Published for SISSA by Springer

Received: June 6, 2018
Revised: November 14, 2018
Accepted: December 6, 2018
Published: January 2, 2019

Constraining new physics in $b \to c\ell\nu$ transitions

Martin Jung and David M. Straub

Excellence Cluster Universe,
Boltzmannstr. 2, 85748 Garching, Germany

E-mail: martin.jung@tum.de, david.straub@tum.de

Abstract: B decays proceeding via $b \to c\ell\nu$ transitions with $\ell = e$ or μ are tree-level processes in the Standard Model. They are used to measure the CKM element V_{cb}, as such forming an important ingredient in the determination of e.g. the unitarity triangle; hence the question to which extent they can be affected by new physics contributions is important, specifically given the long-standing tension between V_{cb} determinations from inclusive and exclusive decays and the significant hints for lepton flavour universality violation in $b \to c\tau\nu$ and $b \to s\ell\ell$ decays. We perform a comprehensive model-independent analysis of new physics in $b \to c\ell\nu$, considering all combinations of scalar, vector and tensor interactions occuring in single-mediator scenarios. We include for the first time differential distributions of $B \to D^*\ell\nu$ angular observables for this purpose. We show that these are valuable in constraining non-standard interactions. Specifically, the zero-recoil endpoint of the $B \to D\ell\nu$ spectrum is extremely sensitive to scalar currents, while the maximum-recoil endpoint of the $B \to D^*\ell\nu$ spectrum with transversely polarized D^* is extremely sensitive to tensor currents. We also quantify the room for e-μ universality violation in $b \to c\ell\nu$ transitions, predicted by some models suggested to solve the $b \to c\tau\nu$ anomalies, from a global fit to $B \to D\ell\nu$ and $B \to D^*\ell\nu$ for the first time. Specific new physics models, corresponding to all possible tree-level mediators, are also discussed. As a side effect, we present V_{cb} determinations from exclusive B decays, both with frequentist and Bayesian statistics, leading to compatible results. The entire numerical analysis is based on open source code, allowing it to be easily adapted once new data or new form factors become available.

Keywords: Beyond Standard Model, Heavy Quark Physics

ArXiv ePrint: 1801.01112

Open Access, © The Authors.
Article funded by SCOAP[3].

https://doi.org/10.1007/JHEP01(2019)009

JHEP01(2019)009

Contents

JHEP01(2019)009

1 Introduction

In the context of the Standard Model (SM), the element V_{cb} of the Cabibbo-Kobayashi-Maskawa (CKM) matrix can be determined in various ways:

- from a global fit including e.g. meson-antimeson mixing observables [1, 2],
- from inclusive measurements of $B \to X_c e\nu$ [3], where X_c is any charmed hadronic final state,
- from exclusive $b \to c\ell\nu$ transitions, specifically $B \to D\ell\nu$ and $B \to D^*\ell\nu$ ($\ell = e, \mu$) decays (see e.g. [4] for a recent review).

When considering the SM as the low-energy limit of a more fundamental theory of "new physics" (NP), these determinations are not applicable model-independently in general. Specifically, flavour-changing neutral current processes like meson-antimeson mixing could easily be affected by NP, invalidating the global fit. In this case, a potential disagreement between the global fit and the tree-level determinations from semi-leptonic B decays can signal the presence of NP. However, even the tree-level processes could in principle be significantly affected by NP. This possibility has been considered in the past in particular in

view of the long-standing tensions between V_{cb} from different decay channels. Clearly, these tensions could be due to statistical fluctuations or underestimated theoretical uncertainties. While the inclusive decay can be computed to high precision in an expansion in α_s and $1/m_{c,b}$, see e.g. [3] for a recent overview, the exclusive decays require the knowledge of hadronic form factors. Lattice QCD (LQCD) calculations of $B \to D$ form factors are now available also at non-zero recoil [5, 6] for the relevant SM operators, but for $B \to D^*$ a full lattice calculation at non-zero recoil is still lacking [7, 8]. In both cases, the dependence on the chosen form factor parametrization has received considerable interest recently [6, 9–16], indicating that at least part of the tension between inclusive and exclusive decays might stem from an underestimation of the systematic or theoretical uncertainties. Nevertheless, entertaining the possibility of NP as the origin of the tensions between SM and data is certainly worthwhile, since these analyses are suggestive, but do not provide proof that the form factor parametrization is indeed the reason for the observed tension.

Additional interest in NP modifying $b \to c\ell\nu$ with light leptons was generated by the signficant deviations from SM expectations in decays based on the $b \to c\tau\nu$ transition, including in $B \to D\tau\nu$, $B \to D^*\tau\nu$, and, most recently, $B_c \to J/\psi\tau\nu$ [17–23]. Many NP models have been proposed to explain these tensions. Depending on the flavour structure of the model, $b \to c\ell\nu$ with light leptons can be affected as well. This is true in particular for models explaining simultaneously the apparent deviations from lepton flavour universality (LFU) in $B \to K\ell\ell$ and $B \to K^*\ell\ell$, with $\ell = e$ or μ (see e.g. [24–27]). Hence an important question is to what extent LFU is tested in $b \to c\ell\nu$, independent of any tension between $b \to c\ell\nu$ data and SM predictions.

Recent analyses of NP in $b \to c\ell\nu$ include [28–34]. Most of them have focused on individual operators or specific subsets and only used experimental information from the measurements of total branching ratios in exclusive decays. Recently however, differential distributions of exclusive measurements, including angular observables in $B \to D^*\ell\nu$, have been released by the BaBar and Belle collaborations [35–38]. As will be shown in section 5, these data contain valuable information that allows to independently constrain different types of non-standard interactions in $b \to c\ell\nu$. The main aim of this paper is to perform a comprehensive model-independent analysis of all possible types of NP effects in $b \to c\ell\nu$, making use of the wealth of experimental data.

This paper is organized as follows: in section 2, the effective Hamiltonian for $b \to c\ell\nu$ is defined and relations among the operators implied by SM gauge invariance are discussed. In section 3, we discuss our treatment of $B \to D$ and $B \to D^*$ form factors that are crucial ingredients in the analysis of exclusive $b \to c\ell\nu$ decays. In section 4, we perform fits to V_{cb} from $B \to D\ell\nu$ and $B \to D^*\ell\nu$. Reproducing the values in the literature, this step is useful as a cross-check of our numerics. We also perform the analysis with frequentist and Bayesian statistics, explicitly demonstrating their agreement. In section 5, we perform the NP analyses, starting with a discussion of NP models with tree-level mediators and their characteristic patterns of Wilson coefficients, and subsequently discussing each of the relevant operator combinations. Section 6 contains our conclusions.

An important feature of our analysis is that it is entirely based on open-source code. We have implemented all observables of interest as well as our predictions for $B \to D$ and

JHEP01(2019)009

$B \to D^*$ form factors in the `flavio` flavour physics package [39]. This has three benefits: first, it makes our analysis transparent and reproducible. Second, it allows anyone to update the best-fit values of V_{cb} or the allowed ranges for the Wilson coefficients when new experimental data or new lattice form factor computations become available. Third, it easily allows to study the viability of more involved NP models with multiple Wilson coefficients, that cannot be easily visualized in two-dimensional plots. Additionally, to corroborate the reliability of our results, we have obtained all numerical results with a completely independent Mathematica code.

2 Effective Hamiltonian

The effective Hamiltonian for $b \to c\ell\nu$ transitions can be written as[1]

$$\mathcal{H}_{\text{eff}}^{b\to c\ell\nu_{\ell'}} = \frac{4G_F}{\sqrt{2}} V_{cb} \left(O_{V_L}^{\ell\ell'} \delta_{\ell\ell'} + \sum_i C_i^{\ell\ell'} O_i^{\ell\ell'} + \text{h.c.} \right), \tag{2.1}$$

where the sum runs over the following operators:

$$\begin{aligned} O_{V_L}^{\ell\ell'} &= (\bar{c}_L \gamma^\mu b_L)(\bar{\ell}_L \gamma_\mu \nu_{\ell' L}), \quad O_{S_R}^{\ell\ell'} = (\bar{c}_L b_R)(\bar{\ell}_R \nu_{\ell' L}), \quad O_T^{\ell\ell'} = (\bar{c}_R \sigma^{\mu\nu} b_L)(\bar{\ell}_R \sigma_{\mu\nu} \nu_{\ell' L}), \\ O_{V_R}^{\ell\ell'} &= (\bar{c}_R \gamma^\mu b_R)(\bar{\ell}_L \gamma_\mu \nu_{\ell' L}), \quad O_{S_L}^{\ell\ell'} = (\bar{c}_R b_L)(\bar{\ell}_R \nu_{\ell' L}), \end{aligned} \tag{2.2}$$

with in general charged-lepton- *and* neutrino-flavour-dependent coefficients. Since we are focusing on decays with light leptons in the final state, we only consider $\ell = e$ or μ, but allow for $\ell' = e, \mu, \tau$, which cannot be distinguished experimentally. We have defined the coefficients $C_i^{\ell\ell'}$ in (2.2) such that they vanish in the SM. A lepton-flavour universal and diagonal NP effect in $C_{V_L}^{\ell\ell'}$ can always be absorbed by a shift in V_{cb}, since V_{cb} is a free parameter in the SM and presently not meaningfully constrained by CKM unitarity. In the following, we will use the shorthands

$$C_i^\ell \equiv C_i^{\ell\ell}, \qquad \tilde{V}_{cb}^\ell = V_{cb}(1 + C_{V_L}^\ell), \qquad \tilde{C}_i^\ell = C_i^\ell/(1 + C_{V_L}^\ell), \tag{2.3}$$

where appropriate.

The operators in the effective Hamiltonian arise from more funadamental interactions at or above the electroweak scale. The available high-energy data from LHC indicate the existence of another energy gap between the electroweak scale and that of NP. In such a scenario interactions beyond the SM can be cast into another effective theory, with operators symmetric under the full SM gauge group. For linearly realized electroweak symmetry breaking this effective theory is called *Standard Model effectivie field theory* (SMEFT), the operators of which can be ordered in terms of their mass dimension, with those at dimension six giving the dominant contributions here [41, 42]. The tree-level

[1] We do not consider scenarios with light right-handed neutrinos. This general form for NP in $b \to c\ell\nu$ transitions has been first considered in ref. [40].

JHEP01(2019)009

matching of SMEFT operators onto the effective Hamiltonian (2.2) reads [43–46]

$$C_{V_L}^{\ell\ell'} = -v^2\,\frac{V_{ci}}{V_{cb}}\,C_{lq}^{(3)\ell\ell' i3} + v^2\,\frac{V_{ci}}{V_{cb}}\,C_{\phi q}^{(3)i3}\,\delta_{\ell\ell'}\,, \qquad C_{V_R}^{\ell\ell'} = \frac{v^2}{2}\,C_{\phi ud}^{23}\,\delta_{\ell\ell'}\,, \tag{2.4}$$

$$C_{S_R}^{\ell\ell'} = -\frac{v^2}{2}\,\frac{V_{ci}}{V_{cb}}\,C_{ledq}^{\ell\ell' 3i}\,, \qquad C_{S_L}^{\ell\ell'} = -\frac{v^2}{2}\,\frac{V_{ci}}{V_{cb}}\,C_{lequ}^{(1)\ell\ell' 3i}\,, \tag{2.5}$$

$$C_{T}^{\ell\ell'} = -\frac{v^2}{2}\,\frac{V_{ci}}{V_{cb}}\,C_{lequ}^{(3)\ell\ell' 3i}\,, \tag{2.6}$$

where the definition of the SMEFT operators can be found in [42][2] and we are employing a weak basis for SMEFT where down-type and charged-lepton mass matrices are diagonal. An important prediction of this framework is that the Wilson coefficient $C_{V_R}^{\ell\ell'}$ is lepton flavour universal and diagonal [45, 47]. A deviation from this prediction would hence indicate a non-linear realization of electroweak symmetry breaking [45]. Presently such a deviation is not observed, however, and we will use $C_{V_R}^{\ell\ell'} \equiv C_{V_R}\delta_{\ell\ell'}$ in the remainder of this paper.

Another implication of SMEFT is that that the Wilson coefficients $C_{ledq}^{\ell\ell' 3i}$, that give rise to $C_{S_R}^{\ell\ell'}$, also generate neutral-current operators of the form $(\bar{q}_L b_R)(\bar{\ell}_R \ell'_L)$, where $q = d, s, b$. For $q = s$ or d, these operators are constrained very strongly by the leptonic decays $B_{d,s} \to \ell\ell'$, that are forbidden for $\ell \neq \ell'$ and strongly helicity suppressed for $\ell = \ell'$ in the SM. From existing bounds and measurements, we find that the SMEFT Wilson coefficients $C_{ledq}^{\ell\ell' 31}$ and $C_{ledq}^{\ell\ell' 32}$ can induce effects in $C_{S_R}^{\ell\ell'}$ at most at the per mil level, which would not lead to any visible effects in $b \to c\ell\nu_{\ell'}$ at the current level of precision. However, sizable effects in $C_{S_R}^{\ell\ell'}$ cannot be excluded, since the coefficients $C_{ledq}^{\ell\ell' 33}$ contributing to the sum in (2.5) only generate the flavour-conserving operators $(\bar{b}_L b_R)(\bar{\ell}_R \ell'_L)$, that are allowed to be sizable.[3]

Finally, the availability of the full anomalous dimension matrix for SMEFT dimension-six operators [49–51] allows for the prediction of operator mixing due to electroweak renormalization effects; this will be discussed briefly at the end of section 5.1.

3 $B \to D^{(*)}$ form factors

The hadronic form factors of the $B \to D^{(*)}$ transitions are crucial both for the determination of the CKM element V_{cb} in the SM and for constraining NP contributions to $b \to c\ell\nu$. An important difference between the two scenarios is that in the SM V_{cb} only changes the overall normalization of the rates, but does not modify the shapes of differential distributions. NP contributions on the other hand can modify these shapes and can also involve additional form factors, in particular tensor form factors. Since our main interest is constraining NP in $b \to c\ell\nu$, we want to use as much information on the form factors from theory as possible, while at the same time remaining conservative enough not to introduce

[2] We use a normalization $\mathcal{L}_{\text{SMEFT}} = \sum_i C_i O_i$, i.e. dimension-6 operators have dimensions of inverse mass squared.

[3] Note that these operators do not contribute to (and thus are not constrained by) leptonic decays of $\Upsilon(nS)$ [48].

JHEP01(2019)009

ficticious tensions with the precise experimental data due to too rigid parametrizations. We therefore use information from four complementary methods to determine the $B \to D^{(*)}$ form factors:

- LQCD. We use all available unquenched LQCD calculations of $B \to D^{(*)}$ form factors. The $B \to D$ vector and scalar form factors have been computed by the HPQCD [5] and the Fermilab/MILC collaborations [6] at several values of q^2, constraining the shape of these form factors in addition to their normalizations. The FLAG collaboration has performed an average of these two computations, fitted to the BCL parametrization [12]. For the $B \to D^*$ form factors, so far only calculations at zero hadronic recoil have been reported [7, 8]; we use their average calculated in [8].

- QCD light-cone sum rules allow to compute the form factors in the region of large hadronic recoil, depending on B meson light-cone distribution amplitudes as non-perturbative input [52]. This method is complementary to LQCD, being valid in the opposite kinematic limit. We use the form factor values and ratios obtained in ref. [52] at[4] $q^2 = 0$, and extract from their values given for ρ^2_{D,D^*} two more, correlated pseudo-datapoints at $w(q^2) = 1.3$.

- Heavy Quark Symmetry and Heavy Quark Effective Theory (HQET). Treating both the bottom and charm quark as heavy compared to a typical scale of QCD interactions, QCD exhibits a symmetry among the heavy quarks [53, 54]. As a consequence, all $B \to D^{(*)}$ form factors either vanish or reduce to a single function — the leading Isgur-Wise function — in the infinite mass limit [55]. Perturbative QCD and power corrections to this limit are partly calculable [13, 56–64], to be discussed below.

- By crossing symmetry, the form factors describing the semi-leptonic transition also describe the pair production of mesons. Unitarity can then be used to impose constraints on the form factors. Taking into account contributions from other two-body channels with the right quantum numbers leads via a conservative application of HQET to the *strong unitarity constraints* [65, 66]. We employ the updated bounds given in [9] for $B \to D$ and the simplified bounds derived in [11] for $B \to D^*$.

We proceed by using the HQET parametrization of all $B \to D^{(*)}$ form factors, including corrections of $O(\alpha_s, \Lambda_{\rm QCD}/m_{c,b})$, in the notation of [13], with two differences:

1. Instead of using the CLN relation between slope and curvature of the leading Isgur-Wise function, we include both as independent parameters in the fit.

2. The treatment of higher-order corrections of $\mathcal{O}(\Lambda^2_{\rm QCD}/m_c^2)$ has recently been shown to have a significant effect on the extraction of V_{cb} in the SM, see the discussions in [9–16]. We make these corrections explicit by including in addition to the subleading Isgur-Wise functions at order $\Lambda_{\rm QCD}/m_{c,b}$ corrections of order $\Lambda^2_{\rm QCD}/m_c^2$ in those HQET

[4]The kinematic variable w is related to q^2 as $w = (m_B^2 + m^2_{D^{(*)}} - q^2)/(2m_B m_{D^{(*)}})$.

JHEP01(2019)009

form factors that are protected from $O(\Lambda_{\rm QCD}/m_c)$ corrections.[5] From comparison of the HQET predictions at $\mathcal{O}(\alpha_s, \Lambda_{\rm QCD}/m_{b,c})$, using the three-point sum rule results for the subleading Isgur-Wise functions [60–62] with LQCD results, we observe a shift of about -10% from these corrections in $h_{A_1}(1)$, while the corrections in $h_+(1)$ are only a few per cent. For $h_{T_1}(1)$ we allow for an independent correction of 10% which is not constrained by lattice data. Note that these corrections are in principle obtainable from LQCD in all form factors, however, so far only results for those appearing in the SM are available.

We then perform Bayesian and frequentist fits of this parametrization to pseudo data points corresponding to the described inputs. The result is a posterior probability distribution or profile likelihood for all the form factor parameters, respectively. These can be interpreted as theory predictions for all $B \to D^{(*)}$ form factors in the entire (semi-leptonic) kinematic range. This theory prediction is then used in our numerical analysis as a prior on (in Bayesian fits) or a pseudo-measurement of (in frequentist fits) the form factor parameters.

4 V_{cb} from exclusive decays in the Standard Model

Fits for the CKM element V_{cb} from the exclusive decays $B \to D\ell\nu$ and $B \to D^*\ell\nu$ measured at the B factories BaBar and Belle have already been performed in the literature (see e.g. [6, 9–16] for recent fits). Here, we repeat this exercise to define our assumptions on form factors and our experimental input. Furthermore, all of our fits are reproducible using open source code, allowing them to be adapted or modified with different theoretical or experimental inputs.

We perform fits to $B \to D\ell\nu$ and $B \to D^*\ell\nu$ decays, where the theoretical uncertainties are dominated by the hadronic form factors. To study the impact of different statistical treatments of these "nuisance" parameters, we consider three different fits:

- A frequentist fit where the theoretical knowledge of form factors is treated as a pseudo-measurement and the individual parameters are profiled over.
- A Bayesian fit where the theoretical knowledge of form factors is treated as a prior probability distribution and the individual parameters are marginalized over.
- A "fast fit" where the theoretical uncertainty on each bin is determined by varying the form factor parameters according to the theoretical constraints and is added in quadrature with the experimental uncertainties.

4.1 V_{cb} from $B \to D\ell\nu$

The BaBar collaboration has measured the differential branching ratio of $B \to D\ell\nu$, reconstructed with hadronic tagging [35], in ten bins, averaged over electrons and muons as well as charged and neutral B decays. Since only statistical uncertainties are given,

[5] Note that two of these corrections are implicitly included in [13] when the normalizations of the $B \to D^{(*)}$ form factors $h_{A_1,+}$ are decoupled from their HQET values.

JHEP01(2019)009

Decay	Observable	Experiment	Comment	Ref.
$B \to D(e,\mu)\nu$	BR	BaBar	global fit	[67]
$B \to D\ell\nu$	$d\Gamma/dw$	BaBar	hadronic tag	[35]
$B \to D(e,\mu)\nu$	$d\Gamma/dw$	Belle	hadronic tag	[37]
$B \to D^*(e,\mu)\nu$	BR	BaBar	global fit	[67]
$B \to D^*\ell\nu$	BR	BaBar	hadronic tag	[68]
$B \to D^*\ell\nu$	BR	BaBar	untagged B^0	[69]
$B \to D^*\ell\nu$	BR	BaBar	untagged $B^\pm$	[70]
$B \to D^*(e,\mu)\nu$	$d\Gamma_{L,T}/dw$	Belle	untagged	[36]
$B \to D^*\ell\nu$	$d\Gamma/d(w,\cos\theta_V,\cos\theta_l,\phi)$	Belle	hadronic tag	[38]

Table 1. Experimental analyses considered. The analyses labeled by $B \to D^{(*)}\ell\nu$ do not differentiate between the lepton species and are hence not used when analyzing scenarios with non-universal coefficients.

we follow [9] and add a fully correlated systematic uncertainty of 6.7% on the rate. To avoid a bias towards lower values of V_{cb} caused by underfluctuations in individual bins ("d'Agostini bias" [71]), we always treat relative systematic errors as relative to the SM predictions rather than the experimental central values. In addition to this differential measurement, we also include a BaBar measurement of the total branching ratio from a global fit, split by electrons and muons [67], that is statistically independent of the former; following ref. [11], we assume the measurement of the total branching ratio to be unaffected by the form factor parametrization. We take into account the significant correlation with the D^* modes extracted in the same analysis. Following HFLAV [72], we apply a rescaling of $-3.7\,\%$ to the published branching ratio to account for updated D branching ratios.

We note that we cannot use the global HFLAV *average* of the $B \to D\ell\nu$ branching ratio because

- it contains older measurements that assumed a particular form factor parametrization and would be inconsistent to use in a NP analysis,
- it contains measurements from the anaylses that we include in binned form, such that including it would amount to double-counting,
- it only considers the average of the electronic and muonic branching ratios, so we cannot use it for the lepton-flavour dependent NP analysis.

The Belle collaboration has measured the differential branching ratios separately for electrons and muons as well as charged and neutral B decays in ten bins each [37], specifying the full correlation matrix. This measurement does not rely on a specific form factor parametrization.

JHEP01(2019)009

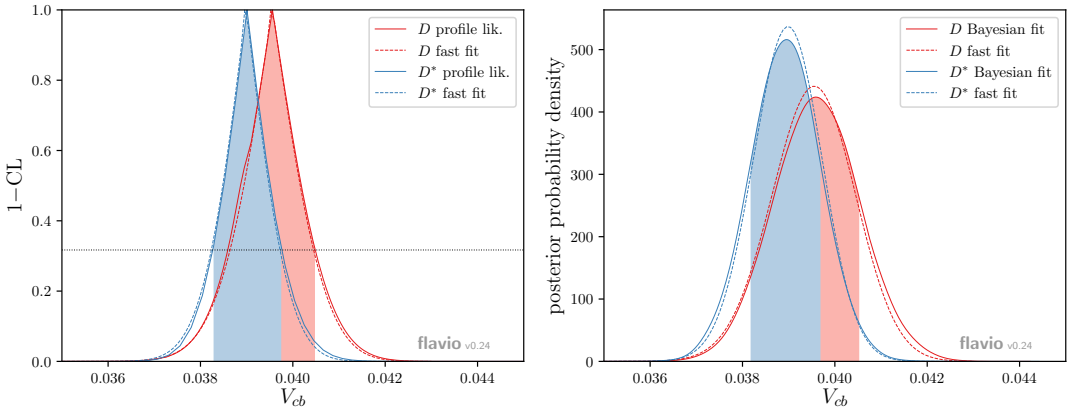

Figure 1. Fit results for V_{cb} from exclusive decays in the Standard Model. Left: frequentist profile likelihood vs. "fast fit" method; the horizontal dotted line delineates the 1σ region. Right: Bayesian posterior probability vs. "fast fit" method.

The combined fit to Belle and BaBar data with the three different statistical approaches, using the form factors described in section 3, yields

$$V_{cb}^{B\to D\ell\nu} = (3.96 \pm 0.09) \times 10^{-2} \qquad \text{(frequentist fit)}, \tag{4.1}$$

$$V_{cb}^{B\to D\ell\nu} = (3.96 \pm 0.09) \times 10^{-2} \qquad \text{(Bayesian fit)}, \tag{4.2}$$

$$V_{cb}^{B\to D\ell\nu} = (3.96 \pm 0.09) \times 10^{-2} \qquad \text{(fast fit)}, \tag{4.3}$$

where the errors in the frequentist fit refer to a change by 0.5 in the profile likelihood and in the Bayesian case correspond to the highest posterior density interval with 68.3% credibility. The agreement of the central value between the frequentist and the Bayesian fit is not surprising as the minimum of the two likelihoods coincides (the prior probability for theory parameters has the same mathematical form as the "pseudo measurements" used in the frequentist fit). That the errors from the profile likelihood and the posterior marginalization agree is less trivial, but is a consequence of all theory and experimental uncertainties being close to Gaussian. The excellent agreement of the two more sophisticated approaches with the "fast fit" approach indicates that the fitted values of the nuisance parameters are close to the theoretical central values (otherwise a mismatch would be observed in the fast fit). The full one-dimensional profile likelihood and posterior probability distribution are shown in figure 1.

We observe good compatibility with other recent extractions from this mode [9, 13, 16]. A direct comparison is not possible, since neither the form factor parametrizations nor the data sets used are identical. The inclusion of additional data in our case is responsible for the slightly smaller uncertainties. Note that the inclusion of the measurement [67] shifts V_{cb} to smaller values compared to [9].

In our numerical analysis of new physics effects in section 5, when allowing for lepton flavour non-universal effects, we only use measurements where electron and muon samples are separated, since the generally different but unknown electron and muon efficiencies prohibit a consistent interpretation of the combined measurements in such scenarios. It is

JHEP01(2019)009

instructive to extract the value of V_{cb} only from these subsets of measurements. Using the frequentist approach, we find

$$V_{cb}^{B\to De\nu} = (4.00^{+0.07}_{-0.17}) \times 10^{-2}\,, \tag{4.4}$$

$$V_{cb}^{B\to D\mu\nu} = (3.96^{+0.11}_{-0.10}) \times 10^{-2}\,. \tag{4.5}$$

We observe consistency among these values and with the global fit, albeit with larger uncertainties.

4.2 V_{cb} from $B \to D^*\ell\nu$

Since the D^* is a vector meson and further decays to e.g. $D\pi$, a four-fold differential decay distribution in three angles and w can be measured. Belle has recently published an analysis with one-dimensional distributions in all four kinematic quantities with full error correlations, based on hadronic tagging [38]. An earlier (and statistically independent) untagged analysis by Belle [36] considers the w-differential branching ratios into longitudinally or transversely polarized D^*, that can be extracted from the angular distribution. Since the error correlations are not publicly available, we simply assume the statistical uncertainties to be fully uncorrelated and the systematic ones to be fully correlated. In addition, we rescale the systematic uncertainties, that are given as relative uncertainties with respect to the measured central values, into relative uncertainties with respect to the SM prediction instead, again to avoid the D'Agostini bias mentioned before. In addition to the differential measurements, we include four measurements of the total branching ratio by BaBar, listed in table 1, which are statistically independent to a good approximation [73]. As mentioned in section 4.1, we do however take into account the significant correlation between the $B \to D^*(e,\mu)\nu$ and $B \to D(e,\mu)\nu$ measurements of the BaBar "global fit". As in the case of $B \to D\ell\nu$, we cannot use the HFLAV average for the $B \to D^*\ell\nu$ branching ratio, but we apply the same rescalings as HFLAV to account e.g. for changes in D^* branching ratios. The central value of the BaBar global fit is hardly modified, but the other three branching ratio measurements are reduced by 5–6% compared to the published values.

The combined fit to these data, using our form factor parametrization with the constraints discussed in section 3, yields

$$V_{cb}^{B\to D^*\ell\nu} = (3.90 \pm 0.07) \times 10^{-2} \qquad \text{(frequentist fit)}, \tag{4.6}$$

$$V_{cb}^{B\to D^*\ell\nu} = (3.90 \pm 0.07) \times 10^{-2} \qquad \text{(Bayesian fit)}, \tag{4.7}$$

$$V_{cb}^{B\to D^*\ell\nu} = (3.90 \pm 0.07) \times 10^{-2} \qquad \text{(fast fit)}. \tag{4.8}$$

Again, we observe excellent agreement of the three different approaches and the same comments as in section 4.1 apply. We conclude that the extraction of V_{cb} from exclusive decays does not depend in a relevant way on the statistical approach taken. The extracted values are also comparable to those in the recent literature.

Again we observe good compatibility with other recent extractions from this mode [10, 13, 14, 16], and the same comments regarding comparability apply as in $B \to D$. The inclusion of additional data in our case is responsible for the slightly smaller uncertainty

JHEP01(2019)009

and lower central value. The latter is also related to a shift from using the experimental values from HEPData, as discussed below.

As for $B \to D\ell\nu$ at the end of section 4.1, we also repeat the extraction of V_{cb} using only the measurements that separate the electron and muon samples, since these measurements are used in lepton flavour non-universal NP scenarios in section 5. Using the frequentist approach, we find

$$V_{cb}^{B\to D^* e\nu} = (3.89 \pm 0.10) \times 10^{-2}\,, \tag{4.9}$$

$$V_{cb}^{B\to D^* \mu\nu} = (3.76 \pm 0.11) \times 10^{-2}\,. \tag{4.10}$$

While consistent with each other and with the global fit, we observe that the muonic data prefer a value of V_{cb} that is lower by about one standard deviation.

Finally we would like to comment on the robustness of the extracted V_{cb} value from binned data. The value obtained from the Belle 2017 data alone depends on the precise inputs used: the difference between the binned data given on HEPData [74] and that in the publication, where the values are rounded to two significant digits, yields a shift in V_{cb} of about one standard deviation.[6] This is problematic, since the uncertainties and correlations themselves have an uncertainty that is likely to be larger than the difference between these inputs. This should be kept in mind when analyzing the unfolded spectrum. We proceed using the inputs given on HEPData where available.

5 New physics

Having extracted the CKM element V_{cb} from data assuming the SM, we next proceed to constrain NP effects. As discussed in section 2, there are five Wilson coefficients per lepton-flavour combination, with relations for the right-handed vector current $C_{V_R}^{\ell\ell'} \equiv C_{V_R}\delta_{\ell\ell'}$, i.e. up to 25 independent Wilson coefficients for $b \to c(e,\mu)\nu$ transitions. Since the ones for $\ell \neq \ell'$ are indistinguishable, these are effectively reduced to 17, and in the lepton-flavour diagonal case only 9 operators remain. Before analyzing them in more detail, we discuss in section 5.1 all possible simplified models that can be generated by the exchange of a single new mediator particle, implying specific combinations of these Wilson coefficients.

While we focus on exclusive modes in the SM V_{cb} fits, for the NP fits we also compare to the inclusive decays $B \to X_c\ell\nu$. Since the full inclusive analysis involves fitting several moments of the spectrum simultaneously with V_{cb}, quark masses, and HQET parameters, reproducing it is beyond the scope of our present analysis. Rather, we use a simplified approach where we approximate the total rate in the presence of new physics as

$$\Gamma(B \to X_c e\nu) \approx \Gamma(B \to X_c e\nu)_{\rm SM}\, \frac{\Gamma(B \to X_c e\nu)^{\rm LO}_{\rm NP}}{\Gamma(B \to X_c e\nu)^{\rm LO}_{\rm SM}}\,, \tag{5.1}$$

where $\Gamma(B \to X_c e\nu)_{\rm SM}$ is the full state-of-the-art SM prediction [3] and the rates with superscript "LO" refer to the partonic leading-order calculations. We confirm the known

[6] This might also explain the difference between the values of V_{cb} obtained from unfolded and folded data in this article.

JHEP01(2019)009

expressions for the LO contributions in the $m_\ell \to 0$ limit [28, 34, 75, 76]:

$$\Gamma^{\rm LO}(B \to X_c \ell\nu) = \Gamma^{\rm LO}_{\rm SM}(B \to X_c \ell\nu)\Big[\left(|1 + C^\ell_{V_L}|^2 + |C_{V_R}|^2\right) + \frac{1}{4}\left(|C^\ell_{S_L}|^2 + |C^\ell_{S_R}|^2\right) + 12|C^\ell_T|^2\Big] + \Gamma^{\rm LO}_{\rm Int}(B \to X_c \ell\nu)\left[{\rm Re}\left[(1 + C^\ell_{V_L})C^*_{V_R}\right] - \frac{1}{2}{\rm Re}(C^\ell_{S_L} C^{\ell *}_{S_R})\right], \quad \text{with} \tag{5.2}$$

$$\Gamma^{\rm LO}_{\rm SM}(B \to X_c \ell\nu) = \Gamma_0\left(1 - 8x_c - 12x_c^2 \log x_c + 8x_c^3 - x_c^4\right) \quad \text{and} \tag{5.3}$$

$$\Gamma^{\rm LO}_{\rm Int}(B \to X_c \ell\nu) = -4\Gamma_0\sqrt{x_c}\left(1 + 9x_c + 6x_c(1 + x_c)\log x_c - 9x_c^2 - x_c^3\right), \tag{5.4}$$

and $\Gamma_0 = G_F^2 m_b^5 |V_{cb}|^2/(192\pi^3)$. $1/m_{c,b}^2$ and α_s corrections to the NP contributions are partly known and can be sizable [28, 34, 76–80]. Specifically for scalar operators the α_s corrections can qualitatively change the result [76]. However, since we do not include effects on the spectra in any case, we stick to the simple expressions given above; we therefore do not consider the inclusive constraints used here as on the same footing as the exclusive ones and do not combine them in a global fit.

Finally, we include the constraint from the total width of the B_c meson, which can be modified significantly in scenarios with scalar couplings [81, 82].

5.1 Tree-level models

Since the $b \to c\ell\nu$ transition is a tree-level process in the SM, NP models with sizable effects in these modes typically involve tree-level contributions as well. The known quantum numbers of the involved fermions allow to determine all possible mediator quantum numbers. These correspond to the following simplified models:

- New vector-like quarks modifiying the W-couplings of the SM quarks,
- tree-level exchange of a heavy charged vector boson (W'),
- tree-level exchange of a heavy charged scalar ($H^\pm$),
- tree-level exchange of a coloured vector or scalar boson (leptoquark).

Vector-like quarks are among the simplest renormalizable extensions of the SM. They are also present, e.g., in models with partial compositeness in the form of fermionic resonances of the strongly interacting sector. An $\mathrm{SU}(2)_L$ singlet vector-like quark with mass m_Ψ, coupling to the SM quark doublet and the Higgs with strength Y, can generate a modified left-handed W coupling of order Y^2v^2/m_Ψ^2, while an $\mathrm{SU}(2)_L$ doublet, coupling to the SM quark singlet and the Higgs, can generate a right-handed W coupling. The resulting contributions to the Wilson coefficients C_{V_L} or C_{V_R}, respectively, are lepton-flavour universal.

The tree-level exchange of W', $H^\pm$, or leptoquarks has been studied extensively in the literature in the context of explanations of the $b \to c\tau\nu$ anomalies (see e.g. [24, 83–92].) The case of leptoquarks is particularly diverse as there are six different representations —

JHEP01(2019)009

Model	C_{V_L}	C_{V_R}	C_{S_R}	C_{S_L}	C_T	$C_{S_L} = 4C_T$	$C_{S_L} = -4C_T$
Vector-like singlet	×						
Vector-like doublet		×					
W'	×						
$H^{\pm}$			×	×			
S_1	×						×
R_2						×	
S_3	×						
U_1	×		×				
V_2			×				
U_3	×						

Table 2. Pattern of Wilson coefficients generated by tree-level models. Crosses correspond to a possible effect at the matching scale. If two crosses appear in a line, the contributions are governed by independent parameters in the model.

three scalars and three vectors — that can in principle contribute to $b \to c\ell\nu$ at tree level. The $b \to c\ell\nu$ Wilson coefficients generated in each of the tree-level models considered are shown in table 2. Crosses correspond to a possible tree-level effect at the matching scale, corresponding to the scale of new physics. If two crosses appear in a line, the contributions are governed by independent parameters in the model.

An interesting observation concerning table 2 is that none of the models generates the tensor operator O_T on its own. At the matching scale, it is only present in the two scalar leptoquark models S_1 and R_2 in a characteristic correlation with the operator O_{S_L}.

Since table 2 is valid at the new physics scale, it is also important to consider renormalization group (RG) effects between this scale and the b quark scale that could possibly change this picture. Normalized as in eq. (2.2), it can be easily seen that the vector operators are not renormalized under QCD as they correspond to conserved currents; the same is true for the combinations $m_b O_{S_{L,R}}$, such that the Wilson coefficients renormalize under QCD like the quark mass. Thus, the operator O_T, which is mildly QCD-renormalized, cannot mix with the other operators under QCD. Therefore the only qualitatively relevant RG mixing effects among the five operators of interest could come from electroweak renormalization in the SMEFT above the electroweak scale. Indeed, the operators $O^{(1)}_{lequ}$ and $O^{(3)}_{lequ}$, that match onto O_{S_L} and O_T, respectively, mix with each other through the weak coupling constants [93]. The RG-induced values of the respective coefficients at the electroweak scale v can be written in leading logarithmic approximation as

$$C_{S_L}(v) \supset \frac{3}{8\pi^2}(3g^2 + 5g'^2) \ln\left(\frac{v}{\Lambda_{\rm NP}}\right) C_T(\Lambda_{\rm NP})\,, \tag{5.5}$$

$$C_T(v) \supset \frac{1}{128\pi^2}(3g^2 + 5g'^2) \ln\left(\frac{v}{\Lambda_{\rm NP}}\right) C_{S_L}(\Lambda_{\rm NP})\,, \tag{5.6}$$

JHEP01(2019)009

where the self-mixing contributions have been omitted for brevity, but are included in the numerical analysis. For $\Lambda_{\rm NP} = 1\,\text{TeV}$, the numerical prefactors are roughly -0.1 and -0.002, respectively, so the effect is small unless the scale separation is very large, in particular given that the tree-level models already predict $C_{S_L} \gg C_T$ at the matching scale.

We thus conclude that table 2 is useful as classification of tree-level models in terms of low-energy effects and is qualitatively stable under quantum corrections. Of course, a realistic model may combine several of the discussed particles and thus lead to a more diverse pattern of effects.

5.2 Right-handed currents

C_{V_R} has been considered as a possible source for a tension between inclusive and exclusive determinations in V_{cb} for a long time [94]. However, updated analyses based on total rates alone have already shown that the scenario is disfavoured as a solution to the present tension [33].

The main novelty of the present analysis is the inclusion of the $B \to D^*\ell\nu$ angular observables in the fit. For the total rate, an effect in C_{V_R} can always be absorbed by an appropriate shift in V_{cb} (or $\tilde{V}_{cb}$), such that constraining right-handed currents requires considering several modes. Including angular observables changes this picture, as the shape of these observables is directly sensitive to right-handed currents. As a consequence, a fit to $B \to D^*\ell\nu$ data alone is able to constrain right-handed currents directly, as shown[7] in figure 2, together with the constraints from $B \to D\ell\nu$ and the inclusive decay, both constraining only combinations of V_{cb} and C_{V_R}. In this plot we assume lepton-flavour universality as discussed above.

We observe that the tensions between the V_{cb} determinations from $B \to D\ell\nu$, $B \to D^*\ell\nu$, and $B \to X_c\ell\nu$, that are anyway milder than in the past, cannot be completely removed by postulating new physics in right-handed currents. What is new is that even $B \to D^*\ell\nu$ alone cannot be brought into perfect agreement with $B \to X_c\ell\nu$ for any value of C_{V_R}.

5.3 Lepton flavour universality violation

In view of the observed tensions with SM expectations in $b \to c\tau\nu$ and $b \to s\ell\ell$ transitions, investigating e-μ universality in $b \to c\ell\nu$ with light leptons is important. Specific new physics models suggested as solutions to the $b \to c\tau\nu$ anomalies actually predict such violation. Some of the experimental analyses *assume* LFU to hold. These analyses cannot be used in a model-independent fit allowing for LFU violation. This is because the measurements are not simply averages of the respective electron and muon observables, but linear combinations with weights depending on the experimental efficiencies that can differ between electrons and muons even as a function of kinematical variables. Thus it is

[7] This plot and all the following Wilson coefficient plots correspond to the two-dimensional profile likelihood in the space of the Wilson coefficients shown. For observables only constraining a single combination of Wilson coefficients, the bands correspond to $-2\Delta \ln L = 1$ and 4, respectively, otherwise to $-2\Delta \ln L = 2.30$ and 6.18, thereby accounting for the different degrees of freedom.

JHEP01(2019)009

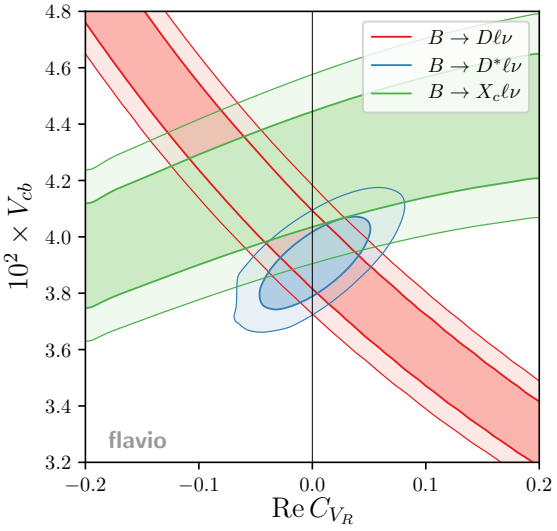

Figure 2. Constraints on right-handed currents from inclusive and exclusive decays, assuming LFU.

of paramount importance that experimental collaborations present their results separately for electrons and muons.

In the meantime, the existing analyses that already include separate results for electrons and muons (see table 1) can be used to perform a fit with a non-universal modification of the SM operator, i.e. $C^e_{V_L} \neq C^\mu_{V_L}$. The fit result in terms of the lepton-flavour-dependent effective CKM elements $\tilde{V}^\ell_{cb}$ is shown in figure 3. Both for $B \to D\ell\nu$ and $B \to D^*\ell\nu$ the fit not only shows perfect agreement with LFU, but also implies a stringent constraint on departures from the LFU limit. Given the good agrement of the constraints from $B \to D\ell\nu$ and $B \to D^*\ell\nu$, we have also performed a combined Bayesian fit of the scenario to both decay modes, marginalizing over all nuisance parameters. We find

$$\frac{1}{2}\left(\tilde{V}^e_{cb} + \tilde{V}^\mu_{cb}\right) = (3.87 \pm 0.09)\%\,, \tag{5.7}$$

$$\frac{1}{2}\left(\tilde{V}^e_{cb} - \tilde{V}^\mu_{cb}\right) = (0.022 \pm 0.023)\%\,, \tag{5.8}$$

with a small correlation of -10%. Equivalently, we find

$$\frac{\tilde{V}^e_{cb}}{\tilde{V}^\mu_{cb}} = 1.011 \pm 0.012\,, \tag{5.9}$$

which can be used as a generic constraint on e-μ universality violation in $b \to c\ell\nu$ processes. This is the first global combination of LFU constraints in $b \to c\ell\nu$ transitions and provides a significantly stricter bound on LFU than the recent measurement in ref. [38] alone.

As already discussed in section 2, a violation of LFU can also manifest itself as a contribution from a "wrong-neutrino" decay generated by $C^{\ell\ell'}_{V_L}$ with $\ell \neq \ell'$. However, this case does not have to be discussed separately as it merely leads to a rescaling of all observables that can be absorbed by defining

$$\tilde{V}^\ell_{cb} = V_{cb}\left[|1 + C^\ell_{V_L}|^2 + \sum_{\ell' \neq \ell} |C^{\ell\ell'}_{V_L}|^2\right]^{1/2}. \tag{5.10}$$

JHEP01(2019)009

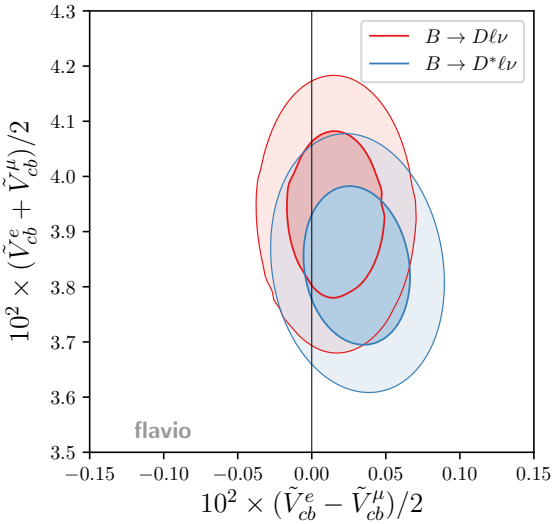

Figure 3. Constraints on LFU violation in the left-handed vector current from exclusive decays. The vertical line corresponds to the LFU limit.

5.4 Scalar operators

The interference of scalar contributions with the SM amplitude in exclusive and inclusive decays arises only from lepton-mass-suppressed terms. Consequently, scalar contributions always lead to an *increase* in the rates for a fixed value of V_{cb}. The suppression of interference terms also implies that there is no qualitative difference between operators with $\ell = \ell'$ or $\ell \neq \ell'$, so we focus on the former for simplicity.

Again the differential distributions contain valuable information about possible scalar contributions. The most striking example is the endpoint of the $B \to D\ell\nu$ differential decay rate, see also, e.g., [95]. In the SM, close to $q^2 = q^2_{\text{max}} = (m_B - m_D)^2$, it behaves as

$$\frac{d\Gamma(B \to D\ell\nu)}{dq^2} \propto f_+^2 \left(q^2 - q^2_{\text{max}}\right)^{3/2}, \tag{5.11}$$

while in presence of NP contributions to scalar operators, it behaves as

$$\frac{d\Gamma(B \to D\ell\nu)}{dq^2} \propto f_0^2 |C_{S_R} + C_{S_L}|^2 \left(q^2 - q^2_{\text{max}}\right)^{1/2}. \tag{5.12}$$

This implies an exceptional sensitivity of the highest q^2 (or lowest w) bin in $B \to D\ell\nu$ to the sum of scalar Wilson coefficients, $C_{S_R} + C_{S_L}$. To illustrate this effect, in figure 4 we show on the left the predictions for the SM (using V_{cb} from eq. (4.1)) and a scenario with a large NP contribution in C_{S_L} for fixed V_{cb}, compared to the experimental data. The scenarios are chosen such that they give the same prediction for the total branching ratio. The qualitatively different endpoint behaviour can clearly distinguish between them, excluding such large scalar contributions.

As a consequence, a fit to the differential $B \to D\ell\nu$ rates leads to a more stringent constraint on scalar operators than $B \to D^*\ell\nu$ or the inclusive decay. While the total rates of these modes constrain only combinations of $|V_{cb}|$ and $|C_{S_L} \pm C_{S_R}|$ or $|C_{S_L}|^2 + |C_{S_R}|^2$,

JHEP01(2019)009

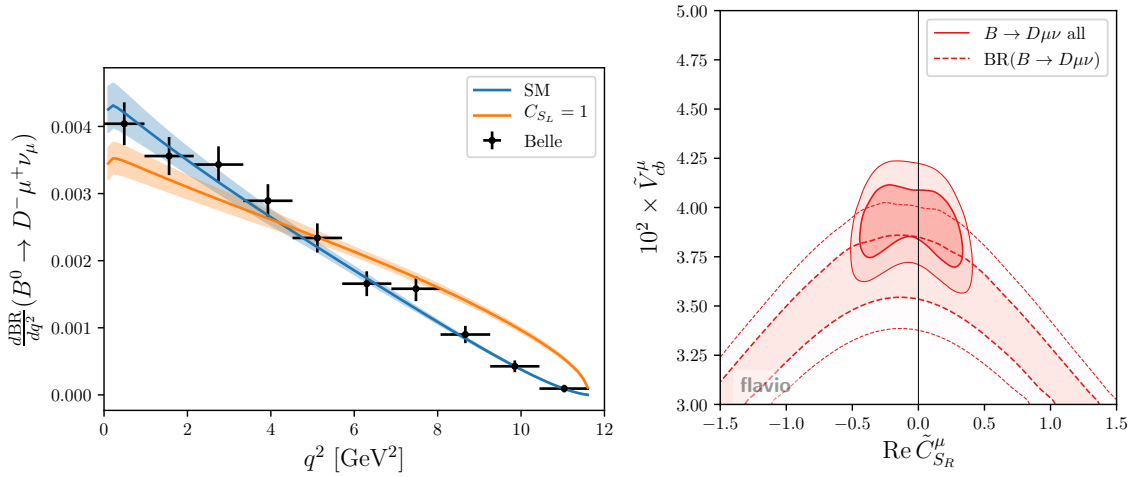

Figure 4. Left: prediction for the differential $B \to D\mu\nu$ branching ratio in the SM (blue band) and a scenario with new physics in C_{S_L} (orange band) vs. the Belle measurement, demonstrating the different endpoint behaviour at zero recoil ($q^2 \approx 11.6\ \mathrm{GeV}^2$). Both scenarios predict the same total $B \to D\mu\nu$ branching ratio. Right: comparison of the constraint on the scalar coefficient $\tilde{C}^\mu_{S_R}$ vs. $\tilde{V}^\mu_{cb}$ from the total $B \to D\mu\nu$ branching ratio measurements only (dashed) and using all $B \to D\mu\nu$ measurements (solid).

these are accessible individually with differential distributions. This is demonstrated in figure 4 on the right, where the constraint resulting from the total rate alone is compared to the one resulting from all available information on that channel. Importantly, including the information from the differential rate, $\tilde{V}_{cb}$ and $\mathrm{Re}(C_{S_R})$ can be determined individually.

The constraining power of $B \to D\ell\nu$ and the complementary dependence of $B \to D\ell\nu$ and $B \to D^*\ell\nu$ on the scalar Wilson coefficients C_{S_L} and C_{S_R} is also demonstrated in figures 5 and 6. In these figures, the constraints are shown separately for the modes involving electron and muons, as there is in general no reason to expect LFU to hold for scalar contributions. Furthermore, here and in the following only the measurements of electronic modes are used to constrain the electronic coefficients and the measurements of muonic modes for the muonic coefficients. We stress that more stringent constraints would be obtained by assuming the coefficient with the other lepton flavour to be free from NP and using both sets of data. In this respect, our constraints are conservative.

In figure 5, corresponding to scenarios with a U_1 or V_2 leptoquark, the electronic modes do not show any preference for non-zero $C^e_{S_R}$, while $B \to D^*\mu\nu$ prefers a sizable value of $C^\mu_{S_R}$ slightly over the SM, but such values are excluded by $B \to D\mu\nu$ in this scenario, and also disfavoured by the B_c lifetime.

A second interesting scenario is having NP in both C_{S_R} and C_{S_L}, as can arise in models with a charged Higgs boson (cf. table 2). The resulting constraints are shown in figure 6, again separately for electronic and muonic modes. In addition to the form factor parameters, also V_{cb} is varied as a nuisance parameter. Consequently, the inclusive decay alone, only entering our analysis via its total rate, cannot constrain the coefficients individually and is not shown. In principle, the same qualification applies to the leptonic

JHEP01(2019)009

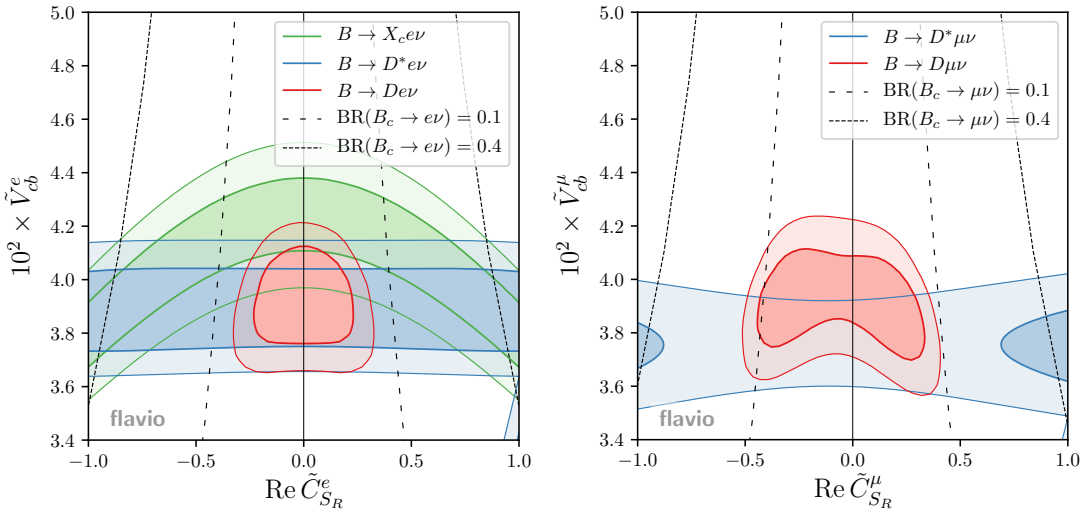

Figure 5. Constraints on the scalar coefficients $\tilde{C}^{e,\mu}_{S_R}$ vs. $\tilde{V}^{e,\mu}_{cb}$, absorbing a potential vector coefficient C_{V_L}, from inclusive and exclusive decays as well as the total width of the B_c meson, seperately for electrons (left) and muons (right).

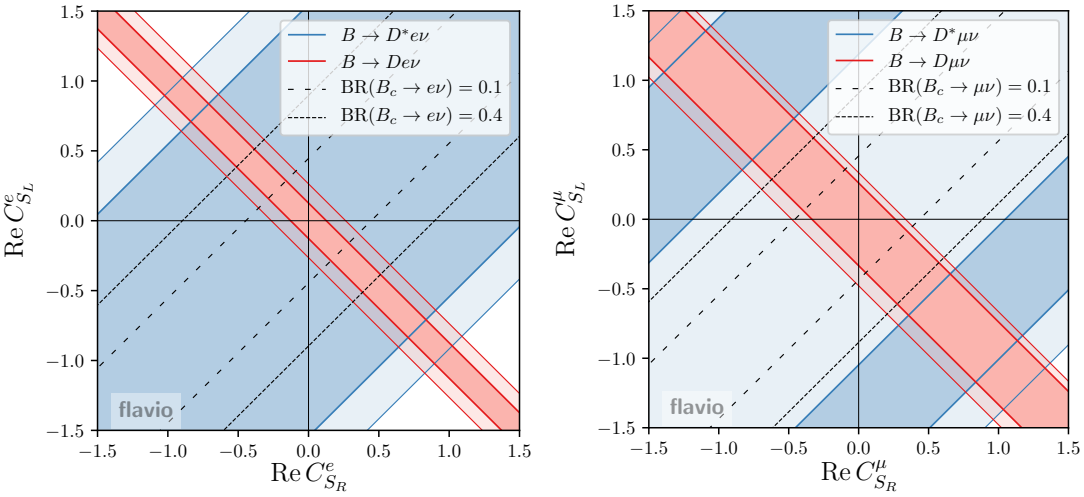

Figure 6. Constraints on the scalar Wilson coefficients from exclusive decays and the total width of the B_c meson, seperately for electrons (left) and muons (right).

decays $B_c \to \ell\nu$. To give an indication, we nevertheless show the constraints that would apply for a conservatively low value of $V_{cb} = 0.035$. The feature that $B \to D\ell\nu$ only constrains the sum and $B \to D^*\ell\nu$ only the difference of these Wilson coefficients is clearly seen. In the muonic case, we observe a mild preference for non-zero values of both Wilson coefficients from $B \to D^{(*)}\ell\nu$. In constrast to the scenario in figure 5, the constraint from $B \to D\ell\nu$ does not exclude sizable NP effects if $C_{S_R} \sim C_{S_L}$. However, the constraint from the B_c lifetime excludes such a scenario, even when allowing for very large modifications of $\sim 40\%$ and a small value of $V_{cb} = 0.035$.

JHEP01(2019)009

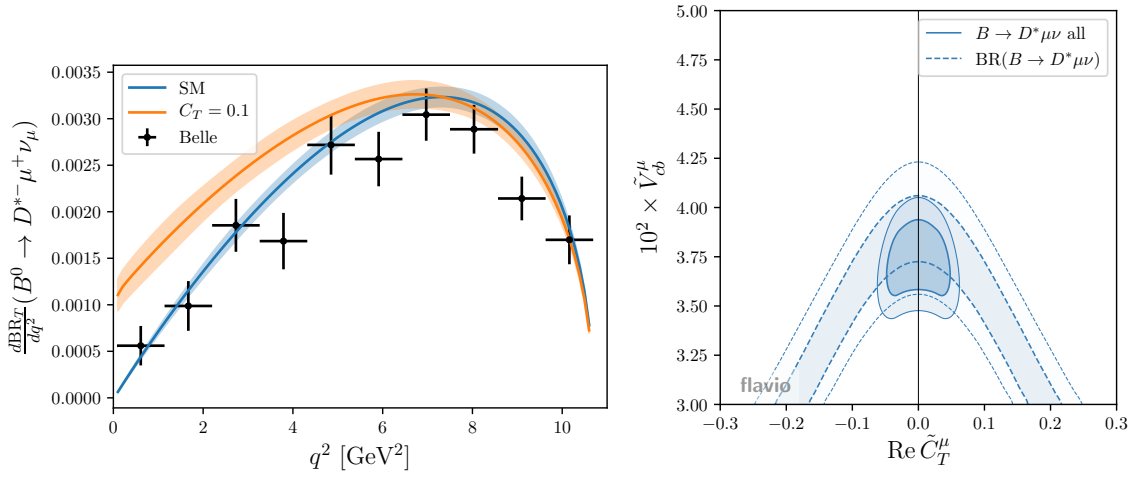

Figure 7. Left: prediction for the transverse differential $B \to D^*\mu\nu$ branching ratio in the SM (blue band) and a scenario with new physics in C_T^μ (orange band) vs. the Belle measurement, demonstrating the different endpoint behaviour at maximum recoil ($q^2 = 0$). Both scenarios predict the same total $B \to D^*\mu\nu$ branching ratio. Right: comparison of the constraint on the tensor coefficient $\tilde{C}_T^\mu$ vs. $\tilde{V}_{cb}^\mu$ from the total $B \to D^*\mu\nu$ branching ratio measurements only (dashed) and using all $B \to D^*\mu\nu$ measurements (solid).

5.5 Tensor operator

In contrast to the scalar operators, for tensor operators $B \to D^*\ell\nu$ leads to a much more stringent constraint. This is due to the existing lepton-specific data on the transverse and longitudinal decay rates (cf. table 1). In the SM the D^* is fully longitudinally polarized at maximum recoil ($q^2_{\text{min}} = m_\ell^2$). This is no longer true in the presence of tensor operators. Indeed, in the limit of $q^2 \to q^2_{\text{min}} \approx 0$, the differential rate to transversely polarized D^* in the presence of NP contributions to C_{V_L} and C_T behaves as

$$\frac{d\Gamma_T(B \to D^*\ell\nu)}{dq^2} \propto q^2 \left|1 + C_{V_L}\right|^2 \left(A_1(0)^2 + V(0)^2\right) + 16 m_B^2 \left|C_T\right|^2 T_1(0)^2 + O\left(\frac{m_{D^*}^2}{m_B^2}\right), \tag{5.13}$$

where the kinematic relation $T_2(0) = T_1(0)$ was used and the D^* mass was neglected for simplicity. As a consequence, this observable is exceptionally sensitive to tensor operators near the maximum recoil point. To illustrate this fact, in figure 7 on the left we show the predictions for the SM and a scenario with a sizable NP contribution in C_T compared to the experimental data. The scenarios are chosen such that they give the same prediction for the total branching ratio. The different behaviour at $q^2 = 0$ allows to clearly distinguish them and disfavours tensor contributions of this size. On the right of figure 7 we demonstrate again this qualitative difference by comparing the constraints from the total $B \to D^*\mu\nu$ rate alone and including the differential distribution.

An additional observable that would be very sensitive to the tensor operator, but has not been measured yet, is the "flat term" in $B \to D\ell\nu$. The normalized differential decay rate as a function of the angle θ_ℓ between the charged lepton and the B in the lepton-

JHEP01(2019)009

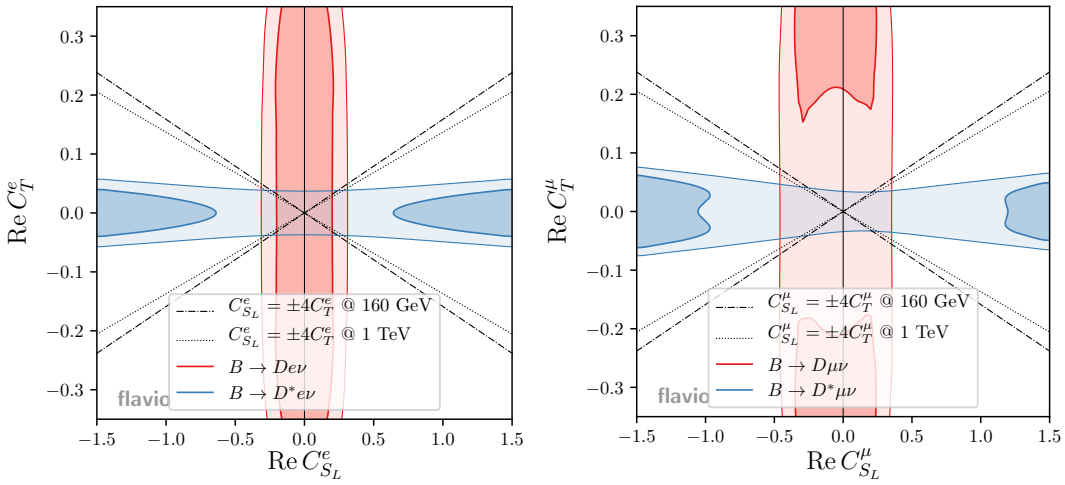

Figure 8. Constraints on $C_{S_R}^{e,\mu}$ vs. $C_T^{e,\mu}$, profiling over V_{cb}. The black dotted and dash-dotted lines show the expected ratio of the Wilson coefficients in the two leptoquark scenarios S_1 and R_2 (cf. table 2), assuming the relation $C_{S_L}^\ell = \pm 4 C_T^\ell$ to hold at the scale 160 GeV or 1 TeV.

neutrino mass frame can be written as

$$\frac{1}{\Gamma_\ell}\frac{d\Gamma_\ell}{d\cos\theta_\ell dq^2} = \frac{3}{4}\left[1 - F_H(q^2)\right]\sin^2\theta_\ell + \frac{1}{2}F_H(q^2) + A_{\rm FB}(q^2)\cos\theta_\ell\,. \tag{5.14}$$

In complete analogy to the $B \to K\ell^+\ell^-$ decay, the observable F_H vanishes in the SM up to tiny lepton mass effects, but can be sizable in the presence of new physics in the tensor operator. Neglecting the lepton masses and allowing for NP in C_T and C_{V_L}, one finds

$$F_H(q^2) \approx \frac{18 q^2 f_T^2(q^2)}{m_B^2 f_+^2(q^2)} \frac{|C_T|^2}{|1 + C_{V_L}|^2}\,. \tag{5.15}$$

Figure 8 shows the constraints on the tensor and left-handed scalar operators, which always appear together in models with a tree-level mediator, see table 2, specifically in leptoquark models. The displayed constraints from $B \to D\ell\nu$ and $B \to D^*\ell\nu$, shown separately for electrons and muons, demonstrate clearly the strong sensitivity of $B \to D^*\ell\nu$ to tensor contributions. While the individual modes $B \to D^* e\nu$, $B \to D\mu\nu$, and $B \to D^*\mu\nu$ show a slight preference for non-zero NP contributions in either $C_{S_L}^\ell$ or C_T^ℓ, the combination of $B \to D\ell\nu$ and $B \to D^*\ell\nu$ constraints allows neither of these solutions and leads to a strong constraint on both operators.

6 Conclusions

Semi-leptonic charged-current transitions $b \to c\ell\nu$ with $\ell = e$ or μ are traditionally used to measure the CKM element V_{cb}. In principle, this transition could be affected by new physics with vector, scalar, or tensor interactions, possibly violating lepton flavour universality. This is motivated by the long-standing tensions between inclusive and exclusive determinations of V_{cb}, but also by hints of a violation of lepton-flavour universality in $b \to c\tau\nu$ and $b \to s\ell\ell$ transitions. We have conducted a comprehensive analysis of general

JHEP01(2019)009

new-physics effects in $b \to c\ell\nu$ transitions, considering for the first time the full operator basis and employing for the first time in a new physics analysis measurements of $B \to D^*\ell\nu$ angular observables.

Our main findings can be summarized as follows.

- Extracting the absolute value of the CKM element V_{cb} from fits to the full sets of $B \to D\ell\nu$ and $B \to D^*\ell\nu$ data in table 1 yields values consistent with the recent literature and no significant tension between determinations from $B \to D\ell\nu$ vs. $B \to D^*\ell\nu$.

- We find no dependence of the V_{cb} extraction on the statistical approach, but find a significant dependence on the treatment of systematic uncertainties in binned observables due to the "d'Agostini bias".

- We find that NP in right-handed currents cannot improve the agreement between inclusive and exclusive determinations of V_{cb}. Thanks to our use of differntial and angular dsitributions, this conclusion can even be drawn considering $B \to D^*\ell\nu$ vs. $B \to X_c\ell\nu$ alone.

- We find strong constraints on violations of e-μ universality, specifically for $C^{\ell}_{V_L}$.

- We demonstrate that the zero-recoil endpoint of the $B \to D\ell\nu$ spectrum is exceptionally sensitive to NP in scalar operators.

- We demonstrate that the maximum-recoil endpoint of the transverse $B \to D^*\ell\nu$ spectrum is exceptionally sensitive to NP in tensor operators.

Our analysis could be improved in several respects. The treatment of experimental data had partly to rely on crude estimates of the systematic uncertainties or correlations, where these were not public. We urge the experimental collaborations to publish this information for future and also existing analyses. Our treatment of the inclusive decay is also approximate, as discussed at the beginning of section 5. Clearly, a full fit to the moments of the inclusive mode would be interesting, but is beyond the scope of our present analysis. Finally, our treatment of $B \to D^*$ form factors had to some extent to rely on the heavy quark expansion, with only partial inclusion of $1/m^2_{c,b}$ contributions. A full calculation of the q^2 dependence from lattice QCD, ideally including tensor form factors, would make these constraints much more reliable. We emphasize again that our analysis can be easily improved once this information becomes available as all of our code is open source.

Acknowledgments

We thank Florian Bernlochner, Christoph Bobeth, Jorge Martin Camalich, Danny van Dyk, Paolo Gambino, Thomas Kuhr, Marcello Rotondo, Stefan Schacht, and Christoph Schwanda for useful discussions. The work of M. J. and D. S. is supported by the DFG cluster of excellence "Origin and Structure of the Universe". The numerical analysis has been carried out on the computing facilities of the Computational Center for Particle and Astrophysics (C2PAP).

JHEP01(2019)009

A Numerical results for $B \to D^{(*)}$ form factors

In this appendix, we give details on the parametrization of form factors discussed in section 3 and present the numerical results of our fit to lattice and LCSR calculations employing the HQET parametrization and unitarity bounds. The $B \to D^{(*)}$ form factors h_i in the HQET basis[8] can be found in ref. [13]. In the heavy quark limit, they vanish or reduce to a common form factor, the leading Isgur-Wise function $\xi(w)$. It is thus convenient to write the form factors as $h_i(w) = \xi(w)\hat{h}(w)$. The expressions for all $\hat{h}(w)$ at next-to-leading order in α_s and next-to-leading power in $\epsilon_{b,c} = \bar{\Lambda}/2m_{b,c}$ can be found in ref. [13]. As discussed in section 3, we modify these expressions by allowing for an additional $O(\epsilon_c^2)$ correction to the form factors that are protected from $O(\epsilon_c)$ corrections:

$$\hat{h}_{A_1}(w) \to \hat{h}_{A_1}(w) + \epsilon_c^2 \delta_{h_{A_1}}\,, \quad \hat{h}_{T_1}(w) \to \hat{h}_{T_1}(w) + \epsilon_c^2 \delta_{h_{T_1}}\,, \quad \hat{h}_{+}(w) \to \hat{h}_{+}(w) + \epsilon_c^2 \delta_{h_{+}}\,. \tag{A.1}$$

We neglect a possible w dependence of the δ_i terms. The leading order Isgur-Wise function ξ can be written to second order in the z expansion as

$$\xi(z) = 1 - 8\rho^2 z + (64c - 16\rho^2)z^2. \tag{A.2}$$

We then perform a Bayesian fit (a Markov Chain Monte Carlo employing flavio [39] and emcee [97]) to the theory constraints described in section 3 of the ten parameters parametrizing the functions $\hat{h}_i$ and ξ.[9] The mean, standard deviation and correlation matrix of nine of those parameters is

$$\begin{pmatrix} \chi_2(1) \\ \chi_2'(1) \\ \chi_3'(1) \\ \eta(1) \\ \eta'(1) \\ \rho^2 \\ c \\ \delta_{h_{A_1}} \\ \delta_{h_+} \end{pmatrix} = \begin{pmatrix} -0.058 \pm 0.019 \\ -0.001 \pm 0.020 \\ 0.035 \pm 0.019 \\ 0.358 \pm 0.043 \\ 0.044 \pm 0.125 \\ 1.306 \pm 0.059 \\ 1.220 \pm 0.109 \\ -2.299 \pm 0.394 \\ 0.485 \pm 0.269 \end{pmatrix} \tag{A.3}$$

$$\rho = \begin{pmatrix} 1.00 & 0.01 & 0.02 & -0.00 & 0.02 & -0.27 & -0.21 & -0.03 & 0.02 \\ 0.01 & 1.00 & -0.00 & -0.02 & -0.02 & 0.00 & 0.14 & 0.01 & 0.00 \\ 0.02 & -0.00 & 1.00 & 0.00 & -0.03 & 0.83 & 0.61 & -0.03 & 0.02 \\ -0.00 & -0.02 & 0.00 & 1.00 & 0.03 & 0.01 & 0.04 & 0.15 & 0.21 \\ 0.02 & -0.02 & -0.03 & 0.03 & 1.00 & -0.14 & -0.16 & -0.05 & -0.22 \\ -0.27 & 0.00 & 0.83 & 0.01 & -0.14 & 1.00 & 0.79 & 0.09 & -0.14 \\ -0.21 & 0.14 & 0.61 & 0.04 & -0.16 & 0.79 & 1.00 & 0.06 & -0.08 \\ -0.03 & 0.01 & -0.03 & 0.15 & -0.05 & 0.09 & 0.06 & 1.00 & -0.24 \\ 0.02 & 0.00 & 0.02 & 0.21 & -0.22 & -0.14 & -0.08 & -0.24 & 1.00 \end{pmatrix}. \tag{A.4}$$

[8] The relation of the HQET form factors to the traditional form factor basis V_i, A_i, T_i and f_i can be found in appendix A of ref. [96].

[9] Again these values have also been obtained by an independent frequentist implementation.

JHEP01(2019)009

The tenth parameter, δ_{T_1}, is not constrained by the fit, thus its posterior is equal to the prior, which we conservatively take to be a Gaussian with mean 3 centered around 0. These form factors have been implemented and set as defaults in flavio version 0.26.

Open Access. This article is distributed under the terms of the Creative Commons Attribution License (CC-BY 4.0), which permits any use, distribution and reproduction in any medium, provided the original author(s) and source are credited.

References

[1] J. Charles et al., *Current status of the standard model CKM fit and constraints on $\Delta F = 2$ new physics*, *Phys. Rev.* **D 91** (2015) 073007 [arXiv:1501.05013] [INSPIRE].

[2] UTfit collaboration, M. Bona, *Latest results for the Unitary Triangle fit from the UTfit collaboration*, PoS(CKM 2016)096

[3] A. Alberti, P. Gambino, K.J. Healey and S. Nandi, *Precision determination of the Cabibbo-Kobayashi-Maskawa element V_{cb}*, *Phys. Rev. Lett.* **114** (2015) 061802 [arXiv:1411.6560] [INSPIRE].

[4] G. Ricciardi, *Semileptonic decays and $|V_{xb}|$ determinations*, arXiv:1712.06988 [INSPIRE].

[5] HPQCD collaboration, H. Na et al., *$B \to Dl\nu$ form factors at nonzero recoil and extraction of $|V_{cb}|$*, *Phys. Rev.* **D 92** (2015) 054510 [*Erratum ibid.* **D 93** (2016) 119906] [arXiv:1505.03925] [INSPIRE].

[6] MILC collaboration, J.A. Bailey et al., *$B \to D\ell\nu$ form factors at nonzero recoil and $|V_{cb}|$ from 2+1-flavor lattice QCD*, *Phys. Rev.* **D 92** (2015) 034506 [arXiv:1503.07237] [INSPIRE].

[7] Fermilab Lattice, MILC collaboration, J.A. Bailey et al., *Update of $|V_{cb}|$ from the $\bar{B} \to D^*\ell\bar{\nu}$ form factor at zero recoil with three-flavor lattice QCD*, *Phys. Rev.* **D 89** (2014) 114504 [arXiv:1403.0635] [INSPIRE].

[8] HPQCD collaboration, J. Harrison, C. Davies and M. Wingate, *Lattice QCD calculation of the $B_{(s)} \to D^*_{(s)}\ell\nu$ form factors at zero recoil and implications for $|V_{cb}|$*, *Phys. Rev.* **D 97** (2018) 054502 [arXiv:1711.11013] [INSPIRE].

[9] D. Bigi and P. Gambino, *Revisiting $B \to D\ell\nu$*, *Phys. Rev.* **D 94** (2016) 094008 [arXiv:1606.08030] [INSPIRE].

[10] D. Bigi, P. Gambino and S. Schacht, *A fresh look at the determination of $|V_{cb}|$ from $B \to D^*\ell\nu$*, *Phys. Lett.* **B 769** (2017) 441 [arXiv:1703.06124] [INSPIRE].

[11] 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].

[12] S. Aoki et al., *Review of lattice results concerning low-energy particle physics*, *Eur. Phys. J.* **C 77** (2017) 112 [arXiv:1607.00299] [INSPIRE].

[13] 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.* **D 97** (2018) 059902] [arXiv:1703.05330] [INSPIRE].

[14] B. Grinstein and A. Kobach, *Model-independent extraction of $|V_{cb}|$ from $\bar{B} \to D^*\ell\overline{\nu}$*, *Phys. Lett.* **B 771** (2017) 359 [arXiv:1703.08170] [INSPIRE].

[15] 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].

JHEP01(2019)009

[16] S. Jaiswal, S. Nandi and S.K. Patra, *Extraction of $|V_{cb}|$ from $B \to D^{(*)}\ell\nu_\ell$ and the standard model predictions of $R(D^{(*)})$*, *JHEP* **12** (2017) 060 [arXiv:1707.09977] [INSPIRE].

[17] BABAR collaboration, J.P. Lees et al., *Measurement of an excess of $\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$ decays and implications for charged Higgs bosons*, *Phys. Rev.* **D 88** (2013) 072012 [arXiv:1303.0571] [INSPIRE].

[18] BELLE collaboration, M. Huschle et al., *Measurement of the branching ratio of $\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$ relative to $\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell$ decays with hadronic tagging at Belle*, *Phys. Rev.* **D 92** (2015) 072014 [arXiv:1507.03233] [INSPIRE].

[19] LHCb collaboration, *Measurement of the ratio of branching fractions $\mathcal{B}(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)/\mathcal{B}(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)$*, *Phys. Rev. Lett.* **115** (2015) 111803 [*Erratum ibid.* **115** (2015) 159901] [arXiv:1506.08614] [INSPIRE].

[20] BELLE collaboration, Y. Sato et al., *Measurement of the branching ratio of $\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau$ relative to $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell$ decays with a semileptonic tagging method*, *Phys. Rev.* **D 94** (2016) 072007 [arXiv:1607.07923] [INSPIRE].

[21] BELLE collaboration, S. Hirose et al., *Measurement of the τ lepton polarization and $R(D^*)$ in the decay $\bar{B} \to D^*\tau^-\bar{\nu}_\tau$*, *Phys. Rev. Lett.* **118** (2017) 211801 [arXiv:1612.00529] [INSPIRE].

[22] LHCb collaboration, *Measurement of the ratio of the $B^0 \to D^{*-}\tau^+\nu_\tau$ and $B^0 \to D^{*-}\mu^+\nu_\mu$ branching fractions using three-prong τ-lepton decays*, *Phys. Rev. Lett.* **120** (2018) 171802 [arXiv:1708.08856] [INSPIRE].

[23] LHCb collaboration, *Measurement of the ratio of branching fractions $\mathcal{B}(B_c^+ \to J/\psi\tau^+\nu_\tau)/\mathcal{B}(B_c^+ \to J/\psi\mu^+\nu_\mu)$*, *Phys. Rev. Lett.* **120** (2018) 121801 [arXiv:1711.05623] [INSPIRE].

[24] 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].

[25] D. Bečirević et al., *Palatable leptoquark scenarios for lepton flavor violation in exclusive $b \to s\ell_1\ell_2$ modes*, *JHEP* **11** (2016) 035 [arXiv:1608.07583] [INSPIRE].

[26] 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].

[27] D. Buttazzo, A. Greljo, G. Isidori and D. Marzocca, *B-physics anomalies: a guide to combined explanations*, *JHEP* **11** (2017) 044 [arXiv:1706.07808] [INSPIRE].

[28] B.M. Dassinger, R. Feger and T. Mannel, *Testing the left-handedness of the $b \to c$ transition*, *Phys. Rev.* **D 75** (2007) 095007 [hep-ph/0701054] [INSPIRE].

[29] B. Dassinger, R. Feger and T. Mannel, *Complete michel parameter analysis of inclusive semileptonic $b \to c$ transition*, *Phys. Rev.* **D 79** (2009) 075015 [arXiv:0803.3561] [INSPIRE].

[30] A. Crivellin, *Effects of right-handed charged currents on the determinations of $|V_{ub}|$ and $|V_{cb}|$*, *Phys. Rev.* **D 81** (2010) 031301 [arXiv:0907.2461] [INSPIRE].

[31] R. Feger et al., *Limit on a right-handed admixture to the weak $b \to c$ current from semileptonic decays*, *Phys. Rev.* **D 82** (2010) 073002 [arXiv:1003.4022] [INSPIRE].

[32] S. Faller, T. Mannel and S. Turczyk, *Limits on new physics from exclusive $B \to D^{(*)}\ell\bar{\nu}$ decays*, *Phys. Rev.* **D 84** (2011) 014022 [arXiv:1105.3679] [INSPIRE].

[33] A. Crivellin and S. Pokorski, *Can the differences in the determinations of V_{ub} and V_{cb} be explained by New Physics?*, *Phys. Rev. Lett.* **114** (2015) 011802 [arXiv:1407.1320] [INSPIRE].

JHEP01(2019)009

[34] 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].

[35] BABAR collaboration, B. Aubert et al., *Measurement of $|V_{cb}|$ and the Form-factor slope in $\bar{B} \to Dl^- \bar{\nu}$ decays in events tagged by a fully reconstructed B meson*, *Phys. Rev. Lett.* **104** (2010) 011802 [arXiv:0904.4063] [INSPIRE].

[36] BELLE collaboration, W. Dungel et al., *Measurement of the form factors of the decay $B^0 \to D^* \ell^+ \nu$ and determination of the CKM matrix element $|V_{cb}|$*, *Phys. Rev.* **D 82** (2010) 112007 [arXiv:1010.5620] [INSPIRE].

[37] BELLE collaboration, R. Glattauer et al., *Measurement of the decay $B \to D \ell \nu_\ell$ 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].

[38] BELLE collaboration, A. Abdesselam et al., *Precise determination of the CKM matrix element $|V_{cb}|$ with $\bar{B}^0 \to D^{*+} \ell^- \bar{\nu}_\ell$ decays with hadronic tagging at Belle*, arXiv:1702.01521 [INSPIRE].

[39] D.M. Straub et al., *Flavio*, https://flav-io.github.io, arXiv:1810.08132.

[40] W.D. Goldberger, *Semileptonic B decays as a probe of new physics*, hep-ph/9902311 [INSPIRE].

[41] W. Buchmüller and D. Wyler, *Effective lagrangian analysis of new interactions and flavor conservation*, *Nucl. Phys.* **B 268** (1986) 621 [INSPIRE].

[42] B. Grzadkowski, M. Iskrzynski, M. Misiak and J. Rosiek, *Dimension-six terms in the standard model lagrangian*, *JHEP* **10** (2010) 085 [arXiv:1008.4884] [INSPIRE].

[43] V. Cirigliano, M. Gonzalez-Alonso and M.L. Graesser, *Non-standard charged current interactions: beta decays versus the LHC*, *JHEP* **02** (2013) 046 [arXiv:1210.4553] [INSPIRE].

[44] 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].

[45] O. Catà and M. Jung, *Signatures of a nonstandard Higgs boson from flavor physics*, *Phys. Rev.* **D 92** (2015) 055018 [arXiv:1505.05804] [INSPIRE].

[46] J. Aebischer, A. Crivellin, M. Fael and C. Greub, *Matching of gauge invariant dimension-six operators for $b \to s$ and $b \to c$ transitions*, *JHEP* **05** (2016) 037 [arXiv:1512.02830] [INSPIRE].

[47] V. Cirigliano, J. Jenkins and M. Gonzalez-Alonso, *Semileptonic decays of light quarks beyond the Standard Model*, *Nucl. Phys.* **B 830** (2010) 95 [arXiv:0908.1754] [INSPIRE].

[48] 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].

[49] E.E. Jenkins, A.V. Manohar and M. Trott, *Renormalization group evolution of the standard model dimension six operators I: formalism and λ dependence*, *JHEP* **10** (2013) 087 [arXiv:1308.2627] [INSPIRE].

[50] E.E. Jenkins, A.V. Manohar and M. Trott, *Renormalization Group Evolution of the Standard Model Dimension Six Operators II: Yukawa Dependence*, *JHEP* **01** (2014) 035 [arXiv:1310.4838] [INSPIRE].

[51] R. Alonso, E.E. Jenkins, A.V. Manohar and M. Trott, *Renormalization group evolution of the standard model dimension six operators III: gauge coupling dependence and phenomenology*, *JHEP* **04** (2014) 159 [arXiv:1312.2014] [INSPIRE].

JHEP01(2019)009

[52] S. Faller, A. Khodjamirian, C. Klein and T. Mannel, *$B \to D^{(*)}$ form factors from QCD light-cone sum rules*, *Eur. Phys. J.* **C 60** (2009) 603 [arXiv:0809.0222] [INSPIRE].

[53] M.A. Shifman and M.B. Voloshin, *On annihilation of mesons built from heavy and light quark and $\bar{B}^0 \leftrightarrow B^0$ oscillations*, *Sov. J. Nucl. Phys.* **45** (1987) 292 [*Yad. Fiz.* **45** (1987) 463] [INSPIRE].

[54] N. Isgur and M.B. Wise, *Weak decays of heavy mesons in the static quark approximation*, *Phys. Lett.* **B 232** (1989) 113 [INSPIRE].

[55] N. Isgur and M.B. Wise, *Weak transition form-factors between heavy mesons*, *Phys. Lett.* **B 237** (1990) 527 [INSPIRE].

[56] M.E. Luke, *Effects of subleading operators in the heavy quark effective theory*, *Phys. Lett.* **B 252** (1990) 447 [INSPIRE].

[57] M. Neubert and V. Rieckert, *New approach to the universal form-factors in decays of heavy mesons*, *Nucl. Phys.* **B 382** (1992) 97 [INSPIRE].

[58] A.F. Falk and M. Neubert, *Second order power corrections in the heavy quark effective theory. 1. Formalism and meson form-factors*, *Phys. Rev.* **D 47** (1993) 2965 [hep-ph/9209268] [INSPIRE].

[59] M. Neubert, *Renormalization of heavy quark currents*, *Nucl. Phys.* **B 371** (1992) 149 [INSPIRE].

[60] M. Neubert, Z. Ligeti and Y. Nir, *QCD sum rule analysis of the subleading Isgur-Wise form-factor $\chi_2(v \cdot v')$*, *Phys. Lett.* **B 301** (1993) 101 [hep-ph/9209271] [INSPIRE].

[61] M. Neubert, Z. Ligeti and Y. Nir, *The subleading Isgur-Wise form-factor $\chi_3(v \cdot v')$ to order α_s in QCD sum rules*, *Phys. Rev.* **D 47** (1993) 5060 [hep-ph/9212266] [INSPIRE].

[62] Z. Ligeti, Y. Nir and M. Neubert, *The subleading Isgur-Wise form-factor $\xi_3(v - v')$ and its implications for the decays $\bar{B} \to D*$ lepton anti-neutrino*, *Phys. Rev.* **D 49** (1994) 1302 [hep-ph/9305304] [INSPIRE].

[63] A. Czarnecki, *Two loop QCD corrections to $b \to c$ transitions at zero recoil*, *Phys. Rev. Lett.* **76** (1996) 4124 [hep-ph/9603261] [INSPIRE].

[64] A. Czarnecki and K. Melnikov, *Two loop QCD corrections to $b \to c$ transitions at zero recoil: analytical results*, *Nucl. Phys.* **B 505** (1997) 65 [hep-ph/9703277] [INSPIRE].

[65] C.G. 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].

[66] I. Caprini, L. Lellouch and M. Neubert, *Dispersive bounds on the shape of $\bar{B} \to D^{(*)}$ lepton anti-neutrino form-factors*, *Nucl. Phys.* **B 530** (1998) 153 [hep-ph/9712417] [INSPIRE].

[67] BABAR collaboration, B. Aubert et al., *Measurements of the semileptonic decays $\bar{B} \to Dl\bar{\nu}$ and $\bar{B} \to D^* l\bar{\nu}$ using a global fit to $DXl\bar{\nu}$ final states*, *Phys. Rev.* **D 79** (2009) 012002 [arXiv:0809.0828] [INSPIRE].

[68] BABAR collaboration, B. Aubert et al., *A measurement of the branching fractions of exclusive $\bar{B} \to D^{(*)}(\pi)\ell^- \bar{\nu}_\ell$ decays in events with a fully reconstructed B meson*, *Phys. Rev. Lett.* **100** (2008) 151802 [arXiv:0712.3503] [INSPIRE].

[69] BABAR collaboration, B. Aubert et al., *Determination of the form-factors for the decay $B^0 \to D^{*-}\ell^+\nu_l$ and of the CKM matrix element $|V_{cb}|$*, *Phys. Rev.* **D 77** (2008) 032002 [arXiv:0705.4008] [INSPIRE].

[70] BABAR collaboration, B. Aubert et al., *Measurement of the decay $B^- \to D^{*0} e^- \bar{\nu}(e)$*, *Phys. Rev. Lett.* **100** (2008) 231803 [arXiv:0712.3493] [INSPIRE].

JHEP01(2019)009

[71] G. D'Agostini, *On the use of the covariance matrix to fit correlated data*, Nucl. Instrum. Meth. **A 346** (1994) 306 [INSPIRE].

[72] HFLAV collaboration, Y. Amhis et al., *Averages of b-hadron, c-hadron and τ-lepton properties as of summer 2016*, Eur. Phys. J. **C 77** (2017) 895 [arXiv:1612.07233] [INSPIRE].

[73] K. Hamano, *Measurement of branching fractions and form factor parameters of $B \to Dl\nu$ and $B \to D^* l\nu$ Decays at BaBar*, Ph.D. thesis, Victoria University, Australia (2008).

[74] Belle collaboration, *Precise determination of the CKM matrix element $|V_{cb}|$ with $\bar{B}^0 \to D^{*+} \ell^- \bar{\nu}_\ell$ decays with hadronic tagging at Belle*, https://www.hepdata.net/record/ins1512299 (2017).

[75] Y. Grossman and Z. Ligeti, *The inclusive $\bar{B} \to \tau\bar{\nu}X$ decay in two Higgs doublet models*, Phys. Lett. **B 332** (1994) 373 [hep-ph/9403376] [INSPIRE].

[76] A. Celis, M. Jung, X.-Q. Li and A. Pich, *Scalar contributions to $b \to c(u)\tau\nu$ transitions*, Phys. Lett. **B 771** (2017) 168 [arXiv:1612.07757] [INSPIRE].

[77] M. Jezabek and J.H. Kuhn, *QCD corrections to semileptonic decays of heavy quarks*, Nucl. Phys. **B 314** (1989) 1 [INSPIRE].

[78] A. Czarnecki and S. Davidson, *QCD corrections to the charged Higgs decay of a heavy quark*, Phys. Rev. **D 48** (1993) 4183 [hep-ph/9301237] [INSPIRE].

[79] A. Czarnecki, M. Jezabek and J.H. Kuhn, *Radiative corrections to $b \to c\tau\bar{\tau}$-neutrino*, Phys. Lett. **B 346** (1995) 335 [hep-ph/9411282] [INSPIRE].

[80] Y. Grossman, H.E. Haber and Y. Nir, *QCD corrections to charged Higgs mediated $b \to c\tau$-neutrino decay*, Phys. Lett. **B 357** (1995) 630 [hep-ph/9507213] [INSPIRE].

[81] 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].

[82] R. Alonso, B. Grinstein and J. Martin Camalich, *Lifetime of B_c^- constrains explanations for anomalies in $B \to D^{(*)}\tau\nu$*, Phys. Rev. Lett. **118** (2017) 081802 [arXiv:1611.06676] [INSPIRE].

[83] A. Crivellin, C. Greub and A. Kokulu, *Explaining $B \to D\tau\nu$, $B \to D^*\tau\nu$ and $B \to \tau\nu$ in a 2HDM of type-III*, Phys. Rev. **D 86** (2012) 054014 [arXiv:1206.2634] [INSPIRE].

[84] A. Celis, M. Jung, X.-Q. Li and A. Pich, *Sensitivity to charged scalars in $B \to D^{(*)}\tau\nu_\tau$ and $B \to \tau\nu_\tau$ decays*, JHEP **01** (2013) 054 [arXiv:1210.8443] [INSPIRE].

[85] M. Tanaka and R. Watanabe, *New physics in the weak interaction of $\bar{B} \to D^{(*)}\tau\bar{\nu}$*, Phys. Rev. **D 87** (2013) 034028 [arXiv:1212.1878] [INSPIRE].

[86] 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].

[87] M. Freytsis, Z. Ligeti and J.T. Ruderman, *Flavor models for $\bar{B} \to D^{(*)}\tau\bar{\nu}$*, Phys. Rev. **D 92** (2015) 054018 [arXiv:1506.08896] [INSPIRE].

[88] L. Calibbi, A. Crivellin and T. Ota, *Effective field theory approach to $b \to s\ell\ell'$, $B \to K^{(*)}\nu\overline{\nu}$ and $B \to D^{(*)}\tau\nu$ with third generation couplings*, Phys. Rev. Lett. **115** (2015) 181801 [arXiv:1506.02661] [INSPIRE].

[89] 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].

[90] 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].

JHEP01(2019)009

[91] 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].

[92] 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].

[93] 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].

[94] M.B. Voloshin, *Bound on $V + A$ admixture in the $b \to c$ current from inclusive versus exclusive semileptonic decays of B mesons*, *Mod. Phys. Lett.* **A 12** (1997) 1823 [hep-ph/9704278] [INSPIRE].

[95] U. Nierste, S. Trine and S. Westhoff, *Charged-Higgs effects in a new $B \to D\tau nu$ differential decay distribution*, *Phys. Rev.* **D 78** (2008) 015006 [arXiv:0801.4938] [INSPIRE].

[96] Y. Sakaki, M. Tanaka, A. Tayduganov and R. Watanabe, *Testing leptoquark models in $\bar{B} \to D^{(*)}\tau\bar{\nu}$*, *Phys. Rev.* **D 88** (2013) 094012 [arXiv:1309.0301] [INSPIRE].

[97] D. Foreman-Mackey, D.W. Hogg, D. Lang and J. Goodman, *emcee: the MCMC hammer*, *Publ. Astron. Soc. Pac.* **125** (2013) 306 [arXiv:1202.3665] [INSPIRE].

JHEP01(2019)009