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Relations between $b \rightarrow c\tau\nu$ decay modes in scalar models

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ABSTRACT: As a consequence of the Ward identity for hadronic matrix elements, we find relations between the differential decay rates of semileptonic decay modes with the underlying quark-level transition $b \rightarrow c\tau\nu$, which are valid in scalar models. The decay-mode dependent scalar form factor is the only necessary theoretical ingredient for the relations. Otherwise, they combine measurable decay rates as a function of the invariant mass-squared of the lepton pair q^2 in such a way that a universal decay-mode independent function is found for decays to vector and pseudoscalar mesons, respectively. This can be applied to the decays $B \rightarrow D^*\tau\nu$, $B_s \rightarrow D_s^*\tau\nu$, $B_c \rightarrow J/\psi\tau\nu$ and $B \rightarrow D\tau\nu$, $B_s \rightarrow D_s\tau\nu$, $B_c \rightarrow \eta_c\tau\nu$, with implications for $R(D^{(*)})$, $R(D_s^{(*)})$, $R(J/\psi)$, $R(\eta_c)$, and $\mathcal{B}(B_c \rightarrow \tau\nu)$. The slope and curvature of the characteristic q^2 -dependence is proportional to scalar new physics parameters, facilitating their straight forward extraction, complementary to global fits.

KEYWORDS: Beyond Standard Model, Heavy Quark Physics

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1 Introduction

There are by now several long-term tensions in flavor physics observables of underlying $b \rightarrow c\tau\nu$ transitions that hint for a violation of lepton-flavor universality (LFU) between light leptons $l = e, \mu$ and heavy τ leptons. Current experimental determinations of the ratios

$$R(\{V, P\}) \equiv \frac{\mathcal{B}(B_q \rightarrow \{V, P\}\tau\nu)}{\mathcal{B}(B_q \rightarrow \{V, P\}l\nu)}, \quad (1.1)$$

are provided by the Heavy Flavor Averaging Group (HFLAV) [1–10],

$$R(D^*) = 0.295 \pm 0.011 \pm 0.008, \quad (1.2)$$

$$R(D) = 0.340 \pm 0.027 \pm 0.013, \quad (1.3)$$

and are in tension with corresponding averages of SM predictions quoted by HFLAV as [1, 11–14]

$$R(D^*)^{\text{SM}} = 0.258 \pm 0.005, \quad (1.4)$$

$$R(D)^{\text{SM}} = 0.299 \pm 0.003. \quad (1.5)$$

An updated SM prediction using additional data on decays to light leptons [15] is provided in ref. [16]

$$R(D^*)^{\text{SM}} = 0.254^{+0.007}_{-0.006}, \quad (1.6)$$

see also refs. [17, 18]. There are further hadronic decays with the same underlying quark level transition like $B_s \rightarrow D_s^{(*)}\tau\nu$, $B_c \rightarrow J/\psi\tau\nu$, $B_c \rightarrow \eta_c\tau\nu$, as well as baryonic decays [19–26]. A 1.8σ -tension has been seen in $B_c \rightarrow J/\psi\tau\nu$ decays

$$R(J/\psi) = 0.71 \pm 0.17 \pm 0.18, \quad [27] \quad (1.7)$$

$$R(J/\psi)^{\text{SM}} = 0.25 \pm 0.03, \quad [28] \quad (1.8)$$

see also refs. [29–36]. Analogous deviations are also seen in $b \rightarrow sl^+l^-$ decays, but there between muon and electron final states [37–47], and there are interesting cross-correlations to high- p_T physics [48–51]. On top of these tensions with LFU, extractions of V_{cb} and V_{ub} from semileptonic decays differ when performed with inclusive and exclusive decays — a long-term story which we anticipate to continue to evolve in unexpected ways also in the future [11–16, 19, 20, 52–66]. A lot of experimental improvement regarding semileptonic decays is expected in the future [67–69]. For progress, form factor results from lattice QCD [30, 70–84] and also LCSRs [85–88] are very important.

A lot of progress has been made in the research of the ability of new physics (NP) models, including from the beginning scalar models, to explain the data [12, 17, 18, 36, 48, 50, 89–91, 91–165]. An important way to probe for NP are relations between different decay modes. In non-leptonic decays this is a tool which is known for a long time, and there based on $SU(3)_F$ methods, see for example refs. [166–173].

For semileptonic $b \rightarrow c\tau\nu$ decays, model-specific relations that connect different decay modes are known for left-handed vector models as the relation [101–103, 110, 127, 144]

$$\text{left-handed vector models:} \quad \frac{R(V)}{R(V)^{\text{SM}}} = \frac{R(P)}{R(P)^{\text{SM}}} = \text{const.} \quad \forall V, P, \quad (1.9)$$

which is e.g. also found in the R -parity violating SUSY model considered in refs. [50, 132]. No matter which decay channel is considered on the left-hand side, the same expression is obtained on the right-hand side. In this paper, we present similar relations between differential decay rates of different decay modes in scalar models. They can be found in eqs. (3.1)–(3.5) and figure 1. The resulting decay-mode independent functions of the invariant lepton mass-squared q^2 are a finger print of the model: its slope and curvature are directly proportional to NP parameters which can thus be readily extracted. A departure from that characteristic function would be a sign of NP beyond scalar models.

In contrast to non-leptonic sum rules, which are based on the approximate flavor symmetry of QCD, the relations that we consider here are based on ones between hadronic form factors which follow from the Ward identity, and are therefore exact. We do not use flavor symmetries to derive these relations.

Note that it is known to be challenging [2, 68, 106, 125, 174, 175] to explain the available $b \rightarrow c\tau\nu$ data with Two-Higgs-Doublet Models (2HDM) [91, 176–187] of type I and II while respecting other constraints [175, 188–196]. Quark flavor constraints from $\mathcal{B}(B \rightarrow X_s\gamma)$, $\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-)$, $\mathcal{B}(B \rightarrow \tau\nu)$ and others, without semileptonic $b \rightarrow c\tau\nu$ and $b \rightarrow sll$ decay modes, imply roughly [175]

$$\begin{aligned} \text{2HDM-I: } & \tan\beta \gtrsim 2 \text{ for } m_{H^\pm} \sim 300 \text{ GeV and } \tan\beta \gtrsim 1.5 \text{ for } m_{H^\pm} \sim 600 \text{ GeV}, \\ \text{2HDM-II: } & m_{H^\pm} \gtrsim 600 \text{ GeV and } \tan\beta \lesssim 25 \text{ for } m_{H^\pm} \leq 1 \text{ TeV}, \end{aligned}$$

see ref. [175] for details. Especially important herein is the bound from $\mathcal{B}(B \rightarrow X_s\gamma)$ [189, 192]. On the other hand, translating the allowed region of the model independent two-dimensional scalar global fit to $b \rightarrow c\tau\nu$ observables performed in refs. [93, 94] into allowed $\tan\beta$ and $m_{H^\pm}$ values in the 2HDM-II, we obtain very small values of order $\tan\beta \lesssim 1$ and $m_{H^\pm} \lesssim 2 \text{ GeV}$. That means the current measurements of $b \rightarrow c\tau\nu$ observables can only be explained simultaneously for parameter values clearly excluded by other bounds, e.g. $\mathcal{B}(B \rightarrow X_s\gamma)$. This observation agrees with figure 6 in ref. [194] where the allowed parameter space for explaining $R(D^*)$ and $R(D)$ also converges only for very small $\tan\beta$ and $m_{H^\pm}$, excluded by other data. Applying the bounds from ref. [175] to the 2HDM-I, the resulting Wilson coefficients [91] are of the order $|C_R| \equiv \cot^2\beta m_b m_\tau / m_{H^\pm}^2 \lesssim 2 \cdot 10^{-5}$, far too small in order to account for either one of $R(D^{(*)})$ [194]. However, examples of more general 2HDMs with flavor-alignment exist that indeed can explain $R(D^{(*)})$ [91, 185, 186].

For $b \rightarrow sll$ LFU ratios $R(K^{(*)})$, the Wilson coefficients $C_{9,10}$ play an important role, see for recent fits ref. [197]. However, in the 2HDM-I or II the contributions to $C_{9,10}$ are suppressed by $\cot^2\beta$, which would only have an impact for $\tan\beta \lesssim 1$, i.e. they can also not account for $R(K^{(*)})$ [198, 199].

Therefore, both charged and neutral current anomalies are challenging for the 2HDM of types I and II. If the anomalies turn out to be true, other forms of 2HDMs with more freedom to account for the data will be needed. In any case the exploration of the parameter space of 2HDMs, with their important interplay of different observables from quark and lepton flavor physics as well as high- p_T measurements, will remain a cornerstone of NP studies.

Note that in order to probe NP in $b \rightarrow c\tau\nu$, it has to be accounted for the additional complication that the measurements e.g. of $R(D^{(*)})$ itself also depend on the specific model, see ref. [62] for details.

We follow here a model-independent way of presenting our results. In section 2 we introduce the notation for differential $b \rightarrow c\tau\nu$ decay rates in the SM and scalar models, including rates for fixed V -polarization and fixed τ -polarization, respectively. We make explicit how these decay rates are related to $b \rightarrow cl\nu$ decay rates to light leptons $l = e, \mu$. In section 3 we present the relations between different decay modes and derive implications for bin-wise integrated rates as well as the LFU observables $R(V)$ and $R(P)$. In section 4 we give numerical results for current and hypothetical future data, after which we conclude in section 5.

2 Decay rates and notation

2.1 SM decay rates

For the Standard Model (SM) expressions of $B_q \rightarrow \{V, P\}\tau\nu$ decays like $B \rightarrow D^*\tau\nu$, $B_s \rightarrow D_s^*\tau\nu$, $B_c \rightarrow J/\psi\tau\nu$ and $B \rightarrow D\tau\nu$, $B_s \rightarrow D_s\tau\nu$, $B_c \rightarrow \eta_c\tau\nu$ we employ the notation of refs. [11, 13, 58]

$$\frac{d\Gamma_{\tau,\text{EXP}}^{\{V,P\}}}{dw} = \frac{d\Gamma_{\tau,1,\text{EXP}}^{\{V,P\}}}{dw} + \frac{d\Gamma_{\tau,2,\text{TH}}^{\{V,P\}}}{dw}, \quad (2.1)$$

$$\frac{d\Gamma_{\tau,1,\text{EXP}}^{\{V,P\}}}{dw} = \left(1 - \frac{m_\tau^2}{q^2}\right)^2 \left(1 + \frac{m_\tau^2}{2q^2}\right) \frac{d\Gamma_{\text{EXP}}^{\{V,P\}}}{dw}, \quad (2.2)$$

$$\frac{d\Gamma_{\tau,2}^{V,\text{TH}}}{dw} = k P_1(w)^2 \frac{m_\tau^2(m_\tau^2 - q^2)^2 r_V^3 (1 + r_V)^2 (w^2 - 1)^{\frac{3}{2}}}{(q^2)^3}, \quad (2.3)$$

$$\frac{d\Gamma_{\tau,2}^{P,\text{TH}}}{dw} = k f_0(w)^2 \frac{m_\tau^2 r_P^2 (r_P^2 - 1)^2 \sqrt{w^2 - 1} (m_\tau^2 - m_{B_q}^2 (1 + r_P^2 - 2r_P w))^2}{(q^2)^3}, \quad (2.4)$$

where

$$r_{\{V,P\}} = \frac{m_{\{V,P\}}}{m_{B_q}}, \quad k = \frac{\eta_{\text{EW}}^2 |V_{cb}|^2 G_F^2 m_{B_q}^5}{32\pi^3}, \quad \eta_{\text{EW}} \simeq 1.0066. \quad (2.5)$$

Here we use furthermore

$$q^2 \equiv (p_{B_q} - p_{\{V,P\}})^2, \quad (2.6)$$

and equivalently, the dimensionless variable

$$w \equiv \frac{m_{B_q}^2 + m_{\{V,P\}}^2 - q^2}{2m_{B_q} m_{\{V,P\}}} \quad (2.7)$$

$$\Leftrightarrow q^2 = -2m_{B_q} m_{\{V,P\}} w + m_{B_q}^2 + m_{\{V,P\}}^2. \quad (2.8)$$

The corresponding physical ranges of these are given as

$$m_\tau^2 \leq q^2 \leq (m_{B_q} - m_{\{V,P\}})^2, \quad (2.9)$$

$$1 \leq w \leq \frac{m_{B_q}^2 + m_{\{V,P\}}^2 - m_\tau^2}{2m_{B_q} m_{\{V,P\}}}. \quad (2.10)$$

Note that $d\Gamma/dw$ and $d\Gamma/dq^2$ are connected by the Jacobian

$$\left| \frac{dq^2}{dw} \right| = 2m_{B_q} m_{\{V,P\}}, \quad (2.11)$$

and that for different decay channels the same q^2 point corresponds to different w points. It is understood implicitly, that form factors of different decay modes are different. $d\Gamma_\tau^{\{V,P\}}/dw$ is the decay rate spectrum with final state τ leptons, and $d\Gamma^{\{V,P\}}/dw$ is the one for light leptons. We denote by the indices “EXP” and “TH” which decay rate functions are directly

measurable and which are to be provided by theory. Of course in principle, assuming the SM, $d\Gamma_{\tau,2}^{\{V,P\}}/dq^2$ can be measured directly. However, for NP tests we cannot assume the SM. $d\Gamma_{\tau,2,\text{TH}}^{\{V,P\}}$ depends on the form factors P_1 and f_0 , respectively, which can be provided by Lattice QCD or Heavy Quark Effective Theory (HQET). They are related as follows to the convention of ref. [57] (BGL), see table I in ref. [13],

$$\mathcal{F}_2^{\text{BGL}} = \frac{1+r_V}{\sqrt{r_V}} P_1, \quad f_0 = f_0^{\text{BGL}}/(m_{B_q}^2 - m_P^2), \quad (2.12)$$

where [11, 57]

$$\langle P(p') | \bar{c} \gamma^\mu b | \bar{B}_q(p) \rangle = f_+(q^2)(p+p')^\mu + f_-(q^2)(p-p')^\mu, \quad (2.13)$$

$$\langle V(p', \varepsilon) | \bar{c} \gamma^\mu b | \bar{B}_q(p) \rangle = i g^{\text{BGL}} \varepsilon^{\mu\alpha\beta\gamma} \varepsilon_\alpha^* p'_\beta p_\gamma, \quad (2.14)$$

$$\langle V(p', \varepsilon) | \bar{c} \gamma^\mu \gamma_5 b | \bar{B}_q(p) \rangle = f^{\text{BGL}} \varepsilon^{*\mu} + (\varepsilon^* \cdot p) [a_+^{\text{BGL}}(p+p')^\mu + a_-^{\text{BGL}}(p-p')^\mu], \quad (2.15)$$

$$f_0(q^2) = f_+(q^2) + \frac{q^2}{m_{B_q}^2 - m_P^2} f_-(q^2), \quad (2.16)$$

$$m_V \mathcal{F}_2^{\text{BGL}}(q^2) = f^{\text{BGL}}(q^2) + (m_{B_q}^2 - m_V^2) a_+^{\text{BGL}}(q^2) + q^2 a_-^{\text{BGL}}(q^2). \quad (2.17)$$

Note that $d\Gamma_{\tau,1,\text{EXP}}^{\{V,P\}}/dw$ contains only information from decays to light leptons $d\Gamma_{\text{EXP}}^{\{V,P\}}/dw$, see eq. (2.2). The latter is given in terms of helicity amplitudes as [58, 90, 91, 200, 201]

$$\frac{d\Gamma_{\text{EXP}}^V}{dw} = \frac{|V_{cb}|^2 G_F^2 (m_D^*)^2 q^2 \sqrt{w^2 - 1}}{48 m_B \pi^3} (H_{V,00}^2 + H_{V,-,-}^2 + H_{V,++}^2), \quad (2.18)$$

$$\frac{d\Gamma_{\text{EXP}}^P}{dw} = \frac{|V_{cb}|^2 G_F^2 (m_D^*)^2 q^2 \sqrt{w^2 - 1}}{48 m_B \pi^3} H_{P,0}^2. \quad (2.19)$$

The analogous expressions for heavy final lepton states are

$$\begin{aligned} \frac{d\Gamma_{\tau,\text{EXP}}^V}{dw} &= \frac{|V_{cb}|^2 G_F^2 (m_D^*)^2 q^2 \sqrt{w^2 - 1}}{48 m_B \pi^3} \left(1 - \frac{m_\tau^2}{q^2}\right)^2 \times \\ &\quad \left((H_{V,00}^2 + H_{V,-,-}^2 + H_{V,++}^2) \left(1 + \frac{m_\tau^2}{2q^2}\right) + \frac{3m_\tau^2}{2q^2} H_{V,0t}^2 \right), \end{aligned} \quad (2.20)$$

$$\frac{d\Gamma_{\tau,\text{EXP}}^P}{dw} = \frac{|V_{cb}|^2 G_F^2 (m_D^*)^2 q^2 \sqrt{w^2 - 1}}{48 m_B \pi^3} \left(H_{P,0}^2 \left(1 + \frac{m_\tau^2}{2q^2}\right) + \frac{3m_\tau^2}{2q^2} H_{P,0t}^2 \right), \quad (2.21)$$

i.e. $d\Gamma_{\tau,2}^{\{V,P\}}/dw$ is proportional to the additional longitudinal helicity amplitude $H_{\{V,P\},0t}^2$. One can measure the decay rates with a fixed D^* helicity, and thereby measure each squared helicity amplitude in eq. (2.18) separately. We write the corresponding decay rates as

$$\frac{d\Gamma_{\text{EXP}}^{V,L}}{dw} \propto |H_{V,00}^2|^2, \quad \frac{d\Gamma_{\text{EXP}}^{V,T\pm}}{dw} \propto |H_{V,\pm\pm}^2|^2. \quad (2.22)$$

They fulfill by definition

$$\frac{d\Gamma_{\text{EXP}}}{dw} = \frac{d\Gamma_{\text{EXP}}^{V,L}}{dw} + \frac{d\Gamma_{\text{EXP}}^{V,T+}}{dw} + \frac{d\Gamma_{\text{EXP}}^{V,T-}}{dw}. \quad (2.23)$$

The corresponding decay rates to τ -leptons are related to those for light leptons as

$$\frac{d\Gamma_{\tau,\text{EXP}}^{V,T\pm}}{dq^2} = \left(1 - \frac{m_\tau^2}{q^2}\right)^2 \left(1 + \frac{m_\tau^2}{2q^2}\right) \frac{d\Gamma_{\text{EXP}}^{V,T\pm}}{dq^2}, \quad (2.24)$$

$$\frac{d\Gamma_{\tau,\text{EXP}}^{V,L}}{dq^2} = \left(1 - \frac{m_\tau^2}{q^2}\right)^2 \left(1 + \frac{m_\tau^2}{2q^2}\right) \frac{d\Gamma_{\text{EXP}}^{V,L}}{dq^2} + \frac{d\Gamma_{\tau,2,\text{TH}}^V}{dq^2}. \quad (2.25)$$

Similarly, for the decay rates with polarized τ -leptons of helicity $\pm 1/2$ we write

$$\frac{d\Gamma_{\tau,\text{EXP}}^{\{V,P\}}}{dw} = \frac{d\Gamma_{\tau,+,\text{EXP}}^{\{V,P\}}}{dw} + \frac{d\Gamma_{\tau,-,\text{EXP}}^{\{V,P\}}}{dw}, \quad (2.26)$$

and where the expressions in terms of helicity amplitudes can be found in refs. [90, 91]. From these we can read off that

$$\frac{d\Gamma_{\tau,-,\text{EXP}}^{\{V,P\}}}{dw} = \left(1 - \frac{m_\tau^2}{q^2}\right)^2 \frac{d\Gamma_{\text{EXP}}^{\{V,P\}}}{dw}, \quad (2.27)$$

$$\frac{d\Gamma_{\tau,+,\text{EXP}}^{\{V,P\}}}{dw} = \frac{m_\tau^2}{2q^2} \left(1 - \frac{m_\tau^2}{q^2}\right)^2 \frac{d\Gamma_{\text{EXP}}^{\{V,P\}}}{dw} + \frac{d\Gamma_{\tau,2,\text{TH}}^{\{V,P\}}}{dw}. \quad (2.28)$$

2.2 Scalar model decay rates

For the NP part of the effective theory of a charged scalar that contributes to $b \rightarrow c\tau\nu$, we adapt the notation of ref. [91],

$$\mathcal{L}_{\text{eff}} = -\frac{4G_F V_{cb}}{\sqrt{2}} (\bar{c} (C_L P_L + C_R P_R) b) (\bar{l} P_L \nu_l), \quad (2.29)$$

where we implicitly use the Wilson coefficients at the m_b -scale. We consider only additional scalar couplings to heavy leptons. For sum and difference of these couplings we use the notation

$$\Sigma C = C_L + C_R, \quad (2.30)$$

$$\Delta C = C_L - C_R. \quad (2.31)$$

For scalar models it is known that the only modification that enters $B_q \rightarrow V\tau\nu$ and $B_q \rightarrow P\tau\nu$ contribute to the longitudinal helicity amplitudes and are proportional to the form factors P_1 and f_0 , respectively [90, 91].

The reason is that from applying the Ward identity one obtains [90]

$$\langle V | \bar{c} \gamma_5 b | B \rangle = \frac{1}{m_b + m_c} q^\mu \langle V | \bar{c} \gamma_\mu \gamma_5 b | B \rangle = \frac{(\varepsilon^* \cdot p_B) m_V}{m_b + m_c} \frac{1 + r_V}{\sqrt{r_V}} P_1. \quad (2.32)$$

Furthermore, for $B \rightarrow D\tau\nu$ it follows [202]

$$\langle P | \bar{c} \gamma_5 b | B \rangle = \frac{m_B^2 - m_D^2}{m_b - m_c} f_0. \quad (2.33)$$

Therefore, in scalar models [90, 91]

$$\frac{d\Gamma_{\tau}^{V,\text{EXP}}}{dq^2} - \frac{d\Gamma_{\tau,1}^{V,\text{EXP}}}{dq^2} = \frac{d\Gamma_{\tau,2}^{V,\text{TH}}}{dq^2} \left| 1 - \Delta C \frac{q^2}{m_{\tau}(m_b + m_c)} \right|^2, \quad (2.34)$$

$$\frac{d\Gamma_{\tau}^{P,\text{EXP}}}{dw} - \frac{d\Gamma_{\tau,1}^{P,\text{EXP}}}{dw} = \frac{d\Gamma_{\tau,2}^{P,\text{TH}}}{dw} \left| 1 + \Sigma C \frac{q^2}{m_{\tau}(m_b - m_c)} \right|^2, \quad (2.35)$$

where on the left hand side are only quantities that can be measured directly, whereas on the right hand side are theoretical parameters only. We have furthermore [91, 139, 203]

$$\mathcal{B}(B_c \rightarrow \tau \nu) = \mathcal{N}^{\text{SM}} |1 - r_{B_c} \Delta C|^2, \quad (2.36)$$

where

$$\mathcal{N}^{\text{SM}} \equiv \tau_{B_c} G_F^2 m_{\tau}^2 f_{B_c}^2 |V_{cb}|^2 \frac{m_{B_c}}{8\pi} \left(1 - \frac{m_{\tau}^2}{m_{B_c}^2} \right)^2, \quad (2.37)$$

is the SM expression for $\mathcal{B}(B_c \rightarrow \tau \nu)$ and we write

$$r_{B_c} \equiv \frac{m_{B_c}^2}{m_{\tau}(m_b + m_c)}. \quad (2.38)$$

3 Universality relations

3.1 Relations for differential rates

We present now a method to differentiate between the SM and scalar models and compare different hadronic $b \rightarrow c \tau \nu$ decay modes in a very direct way. In order to do so, only theory input on the respective mode-dependent $d\Gamma_{\tau,2}^{\{V,P\}}/dq^2$ is necessary. Using the decay rate expressions introduced in section 2, that knowledge makes it possible to isolate q^2 -dependent functions which do not depend on the concrete decay channel anymore, thereby in turn connecting different decay channels:

$$\forall B_q \rightarrow V \tau \nu : \quad S_{\Delta C}(q^2) = \frac{\frac{d\Gamma_{\tau,\text{EXP}}^V}{dq^2} - \left(1 - \frac{m_{\tau}^2}{q^2}\right)^2 \left(1 + \frac{m_{\tau}^2}{2q^2}\right) \frac{d\Gamma_{\tau,\text{EXP}}^V}{dq^2}}{\frac{d\Gamma_{\tau,2}^{V,\text{TH}}}{dq^2}} \quad (3.1)$$

$$= \frac{\frac{d\Gamma_{\tau,\text{EXP}}^{V,L}}{dq^2} - \left(1 - \frac{m_{\tau}^2}{q^2}\right)^2 \left(1 + \frac{m_{\tau}^2}{2q^2}\right) \frac{d\Gamma_{\tau,\text{EXP}}^{V,L}}{dq^2}}{\frac{d\Gamma_{\tau,2}^{V,\text{TH}}}{dq^2}} \quad (3.2)$$

$$= \frac{\frac{d\Gamma_{\tau,+,\text{EXP}}^V}{dq^2} - \frac{m_{\tau}^2}{2q^2} \left(1 - \frac{m_{\tau}^2}{q^2}\right)^2 \frac{d\Gamma_{\tau,\text{EXP}}^V}{dq^2}}{\frac{d\Gamma_{\tau,2}^{V,\text{TH}}}{dq^2}}, \quad (3.3)$$

and

$$\forall B_q \rightarrow P\tau\nu : \quad S_{\Sigma C}(q^2) = \frac{\frac{d\Gamma_{\tau,\text{EXP}}^P}{dq^2} - \left(1 - \frac{m_\tau^2}{q^2}\right)^2 \left(1 + \frac{m_\tau^2}{2q^2}\right) \frac{d\Gamma_{\text{EXP}}^P}{dq^2}}{\frac{d\Gamma_{\tau,2}^{P,\text{TH}}}{dq^2}} \quad (3.4)$$

$$= \frac{\frac{d\Gamma_{\tau,+,\text{EXP}}^P}{dq^2} - \frac{m_\tau^2}{2q^2} \left(1 - \frac{m_\tau^2}{q^2}\right)^2 \frac{d\Gamma_{\text{EXP}}^P}{dq^2}}{\frac{d\Gamma_{\tau,2}^{P,\text{TH}}}{dq^2}}, \quad (3.5)$$

with the functions

$$S_{\Delta C}(q^2) \equiv 1 - 2\text{Re}(\Delta C) \frac{q^2}{m_\tau(m_b + m_c)} + |\Delta C|^2 \left(\frac{q^2}{m_\tau(m_b + m_c)} \right)^2, \quad (3.6)$$

$$S_{\Sigma C}(q^2) \equiv 1 + 2\text{Re}(\Sigma C) \frac{q^2}{m_\tau(m_b - m_c)} + |\Sigma C|^2 \left(\frac{q^2}{m_\tau(m_b - m_c)} \right)^2, \quad (3.7)$$

and in the SM, trivially

$$S_{\{\Delta C, \Sigma C\}}(q^2) \stackrel{\text{SM}}{=} 1. \quad (3.8)$$

The slope and curvature of $S_{\Delta C}(q^2)$ and $S_{\Sigma C}(q^2)$ are directly related to scalar NP parameters. The notation “ $\forall B_q \rightarrow V\tau\nu$ ” and “ $\forall B_q \rightarrow P\tau\nu$ ” implies that the relations hold equally for all decay channels like $B \rightarrow D^*\tau\nu$, $B_s \rightarrow D_s^*\tau\nu$, $B_c \rightarrow J/\psi\tau\nu$, and $B \rightarrow D\tau\nu$, $B_s \rightarrow D_s\tau\nu$, $B_c \rightarrow \eta_c\tau\nu$, respectively, with the same respective q^2 -dependent left hand side.

Eqs. (3.1)–(3.5) are ultimately a consequence of the relation between the hadronic matrix elements eqs. (2.32), (2.33), following from the Ward identity. They are broken by models other than the SM and scalar models, like vector and tensor models. Moreover, when some observables like $R(D^{(*)})$ deviate from the SM, then the simultaneous validity of the above relations is a hint for scalar models. In scalar models with right-handed neutrinos, see refs. [145, 159, 205, 206], eqs. (3.1)–(3.5) apply with modified functions $S_{\{\Delta C, \Sigma C\}}(q^2)$ that contain corresponding additional Wilson coefficients.

In the SM-limit eqs. (3.1) and (3.4) trivially recover eq. (2.1). Of course the division by $d\Gamma_{\tau,2}^{\{V,P\}}/dq^2$ is only possible between the endpoints of each decay channel, i.e. for each decay channel, eqs. (3.1)–(3.5) are only valid for

$$m_\tau^2 < q^2 < q_{\text{max}}^2(\{V, P\}), \quad (3.9)$$

which is decay-mode dependent. Note further, that the relations hold as a function of q^2 . For different decay channels, a given q^2 point corresponds to different w values, see eq. (2.7). That is why we employ $d\Gamma_{\tau}^{\{V,P\}}/dq^2$ here, rather than $d\Gamma_{\tau}^{\{V,P\}}/dw$. In figure 1, we show the q^2 -dependence of eqs. (3.1)–(3.5) for example values of $C_{L,R}$ which correspond to minima that are found in global fits to the available $b \rightarrow c\tau\nu$ decay data [93, 94]. Note that a scalar model at the scale of new physics generates a strongly suppressed tensor operator at the m_b -scale through renormalization group equation (RGE)-running. We have [93, 204]

$$C_V^L(m_b) = C_V^L(1 \text{ TeV}), \quad C_S^R(m_b) = 1.737 C_S^R(1 \text{ TeV}), \quad (3.10)$$

$$C_S^L(m_b) = 1.752 C_S^L(1 \text{ TeV}), \quad C_T(m_b) = -0.004 C_S^L(1 \text{ TeV}). \quad (3.11)$$

Consequently, we neglect the tensor Wilson coefficient in figure 1.

Figure 1. The universal q^2 -dependence $S_{\{\Delta C, \Sigma C\}}(q^2)$, eqs. (3.6), (3.7), that appears on the left-hand-side of the relations eqs. (3.1)–(3.5) of $B_q \rightarrow \{V, P\}\tau\nu$ decays in scalar models independent of the decay mode. The example values correspond to the minima $(C_R, C_L) = (-0.37, -0.51)$ and $(C_R, C_L) = (0.29, -0.25)$ at 1 TeV found in fits to the global $b \rightarrow c\tau\nu$ data in table II of ref. [94], and that we RGE-evolve [93, 204] down to the m_b -scale. It is understood, that for a given decay channel the shown curve is only valid between the endpoints $m_\tau^2 < q^2 < q_{\max}^2(\{V, P\})$, see eq. (3.9). The region $q^2 < m_\tau^2$ is unphysical. From the curvature and slope of $S_{\{\Delta C, \Sigma C\}}(q^2)$ one can directly extract the NP parameters.

On top of the above relations that allow the differentiation between SM and scalar models by measuring the characteristic q^2 -dependence, we have additional relations between the decays to τ leptons and light leptons that do not allow the differentiation between SM and scalar models, but only the one of other models from the SM and scalar models. These are

$$0 = \frac{d\Gamma_{\tau, \text{EXP}}^{V, T \pm}}{dq^2} - \left(1 - \frac{m_\tau^2}{q^2}\right)^2 \left(1 + \frac{m_\tau^2}{2q^2}\right) \frac{d\Gamma_{\text{EXP}}^{V, T \pm}}{dq^2} \quad (3.12)$$

$$= \frac{d\Gamma_{\tau, -, \text{EXP}}^{\{V, P\}}}{dq^2} - \left(1 - \frac{m_\tau^2}{q^2}\right)^2 \frac{d\Gamma_{\text{EXP}}^{\{V, P\}}}{dq^2}. \quad (3.13)$$

Again, vector and tensor models would violate these relations.

Eqs. (3.1)–(3.5) can also be used in order to test form factor calculations. In the ratios

$$\frac{d\Gamma_{\tau}^{\{V_1, P_1\}, \text{EXP}}/dq^2 - d\Gamma_{\tau, 1}^{\{V_1, P_1\}, \text{EXP}}/dq^2}{d\Gamma_{\tau}^{\{V_2, P_2\}, \text{EXP}}/dq^2 - d\Gamma_{\tau, 1}^{\{V_2, P_2\}, \text{EXP}}/dq^2} = \frac{d\Gamma_{\tau, 2}^{\{V_1, P_1\}, \text{TH}}/dq^2}{d\Gamma_{\tau, 2}^{\{V_2, P_2\}, \text{TH}}/dq^2}, \quad (3.14)$$

scalar NP cancels out, i.e. we can check the ratios $P_1^{V_1}(q^2)^2/P_1^{V_2}(q^2)^2$ and $f_0^{P_1}(q^2)^2/f_0^{P_2}(q^2)^2$ directly from data, relying not anymore on the SM, but on the weaker assumption that at

most scalar NP is present. Of course, more general NP would invalidate this test. However, this would then also be seen in the violation of eqs. (3.12), (3.13).

Comparing to results present in the literature, the analytic relations found here are different from the numerical sum rule for the integrated observables $R(D^*)$, $R(D)$ and $R(\Lambda_c)$ in eqs. (28), (29) of ref. [93], see also ref. [94]. While eqs. (3.1)–(3.5) are model-specific, i.e. can be used to differentiate between models, the sum rule in refs. [93, 94] is valid for any NP model and can thus be used as a consistency check of the data.

Eqs. (3.2), (3.3) and (3.5) agree with the observation made in refs. [91, 127], that in scalar models, the expressions including observables of one decay mode $R(D^*)(q^2) - R_L(D^*)(q^2)$ and $R(D^*)(q^2)(A_\lambda^{D^*}(q^2) + 1)$ stay SM-like, i.e. are not suited to distinguish SM and scalar models, but only to differentiate other models. Here, $R_L(D^*)(q^2)$ is the LFU ratio of the longitudinal decay rates, and $A_\lambda^{D^*}(q^2)$ is the asymmetry in the τ -polarization, see refs. [91, 127] for details.

3.2 Relations for integrated rates

3.2.1 Bin-wise relations

In practice, only binned measurements of the q^2 -dependent decay rates are performed. The integration of the relations eqs. (3.12), (3.13) is straight forward. For eqs. (3.1)–(3.5) there are two different options: (a) Integrate them in the form as written, or (b) before that multiply both sides by $d\Gamma_{\tau,2}^{\{V,P\}}/dq^2$. Option (a) gives

$$\begin{aligned} \forall B_q \rightarrow V\tau\nu: \quad & \int_{\text{bin}} \frac{d\Gamma_\tau^{V,\text{EXP}}/dq^2}{d\Gamma_{\tau,2}^{V,\text{TH}}/dq^2} dq^2 - \int_{\text{bin}} \frac{d\Gamma_{\tau,1}^{V,\text{EXP}}/dq^2}{d\Gamma_{\tau,2}^{V,\text{TH}}/dq^2} dq^2 \\ & = 1 - 2\text{Re}(\Delta C) \int_{\text{bin}} \frac{q^2}{m_\tau(m_b + m_c)} dq^2 + |\Delta C|^2 \int_{\text{bin}} \left(\frac{q^2}{m_\tau(m_b + m_c)} \right)^2 dq^2, \end{aligned} \quad (3.15)$$

$$\begin{aligned} \forall B_q \rightarrow P\tau\nu: \quad & \int_{\text{bin}} \frac{d\Gamma_\tau^{P,\text{EXP}}/dq^2}{d\Gamma_{\tau,2}^{P,\text{TH}}/dq^2} dq^2 - \int_{\text{bin}} \frac{d\Gamma_{\tau,1}^{P,\text{EXP}}/dq^2}{d\Gamma_{\tau,2}^{P,\text{TH}}/dq^2} dq^2 \\ & = 1 + 2\text{Re}(\Sigma C) \int_{\text{bin}} \frac{q^2}{m_\tau(m_b - m_c)} dq^2 + |\Sigma C|^2 \int_{\text{bin}} \left(\frac{q^2}{m_\tau(m_b - m_c)} \right)^2 dq^2, \end{aligned} \quad (3.16)$$

and completely analogous equations for the decay rates with fixed D^* - and τ -polarization, respectively. We stress that it is implied that eqs. (3.15) and (3.16) are valid for any decay mode to vector or pseudoscalar final states, respectively, as long as on the left and the right hand side the same q^2 -bin is considered. Of course it is only possible to compare bins which are kinematically accessible for each considered decay. Eqs. (3.15) and (3.16) also make clear how to put the lattice form factor check eq. (3.14) into its corresponding binned version.

In practice it is challenging to obtain the integrals in eqs. (3.15) and (3.16), because what actually is measured by experiment is $\int_{\text{bin}} d\Gamma_\tau^{\{V,P\}}/dq^2 dq^2$. However, once the q^2 -distribution of the above decays is measured, the evaluation of eqs. (3.15), (3.16) could be

facilitated by performing the folding with the additional theory factors with the software package HAMMER [62].

Option (b) for integrating eqs. (3.1)–(3.5), i.e. first multiplying by $d\Gamma_{\tau,2}^{\{V,P\}}/dq^2$, does not need this reweighting procedure. We obtain:

$$\begin{aligned} \forall B_q \rightarrow V\tau\nu: & \int_{\text{bin}} \frac{d\Gamma_{\tau}^{V,\text{EXP}}}{dq^2} dq^2 - \int_{\text{bin}} \frac{d\Gamma_{\tau,1}^{V,\text{EXP}}}{dq^2} dq^2 - \int_{\text{bin}} \frac{d\Gamma_{\tau,2}^{V,\text{TH}}}{dq^2} dq^2 \\ & = -2\text{Re}(\Delta C) \int_{\text{bin}} \frac{q^2}{m_{\tau}(m_b+m_c)} \frac{d\Gamma_{\tau,2}^{V,\text{TH}}}{dq^2} dq^2 + |\Delta C|^2 \int_{\text{bin}} \left(\frac{q^2}{m_{\tau}(m_b+m_c)} \right)^2 \frac{d\Gamma_{\tau,2}^{V,\text{TH}}}{dq^2} dq^2, \end{aligned} \quad (3.17)$$

$$\begin{aligned} \forall B_q \rightarrow P\tau\nu: & \int_{\text{bin}} \frac{d\Gamma_{\tau}^{P,\text{EXP}}}{dq^2} dq^2 - \int_{\text{bin}} \frac{d\Gamma_{\tau,1}^{P,\text{EXP}}}{dq^2} dq^2 - \int_{\text{bin}} \frac{d\Gamma_{\tau,2}^{P,\text{TH}}}{dq^2} dq^2 \\ & = 2\text{Re}(\Sigma C) \int_{\text{bin}} \frac{q^2}{m_{\tau}(m_b-m_c)} \frac{d\Gamma_{\tau,2}^{P,\text{TH}}}{dq^2} dq^2 + |\Sigma C|^2 \int_{\text{bin}} \left(\frac{q^2}{m_{\tau}(m_b-m_c)} \right)^2 \frac{d\Gamma_{\tau,2}^{P,\text{TH}}}{dq^2} dq^2, \end{aligned} \quad (3.18)$$

and again analogous equations for the decay rates with fixed D^* - or τ -polarization.

If the above equations are applied to multiple bins of one or several decay modes, it can be directly solved for the NP parameters. Furthermore, it can in principle be solved for the NP parameters multiple times, generating additional relations. In the next section we make this explicit for the case where the bin is the complete q^2 -range.

3.2.2 Relations for $R(V)$ and $R(P)$

We discuss now the special case of eqs. (3.17), (3.18) when the bin that we integrate over is the complete q^2 -range. To that end we define

$$R_{\tau,i}^n(\{V,P\}) \equiv \frac{1}{\Gamma^{\{V,P\}}} \int_{m_{\tau}^2}^{(m_{B_q}-m_{\{V,P\}})^2} \left(\frac{q^2}{m_{\tau}(m_b \pm m_c)} \right)^n \frac{d\Gamma_{\tau,i}^{\{V,P\}}}{dq^2} dq^2, \quad i = 1, 2, \quad (3.19)$$

$$R_{\tau,i}(\{V,P\}) \equiv R_{\tau,i}^0(\{V,P\}), \quad (3.20)$$

$$R(\{V,P\}) \equiv R_{\tau}^0(\{V,P\}), \quad (3.21)$$

with $\Gamma^{\{V,P\}}$ being the integrated decay rate for decays to light leptons, so that $R(V)$ and $R(P)$ are defined as usual.

Note that instead of employing the experimental measurement of $R_{\tau,1}(\{V,P\})$ from decays to light leptons, see eqs. (2.2), (3.19), we can also use the corresponding SM expression, because we assume the decays to light leptons to be SM-like. With

$$R^{\text{SM}}(\{V,P\}) = R_{\tau,1}^{\text{TH}}(\{V,P\}) + R_{\tau,2}^{\text{TH}}(\{V,P\}), \quad (3.22)$$

$$\Delta R(\{V,P\}) \equiv R^{\text{EXP}}(\{V,P\}) - R^{\text{SM}}(\{V,P\}), \quad (3.23)$$

and a bin over the complete q^2 -range we have from eqs. (3.17), (3.18)

$$\forall V: \quad \Delta R(V) = -2 R_{\tau,2}^{1,\text{TH}}(V) \text{Re}(\Delta C) + R_{\tau,2}^{2,\text{TH}}(V) |\Delta C|^2, \quad (3.24)$$

$$\forall P: \quad \Delta R(P) = 2 R_{\tau,2}^{1,\text{TH}}(P) \text{Re}(\Sigma C) + R_{\tau,2}^{2,\text{TH}}(P) |\Sigma C|^2, \quad (3.25)$$

respectively. We stress again that these relations are valid for any decay mode $B_q \rightarrow V\tau\nu$ and $B_q \rightarrow P\tau\nu$, respectively. Additionally, we have from eq. (2.36)

$$\mathcal{B}(B_c \rightarrow \tau\nu)/\mathcal{N}^{\text{SM}} - 1 = -2r_{B_c} \text{Re}(\Delta C) + r_{B_c}^2 |\Delta C|^2. \quad (3.26)$$

Using eqs. (3.24) and (3.25) for multiple decay channels, and eliminating ΔC and ΣC , we obtain:

$$\frac{\Delta R(V_1)}{\Delta R(V_2)} = \frac{\left(R_{\tau,2}^{1,\text{TH}}(V_3) R_{\tau,2}^{2,\text{TH}}(V_1) - R_{\tau,2}^{1,\text{TH}}(V_1) R_{\tau,2}^{2,\text{TH}}(V_3) \right) \frac{\Delta R(V_1)}{\Delta R(V_3)}}{R_{\tau,2}^{1,\text{TH}}(V_2) R_{\tau,2}^{2,\text{TH}}(V_1) - R_{\tau,2}^{1,\text{TH}}(V_1) R_{\tau,2}^{2,\text{TH}}(V_2) + \left(R_{\tau,2}^{1,\text{TH}}(V_3) R_{\tau,2}^{2,\text{TH}}(V_2) - R_{\tau,2}^{1,\text{TH}}(V_2) R_{\tau,2}^{2,\text{TH}}(V_3) \right) \frac{\Delta R(V_1)}{\Delta R(V_3)}} \quad (3.27)$$

$$\frac{\Delta R(V_1)}{\Delta R(V_2)} = \frac{\left(r_{B_c}^2 R_{\tau,2}^{1,\text{TH}}(V_1) - r_{B_c} R_{\tau,2}^{2,\text{TH}}(V_1) \right) \times \frac{\Delta R(V_1)}{\mathcal{B}(B_c \rightarrow \tau\nu)/\mathcal{N}^{\text{SM}} - 1}}{R_{\tau,2}^{1,\text{TH}}(V_1) R_{\tau,2}^{2,\text{TH}}(V_2) - R_{\tau,2}^{1,\text{TH}}(V_2) R_{\tau,2}^{2,\text{TH}}(V_1) + \left(r_{B_c}^2 R_{\tau,2}^{1,\text{TH}}(V_2) - r_{B_c} R_{\tau,2}^{2,\text{TH}}(V_2) \right) \frac{\Delta R(V_1)}{\mathcal{B}(B_c \rightarrow \tau\nu)/\mathcal{N}^{\text{SM}} - 1}} \quad (3.28)$$

We can also solve directly for the NP parameters:

$$|\Delta C|^2 = \frac{R_{\tau,2}^{1,\text{TH}}(V_1) \Delta R(V_2) - R_{\tau,2}^{1,\text{TH}}(V_2) \Delta R(V_1)}{R_{\tau,2}^{1,\text{TH}}(V_1) R_{\tau,2}^{2,\text{TH}}(V_2) - R_{\tau,2}^{1,\text{TH}}(V_2) R_{\tau,2}^{2,\text{TH}}(V_1)} \quad (3.29)$$

$$= \frac{(\mathcal{B}^{\text{EXP}}(B_c \rightarrow \tau\nu)/\mathcal{N}^{\text{SM}} - 1) R_{\tau,2}^{1,\text{TH}}(V_1) - r_{B_c} \Delta R(V_1)}{r_{B_c}^2 R_{\tau,2}^{1,\text{TH}}(V_1) - r_{B_c} R_{\tau,2}^{2,\text{TH}}(V_1)}, \quad (3.30)$$

$$-2 \text{Re}(\Delta C) = \frac{R_{\tau,2}^{2,\text{TH}}(V_2) \Delta R(V_1) - R_{\tau,2}^{2,\text{TH}}(V_1) \Delta R(V_2)}{R_{\tau,2}^{1,\text{TH}}(V_1) R_{\tau,2}^{2,\text{TH}}(V_2) - R_{\tau,2}^{1,\text{TH}}(V_2) R_{\tau,2}^{2,\text{TH}}(V_1)} \quad (3.31)$$

$$= \frac{r_{B_c}^2 \Delta R(V_1) - (\mathcal{B}^{\text{EXP}}(B_c \rightarrow \tau\nu)/\mathcal{N}^{\text{SM}} - 1) R_{\tau,2}^{2,\text{TH}}(V_1)}{r_{B_c}^2 R_{\tau,2}^{1,\text{TH}}(V_1) - r_{B_c} R_{\tau,2}^{2,\text{TH}}(V_1)}. \quad (3.32)$$

For the pseudoscalar final states it follows similarly, that

$$\frac{\Delta R(P_1)}{\Delta R(P_2)} = \frac{\left(R_{\tau,2}^{1,\text{TH}}(P_3) R_{\tau,2}^{2,\text{TH}}(P_1) - R_{\tau,2}^{1,\text{TH}}(P_1) R_{\tau,2}^{2,\text{TH}}(P_3) \right) \frac{\Delta R(P_1)}{\Delta R(P_3)}}{R_{\tau,2}^{1,\text{TH}}(P_2) R_{\tau,2}^{2,\text{TH}}(P_1) - R_{\tau,2}^{1,\text{TH}}(P_1) R_{\tau,2}^{2,\text{TH}}(P_2) + \left(R_{\tau,2}^{1,\text{TH}}(P_3) R_{\tau,2}^{2,\text{TH}}(P_2) - R_{\tau,2}^{1,\text{TH}}(P_2) R_{\tau,2}^{2,\text{TH}}(P_3) \right) \frac{\Delta R(P_1)}{\Delta R(P_3)}}, \quad (3.33)$$

$$|\Sigma C|^2 = \frac{R_{\tau,2}^{1,\text{TH}}(P_1) \Delta R(P_2) - R_{\tau,2}^{1,\text{TH}}(P_2) \Delta R(P_1)}{R_{\tau,2}^{1,\text{TH}}(P_1) R_{\tau,2}^{2,\text{TH}}(P_2) - R_{\tau,2}^{1,\text{TH}}(P_2) R_{\tau,2}^{2,\text{TH}}(P_1)}, \quad (3.34)$$

$$2 \text{Re}(\Sigma C) = \frac{R_{\tau,2}^{2,\text{TH}}(P_2) \Delta R(P_1) - R_{\tau,2}^{2,\text{TH}}(P_1) \Delta R(P_2)}{R_{\tau,2}^{1,\text{TH}}(P_1) R_{\tau,2}^{2,\text{TH}}(P_2) - R_{\tau,2}^{1,\text{TH}}(P_2) R_{\tau,2}^{2,\text{TH}}(P_1)} \quad (3.35)$$

Analogous relations can be obtained for fixed τ or V polarization.

3.2.3 Approximate relations

In the limit of a small NP contribution, i.e. in case that

$$\frac{|R_{\tau,2}^{2,\text{TH}}(V)|}{2|R_{\tau,2}^{1,\text{TH}}(V)|} \frac{|\Delta C|^2}{|\text{Re}(\Delta C)|} \ll 1, \quad (3.36)$$

$$\frac{1}{2} r_{B_c} \frac{|\Delta C|^2}{|\text{Re}(\Delta C)|} \sim 2 \frac{|\Delta C|^2}{|\text{Re}(\Delta C)|} \ll 1, \quad (3.37)$$

we find approximate relations that are simpler than the ones derived in section 3.2.2. From eqs. (3.24), (3.26) we have in this case

$$\frac{\Delta R(V_1)}{\Delta R(V_2)} = \frac{R_{\tau,2}^{1,\text{TH}}(V_1)}{R_{\tau,2}^{1,\text{TH}}(V_2)}, \quad (3.38)$$

and

$$-2 \operatorname{Re}(\Delta C) = \frac{\Delta R(V)}{R_{\tau,2}^{1,\text{TH}}(V)} = \frac{1}{r_{B_c}} \left(\frac{\mathcal{B}(B_c \rightarrow \tau \nu)}{\mathcal{N}^{\text{SM}}} - 1 \right). \quad (3.39)$$

When $|\Delta C|^2$ is not known, a check of eqs. (3.36) and (3.37) is not available. However, the conditions eqs. (3.36), (3.37) also imply the weaker inequalities

$$\frac{|R_{\tau,2}^{2,\text{TH}}(V)|}{2|R_{\tau,2}^{1,\text{TH}}(V)|} |\operatorname{Re}(\Delta C)| \ll 1, \quad (3.40)$$

$$\frac{1}{2} r_{B_c} |\operatorname{Re}(\Delta C)| \sim 2 |\operatorname{Re}(\Delta C)| \ll 1, \quad (3.41)$$

which can be used for a consistency check after the extraction of $\operatorname{Re}(\Delta C)$ through eq. (3.39).

Analogously, for semileptonic decays to pseudoscalars we have the approximate relations

$$\frac{\Delta R(P_1)}{\Delta R(P_2)} = \frac{R_{\tau,2}^{1,\text{TH}}(P_1)}{R_{\tau,2}^{1,\text{TH}}(P_2)}, \quad (3.42)$$

$$2 \operatorname{Re}(\Sigma C) = \frac{\Delta R(P)}{R_{\tau,2}^{1,\text{TH}}(P)}, \quad (3.43)$$

which are valid if the relation

$$\frac{|R_{\tau,2}^{2,\text{TH}}(P)|}{2|R_{\tau,2}^{1,\text{TH}}(P)|} \frac{|\Sigma C|^2}{|\operatorname{Re}(\Sigma C)|} \leq \frac{|R_{\tau,2}^{2,\text{TH}}(P)|}{2|R_{\tau,2}^{1,\text{TH}}(P)|} |\operatorname{Re}(\Sigma C)| \ll 1 \quad (3.44)$$

is fulfilled.

4 Application to data

4.1 Current data

4.1.1 Relations between $\mathcal{B}(B_c \rightarrow \tau \nu)$, $R(D^*)$ and $R(J/\psi)$ for small scalar NP

We apply the relations of section 3 to the current measurements of charged current LFU observables that we list in section 1. With current data we can test the approximate relation eq. (3.39) for $V = D^*$ and $V = J/\psi$. Note that no direct measurement of $R_{\tau,1}^{\text{EXP}}(D^*)$ is available, so that we use its SM value, see eq. (3.22). We use the fit results for $B \rightarrow D^* \tau \nu$ from ref. [16], including $R(D^*)^{\text{SM}}$ as given in eq. (1.6), which employs recent data on decays

to light leptons [1, 15, 56], as well as HQET input for P_1 , see ref. [16] for details. For the needed integrals we obtain

$$R_{\tau,2}^{1,\text{TH}}(D^*) = 0.018_{-0.004}^{+0.005}, \quad (4.1)$$

$$R_{\tau,2}^{2,\text{TH}}(D^*) = 0.013 \pm 0.003. \quad (4.2)$$

For $B_c \rightarrow J/\psi \tau \nu$ we use eqs. (1.7), (1.8) and the fit results provided in ref. [28]. We obtain for the needed integrals

$$R_{\tau,2}^{1,\text{TH}}(J/\psi) = 0.017 \pm 0.005, \quad (4.3)$$

$$R_{\tau,2}^{2,\text{TH}}(J/\psi) = 0.012_{-0.003}^{+0.004}. \quad (4.4)$$

Therein, we also take into account the correlations between the z -expansion coefficients of the form factors of $B_c \rightarrow J/\psi \tau \nu$ provided in ref. [28], however, we do not take into account further correlations like with the form factor coefficients of $B \rightarrow D^* \tau \nu$. Note that our input from refs. [16, 28] takes into account statistical and systematic errors, and so do consequently also our numerical results. We use furthermore [207]

$$f_{B_c} = (0.434 \pm 0.015) \text{ GeV}. \quad (4.5)$$

The approximate relation eq. (3.39) implies

$$\mathcal{B}(B_c \rightarrow \tau \nu) = \mathcal{N}^{\text{SM}} \left(1 + r_{B_c} \frac{\Delta R(D^*)}{R_{\tau,2}^{1,\text{TH}}(D^*)} \right), \quad (4.6)$$

$$R(J/\psi) = R(J/\psi)^{\text{SM}} + \Delta R(D^*) \frac{R_{\tau,2}^{1,\text{TH}}(J/\psi)}{R_{\tau,2}^{1,\text{TH}}(D^*)}, \quad (4.7)$$

see eq. (2.37) for the definition of $\mathcal{N}^{\text{SM}}$. Before we evaluate these expressions numerically, we perform the consistency check eq. (3.41) required for actually applying the used approximation from section 3.2.3. We obtain

$$\text{Re}(\Delta C) = -\frac{1}{2} \frac{\Delta R(D^*)}{R_{\tau,2}^{1,\text{TH}}(D^*)} = -1.1_{-0.7}^{+0.5}. \quad (4.8)$$

Note that $\text{Re}(\Delta C)$ in eq. (4.8) is large and actually violates the consistency check, therefore invalidating eqs. (4.6)–(4.8). In the next section we therefore consider a relation that does not rely on the approximation of small Wilson coefficients.

4.1.2 Relation between $\mathcal{B}(B_c \rightarrow \tau \nu)$, $R(D^*)$ and $R(J/\psi)$ for arbitrary scalar NP

As described in section 4.1.1, with current data the approximate relation between $\mathcal{B}(B_c \rightarrow \tau \nu)$ and $R(D^*)$ is not applicable, because $|\Delta C|^2$ turns out to be too large. Consequently, instead of the approximate relations from section 3.2.3, we need to use the exact

Observable	Hypothetical Future Data
$R(J/\psi)^{\text{EXP}}$	0.71 ± 0.05
$R(D^*)^{\text{EXP}}$	0.295 ± 0.006

Table 1. Future scenario for hypothetical experimental data, with combined statistical and systematic errors.

relations from section 3.2.2. We have

$$R(J/\psi) = R(J/\psi)^{\text{SM}} + \frac{\left(\frac{\mathcal{B}(B_c \rightarrow \tau\nu)}{\mathcal{N}_{\text{SM}}} - 1\right) (R_{\tau,2}^{1,\text{TH}}(J/\psi) R_{\tau,2}^{2,\text{TH}}(D^*) - R_{\tau,2}^{1,\text{TH}}(D^*) R_{\tau,2}^{2,\text{TH}}(J/\psi)) + r_{B_c} \Delta R(D^*) (R_{\tau,2}^{2,\text{TH}}(J/\psi) - r_{B_c} R_{\tau,2}^{1,\text{TH}}(J/\psi))}{r_{B_c} (R_{\tau,2}^{2,\text{TH}}(D^*) - r_{B_c} R_{\tau,2}^{1,\text{TH}}(D^*))}. \quad (4.9)$$

As input for $B \rightarrow D^* \tau \nu$ and $B_c \rightarrow J/\psi \tau \nu$ we employ again the fit results from refs. [16, 28]. Furthermore, we vary $\mathcal{B}(B_c \rightarrow \tau \nu)$ in the conservative region $0 \leq \mathcal{B}(B_c \rightarrow \tau \nu) \leq 0.6$ [93, 94], see also refs. [127, 139, 203, 208–210]. We use the fit results eqs. (4.1)–(4.4) in eq. (4.9) and for simplicity use Gaussian error propagation without correlations to calculate the error of $R(J/\psi)$. We obtain thereby the scalar model prediction

$$R(J/\psi) = 0.29 \pm 0.04, \quad (4.10)$$

which has a 1.7σ tension with the current measurement eq. (1.7).

4.2 Future data scenario

In order to further explore the implications of eq. (4.9), we consider a hypothetical future data set given in table 1, and motivated from prospects at Belle II and LHCb. At 50 ab^{-1} Belle II expects a relative error on $R(D^*)$ of $(\pm 1.0 \pm 2.0)\%$, see table 50 in ref. [68]. At 50 fb^{-1} LHCb expects an absolute precision, combining statistical and systematical errors, for $R(D^*)$ of ~ 0.006 and for $R(J/\psi)$ of ~ 0.05 , see figure 55 in ref. [67]. With the input of $R(D^*)$ from table 1, we find the prediction eq. (4.10) almost unchanged,

$$R(J/\psi) = 0.29 \pm 0.03. \quad (4.11)$$

This highlights the importance of a future improvement of the theory uncertainty of the scalar form factors. However, the deviation of $R(J/\psi)^{\text{EXP}}$ as given in table 1 would amount in this scenario to an exclusion of scalar models by 7.2σ .

Note that with future data of course many more opportunities arise to apply the methods presented above, when the spectrum of $b \rightarrow c \tau \nu$ decays is measured. This will further enhance the possible significances for the exclusion of models, as well as the ability to detect NP.

5 Conclusions

We find relations between differential decay rates of different $b \rightarrow c\tau\nu$ decay modes in scalar models. The relations are given in eqs. (3.1)–(3.5) and show a universal q^2 -dependence for all decay modes to vector and pseudoscalar final states, respectively. They follow ultimately from the Ward identity for scalar hadronic matrix elements. Models different from scalar models break the relations. Requiring only theoretical knowledge on the scalar $B \rightarrow \{V, P\}$ form factor, and otherwise only experimental measurements of various decay rates and their phase space weighted form, it is possible to disentangle Standard Model (SM) and scalar models by determining the characteristic decay mode independent function $S_{\{\Delta C, \Sigma C\}}(q^2)$, see eqs. (3.6), (3.7), that we show in figure 1.

From the slope and curvature of $S_{\{\Delta C, \Sigma C\}}(q^2)$ one can directly extract new physics parameters. The SM-limit is given by $S_{\Delta C}(q^2) = S_{\Sigma C}(q^2) = 1$. Furthermore, the cancellation of scalar new physics in the ratio eq. (3.14) allows for a check of lattice results for scalar form factors. The check does not rely on the SM, but on the weaker assumption that at most scalar new physics is present. Signatures of other new physics models would also be seen in the violation of other relations, like eqs. (3.12), (3.13).

We make explicit the implications for corresponding bin-wise integrated rates as well as for ratios of $\Delta R(\{V, P\}) \equiv R^{\text{EXP}}(\{V, P\}) - R(\{V, P\})^{\text{SM}}$ for different decay channels, see eqs. (3.27), (3.28), (3.33). For small new physics Wilson coefficients, i.e. in case their second order contribution is negligible, we obtain the simpler approximate relations eqs. (3.38), (3.39), (3.42). We note that a generalization of these results to $b \rightarrow u\tau\nu$ decays seems straight forward.

Note that in case the anomalies turn out to be a statistical fluctuation, the 2HDM type II would again be a very important and viable candidate for further studies. In that case, and disregarding the flipped sign solution, Higgs data shows that we are close to the alignment limit $\cos(\beta - \alpha) = 0$, see the constraints on the parameter space of $\tan\beta$ vs. $\cos(\beta - \alpha)$ from ATLAS and CMS Run I+II in figure 11 of ref. [211]. However, without imposing a symmetry it would actually be unnatural if the alignment limit was fulfilled exactly, which raises the interest in the parameter space with $1\% \lesssim \cos(\beta - \alpha) \lesssim 10\%$ and the corresponding more stringent bounds in that region, roughly overall about $\tan\beta \lesssim 15$.

Future experimental results will show if the charged current anomalies are indeed true. With future theoretical results on the scalar form factors from lattice QCD as well as experimental measurements of the q^2 -dependence of $b \rightarrow c\tau\nu$ decays, using the above methodology we will then be able to improve the probes for new physics in a very direct and clear way.

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References

- [1] HFLAV collaboration, *Averages of b -hadron, c -hadron, and τ -lepton properties as of 2018*, [arXiv:1909.12524](#) [[INSPIRE](#)].
- [2] BABAR collaboration, *Evidence for an excess of $\bar{B} \rightarrow D^{(*)}\tau^-\bar{\nu}_\tau$ decays*, *Phys. Rev. Lett.* **109** (2012) 101802 [[arXiv:1205.5442](#)] [[INSPIRE](#)].
- [3] BABAR collaboration, *Measurement of an Excess of $\bar{B} \rightarrow D^{(*)}\tau^-\bar{\nu}_\tau$ Decays and Implications for Charged Higgs Bosons*, *Phys. Rev. D* **88** (2013) 072012 [[arXiv:1303.0571](#)] [[INSPIRE](#)].
- [4] BELLE collaboration, *Measurement of the branching ratio of $\bar{B} \rightarrow D^{(*)}\tau^-\bar{\nu}_\tau$ relative to $\bar{B} \rightarrow D^{(*)}\ell^-\bar{\nu}_\ell$ decays with hadronic tagging at Belle*, *Phys. Rev. D* **92** (2015) 072014 [[arXiv:1507.03233](#)] [[INSPIRE](#)].
- [5] LHCb collaboration, *Measurement of the ratio of branching fractions $\mathcal{B}(\bar{B}^0 \rightarrow D^{*+}\tau^-\bar{\nu}_\tau)/\mathcal{B}(\bar{B}^0 \rightarrow D^{*+}\mu^-\bar{\nu}_\mu)$* , *Phys. Rev. Lett.* **115** (2015) 111803 [Erratum *ibid.* **115** (2015) 159901] [[arXiv:1506.08614](#)] [[INSPIRE](#)].
- [6] BELLE collaboration, *Measurement of the τ lepton polarization and $R(D^*)$ in the decay $\bar{B} \rightarrow D^*\tau^-\bar{\nu}_\tau$* , *Phys. Rev. Lett.* **118** (2017) 211801 [[arXiv:1612.00529](#)] [[INSPIRE](#)].
- [7] BELLE collaboration, *Measurement of the τ lepton polarization and $R(D^*)$ in the decay $\bar{B} \rightarrow D^*\tau^-\bar{\nu}_\tau$ with one-prong hadronic τ decays at Belle*, *Phys. Rev. D* **97** (2018) 012004 [[arXiv:1709.00129](#)] [[INSPIRE](#)].
- [8] LHCb collaboration, *Measurement of the ratio of the $B^0 \rightarrow D^{*-}\tau^+\nu_\tau$ and $B^0 \rightarrow D^{*-}\mu^+\nu_\mu$ branching fractions using three-prong τ -lepton decays*, *Phys. Rev. Lett.* **120** (2018) 171802 [[arXiv:1708.08856](#)] [[INSPIRE](#)].
- [9] LHCb collaboration, *Test of Lepton Flavor Universality by the measurement of the $B^0 \rightarrow D^{*-}\tau^+\nu_\tau$ branching fraction using three-prong τ decays*, *Phys. Rev. D* **97** (2018) 072013 [[arXiv:1711.02505](#)] [[INSPIRE](#)].
- [10] BELLE collaboration, *Measurement of $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ with a semileptonic tagging method*, [arXiv:1904.08794](#) [[INSPIRE](#)].
- [11] D. Bigi and P. Gambino, *Revisiting $B \rightarrow D\ell\nu$* , *Phys. Rev. D* **94** (2016) 094008 [[arXiv:1606.08030](#)] [[INSPIRE](#)].
- [12] F.U. Bernlochner, Z. Ligeti, M. Papucci and D.J. Robinson, *Combined analysis of semileptonic B decays to D and D^* : $R(D^{(*)})$, $|V_{cb}|$, and new physics*, *Phys. Rev. D* **95** (2017) 115008 [Erratum *ibid.* **97** (2018) 059902] [[arXiv:1703.05330](#)] [[INSPIRE](#)].
- [13] D. Bigi, P. Gambino and S. Schacht, *$R(D^*)$, $|V_{cb}|$, and the Heavy Quark Symmetry relations between form factors*, *JHEP* **11** (2017) 061 [[arXiv:1707.09509](#)] [[INSPIRE](#)].
- [14] S. Jaiswal, S. Nandi and S.K. Patra, *Extraction of $|V_{cb}|$ from $B \rightarrow D^{(*)}\ell\nu_\ell$ and the Standard Model predictions of $R(D^{(*)})$* , *JHEP* **12** (2017) 060 [[arXiv:1707.09977](#)] [[INSPIRE](#)].
- [15] BELLE collaboration, *Measurement of the CKM matrix element $|V_{cb}|$ from $B^0 \rightarrow D^{*-}\ell^+\nu_\ell$ at Belle*, *Phys. Rev. D* **100** (2019) 052007 [[arXiv:1809.03290](#)] [[INSPIRE](#)].

- [16] P. Gambino, M. Jung and S. Schacht, *The V_{cb} puzzle: An update*, *Phys. Lett. B* **795** (2019) 386 [[arXiv:1905.08209](#)] [[INSPIRE](#)].
- [17] S. Jaiswal, S. Nandi and S.K. Patra, *Updates on extraction of $|V_{cb}|$ and SM prediction of $R(D^*)$ in $B \rightarrow D^* \ell \nu_\ell$ decays*, *JHEP* **06** (2020) 165 [[arXiv:2002.05726](#)] [[INSPIRE](#)].
- [18] S. Iguro and R. Watanabe, *Bayesian fit analysis to full distribution data of $\bar{B} \rightarrow D^{(*)} \ell \bar{\nu} : |V_{cb}|$ determination and new physics constraints*, *JHEP* **08** (2020) 006 [[arXiv:2004.10208](#)] [[INSPIRE](#)].
- [19] F.U. Bernlochner, Z. Ligeti, D.J. Robinson and W.L. Sutcliffe, *New predictions for $\Lambda_b \rightarrow \Lambda_c$ semileptonic decays and tests of heavy quark symmetry*, *Phys. Rev. Lett.* **121** (2018) 202001 [[arXiv:1808.09464](#)] [[INSPIRE](#)].
- [20] F.U. Bernlochner, Z. Ligeti, D.J. Robinson and W.L. Sutcliffe, *Precise predictions for $\Lambda_b \rightarrow \Lambda_c$ semileptonic decays*, *Phys. Rev. D* **99** (2019) 055008 [[arXiv:1812.07593](#)] [[INSPIRE](#)].
- [21] A. Datta, S. Kamali, S. Meinel and A. Rashed, *Phenomenology of $\Lambda_b \rightarrow \Lambda_c \tau \bar{\nu}_\tau$ using lattice QCD calculations*, *JHEP* **08** (2017) 131 [[arXiv:1702.02243](#)] [[INSPIRE](#)].
- [22] W. Detmold, C. Lehner and S. Meinel, *$\Lambda_b \rightarrow p \ell^- \bar{\nu}_\ell$ and $\Lambda_b \rightarrow \Lambda_c \ell^- \bar{\nu}_\ell$ form factors from lattice QCD with relativistic heavy quarks*, *Phys. Rev. D* **92** (2015) 034503 [[arXiv:1503.01421](#)] [[INSPIRE](#)].
- [23] T. Mannel and D. van Dyk, *Zero-recoil sum rules for $\Lambda_b \rightarrow \Lambda_c$ form factors*, *Phys. Lett. B* **751** (2015) 48 [[arXiv:1506.08780](#)] [[INSPIRE](#)].
- [24] P. Böer, M. Bordone, E. Graverini, P. Owen, M. Rotondo and D. Van Dyk, *Testing lepton flavour universality in semileptonic $\Lambda_b \rightarrow \Lambda_c^*$ decays*, *JHEP* **06** (2018) 155 [[arXiv:1801.08367](#)] [[INSPIRE](#)].
- [25] P. Böer, A. Kokulu, J.-N. Toelstede and D. van Dyk, *Angular Analysis of $\Lambda_b \rightarrow \Lambda_c(\rightarrow \Lambda \pi) \ell \bar{\nu}$* , *JHEP* **12** (2019) 082 [[arXiv:1907.12554](#)] [[INSPIRE](#)].
- [26] P. Colangelo, F. De Fazio and F. Loparco, *Inclusive semileptonic Λ_b decays in the Standard Model and beyond*, [arXiv:2006.13759](#) [[INSPIRE](#)].
- [27] LHCb collaboration, *Measurement of the ratio of branching fractions $\mathcal{B}(B_c^+ \rightarrow J/\psi \tau^+ \nu_\tau)/\mathcal{B}(B_c^+ \rightarrow J/\psi \mu^+ \nu_\mu)$* , *Phys. Rev. Lett.* **120** (2018) 121801 [[arXiv:1711.05623](#)] [[INSPIRE](#)].
- [28] T.D. Cohen, H. Lamm and R.F. Lebed, *Precision Model-Independent Bounds from Global Analysis of $b \rightarrow c \ell \nu$ Form Factors*, *Phys. Rev. D* **100** (2019) 094503 [[arXiv:1909.10691](#)] [[INSPIRE](#)].
- [29] T.D. Cohen, H. Lamm and R.F. Lebed, *Model-independent bounds on $R(J/\psi)$* , *JHEP* **09** (2018) 168 [[arXiv:1807.02730](#)] [[INSPIRE](#)].
- [30] C.W. Murphy and A. Soni, *Model-Independent Determination of $B_c^+ \rightarrow \eta_c \ell^+ \nu$ Form Factors*, *Phys. Rev. D* **98** (2018) 094026 [[arXiv:1808.05932](#)] [[INSPIRE](#)].
- [31] R. Watanabe, *New Physics effect on $B_c \rightarrow J/\psi \tau \bar{\nu}$ in relation to the $R_{D^{(*)}}$ anomaly*, *Phys. Lett. B* **776** (2018) 5 [[arXiv:1709.08644](#)] [[INSPIRE](#)].
- [32] A. Issadykov and M.A. Ivanov, *The decays $B_c \rightarrow J/\psi + \bar{\ell} \nu_\ell$ and $B_c \rightarrow J/\psi + \pi(K)$ in covariant confined quark model*, *Phys. Lett. B* **783** (2018) 178 [[arXiv:1804.00472](#)] [[INSPIRE](#)].

- [33] R. Dutta and A. Bhol, $B_c \rightarrow (J/\psi, \eta_c)\tau\nu$ semileptonic decays within the standard model and beyond, *Phys. Rev. D* **96** (2017) 076001 [[arXiv:1701.08598](#)] [[INSPIRE](#)].
- [34] W. Wang and R. Zhu, Model independent investigation of the $R_{J/\psi, \eta_c}$ and ratios of decay widths of semileptonic B_c decays into a P-wave charmonium, *Int. J. Mod. Phys. A* **34** (2019) 1950195 [[arXiv:1808.10830](#)] [[INSPIRE](#)].
- [35] K. Azizi, Y. Sarac and H. Sundu, Lepton flavor universality violation in semileptonic tree level weak transitions, *Phys. Rev. D* **99** (2019) 113004 [[arXiv:1904.08267](#)] [[INSPIRE](#)].
- [36] D. Leljak, B. Melic and M. Patra, On lepton flavour universality in semileptonic $B_c \rightarrow \eta_c, J/\psi$ decays, *JHEP* **05** (2019) 094 [[arXiv:1901.08368](#)] [[INSPIRE](#)].
- [37] LHCb collaboration, Test of lepton universality using $B^+ \rightarrow K^+\ell^+\ell^-$ decays, *Phys. Rev. Lett.* **113** (2014) 151601 [[arXiv:1406.6482](#)] [[INSPIRE](#)].
- [38] LHCb collaboration, Test of lepton universality with $B^0 \rightarrow K^{*0}\ell^+\ell^-$ decays, *JHEP* **08** (2017) 055 [[arXiv:1705.05802](#)] [[INSPIRE](#)].
- [39] LHCb collaboration, Search for lepton-universality violation in $B^+ \rightarrow K^+\ell^+\ell^-$ decays, *Phys. Rev. Lett.* **122** (2019) 191801 [[arXiv:1903.09252](#)] [[INSPIRE](#)].
- [40] BELLE collaboration, Test of lepton flavor universality in $B \rightarrow K^*\ell^+\ell^-$ decays at Belle, [arXiv:1904.02440](#) [[INSPIRE](#)].
- [41] G. Hiller and F. Krüger, More model-independent analysis of $b \rightarrow s$ processes, *Phys. Rev. D* **69** (2004) 074020 [[hep-ph/0310219](#)] [[INSPIRE](#)].
- [42] T. Huber, E. Lunghi, M. Misiak and D. Wyler, Electromagnetic logarithms in $\bar{B} \rightarrow X_s \ell^+ \ell^-$, *Nucl. Phys. B* **740** (2006) 105 [[hep-ph/0512066](#)] [[INSPIRE](#)].
- [43] C. Bobeth, G. Hiller and G. Piranishvili, Angular distributions of $\bar{B} \rightarrow \bar{K} \ell^+ \ell^-$ decays, *JHEP* **12** (2007) 040 [[arXiv:0709.4174](#)] [[INSPIRE](#)].
- [44] M. Bordone, G. Isidori and A. Pattori, On the Standard Model predictions for R_K and R_{K^*} , *Eur. Phys. J. C* **76** (2016) 440 [[arXiv:1605.07633](#)] [[INSPIRE](#)].
- [45] G. Hiller and M. Schmaltz, R_K and future $b \rightarrow s \ell \ell$ physics beyond the standard model opportunities, *Phys. Rev. D* **90** (2014) 054014 [[arXiv:1408.1627](#)] [[INSPIRE](#)].
- [46] G. Hiller and M. Schmaltz, Diagnosing lepton-nonuniversality in $b \rightarrow s \ell \ell$, *JHEP* **02** (2015) 055 [[arXiv:1411.4773](#)] [[INSPIRE](#)].
- [47] D. Aloni, A. Dery, C. Frugiuele and Y. Nir, Testing minimal flavor violation in leptoquark models of the $R_{K^{(*)}}$ anomaly, *JHEP* **11** (2017) 109 [[arXiv:1708.06161](#)] [[INSPIRE](#)].
- [48] Y. Afik, S. Bar-Shalom, J. Cohen, A. Soni and J. Wudka, High p_T correlated tests of lepton universality in lepton(s) + jet(s) processes; an EFT analysis, [arXiv:2005.06457](#) [[INSPIRE](#)].
- [49] C. Borschensky, B. Fuks, A. Kulesza and D. Schwartländer, Scalar leptoquark pair production at hadron colliders, *Phys. Rev. D* **101** (2020) 115017 [[arXiv:2002.08971](#)] [[INSPIRE](#)].
- [50] W. Altmannshofer, P.S. Bhupal Dev and A. Soni, $R_{D^{(*)}}$ anomaly: A possible hint for natural supersymmetry with R-parity violation, *Phys. Rev. D* **96** (2017) 095010 [[arXiv:1704.06659](#)] [[INSPIRE](#)].
- [51] S. Iguro, Y. Omura and M. Takeuchi, Test of the $R(D^{(*)})$ anomaly at the LHC, *Phys. Rev. D* **99** (2019) 075013 [[arXiv:1810.05843](#)] [[INSPIRE](#)].

- [52] P. Gambino, K.J. Healey and S. Turczyk, *Taming the higher power corrections in semileptonic B decays*, *Phys. Lett. B* **763** (2016) 60 [[arXiv:1606.06174](#)] [[INSPIRE](#)].
- [53] BELLE collaboration, *Measurement of the decay $B \rightarrow D\ell\nu_\ell$ in fully reconstructed events and determination of the Cabibbo-Kobayashi-Maskawa matrix element $|V_{cb}|$* , *Phys. Rev. D* **93** (2016) 032006 [[arXiv:1510.03657](#)] [[INSPIRE](#)].
- [54] BABAR collaboration, *Measurement of $|V_{cb}|$ and the Form-Factor Slope in $\bar{B} \rightarrow D\ell^-\bar{\nu}$ Decays in Events Tagged by a Fully Reconstructed B Meson*, *Phys. Rev. Lett.* **104** (2010) 011802 [[arXiv:0904.4063](#)] [[INSPIRE](#)].
- [55] I. Caprini, L. Lellouch and M. Neubert, *Dispersive bounds on the shape of $\bar{B} \rightarrow D^{(*)}\ell\bar{\nu}$ form-factors*, *Nucl. Phys. B* **530** (1998) 153 [[hep-ph/9712417](#)] [[INSPIRE](#)].
- [56] BELLE collaboration, *Precise determination of the CKM matrix element $|V_{cb}|$ with $\bar{B}^0 \rightarrow D^{*+}\ell^-\bar{\nu}_\ell$ decays with hadronic tagging at Belle*, [arXiv:1702.01521](#) [[INSPIRE](#)].
- [57] C. Boyd, B. Grinstein and R.F. Lebed, *Precision corrections to dispersive bounds on form-factors*, *Phys. Rev. D* **56** (1997) 6895 [[hep-ph/9705252](#)] [[INSPIRE](#)].
- [58] D. Bigi, P. Gambino and S. Schacht, *A fresh look at the determination of $|V_{cb}|$ from $B \rightarrow D^*\ell\nu$* , *Phys. Lett. B* **769** (2017) 441 [[arXiv:1703.06124](#)] [[INSPIRE](#)].
- [59] B. Grinstein and A. Kobach, *Model-Independent Extraction of $|V_{cb}|$ from $\bar{B} \rightarrow D^*\ell\bar{\nu}$* , *Phys. Lett. B* **771** (2017) 359 [[arXiv:1703.08170](#)] [[INSPIRE](#)].
- [60] BABAR collaboration, *Extraction of form Factors from a Four-Dimensional Angular Analysis of $\bar{B} \rightarrow D^*\ell^-\bar{\nu}_\ell$* , *Phys. Rev. Lett.* **123** (2019) 091801 [[arXiv:1903.10002](#)] [[INSPIRE](#)].
- [61] F.U. Bernlochner, Z. Ligeti and D.J. Robinson, *$N = 5, 6, 7, 8$: Nested hypothesis tests and truncation dependence of $|V_{cb}|$* , *Phys. Rev. D* **100** (2019) 013005 [[arXiv:1902.09553](#)] [[INSPIRE](#)].
- [62] F.U. Bernlochner, S. Duell, Z. Ligeti, M. Papucci and D.J. Robinson, *Das ist der HAMMER: Consistent new physics interpretations of semileptonic decays*, *Eur. Phys. J. C* **80** (2020) 883 [[arXiv:2002.00020](#)] [[INSPIRE](#)].
- [63] F.U. Bernlochner, Z. Ligeti, M. Papucci and D.J. Robinson, *Tensions and correlations in $|V_{cb}|$ determinations*, *Phys. Rev. D* **96** (2017) 091503 [[arXiv:1708.07134](#)] [[INSPIRE](#)].
- [64] LHCb collaboration, *Measurement of $|V_{cb}|$ with $B_s^0 \rightarrow D_s^{(*)-}\mu^+\nu_\mu$ decays*, *Phys. Rev. D* **101** (2020) 072004 [[arXiv:2001.03225](#)] [[INSPIRE](#)].
- [65] LHCb collaboration, *Measurement of the shape of the $B_s^0 \rightarrow D_s^{*-}\mu^+\nu_\mu$ differential decay rate*, [arXiv:2003.08453](#) [[INSPIRE](#)].
- [66] P. Colangelo and F. De Fazio, *Tension in the inclusive versus exclusive determinations of $|V_{cb}|$: a possible role of new physics*, *Phys. Rev. D* **95** (2017) 011701 [[arXiv:1611.07387](#)] [[INSPIRE](#)].
- [67] A. Cerri et al., *Report from Working Group 4: Opportunities in Flavour Physics at the HL-LHC and HE-LHC*, *CERN Yellow Rep. Monogr.* **7** (2019) 867 [[arXiv:1812.07638](#)] [[INSPIRE](#)].
- [68] BELLE-II collaboration, *The Belle II Physics Book*, *PTEP* **2019** (2019) 123C01 [Erratum *ibid.* **2020** (2020) 029201] [[arXiv:1808.10567](#)] [[INSPIRE](#)].
- [69] P. Gambino et al., *Challenges in Semileptonic B Decays*, [arXiv:2006.07287](#) [[INSPIRE](#)].

- [70] FERMILAB LATTICE and MILC collaborations, *Update of $|V_{cb}|$ from the $\bar{B} \rightarrow D^* \ell \bar{\nu}$ form factor at zero recoil with three-flavor lattice QCD*, *Phys. Rev. D* **89** (2014) 114504 [[arXiv:1403.0635](#)] [[INSPIRE](#)].
- [71] MILC collaboration, *$B \rightarrow D \ell \nu$ form factors at nonzero recoil and $|V_{cb}|$ from 2 + 1-flavor lattice QCD*, *Phys. Rev. D* **92** (2015) 034506 [[arXiv:1503.07237](#)] [[INSPIRE](#)].
- [72] HPQCD collaboration, *$B \rightarrow D \ell \nu$ form factors at nonzero recoil and extraction of $|V_{cb}|$* , *Phys. Rev. D* **92** (2015) 054510 [Erratum *ibid.* **93** (2016) 119906] [[arXiv:1505.03925](#)] [[INSPIRE](#)].
- [73] HPQCD collaboration, *Lattice QCD calculation of the $B_{(s)} \rightarrow D_{(s)}^* \ell \nu$ form factors at zero recoil and implications for $|V_{cb}|$* , *Phys. Rev. D* **97** (2018) 054502 [[arXiv:1711.11013](#)] [[INSPIRE](#)].
- [74] E. McLean, C.T.H. Davies, A.T. Lytle and J. Koponen, *Lattice QCD form factor for $B_s \rightarrow D_s^* \ell \nu$ at zero recoil with non-perturbative current renormalisation*, *Phys. Rev. D* **99** (2019) 114512 [[arXiv:1904.02046](#)] [[INSPIRE](#)].
- [75] FERMILAB LATTICE and MILC collaborations, *$B \rightarrow D^* \ell \nu$ at non-zero recoil*, *PoS LATTICE2018* (2019) 282 [[arXiv:1901.00216](#)] [[INSPIRE](#)].
- [76] JLQCD collaboration, *$B \rightarrow D^{(*)} \ell \nu$ form factors from $N_f = 2 + 1$ QCD with Möbius domain-wall quarks*, *PoS LATTICE2018* (2018) 311 [[arXiv:1811.00794](#)] [[INSPIRE](#)].
- [77] P. Gambino and S. Hashimoto, *Inclusive Semileptonic Decays from Lattice QCD*, *Phys. Rev. Lett.* **125** (2020) 032001 [[arXiv:2005.13730](#)] [[INSPIRE](#)].
- [78] J. Flynn, R. Hill, A. Jüttner, A. Soni, J.T. Tsang and O. Witzel, *Semileptonic $B \rightarrow \pi \ell \nu$, $B \rightarrow D \ell \nu$, $B_s \rightarrow K \ell \nu$, and $B_s \rightarrow D_s \ell \nu$ decays*, *PoS LATTICE2019* (2019) 184 [[arXiv:1912.09946](#)] [[INSPIRE](#)].
- [79] J.M. Flynn, R.C. Hill, A. Jüttner, A. Soni, J.T. Tsang and O. Witzel, *Semi-leptonic form factors for $B_s \rightarrow K \ell \nu$ and $B_s \rightarrow D_s \ell \nu$* , *PoS LATTICE2018* (2019) 290 [[arXiv:1903.02100](#)] [[INSPIRE](#)].
- [80] J. Flynn et al., *Form factors for semi-leptonic B decays*, *PoS LATTICE2016* (2016) 296 [[arXiv:1612.05112](#)] [[INSPIRE](#)].
- [81] HPQCD collaboration, *B_c decays from highly improved staggered quarks and NRQCD*, *PoS LATTICE2016* (2016) 281 [[arXiv:1611.01987](#)] [[INSPIRE](#)].
- [82] ALPHA collaboration, *Nonperturbative heavy quark effective theory*, *JHEP* **02** (2004) 022 [[hep-lat/0310035](#)] [[INSPIRE](#)].
- [83] ALPHA collaboration, *Matching of heavy-light flavour currents between HQET at order $1/m$ and QCD: I. Strategy and tree-level study*, *JHEP* **05** (2014) 060 [[arXiv:1312.1566](#)] [[INSPIRE](#)].
- [84] M. Della Morte, J. Heitger, H. Simma and R. Sommer, *Non-perturbative Heavy Quark Effective Theory: An application to semi-leptonic B -decays*, *Nucl. Part. Phys. Proc.* **261-262** (2015) 368 [[arXiv:1501.03328](#)] [[INSPIRE](#)].
- [85] N. Gubernari, A. Kokulu and D. van Dyk, *$B \rightarrow P$ and $B \rightarrow V$ Form Factors from B -Meson Light-Cone Sum Rules beyond Leading Twist*, *JHEP* **01** (2019) 150 [[arXiv:1811.00983](#)] [[INSPIRE](#)].
- [86] S. Faller, A. Khodjamirian, C. Klein and T. Mannel, *$B \rightarrow D^{(*)}$ Form Factors from QCD Light-Cone Sum Rules*, *Eur. Phys. J. C* **60** (2009) 603 [[arXiv:0809.0222](#)] [[INSPIRE](#)].

- [87] M. Bordone, M. Jung and D. van Dyk, *Theory determination of $\bar{B} \rightarrow D^{(*)} \ell^- \bar{\nu}$ form factors at $\mathcal{O}(1/m_c^2)$* , *Eur. Phys. J. C* **80** (2020) 74 [[arXiv:1908.09398](#)] [[INSPIRE](#)].
- [88] M. Bordone, N. Gubernari, D. van Dyk and M. Jung, *Heavy-Quark expansion for $\bar{B}_s \rightarrow D_s^{(*)}$ form factors and unitarity bounds beyond the $SU(3)_F$ limit*, *Eur. Phys. J. C* **80** (2020) 347 [[arXiv:1912.09335](#)] [[INSPIRE](#)].
- [89] J.F. Kamenik and F. Mescia, *$B \rightarrow D\tau\nu$ Branching Ratios: Opportunity for Lattice QCD and Hadron Colliders*, *Phys. Rev. D* **78** (2008) 014003 [[arXiv:0802.3790](#)] [[INSPIRE](#)].
- [90] S. Fajfer, J.F. Kamenik and I. Nisandzic, *On the $B \rightarrow D^* \tau \bar{\nu}_\tau$ Sensitivity to New Physics*, *Phys. Rev. D* **85** (2012) 094025 [[arXiv:1203.2654](#)] [[INSPIRE](#)].
- [91] A. Celis, M. Jung, X.-Q. Li and A. Pich, *Sensitivity to charged scalars in $B \rightarrow D^{(*)} \tau \nu_\tau$ and $B \rightarrow \tau \nu_\tau$ decays*, *JHEP* **01** (2013) 054 [[arXiv:1210.8443](#)] [[INSPIRE](#)].
- [92] M. Tanaka and R. Watanabe, *New physics in the weak interaction of $\bar{B} \rightarrow D^{(*)} \tau \bar{\nu}$* , *Phys. Rev. D* **87** (2013) 034028 [[arXiv:1212.1878](#)] [[INSPIRE](#)].
- [93] M. Blanke et al., *Impact of polarization observables and $B_c \rightarrow \tau \nu$ on new physics explanations of the $b \rightarrow c \tau \nu$ anomaly*, *Phys. Rev. D* **99** (2019) 075006 [[arXiv:1811.09603](#)] [[INSPIRE](#)].
- [94] M. Blanke, A. Crivellin, T. Kitahara, M. Moscati, U. Nierste and I. Nišandžić, *Addendum to “Impact of polarization observables and $B_c \rightarrow \tau \nu$ on new physics explanations of the $b \rightarrow c \tau \nu$ anomaly”*, *arXiv:1905.08253* [Addendum *ibid.* **100** (2019) 035035] [[INSPIRE](#)].
- [95] M. Freytsis, Z. Ligeti and J.T. Ruderman, *Flavor models for $\bar{B} \rightarrow D^{(*)} \tau \bar{\nu}$* , *Phys. Rev. D* **92** (2015) 054018 [[arXiv:1506.08896](#)] [[INSPIRE](#)].
- [96] S. Bhattacharya, S. Nandi and S.K. Patra, *Looking for possible new physics in $B \rightarrow D^{(*)} \tau \nu_\tau$ in light of recent data*, *Phys. Rev. D* **95** (2017) 075012 [[arXiv:1611.04605](#)] [[INSPIRE](#)].
- [97] M.A. Ivanov, J.G. Körner and C.-T. Tran, *Probing new physics in $\bar{B}^0 \rightarrow D^{(*)} \tau^- \bar{\nu}_\tau$ using the longitudinal, transverse, and normal polarization components of the tau lepton*, *Phys. Rev. D* **95** (2017) 036021 [[arXiv:1701.02937](#)] [[INSPIRE](#)].
- [98] A.K. Alok, D. Kumar, J. Kumar, S. Kumbhakar and S.U. Sankar, *New physics solutions for R_D and R_{D^*}* , *JHEP* **09** (2018) 152 [[arXiv:1710.04127](#)] [[INSPIRE](#)].
- [99] S. Bifani, S. Descotes-Genon, A. Romero Vidal and M.-H. Schune, *Review of Lepton Universality tests in B decays*, *J. Phys. G* **46** (2019) 023001 [[arXiv:1809.06229](#)] [[INSPIRE](#)].
- [100] R.-X. Shi, L.-S. Geng, B. Grinstein, S. Jäger and J. Martin Camalich, *Revisiting the new-physics interpretation of the $b \rightarrow c \tau \nu$ data*, *JHEP* **12** (2019) 065 [[arXiv:1905.08498](#)] [[INSPIRE](#)].
- [101] A. Greljo, G. Isidori and D. Marzocca, *On the breaking of Lepton Flavor Universality in B decays*, *JHEP* **07** (2015) 142 [[arXiv:1506.01705](#)] [[INSPIRE](#)].
- [102] S.M. Boucenna, A. Celis, J. Fuentes-Martin, A. Vicente and J. Virto, *Non-abelian gauge extensions for B -decay anomalies*, *Phys. Lett. B* **760** (2016) 214 [[arXiv:1604.03088](#)] [[INSPIRE](#)].
- [103] S.M. Boucenna, A. Celis, J. Fuentes-Martin, A. Vicente and J. Virto, *Phenomenology of an $SU(2) \times SU(2) \times U(1)$ model with lepton-flavour non-universality*, *JHEP* **12** (2016) 059 [[arXiv:1608.01349](#)] [[INSPIRE](#)].
- [104] E. Megias, M. Quirós and L. Salas, *Lepton-flavor universality violation in R_K and $R_{D^{(*)}}$ from warped space*, *JHEP* **07** (2017) 102 [[arXiv:1703.06019](#)] [[INSPIRE](#)].

- [105] X.-Q. Li, Y.-D. Yang and X. Zhang, *Revisiting the one leptoquark solution to the $R(D^{(*)})$ anomalies and its phenomenological implications*, *JHEP* **08** (2016) 054 [[arXiv:1605.09308](#)] [[INSPIRE](#)].
- [106] S. Fajfer, J.F. Kamenik, I. Nisandzic and J. Zupan, *Implications of Lepton Flavor Universality Violations in B Decays*, *Phys. Rev. Lett.* **109** (2012) 161801 [[arXiv:1206.1872](#)] [[INSPIRE](#)].
- [107] N.G. Deshpande and A. Menon, *Hints of R -parity violation in B decays into $\tau\nu$* , *JHEP* **01** (2013) 025 [[arXiv:1208.4134](#)] [[INSPIRE](#)].
- [108] Y. Sakaki, M. Tanaka, A. Tayduganov and R. Watanabe, *Testing leptoquark models in $\bar{B} \rightarrow D^{(*)}\tau\bar{\nu}$* , *Phys. Rev. D* **88** (2013) 094012 [[arXiv:1309.0301](#)] [[INSPIRE](#)].
- [109] M. Duraisamy, P. Sharma and A. Datta, *Azimuthal $B \rightarrow D^*\tau^-\bar{\nu}_\tau$ angular distribution with tensor operators*, *Phys. Rev. D* **90** (2014) 074013 [[arXiv:1405.3719](#)] [[INSPIRE](#)].
- [110] L. Calibbi, A. Crivellin and T. Ota, *Effective Field Theory Approach to $b \rightarrow s\ell\ell^{(\prime)}$, $B \rightarrow K^{(*)}\nu\bar{\nu}$ and $B \rightarrow D^{(*)}\tau\nu$ with Third Generation Couplings*, *Phys. Rev. Lett.* **115** (2015) 181801 [[arXiv:1506.02661](#)] [[INSPIRE](#)].
- [111] S. Fajfer and N. Košnik, *Vector leptoquark resolution of R_K and $R_{D^{(*)}}$ puzzles*, *Phys. Lett. B* **755** (2016) 270 [[arXiv:1511.06024](#)] [[INSPIRE](#)].
- [112] R. Barbieri, G. Isidori, A. Pattori and F. Senia, *Anomalies in B -decays and $U(2)$ flavour symmetry*, *Eur. Phys. J. C* **76** (2016) 67 [[arXiv:1512.01560](#)] [[INSPIRE](#)].
- [113] R. Alonso, B. Grinstein and J. Martin Camalich, *Lepton universality violation and lepton flavor conservation in B -meson decays*, *JHEP* **10** (2015) 184 [[arXiv:1505.05164](#)] [[INSPIRE](#)].
- [114] M. Bauer and M. Neubert, *Minimal Leptoquark Explanation for the $R_{D^{(*)}}$, R_K , and $(g-2)_g$ Anomalies*, *Phys. Rev. Lett.* **116** (2016) 141802 [[arXiv:1511.01900](#)] [[INSPIRE](#)].
- [115] D. Das, C. Hati, G. Kumar and N. Mahajan, *Towards a unified explanation of $R_{D^{(*)}}$, R_K and $(g-2)_\mu$ anomalies in a left-right model with leptoquarks*, *Phys. Rev. D* **94** (2016) 055034 [[arXiv:1605.06313](#)] [[INSPIRE](#)].
- [116] N.G. Deshpande and X.-G. He, *Consequences of R -parity violating interactions for anomalies in $\bar{B} \rightarrow D^{(*)}\tau\bar{\nu}$ and $b \rightarrow s\mu^+\mu^-$* , *Eur. Phys. J. C* **77** (2017) 134 [[arXiv:1608.04817](#)] [[INSPIRE](#)].
- [117] S. Sahoo, R. Mohanta and A.K. Giri, *Explaining the R_K and $R_{D^{(*)}}$ anomalies with vector leptoquarks*, *Phys. Rev. D* **95** (2017) 035027 [[arXiv:1609.04367](#)] [[INSPIRE](#)].
- [118] B. Dumont, K. Nishiwaki and R. Watanabe, *LHC constraints and prospects for S_1 scalar leptoquark explaining the $\bar{B} \rightarrow D^{(*)}\tau\bar{\nu}$ anomaly*, *Phys. Rev. D* **94** (2016) 034001 [[arXiv:1603.05248](#)] [[INSPIRE](#)].
- [119] D. Bečirević, S. Fajfer, N. Košnik and O. Sumensari, *Leptoquark model to explain the B -physics anomalies, R_K and R_D* , *Phys. Rev. D* **94** (2016) 115021 [[arXiv:1608.08501](#)] [[INSPIRE](#)].
- [120] R. Barbieri, C.W. Murphy and F. Senia, *B -decay Anomalies in a Composite Leptoquark Model*, *Eur. Phys. J. C* **77** (2017) 8 [[arXiv:1611.04930](#)] [[INSPIRE](#)].
- [121] L. Di Luzio, A. Greljo and M. Nardecchia, *Gauge leptoquark as the origin of B -physics anomalies*, *Phys. Rev. D* **96** (2017) 115011 [[arXiv:1708.08450](#)] [[INSPIRE](#)].

- [122] C.-H. Chen, T. Nomura and H. Okada, *Excesses of muon $g - 2$, $R_{D^{(*)}}$, and R_K in a leptoquark model*, *Phys. Lett. B* **774** (2017) 456 [[arXiv:1703.03251](#)] [[INSPIRE](#)].
- [123] M. Bordone, C. Cornella, J. Fuentes-Martin and G. Isidori, *A three-site gauge model for flavor hierarchies and flavor anomalies*, *Phys. Lett. B* **779** (2018) 317 [[arXiv:1712.01368](#)] [[INSPIRE](#)].
- [124] D. Bečirević, I. Doršner, S. Fajfer, N. Košnik, D.A. Faroughy and O. Sumensari, *Scalar leptoquarks from grand unified theories to accommodate the B -physics anomalies*, *Phys. Rev. D* **98** (2018) 055003 [[arXiv:1806.05689](#)] [[INSPIRE](#)].
- [125] A. Crivellin, C. Greub and A. Kokulu, *Explaining $B \rightarrow D\tau\nu$, $B \rightarrow D^*\tau\nu$ and $B \rightarrow \tau\nu$ in a 2HDM of type-III*, *Phys. Rev. D* **86** (2012) 054014 [[arXiv:1206.2634](#)] [[INSPIRE](#)].
- [126] A. Crivellin, J. Heeck and P. Stoffer, *A perturbed lepton-specific two-Higgs-doublet model facing experimental hints for physics beyond the Standard Model*, *Phys. Rev. Lett.* **116** (2016) 081801 [[arXiv:1507.07567](#)] [[INSPIRE](#)].
- [127] A. Celis, M. Jung, X.-Q. Li and A. Pich, *Scalar contributions to $b \rightarrow c(u)\tau\nu$ transitions*, *Phys. Lett. B* **771** (2017) 168 [[arXiv:1612.07757](#)] [[INSPIRE](#)].
- [128] C.-H. Chen and T. Nomura, *Charged-Higgs on $R_{D^{(*)}}$, τ polarization, and FBA*, *Eur. Phys. J. C* **77** (2017) 631 [[arXiv:1703.03646](#)] [[INSPIRE](#)].
- [129] S. Iguro and K. Tobe, *$R(D^{(*)})$ in a general two Higgs doublet model*, *Nucl. Phys. B* **925** (2017) 560 [[arXiv:1708.06176](#)] [[INSPIRE](#)].
- [130] C.-H. Chen and T. Nomura, *Charged Higgs boson contribution to $B_q^- \rightarrow \ell\bar{\nu}$ and $\bar{B} \rightarrow (P, V)\ell\bar{\nu}$ in a generic two-Higgs doublet model*, *Phys. Rev. D* **98** (2018) 095007 [[arXiv:1803.00171](#)] [[INSPIRE](#)].
- [131] S.-P. Li, X.-Q. Li, Y.-D. Yang and X. Zhang, *$R_{D^{(*)}}$, $R_{K^{(*)}}$ and neutrino mass in the 2HDM-III with right-handed neutrinos*, *JHEP* **09** (2018) 149 [[arXiv:1807.08530](#)] [[INSPIRE](#)].
- [132] W. Altmannshofer, P.S.B. Dev, A. Soni and Y. Sui, *Addressing $R_{D^{(*)}}$, $R_{K^{(*)}}$, muon $g - 2$ and ANITA anomalies in a minimal R -parity violating supersymmetric framework*, *Phys. Rev. D* **102** (2020) 015031 [[arXiv:2002.12910](#)] [[INSPIRE](#)].
- [133] S. Bar-Shalom, J. Cohen, A. Soni and J. Wudka, *Phenomenology of TeV-scale scalar Leptoquarks in the EFT*, *Phys. Rev. D* **100** (2019) 055020 [[arXiv:1812.03178](#)] [[INSPIRE](#)].
- [134] S. Nandi, S.K. Patra and A. Soni, *Correlating new physics signals in $B \rightarrow D^{(*)}\tau\nu_\tau$ with $B \rightarrow \tau\nu_\tau$* , [[arXiv:1605.07191](#)] [[INSPIRE](#)].
- [135] P. Asadi, M.R. Buckley and D. Shih, *Asymmetry Observables and the Origin of $R_{D^{(*)}}$ Anomalies*, *Phys. Rev. D* **99** (2019) 035015 [[arXiv:1810.06597](#)] [[INSPIRE](#)].
- [136] P. Asadi, M.R. Buckley and D. Shih, *It's all right(-handed neutrinos): a new W' model for the $R_{D^{(*)}}$ anomaly*, *JHEP* **09** (2018) 010 [[arXiv:1804.04135](#)] [[INSPIRE](#)].
- [137] P. Asadi and D. Shih, *Maximizing the Impact of New Physics in $b \rightarrow c\tau\nu$ Anomalies*, *Phys. Rev. D* **100** (2019) 115013 [[arXiv:1905.03311](#)] [[INSPIRE](#)].
- [138] R. Alonso, J. Martin Camalich and S. Westhoff, *Tau properties in $B \rightarrow D\tau\nu$ from visible final-state kinematics*, *Phys. Rev. D* **95** (2017) 093006 [[arXiv:1702.02773](#)] [[INSPIRE](#)].
- [139] R. Alonso, B. Grinstein and J. Martin Camalich, *Lifetime of B_c^- Constrains Explanations for Anomalies in $B \rightarrow D^{(*)}\tau\nu$* , *Phys. Rev. Lett.* **118** (2017) 081802 [[arXiv:1611.06676](#)] [[INSPIRE](#)].

- [140] R. Alonso, A. Kobach and J. Martin Camalich, *New physics in the kinematic distributions of $\bar{B} \rightarrow D^{(*)}\tau^- (\rightarrow \ell^- \bar{\nu}_\ell \nu_\tau) \bar{\nu}_\tau$* , *Phys. Rev. D* **94** (2016) 094021 [[arXiv:1602.07671](#)] [[INSPIRE](#)].
- [141] B. Bhattacharya, A. Datta, S. Kamali and D. London, *A measurable angular distribution for $\bar{B} \rightarrow D^* \tau^- \bar{\nu}_\tau$ decays*, *JHEP* **07** (2020) 194 [[arXiv:2005.03032](#)] [[INSPIRE](#)].
- [142] B. Bhattacharya, A. Datta, S. Kamali and D. London, *CP Violation in $\bar{B}^0 \rightarrow D^{*+} \mu^- \bar{\nu}_\mu$* , *JHEP* **05** (2019) 191 [[arXiv:1903.02567](#)] [[INSPIRE](#)].
- [143] B. Bhattacharya, A. Datta, J.-P. Guévin, D. London and R. Watanabe, *Simultaneous Explanation of the R_K and $R_{D^{(*)}}$ Puzzles: a Model Analysis*, *JHEP* **01** (2017) 015 [[arXiv:1609.09078](#)] [[INSPIRE](#)].
- [144] B. Bhattacharya, A. Datta, D. London and S. Shivashankara, *Simultaneous Explanation of the R_K and $R(D^{(*)})$ Puzzles*, *Phys. Lett. B* **742** (2015) 370 [[arXiv:1412.7164](#)] [[INSPIRE](#)].
- [145] Z. Ligeti, M. Papucci and D.J. Robinson, *New Physics in the Visible Final States of $B \rightarrow D^{(*)} \tau \nu$* , *JHEP* **01** (2017) 083 [[arXiv:1610.02045](#)] [[INSPIRE](#)].
- [146] D. Becirevic, S. Fajfer, I. Nisandžić and A. Tayduganov, *Angular distributions of $\bar{B} \rightarrow D^{(*)} \ell \bar{\nu}_\ell$ decays and search of New Physics*, *Nucl. Phys. B* **946** (2019) 114707 [[arXiv:1602.03030](#)] [[INSPIRE](#)].
- [147] D. Bečirević, M. Fedele, I. Nisandžić and A. Tayduganov, *Lepton Flavor Universality tests through angular observables of $\bar{B} \rightarrow D^{(*)} \ell \bar{\nu}$ decay modes*, [arXiv:1907.02257](#) [[INSPIRE](#)].
- [148] P. Biancofiore, P. Colangelo and F. De Fazio, *On the anomalous enhancement observed in $B \rightarrow D^{(*)} \tau \bar{\nu}_\tau$ decays*, *Phys. Rev. D* **87** (2013) 074010 [[arXiv:1302.1042](#)] [[INSPIRE](#)].
- [149] P. Colangelo and F. De Fazio, *Scrutinizing $\bar{B} \rightarrow D^* (D\pi) \ell^- \bar{\nu}_\ell$ and $\bar{B} \rightarrow D^* (D\gamma) \ell^- \bar{\nu}_\ell$ in search of new physics footprints*, *JHEP* **06** (2018) 082 [[arXiv:1801.10468](#)] [[INSPIRE](#)].
- [150] R. Martinez, C.F. Sierra and G. Valencia, *Beyond $\mathcal{R}(D^{(*)})$ with the general type-III 2HDM for $b \rightarrow c \tau \nu$* , *Phys. Rev. D* **98** (2018) 115012 [[arXiv:1805.04098](#)] [[INSPIRE](#)].
- [151] D. Aloni, Y. Grossman and A. Soffer, *Measuring CP-violation in $b \rightarrow c \tau^- \bar{\nu}_\tau$ using excited charm mesons*, *Phys. Rev. D* **98** (2018) 035022 [[arXiv:1806.04146](#)] [[INSPIRE](#)].
- [152] D. Aloni, A. Efrati, Y. Grossman and Y. Nir, *Υ and ψ leptonic decays as probes of solutions to the $R_D^{(*)}$ puzzle*, *JHEP* **06** (2017) 019 [[arXiv:1702.07356](#)] [[INSPIRE](#)].
- [153] O. Deschamps, S. Descotes-Genon, S. Monteil, V. Niess, S. T’Jampens and V. Tisserand, *The Two Higgs Doublet of Type II facing flavour physics data*, *Phys. Rev. D* **82** (2010) 073012 [[arXiv:0907.5135](#)] [[INSPIRE](#)].
- [154] A.K. Alok, D. Kumar, S. Kumbhakar and S. Uma Sankar, *Solutions to R_D - R_{D^*} in light of Belle 2019 data*, *Nucl. Phys. B* **953** (2020) 114957 [[arXiv:1903.10486](#)] [[INSPIRE](#)].
- [155] A. Crivellin, D. Müller and T. Ota, *Simultaneous explanation of $R(D^{(*)})$ and $b \rightarrow s \mu^+ \mu^-$: the last scalar leptoquarks standing*, *JHEP* **09** (2017) 040 [[arXiv:1703.09226](#)] [[INSPIRE](#)].
- [156] A. Crivellin, D. Müller and F. Saturnino, *Flavor Phenomenology of the Leptoquark Singlet-Triplet Model*, *JHEP* **06** (2020) 020 [[arXiv:1912.04224](#)] [[INSPIRE](#)].
- [157] S. Bhattacharya, S. Nandi and S. Kumar Patra, *$b \rightarrow c \tau \nu_\tau$ Decays: a catalogue to compare, constrain, and correlate new physics effects*, *Eur. Phys. J. C* **79** (2019) 268 [[arXiv:1805.08222](#)] [[INSPIRE](#)].

- [158] S. Iguro, T. Kitahara, Y. Omura, R. Watanabe and K. Yamamoto, *D^* polarization vs. $R_{D^{(*)}}$ anomalies in the leptoquark models*, *JHEP* **02** (2019) 194 [[arXiv:1811.08899](#)] [[INSPIRE](#)].
- [159] S. Iguro and Y. Omura, *Status of the semileptonic B decays and muon $g-2$ in general 2HDMs with right-handed neutrinos*, *JHEP* **05** (2018) 173 [[arXiv:1802.01732](#)] [[INSPIRE](#)].
- [160] D. Bardhan, P. Byakti and D. Ghosh, *A closer look at the R_D and R_{D^*} anomalies*, *JHEP* **01** (2017) 125 [[arXiv:1610.03038](#)] [[INSPIRE](#)].
- [161] A. Azatov, D. Bardhan, D. Ghosh, F. Sgarlata and E. Venturini, *Anatomy of $b \rightarrow c\tau\nu$ anomalies*, *JHEP* **11** (2018) 187 [[arXiv:1805.03209](#)] [[INSPIRE](#)].
- [162] D. Bardhan and D. Ghosh, *B -meson charged current anomalies: The post-Moriond 2019 status*, *Phys. Rev. D* **100** (2019) 011701 [[arXiv:1904.10432](#)] [[INSPIRE](#)].
- [163] I. Bigaran, J. Gargalionis and R.R. Volkas, *A near-minimal leptoquark model for reconciling flavour anomalies and generating radiative neutrino masses*, *JHEP* **10** (2019) 106 [[arXiv:1906.01870](#)] [[INSPIRE](#)].
- [164] J. Gargalionis, I. Popa-Mateiu and R.R. Volkas, *Radiative neutrino mass model from a mass dimension-11 $\Delta L = 2$ effective operator*, *JHEP* **03** (2020) 150 [[arXiv:1912.12386](#)] [[INSPIRE](#)].
- [165] Y. Cai, J. Gargalionis, M.A. Schmidt and R.R. Volkas, *Reconsidering the One Leptoquark solution: flavor anomalies and neutrino mass*, *JHEP* **10** (2017) 047 [[arXiv:1704.05849](#)] [[INSPIRE](#)].
- [166] M. Gronau and D. London, *Isospin analysis of CP asymmetries in B decays*, *Phys. Rev. Lett.* **65** (1990) 3381 [[INSPIRE](#)].
- [167] M. Gronau, O.F. Hernandez, D. London and J.L. Rosner, *Decays of B mesons to two light pseudoscalars*, *Phys. Rev. D* **50** (1994) 4529 [[hep-ph/9404283](#)] [[INSPIRE](#)].
- [168] M. Gronau, O.F. Hernandez, D. London and J.L. Rosner, *Broken SU(3) symmetry in two-body B decays*, *Phys. Rev. D* **52** (1995) 6356 [[hep-ph/9504326](#)] [[INSPIRE](#)].
- [169] A. Dery, M. Ghosh, Y. Grossman and S. Schacht, *SU(3)_F analysis for beauty baryon decays*, *JHEP* **03** (2020) 165 [[arXiv:2001.05397](#)] [[INSPIRE](#)].
- [170] Y. Grossman and S. Schacht, *U-Spin Sum Rules for CP Asymmetries of Three-Body Charmed Baryon Decays*, *Phys. Rev. D* **99** (2019) 033005 [[arXiv:1811.11188](#)] [[INSPIRE](#)].
- [171] G. Hiller, M. Jung and S. Schacht, *SU(3)-flavor anatomy of nonleptonic charm decays*, *Phys. Rev. D* **87** (2013) 014024 [[arXiv:1211.3734](#)] [[INSPIRE](#)].
- [172] S. Müller, U. Nierste and S. Schacht, *Sum Rules of Charm CP Asymmetries beyond the SU(3)_F Limit*, *Phys. Rev. Lett.* **115** (2015) 251802 [[arXiv:1506.04121](#)] [[INSPIRE](#)].
- [173] Y. Grossman and D.J. Robinson, *SU(3) Sum Rules for Charm Decay*, *JHEP* **04** (2013) 067 [[arXiv:1211.3361](#)] [[INSPIRE](#)].
- [174] A. Crivellin, A. Kokulu and C. Greub, *Flavor-phenomenology of two-Higgs-doublet models with generic Yukawa structure*, *Phys. Rev. D* **87** (2013) 094031 [[arXiv:1303.5877](#)] [[INSPIRE](#)].
- [175] J. Haller, A. Hoecker, R. Kogler, K. Mönig, T. Peiffer and J. Stelzer, *Update of the global electroweak fit and constraints on two-Higgs-doublet models*, *Eur. Phys. J. C* **78** (2018) 675 [[arXiv:1803.01853](#)] [[INSPIRE](#)].

- [176] J.F. Gunion, H.E. Haber, G.L. Kane and S. Dawson, *The Higgs Hunter's Guide*, vol. 80 (2000) [[INSPIRE](#)].
- [177] J. Kalinowski, *Semileptonic Decays of B Mesons into $\tau\nu_\tau$ in a Two Higgs Doublet Model*, *Phys. Lett. B* **245** (1990) 201 [[INSPIRE](#)].
- [178] W.-S. Hou, *Enhanced charged Higgs boson effects in $B^- \rightarrow \tau\bar{\nu}, \mu\bar{\nu}$ and $b \rightarrow \tau\bar{\nu} + X$* , *Phys. Rev. D* **48** (1993) 2342 [[INSPIRE](#)].
- [179] J.F. Gunion and H.E. Haber, *The CP conserving two Higgs doublet model: The Approach to the decoupling limit*, *Phys. Rev. D* **67** (2003) 075019 [[hep-ph/0207010](#)] [[INSPIRE](#)].
- [180] G.C. Branco, P.M. Ferreira, L. Lavoura, M.N. Rebelo, M. Sher and J.P. Silva, *Theory and phenomenology of two-Higgs-doublet models*, *Phys. Rept.* **516** (2012) 1 [[arXiv:1106.0034](#)] [[INSPIRE](#)].
- [181] H.E. Haber, *The Higgs data and the Decoupling Limit*, in *1st Toyama International Workshop on Higgs as a Probe of New Physics 2013*, (2013) [[arXiv:1401.0152](#)] [[INSPIRE](#)].
- [182] N. Craig, J. Galloway and S. Thomas, *Searching for Signs of the Second Higgs Doublet*, [arXiv:1305.2424](#) [[INSPIRE](#)].
- [183] S. Gori, H.E. Haber and E. Santos, *High scale flavor alignment in two-Higgs doublet models and its phenomenology*, *JHEP* **06** (2017) 110 [[arXiv:1703.05873](#)] [[INSPIRE](#)].
- [184] B. Grzadkowski, H.E. Haber, O.M. Ogreid and P. Osland, *Heavy Higgs boson decays in the alignment limit of the 2HDM*, *JHEP* **12** (2018) 056 [[arXiv:1808.01472](#)] [[INSPIRE](#)].
- [185] M. Jung, A. Pich and P. Tuzon, *Charged-Higgs phenomenology in the Aligned two-Higgs-doublet model*, *JHEP* **11** (2010) 003 [[arXiv:1006.0470](#)] [[INSPIRE](#)].
- [186] A. Pich and P. Tuzon, *Yukawa Alignment in the Two-Higgs-Doublet Model*, *Phys. Rev. D* **80** (2009) 091702 [[arXiv:0908.1554](#)] [[INSPIRE](#)].
- [187] J. Bernon, J.F. Gunion, H.E. Haber, Y. Jiang and S. Kraml, *Scrutinizing the alignment limit in two-Higgs-doublet models: $m_h = 125$ GeV*, *Phys. Rev. D* **92** (2015) 075004 [[arXiv:1507.00933](#)] [[INSPIRE](#)].
- [188] A.G. Akeroyd et al., *Prospects for charged Higgs searches at the LHC*, *Eur. Phys. J. C* **77** (2017) 276 [[arXiv:1607.01320](#)] [[INSPIRE](#)].
- [189] M. Misiak and M. Steinhauser, *Weak radiative decays of the B meson and bounds on $M_{H^\pm}$ in the Two-Higgs-Doublet Model*, *Eur. Phys. J. C* **77** (2017) 201 [[arXiv:1702.04571](#)] [[INSPIRE](#)].
- [190] ATLAS collaboration, *Search for charged Higgs bosons decaying via $H^\pm \rightarrow \tau^\pm \nu_\tau$ in the $\tau + \text{jets}$ and $\tau + \text{lepton}$ final states with 36 fb^{-1} of pp collision data recorded at $\sqrt{s} = 13$ TeV with the ATLAS experiment*, *JHEP* **09** (2018) 139 [[arXiv:1807.07915](#)] [[INSPIRE](#)].
- [191] M. Misiak, A. Rehman and M. Steinhauser, *On charm-mass dependent NNLO corrections to $\mathcal{B}(\bar{B} \rightarrow X_s \gamma)$* , *PoS RADCOR2019* (2019) 033 [[arXiv:2002.03021](#)] [[INSPIRE](#)].
- [192] M. Misiak, A. Rehman and M. Steinhauser, *Towards $\bar{B} \rightarrow X_s \gamma$ at the NNLO in QCD without interpolation in m_c* , *JHEP* **06** (2020) 175 [[arXiv:2002.01548](#)] [[INSPIRE](#)].
- [193] PARTICLE DATA GROUP collaboration, *Review of Particle Physics*, *Prog. Theor. Exp. Phys.* **2020** (2020) 083C01.
- [194] T. Enomoto and R. Watanabe, *Flavor constraints on the Two Higgs Doublet Models of Z_2 symmetric and aligned types*, *JHEP* **05** (2016) 002 [[arXiv:1511.05066](#)] [[INSPIRE](#)].

- [195] X.-D. Cheng, Y.-D. Yang and X.-B. Yuan, *Phenomenological discriminations of the Yukawa interactions in two-Higgs doublet models with Z_2 symmetry*, *Eur. Phys. J. C* **74** (2014) 3081 [[arXiv:1401.6657](#)] [[INSPIRE](#)].
- [196] A. Arbey, F. Mahmoudi, O. Stal and T. Stefaniak, *Status of the Charged Higgs Boson in Two Higgs Doublet Models*, *Eur. Phys. J. C* **78** (2018) 182 [[arXiv:1706.07414](#)] [[INSPIRE](#)].
- [197] J. Aebischer, W. Altmannshofer, D. Guadagnoli, M. Reboud, P. Stangl and D.M. Straub, *B-decay discrepancies after Moriond 2019*, *Eur. Phys. J. C* **80** (2020) 252 [[arXiv:1903.10434](#)] [[INSPIRE](#)].
- [198] L. Delle Rose, S. Khalil, S.J.D. King and S. Moretti, *R_K and R_{K^*} in an Aligned 2HDM with Right-Handed Neutrinos*, *Phys. Rev. D* **101** (2020) 115009 [[arXiv:1903.11146](#)] [[INSPIRE](#)].
- [199] P. Arnan, D. Bećirević, F. Mescia and O. Sumensari, *Two Higgs doublet models and $b \rightarrow s$ exclusive decays*, *Eur. Phys. J. C* **77** (2017) 796 [[arXiv:1703.03426](#)] [[INSPIRE](#)].
- [200] J.G. Korner and G.A. Schuler, *Exclusive Semileptonic Heavy Meson Decays Including Lepton Mass Effects*, *Z. Phys. C* **46** (1990) 93 [[INSPIRE](#)].
- [201] X.-Y. Pham, *New method for determination of the $D \rightarrow \bar{K}^* + e^+ + \nu$ axial-vector form factors without resorting to angular distributions*, *Phys. Rev. D* **46** (1992) 1909 [Erratum *ibid.* **47** (1993) 350] [[INSPIRE](#)].
- [202] J. Koponen et al., *The shape of the $D \rightarrow K$ semileptonic form factor from full lattice QCD and V_{cs}* , [arXiv:1305.1462](#) [[INSPIRE](#)].
- [203] C. Murgui, A. Peñuelas, M. Jung and A. Pich, *Global fit to $b \rightarrow c\tau\nu$ transitions*, *JHEP* **09** (2019) 103 [[arXiv:1904.09311](#)] [[INSPIRE](#)].
- [204] M. González-Alonso, J. Martin Camalich and K. Mimouni, *Renormalization-group evolution of new physics contributions to (semi)leptonic meson decays*, *Phys. Lett. B* **772** (2017) 777 [[arXiv:1706.00410](#)] [[INSPIRE](#)].
- [205] W.D. Goldberger, *Semileptonic B decays as a probe of new physics*, [hep-ph/9902311](#) [[INSPIRE](#)].
- [206] R. Mandal, C. Murgui, A. Peñuelas and A. Pich, *The role of right-handed neutrinos in $b \rightarrow c\tau\bar{\nu}$ anomalies*, *JHEP* **08** (2020) 022 [[arXiv:2004.06726](#)] [[INSPIRE](#)].
- [207] HPQCD collaboration, *B-meson decay constants: a more complete picture from full lattice QCD*, *Phys. Rev. D* **91** (2015) 114509 [[arXiv:1503.05762](#)] [[INSPIRE](#)].
- [208] M. Beneke and G. Buchalla, *The B_c Meson Lifetime*, *Phys. Rev. D* **53** (1996) 4991 [[hep-ph/9601249](#)] [[INSPIRE](#)].
- [209] A.G. Akeroyd and C.-H. Chen, *Constraint on the branching ratio of $B_c \rightarrow \tau\bar{\nu}$ from LEP1 and consequences for $R(D^{(*)})$ anomaly*, *Phys. Rev. D* **96** (2017) 075011 [[arXiv:1708.04072](#)] [[INSPIRE](#)].
- [210] L3 collaboration, *Measurement of $D_s^- \rightarrow \tau^- \bar{\nu}_\tau$ and a new limit for $B^- \rightarrow \tau^- \bar{\nu}_\tau$* , *Phys. Lett. B* **396** (1997) 327 [[INSPIRE](#)].
- [211] S. Kraml, T.Q. Loc, D.T. Nhung and L.D. Ninh, *Constraining new physics from Higgs measurements with Lilith: update to LHC Run 2 results*, *SciPost Phys.* **7** (2019) 052 [[arXiv:1908.03952](#)] [[INSPIRE](#)].