green one is obtained by taking into account all of the  $b \rightarrow c\tau\bar{\nu}_\tau$  observables. The black star and red hatched region represent the ACDFR model [105] and the GMR analysis [106], respectively. See the text for details.

As the next step in our analysis, we will explore in a more detailed way the four 2P models  $LL$ ,  $LR$ ,  $RL$ , and  $RR$ , which according to our  $\chi^2$  analysis are the best candidates to address the charged-current  $B$  anomalies. By considering two different datasets,  $R(D)$  and  $R(D^*)$ , and all of the  $b \rightarrow c\tau\bar{\nu}_\tau$  observables, we determine the regions in the parameter space favored by the experimental data.

### A. $LL$ scenarios ( $C_{LL}^V \neq 0$ )

In this scenario, we consider a  $W'$  boson that couples only to LH quark and LH lepton currents inducing the semitauonic operator  $(\bar{c}\gamma_\mu P_L b)(\bar{\tau}\gamma^\mu P_L \nu_\tau)$ , i.e.,  $C_{LL}^V \neq 0$ . In Figs. 2(a) and 2(b), we show the 95% confidence level (C.L.) allowed parameter space in the  $(\epsilon_{cb}^L, \epsilon_{\tau\nu_\tau}^L)$  plane, associated with the couplings in Eq. (8), for  $M_{W'} = 0.5$  TeV and  $M_{W'} = 1$  TeV, respectively. In order to see the impact of the polarization measurements [10,11,26], the purple region is obtained by considering the HFLAV 2019 averages on  $R(D)$  and  $R(D^*)$  [16], while the green region is obtained by taking into account all of the  $b \rightarrow c\tau\bar{\nu}_\tau$  observables—namely,  $R(D^{(*)})$ ,  $R(J/\psi)$ ,  $F_L(D^*)$ , and  $P_\tau(D^*)$  (see Table I)—and considering the upper limit  $\text{BR}(B_c^- \rightarrow \tau^-\bar{\nu}_\tau) < 10\%$ . It is observed that the allowed region for  $R(D^{(*)})$  is significantly reduced to two symmetrical regions when all of the  $b \rightarrow c\tau\bar{\nu}_\tau$  observables are considered. This is due mainly to the effect of the polarization  $F_L(D^*)$ , whereas observables such as  $R(J/\psi)$  and  $P_\tau(D^*)$  have little influence due to their large

experimental uncertainties. This effect is in agreement with the analysis presented in Ref. [36]. It is remarkable that the  $R(D^{(*)})$  HFLAV 2019 averages allow the solution  $(\epsilon_{\tau\nu_\tau}^L, \epsilon_{cb}^L) = (0, 0)$ ; this result is consistent with the SM and does not require NP explanations.

In order to improve our analysis, we will include some of the benchmark models that have already been studied in the literature [95,104–106]:

- In Ref. [105], Abdullah, Calle, Dutta, Floréz, and Restrepo considered a simplified  $W'$  model (referred to by us as the ACDFR model) which preferentially couples to the bottom and charm quarks and  $\tau$  leptons, through the NP couplings  $g'_q$  and  $g'_\ell$ , respectively. They showed that for  $W'$  masses in the range [250, 750] GeV and couplings  $g'_q = g'_\ell = 0.1$ , such scenario could be probed at the LHC with a luminosity of  $100 \text{ fb}^{-1}$ . This model is represented in Figs. 2(a) and 2(b) by the black stars. We notice that for  $M_{W'} = 0.5$  TeV the ACDFR model is enabled both for HFLAV 2019 and all observables, while for  $M_{W'} = 1$  TeV, it is still allowed by HFLAV 2019.
- In Ref. [106], Greljo, Martin, and Ruiz performed a study (referred to by us as the GMR analysis) of the connection between NP scenarios addressing the  $R(D^{(*)})$  anomalies and the mono-tau signature at the LHC,  $pp \rightarrow \tau_h X + \text{MET}$ . By using current ATLAS [127] and CMS [128] data, they constrained different scenarios—particularly those regarding a  $W'$  boson scenario—and they found that [106]

$$\epsilon_{cb}^L \epsilon_{\tau\nu_\tau}^L = (0.14 \pm 0.03) \left( \frac{M_{W'}}{\text{TeV}} \right)^2 \quad (20)$$

for  $W'$  masses in the range  $[0.5, 3.5]$  TeV, which is in agreement with the value  $\epsilon_{cb}^L \epsilon_{\tau\nu_\tau}^L = 0.107 (M_{W'}/\text{TeV})^2$  obtained in [48]. This result is represented by the red hatched region in Figs. 2(a) and 2(b). We can appreciate that the allowed parameter region by  $R(D^{(*)})$  HFLAV 2019 and all  $b \rightarrow c\tau\bar{\nu}_\tau$  observables of our analysis are consistent and overlap with this region.

- (c) In Refs. [95,104] the authors introduced a color-neutral  $SU(2)_L$  triplet of massive vector bosons that couple predominantly with third generation fermions (both quarks  $g_q$  and  $g_\ell$  leptons), with an underlying dynamics generated by an approximated  $U(2)_q \times U(2)_\ell$  flavor symmetry; however, in light of new experimental measurements, this model is disfavored unless a fine-tuning of the couplings is carried out.

### B. RR scenarios ( $C_{RR}^V \neq 0$ )

In this scenario, the  $W'$  is the gauge boson associated with the interaction between the RH quark and RH lepton currents involving a RH sterile neutrino. This RH current interpretation to the  $R(D^{(*)})$  anomalies have been discussed recently in the literature within different NP realizations [63,107–114]. We plot in Figs. 3(a) and 3(b) the 95% C.L. allowed parameter space in the  $(\epsilon_{cb}^R, \epsilon_{\tau\nu_\tau}^R)$  plane for masses  $M_{W'} = 1$  and 1.2 TeV, respectively. The purple and green regions are obtained by taking into account only  $R(D)$  and  $R(D^*)$  from the HFLAV 2019 averages [16] and all the

$b \rightarrow c\tau\bar{\nu}_\tau$  observables, respectively. It is found that the allowed region for  $R(D^{(*)})$  is significantly reduced to fourfold symmetrical regions when all of the  $b \rightarrow c\tau\bar{\nu}_\tau$  observables are considered. As in the  $LL$  scenarios previously discussed, this is mainly due to the effect of the polarization  $F_L(D^*)$ . For further discussion, we consider some benchmark models:

- (a) The authors of Refs. [109,110] presented a model where the SM is extended by the gauge group  $SU(3)_C \times SU(2)_L \times SU(2)_V \times U(1)'$ , with  $g_V$  and  $g'$  being the corresponding new gauge couplings. After the spontaneous symmetry breaking  $SU(2)_V \times U(1)' \rightarrow U(1)_Y$ , new heavy vector bosons are generated. In addition, the SM fermion content is accompanied by new heavy vectorlike fermions (both quarks and leptons) that mix with the RH fermions of the SM, which is required in order to provide an explanation of the  $R(D^{(*)})$  anomalies. Since the results in [109,110] are very similar, for simplicity, we will consider the analysis of Ref. [110] for comparison (referred to as the 3221 gauge model). Translating the notation in [110] into ours, we have  $\epsilon_{cb}^R = g_V c_q^{23}$  and  $\epsilon_{\tau\nu_\tau}^R = g_V c_N^3$ , with  $c_q^{23}, c_N^3$  coefficients that encode the flavor dependence. Given that  $M_{W'} = g_V v_V / 2$  [110], a viable  $1\sigma$  solution to the anomalies is obtained for a vacuum expectation value (VEV) of  $v_V \simeq 2000$  GeV,  $g_V \simeq \mathcal{O}(1-3)$ , and  $c_q^{23} = c_N^3 \simeq 1$ , implying  $W'$  masses in the range  $1000 \lesssim M_{W'}(\text{GeV}) \lesssim 3000$  to avoid the perturbative limit [110]. By taking representative values of  $v_V \simeq 2000$  GeV and  $g_V \simeq 1-1.2$ , the 3221 gauge model is depicted by the blue squared in Figs. 3(a) and 3(b)

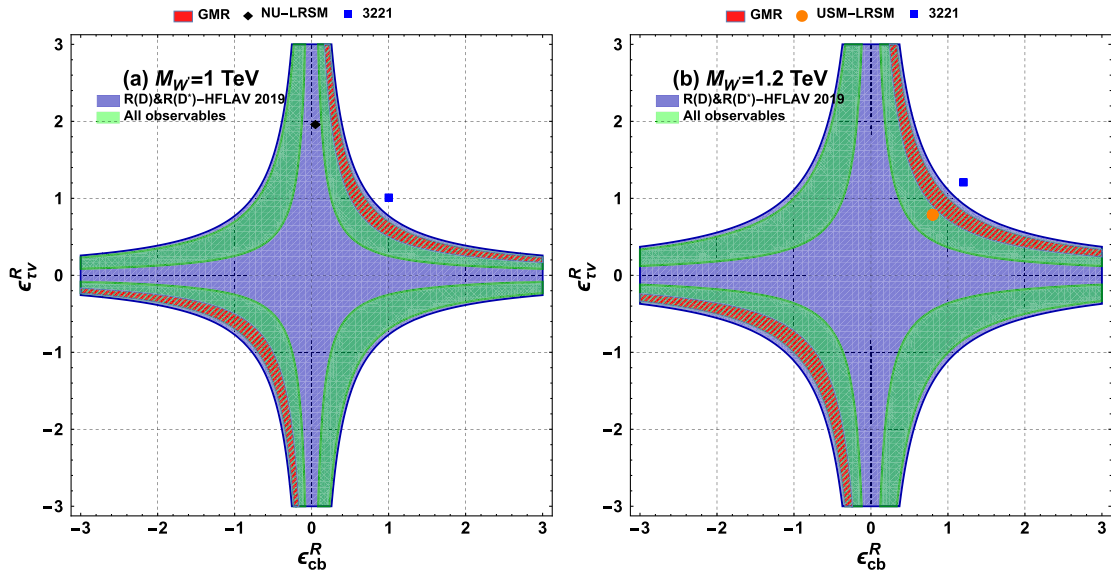


FIG. 3. The 95% C.L. allowed parameter space in the  $(\epsilon_{cb}^R, \epsilon_{\tau\nu_\tau}^R)$  plane for (a)  $M_{W'} = 1$  TeV and (b)  $M_{W'} = 1.2$  TeV. The purple region is obtained by considering only  $R(D^{(*)})$  from HFLAV 2019 averages, while the green one is obtained by taking into account all of the  $b \rightarrow c\tau\bar{\nu}_\tau$  observables. The black diamond, blue squared, red hatched region, and orange circle represent the NU-LRSM model [100,101], 3221 gauge model [109,110], GMR analysis [106], and USM-LRSM [108], respectively. See the text for details.

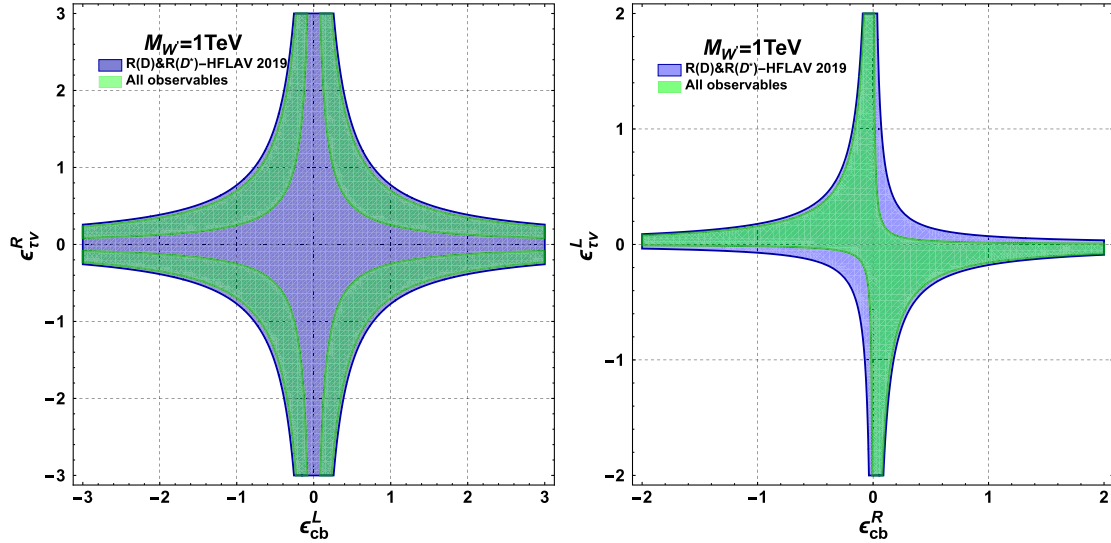


FIG. 4. The 95% C.L. allowed parameter space in the  $(\epsilon_{cb}^L, \epsilon_{\tau\tau}^R)$  and  $(\epsilon_{cb}^R, \epsilon_{\tau\tau}^L)$  planes for a mass value of  $M_{W'} = 1$  TeV.

for  $M_{W'} = 1$  and 1.2 TeV, respectively. According to our analysis, this model is disfavored by the new data. We have also checked that, for  $W'$  masses higher than 1.2 TeV, this is still disfavored. However, as discussed in [111], there is a freedom in the flavor structure of the  $c_q^{23}, c_N^3$  couplings, and it is possible to get, in general, different values  $c_q^{23} \neq c_N^3$  than the ones assumed in [110].

- (b) In the GMR analysis [106] previously discussed, the authors also found that, for RH  $W'$  models, the solution is

$$\epsilon_{cb}^R \epsilon_{\tau\tau}^R = (0.6 \pm 0.1) \left( \frac{M_{W'}}{\text{TeV}} \right)^2, \quad (21)$$

which is represented by the red hatched region in Figs. 3(a) and 3(b), which is consistent with the value  $\epsilon_{cb}^R \epsilon_{\tau\tau}^R = 0.55 (M_{W'}/\text{TeV})^2$  obtained in [48]. Again, the allowed parameter region by  $R(D^{(*)})$  HFLAV 2019 and all  $b \rightarrow c\tau\bar{\nu}_\tau$  observables of our analysis are consistent and overlap with this region.

- (c) In Refs. [100,101], the anomalies have been addressed within the framework of the nonuniversal left-right symmetric model (NU-LRSM) with enhanced couplings to the third generation. In terms of our notation, we have the result that, in the NU-LRSM, the effective couplings are  $\epsilon_{cb}^R = g_R |V_{Rcb}|$  and  $\epsilon_{\tau\tau}^R = g_R |V_{R3\tau}^\ell|$ , with  $g_R$  being the RH gauge coupling,  $V_{Rcb}$  and  $V_{R3\tau}^\ell$  the RH quark and lepton mixing element, respectively. It is assumed that, taking  $M_{W'} \simeq 1$  TeV,  $g_R \simeq 1$ ,  $|V_{R3\tau}^\ell| \simeq 1$ , and  $|V_{Rcb}| \simeq |V_{cb}|$  [100,101], as shown by the black diamond in Fig. 3(a), the model accommodates the tension in  $R(D^{(*)})$ . One can observe that this framework is still allowed by the HFLAV 2019 average, but not with all observables data.

- (d) A class of LRSM (parity symmetric and asymmetric) that implemented vectorlike fermions to generate quark and lepton masses via a universal seesaw mechanism (USM) have been studied in Ref. [108] to explain the anomalies. In the USM-LRSM, the mass of the RH charged gauge boson is given by  $M_{W'} = M_{W_R} = g_R \kappa_R / \sqrt{2}$ , with  $\kappa_R \sim 2$  TeV being the VEV of the neutral member of the doublet  $\chi_R$  (for details, see Ref. [108]), and the effective couplings are simply  $\epsilon_{cb}^R = g_R / \sqrt{2}$  and  $\epsilon_{\tau\tau}^R = g_R / \sqrt{2}$ . Taking the lower mass limit  $M_{W_R} \simeq 1.2$  TeV (obtained for the parity asymmetric case [108]), the USM-LRSM is represented by the orange circle in Fig. 3(b). This setup is allowed by both  $R(D^{(*)})$  and all of the  $b \rightarrow c\tau\bar{\nu}_\tau$  observables.

### C. RL and LR scenarios ( $C_{RL}^V \neq 0$ and $C_{LR}^V \neq 0$ )

Finally, we consider a class of scenarios where the quark and lepton currents with different quiralities projection couple to the  $W'$  boson, i.e., semitauonic operators of the types  $(\bar{c}\gamma_\mu P_R b)(\bar{\tau}\gamma^\mu P_L \nu_\tau)$  and  $(\bar{c}\gamma_\mu P_L b)(\bar{\tau}\gamma^\mu P_R \nu_\tau)$  that implies  $C_{RL}^V \neq 0$  and  $C_{LR}^V \neq 0$ , respectively. For a representative mass value of  $M_{W'} = 1$  TeV, we display in Fig. 4 the 95% C.L. allowed parameter space for the couplings in the LR (left panel) and RL (right panel) scenarios. The case of  $M_{W'} \geq 1$  TeV requires higher effective coupling values. For the LR case, it can be inferred that the allowed region for  $R(D^{(*)})$  is reduced to fourfold symmetrical regions when all of the  $b \rightarrow c\tau\bar{\nu}_\tau$  observables are considered. While for the RL case, the permitted region is barely reduced when all observables are taken into account. In both scenarios, it is found that a NP solution (0, 0) is admissible.

So far, particular NP models realization of such LR and RL scenarios have not been studied in the literature.



However, interestingly enough, recently Bhattacharya *et al.* [129] have explored the possibility of how the measurement of  $CP$ -violating observables in  $\bar{B}^0 \rightarrow D^{*+}\mu^-\bar{\nu}_\mu$  can be used to differentiate the NP scenarios. Particularly, they found that the only way to generate sizable  $CP$ -violating effects is with LH and RH  $W'$  bosons (with sizable mixing) that contribute to  $b \rightarrow c\ell\bar{\nu}_\ell$  [129].

#### IV. CONCLUSIONS

Motivated by the new HFLAV world average values on the ratios  $R(D^{(*)})$ , due to the recent Belle measurements, we addressed the anomalies  $R(D^{(*)})$  related to the charged-current transition  $b \rightarrow c\tau\bar{\nu}_\tau$  within a general  $W'$  boson scenario. In order to provide a robust analysis, we considered in addition the available experimental information on all of the charged transition  $b \rightarrow c\tau\bar{\nu}_\tau$  observables—namely, the ratios  $R(J/\psi)$ ,  $R(X_c)$  and the polarizations  $P_\tau(D^*)$ ,  $F_L(D^*)$ , as well as the upper limit  $\text{BR}(B_c^- \rightarrow \tau^-\bar{\nu}_\tau) < 10\%$ . We carried out a model-independent study, based on the most general effective Lagrangian given in terms of the flavor-dependent couplings  $\epsilon_{cb}^{L,R}$  and  $\epsilon_{\tau\nu}^{L,R}$  of the currents  $\bar{c}\gamma_\mu P_{L,R}b$  and  $\bar{\tau}\gamma^\mu P_{L,R}\nu_\tau$ , that yields a tree-level effective contribution generated by a general  $W'$  boson. With the above-mentioned observables, we performed a  $\chi^2$  analysis by considering the cases of two, three, and four nonzero  $\epsilon_{cb}^{L,R}$  and  $\epsilon_{\tau\nu}^{L,R}$  couplings (with different chiral charges), referred to as the 2P, 3P, and 4P models, respectively. It is found that the

2P models represent the best candidate to adjust the experimental charged current  $B$  anomalies.

Next, we studied all of the possible combinations of 2P models ( $LL$ ,  $RR$ ,  $LR$ , and  $RL$  scenarios) and took into account two different datasets:  $R(D^{(*)})$  only and all  $b \rightarrow c\tau\bar{\nu}_\tau$  observables; we determined the regions in parameter space favored by these observables for different values of the  $W'$  boson mass preferred in the literature. For the  $LL$  and  $RR$  scenarios, we obtained that part of the allowed parametric space is consistent with the mono-tau signature  $pp \rightarrow \tau_h X + \text{MET}$  at the LHC. In order to improve the discussion, we included in our analysis some of the  $W'$  boson NP realizations that have already been studied in the  $LL$  and  $RR$  scenarios. We found which of these benchmark models are favored or disfavored by the new data. Regarding the  $LR$  and  $RL$  scenarios, as far as we know, these have not been previously reported in the literature, and our results showed that it would be interesting to study a particular NP model since this could generate  $CP$ -violating effects in  $\bar{B}^0 \rightarrow D^{*+}\mu^-\bar{\nu}_\mu$ , as discussed in [129].

#### ACKNOWLEDGMENTS

We are grateful to William A. Ponce and Carlos E. Vera for their contributions at the early stage of this work. N. Q. acknowledges support from the Dirección General de Investigaciones, Universidad Santiago de Cali, under Project No. 935-621118-3.

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