

Theory of $B \rightarrow \tau\nu$ and $B \rightarrow D^{(*)}\tau\nu$

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1 Introduction

B physics plays an important role in testing the Standard Model (SM) at low energies. Recent experimental results on CP violation in the $B_s \rightarrow J/\psi\phi$ decay and the decay rate for $\mathcal{B}(B_s \rightarrow \mu^+\mu^-)$ severely constrain possible New Physics (NP) contributions to these observables. Analogously, measurements of $\mathcal{B}(B \rightarrow \tau\nu)$ and $\mathcal{B}(B \rightarrow D^{(*)}\tau\nu)$ probe the possible impact of beyond SM physics in the leptonic and semileptonic B decays. Within the SM, these decay modes are important since they contribute in obtaining precise values of the $|V_{ub}|$ and $|V_{cb}|$ together with the relevant hadronic decay constants or form factors. For example due to the large mass of the τ , semileptonic decays $B \rightarrow D^{(*)}\tau\nu$ are sensitive to additional form factors, which are unimportant in the corresponding B decays with light leptons in the final state. In addition these tauonic decay modes represent sensitive tests of lepton flavor universality (LFU) in charged current interactions. The most recent world average of the leptonic $B \rightarrow \tau\nu$ branching fraction measurements $\mathcal{B}(B^- \rightarrow \tau^-\bar{\nu}_\tau) = (11.4 \pm 2.3) \times 10^{-5}$ [1] deviates somewhat from its SM prediction (with the V_{ub} CKM element taken from the global fit [2]). In contrast, the measured exclusive semileptonic $b \rightarrow u\ell\nu$ transition branching fraction $\mathcal{B}(\bar{B}^0 \rightarrow \pi^+\ell^-\bar{\nu}_\ell) = (14.6 \pm 0.7) \times 10^{-5}$ [3, 4] is consistent with SM result used by UTFit, $\mathcal{B}(\bar{B}^0 \rightarrow \pi^+\ell^-\bar{\nu}_\ell) = (1.31 \pm 0.06 \pm 0.06) \times 10^{-4}$ [2]. Furthermore, the BaBar collaboration has recently published results of their measurements of $B \rightarrow D^{(*)}\tau\nu$ branching fractions normalized to the corresponding $B \rightarrow D^{(*)}\ell\nu$ modes (with $\ell = e, \mu$) [7]

$$\mathcal{R}_{\tau/\ell}^* = \mathcal{B}(B \rightarrow D^*\tau^-\bar{\nu}_\tau)/\mathcal{B}(B \rightarrow D^*\ell^-\bar{\nu}_\ell) = 0.332 \pm 0.03, \quad (1a)$$

$$\mathcal{R}_{\tau/\ell} = \mathcal{B}(B \rightarrow D\tau^-\bar{\nu}_\tau)/\mathcal{B}(B \rightarrow D\ell^-\bar{\nu}_\ell) = 0.440 \pm 0.072, \quad (1b)$$

where the statistical and systematic uncertainties have been combined in quadrature. Both values $\mathcal{R}_{\tau/\ell}^*$ and $\mathcal{R}_{\tau/\ell}$ are in agreement with previous measurements, but larger

(at 3.4σ significance when combined) than the SM values $\mathcal{R}_{\tau/\ell}^{*,\text{SM}} = 0.252(3)$ and $\mathcal{R}_{\tau/\ell}^{\text{SM}} = 0.296(16)$ [8]. If confirmed, these results might point to NP in (semi)tauonic $b \rightarrow u(c)$ transitions.

2 $B \rightarrow \tau\nu$

During the last three years there has been a systematic disagreement between the experimental and SM predicted theoretical values for the branching ratio of $B \rightarrow \tau\nu$. The latest Belle collaboration result $\mathcal{B}(B^- \rightarrow \tau^- \bar{\nu}_\tau) = (0.72_{-0.25}^{+0.27} \pm 0.11) \times 10^{-4}$ [9] ameliorates somewhat the enduring tension with the measured value of $\sin 2\beta$ in the global CKM fit. However, the current world average experimental value still deviates from the SM prediction by 2.6σ significance if Gaussian errors are assumed [10].

The B meson coupling constant is the only hadronic parameter entering the theoretical branching ratio prediction. The errors of the most recent lattice QCD results are at the level of 5% [5] and already subleading compared to the dominant parametric uncertainty due to $|V_{ub}|$. One can eliminate the V_{ub} dependence completely by introducing the LFU probing ratio $\mathcal{R}_{\tau/\ell}^\pi \equiv [\tau(B^0)/\tau(B^-)][\mathcal{B}(B^- \rightarrow \tau^- \bar{\nu}_\tau)/\mathcal{B}(\bar{B}^0 \rightarrow \pi^+ \ell^- \bar{\nu}_\ell)] = 0.73 \pm 0.1$. This is to be compared to the SM prediction of $\mathcal{R}_{\tau/\ell}^{\pi,\text{SM}} = 0.31(6)$ [6]. The measured value is more than a factor of 2 bigger – a discrepancy with 2.6σ significance if Gaussian errors are assumed.

3 New Physics in $b \rightarrow c(u)\tau\nu$

The τ lepton in the final state of the (semi)leptonic B meson decays is particularly interesting due to the large τ mass which allows to probe parts of amplitudes in B meson (semi)leptonic decays which are not accessible if the final state contains only light leptons. Possible NP effects in the ratios $\mathcal{R}_{\tau/\ell}^{(*)}$ and $\mathcal{R}_{\tau/\ell}^\pi$ can be approached by using the effective Lagrangian approach [6, 8]. The SM Lagrangian is extended with a set of higher dimensional operators, \mathcal{Q}_i , that are generated at a NP scale Λ above the electroweak symmetry breaking scale $v = (\sqrt{2}/4G_F)^{1/2} \simeq 174$ GeV

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_a \frac{z_a}{\Lambda^{d_a-4}} \mathcal{Q}_i + \text{h.c.}, \quad (2)$$

where d_a stand for the dimensions of the operators \mathcal{Q}_a , while z_a are the dimensionless Wilson coefficients (below we also use $c_a \equiv z_a(v/\Lambda)^{d_a-4}$). Two restrictions are enforced: (i) dangerous down-type flavor changing neutral currents (FCNCs) and (ii) LFU violations in the pion and kaon sectors are not to be generated at the tree level.

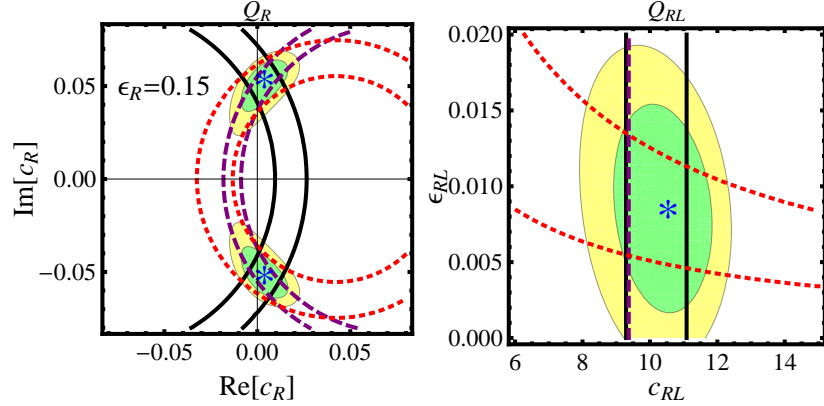


Figure 1: Preferred parameter regions for effective operators \mathcal{Q}_R^i (left plot, as a function of complex c_R Wilson coefficient, and ϵ_R fixed to the best fit value), and for \mathcal{Q}_{RL}^i (right plot, as a function of real c_{RL} Wilson coefficient and the mixing ratio ϵ_{RL}). The best fit points are marked with an asterisk.

The lowest dimensional operators that can modify $R_{\tau/\ell}^{(*)}$ and $\mathcal{R}_{\tau/\ell}^\pi$ are then

$$\mathcal{Q}_L = (\bar{q}_3 \gamma_\mu \tau^a q_3) \mathcal{J}_{3,a}^\mu, \quad \mathcal{Q}_R^i = (\bar{u}_{R,i} \gamma_\mu b_R) (H^\dagger \tau^a \tilde{H}) \mathcal{J}_{3,a}^\mu, \quad (3a)$$

$$\mathcal{Q}_{LR} = i \partial_\mu (\bar{q}_3 \tau^a H b_R) \sum_j \mathcal{J}_{j,a}^\mu, \quad \mathcal{Q}_{RL}^i = i \partial_\mu (\bar{u}_{R,i} \tilde{H}^\dagger \tau^a q_3) \sum_j \mathcal{J}_{j,a}^\mu, \quad (3b)$$

where $\tau_a = \sigma_a/2$, $\mathcal{J}_{j,a}^\mu = (\bar{l}_j \gamma^\mu \tau_a l_j)$, $\tilde{H} \equiv i \sigma_2 H^*$ and i, j are generational indices. We work in the down quark mass basis, where $q_i = (V_{CKM}^{ji*} u_{L,j}, d_{L,i})^T$, and charged lepton mass basis, $l_i = (V_{PMNS}^{ji*} \nu_{L,j}, e_{L,i})^T$. The requirement that there are no down-type tree-level FCNCs imposes flavor alignment in the down sector for the operators \mathcal{Q}_L , \mathcal{Q}_{LR} and \mathcal{Q}_{RL}^i . An additional possibility is to assume [6] the presence of new light invisible fermions, imitating the missing energy signature of SM neutrinos in the $b \rightarrow u_i \tau \nu$ decays.

In the presence of general flavor violating NP, contributions to $b \rightarrow u$ transitions are not generally related to $b \rightarrow c$ transitions. In the case of \mathcal{Q}_R^i for example, the SM expectations are rescaled by $|1 - c_R/2V_{cb}|^2$ in the case of $\mathcal{R}_{\tau/\ell}$ and by $|1 + \epsilon_R c_R/2V_{ub}|^2$ for $\mathcal{R}_{\tau/\ell}^\pi$. The parameters (c_i, ϵ_i) can be obtained by fitting the data using CKM inputs from the global fit as given in [6]. The results are presented in Fig. 1.

Among existing NP models the two-Higgs doublet models (2HDMs) are obvious candidates to induce the \mathcal{Q}_{RL}^i operators. Unfortunately, none of the 2HDMs with natural flavor conservation can simultaneously account for the three considered LFU ratios, while in ref. [6] a 2HDM with more general flavor structure has been considered explaining all the observed deviations.

4 New Observables in $B \rightarrow D\tau\nu$ and $B \rightarrow D^*\tau\nu$

Recently, the authors of [13] noticed that the two form factors appearing in $B \rightarrow D\tau\nu_\tau$ can be related as $F_0(q^2)/F_+(q^2) = 1 - \alpha q^2$ where the current lattice knowledge of both form factors allows for a very precise determination of $\alpha = 0.020(1) \text{ GeV}^{-2}$. Based on the regions of q^2 directly accessible to the lattice computations, they suggested to measure $R_{\tau,\mu}^D = \frac{\mathcal{B}(B \rightarrow D\tau\nu_\tau)}{\mathcal{B}(B \rightarrow D\mu\nu_\mu)}|_{q^2 \leq 8 \text{ GeV}^2}$, which is precisely predicted in the SM with $R_{\tau,\mu}^{D,\text{SM}} = 0.20 \pm 0.02$.

In the decay amplitude of $B \rightarrow D^*\tau\nu_\tau$ it is convenient to introduce helicity amplitudes (for details see [8]). The presence of the pseudo-scalar NP operator only affects the H_{0t} helicity amplitude and can be included as

$$H_{0t} = H_{0t}^{\text{SM}} \left[1 + (g_{SR} - g_{SL}) \frac{q^2}{m_b + m_c} \right]. \quad (4)$$

The experimental branching fraction measurements of $B \rightarrow D^{(*)}\tau\bar{\nu}_\tau$ decays are systematically above SM predictions. It was found in [8] that a fit to the experimental results prefers a non-SM solution with $g_{SL} \simeq -0.9 \text{ GeV}^{-1}$. It is important to point out that these NP operators only contribute to the longitudinally polarized D^* (D_L^*) in the final state.

The helicity amplitudes H_{00} and H_{0t} contribute D_L^* 's, leading to a prediction for the longitudinal rate. One can also study the singly differential longitudinal rate ratio $R_L^*(q^2)$ defined analogously to $R^*(q^2)$ as described in [8]. A simple angular (opening angle) asymmetry is defined as the difference between partial rates where the angle θ between the D^* and τ three-momenta in the $\tau - \bar{\nu}_\tau$ rest-frame (see.g. [8]) is bigger or smaller than $\pi/2$. In the decay modes with light leptons, this asymmetry (A_θ^ℓ) can be used to probe for the presence of right-handed $b \rightarrow c$ currents, since these contribute with opposite sign to $H_{\pm\pm}$ relative to the SM. In the tau modes, it is sensitive only to the real part of NP $g_{SR} - g_{SL}$ contributions and thus provides complementary information compared to the total rate (or R^*). On the other hand, the inclusive asymmetry A_θ integrated over q^2 is very small in the SM with $A_{\theta,\text{SM}} = -6.0(8)\%$; for our NP benchmark point we obtain $A_{\theta,\text{NP}} = 3.4\%$, but even values as low as -30% are still allowed. In [8] it was found that the tau spin asymmetry, defined as $A_\lambda(q^2) = [d\Gamma_\tau/dq^2(\lambda_\tau = -1/2) - d\Gamma_\tau/dq^2(\lambda_\tau = 1/2)]/[d\Gamma_\tau/dq^2]$, where $\lambda_\tau = \pm 1/2$ are tau helicities defined in $\tau\nu_\tau$ center of mass frame, can provide additional useful information.

5 Summary

Within an effective field theory approach the most general lowest dimensional contributions to helicity suppressed (semi)leptonic $b \rightarrow c(u)$ transitions have been considered and found that a precise study of the exclusive decay mode $B \rightarrow D^*\tau\bar{\nu}_\tau$ could

clarify the possible existence of such non-SM physics. Recent experimental value $\mathcal{B}(B \rightarrow \tau\nu)$ is closer to SM prediction and more data on the V_{ub} independent ratio $\mathcal{B}(B^- \rightarrow \tau^-\bar{\nu}_\tau)/\mathcal{B}(\bar{B}^0 \rightarrow \pi^+\ell^-\bar{\nu}_\ell)$ will clarify presence of new physics in $b \rightarrow u\tau\nu_\tau$ transitions. The $B \rightarrow D^*\tau\bar{\nu}_\tau$ mode has a unique sensitivity to the pseudoscalar density operator which does not contribute to the $B \rightarrow D\tau\nu_\tau$ decay mode, while the opposite is true for the scalar density operator. Therefore, the precise experimental study of both $B \rightarrow D^{(*)}\tau\bar{\nu}_\tau$ decay modes will be extremely useful in constraining these kinds of beyond SM physics, especially, since present branching fraction measurements of all helicity suppressed (semi)leptonic modes of B mesons are systematically above SM predictions.

References

- [1] K. Ikado et al. (Belle Collaboration), Phys. Rev. Lett. **97**, 251802 (2006); B. Aubert et al. (BABAR Collaboration), Phys. Rev. D **77**, 011107 (2008); B. Aubert et al. (BABAR Collaboration), Phys. Rev. D **81**, 051101 (2010); K. Hara et al. (Belle Collaboration), Phys. Rev. D **82**, 071101 (2010); Y. Yook (Belle Collaboration), in ICHEP 2012 Conference (unpublished).
- [2] M. Bona *et al.* [UTfit Collaboration], Phys. Lett.B **687**, 61 (2010). J. Charles, O. Deschamps, S. Descotes-Genon, R. Itoh, H. Lacker, A. Menzel, S. Monteil and V. Niess *et al.*, Phys. Rev. D **84** 033005 (2011), B. Aubert et al. [BABAR Collaboration], Phys. Rev. D **81**, (2010) 051101.
- [3] P. del Amo Sanchez et al. BABAR Collaboration, Phys. Rev. D **83**, 032007 (2011);
- [4] D. Asner et al. (Heavy Flavor Averaging Group Collaboration), arXiv:1010.1589; and updates on the HFAG web site <http://www.slac.stanford.edu/xorg/hfag/>.
- [5] J. Laiho, E. Lunghi, and R. Van de Water, Proc. Sci. LATTICE2011, 018 (2011).
- [6] S. Fajfer, J.F. Kamenik, I. Nišandžić and J. Zupan, Phys. Rev. Lett. **109** , 161801 (2012) .
- [7] J. P. Lees , et al. (BABAR Collaboration), Phys. Rev. Lett. **109**, 101802 (2012).
- [8] S. Fajfer, J.F. Kamenik and I. Nišandžić, Phys. Rev. D. **D85**, 094025 (2012).
- [9] I. Adachi et al, Belle Collaboration, arXiv:1208.4678.
- [10] CKM fitter group (http://ckmfitter.in2p3.fr/www/html/ckm_main.html).
- [11] G. Blankenburg and G. Isidori, Eur.Phys.J.Plus **127** , 85 (2012).

- [12] A. Celis, M. Jung, X-Q.Li, and A. Pich, arXiv:1210.8443.
- [13] D. Becirevic, N. Košnik and A. Tayduganov, Phys. Lett. B **716**, 208 (2012).