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Impact of $\Lambda_b \to \Lambda_c \tau\nu$ measurement on New Physics in $b \to c\, l\nu$ transitions

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Measurements of the branching ratios of $B \to D^{(*)}\tau\bar{\nu}/B \to D^{(*)}\ell\bar{\nu}$ and $B_c \to J/\psi\,\tau\bar{\nu}/B_c \to J/\psi\,\ell\bar{\nu}$ by the BaBar, Belle and LHCb collaborations consistently point towards an abundance of taus compared to channels with light leptons. However, the ratio $\Lambda_b \to \Lambda_c\tau\bar{\nu}/\Lambda_b \to \Lambda_c\ell\bar{\nu}$ shows a relative deficit in taus. In this paper, we critically address whether data still points towards a coherent pattern of deviations, in particular in light of the sum rule relating these decays in a model-independent way. We find that no common new physics explanation of all ratios is possible (within 2σ or 1.5σ, depending on the $\mathcal{R}(\Lambda_c)$ normalization to light lepton channels). While this inconsistency could be a statistical fluctuation, further measurements are required in order to converge to a coherent pattern of experimental results.

I. INTRODUCTION

The Standard Model (SM) has a solid experimental foundation since its formulation half a century ago [1–3]. However, several incontestable observations, like the presence of dark matter or neutrino oscillation (see, e.g., Refs. [4, 5] for recent reviews), prove the existence of New Physics (NP). In the quest for its search, a useful approach is to look at the violation of (approximate) symmetries of the SM, like, e.g., lepton flavour universality (LFU) which is only broken in the SM Lagrangian by the small Yukawa couplings.

In fact, several hints for the violation of LFU have emerged over the last years (see e.g. Refs. [6–8] for a recent review). In particular, ratios of the semi-leptonic b hadrons decays

$$\begin{aligned}\mathcal{R}(D^{(*)}) &\equiv \mathrm{BR}(B \to D^{(*)}\tau\bar{\nu})/\mathrm{BR}(B \to D^{(*)}\ell\bar{\nu})\,,\\ \mathcal{R}(J/\psi) &\equiv \mathrm{BR}(B_c \to J/\psi\,\tau\bar{\nu})/\mathrm{BR}(B_c \to J/\psi\,\ell\bar{\nu})\,,\\ \mathcal{R}(\Lambda_c) &\equiv \mathrm{BR}(\Lambda_b \to \Lambda_c\tau\bar{\nu})/\mathrm{BR}(\Lambda_b \to \Lambda_c\ell\bar{\nu})\,,\end{aligned} \tag{1}$$

where CKM and hadronic uncertainties drop out and are reduced, respectively, show deviations from the SM predictions.[1]

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[1] Here and in the following, $\ell = e, \mu$, while $l = e, \mu, \tau$.

Both $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ have been measured by BaBar [9, 10] and Belle [11–15] and a first combined measurement of these ratios has just recently been announced by LHCb [16], which previously had measured only the latter one [17–19]. A global average for these quantities has been provided by the HFLAV collaboration [20],

$$\begin{aligned}\mathcal{R}(D) &= 0.358 \pm 0.025 \pm 0.012\,,\\ \mathcal{R}(D^*) &= 0.285 \pm 0.010 \pm 0.008\,,\end{aligned} \tag{2}$$

where the first uncertainty is statistical and the second is systematic. When comparing this result with the recent SM predictions [20–26],

$$\begin{aligned}\mathcal{R}_{\rm SM}(D) &= 0.298 \pm 0.004\,,\\ \mathcal{R}_{\rm SM}(D^*) &= 0.254 \pm 0.005\,,\end{aligned} \tag{3}$$

one observes a tension at the level of $3.2\,\sigma$. As the determination of $|V_{cb}|$ from the modes with light leptons is consistent with global CKM fits [27, 28], it is regularly assumed that the deviation implies an over-abundance of taus.

An analogous behaviour has been observed for $\mathcal{R}(J/\psi)$ [29]

$$\mathcal{R}(J/\psi) = 0.71 \pm 0.17 \pm 0.18\,. \tag{4}$$

To compare this result with SM predictions, we can rely on the latest estimates [30–33],

$$\mathcal{R}_{\rm SM}(J/\psi) = 0.258 \pm 0.004\,, \tag{5}$$

that are compatible with data at the $1.8\,\sigma$ level. However, we are still missing a determination of the tensor form factors from lattice, and the lack of a precise knowledge for these form factors from other sources precludes an accurate NP analysis [31, 34–37]. For this reason, we do not include this observable in our NP analysis.

Finally, LHCb [38] finds

$$\mathcal{R}(\Lambda_c) = 0.242 \pm 0.026 \pm 0.040 \pm 0.059\,, \tag{6}$$

where the first uncertainty is statistical, the second is systematic and the third is due to external branching fraction measurements. A recent reanalysis of this result has been performed in Ref. [39] where, in order to reduce systematic errors, the tau decay channel measured by the LHCb collaboration is normalized to the SM prediction for $\Gamma(\Lambda_b \to \Lambda_c \mu\bar{\nu})$, rather than employing its experimental average. Such a procedure improves the accuracy and slightly amplifies the central value, yielding

$$\mathcal{R}(\Lambda_c) = |0.04/V_{cb}|^2 (0.285 \pm 0.073)\,. \tag{7}$$

In comparison the SM prediction, where the absence of a subleading Isgur-Wise function at $\mathcal{O}(\bar{\Lambda}/m_{c,b})$ in the $\Lambda_b \to \Lambda_c$ transition suppresses the theoretical uncertainty [40], is equal to [41–47]

$$\mathcal{R}_{\rm SM}(\Lambda_c) = 0.324 \pm 0.004\,. \tag{8}$$

Although this value does not point towards a strong tension with the SM, it actually hints this time to an under-abundance of taus.

This opposite behaviour compared to the other ratios is unexpected as all processes are described by the same effective Hamiltonian for $b \to c l \nu$ transitions. Many model-independent NP analyses have been performed to explain either the deviation observed in $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ [48–78], and/or $\mathcal{R}(\Lambda_c)$ alone [47, 79–84], with NP effects connected to tau leptons. However, a joint description of the three LFU ratios is mandatory, because the three decay modes are correlated in a model-independent way: $\mathcal{R}(D)$, $\mathcal{R}(D^*)$ and $\mathcal{R}(\Lambda_c)$ fulfill a sum rule which is rooted in their properties in the heavy quark limit [85, 86].

The intent of this paper is therefore to critically scrutinize the compatibility of data. We try to understand, by means of an EFT approach, whether it is possible to introduce further NP effects in order to address experimental measurements, or if on the other hand we are facing a situation where current results are incompatible among themselves. While most previous analyses were restricted to NP contributions in tau final states, we also consider the possibility to introduce NP coupled to light leptons, thereby modifying the sum rule in order to potentially accommodate data.

This paper is organized a follows: in Sec. II we introduce the EFT formalism employed to perform the NP analyses and in Sec. III we update the sum rule, which is modified once taking the latest results into account. In Sec. IV we review all the possible, simple UV completions that can produce the effects described by the EFT at the low-scale, and in Sec. V we report the results of our fits. We draw our conclusions in Sec. VI.

II. EFT FORMALISM

We use the effective Hamiltonian

$$\begin{aligned}\mathcal{H}_{\rm eff} = 2\sqrt{2}G_F V_{cb}\big[&(1+C^l_{V_L})O^l_{V_L} + C^l_{S_R}O^l_{S_R}\\ &+C^l_{S_L}O^l_{S_L} + C^l_T O^l_T\big]\,,\end{aligned} \tag{9}$$

with the dimension-six operators

$$\begin{aligned}O^l_{V_L} &= (\bar{c}\gamma^\mu P_L b)\left(\bar{l}\gamma_\mu P_L \nu_l\right)\,,\\ O^l_{S_R} &= (\bar{c}P_R b)\left(\bar{l}P_L \nu_l\right)\,,\\ O^l_{S_L} &= (\bar{c}P_L b)\left(\bar{l}P_L \nu_l\right)\,,\\ O^l_T &= (\bar{c}\sigma^{\mu\nu}P_L b)\left(\bar{l}\sigma_{\mu\nu}P_L \nu_l\right)\,,\end{aligned} \tag{10}$$

where $\sigma_{\mu\nu} = \frac{i}{2}[\gamma_\mu, \gamma_\nu]$. Note that in our convention for the effective Hamiltonian the Wilson coefficients (WCs) C^l_i describe a genuine NP effect, and vanish in the SM. Moreover, we do not include effects of possibly light right-handed neutrinos,[2] nor do we consider NP effects in right-handed quark vector currents, which are LFU at the dimension-six level [93–96].

Finally, it is important to remember that the operators and WCs in Eq. (9) are scale-dependent. We perform our analysis for a heavy NP scale, which we take to be 2 TeV for concreteness. To connect these coefficients to the decay scale $\mu = \mu_b = 4.2\,$GeV, we use the renormalization-group evolution (RGE) for the dimension-six operators at the QCD next-to-leading and the electroweak leading orders including the top-quark threshold corrections [97] and take the QCD one-loop matching corrections into account at the NP scale [98],

$$\begin{aligned}C^l_{V_L}(\mu_b) &= 1.12\, C^l_{V_L}(2\,\text{TeV})\,,\\ C^l_{S_R}(\mu_b) &= 2.00\, C^l_{S_R}(2\,\text{TeV})\,,\\ \begin{pmatrix} C^l_{S_L}(\mu_b)\\ C^l_T(\mu_b)\end{pmatrix} &= \begin{pmatrix} 1.91 & -0.38\\ 0. & 0.89\end{pmatrix}\begin{pmatrix} C^l_{S_L}(2\,\text{TeV})\\ C^l_T(2\,\text{TeV})\end{pmatrix}.\end{aligned} \tag{11}$$

III. UPDATED SUM RULE

$\mathcal{R}(D^{(*)})$ and $\mathcal{R}(\Lambda_c)$ have strong theoretical correlations as they depend on the same transition at the quark level. Given the newly measured value for $\mathcal{R}(\Lambda_c)$ [38], and the updates for $\mathcal{R}(D^{(*)})$ [16], we update here the sum rule connecting the three LFU ratios [85, 86]. For this we start from a semi-numerical formula for $\mathcal{R}(\Lambda_c)$, assuming NP contributions to the tau channel only and using the $\Lambda_b \to \Lambda_c$ lattice QCD results of Refs. [43, 45, 75]:

$$\frac{\mathcal{R}(\Lambda_c)}{\mathcal{R}_{\rm SM}(\Lambda_c)} = \left|1+C^\tau_{V_L}\right|^2 + 0.50\,{\rm Re}\left[\left(1+C^\tau_{V_L}\right)C^{\tau*}_{S_R}\right] + 0.33\,{\rm Re}\left[\left(1+C^\tau_{V_L}\right)C^{\tau*}_{S_L}\right] + 0.52\,{\rm Re}\left(C^\tau_{S_L}C^{\tau*}_{S_R}\right) + 0.32\left(|C^\tau_{S_L}|^2+|C^\tau_{S_R}|^2\right) - 3.11\,{\rm Re}\left[\left(1+C^\tau_{V_L}\right)C^{\tau*}_{T}\right] + 10.4\,|C^\tau_T|^2\,, \tag{12}$$

where the Wilson coefficients are at the scale $\mu=\mu_b$ [45], and we used $m_c(\mu_b)=0.92\,{\rm GeV}$ for the form factors of the scalar and pseudoscalar currents.

Combining this with the general NP formulae for $\mathcal{R}(D^{(*)})$ [99] and Eq. (12), we find[3]

$$\frac{\mathcal{R}(\Lambda_c)}{\mathcal{R}_{\rm SM}(\Lambda_c)} = 0.280\,\frac{\mathcal{R}(D)}{\mathcal{R}_{\rm SM}(D)} + 0.720\,\frac{\mathcal{R}(D^*)}{\mathcal{R}_{\rm SM}(D^*)} + \delta_{\Lambda_c}\,, \tag{13}$$

with

$$\delta_{\Lambda_c} = {\rm Re}\left[\left(1+C^\tau_{V_L}\right)\left(0.314\,C^{\tau*}_T - 0.003\,C^{\tau*}_{S_R}\right)\right] + 0.014\left(|C^\tau_{S_L}|^2+|C^\tau_{S_R}|^2\right) + 0.004\,{\rm Re}\left(C^\tau_{S_L}C^{\tau*}_{S_R}\right) - 1.30\,|C^\tau_T|^2\,. \tag{14}$$

This is to be compared with

$$\frac{\mathcal{R}(\Lambda_c)}{\mathcal{R}_{\rm SM}(\Lambda_c)} \simeq 0.262\,\frac{\mathcal{R}(D)}{\mathcal{R}_{\rm SM}(D)} + 0.738\,\frac{\mathcal{R}(D^*)}{\mathcal{R}_{\rm SM}(D^*)}\,, \tag{15}$$

found in Ref. [86] and implying the prediction $\mathcal{R}(\Lambda_c) = 0.38\pm0.01\pm0.01$.

It is interesting to notice that a deviation in $\mathcal{R}(D^*)$ from the SM has a stronger impact on $\mathcal{R}(\Lambda_c)$ compared to one in $\mathcal{R}(D)$. Therefore, the latest measurement of LHCb [16] with a value for $\mathcal{R}(D^*)$ quite close to the SM value while that of $\mathcal{R}(D)$ being further away, decreases the expected deviation in $\mathcal{R}(\Lambda_c)$.

Equation (13) holds in any tau-philic NP scenario described by the effective Hamiltonian in Eq. (9). Moreover, for $|C^\tau_T|\ll 1$, the correction factor δ_{Λ_c} is irrelevant. We therefore obtain the model-independent prediction

$$\begin{aligned}\mathcal{R}(\Lambda_c) &\simeq \mathcal{R}_{\rm SM}(\Lambda_c)\left(0.280\,\frac{\mathcal{R}(D)}{\mathcal{R}_{\rm SM}(D)} + 0.720\,\frac{\mathcal{R}(D^*)}{\mathcal{R}_{\rm SM}(D^*)}\right)\\ &= \mathcal{R}_{\rm SM}(\Lambda_c)\,(1.172\pm0.038)\\ &= 0.380\pm0.012\pm0.005\,,\end{aligned} \tag{16}$$

where the first error arises from the experimental uncertainty of $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$, and the second one from $\mathcal{R}_{\rm SM}(\Lambda_c)$. While the central value of the predicted $\mathcal{R}(\Lambda_c)$ is unchanged respect to Ref. [86], the obtained errors are smaller.

IV. NP SCENARIOS

In this Section we consider NP scenarios including WCs by the addition of at most two new heavy fields. In the cases of two fields, we allow one of them to couple to tau leptons, and the other to both light leptons with the same strength.[4] We consider all NP WCs to be real, unless stated otherwise.

A. Scalar Leptoquarks

Out of the five scalar Leptoquarks (LQs) [101], only three can generate $b\to c l\nu$ transitions:

- $S_1 = (\bar{\mathbf{3}},\mathbf{1},1/3)$ gives $C^l_{V_L}$ and/or the combination $C^l_{S_L}=-4C^l_T$ (at the matching scale) that becomes $C^l_{S_L}(\mu_b)\simeq -8.9C^l_T(\mu_b)$ at the decay scale. Solutions to the $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ anomalies by means of this LQ can be found in Refs. [57, 102–112]. Note however that the $SU(2)_L$ symmetry implies an inevitable correlation between $C^l_{V_L}$ and a tree-level contribution to $b\to s\nu_l\bar{\nu}_l$. Hence, a constraint from $B\to K^*\nu\bar\nu$ measurement is unavoidable [113–115]. Moreover, additional severe bounds come from the S_1–ν_l box diagrams contributions to ΔM_s [116, 117].
- $R_2 = (\mathbf{3},\mathbf{2},7/6)$, a weak doublet scalar whose footprints at the B-meson scale are described by a contribution satisfying $C^l_{S_L}=4C^l_T$. Once again, due to RGE this relation becomes $C^l_{S_L}(\mu_b)\simeq 8.4C^l_T(\mu_b)$ at the low scale. In this specific scenario we allow the WCs to be complex, since this is a necessary requirement in order to address at the same time $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ [85, 86, 100, 109, 118–121].
- $S_3 = (\bar{\mathbf{3}},\mathbf{3},1/3)$, an $SU(2)_L$-triplet scalar that is parametrized at the low scale by the WC $C^l_{V_L}$. Models which contain such a solution to the LFU ratios have been studied in Refs. [52, 57, 102, 103, 105, 108, 121]. Similarly to the S_1 case, also this scenario suffers from the constraint induced by $B\to K^*\nu\bar\nu$, severely limiting the allowed size for $C^l_{V_L}$ [103].

[2] Studies including right-handed neutrinos in $\mathcal{R}(D^{(*)})$ have been carried out, e.g., in Refs. [87–92].

[3] We obtain this sum rule by imposing a condition such that a $C^\tau_{V_L}C^{\tau*}_{S_L}$ interference term is absent in δ_{Λ_c}, while Ref. [85] has imposed such a condition for $C^\tau_{V_L}C^{\tau*}_{S_R}$. We find that although both procedures are numerically equivalent, our procedure is slightly more accurate whenever the δ_{Λ_c} term is ignored.

[4] Strictly speaking, if the NP field coupling to light leptons is a leptoquark, the stringent constraints from lepton flavour violating decays require the introduction of *two* such fields, one coupling to muons and the other to electrons [100].

It is important to remember that, in order to avoid the undesirable effect of proton decays, one has to forbid di-quark couplings to the LQ for S_1 and S_3 (e.g. by a symmetry, see Ref. [122]).

B. Vector Leptoquarks

A second family of solutions for the LFU ratios involves vector LQs.[5] Out of the five vector LQs [101] only two can produce effects of interest in our study, namely:

- $U_1 = (\mathbf{3}, \mathbf{1}, 2/3)$, an $SU(2)_L$-singlet vector that produces at the low scale the WCs $C^l_{V_L}$ and/or $C^l_{S_R}$. Models that include this LQ in a Pati-Salam extension of the SM can be found, e.g., in Refs. [69, 109, 110, 117, 123–149].

- $V_2 = (\bar{\mathbf{3}}, \mathbf{2}, 5/6)$, a weak doublet vector whose effects at the decay scale can be described by means of the WC $C^l_{S_R}$. An example for this kind of solution can be found, e.g., in Ref. [150]. This scenario, previously disfavoured due to its limited impact on $\mathcal{R}(D^*)$, is now viable again due to the recent LHCb result hinting at a smaller deviation in $\mathcal{R}(D^*)$ compared to the one in $\mathcal{R}(D)$ [16]. Note that, in order to avoid proton decay, also this scenario requires a symmetry that prevents di-quark coupling to V_2.

C. Charged Higgses

A charged scalar boson ($H^\pm$) generates the WCs $C^l_{S_R}$ and $C^l_{S_L}$. The 2HDM model of type II at large $\tan\beta$ [151–153] leads to the wrong sign to fit data, but the 2HDM with a generic flavour structure [87, 154–170] can lead to constructive effects. It is interesting to note that while a fit including only $C^l_{S_L}$ requires it to be complex in order to properly address the data, this is no longer necessary once both WCs are allowed at the same time, as in our fits.

D. Singly charged vector boson

W', being a charged vector boson, generates $C^l_{V_L}$ [171–176]. However, such solutions are no more viable due to constraints from ΔM_s, $b \to s\nu\nu$ and LHC direct searches like $pp(b\bar{b}) \to Z' \to \tau^+\tau^-$, which arose due to $SU(2)_L$ invariance. Similarly, a W'_R scenario [88] is no longer compatible with collider bounds [177].

[5] It is worth mentioning that these solutions usually require some sort of UV completion in order to explain the origin of a massive spin-1 particle.

scenario	$\mathcal{R}(D)$	$\mathcal{R}(D^*)$	$\mathcal{R}(\Lambda_c)$
exp.	0.36(3)	0.29(1)	0.24(7)
$\boldsymbol{S_1}$	0.36(3)	0.29(1)	0.38(3)
$\boldsymbol{R_2}$	0.36(3)	0.28(1)	0.40(4)
$\boldsymbol{S_3}$	0.33(2)	0.29(1)	0.38(2)
$\boldsymbol{U_1}$	0.36(3)	0.28(1)	0.37(2)
$\boldsymbol{V_2}$	0.36(3)	0.28(1)	0.36(1)
$\boldsymbol{H^\pm}$	0.36(3)	0.28(1)	0.36(2)

TABLE I. Predicted values for $\mathcal{R}(\Lambda_c)$ from a fit to $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ for several single particle extensions of the SM which couple to tau leptons.

V. RESULTS AND DISCUSSION

We are now ready to assess how 1D and 2D extension of the SM perform in explaining $\mathcal{R}(D)$, $\mathcal{R}(D^*)$ and $\mathcal{R}(\Lambda_c)$, where the dimensionality of the extension refers to the number of new fields, not to the number of WCs generated. Our fits are performed by carrying out a Markov Chain Monte Carlo Bayesian analysis, implementing the full analytic expressions and including all theoretical correlations for all the analysed modes, using the `HEPfit` code [178]. Flat priors with large intervals for the NP WCs have been allowed in all cases, in order to obtain prior-independent results. Given that our goal is to test the validity of the sum rule among the three LFU ratios, we proceed in the following way: as a first step, we perform a fit only to the ratios in order to assess how they comply with the sum rule; in the case of a positive result, we therefore inspect and comment on how they fare once additional constraints are considered, like, e.g., the $B_c \to \tau\nu$ decay (which we allow to be as large as 60% [85]), the D^{*-} polarization [179] or constraints on $|V_{cb}|$ coming from fits to the Unitary Triangle [27, 28].

For the sake of clarity, we list below our SM predictions for the three LFU ratios, based on the lattice results available for all three channels [43, 180, 181]:

$$\begin{aligned} \mathcal{R}_{\rm SM}(D) &= 0.299 \pm 0.011\,, \\ \mathcal{R}_{\rm SM}(D^*) &= 0.265 \pm 0.013\,, \\ \mathcal{R}_{\rm SM}(\Lambda_c) &= 0.333 \pm 0.010\,. \end{aligned} \tag{17}$$

Our conclusions below are however unchanged if one employs instead the HFLAV average of the SM prediction, as reported in Eq. (3).

A. 1D scenarios

Assuming that NP couples to taus only, none of the extensions discussed in the previous Section is capable of describing in a satisfactory way the measurements of the three LFU ratios. This does not come as a surprise, since it was already known that the three ratios are connected

scenario	$\mathcal{R}(\Lambda_c)$	$\mathcal{R}(D)$	$\mathcal{R}(D^*)$
exp.	0.24(7)	0.36(3)	0.29(1)
$\boldsymbol{S_1}$	0.23(7)	0.21(8)	0.16(8)
$\boldsymbol{S_3}$	0.21(8)	0.18(7)	0.17(6)
$\boldsymbol{U_1}$	0.22(8)	0.15(8)	0.17(8)

TABLE II. Predicted values for $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ from a fit to the experimental value of $\mathcal{R}(\Lambda_c)$ [38].

scenario	$\mathcal{R}(\Lambda_c)$	$\mathcal{R}(D)$	$\mathcal{R}(D^*)$
Ref. [39]	0.29(7)	0.36(3)	0.29(1)
$\boldsymbol{S_1}$	0.28(7)	0.25(8)	0.19(8)
$\boldsymbol{S_3}$	0.27(7)	0.23(6)	0.21(6)
$\boldsymbol{U_1}$	0.28(7)	0.17(9)	0.22(8)

TABLE III. Predicted values for $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ using the value of $\mathcal{R}(\Lambda_c)$ from Ref. [39], assuming $|V_{cb}| = 0.04$.

by the sum rule derived in Refs. [85, 86] and Sec. III: if two of them are measured above the SM prediction, like is the case for $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$, a similar behaviour is expected for the third one, contrary to what is the case for $\mathcal{R}(\Lambda_c)$. For a recent result of 1D global fits to all relevant data in this sector, we refer the reader to Ref. [99].

To better assess the (in)compatibility of data under the 1D hypotheses, we therefore performed the following test: first, for each scenario capable to fit $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$, we predict the value for $\mathcal{R}(\Lambda_c)$; in a similar fashion, for each scenario capable to fit $\mathcal{R}(\Lambda_c)$, we predict the values for $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$. It is worth mentioning that, as already observed in Refs. [85, 86], the only prediction for $\mathcal{R}(\Lambda_c)$ affected (albeit marginally) by allowing the $B_c \to \tau\nu$ decay up to 60% instead of a lower value, e.g. 30%, is the one involving a charged Higgs. We report our findings in Tables I and II, respectively. Note that in Table II we report only the scenarios of a scalar LQ S_1 or S_3, or of a vector LQ U_1, since those are the only ones capable to reproduce the measured value of $\mathcal{R}(\Lambda_c)$. As expected, in the case where the meson LFU ratios are considered in the fit, a large prediction for the baryon one is obtained, compatible with the prediction of the sum rule in Eq. (16), larger than the SM prediction and hence $\sim 2\sigma$ above its measured value. On the other hand, when predicting the values for $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ from a fit to $\mathcal{R}(\Lambda_c)$, the opposite pattern is observed: a value for the latter ratio complying with data would imply values for the former ones smaller than their SM predictions, and $\sim 2\sigma$ below their measured values. It is worth mentioning that, if one uses for $\mathcal{R}(\Lambda_c)$ the value suggested in Ref. [39], the discrepancy among predicted values and measured ones is reduced to $\sim 1.5\sigma$, as shown in Table III.

Nevertheless, the current uncertainty on $\mathcal{R}(\Lambda_c)$ is still large enough that those models cannot be ruled out at present, and a potential decrease in the discrepancy among $\mathcal{R}(D)$, $\mathcal{R}(D^*)$ and their SM prediction could reduce the induced tension in $\mathcal{R}(\Lambda_c)$, or vice versa.

B. 2D scenarios

Here we allow a first new field to couple to taus only, and a second one to couple to muons and electrons equally. For this reason, we identify fields belonging to the first class with the label τ, e.g., R_2^τ, while fields related to the second one are labelled with ℓ, e.g., S_1^ℓ. Having at hand six possible kinds of fields parametrized by a different low-energy EFT description, and each being allowed to couple either to the heavy charged lepton or to the light ones, we ultimately inspected a total of 36 potential 2D scenarios. Out of all these possibilities, we only found two scenarios capable to reproduce in a satisfactory way all three LFU ratios, with all the other scenarios still implying an over-production of taus in $\mathcal{R}(\Lambda_c)$ at the $2\,\sigma$ level. The first viable model is composed by an S_1 LQ coupling to light fermions, together with an R_2 coupled to taus, namely the pair formed by S_1^ℓ and R_2^τ. The second possibility shares the same NP extension coupled to muons and electrons, but requires furthermore a charged Higgs coupled to taus, i.e., the pair formed by S_1^ℓ and $H^{\pm\tau}$. The fact that both scenarios rely on the presence of an $SU(2)_L$-singlet scalar LQ coupled to light fermions is the reason why these scenarios apparently comply with data, but is also the origin why they ultimately fail once faced with additional constraints.

Indeed, once NP is allowed to couple to both heavy and light charged leptons, the numerical formulae for the LFU ratios and for the sum rule connecting them have to be modified accordingly. Observing now that S_1^ℓ implies the presence of a tensor WC, a strong violation of the sum rule (and hence a potential opposite behaviour of $\mathcal{R}(\Lambda_c)$ w.r.t. $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$) could be induced in the case of a non-negligible size for this coefficient. This is indeed what we find in our fits, where in both viable scenarios we need a strong contribution to the scalar and tensor currents, equal to $C_{S_L}^\ell = -4C_T^\ell \simeq \pm 1$, in order to obtain a value $\mathcal{R}(\Lambda_c) \simeq 0.24$.

Moreover, this is not the only requirement for the WCs coupling to light leptons: S_1^ℓ also generates a vector current mediated by $C_{V_L}^\ell$, whose value is constrained by the fit in strong correlation with that of the former pair of WCs, and determined to be in both scenarios equal to $C_{V_L}^\ell \simeq -1$. This corresponds to a -100% correction in the light leptons vector current w.r.t. the SM contribution, inducing a complete cancellation of this term.

However, these solutions are actually not viable once further constraints are taken into account: NP contributions to the vector current involving light leptons are strongly constrained by CKM fits since they would heavily alter the determination of $|V_{cb}|$ from various modes [27, 28], and are also constrained by high-p_{T} lepton tail searches at the LHC $|C^e_{V_L}| < 0.25$ [120, 182] and, even more, by the aforementioned bound imposed on S_1 LQs by $B \to K^*\nu\bar{\nu}$ measurement [113], which implies $-0.011 \le C^{\ell}_{V_L} \le 0.027$ [115]; on the other hand, a strong NP tensor component for light leptons is also heavily constrained by the high-$p_{\rm T}$ search [183], which implies $|C^e_T| < 0.32$, or by an analysis of angular distribution [184, 185] and D^{*-} polarization data [179], which requires it to be even smaller, namely $|C^{\ell}_T| \le 0.05$ [186].

C. General Model-Independent fit

For completeness, we conclude our analysis of viable NP scenarios by performing a fully model-independent fit for eight generic WCs, i.e., $C^{\tau,\ell}_{V_L,S_{L,R},T} \neq 0$, which we take to be real.[6] The results turn out to be similar to the ones observed for the 2D scenarios: while it is indeed possible to find regions of the eight-dimensional WC parameter space where the values for all three LFU ratios are found to be compatible with observed measurements, when additional constraints like the $|V_{cb}|$ determination within CKM fits, angular distributions data, D^{*-} polarization and collider bounds are considered, these solutions are no longer acceptable.

VI. CONCLUSIONS

In this paper, we have critically analysed the latest results concerning LFU ratios in B-meson charged-current decays, aiming to assess the compatibility of data which is challenged by the measurement of $\mathcal{R}(\Lambda_c)$: the latter result, being smaller than the SM prediction, is in contrast with $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$, where an enhancement w.r.t. the SM of $3.2\,\sigma$ is observed. Since all these ratios are mediated by the same $b \to c l\bar{\nu}$ transition, their NP predictions are connected in a model-independent way by a sum rule, which we updated here while investigating whether the data at hand complies with it. For this we have relaxed one assumption of the sum rule, namely that NP affects $b \to c\tau\nu$ but not $b \to c\ell\nu$ with $\ell = e, \mu$. Due to the sum rule, no single particle can explain all three LFU ratios at the same time, and even when considering the different normalization suggested in Ref. [39] for $\mathcal{R}(\Lambda_c)$ the discrepancy is still at the $\sim 1.5\,\sigma$ level.

We therefore investigated whether the addition of a second NP field, this time coupling equally to light charged leptons $\ell = e, \mu$, could induce a modification in the sum rule such that it is possible to address the opposite behaviour of $\mathcal{R}(\Lambda_c)$ compared to $\mathcal{R}(D^{(*)})$. While we found two possible scenarios capable to address the three LFU ratios at the same time, namely one formed by the pair S_1^{ℓ} and R_2^{τ}, and the second formed by the couple S_1^{ℓ} and $H^{\pm\tau}$, we ultimately ruled out these possibilities as well using CKM fits, $B \to K^*\nu\bar{\nu}$, angular distributions and high-p_T collider bounds.

We further performed a fit to eight WCs, half of them related to taus with the remaining associated with light charged leptons. Even in this general case we found that while a fit to the three LFU ratios might find viable solutions in the eight-dimensional WC parameter space, once additional constraints are taken into account such a solution is no longer acceptable. We therefore concluded that present data cannot be addressed, neither in the SM nor beyond, in a satisfactory way, as current experimental results for $\mathcal{R}(D^{(*)})$ and $\mathcal{R}(\Lambda_c)$ show an inconsistent pattern. It is therefore mandatory to obtain further experimental results in this sector in order to eventually converge to a coherent data pattern, differently from what we currently observe. Whether this pattern will lead us to the SM or to NP, only time will tell.

With our current input and assumptions, we predict that at least one of the central values of $\mathcal{R}(D^{(*)})$ or $\mathcal{R}(\Lambda_c)$ will move from its present value once more statistics is accumulated, independently of the presence or nature of NP. Moreover, it might also be possible that NP is present in the q^2 distributions of light lepton modes, while still resulting in consistent values for $|V_{cb}|$, if a different theoretical approach for the form factors is used [187]. Interestingly, this might provide a connection to the anomaly in ΔA_{FB} [188], which requires different NP related to muons and electrons [114]. Furthermore, in a UV complete (or simplified) model, NP effects in $\Delta F = 2$ processes occur in general, such that the global CKM fit could allow for larger NP effects in the determination of $|V_{cb}|$.

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[6] We do not consider the introduction of imaginary parts for these coefficients to be able to alter our conclusions, mainly due to the fact that the interference terms among different WCs in the sum rule of Eq. (16) are proportional to lepton masses, hence negligible for $\ell = e$, μ. Similarly, for right-handed neutrino interactions the interference terms do not exist for any of the three modes, and hence also their inclusion would not have an impact on our results.

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