

Lepton universality violation and right-handed currents in $b \rightarrow c\tau\nu$ Xiao-Gang He^{a,b,c,*}, German Valencia^{d,*}^a Department of Physics, National Taiwan University, Taipei 10617, Taiwan^b Physics Division, National Center for Theoretical Sciences, Hsinchu 30013, Taiwan^c Tsung-Dao Lee Institute, and School of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai 200240, China^d School of Physics and Astronomy, Monash University, Melbourne VIC-3800, Australia

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ABSTRACT

We consider the recent LHCb result for $B_c \rightarrow J/\psi\tau\nu$ in conjunction with the existing anomalies in $R(D)$ and $R(D^*)$ within the framework of a right-handed current with enhanced couplings to the third generation. The model predicts a linear relation between the observables and their SM values in terms of two combinations of parameters. The strong constraints from $b \rightarrow s\gamma$ on $W - W'$ mixing effectively remove one of the combinations of parameters resulting in an approximate proportionality between all three observables and their SM values. To accommodate the current averages for $R(D)$ and $R(D^*)$, the W' mass should be near 1 TeV, and possibly accessible to direct searches at the LHC. In this scenario we find that $R(J/\psi)$ is enhanced by about 20% with respect to its SM value and about 1.5σ below the central value of the LHCb measurement. The predicted $d\Gamma/dq^2$ distribution for $B \rightarrow D(D^*)\tau\nu$ is in agreement with the measurement and the model satisfies the constraint from the B_c lifetime.

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1. Introduction

A series of measurements of semileptonic $b \rightarrow c\tau\nu$ modes have shown hints of deviations from the standard model (SM) for several years. The mode $B \rightarrow D\tau\nu$ has been measured by both BaBar [1,2] and Belle [3]; and the mode $B \rightarrow D^*\tau\nu$ has been measured by BaBar [1,2], Belle [3–5] and LHCb [6,7]. The average of these measurements performed by the HFLAV [8] collaboration is

$$\begin{aligned} R(D) &= \frac{B(\bar{B} \rightarrow D\tau^-\bar{\nu}_\tau)}{B(\bar{B} \rightarrow D\ell^-\bar{\nu}_\ell)} = 0.407 \pm 0.039 \pm 0.024 \\ R(D^*) &= \frac{B(\bar{B} \rightarrow D^*\tau^-\bar{\nu}_\tau)}{B(\bar{B} \rightarrow D^*\ell^-\bar{\nu}_\ell)} = 0.304 \pm 0.013 \pm 0.007. \end{aligned} \quad (1)$$

The current SM predictions for these quantities are from the lattice for $R(D)$ [9,10] and from models for $R(D^*)$ [11] and are given by

$$\begin{aligned} R(D) &= 0.299 \pm 0.011 \\ R(D^*) &= 0.252 \pm 0.003. \end{aligned} \quad (2)$$

Very recently, the corresponding measurement for the mode $B_c^+ \rightarrow J/\psi\tau^+\nu_\tau$ has been reported by LHCb [12]

$$R(J/\psi) = \frac{B(B_c^+ \rightarrow J/\psi\tau^+\nu_\tau)}{B(B_c^+ \rightarrow J/\psi\mu^+\nu_\mu)} = 0.71 \pm 0.17 \pm 0.18. \quad (3)$$

Different models for the form factors produce a SM result in the range 0.25 to 0.28 [13–16] which is about 2σ lower. For definiteness, we will use as SM value the most recent result [17]

$$R(J/\psi) = 0.283 \pm 0.048. \quad (4)$$

Not surprisingly, these anomalies have generated a large number of possible new physics explanations including additional Higgs doublets, gauge bosons and leptoquarks [18–47].

In Ref. [26] we have studied $R(D)$ and $R(D^*)$ in the context of a right-handed W' with enhanced couplings to the third generation [48,49]. Here, we revisit this possibility motivated by the new measurement of $R(J/\psi)$, and to address additional constraints from the $d\Gamma/dq^2$ distributions [34] and the B_c^\pm lifetime [50].

2. Charged current interactions

The gauge group of our model is $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$, but the three generations of fermions are chosen to transform differently to achieve non-universality. In the weak interaction basis, the first two generations of quarks $Q_L^{1,2}, U_R^{1,2}, D_R^{1,2}$

* Corresponding authors.

E-mail addresses: hexg@phys.ntu.edu.tw (X.-G. He), german.valencia@monash.edu (G. Valencia).

transform as $(3, 2, 1)(1/3)$, $(3, 1, 1)(4/3)$ and $(3, 1, 1)(-2/3)$, and the leptons $L_L^{1,2}$, $E_R^{1,2}$ transform as $(1, 2, 1)(-1)$ and $(1, 1, 1)(-2)$. The third generation, on the other hand, has transformation properties under the gauge group given by $Q_L^3(3, 2, 1)(1/3)$, $Q_R^3(3, 1, 2)(1/3)$, $L_L^3(1, 2, 1)(-1)$ and $L_R^3(1, 1, 2)(-1)$. In this way $SU(2)_R$ acts only on the third generation and singles it out providing the source of lepton universality violation to explain the anomalies mentioned above. The model is detailed in Refs. [48,49], but here we provide its salient ingredients.

To separate the symmetry breaking scales of $SU(2)_L$ and $SU(2)_R$, we introduce the two Higgs multiplets $H_L(1, 2, 1)(-1)$ and $H_R(1, 1, 2)(-1)$ with respective vevs v_L and v_R . An additional bi-doublet $\phi(1, 2, 2)(0)$ scalar with vevs $v_{1,2}$ is needed to provide mass to the fermions. Since both v_1 and v_2 are required to be non-zero for fermion mass generation, the W_L and W_R gauge bosons of $S(2)_L$ and $SU(2)_R$ will mix with each other. In terms of the mass eigenstates W and W' , the mixing can be parametrized as

$$\begin{aligned} W_L &= \cos \xi_W W - \sin \xi_W W', \\ W_R &= \sin \xi_W W + \cos \xi_W W'. \end{aligned} \quad (5)$$

In the mass eigenstate basis the quark-gauge-boson interactions are given by,

$$\begin{aligned} \mathcal{L}_W &= -\frac{g_L}{\sqrt{2}} \bar{U}_L \gamma^\mu V_{KM} D_L (\cos \xi_W W_\mu^+ - \sin \xi_W W_\mu'^+) \\ &\quad - \frac{g_R}{\sqrt{2}} \bar{U}_R \gamma^\mu V_R D_R (\sin \xi_W W_\mu^+ + \cos \xi_W W_\mu'^+) + \text{h. c.}, \end{aligned} \quad (6)$$

where $U = (u, c, t)$, $D = (d, s, b)$, V_{KM} is the Kobayashi-Maskawa mixing matrix and $V_R \equiv (V_{Rij}) = (V_{Rti}^* V_{Rbj}^d)$ with $V_{Rij}^{u,d}$ the unitary matrices which rotate the right handed quarks u_{Ri} and d_{Ri} from the weak eigenstate basis to the mass eigenstate basis.

The model has a different neutrino spectrum than the SM: three left-handed neutrinos ν_{Li} and one right-handed neutrino ν_{R3} . Additional scalars $\Delta_L(1, 3, 1)(2)$ and $\Delta_R(1, 1, 3)(2)$ with vevs $v_{\Delta}^{L,R}$ are needed to generate neutrino masses. In order for the possibly enhanced $SU(2)_R$ interaction with the third generation to explain the B decay anomalies, we need the right-handed neutrino to be light, which requires $v_{\Delta}^{L,R}$ to be small. In this model, the neutrinos will receive Majorana masses from the vevs of $\Delta_{L,R}$ and Dirac masses from ϕ . The mass eigenstates $(\nu_L^m, (\nu_{R3}^m)^c)$ are related by a unitary transformation to the weak eigenstates as

$$\begin{pmatrix} \nu_L \\ \nu_{R3}^c \end{pmatrix} = \begin{pmatrix} U_L & U_{RL} \\ U_{LR} & U_R \end{pmatrix} \begin{pmatrix} \nu_L^m \\ (\nu_{R3}^m)^c \end{pmatrix}. \quad (7)$$

In our model $U_L = (U_{Lij})$, $U_{RL} = (U_{RLi3})$ and $U_{LR} = (U_{LR3i})$ and $U_R = (U_{R33})$ are 3×3 , 3×1 , 1×3 and 1×1 matrices, respectively.

Writing the rotation of charged lepton weak eigenstates $\ell_{L,R}$ into mass eigenstates $\ell_{L,R}^m$ as $\ell_{L,R} = V_{L,R}^\ell \ell_{L,R}^m$, the lepton interaction with W and W' becomes

$$\begin{aligned} \mathcal{L}_W &= -\frac{g_L}{\sqrt{2}} (\bar{\nu}_L \gamma^\mu U^{\ell\dagger} \ell_L + \bar{\nu}_{R3}^c \gamma^\mu U_{RLj3}^{\ell*} \ell_{Lj}) (\cos \xi_W W_\mu^+ \\ &\quad - \sin \xi_W W_\mu'^+) - \frac{g_R}{\sqrt{2}} (\bar{\nu}_{Lj}^c \gamma^\mu U_{LRij}^\ell \ell_{Rj} + \bar{\nu}_{R3} \gamma^\mu U_{R3j}^\ell \ell_{Rj}) \\ &\quad \times (\sin \xi_W W_\mu^+ + \cos \xi_W W_\mu'^+) + \text{h. c.}, \end{aligned} \quad (8)$$

where

$$\begin{aligned} U^{\ell\dagger} &= U_L^\dagger V_L^\ell, \quad U_{RLj3}^{\ell*} = (U_{RLi3}^* V_{Lij}^\ell), \\ U_{LRij}^\ell &= U_{LR3i} V_{R3j}^\ell, \quad U_{R3j}^\ell = U_{R33} V_{R3j}^\ell. \end{aligned} \quad (9)$$

U^ℓ is approximately the PMNS matrix. From Eqs. (6) and (8) we see that a large g_R/g_L will enhance the third generation interactions with W' .

The final neutrino flavor is not identified in B meson decays so it must be summed. For the processes involving left- and right-handed charged leptons, neglecting neutrino masses compared with the charged lepton masses, the final decay rates into a charged lepton ℓ_j , when summed over the different neutrino final states, are proportional to

$$\begin{aligned} \text{For } \ell_{Lj}: \quad & \sum_i |U_{ij}^\ell|^2 + |U_{RLj3}^\ell|^2 = \sum_i |U_{Li}^* V_{Lij}^\ell|^2 + |U_{RLi3}^* V_{Lij}^\ell|^2 \\ &= \left(\sum_i |U_{Li}^*|^2 + |U_{RLi3}^*|^2 \right) |V_{Lij}^\ell|^2 = \sum_i |V_{Lij}^\ell|^2 = 1, \\ \text{For } \ell_{Rj}: \quad & \sum_i |U_{LRij}^\ell|^2 + |U_{R3j}^\ell|^2 \\ &= \sum_i |U_{LR3i} V_{R3j}^\ell|^2 + |U_{R33} V_{R3j}^\ell|^2 \\ &= \left(\sum_i |U_{LR3i}|^2 + |U_{R33}|^2 \right) |V_{R3j}^\ell|^2 = |V_{R3j}^\ell|^2. \end{aligned} \quad (10)$$

To obtain these results we used the unitarity of U : $\sum_i |U_{Li}^*|^2 + |U_{RLi3}^*|^2 = 1$, $\sum_i |U_{LR3i}|^2 + |U_{R33}|^2 = 1$ and the unitarity of $V_{L,R}^\ell$.

3. Γ and $d\Gamma/dq^2$ predictions

The starting point for our calculations is the differential decay rate $d\Gamma/dq^2$ with $q^2 = (p_B - p_{D^{(*)}})^2$ for the SM. We use the notation, parameterization and values of Ref. [2] for all the relevant form factors. This will be sufficient for a comparison to the experimentally determined shape of this distribution as well as the total decay rate. Of course, $d\Gamma/dq^2$ is obtained after integrating over angles and summing over polarizations. Other observables, such as angular correlations, can also be used to discriminate between the SM and new physics scenarios as well, but we will not consider that possibility in this paper as they have not been measured yet.

In the type of model we consider, in addition to the SM diagram, there is a W' mediated diagram as well as interference between these two. When all the neutrino masses can be neglected, there is no interference between the left and right-handed lepton currents and this allows us to write simple formulas for both $d\Gamma/dq^2$ and the decay rate Γ in terms of the corresponding SM results and the following two combinations of constants:

$$\begin{aligned} F_{\text{dir}}^{bc} &= \left(1 + \left(\frac{g_R M_W}{g_L M_{W'}} \right)^4 \frac{|V_{R3\ell}^\ell|^2 |V_{Rcb}|^2}{|V_{cb}|^2} \right) \\ F_{\text{mix}}^{bc} &= \xi_W \frac{g_R \text{Re}(V_{cb}^* V_{Rcb})}{g_L |V_{cb}|^2} \left(1 - \left(\frac{M_W}{M_{W'}} \right)^2 \right) \\ &\quad \times \left(1 + \left(\frac{g_R M_W}{g_L M_{W'}} \right)^2 |V_{R3\ell}^\ell|^2 \right). \end{aligned} \quad (11)$$

The first term arises from the separate W and W' contributions, whereas the second term is induced by $W - W'$ mixing. The superscript bc is used to denote the $b \rightarrow c$ quark transition and is useful in order to generalize the notation to other cases. Our results for the different modes are then:

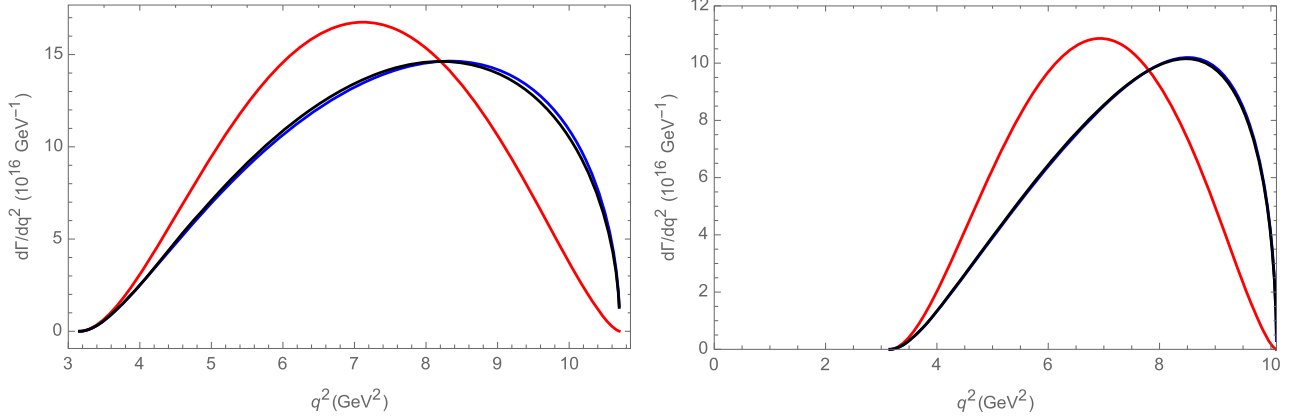


Fig. 1. Differential decay distribution $d\Gamma/dq^2$ for the SM, black curve; for a pure vector (axial-vector) hadronic form-factor, red (blue) curve normalized to the same total decay rate. Left panel for $B \rightarrow D^* \tau \nu$ and right panel for $B_c \rightarrow J/\psi \tau \nu$. (The red curves are those that peak at lower q^2 , the blue and black curves are almost indistinguishable.)

- Leptonic decay $B_c^\pm \rightarrow \ell^\pm \nu_\ell$. The hadronic transition in this case proceeds only through the axial vector form factor thus yielding

$$\frac{\Gamma(B_c^- \rightarrow \tau^- \nu)}{\Gamma(B_c^- \rightarrow \tau^- \nu_\tau)_{SM}} = F_{\text{dir}}^{bc} - 2 F_{\text{mix}}^{bc}. \quad (12)$$

- Semileptonic decay $B \rightarrow D \tau \nu$. In this case only the vector form factor contributes to the hadronic transition resulting in

$$\frac{d\Gamma(B \rightarrow D \tau \nu)}{dq^2} = \frac{d\Gamma(B \rightarrow D \tau \nu)}{dq^2} \Big|_{SM} \left(F_{\text{dir}}^{bc} + 2 F_{\text{mix}}^{bc} \right). \quad (13)$$

This implies that the normalized distribution $1/\Gamma d\Gamma/dq^2$ for this mode is identical to the SM. Upon integration,

$$R(D) = R(D)_{SM} \left(F_{\text{dir}}^{bc} + 2 F_{\text{mix}}^{bc} \right). \quad (14)$$

- Semileptonic decay $B \rightarrow D^* \tau \nu$. This mode is more complicated in that both the vector and axial vector form factors contribute and they behave differently. Defining

$$V = \langle D^* | \bar{c} \gamma_\mu b | B \rangle, \quad A = \langle D^* | \bar{c} \gamma_\mu \gamma_5 b | B \rangle \quad (15)$$

we can write the differential decay rate as

$$\begin{aligned} & \frac{d\Gamma(B \rightarrow D^* \tau \nu)}{dq^2} \\ &= \frac{d\Gamma(B \rightarrow D^* \tau \nu)}{dq^2} \Big|_{SM} \left(F_{\text{dir}}^{bc} + 2 F_{\text{mix}}^{bc} \frac{|V|^2 - |A|^2}{|V|^2 + |A|^2} \right). \end{aligned} \quad (16)$$

Using the values of the form factors given in Ref. [2], the SM is dominated by the axial-vector hadronic form factor as can be seen from Fig. 1. A transition through a purely axial-vector form factor (blue curve) has a spectrum shape almost indistinguishable from the SM case (black curve). On the other hand, a transition through a purely vector hadronic form factor produces a spectrum shifted towards lower q^2 , as shown by the red curve in the same figure. The vector and axial-vector form factors do not interfere in this distribution, and their respective contributions to the total decay rate in the SM are

$$\begin{aligned} \Gamma(B \rightarrow D^* \tau \nu) &= (0.41 + 6.92) \times 10^{-15} \text{ GeV}^{-1} \\ &= 7.33 \times 10^{-15} \text{ GeV}^{-1}. \end{aligned} \quad (17)$$

This implies that the vector form factor contributes only 5.6% of the SM rate. Integrating Eq. (16) we find

$$R(D^*) \approx R(D^*)_{SM} \left(F_{\text{dir}}^{bc} - 1.77 F_{\text{mix}}^{bc} \right), \quad (18)$$

very close to the result one would obtain from a pure axial-vector transition.

- Semileptonic decay $B_c \rightarrow J/\psi \tau \nu$. This is also a pseudoscalar to vector transition so it has the same behaviour as the previous mode.

$$\begin{aligned} & \frac{d\Gamma(B_c \rightarrow J/\psi \tau \nu)}{dq^2} \\ &= \frac{d\Gamma(B_c \rightarrow J/\psi \tau \nu)}{dq^2} \Big|_{SM} \left(F_{\text{dir}}^{bc} + 2 F_{\text{mix}}^{bc} \frac{|V'|^2 - |A'|^2}{|V'|^2 + |A'|^2} \right) \end{aligned} \quad (19)$$

where now

$$V' = \langle J/\psi | \bar{c} \gamma_\mu b | B_c \rangle, \quad A' = \langle J/\psi | \bar{c} \gamma_\mu \gamma_5 b | B_c \rangle. \quad (20)$$

In this case we use the values for the form factors as given in Ref. [17] to display the SM differential distribution on the right panel of Fig. 1 as the black curve. Once again the blue (almost indistinguishable from the black one) and red curves illustrate transitions mediated by a purely axial-vector or vector form factors respectively, normalized to the total decay rate. We see that in this case the axial-vector hadronic form factor is even more dominant than in $B \rightarrow D^* \tau \nu$. Their respective contributions to the total decay rate in the SM in this mode are

$$\begin{aligned} \Gamma(B_c \rightarrow J/\psi \tau \nu) &= (0.067 + 4.27) \times 10^{-15} \text{ GeV}^{-1} \\ &= 4.337 \times 10^{-15} \text{ GeV}^{-1}, \end{aligned} \quad (21)$$

the vector form factor barely contributes 1.5% of the SM rate. It follows that for our model,

$$R(J/\psi) \approx R(J/\psi)_{SM} \left(F_{\text{dir}}^{bc} - 1.94 F_{\text{mix}}^{bc} \right). \quad (22)$$

The two experimental results for $R(D)$ and $R(D^*)$ can be fit by the model choosing the parameters

$$F_{\text{dir}}^{bc} = 1.28, \quad F_{\text{mix}}^{bc} = 0.04. \quad (23)$$

These parameters result in a differential distribution $d\Gamma/dq^2$ for $B \rightarrow D^* \tau \nu$ that is dominated by the axial-form factor and is thus very similar to the SM one as shown in Fig. 2. It should be clear from this result, in conjunction with the BaBar comparison of the SM vs observed distribution [2], that $d\Gamma/dq^2$ is in agreement with the results of our model. This is shown in the right panel of Fig. 2

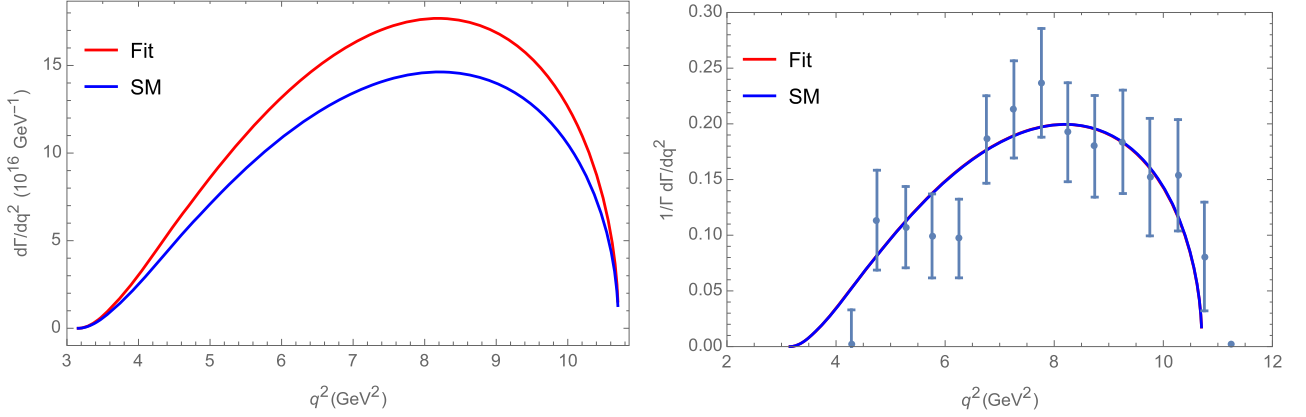


Fig. 2. Differential decay distribution $d\Gamma/dq^2$ in the SM and the fit with the NP contributions as in Eq. (23) for $B \rightarrow D^* \tau \nu$ (left panel). Normalized distributions compared to the BaBar data [2] (right panel). Note how the model prediction for the shape of the distribution (red) is indistinguishable from the SM (blue) in the right panel because the mixing contribution is very small. (The red curve on the left panel is above the blue curve. In the right panel the red and blues curves are almost indistinguishable.)

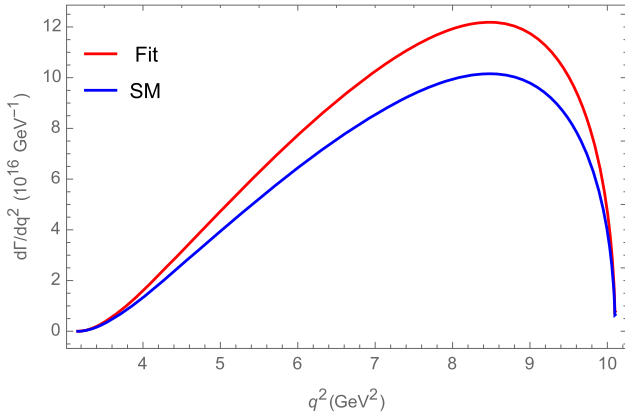


Fig. 3. Differential decay distribution $d\Gamma/dq^2$ in the SM and the best fit with the NP contributions as in Eq. (23) for $B_c \rightarrow J/\psi \tau \nu$. (The curve for the fit is above the curve for the SM.)

where the normalized distributions are compared with the BaBar data. The SM and our model are a good fit to the data and they are almost indistinguishable. This is due to the dominance of the F_{dir}^{bc} term over the mixing contribution.

Including the latest result, $R(J/\psi)$, does not change the fit significantly due to its large uncertainty. The prediction for this quantity, $R(J/\psi) = 0.34$, is thus on the low side of the central value by about 1.5 standard deviations. The differential distribution $d\Gamma/dq^2$ in this case is also very similar to the SM one, as seen in Fig. 3, and would not serve to distinguish this model.

The rate $\Gamma(B_c^- \rightarrow \tau^- \nu)$ is predicted from Eq. (12) to be about 20% larger than its SM value, which is well within the bound from the B_c lifetime discussed in Ref. [50].

4. Discussion

We now examine the parameter values of Eq. (23) in the context of the model with RH currents as shown in Eq. (11). The anomalies suggest that only the τ lepton is affected as the experiment sees no difference between muons and electrons. The model must then single out only the third family for enhancement with $|V_{R3\tau}^\ell| \sim 1$. Now $V_{Rcb} \equiv V_{Rtc}^{u*} V_{Rbb}^d$ and $V_{Rbb}^d \sim 1$ and V_{Rtc}^{u*} is of the same order as V_{cb} , as discussed in our global analysis of the model in Ref. [51]. This requires $g_R/g_L M_W/M_{W'} \sim 0.7$ to reproduce the first result of Eq. (11). Requiring the model to be perturbative implies that $g_R/g_L \lesssim 10$. If we take this ratio to be in the range

(5–10) we find in turn that $M_{W'}$ is in the range 574–1150 GeV, well within the direct reach of LHC.

The second combination of parameters, F_{mix}^{bc} , requires that we re-examine bounds on $W - W'$ mixing, in particular the combination $\xi_{\text{eff}} = \xi_W g_R/g_L$. This combination is constrained by $b \rightarrow s\gamma$ [52,48,53] and we applied this constraint to our model in Ref. [26]. We can update that result using the most recent HFLAV collaboration average: $B(b \rightarrow X_s \gamma) = (3.32 \pm 0.15) \times 10^{-4}$ [8] combined with the NNLL SM calculation $B(b \rightarrow X_s \gamma) = (3.15 \pm 0.23) \times 10^{-4}$ [54]. Assuming that the new physics interferes constructively with the SM, at the 3σ level the allowed range becomes $-1.4 \times 10^{-3} \lesssim \xi_{\text{eff}} \lesssim 1.8 \times 10^{-3}$.

This range severely restricts the possible size of F_{mix}^{bc} . For example, if we use $F_{\text{dir}}^{bc} = 1.28$ in Eq. (11) in combination with the above constraint on ξ_{eff} , we find

$$-2.1 \times 10^{-3} \lesssim F_{\text{mix}}^{bc} \lesssim 2.7 \times 10^{-3}, \quad (24)$$

and it is not possible to reach the value $F_{\text{mix}}^{bc} = 0.04$ in the fit, Eq. (11). Under these conditions the three observables $R(D)$, $R(D^*)$, and $R(J/\psi)$ become approximately proportional to the SM results,

$$\frac{R(D)}{R(D)_{\text{SM}}} \approx \frac{R(D^*)}{R(D^*)_{\text{SM}}} \approx \frac{R(J/\psi)}{R(J/\psi)_{\text{SM}}}. \quad (25)$$

It is interesting to notice that this universal enhancement of the three asymmetries reproduces what is found in models with an additional $SU(2)_L$ symmetry [35,36].

We illustrate the situation in Fig. 4 which takes into account these constraints. The very narrow width of the model prediction range is due to the tight constraint on mixing and comparison with data implies that the model needs a W' mass very close to 1 TeV to successfully explain these anomalies.

The best direct limits on such a W' come from 19.7 fb^{-1} of CMS data at $\sqrt{s} = 8 \text{ TeV}$ [55]. The first result presented in that paper excludes an SSM W'^1 with mass below 2.7 TeV. Since the production couplings for W' are model dependent it is more useful to quantify the constraint as $\sigma \times B(W' \rightarrow \tau \nu) \lesssim 3 \text{ fb}$. In the SSM model considered by CMS $B(W' \rightarrow \tau \nu) \approx 8.5\%$ for W' masses of order a TeV, where decay into top-bottom is allowed. In the

¹ For SSM it is assumed that the W' is a heavy copy of the SM W , with its same couplings to fermions.

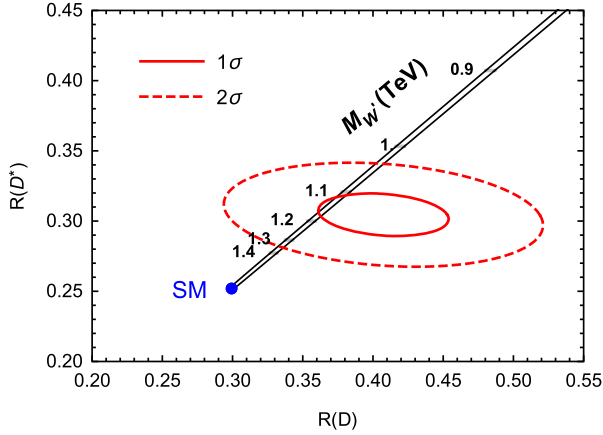


Fig. 4. $R(D)$ vs $R(D^*)$. 1σ (solid curve) and 2σ (dashed curve) allowed regions from the HFLAV collaboration [8] shown in red, the SM central values of Eq. (2) as the blue point and the predictions of this model as the black region. The tick marks along the model prediction indicate the required W' mass in TeV. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

non-universal model discussed here, this branching fraction approaches 25% when $g_R \gg g_L$ and W' couples almost exclusively to the third generation. At the same time the production cross-section at LHC for our W' would be very suppressed due to its negligible couplings to the light fermions. Roughly then,

$$\sigma \times B(W' \rightarrow \tau\nu) \sim (\sigma \times B(W' \rightarrow \tau\nu))_{SM} \frac{25\%}{8.5\%} \left(\left| \frac{g_R}{g_L} \frac{V_{Rud}}{V_{ud}} \right|^2 \text{ or } \xi_W^2 \right). \quad (26)$$

For the first term in the last bracket, corresponding to a direct coupling of the W' to the light quarks, we have: $V_{Rud} = V_{Rtu}^{u*} V_{Rbd}^d$; $V_{Rbd}^d \lesssim 2.5 \times 10^{-4}$ from B_d mixing [56]; and fitting the existing body of FCNC constraints implies that $V_{Rtu}^{u*} \sim 10^{-3}$ [51]. For the second term in the bracket we already saw that ξ_W is at most 10^{-3} in this scenario and we conclude that the corresponding $\sigma \times B(W' \rightarrow \tau\nu)$ in our model is more than 6 orders of magnitude smaller than that of an SSM W' and the CMS data does not place any significant constraint.

The CMS paper also quantifies their result using a type of non-universal W' that also singles out the third generation dubbed 'NUGIM' [57,58]. In this case the CMS data excludes a W' with mass below 2.0–2.7 TeV. Comparing the relevant figure of merit, $\sigma \times B(W' \rightarrow \tau\nu)$, of this model to ours we see that $B(W' \rightarrow \tau\nu)$ can be quite similar but

$$\sigma(pp \rightarrow W')_{\text{this model}} \sim \sigma(pp \rightarrow W')_{\text{NUGIM}} \left| \frac{V_{Rud}}{(s_E/c_E)} \right|^2. \quad (27)$$

Whereas V_{Rud} can (and in fact is constrained to be) very small, the parameter s_E/c_E of NUGIM is of order one (for this reason the $W - W'$ mixing in the NUGIM model is not important in $\sigma(pp \rightarrow W')$). The net result is that the CMS limits do not directly apply to our model. A separate study is needed for an accurate comparison of our model to LHC results, taking into account production from heavier quarks.

As mentioned before, our model relies on the existence of an additional light neutrino to explain these anomalies and this can have other observable consequences. In Ref. [26] we have already seen that there are no significant constraints from the invisible Z width. At the same time the model can provide an *enhancement*

to the rare $K \rightarrow \pi\nu\nu$ modes [59] where new results are expected from NA62 and KOTO.

The existence of a light right-handed neutrino contributes to the effective neutrino number ΔN_{eff} which is also constrained by cosmological considerations and this may affect the viability of our model. There is some uncertainty as to the value of this constraint, but commonly used numbers are, for example [60],

$$\Delta N_{eff} < \begin{cases} 0.28 & \text{for } H_0 = 68.7_{-0.7}^{+0.6} \text{ km/s/Mpc} \\ 0.77 & \text{for } H_0 = 71.3_{-2.2}^{+1.9} \text{ km/s/Mpc}. \end{cases} \quad (28)$$

As we saw above, our model requires

$$\left(\frac{g_R M_W}{g_L M_{W'}} \right)^4 \frac{|V_{R3\tau}^\ell|^2 |V_{Rcb}|^2}{|V_{cb}|^2} \sim 0.3 \quad (29)$$

to explain the $R_{D^{(*)}}$ anomalies and this is only slightly weaker than the usual weak interaction. At the same time, the exchange of a W' can bring the new ν_R into thermal equilibrium with the SM particles through scattering of right-handed neutrinos with taus at a rate proportional to $(g_R M_W / g_L M_{W'})^4 |V_{R3\tau}^\ell|^4$ relative to the usual weak interaction. In fact, with $V_{Rcb}/V_{cb} \sim 1$ this would result in $\Delta N_{eff} \sim 1$ bringing into question the viability of our model. The mixing induced interaction, proportional to ξ_W , is smaller and does not lead to large contributions to ΔN_{eff} .

However, the aforementioned scattering of right-handed neutrinos with taus is only effective for temperatures T_R above $T_\tau \sim m_\tau$. At the time of big bang nucleosynthesis (BBN), the temperature is about $T_{BBN} \sim 1$ MeV, implying that ΔN_{eff} is suppressed by a factor

$$r = \left(\frac{g_*(T_{BBN})}{g_*(T_R)} \right)^{4/3} \quad (30)$$

where $g_*(T)$ is the effective number of relativistic degrees of freedom at temperature T and $g_*(T_{BBN}) = 10.75$. In addition, $g_*(T_R)$ is larger than $g_*(T_{QCD}) \sim 58$ since the QCD phase transition temperature T_{QCD} is of order a few hundred MeV [61]. All this implies that the contribution to ΔN_{eff} from our additional neutrino is less than 0.1 and safely within the BBN constraint.

Similarly, τ decay processes into ν_R plus other SM particles are also suppressed by the same factor r , but one might worry about additional processes without this suppression. For example, ν_R scattering off an electron or a muon. However, these are proportional to the additional mixing parameters $|V_{R3e(\mu)}^\ell|^4$ and can be made sufficiently small by lowering $V_{R3e(\mu)}^\ell$.

Another potentially worrisome process is the exchange of a Z' in the scattering of a ν_R off an electron or SM neutrino ν_L . In this case the interaction strength is proportional to $(g_Y^2/M_{Z'}^2)^2$ [49], and when compared to Z exchange induced ν_L scattering off an electron or ν_L , it is suppressed by a factor of $(M_Z/M_{Z'})^4$. The constraint on ΔN_{eff} becomes in this case a lower bound on the Z' mass, $M_{Z'} \gtrsim 200$ GeV.

In conclusion we find that new right handed currents affect the semi-tauonic B decay anomalies in a way that is consistent with current bounds, including those on the effective number of neutrino species from BBN. A confirmation of a high value for $R(J/\psi)$ would exclude them as a viable explanation and would also exclude new left-handed currents. The most promising way to rule out this explanation of the anomalies is the exclusion of a W' in the τ -channel at LHC in the mass range 1–1.4 TeV. The suppression of our W' couplings to light fermions significantly complicates this comparison.

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