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

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

I. INTRODUCTION

The B meson system have constituted a good scenario for studying, 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 flavor universality (LFU), so far one of the cornerstones of the SM. Any mismatch between the theoretical and experimental predictions may be an indication of LFU violation, therefore a hint of NP beyond the SM [1, 2].

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

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

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 $R(D^{(*)})$ have been done recently [17–21], whose average values [15, 16] are shown in Table I. Despite all these advancements, the experimental measurements on $R(D^{(*)})$ still exhibit a deviation in comparison with 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 0.2σ and 1.1σ, respectively. Incorporating these Belle results, in Table I we display the new 2019 world averages values reported by Heavy Flavor Averaging Group (HFLAV) on the measurements of $R(D)$ and $R(D^*)$ [15, 16], that now exceed the SM predictions by 1.4σ and 2.5σ, 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], both at 1σ and 2σ. The black (solid 1σ and dotted 2σ) and red (dashed) contours shows 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.

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

Observable	Exp measurement	SM prediction
$R(D)$	$0.307 \pm 0.037 \pm 0.016$ Belle-2019 [22]	0.299 ± 0.003 [15, 16]
	$0.340 \pm 0.027 \pm 0.013$ HFLAV [15]	
$R(D^*)$	$0.283 \pm 0.018 \pm 0.014$ Belle-2019 [22]	0.258 ± 0.005 [15, 16]
	$0.295 \pm 0.011 \pm 0.008$ HFLAV [15]	
$R(J/\psi)$	$0.71 \pm 0.17 \pm 0.18$ [23]	0.283 ± 0.048 [25]
$P_\tau(D^*)$	$-0.38 \pm 0.51^{+0.21}_{-0.16}$ [10, 11]	-0.497 ± 0.013 [31]
$F_L(D^*)$	$0.60 \pm 0.08 \pm 0.035$ [30]	0.46 ± 0.04 [32]
$R(X_c)$	0.223 ± 0.030 [125]	0.216 ± 0.003 [125]

Further hints of LFU violation in the charged current $b \to c\tau\bar{\nu}_\tau$ has been recently obtained by LHCb in the measurement of the ratio [23]

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

that also shows tension with regard to the SM prediction (around 2σ) [24–29]. In further calculations, we will use the theoretical prediction of Ref. [25] (see Table I) that is in agreement with other estimations [24, 26–29]. Additionally, polarization observables associated to the channel $B \to D^*\tau\bar{\nu}_\tau$ have been observed by the Belle experiment, namely, the τ lepton polarization $P_\tau(D^*)$ [10, 11] and the D^* longitudinal polarization $F_L(D^*)$ [30]. We present in Table I these measurements, as well as their corresponding SM values [31, 32], which also exhibit a deviation from the experimental data.

The incompatibility of these measurements with the SM could be an evidence of LFU violation in B decays, therefore, an indication of NP sensitive to the third generation of quarks and leptons. In order to understand these discrepancies, an enormous number of theoretical studies have been proposed. On one hand, model-independent analyses of the impact of NP effective operators have been extensively studied (for the most recent ones that include

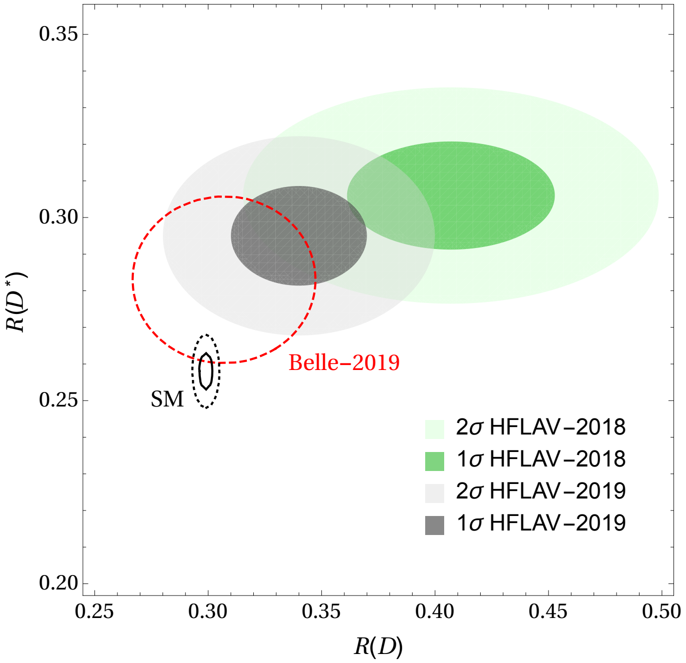

FIG. 1. The HFLAV-2018 and HFLAV-2019 averages (green and gray region, respectively) [15, 16] into the $R(D)$ vs. $R(D^*)$ plane. The black (1σ solid an 2σ dotted) and red (dashed) contours shows the SM predictions and the recent Belle measurements [22], respectively.

the new Belle measurements, see Refs. [33–37])[1]. On the other hand, particular NP scenarios such as: charged scalars [46–62], leptoquarks (both scalar and vector) [64–97], extra gauge bosons [47, 94, 98–111], right-handed neutrinos [62, 106–113], R-parity violating (RPV) supersymmetric couplings [31, 114–120]; have been studied as well. Complementary test at the LHC searches of some of these scenarios have been also explored [44, 47, 52, 104, 105, 109, 114]. Furthermore, the polarizations of the τ lepton and D^* are also useful observables to potentially distinguish the underlying NP [31, 32, 44, 45].

The potential NP scenarios that could explain the $R(D^{(*)})$ and $R(J/\psi)$ anomalies, would also affect the branching ratio associated to the leptonic decay $B_c^- \to \tau^-\bar{\nu}_\tau$ [121, 122], since all of them are generated by the same quark level transition $b \to c\tau\bar{\nu}_\tau$. In Ref. [121], a constraint of $\text{BR}(B_c^- \to \tau^-\bar{\nu}_\tau) \lesssim 30\%$ is imposed by considering the lifetime of B_c. While a stronger bound of $\text{BR}(B_c^- \to \tau^-\bar{\nu}_\tau) \lesssim 10\%$ has been obtained in Ref. [122] from the LEP data taken at the Z peak. In the SM, the branching fraction of this tauonic decay is given by the expression [121, 122]

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

where G_F is the Fermi constant, V_{cb} denotes the CKM matrix element involved, and f_{B_c} and τ_{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, $|V_{cb}| = (40.5 \pm 1.5) \times 10^{-3}$ from Particle Data Group (PDG) [123] and $f_{B_c} = (434 \pm 15)$ MeV from lattice QCD [124], we get a value of

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

It is worth to mention that taking the value for $|V_{cb}| = (39.18 \pm 0.94 \pm 0.36) \times 10^{-3}$ reported by HFLAV [15], a value of $\text{BR}(B_c^- \to \tau^-\bar{\nu}_\tau)_{\text{SM}} = (2.02 \pm 0.11)\%$ is obtained, which is consistent with (4). For later use in our phenomenological analysis, we will take Eq. (4) and the upper limit $\text{BR}(B_c^- \to \tau^-\bar{\nu}_\tau) \lesssim 10\%$. Moreover, we will include the inclusive semileptonic decay $B \to X_c\tau^-\bar{\nu}_\tau$ that is also generated via the same transition $b \to c\tau^-\bar{\nu}_\tau$. Including non-perturbative corrections of the order $\mathcal{O}(1/m_b^2)$ and using the $1S$ mass scheme, in Ref. [125] a very recent estimation has been calculated $R(X_c)_{\text{SM}} = 0.228 \pm 0.030$ that is agreement (0.2σ) with the experimental value $R(X_c)_{\text{exp}} = 0.223 \pm 0.030$ [125] (these values are also collected in Table I).

To the light of the new HFLAV world average values $R(D^{(*)})$ [15, 16] (due to the vey recent Belle measurements [22]) and the polarization observables $P_\tau(D^*)$, $F_L(D^*)$ measured by Belle [10, 11, 30], 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 $\epsilon_{\tau\nu_\tau}^{L,R}$ of the currents $(\bar{c}\gamma_\mu P_{L,R}b)$ and $(\bar{\tau}\gamma^\mu P_{L,R}\nu_\tau)$, respectively (see section II for details), that yields to a tree-level effective contribution to the $b \to c\tau\bar{\nu}_\tau$ transition. We implement a χ^2 analysis by considering all the scenarios with different chiral charges that explain the $R(D^{(*)})$ discrepancies. We also analyze the effect of including into account all the charged transition $b \to c\tau\bar{\nu}_\tau$ observables, namely $R(J/\psi)$, $P_\tau(D^*), F_L(D^*), R(X_c)$, and $\text{BR}(B_c^- \to \tau^-\bar{\nu}_\tau)$. 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 [94, 99, 100, 103–105, 107–109]. Most of these models were implemented by considering the previous HFLAV averages and, in addition, not all them considered the polarization observables $P_\tau(D^*)$, $F_L(D^*)$; therefore, we explore which of these benchmark models are still favored (or disfavored) by the new $b \to c\tau\bar{\nu}_\tau$ data.

It is important to remark that since we are not implementing any NP realization in our analysis, we will get out from our discussion the possible connection with a Z' boson that appears in particular UV completions, as done for instance in Refs. [94, 103, 105, 108–111].

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 $b \to c\tau\bar{\nu}_\tau$. 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 χ^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 the parameter space favored by two different datasets: $R(D)$ and $R(D^*)$ and all the $b \to c\tau\bar{\nu}_\tau$ observables; and compare with some benchmark models studied in the literature. Our main conclusions are given in Sec. IV.

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[1] For previous works, see for instance Refs. [25, 38–46].

II. A GENERAL W' BOSON SCENARIO

The most general Lorentz invariant Lagrangian describing the couplings of a general W' boson to quarks and leptons maybe written as[2]

$$\mathcal{L}_{\rm eff}^{W'} = \frac{W'_\mu}{\sqrt{2}}\Big[\bar{u}_i(\epsilon^L_{u_id_j}P_L+\epsilon^R_{u_id_j}P_R)\gamma^\mu d_j + \bar{\ell}_i(\epsilon^L_{\ell_i\nu_j}P_L+\epsilon^R_{\ell_i\nu_j}P_R)\gamma^\mu\nu_j\Big] + \text{h.c.}, \tag{5}$$

where $P_{R/L}=(1\pm\gamma_5)/2$ are the right-handed (RH) and left-handed (LH) chirality projectors, respectively; and the coefficients $\epsilon^L_{u_id_j}$, $\epsilon^R_{u_id_j}$, $\epsilon^L_{\ell_i\nu_j}$, and $\epsilon^R_{\ell_i\nu_j}$ 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 LH couplings $\epsilon^L_{u_id_j}=g_LV_{u_id_j}$ and $\epsilon^L_{\ell_i\nu_i}=g_L$ are present, with g_L the $SU(2)_L$ gauge coupling constant and $V_{u_id_j}$ the corresponding Cabbibo-Kobayashi-Maskawa (CKM) quark matrix element, respectively.

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

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

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 $b\to c\tau\bar{\nu}_\tau$ transition; thus, the total low-energy effective Lagrangian has the following form

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

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

$$C_V^{LL} \equiv \frac{\sqrt{2}}{4G_FV_{cb}}\frac{\epsilon^L_{cb}\epsilon^L_{\tau\nu_\tau}}{M^2_{W'}}, \tag{8}$$

$$C_V^{RL} \equiv \frac{\sqrt{2}}{4G_FV_{cb}}\frac{\epsilon^R_{cb}\epsilon^L_{\tau\nu_\tau}}{M^2_{W'}}, \tag{9}$$

$$C_V^{LR} \equiv \frac{\sqrt{2}}{4G_FV_{cb}}\frac{\epsilon^L_{cb}\epsilon^R_{\tau\nu_\tau}}{M^2_{W'}}, \tag{10}$$

$$C_V^{RR} \equiv \frac{\sqrt{2}}{4G_FV_{cb}}\frac{\epsilon^R_{cb}\epsilon^R_{\tau\nu_\tau}}{M^2_{W'}}, \tag{11}$$

with $M_{W'}$ the W' boson mass, and $\epsilon^{L,R}_{cb}$ and $\epsilon^{L,R}_{\tau\nu_\tau}$ the effective flavor-dependent couplings of Eq. (5). In order to provide an explanation to the anomalies, we will adopt the phenomenological assumption in which NP is only sensitive to the third generation of quarks and leptons ($\epsilon^{L,R}_{cb}\neq 0$ and $\epsilon^{L,R}_{\tau\nu_\tau}\neq 0$). Therefore, NP effects are negligible for light lepton modes (e or μ), i.e., we set $\epsilon^{L,R}_{e\nu_e}=\epsilon^{L,R}_{\mu\nu_\mu}=0$[3]. In addition, for simplicity, we take all the effective couplings to be real.

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

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

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[2] See the review *W'-boson searches* in the PDG [123].

[3] Under this assumption, we avoid LFU constraints from the τ lepton decay $\tau\to\ell\bar{\nu}_\tau\nu_\ell$

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 [44, 108, 111]

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

$$R(D^*) = R(D^*)_{\rm SM}\Big(|1 + C_V^{LL}|^2 + |C_V^{RL}|^2 + |C_V^{LR}|^2 + |C_V^{RR}|^2 - 1.81\ {\rm Re}\big[(1 + C_V^{LL})C_V^{RL*} + (C_V^{RR})C_V^{LR*}\big]\Big), \tag{13}$$

$$R(J/\psi) = R(J/\psi)_{\rm SM}\Big(|1 + C_V^{LL}|^2 + |C_V^{RL}|^2 + |C_V^{LR}|^2 + |C_V^{RR}|^2 - 1.92\ {\rm Re}\big[(1 + C_{LL}^{V})C_V^{RL*} + (C_V^{RR})C_V^{LR*}\big]\Big), \tag{14}$$

$$F_L(D^*) = F_L(D^*)_{\rm SM}\ r_{D^*}^{-1}\Big(\big|1 + C_V^{LL} - C_V^{RL}\big|^2 + \big|C_V^{RR} - C_V^{LR}\big|^2\Big), \tag{15}$$

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

respectively, with $r_{D^*} = R(D^*)/R(D^*)_{\rm SM}$. The numerical formula for $R(J/\psi)$ have been obtained by using the analytic expressions and form factors given in Ref. [25]. Similarly, the leptonic decay $B_c^- \to \tau^-\bar{\nu}_\tau$ will be also modified [44, 111]

$$ {\rm BR}(B_c^- \to \tau^-\bar{\nu}_\tau) = {\rm BR}(B_c^- \to \tau^-\bar{\nu}_\tau)_{\rm SM}\ \Big(\big|1 + C_V^{LL} - C_V^{RL}\big|^2 + |C_V^{RR} - C_V^{LR}|^2\Big), \tag{17}$$

as well as the ratio $R(X_c)$ of inclusive semileptonic B decays[4] [125]

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

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

III. PHENOMENOLOGICAL ANALYSIS

Table I shows the most recent measurements for several flavor observables, in what follows we will denote these values as $\mathcal{O}_{\rm exp}$, the corresponding theoretical expressions $\mathcal{O}_{\rm th}$ are shown in Eqs. (12)-(18). The χ^2 function is given by the sum of the squared pulls, i.e., $\chi^2 = \sum_i {\rm pull}_i^2$, where ${\rm pull}_i = (\mathcal{O}_{\rm exp}^i - \mathcal{O}_{\rm th}^i)/\sqrt{\sigma_{\rm exp}^{i2} + \sigma_{\rm th}^{i2}}$. Here $\sigma_{\rm exp,th}^i$ corresponds to the experimental (theoretical) error. 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 τ-ν_τ interaction term in the lepton sector, this means that it is at least necessary to have two nonzero couplings in the Lagrangian (5). These models will be referred to as 2P models, 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 $(\epsilon_{cb}^{L,R}, \epsilon_{\tau\nu_\tau}^{L,R})$ 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 been already studied in the literature; however, the LR and RL models, as far as we know, have not been reported yet. The same is true for the 3P and the 4P models.

In order to check if it is possible to adjust the deviations of the standard model predictions with these models, we carried out a χ^2 analysis with the seven experimental observables mentioned above. Owing to the absence of the experimental measurement on $B_c^- \to \tau^-\bar{\nu}_\tau$, we used the SM estimation given in Eq. (4), which is consistent with the strongest upper limit ${\rm BR}(B_c^- \to \tau^-\bar{\nu}_\tau) < 10\%$ [122]. The fit results are shown in Table II. In this fit the number of degrees of freedom is given by dof $= 7 - p$, where p is the number of parameters. The goodness of fit $\chi^2_{\rm min}$/dof is of order 1 for 2P models (except the RL model), for the 3P models and the 4P model $\chi^2_{\rm min}$/dof ~ 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. In order to keep the couplings in the perturbative regime, we took the mass of the W' boson as

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[4] We thank Saeed Kamali for useful conversations.

		pull$_i$								best-fit point			
	parameters on	$R(D)$	$R(D^*)$	$R(J/\psi)$	$P_\tau(D^*)$	$F_L(D^*)$	$R(X_c)$	BR$(B_c \to \tau\bar{\nu})$	$\chi^2_{\rm min}$	ϵ^L_{cb}	ϵ^R_{cb}	$\epsilon^L_{\tau\nu}$	$\epsilon^R_{\tau\nu}$
2P	$(\epsilon^L_{cb},\, \epsilon^L_{\tau\nu})$	-0.047	0.028	1.53	0.21	1.46	-0.93	-0.27	5.49	-0.340	—	-0.280	—
	$(\epsilon^L_{cb},\, \epsilon^R_{\tau\nu})$	-0.050	0.023	1.53	-0.013	1.46	-0.94	-0.27	5.44	0.544	—	—	0.963
	$(\epsilon^R_{cb},\, \epsilon^L_{\tau\nu})$	2.38	0.81	1.58	0.17	1.61	-0.059	-0.26	11.48	—	-0.252	0.289	—
	$(\epsilon^R_{cb},\, \epsilon^R_{\tau\nu})$	-0.050	0.023	1.53	-0.013	1.46	-0.94	-0.27	5.44	—	0.544	—	0.963
3P	$(\epsilon^L_{cb},\, \epsilon^R_{cb},\, \epsilon^L_{\tau\nu})$	0.27	-0.15	1.52	0.22	1.41	-0.91	-0.27	5.35	0.272	-0.044	0.326	—
	$(\epsilon^R_{cb},\, \epsilon^L_{\tau\nu},\, \epsilon^R_{\tau\nu})$	0.27	-0.15	1.52	0.011	1.41	-0.91	-0.27	5.31	—	0.498	-0.031	1.014
	$(\epsilon^L_{cb},\, \epsilon^L_{\tau\nu},\, \epsilon^R_{\tau\nu})$	-0.050	0.023	1.53	-7.4×10^{-7}	1.46	-0.94	-0.27	5.44	0.558	—	0.010	0.911
4P	$(\epsilon^L_{cb},\, \epsilon^R_{cb},\, \epsilon^L_{\tau\nu},\, \epsilon^R_{\tau\nu})$	0.27	-0.15	1.52	-4.1×10^{-6}	1.41	-0.91	-0.27	5.31	1.120	-0.098	0.007	-0.428

TABLE II. By turning on the parameters of the second column (keeping the remaining parameters of the 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 the rows 7-9 as 3P models. In the last row, it is shown the model with all the parameters turned on. The pulls for each observable are shown in columns 3-8, the minimum value for the χ^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 $\chi^2_{\rm min}/{\rm dof} \sim 1.36$ 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 $\chi^2_{\rm min}$ stays nearly at the same value.

$M_{W'} = 1$ 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.

As the next step in our analysis, we will explore into a more detailed way the four 2P models LL, LR, RL, and RR, which according to our χ^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 the $b \to c\tau\bar{\nu}_\tau$ observables, we determine the regions in the parameter space favored by the experimental data.

A. LL scenarios ($C^V_{LL} \neq 0$)

Within this scenario, we consider a W' boson that only couples to LH quark and LH leptons currents inducing the semi-tauonic operator $(\bar{c}\gamma_\mu P_L b)(\bar{\tau}\gamma^\mu P_L \nu_\tau)$, i.e., $C^V_{LL} \neq 0$. In Figs. 2(a) and 2(b), we show the 95% confidence level (CL) allowed parameter space in the $(\epsilon^L_{cb}, \epsilon^L_{\tau\nu_\tau})$ 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, 30], 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 the $b \to c\tau\bar{\nu}_\tau$ observables, namely $R(D^{(*)})$, $R(J/\psi)$, $F_L(D^*)$, $P_\tau(D^*)$ (see Table I), and considering the upper limit ${\rm BR}(B_c^- \to \tau^-\bar{\nu}_\tau) < 10\%$. It is observed that the allowed region for $R(D^{(*)})$ is significantly reduced to two symmetrical regions when all the $b \to c\tau\bar{\nu}_\tau$ observables are considered. This is mainly due 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. [35]. It is remarkable that the $R(D^{(*)})$ HFLAV-2019 averages allow the solution $(\epsilon^L_{\tau\nu_\tau}, \epsilon^L_{cb}) = (0,0)$; 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 [94, 103–105]:

- In Ref. [104], Abdullah, Calle, Dutta, Floréz, and Restrepo (referred by us as ACDFR model) considered a simplified W' model which preferentially couples to the bottom and charm quarks and τ leptons, through the NP couplings g'_q and g'_ℓ, 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 fb^{-1}. This model is represented in Figs. 2(a) and 2(b) by the black star. 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 is still allowed by HFLAV-2019.

- In Ref. [105], Greljo, Martin, and Ruiz (referred by us as GMR analysis) performed a study between the connection of NP scenarios addressing the $R(D^{(*)})$ anomalies and the mono-tau signature at the LHC, $pp \to \tau_h X$ + MET. By using the current ATLAS [126] and CMS [127] data they constrained different scenarios,

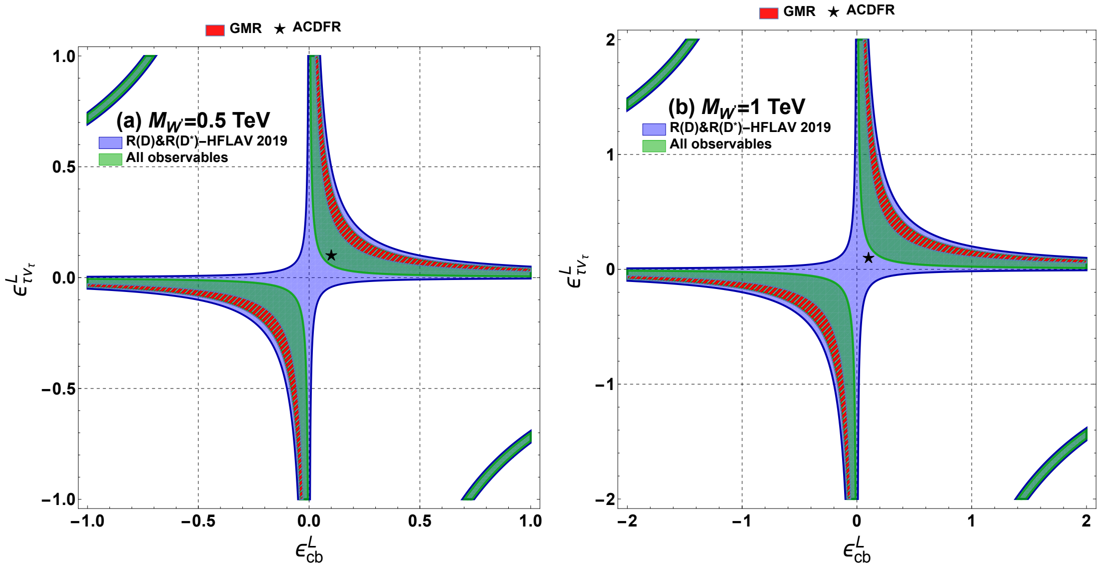

FIG. 2. The 95% CL allowed parameter space in the $(\epsilon^L_{cb}, \epsilon^L_{\tau\nu_\tau})$ plane for (a) $M_{W'} = 0.5$ TeV and (b) $M_{W'} = 1$ TeV. The purple region is obtained by considering only $R(D^{(*)})$ from HFLAV-2019 average, while the green one is obtained by taking into account all the $b \to c\tau\bar{\nu}_\tau$ observables. The black star and red hatched region represent the ACDFR model [104] and GMR analysis [105], respectively. See text for details.

particularly, regarding a W' boson scenario, they found that [105]

$$\epsilon^L_{cb}\epsilon^L_{\tau\nu_\tau} = (0.14 \pm 0.03)\left(\frac{M_{W'}}{\text{TeV}}\right)^2, \tag{19}$$

for W' masses in the range $[0.5, 3.5]$ TeV, which is in agreement with the value $\epsilon^L_{cb}\epsilon^L_{\tau\nu_\tau} = 0.107\ (M_{W'}/\text{TeV})^2$ obtained in [47]. 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 $b \to c\tau\bar{\nu}_\tau$ observables of our analysis are consistent and overlapped with this region.

- In Refs. [94, 103] the authors introduced a color-neutral $SU(2)_L$ triplet of massive vector bosons that couple predominantly to third generation fermions (both quarks g_q and g_ℓ leptons), with an underlying dynamics generated by an approximated $U(2)_q \times U(2)_\ell$ flavor symmetry; however, to the light of the new experimental measurements this model is disfavored, unless a fine-tuning of the couplings were carried out.

B. RR scenarios ($C^V_{RR} \neq 0$)

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 [62, 106–113]. We plot in Figs. 3(a) and 3(b) the 95% CL allowed parameter space in the $(\epsilon^R_{cb}, \epsilon^R_{\tau\nu_\tau})$ plane for masses $M_{W'} = 1$ TeV and 1.2 TeV, respectively. The purple and green regions are obtained by taking into account only $R(D)$ and $R(D^*)$ from HFLAV-2019 averages [16] and all the $b \to c\tau\bar{\nu}_\tau$ observables, respectively. It is found that the allowed region for $R(D^{(*)})$ is significantly reduced to four-fold symmetrical regions when all the $b \to c\tau\bar{\nu}_\tau$ observables are considered. As in the LL scenarios previously discussed, this is mainly due to the effect of the polarization $F_L(D^*)$. To further discussion, we consider some benchmark models:

- The authors of Refs. [108, 109] 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' the corresponding new gauge couplings. After the spontaneous symmetry breaking $SU(2)_V \times U(1)' \to U(1)_Y$, new heavy vector bosons are generated. In addition, the SM fermions content is accompanied with new heavy vector-like 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 [108, 109] are very similar, for simplicity, we will consider the analysis of Ref. [109] for

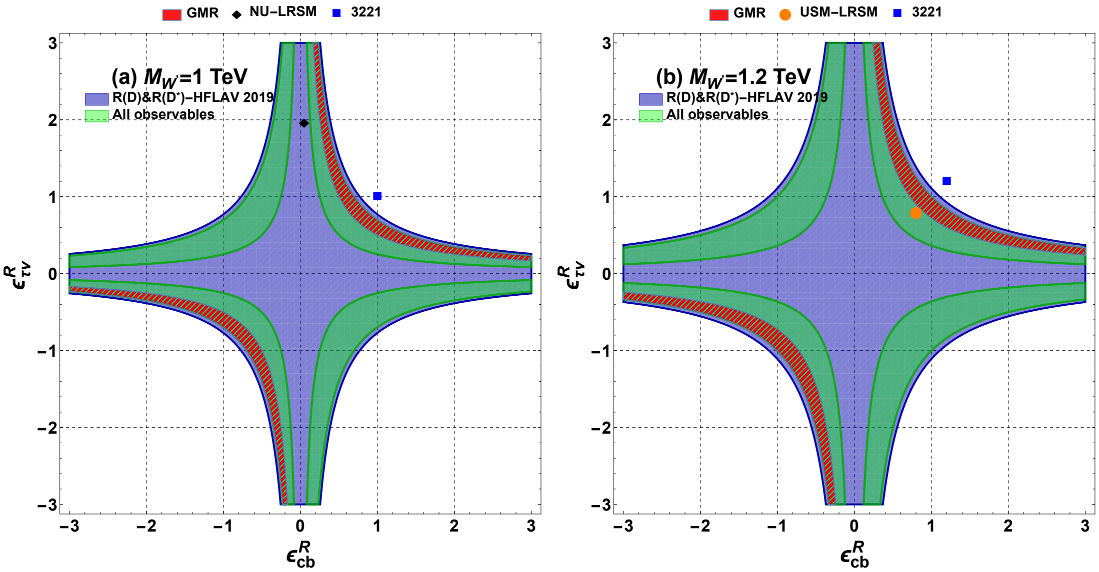

FIG. 3. The 95% CL allowed parameter space in the $(\epsilon^R_{cb}, \epsilon^R_{\tau\nu_\tau})$ plane for (a) $M_{W'} = 1$ TeV and (b) $M_{W'} = 1.2$ TeV. The purple region is obtained by considering only $R(D^{(*)})$ from HFLAV-2019 averages, while the green one is obtained by taking into account all the $b \to c\tau\bar{\nu}_\tau$ observables. The black diamond, blue squared, red hatched region, and orange circle represent the NU-LRSM model [99, 100], 3321 gauge model [108, 109], GMR analysis [105], and USM-LRSM [107], respectively. See text for details.

comparison (referred to as 3221 gauge model). Translating the notation in [109] into ours, we have $\epsilon^R_{cb} = g_V c_q^{23}$ and $\epsilon^R_{\tau\nu_\tau} = g_V c_N^3$, with c_q^{23}, c_N^3 coefficients that encode the flavor dependence. Given that $M_{W'} = g_V v_V/2$ [109], a viable 1σ 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 [109]. 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) for $M_{W'} = 1$ TeV 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 [110], 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 $c_q^{23} \neq c_N^3$ that the ones assumed in [109].

- In the GMR analysis [105] previously discussed, the authors also found that for RH W' models the solution is

$$\epsilon^R_{cb}\epsilon^R_{\tau\nu_\tau} = (0.6 \pm 0.1)\left(\frac{M_{W'}}{\text{TeV}}\right)^2, \tag{20}$$

  that is represented by the red hatched region in Figs. 3(a) and 3(b), which is consistent with the value $\epsilon^R_{cb}\epsilon^R_{\tau\nu_\tau} = 0.55\ (M_{W'}/\text{TeV})^2$ obtained in [47]. Again, the allowed parameter region by $R(D^{(*)})$ HFLAV 2019 and all $b \to c\tau\bar{\nu}_\tau$ observables of our analysis are consistent and overlapped with this region.

- In Refs. [99, 100] the anomalies have been addressed within the framework of the non-universal left-right symmetric model (NU-LRSM) with enhanced couplings to the third generation. In terms of our notation, we have that in the NU-LRSM the effective couplings are $\epsilon^R_{cb} = g_R|V_{Rcb}|$ and $\epsilon^R_{\tau\nu_\tau} = g_R|V^\ell_{R3\tau}|$, with g_R the RH gauge coupling, V_{Rcb} and $V^\ell_{R3\tau}$ the RH quark and lepton mixing element, respectively. It is assumed that taking $M_{W'} \simeq 1$ TeV, $g_R \simeq 1$, $|V^\ell_{R3\tau}| \simeq 1$, $|V_{Rcb}| \simeq |V_{cb}|$ [99, 100], as shown by the black diamond in Fig. 3(a), the model accommodated 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.

- A class of LRSM (parity symmetric and asymmetric) that implemented vector-like fermions to generate quark and lepton masses via a universal seesaw mechanism (USM) have been studied in Ref. [107] 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 the VEV of the neutral member of the doublet χ_R (for details, see Ref. [107]); and the effective couplings are simply $\epsilon^R_{cb} = g_R/\sqrt{2}$ and $\epsilon^R_{\tau\nu_\tau} = g_R/\sqrt{2}$. Taking the lower mass limit $M_{W_R} \simeq 1.2$ TeV (obtained

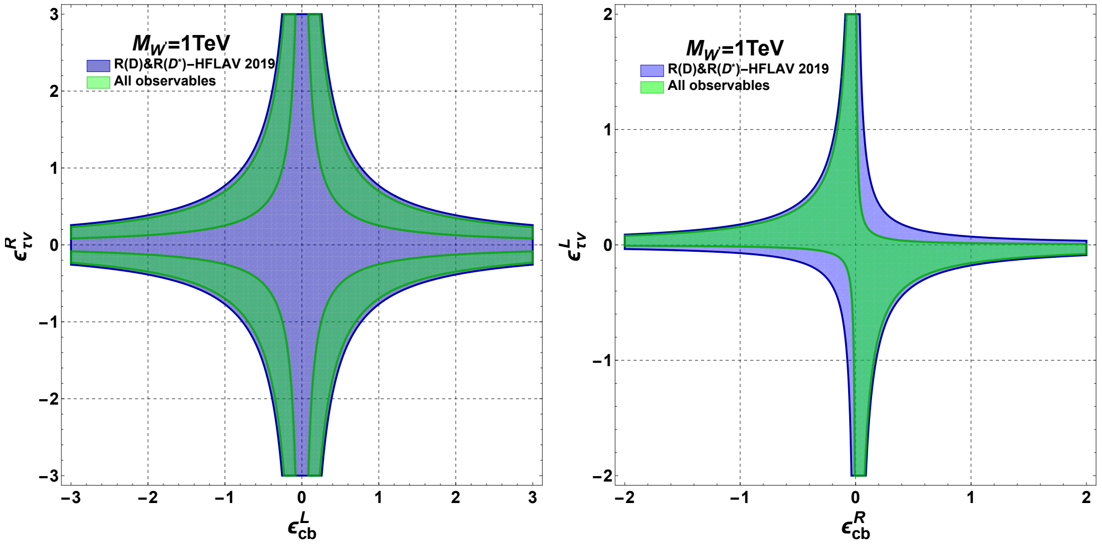

FIG. 4. The 95% CL allowed parameter space in the $(\epsilon^L_{cb}, \epsilon^R_{\tau\nu_\tau})$ and $(\epsilon^R_{cb}, \epsilon^L_{\tau\nu_\tau})$ planes for a mass value of $M_{W'} = 1$ TeV.

for the parity asymmetric case [107]), the USM-LRSM is represented by the orange circle in Fig. 3(b). This set up is allowed both by $R(D^{(*)})$ and all $b \to c\tau\bar{\nu}_\tau$ observables.

C. RL and LR scenarios ($C^V_{RL} \neq 0$ and $C^V_{LR} \neq 0$)

Finally, we consider a class of scenarios where the quark and lepton currents with different quirality projection couple to the W' boson, i.e., semi-tauonic operators of the type $(\bar{c}\gamma_\mu P_R b)(\bar{\tau}\gamma^\mu P_L \nu_\tau)$ and $(\bar{c}\gamma_\mu P_L b)(\bar{\tau}\gamma^\mu P_R \nu_\tau)$ that implies $C^V_{RL} \neq 0$ and $C^V_{LR} \neq 0$, respectively. For a representative mass value of $M_{W'} = 1$ TeV, we display in Fig. 4 the 95% CL allowed parameter space for the couplings in the LR [left] and RL [right] scenarios. The case of $M_{W'} \geq 1$ TeV requires higher effective couplings values. For the LR case, it can be inferred that the allowed region for $R(D^{(*)})$ is reduced to four-fold symmetrical regions when all the $b \to c\tau\bar{\nu}_\tau$ observables are considered. While for the RL case, the permitted region is barely reduced when all observables are taken into account. In both scenarios 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 the authors of Ref. [128] have explored the possibility of how the measurement of CP-violating observables in $\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu$ can be used to differentiate the NP scenarios. Particularly, they found that the only way to generate sizeable CP-violating effects is with a LH and RH W' bosons (with sizeable mixing) that contribute to $b \to c\ell\bar{\nu}_\ell$ [128].

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 $b \to c\tau\bar{\nu}_\tau$ within a general W' boson scenario. In order to provide a robust analysis, we considered in addition the available experimental information on all the charged transition $b \to c\tau\bar{\nu}_\tau$ observables, namely the ratios $R(J/\psi)$, $R(X_c)$, polarizations $P_\tau(D^*), F_L(D^*)$, as well as the upper limit $\text{BR}(B_c^- \to \tau^-\bar{\nu}_\tau) < 10\%$. We have carried out a model-independent study based on the most general effective Lagrangian given in terms of the flavor-dependent couplings $\epsilon^{L,R}_{cb}$ and $\epsilon^{L,R}_{\tau\nu_\tau}$ of the currents $\bar{c}\gamma_\mu P_{L,R} b$ and $\bar{\tau}\gamma^\mu P_{L,R}\nu_\tau$, that yields to a tree-level effective contribution generated by a general W' boson. With the above mentioned observables, we performed a χ^2 analysis by considering the cases of two, three and four nonzero $\epsilon^{L,R}_{cb}$ and $\epsilon^{L,R}_{\tau\nu_\tau}$ couplings (with different chiral charges), referred to as 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 the possible combinations of 2P models (LL, RR, LR, and RL scenarios) and taken into account two different dataset: $R(D^{(*)})$ only and all $b \to c\tau\bar{\nu}_\tau$ observables; we determined the regions in the parameter space favored by these observables for different values of the W' boson mass preferred by the literature. For the LL

and RR scenarios, we obtained that part of the allowed parametric space is consistent with the mono-tau signature $pp \to \tau_h X + \text{MET}$ at the LHC. In order to improve the discussion, we have included into 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 to $\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu$, as discussed in [128].

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