1

New Physics in $b \to c\tau\nu$: Impact of Polarisation Observables and $B_c \to \tau\nu$

Marta Moscati^{*}

Institut für Theoretische Teilchenphysik (TTP),

Karlsruher Institut für Technologie (KIT), 76131 Karlsruhe, Germany

The experimental values of the lepton-flavour-universality tests $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ show a tension of about 3.1 σ with their Standard Model prediction. Motivated by this tension, we perform a fit of the $b \to c\tau\nu$ data. We consider one-particle scenarios imposing consecutive limits on BR $(B_c \to \tau\nu_{\tau})$, and analyse how these limits affect the fits. We include the polarisation observables available to date and predict those that are still to be measured, and conclude that they have a high model-resolving power. For each scenario we also predict $\mathcal{R}(\Lambda_c)$, observing that an enhancement of $\mathcal{R}(D^{(*)})$ implies an enhancement of $\mathcal{R}(\Lambda_c)$ in any scenario. We trace back this enhancement to a sum-rule valid irrespective of the scenario used to fit $\mathcal{R}(D^{(*)})$.

I. INTRODUCTION

The lepton-flavour-universality tests $\mathcal{R}(D^{(*)}) \equiv$ BR $(B \to D^{(*)}\tau\nu)/\text{BR}(B \to D^{(*)}\ell\nu)$, measured by the BaBar, Belle and LHCb collaborations [1–10], are in tension with the Standard Model (SM) prediction with a combined difference of about 3.1 σ . The average of the measurements can be found in [11], and Figure 1 displays a summary plot. Data on the angular distri-



FIG. 1: Summary plot of the measurements of $\mathcal{R}(D^{(*)})$, taken from [11].

bution of the final state particles in $B \to D^* \tau \nu$ are also available from the Belle collaboration [5, 6, 12]

$$F_{L}(D^{*}) = \frac{\Gamma(B \to D_{L}^{*} \tau \nu)}{\Gamma(B \to D^{*} \tau \nu)} = 0.60 \pm 0.08 \pm 0.035 P_{\tau}(D^{*}) = \frac{\Gamma(B \to D^{*} \tau^{\lambda = +1/2} \nu) - \Gamma(B \to D^{*} \tau^{\lambda = -1/2} \nu)}{\Gamma(B \to D^{*} \tau \nu)} = -0.38 \pm 0.51 \overset{(1)}{-0.16}$$

In our analysis [13, 14] we fitted these data to scenarios of new physics (NP) in which a single heavy mediator contributes to the transition $b \to c\tau\nu$, without contributing to the channels with a light lepton¹.

II. NEW PHYSICS SCENARIOS

The contributions of a NP mediator with mass above the *B* meson mass to $b \rightarrow c\tau\nu$ transitions, excluding the presence of light right-handed neutrinos, can be parametrised in terms of an effective field theory (EFT) as

$$\mathcal{H}_{\text{eff}} = 2\sqrt{2}G_F V_{cb} \left[(1 + C_V^L) O_V^L + C_S^R O_S^R + C_S^L O_S^L + C_T O_T \right],$$

$$(2)$$

with

$$\begin{aligned}
O_V^L &= (\bar{c}\gamma^{\mu}P_Lb)(\bar{\tau}\gamma_{\mu}P_L\nu_{\tau}), \\
O_S^R &= (\bar{c}P_Rb)(\bar{\tau}P_L\nu_{\tau}), \\
O_S^L &= (\bar{c}P_Lb)(\bar{\tau}P_L\nu_{\tau}), \\
O_T &= (\bar{c}\sigma^{\mu\nu}P_Lb)(\bar{\tau}\sigma_{\mu\nu}P_L\nu_{\tau}).
\end{aligned}$$
(3)

The 1 in the vectorial coupling represents the SM contribution, while all the remaining Wilson coefficients (WCs) encode only NP contributions.

The addition of a single NP particle to the SM can only give rise to a restricted subset of combinations of WCs. With the further assumption of real couplings, the parameters to fit are at most two. We can hence have the one-dimensional scenarios²:

- C_V^L : arising from the SU(2)_L-singlet vector leptoquark (LQ) U_1 [19–39], the scalar SU(2)_Ltriplet and/or scalar SU(2)_L-singlet LQ [40–48] with left-handed couplings only, or in models with left-handed W' bosons [49–52].
- C_S^{R} : arising from charged scalars or from the $SU(2)_L$ -doublet vector LQ V_2 [53, 54].

^{*}Electronic address: marta.moscati@kit.edu

¹ For an analysis of NP effects in $b \to u\ell\nu$ see [15].

² For a discussion of the effects of a tensor coupling see [16-18].

- C_S^L : arising from charged scalars in the hypothesis of a mechanism making O_S^L the dominant operator [55–64].
- $C_S^L = 4C_T$: arising from the scalar SU(2)_Ldoublet S_2 (also called R_2) LQ [65, 66]. Note that the relation holds at the NP scale, and gets modified by QCD and electroweak (EW) renormalization-group (RG) effects [67, 68].

or the two-dimensional scenarios

- $(C_V^L, C_S^L = -4C_T)$: arising from the SU(2)_Lsinglet scalar LQ (S₁). The relation $C_S^L = -4C_T$ holds again at the NP scale and must be evolved to the m_B scale [68].
- (C_S^R, C_S^L) : arising from charged scalars.
- (C_V^L, C_S^R) : arising from vector LQs like the $SU(2)_L$ -singlet LQ U_1 .
- (Re[$C_S^L = 4C_T$], Im[$C_S^L = 4C_T$]): as pointed out in [66], the scenario $C_S^L = 4C_T$ is able to reproduce the $\mathcal{R}(D^{(*)})$ data only under the assumption of complex couplings. For this reason we also include it in the two-dimensional fits, fitting separately the real and the imaginary part.

III. CONSTRAINTS FROM $BR(B_c \rightarrow \tau \nu_{\tau})$

The vector (C_V^L) and pseudoscalar $(C_P = C_S^R - C_S^L)$ couplings also mediate the decay $B_c \to \tau \nu$ [69, 70]. Although the branching ratio BR $(B_c \to \tau \nu_{\tau})$ has not been measured yet, the comparison between the measured and SM-expected [71–75] B_c lifetime allows to set an upper limit on BR $(B_c \to \tau \nu_{\tau})$. This approach was used in [70] to set an upper limit of 30%. This limit can be relaxed if one takes into account the uncertainties in the theoretical calculation of the lifetime, originating from the large dependance on m_c and from the calculation methods applied, namely heavy quark expansion and non-relativistic QCD (NRQCD).

Furthermore, the authors of [76] set the upper limit $BR(B_c \to \tau \nu_{\tau}) < 10\%$ using LEP data from an admixture of $B_c \to \tau \nu$ and $B^- \to \tau \nu$ and using the fragmentation functions ratio f_c/f_u measured at hadron colliders, which have both different production mechanisms and different kinematics. Evaluating f_c at the Z peak with e^+e^- by means of NRQCD mildens the constraint by a factor of 3-4. A more conservative estimate would further take the theoretical uncertainties into account.

In light of the above considerations, each NP scenario is analysed under three different assumptions: BR $(B_c \rightarrow \tau \nu_{\tau}) < 10, 30, 60\%$. These constraints are imposed as a hard cut on the region of parameter space allowed for the fit.

IV. FIT RESULTS

The results of the fits from [14] are displayed in Tables I, II. The subscript, where present, refers to the limit on BR($B_c \to \tau \nu_{\tau}$). Its absence indicates that the result does not change when changing the limit on $BR(B_c \to \tau \nu_{\tau})$. For each scenario we quote the goodness of fit in terms of *p*-value and the pull of the bestfit point with the SM. The last six columns display the values of the observables at the best-fit point. For the measured ones $(\mathcal{R}(D), \mathcal{R}(D^*), F_L(D^*), P_{\tau}(D^*))$ we also show the pull with respect to the experimental value. The one- and two- σ intervals for the 1D fits are displayed in Table I, while the same regions for the 2D fits are plotted in Figure 2. The purple regions in scenarios $(C_V^L, C_S^L = -4C_T), (C_V^L, C_S^R), (\operatorname{Re}[C_S^L = -4C_T))$ $4C_T$], Im $[C_S^L = 4C_T]$) are excluded at 2σ by collider bounds [77]. These constraints are displayed as a dashed line for (C_S^R, C_S^L) , since a collider study of this scenario requires a model-dependent analysis rather than an EFT one.

Concerning BR($B_c \to \tau \nu_{\tau}$), the most striking result from Table II is that with a 60% limit, the scenario (C_S^R, C_S^L) is the one preferred by the current experimental data. Its *p*-value diminishes drastically as soon as we impose a more severe BR($B_c \to \tau \nu_{\tau}$) constraint. We conclude that a description of the $\mathcal{R}(D^{(*)})$ anomaly in terms of charged Higgs predicts BR($B_c \to \tau \nu_{\tau}$) > 30%.

A. Correlations between observables and $\mathcal{R}(\Lambda_c)$ sum rule

For the two dimensional scenario we also analysed the correlation between the observables in the last six columns of Table II. In order to do so, we projected the two-sigma regions resulting from the fits with the $BR(B_c \rightarrow \tau \nu_{\tau}) < 60\%$ limit into planes having as axes two out of the six observables. These plots are displayed in Figures 3 and 4 and allow us to draw two conclusions.

From Figure 3 we see that in planes in which one of the axes is a polarisation observable, the sigma regions of different scenarios separate clearly, hence indicating that these observables have a strong impact in distinguishing among models. In particular, a closer look at Table II reveals that the recent measurement of $F_L(D^*)$ favours the scenario (C_S^R, C_S^L) .

In Figure 4, instead, we see that the value of $\mathcal{R}(\Lambda_c)$ predicted in models fitting $\mathcal{R}(D^{(*)})$ is always increased with respect to its SM prediction [78, 79]. This en-



FIG. 2: 2σ regions of the 2D fit. [14]

hancement can be traced back to the sum rule

$$\frac{\mathcal{R}(\Lambda_c)}{\mathcal{R}_{\rm SM}(\Lambda_c)} \simeq 0.262 \frac{\mathcal{R}(D)}{\mathcal{R}_{\rm SM}(D)} + 0.738 \frac{\mathcal{R}(D^*)}{\mathcal{R}_{\rm SM}(D^*)}, \quad (4)$$

which holds irrespective of the NP model considered, and that can be understood in the heavy-quark limit. Substituting the current experimental averages of $\mathcal{R}(D^{(*)})$, we find

$$\mathcal{R}(\Lambda_c) = 0.38 \pm 0.01 \pm 0.01 \,, \tag{5}$$

where the first error arises from the experimental uncertainty of $\mathcal{R}(D^{(*)})$, while the second comes from the form factors.

V. SUMMARY

Motivated by the $\mathcal{R}(D^{(*)})$ anomaly, we updated the fit of $b \to c\tau\nu$ data, including the recent experimental results from the Belle collaboration and restricting to scenarios with a single additional mediator. We revised the limit from BR $(B_c \to \tau\nu_{\tau})$ and analysed its impact on each of the scenarios. The fit allowed us to appreciate the model-resolving power of polarisation observables, and to conclude that if the origin of the $\mathcal{R}(D^{(*)})$ anomaly is new physics, we expect a value of $\mathcal{R}(\Lambda_c)$ higher than the one predicted by the Standard Model, irrespective of which additional particle mediates the decay.

Acknowledgments

I am grateful to Monika Blanke, Andreas Crivellin, Stefan de Boer, Teppei Kitahara, Uli Nierste and Ivan Nišandžić for the fruitful collaboration that led to the results presented in this proceeding. I would also like to thank the organisers of the FPCP 2019 and to acknowledge the support of the DFG-funded Doctoral School KSETA and of the research training group GRK 1694.



FIG. 3: Correlation plots among polarisation observables for the 2D fits [14]. The red star represents the Standard Model prediction.

- [1] J. Ρ. Lees etal.BaBar Collaboration], Phys. Rev. Lett. 109(2012)101802 doi:10.1103/PhysRevLett.109.101802 [arXiv:1205.5442 [hep-ex]].
- [2] J. Ρ. Lees etal.BaBar Collaboration], Rev. (2013)Phys. D 88 no.7, 072012 doi:10.1103/PhysRevD.88.072012 [arXiv:1303.0571 [hep-ex]].



FIG. 4: Correlation plots between $\mathcal{R}(\Lambda_c)$ and $\mathcal{R}(D^{(*)})$ for the 2D fits [14]. The red star represents the Standard Model prediction.

- M. Huschle et al. [Belle Collaboration], Phys. Rev. D 92 (2015) no.7, 072014 doi:10.1103/PhysRevD.92.072014 [arXiv:1507.03233 [hep-ex]].
- [4] Y. Sato *et al.* [Belle Collaboration], Phys. Rev. D 94 (2016) no.7, 072007 doi:10.1103/PhysRevD.94.072007
 [arXiv:1607.07923 [hep-ex]].
- [5] S. Hirose *et al.* [Belle Collaboration], Phys. Rev. Lett. **118** (2017) no.21, 211801 doi:10.1103/PhysRevLett.118.211801 [arXiv:1612.00529 [hep-ex]].
- [6] S. Hirose *et al.* [Belle Collaboration], Phys. Rev. D 97 (2018) no.1, 012004 doi:10.1103/PhysRevD.97.012004 [arXiv:1709.00129 [hep-ex]].
- [7] R. Aaij et al. [LHCb Collaboration], Phys. Rev. Lett. 115 (2015) no.11, 111803 Erratum:
 [Phys. Rev. Lett. 115 (2015) no.15, 159901] doi:10.1103/PhysRevLett.115.159901, 10.1103/Phys-RevLett.115.111803 [arXiv:1506.08614 [hep-ex]].
- [8] R. Aaij et al. [LHCb Collaboration], Phys. Rev. Lett. **120** (2018) no.17, 171802 doi:10.1103/PhysRevLett.120.171802 [arXiv:1708.08856 [hep-ex]].
- [9] R. Aaij *et al.* [LHCb Collaboration], Phys. Rev. D 97 (2018) no.7, 072013 doi:10.1103/PhysRevD.97.072013

[arXiv:1711.02505 [hep-ex]].

- [10] A. Abdesselam *et al.* [Belle Collaboration], arXiv:1904.08794 [hep-ex].
- [11] Y. Amhis *et al.* [HFLAV Collaboration], Eur. Phys. J. C **77** (2017) no.12, 895 doi:10.1140/epjc/s10052-017-5058-4 [arXiv:1612.07233 [hep-ex]]. Updated average of R(D) and $R(D^*)$ for Spring 2019 at https://hflav-eos.web.cern.ch/hflav-eos/ semi/spring19/html/RDsDsstar/RDRDs.html
- [12] K. Adamczyk, "B to semitauonic decays at Belle/Belle II", Talk at 10th International Workshop on the CKM Unitarity Triangle, Heidelberg, 17-21 Sep 2018, https://indico.cern.ch/event/684284/ timetable/#20180917.detailed.
- [13] M. Blanke, A. Crivellin, S. de Boer, T. Kitahara, M. Moscati, U. Nierste and I. Nišandžić, Phys. Rev. D **99** (2019) no.7, 075006 doi:10.1103/PhysRevD.99.075006 [arXiv:1811.09603 [hep-ph]].
- [14] M. Blanke, A. Crivellin, T. Kitahara, M. Moscati, U. Nierste and I. Nišandžić, arXiv:1905.08253 [hepph].
- [15] P. Colangelo, F. De Fazio and F. Loparco, arXiv:1906.07068 [hep-ph].
- [16] P. Biancofiore, P. Colangelo and F. De Fazio,

Phys. Rev. D 87, no. 7, 074010 (2013) doi:10.1103/PhysRevD.87.074010 [arXiv:1302.1042 [hep-ph]].

- [17] P. Colangelo and F. De Fazio, Phys. Rev. D 95, no.
 1, 011701 (2017) doi:10.1103/PhysRevD.95.011701
 [arXiv:1611.07387 [hep-ph]].
- [18] P. Colangelo and F. De Fazio, JHEP 1806, 082 (2018) doi:10.1007/JHEP06(2018)082 [arXiv:1801.10468 [hep-ph]].
- [19] R. Alonso, В. Grinstein and J. Mar-Camalich, JHEP 1510(2015) $_{\mathrm{tin}}$ 184doi:10.1007/JHEP10(2015)184 [arXiv:1505.05164 [hep-ph]].
- [20] L. Calibbi, A. Crivellin and T. Ota, Phys. Rev. Lett. **115** (2015) 181801 doi:10.1103/PhysRevLett.115.181801 [arXiv:1506.02661 [hep-ph]].
- S. Fajfer and N. Konik, Phys. Lett. B **755** (2016) 270 doi:10.1016/j.physletb.2016.02.018 [arXiv:1511.06024 [hep-ph]].
- [22] R. Barbieri, G. Isidori, A. Pattori and F. Senia, Eur. Phys. J. C 76 (2016) no.2, 67 doi:10.1140/epjc/s10052-016-3905-3 [arXiv:1512.01560 [hep-ph]].
- [23] R. Barbieri, C. W. Murphy and F. Senia, Eur. Phys. J. C 77 (2017) no.1, 8 doi:10.1140/epjc/s10052-016-4578-7 [arXiv:1611.04930 [hep-ph]].
- [24] G. Hiller, D. Loose and K. Schnwald, JHEP 1612 (2016) 027 doi:10.1007/JHEP12(2016)027 [arXiv:1609.08895 [hep-ph]].
- [25] B. Bhattacharya, A. Datta, J. P. Guvin, D. London and R. Watanabe, JHEP **1701** (2017) 015 doi:10.1007/JHEP01(2017)015 [arXiv:1609.09078 [hep-ph]].
- [26] D. Buttazzo, A. Greljo, G. Isidori and D. Marzocca, JHEP **1711** (2017) 044 doi:10.1007/JHEP11(2017)044 [arXiv:1706.07808 [hep-ph]].
- [27] J. Kumar, D. London and R. Watanabe, Phys. Rev. D **99** (2019) no.1, 015007 doi:10.1103/PhysRevD.99.015007 [arXiv:1806.07403 [hep-ph]].
- [28] N. Assad, B. Fornal and B. Grinstein, Phys. Lett. B 777 (2018) 324 doi:10.1016/j.physletb.2017.12.042 [arXiv:1708.06350 [hep-ph]].
- [29] L. Di Luzio, A. Greljo and M. Nardecchia, Phys. Rev. D 96 (2017) no.11, 115011 doi:10.1103/PhysRevD.96.115011 [arXiv:1708.08450 [hep-ph]].
- [30] L. Calibbi, A. Crivellin and T. Li, Phys. Rev. D 98 (2018) no.11, 115002 doi:10.1103/PhysRevD.98.115002 [arXiv:1709.00692 [hep-ph]].
- [31] M. Bordone, C. Cornella, J. Fuentes-Martin and G. Isidori, Phys. Lett. B **779** (2018) 317 doi:10.1016/j.physletb.2018.02.011 [arXiv:1712.01368 [hep-ph]].
- [32] R. Barbieri and A. Tesi, Eur. Phys. J. C 78 (2018) no.3, 193 doi:10.1140/epjc/s10052-018-5680-9 [arXiv:1712.06844 [hep-ph]].
- [33] M. Blanke and A. Crivellin, Phys. Rev. Lett. **121** (2018) no.1, 011801 doi:10.1103/PhysRevLett.121.011801

[arXiv:1801.07256 [hep-ph]].

- [34] A. Greljo and B. A. Stefanek, Phys. Lett. B
 782 (2018) 131 doi:10.1016/j.physletb.2018.05.033
 [arXiv:1802.04274 [hep-ph]].
- [35] M. Bordone, C. Cornella, J. Fuentes-Martn and G. Isidori, JHEP **1810** (2018) 148 doi:10.1007/JHEP10(2018)148 [arXiv:1805.09328 [hep-ph]].
- [36] S. Matsuzaki, K. Nishiwaki and K. Yamamoto, JHEP
 1811 (2018) 164 doi:10.1007/JHEP11(2018)164
 [arXiv:1806.02312 [hep-ph]].
- [37] A. Crivellin, C. Greub, D. Mller and F. Saturnino, Phys. Rev. Lett. **122** (2019) no.1, 011805 doi:10.1103/PhysRevLett.122.011805
 [arXiv:1807.02068 [hep-ph]].
- [38] L. Di Luzio, J. Fuentes-Martin, A. Greljo, M. Nardecchia and S. Renner, JHEP **1811** (2018) 081 doi:10.1007/JHEP11(2018)081 [arXiv:1808.00942 [hep-ph]].
- [39] A. Biswas, D. Kumar Ghosh, N. Ghosh, A. Shaw and A. K. Swain, arXiv:1808.04169 [hep-ph].
- [40] N. G. Deshpande and A. Menon, JHEP 1301 (2013)
 025 doi:10.1007/JHEP01(2013)025 [arXiv:1208.4134
 [hep-ph]].
- [41] M. Tanaka and R. Watanabe, Phys. Rev. D 87 (2013) no.3, 034028 doi:10.1103/PhysRevD.87.034028
 [arXiv:1212.1878 [hep-ph]].
- [42] Y. Sakaki, M. Tanaka, A. Tayduganov and R. Watanabe, Phys. Rev. D 88 (2013) no.9, 094012 doi:10.1103/PhysRevD.88.094012 [arXiv:1309.0301 [hep-ph]].
- [43] M. Freytsis, Z. Ligeti and J. T. Ruderman, Phys. Rev. D 92 (2015) no.5, 054018 doi:10.1103/PhysRevD.92.054018 [arXiv:1506.08896 [hep-ph]].
- [44] M. Bauer and M. Neubert, Phys.
 Rev. Lett. **116** (2016) no.14, 141802
 doi:10.1103/PhysRevLett.116.141802
 [arXiv:1511.01900 [hep-ph]].
- [45] Y. Cai, J. Gargalionis, M. A. Schmidt and R. R. Volkas, JHEP **1710** (2017) 047 doi:10.1007/JHEP10(2017)047 [arXiv:1704.05849 [hep-ph]].
- [46] A. Crivellin, D. Mller and T. Ota, JHEP **1709** (2017)
 040 doi:10.1007/JHEP09(2017)040 [arXiv:1703.09226 [hep-ph]].
- [47] W. Altmannshofer, P. S. Bhupal Dev and A. Soni, Phys. Rev. D 96 (2017) no.9, 095010 doi:10.1103/PhysRevD.96.095010 [arXiv:1704.06659 [hep-ph]].
- [48] D. Marzocca, JHEP **1807** (2018) 121 doi:10.1007/JHEP07(2018)121 [arXiv:1803.10972 [hep-ph]].
- [49] X. G. He and G. Valencia, Phys. Rev. D 87 (2013) no.1, 014014 doi:10.1103/PhysRevD.87.014014
 [arXiv:1211.0348 [hep-ph]].
- [50] A. Greljo, G. Isidori and D. Marzocca, JHEP
 1507 (2015) 142 doi:10.1007/JHEP07(2015)142
 [arXiv:1506.01705 [hep-ph]].
- [51] S. M. Boucenna, A. Celis, J. Fuentes-Martin, A. Vicente and J. Virto, Phys. Lett. B **760** (2016) 214 doi:10.1016/j.physletb.2016.06.067 [arXiv:1604.03088 [hep-ph]].

- [52] X. G. He and G. Valencia, Phys. Lett. B 779 (2018) 52 doi:10.1016/j.physletb.2018.01.073 [arXiv:1711.09525 [hep-ph]].
- [53] N. Kosnik, Phys. Rev. D 86 (2012) 055004 doi:10.1103/PhysRevD.86.055004 [arXiv:1206.2970 [hep-ph]].
- [54] A. Biswas, A. Shaw and A. K. Swain, arXiv:1811.08887 [hep-ph].
- [55] A. Crivellin, C. Greub and A. Kokulu, Phys. Rev. D 86 (2012) 054014 doi:10.1103/PhysRevD.86.054014 [arXiv:1206.2634 [hep-ph]].
- [56] A. Crivellin, A. Kokulu and C. Greub, Phys. Rev. D 87 (2013) no.9, 094031 doi:10.1103/PhysRevD.87.094031 [arXiv:1303.5877 [hep-ph]].
- [57] A. Celis, M. Jung, X. Q. Li and A. Pich, JHEP
 1301 (2013) 054 doi:10.1007/JHEP01(2013)054
 [arXiv:1210.8443 [hep-ph]].
- [58] P. Ko, Y. Omura and C. Yu, JHEP **1303** (2013) 151 doi:10.1007/JHEP03(2013)151 [arXiv:1212.4607 [hepph]].
- [59] A. Crivellin, J. Heeck and P. Stoffer, Phys. Rev. Lett. **116** (2016) no.8, 081801 doi:10.1103/PhysRevLett.116.081801
 [arXiv:1507.07567 [hep-ph]].
- [60] L. Dhargyal, Phys. Rev. D 93 (2016) no.11, 115009 doi:10.1103/PhysRevD.93.115009 [arXiv:1605.02794 [hep-ph]].
- [61] C. H. Chen and T. Nomura, Eur. Phys. J. C 77 (2017) no.9, 631 doi:10.1140/epjc/s10052-017-5198-6 [arXiv:1703.03646 [hep-ph]].
- [62] S. Iguro and K. Tobe, Nucl. Phys. B 925 (2017) 560 doi:10.1016/j.nuclphysb.2017.10.014 [arXiv:1708.06176 [hep-ph]].
- [63] R. Martinez, C. F. Sierra and G. Valencia, Phys. Rev. D 98 (2018) no.11, 115012 doi:10.1103/PhysRevD.98.115012 [arXiv:1805.04098 [hep-ph]].
- [64] A. Biswas, D. K. Ghosh, S. K. Patra and A. Shaw, arXiv:1801.03375 [hep-ph].
- [65] D. Beirevi, S. Fajfer, N. Konik and O. Sumensari, Phys. Rev. D 94 (2016) no.11, 115021 doi:10.1103/PhysRevD.94.115021 [arXiv:1608.08501 [hep-ph]].
- [66] D. Beirevi, I. Dorner, S. Fajfer, N. Konik, D. A. Faroughy and O. Sumensari, Phys. Rev. D 98 (2018) no.5, 055003 doi:10.1103/PhysRevD.98.055003 [arXiv:1806.05689 [hep-ph]].

- [67] R. Alonso, E. E. Jenkins, A. V. Manohar and M. Trott, JHEP **1404** (2014) 159 doi:10.1007/JHEP04(2014)159 [arXiv:1312.2014 [hep-ph]].
- [68] M. Gonzlez-Alonso, J. Martin Camalich and K. Mimouni, Phys. Lett. B **772** (2017) 777 doi:10.1016/j.physletb.2017.07.003 [arXiv:1706.00410 [hep-ph]].
- [69] M. Gonzlez-Alonso and J. Martin Camalich, JHEP
 1612 (2016) 052 doi:10.1007/JHEP12(2016)052
 [arXiv:1605.07114 [hep-ph]].
- [70] R. Alonso, B. Grinstein and J. Martin Camalich, Phys. Rev. Lett. **118** (2017) no.8, 081802 doi:10.1103/PhysRevLett.118.081802
 [arXiv:1611.06676 [hep-ph]].
- [71] S. S. Gershtein, V. V. Kiselev, A. K. Likhoded and A. V. Tkabladze, Phys. Usp. 38 (1995) 1 [Usp. Fiz. Nauk 165 (1995) 3] doi:10.1070/PU1995v038n01ABEH000063 [hepph/9504319].
- [72] I. I. Y. Bigi, Phys. Lett. B 371, 105 (1996) doi:10.1016/0370-2693(95)01574-4 [hep-ph/9510325].
- [73] M. Beneke and G. Buchalla, Phys. Rev. D 53 (1996) 4991 doi:10.1103/PhysRevD.53.4991 [hepph/9601249].
- [74] C. H. Chang, S. L. Chen, T. F. Feng and X. Q. Li, Phys. Rev. D 64 (2001) 014003 doi:10.1103/PhysRevD.64.014003 [hep-ph/0007162].
- [75] V. V. Kiselev, A. E. Kovalsky and A. K. Likhoded, Nucl. Phys. B 585 (2000) 353 doi:10.1016/S0550-3213(00)00386-2 [hep-ph/0002127].
- [76] A. G. Akeroyd and C. H. Chen, Phys. Rev. D 96 (2017) no.7, 075011 doi:10.1103/PhysRevD.96.075011
 [arXiv:1708.04072 [hep-ph]].
- [77] A. Greljo, J. Martin Camalich and J. D. Ruizlvarez, Phys. Rev. Lett. **122** (2019) no.13, 131803 doi:10.1103/PhysRevLett.122.131803
 [arXiv:1811.07920 [hep-ph]].
- [78] W. Detmold, C. Lehner and S. Meinel, Phys. Rev. D **92** (2015) no.3, 034503 doi:10.1103/PhysRevD.92.034503 [arXiv:1503.01421 [hep-lat]].
- [79] F. U. Bernlochner, Z. Ligeti, D. J. Robinson and W. L. Sutcliffe, Phys. Rev. D 99 (2019) no.5, 055008 doi:10.1103/PhysRevD.99.055008 [arXiv:1812.07593 [hep-ph]].

1D hyp.	best-fit	1σ range	2σ range	p-value (%)	$\mathrm{pull}_{\mathrm{SM}}$	$\mathcal{R}(D)$	$\mathcal{R}(D^*)$	$F_L(D^*)$	$P_{\tau}(D^*)$	$P_{\tau}(D)$	$\mathcal{R}(\Lambda_c)$
C_V^L	0.07	[0.05, 0.09]	[0.04, 0.11]	44	4.0	$0.347 \\ +0.2 \sigma$	$\begin{array}{c c} 0.292 \\ -0.2 \sigma \end{array}$	$0.46 \\ -1.6 \sigma$	$-0.49 \\ -0.2 \sigma$	0.32	0.38
C_S^R	0.09	[0.06, 0.11]	[0.03, 0.14]	2.7	3.1	$0.380 \\ +1.4 \sigma$	$0.260 \\ -2.6 \sigma$	$\begin{array}{c} 0.47 \\ -1.5 \sigma \end{array}$	$-0.46 \\ -0.1 \sigma$	0.46	0.36
C_S^L	0.07	[0.04, 0.10]	[-0.00, 0.13]	0.26	2.1	$0.364 \\ +0.8 \sigma$	$0.250 \\ -3.3 \sigma$	$\begin{array}{c c} 0.45 \\ -1.7 \sigma \end{array}$	$-0.51 \\ -0.2 \sigma$	0.44	0.35
$C_S^L = 4C_T$	-0.03	[-0.07, 0.01]	[-0.11, 0.04]	0.04	0.7	$0.278 \\ -2.1 \sigma$	$0.263 \\ -2.3 \sigma$	$0.46 \\ -1.6 \sigma$	$-0.47 \\ -0.2 \sigma$	0.27	0.33

TABLE I: Results of the fit with one-dimensional scenarios. [14]

TABLE II: Results of the fits with two-dimensional scenarios. [14]

2D hyp.	best-fit	p-value (%)	$\mathrm{pull}_\mathrm{SM}$	$\mathcal{R}(D)$	$\mathcal{R}(D^*)$	$F_L(D^*)$	$P_{\tau}(D^*)$	$P_{\tau}(D)$	$\mathcal{R}(\Lambda_c)$
$(C_{\pm}^{L}, C_{\pm}^{L} = -4C_{\pi})$	(0.10 - 0.04)	29.8	3.6	0.333	0.297	0.47	-0.48	0.25	0.38
$(O_V, O_S = 4O_T)$	(0.10, -0.04)			-0.2σ	$+0.2\sigma$	-1.5σ	-0.2σ		
$\left(C_{L}^{R},C_{L}^{L}\right)$	$\begin{array}{c} (0.29, -0.25) \\ (-0.16, -0.69) \end{array}$	75.7	3.9	0.338	0.297	0.54	-0.27	0.39	0.38
$(0^{\circ}_{S}, 0^{\circ}_{S})_{60\%}$				0.1σ	$+0.1\sigma$	-0.7σ	$+0.2\sigma$		
$(C^R C^L)$	$\begin{array}{c} (0.21, -0.15) \\ (-0.26, -0.61) \end{array}$	30.9	3.6	0.353	0.280	0.51	-0.35	0.42	0.37
$(O_S, O_S) _{30\%}$				$+0.4\sigma$	-1.1σ	-1.0σ	0.0σ		
$(C^R C^L)$	(0.11, -0.04) (-0.37, -0.51)	2.6	2.9	0.366	0.263	0.48	-0.44	0.44	0.36
$(O_S, O_S) _{10\%}$				$+0.9\sigma$	-2.3σ	-1.4σ	-0.1σ		
(C^L, C^R)	(0.08, -0.01)	26.6	3.6	0.343	0.294	0.46	-0.49	0.31	0.38
$(\mathcal{O}_V,\mathcal{O}_S)$				$+0.1\sigma$	-0.1σ	-1.6σ	-0.2σ		
$(\text{Re}[C^{L} - 4C_{-}] \text{Im}[C^{L} - 4C_{-}])$	$(-0.06, \pm 0.31)$	25.0	3.6	0.339	0.295	0.45	-0.41	0.41	0.38
$(\text{Re}[C_S = 4C_T], \text{Re}[C_S = 4C_T]) _{60,30\%}$				0.0σ	0.0σ	-1.7σ	-0.1σ		
$\left \left(\operatorname{Bo}[C^{L} = 4C_{-}] \right) \operatorname{Im}[C^{L} = 4C_{-}] \right $	$(-0.03, \pm 0.24)$	5.9	3.2	0.330	0.275	0.46	-0.45	0.38	0.36
$(\operatorname{IUE}_{CS} - 4C_{T}), \operatorname{III}_{CS} = 4C_{T}) _{10\%}$				-0.3σ	-1.4σ	-1.6σ	-0.1σ		