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$|V_{cb}|$ and New Physics

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The CKM matrix element $|V_{cb}|$ has been measured from the semi-leptonic inclusive and exclusive B meson decays with the Standard Model hypothesis. This proceedings review recent studies on New Physics effects related to these $|V_{cb}|$ measurements. In short, one can find that NP with $\sim 5\%$ of the SM size could be allowed consistently with Belle data for the $\bar{B} \to D^{(*)}\ell\nu$ processes and theory evaluations for the form factors. A corresponding LHC study is also presented, in which $\ell^{\pm}$ + missing searches with data available by ATLAS can probe New Physics signal.

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1. Introduction

The $|V_{cb}|$ measurements have been developed along with theoretical understanding and improvement on B meson transitions to charmed mesons. A current status on the $|V_{cb}|$ determinations from the inclusive ($\bar{B} \to X_c \ell \bar{\nu}$) and exclusive ($\bar{B} \to D^{(*)} \ell \nu$) processes is summarized in Fig. 1. A discrepancy among these two determinations, referred to as V_{cb} puzzle, is about 3σ.

The inclusive process $\bar{B} \to X_c \ell \bar{\nu}$ is described by means of the heavy quark expansion for $\bar{\Lambda}/m_b$, with which non-perturbative effects are taken as free parameters to be fitted together with $|V_{cb}|$. Corrections up to $(\bar{\Lambda}/m_b)^3$ are included in the recent fit analysis [1] determining $|V_{cb}|$ as in Fig. 1, whereas $(\bar{\Lambda}/m_b)^{4,5}$ were found to be negligible [2]. See also the PDG review [1]. Note that the expansion for $\bar{B} \to X_c \ell \bar{\nu}$ starts at $(\bar{\Lambda}/m_b)^2$. That is, no $(\bar{\Lambda}/m_b)^1$ term exists due to heavy quark symmetry.

The $|V_{cb}|$ determination from the exclusive processes $\bar{B} \to D^{(*)} \ell \nu$ requires precise knowledge of the $\bar{B} \to D^{(*)}$ meson transitions which rely on form factor descriptions. There have been two conventional parameterizations for the form factors:

- CLN [3] is the Heavy Quark Effective Theory (HQET) based description, where corrections for the form factors up to $(\bar{\Lambda}/m_{b,c})^1$ are taken with an approximation numerically inferred from unitarity bound. This CLN manner has the reduced number of parameters in the form factors and relates all the form factors with a few common parameters. At present, however, it is known that the approximation does not fully account for the $(\bar{\Lambda}/m_{b,c})^1$ correction and cannot for higher order one, which should be taken if compared with the inclusive case as mentioned above. An extended CLN approach, relaxing the approximation, is studied in Ref. [5] and its result is shown in Fig. 1.

- BGL [4] gives a general form factor parameterization by exploiting properties of the hadronic matrix element such as analyticity and dispersion relation. Thus, the BGL manner consists of a larger number of independent parameters. This means that large statistics for experimental data and precise theory evaluations are required, which are indeed available in the recent years. The result based on BGL is adopted as the PDG summary as shown in Fig. 1.

Although the CLN and BGL results are consistent with each other, two significant points can be observed. (i) The HQET description can give a more general form beyond CLN, which is fair to be compared with the inclusive process. This is also motivated from the fact that the NNLO correction may be competitive with NLO since one can see $(\bar{\Lambda}/m_b)^1 \sim (\bar{\Lambda}/m_c)^2$. (ii) The $|V_{cb}|$ determination is done with the SM hypothesis, but the present large experimental dataset should be able to investigate a NP possibility in the processes.

The first point has been studied in Refs. [6, 7], in which the authors have proposed two viable parameterization models by taking into account the $(\bar{\Lambda}/m_c)^2$ corrections. Regarding the second point, the HQET description also has benefit for the NP study since the HQET property relates all the types of the currents $\bar{c}\Gamma b$ with the different Lorenz structures Γ, as opposed to BGL which requires full independent parameters for each NP current.

Section 2 reviews a recent analysis to simultaneously determine $|V_{cb}|$, the HQET parameters, and the allowed NP contribution, fitted to all the available Belle dataset and the existing theory

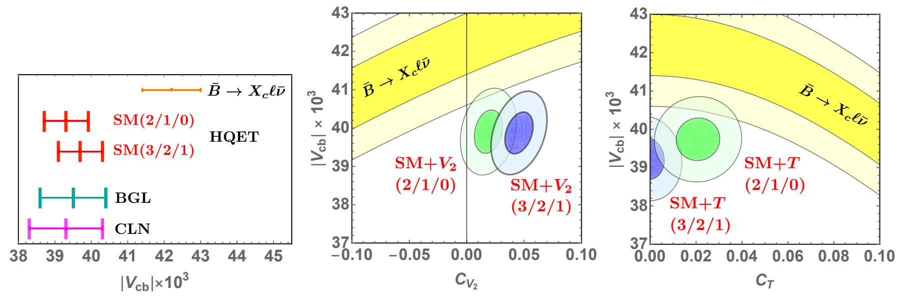

Figure 1: Left: the recent $|V_{cb}|$ determinations in the SM from the inclusive and exclusive processes. The results from Ref. [8] are highlighted in red. Middle/Right: the fit results on the $(|V_{cb}|, C_X)$ plane for the SM + NP scenarios, obtained from Ref. [8]. See the main text for the convention.

calculations of the form factors. Section 3 presents a recent study of $\ell^\pm$ + missing search at a high p_T region to constrain the NP effect, which is preferred from the $|V_{cb}|$ fit analysis. Closing remarks are given in Sec. 4.

2. From Belle data: exclusive mode

In Refs. [6, 7], the authors have revisited the HQET parameterization by adopting the setup beyond the CLN approximation up to the $(\bar{\Lambda}/m_c)^2$ corrections. The HQET property introduces one Isgur-Wise function $\xi(w)$ at LO, three at NLO, and six at NNLO of the heavy quark expansion to represent the $\bar{B} \to D^{(*)}$ transitions. All of them are then parameterized with $z = (\sqrt{w+1} - \sqrt{2})/(\sqrt{w+1} + \sqrt{2})$ expansion where $w = p_B \cdot p_{D^{(*)}}/(m_B m_{D^{(*)}})$. For instance, one writes

$$\xi(w) \equiv \sum_{n=0}^{N_{\rm LO}} a_\xi^{(n)} z^n \,, \tag{1}$$

for LO and so on. The truncation order is arbitrary and thus needs modeling. At present, the two modelings are proposed [7] such as $(N_{\rm LO}/N_{\rm NLO}/N_{\rm NNLO}) = (3/2/1)$ and $(2/1/0)$ leading to 13 and 23 parameters $a_f^{(n)}$ respectively in total, which have to be determined.

The above HQET parameters are universal for any types of the $\bar{c}\Gamma b$ current. In Ref. [8], the authors have employed this parameterization and performed a Bayesian fit analysis for $|V_{cb}|$ and the HQET parameters with/without NP contributions, based on a Markov-Chain-Monte-Carlo method. The fit includes experimental full distribution data of $\bar{B} \to D^{(*)}\ell\nu$ for $\ell = e, \mu$ available from Belle [9–11] and theory evaluations on the form factors from Lattice [12–14], QCDSR [16–18], and recent development of LCSR [15]. The SM + NP currents for $b \to c\ell\nu$ are introduced by means of the Effective Field Theory (EFT) description such that

$$\mathcal{L} = 2\sqrt{2} G_F V_{cb} \Big[(1 + C_{V_1}) O_{\rm SM} + \sum_X C_X O_X \Big] \,, \tag{2}$$

where X stands for the type of the NP current, defined as in Ref. [19], and e-μ universality is assumed for C_X, justified from available data [1]. The SM-like NP contribution C_{V_1} just rescales V_{cb}, which cannot be simultaneously fitted to data. The scalar NP currents are constrained from

$B_c \to \ell\nu$, whose bound $|C_{S_1,S_2}| \lesssim 10^{-3}$ is beyond the reach of the present fit analysis (for the case of e-μ universality). Thus, the fit analysis for SM + NP is applicable only to the O_{V_2} and O_T scenarios.

The fit results are shown in Fig. 1. One can see that the present SM values of $|V_{cb}|$ for the two HQET parameterizations are consistent with the previous studies for the CLN and BGL ones, which means that the V_{cb} puzzle still remains. See Ref. [8] for details of the fitted HQET parameters. The SM + NP fit results indicate that a non-zero NP contribution is favoured in the V_2 scenario at more than 2σ significance, which has the same level of the maximum likelihood as the SM fit. As for the T scenario, on the other hand, a non-zero NP possibility relies on the FF modeling. In any case, however, the V_{cb} puzzle is not resolved.

Based on the HQET parameters fitted in this analysis, the new SM predictions of $R_{D^{(*)}}$ can be evaluated as $R_D^{\rm SM} = 0.297(6)$ and $R_{D^*}^{\rm SM} = 0.245(4)$ for the (3/2/1) modeling.

3. From LHC data: high-p_T tail

The aforementioned $|V_{cb}|$ fit study shows that NP can exist in $b \to c\ell\nu$, which therefore motivates us to probe the NP signal at the LHC. The corresponding process is $bc \to \ell\nu$ and hence one lepton + missing search is applicable in this case.

The case of $\tau^\pm$ + missing has been studied to see if the $R_{D^{(*)}}$ anomaly is confirmed by the LHC searches. Then, the bound on the NP contribution, in terms of C_X (for τ similar to eq. (2)), has been obtained [20] with use of ATLAS [21] and CMS [22] data.

In Ref. [19], a similar analysis has been applied to the light lepton case with the following additional concern. The present process has sensitivity for the NP search at the high-p_T^ℓ range of the lepton, sufficiently away from the SM $W^\pm$ boson resonance.[1] A typical range to maximize the sensitivity is $p_T^\ell \sim 1\,\text{TeV}$, and hence it could break down the EFT picture of NP as introduced in eq. (2) if a mediator mass $M_{\rm NP}$ in a NP model that forms eq. (2) is close to $p_T \sim \sqrt{q^2}$ such that

$$C_X \equiv -\frac{h_1 h_2}{M_{\rm NP}^2} \neq \frac{h_1 h_2}{q^2 - M_{\rm NP}^2}\,, \tag{3}$$

where h_i shows couplings of the mediator particle to b, c, ℓ, and ν.

This effect has been taken by considering leptoquark (LQ) models that generate all the types of the NP currents in eq. (2) for $q^2 \ll M_{\rm NP}^2$, and the mediator mass dependence on the C_X bound is obtained as shown in Fig. 2. The result shows that the C_X bounds for $M_{\rm NP} = 2\,\text{TeV}$ ($5\,\text{TeV}$) LQ are 40 – 100% (10 – 20%) weaker than those for the EFT case. The plots also show that the EFT description becomes a good approximation for $M_{\rm NP} \gtrsim 10\,\text{TeV}$ as expected from eq. (3). The bottom plots of the figure indicate that the present LHC bound from ATLAS $139\,\text{fb}^{-1}$ data [23] allows the favoured value for C_T and C_{V_2}, obtained from the $|V_{cb}|$ fit study, whereas the future prospect at $3\,\text{ab}^{-1}$ could be competitive.

Regarding the τ case, a similar mass dependence on the C_X bound is obtained. A significant point is that the EFT bound, $|C_T|_{\text{LHC, EFT}} < 0.20$ for instance, excludes the solution to the $R_{D^{(*)}}$ anomaly in the T scenario $|C_T|_{R_{D^{(*)}}} \approx |0.15 + i0.19| \approx 0.24$. However, the solution is still viable for

[1] To be precise, the physical quantity for the analysis is the transverse mass m_T. See Ref. [19] and references therein.

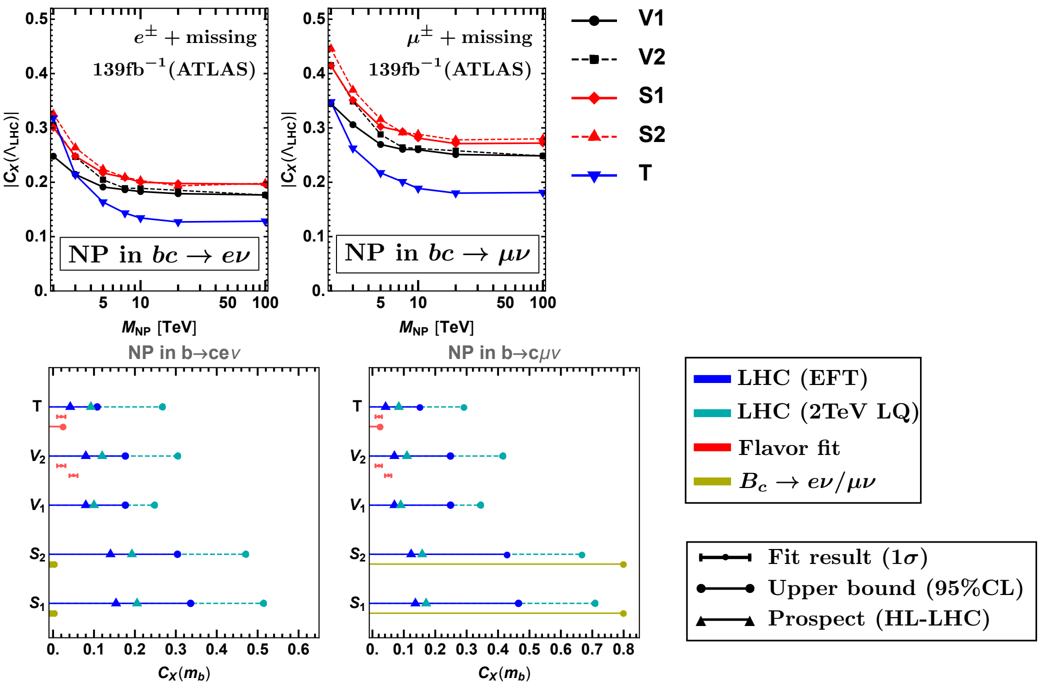

Figure 2: Top: the 95% CL upper bounds on $C_X(\Lambda_{\rm LHC})$ obtained from the $\ell\nu$ search data by ATLAS [23], for the scale to be $\Lambda_{\rm LHC} = 1$ TeV. Bottom: the combined plots of the LHC bound and the flavour fit for the $|V_{cb}|$ determination.

the LQ model with $M_{\rm NP} = 2$ TeV, since the proper bound is now given as $|C_T|_{\rm LHC,\, 2\, TeV\, LQ} < 0.42$ in this case. See Ref. [19] for more detail.

4. Closing remarks

The current $|V_{cb}|$ measurement is so precise that the large number of the HQET parameters for $\bar{B} \to D^{(*)}$ can be simultaneously fitted and that the NP effect can be analyzed. For now, the NP effect with $\sim 5\%$ of the SM size can be hidden in the $|V_{cb}|$ determination consistently with the available Belle dataset as shown in Ref. [8]. This NP possibility can be tested by the LHC from the $\ell^{\pm}$ + missing search. The present analysis in Ref. [19] shows that the aforementioned possible NP effect is allowed and could be probed by the future HL-LHC search, for which the mediator mass dependence on the LHC bound could be important.

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