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# Simultaneous extractions of $|V_{ub}|$ and $|V_{cb}|$ with only the exclusive $\Lambda_b$ decays

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## ABSTRACT

We perform the simultaneous  $|V_{ub}|$  and  $|V_{cb}|$  extractions with only the exclusive  $\Lambda_b$  decays of  $\Lambda_b \rightarrow (p, \Lambda_c^+) \mu \bar{\nu}_\mu$ ,  $\Lambda_b \rightarrow p\pi^-$  and  $\Lambda_b \rightarrow \Lambda_c^+(\pi^-, D^-)$ . We obtain that  $|V_{ub}| = (3.7 \pm 0.3) \times 10^{-3}$  and  $|V_{cb}| = (45.9 \pm 2.7) \times 10^{-3}$ . Our value of  $|V_{ub}|$  is larger than that of  $(3.27 \pm 0.15 \pm 0.16 \pm 0.06) \times 10^{-3}$ , previously extracted by the LHC Collaboration from the exclusive  $\Lambda_b$  decays also, but nearly identical to  $(3.72 \pm 0.19) \times 10^{-3}$  from the exclusive  $B$  decays. On the other hand, our extracted result of  $|V_{cb}|$  favors the value of  $(42.2 \pm 0.8) \times 10^{-3}$  from the inclusive  $B$  decays.

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## 1. introduction

The Cabibbo–Kobayashi–Maskawa (CKM) quark mixing matrix elements,  $V_{ub}$  and  $V_{cb}$ , in the standard model have been studied extensively in the literature [1]. It is known that there are long-standing discrepancies for their determinations from the exclusive and inclusive  $B$  decays. Explicitly, it is given that [1]

$$\begin{aligned} |V_{ub}|_{in} &= (4.49 \pm 0.16_{-0.18}^{+0.16}) \times 10^{-3}, \\ |V_{ub}|_{ex} &= (3.72 \pm 0.19) \times 10^{-3}, \\ |V_{cb}|_{in} &= (42.2 \pm 0.8) \times 10^{-3}, \\ |V_{cb}|_{ex} &= (39.2 \pm 0.7) \times 10^{-3}, \end{aligned} \quad (1)$$

where the subscripts “in” and “ex” stand for the extractions from the inclusive and exclusive  $B$  decays, respectively. Clearly, it is important to have some examinations besides the  $B$  meson ones, such as those from the inclusive and exclusive  $\Lambda_b$  decays. Indeed, with the branching ratios of the  $\Lambda_b \rightarrow \Lambda_c^+ \ell \bar{\nu}_\ell$  and  $\Lambda_b \rightarrow \Lambda_c^+ M_{(c)}$  decays, where  $M = (\pi^-, K^-)$  and  $M_c = (D^-, D_s^-)$ ,  $|V_{cb}|$  is extracted to be  $(44.6 \pm 3.2) \times 10^{-3}$  [2]. The extraction is in accordance with the recent studies, where  $|V_{cb}|_{ex}$  has been raised to agree with  $|V_{ub}|_{ex}$  [3]. In addition, an extraction of  $|V_{ub}|/|V_{cb}|$  from  $\Lambda_b \rightarrow p\mu\bar{\nu}_\mu$  and  $\Lambda_b \rightarrow \Lambda_c^+\mu\bar{\nu}_\mu$  has been performed by the LHCb Collaboration [4].

In Ref. [4], although the absolute branching ratio of  $\Lambda_b \rightarrow p\ell\bar{\nu}_\ell$  has not been observed, the ratio of the partial branching fractions of  $\Lambda_b \rightarrow p\mu\bar{\nu}_\mu$  and  $\Lambda_b \rightarrow \Lambda_c^+\mu\bar{\nu}_\mu$  has been used, which is given by [4]

$$\mathcal{R}_{ub/cb} \equiv \frac{\mathcal{B}(\Lambda_b \rightarrow p\mu\bar{\nu}_\mu)_{q^2 > 15 \text{ GeV}^2}}{\mathcal{B}(\Lambda_b \rightarrow \Lambda_c^+\mu\bar{\nu}_\mu)_{q^2 > 7 \text{ GeV}^2}} = (1.00 \pm 0.09) \times 10^{-2}, \quad (2)$$

with the selected transferred energy squared  $q^2$  regions of  $q^2 > 15 \text{ GeV}^2$  and  $7 \text{ GeV}^2$ . According to the theoretical calculation, formulated by

$$\frac{\mathcal{B}_{th}(\Lambda_b \rightarrow p\mu\bar{\nu}_\mu)_{q^2 > 15 \text{ GeV}^2}}{\mathcal{B}_{th}(\Lambda_b \rightarrow \Lambda_c^+\mu\bar{\nu}_\mu)_{q^2 > 7 \text{ GeV}^2}} = \frac{|V_{ub}|^2/|V_{cb}|^2}{R_{FF}}, \quad (3)$$

with  $R_{FF} = 0.68 \pm 0.07$  as the ratio of the  $\Lambda_b \rightarrow \Lambda_c$  and  $\Lambda_b \rightarrow p$  transition form factors, calculated by the lattice QCD (LQCD) [5], it is presented that  $|V_{ub}|/|V_{cb}| = 0.083 \pm 0.004 \pm 0.004$ . The simplest way to extract  $|V_{ub}|$  is by putting the existing value of  $|V_{cb}|$  into  $|V_{ub}|/|V_{cb}|$ . With  $|V_{cb}| = (39.5 \pm 0.8) \times 10^{-3}$  from the  $B \rightarrow D^{(*)} \ell \bar{\nu}_\ell$  decays<sup>1</sup> it was extracted by LHCb that  $|V_{ub}| = (3.27 \pm 0.15 \pm 0.16 \pm 0.06) \times 10^{-3}$  [4], which is even  $2\sigma$  lower than  $|V_{ub}|_{ex}$  in Eq. (1), indicating that the discrepancy between the exclusive and inclusive  $|V_{ub}|$  determinations cannot be alleviated in the exclusive  $\Lambda_b$  decays. On the other hand, by using  $|V_{cb}| = (44.6 \pm 3.2) \times 10^{-3}$

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<sup>1</sup> The data from PDG of the 2014 edition [6].

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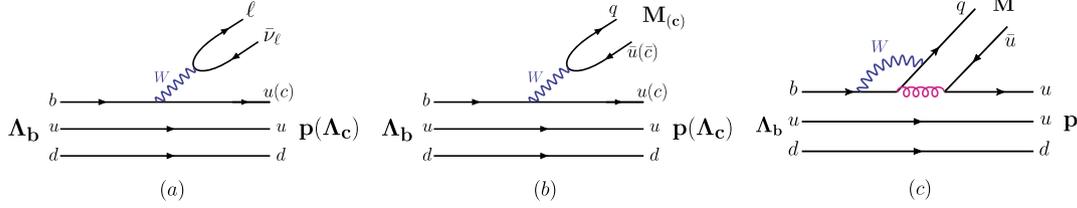


Fig. 1. Feynman diagrams depicted for (a) semileptonic  $\Lambda_b \rightarrow (p, \Lambda_c)\ell\bar{\nu}_\ell$ , (b) tree-level  $\Lambda_b \rightarrow pM, \Lambda_c M(c)$ , and (c) penguin-level  $\Lambda_b \rightarrow pM$  decays.

from the exclusive  $\Lambda_b$  decays [2] into the most recent value of  $|V_{ub}|/|V_{cb}| = 0.095 \pm 0.005$  in the PDG [1] that combines the values from both the exclusive  $B$  and  $\Lambda_b$  decays, it gives rise to  $|V_{ub}| = (4.3 \pm 0.4) \times 10^{-3}$ , and draws a different conclusion.

The two  $|V_{ub}|$  values deviate with each other. Besides, none of them can be claimed to be purely extracted from the exclusive  $\Lambda_b$  decays. In this study, we propose to have a complete global fit with the currently existing data in the exclusive  $\Lambda_b$  decays, such as  $\mathcal{R}_{ub/cb}$  and  $\Lambda_b \rightarrow p\pi^-$ , performing the simultaneous  $|V_{ub}|$  and  $|V_{cb}|$  determinations. Since  $R_{FF}$  will be no longer taken as an independent theoretical input in the extraction, the uncertainties due to the theoretical calculations of the  $\Lambda_b \rightarrow (\Lambda_c^+, p)$  form factors can be reduced. In addition, the possible data correlations should be carefully considered. We will also take into account the recently updated  $\mathcal{B}(\Lambda_c^+ \rightarrow pK^-\pi^+)$  data. As a result, we can unambiguously extract  $|V_{ub}|$  and  $|V_{cb}|$  by fitting with only the exclusive  $\Lambda_b$  decays, which are connected by the two ratios in Eqs. (2) and (3), to be regarded as the independent examination other than the  $B$  meson ones.

The paper is organized as follows. In Sec. II, we show the formalism. We give our numerical results and discussions in Sec. III. We conclude in Sec. VI.

## 2. Formalism

As seen in Fig. 1, in terms of the quark-level effective Hamiltonian for the semileptonic  $b \rightarrow u\ell\bar{\nu}_\ell$  and non-leptonic  $b \rightarrow u\bar{u}q$  transitions, the amplitudes of the  $\Lambda_b \rightarrow p\ell\bar{\nu}_\ell$  and  $\Lambda_b \rightarrow pM$  decays are found to be [7,5]

$$\begin{aligned} \mathcal{A}(\Lambda_b \rightarrow p\ell\bar{\nu}_\ell) &= \frac{G_F}{\sqrt{2}} V_{ub} \langle p | \bar{u} \gamma_\mu (1 - \gamma_5) b | \Lambda_b \rangle \bar{\ell} \gamma^\mu (1 - \gamma_5) \nu_\ell, \\ \mathcal{A}(\Lambda_b \rightarrow pM) &= i \frac{G_F}{\sqrt{2}} f_M q^\mu \left[ \alpha_M \langle p | \bar{u} \gamma_\mu b | \Lambda_b \rangle + \beta_M \langle p | \bar{u} \gamma_\mu \gamma_5 b | \Lambda_b \rangle \right], \end{aligned} \quad (4)$$

where  $G_F$  is the Fermi constant,  $V_{ij}$  are the CKM quark mixing matrix elements, and the matrix element of  $\langle M | \bar{q} \gamma^\mu (1 - \gamma_5) u | 0 \rangle = i f_M q^\mu$  corresponds to the meson production with  $f_M$  being the decay constant of  $M$ . In Eq. (4), the parameter  $\alpha_M$  ( $\beta_M$ ) is given by  $\alpha_M$  ( $\beta_M$ ) =  $V_{ub} V_{uq}^* a_1 - V_{tb} V_{tq}^* (a_4 \pm r_M a_6)$  with  $r_M \equiv 2m_M^2/[m_b(m_q + m_u)]$  based on the factorization approach, where  $a_{1,4,6} \equiv c_{1,4,6}^{eff} + c_{2,3,5}^{eff}/N_c^{eff}$  with the effective Wilson coefficients  $c_i^{eff}$  and color number  $N_c^{eff}$  [8], while  $q = (d, s)$  for  $M = (\pi^-, K^-)$ . Similarly, the amplitudes of the  $\Lambda_b \rightarrow \Lambda_c \ell \bar{\nu}_\ell$  and  $\Lambda_b \rightarrow \Lambda_c M(c)$  decays are given by

$$\begin{aligned} \mathcal{A}(\Lambda_b \rightarrow \Lambda_c \ell \bar{\nu}_\ell) &= \frac{G_F}{\sqrt{2}} V_{cb} \langle \Lambda_c | \bar{c} \gamma_\mu (1 - \gamma_5) b | \Lambda_b \rangle \bar{\ell} \gamma^\mu (1 - \gamma_5) \nu_\ell, \end{aligned}$$

$$\begin{aligned} \mathcal{A}(\Lambda_b \rightarrow \Lambda_c M(c)) &= i \frac{G_F}{\sqrt{2}} V_{cb} V_{\alpha\beta}^* a_1^{M(c)} f_{M(c)} q^\mu \langle \Lambda_c | \bar{c} \gamma_\mu (1 - \gamma_5) b | \Lambda_b \rangle, \end{aligned} \quad (5)$$

where  $V_{\alpha\beta} = V_{u(c)q}$  ( $q = d, s$ ) for  $M(c) = \pi^-(D^-), K^-(D_s^-)$  and  $a_1^{M(c)}$  are similar to  $a_1$  in Eq. (4) but for the  $M(c)$  modes. The amplitude of the  $\Lambda_c^+ \rightarrow \Lambda \ell \bar{\nu}_\ell$  decay through  $c \rightarrow s \ell \bar{\nu}_\ell$  can be given by replacing  $(b, c)$  with  $(c, s)$  in  $\mathcal{A}(\Lambda_b \rightarrow \Lambda_c^+ \ell \bar{\nu}_\ell)$  of Eq. (5). Note that the extractions with the  $\Lambda_b \rightarrow pM$  and  $\Lambda_b \rightarrow \Lambda_c M(c)$  decays are based on the validity of the factorization approach, which is supported by the recent observations. For example, with the factorization the ratios of  $\mathcal{B}(\Lambda_b \rightarrow \Lambda_c^+ \pi^-)/\mathcal{B}(\Lambda_b \rightarrow \Lambda_c^+ K^-)$ ,  $\mathcal{B}(\Lambda_b \rightarrow \Lambda_c^+ D_s^-)/\mathcal{B}(\Lambda_b \rightarrow \Lambda_c^+ D^-)$  and  $\mathcal{B}(\Lambda_b \rightarrow p\pi^-)/\mathcal{B}(\Lambda_b \rightarrow pK^-)$  are calculated to be 13.2, 25.1, and 0.84 [7,9], in agreement with the data of  $13.6 \pm 1.6$ ,  $24.0 \pm 3.8$ , and  $0.84 \pm 0.09$  [1,10], respectively. The other justification is from the soft-collinear effective theory [11]. It is proposed that, if the factorization works, the non-leptonic  $\Lambda_b \rightarrow \Lambda_c^+ \pi^-$  decay can be related to the semileptonic  $\Lambda_b \rightarrow \Lambda_c^+ \ell \bar{\nu}_\ell$  decays, resulting in the predictions of  $\mathcal{B}(\Lambda_b \rightarrow \Lambda_c^+ \ell \bar{\nu}_\ell) \approx 6 \times 10^{-2}$  and  $\mathcal{B}(\Lambda_b \rightarrow \Lambda_c \pi^-) = 4.6 \times 10^{-3}$ , which remarkably agree with the data of  $(6.2^{+1.4}_{-1.3}) \times 10^{-2}$  and  $(4.9 \pm 0.4) \times 10^{-3}$  in the PDG [1], respectively.

The amplitudes in Eqs. (4) and (5) are related to the matrix elements of the  $\mathbf{B}_1 \rightarrow \mathbf{B}_2$  transitions with  $(\mathbf{B}_1, \mathbf{B}_2) = (\Lambda_b, p)$ ,  $(\Lambda_b, \Lambda_c^+)$ , and  $(\Lambda_c^+, \Lambda)$  for the transition currents of  $b \rightarrow u$ ,  $b \rightarrow c$ , and  $c \rightarrow s$ , respectively, given by [12]

$$\begin{aligned} \langle \mathbf{B}_2 | \bar{q}_2 \gamma_\mu q_1 | \mathbf{B}_1 \rangle &= \bar{u}(p', s') \left[ f_0(q^2)(m_1 - m_2) \frac{q^\mu}{q^2} + f_+(q^2) \frac{m_1 + m_2}{s_+} \right. \\ &\quad \times \left( p^\mu + p'^\mu - (m_1^2 - m_2^2) \frac{q^\mu}{q^2} \right) \\ &\quad \left. + f_\perp(q^2) \left( \gamma^\mu - \frac{2m_2}{s_+} p^\mu - \frac{2m_1}{s_+} p'^\mu \right) \right] u(p, s), \\ \langle \mathbf{B}_2 | \bar{q}_2 \gamma_\mu \gamma_5 q_1 | \mathbf{B}_1 \rangle &= -\bar{u}(p', s') \gamma_5 \left[ g_0(q^2)(m_1 + m_2) \frac{q^\mu}{q^2} + g_+(q^2) \frac{m_1 - m_2}{s_-} \right. \\ &\quad \times \left( p^\mu + p'^\mu - (m_1^2 - m_2^2) \frac{q^\mu}{q^2} \right) \\ &\quad \left. + g_\perp(q^2) \left( \gamma^\mu + \frac{2m_2}{s_-} p^\mu - \frac{2m_1}{s_-} p'^\mu \right) \right] u(p, s), \end{aligned} \quad (6)$$

where  $q = p - p'$ ,  $s_\pm = (m_1 \pm m_2)^2 - q^2$ , and  $f = f_j$  and  $g_j$  ( $j = 0, +, \perp$ ) are the form factors in the helicity-based definition. The momentum dependences of  $f$  are written as [5]

$$f(t) = \frac{1}{1 - t/(m_{pole}^f)^2} \left[ a_0^f + a_1^f \frac{\sqrt{t_+ - t_0} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - t_0} + \sqrt{t_+ - t_0}} \right], \quad (7)$$

where  $m_{pole}^f$  are the pole masses and  $t_0 = (m_1 - m_2)^2$ , while  $t_+$  and  $a_{0,1}^f$  have been given in Refs. [5,13]. Consequently, one is able

to integrate over the variables of the phase spaces in the two and three-body decays for the decay widths [1].

To demonstrate that the inclusions of  $\mathcal{B}(\Lambda_b \rightarrow pM, \Lambda_c M_{(c)})$  in the extractions of  $|V_{ub}|$  and  $|V_{cb}|$  can reduce the theoretical uncertainties from the  $\Lambda_b \rightarrow (p, \Lambda_c)$  transition form factors due to the LQCD calculations in Eq. (6), we define

$$\mathcal{F}(\Lambda_b \rightarrow \mathbf{B}_Q)_{q^2} = \frac{1}{|V_{Qb}|^2} \int_{q^2} \frac{\hat{\tau}_{\Lambda_b}}{(2\pi)^3 32 m_{\Lambda_b}^3} \frac{d\Gamma(\Lambda_b \rightarrow \mathbf{B}_Q \ell \bar{\nu}_\ell)}{dq^2} dq^2, \quad (8)$$

which leads to that  $\mathcal{B}(\Lambda_b \rightarrow \mathbf{B}_Q \ell \bar{\nu}_\ell) = |V_{Qb}|^2 \mathcal{F}(\Lambda_b \rightarrow \mathbf{B}_Q)_{q^2 > 0 \text{ GeV}^2}$  with  $q^2 > (m_\ell + m_{\bar{\nu}})^2 \simeq 0 \text{ GeV}^2$ , where  $Q = (c, u)$  for  $\mathbf{B}_Q = (\Lambda_c, p)$  and  $\hat{\tau}_{\Lambda_b} \equiv \tau_{\Lambda_b} / (6.582 \times 10^{-25})$ . Clearly,  $R_{FF}$  defined in Ref. [4] for the extraction of  $|V_{ub}|/|V_{cb}|$  is in fact the ratio of  $\mathcal{F}(\Lambda_b \rightarrow \Lambda_c)_{q^2 > 7 \text{ GeV}^2}$  to  $\mathcal{F}(\Lambda_b \rightarrow p)_{q^2 > 15 \text{ GeV}^2}$ .

### 3. Numerical results and discussions

For the numerical analysis, we perform the minimum  $\chi^2$  fit with the experimental inputs given in Table 1, where  $|V_{ub}|$  and  $|V_{cb}|$  are treated as the free parameters to be determined. The theoretical inputs for the CKM matrix elements and decay constants are given by [1]

$$\begin{aligned} (|V_{tb}|, 10^3 |V_{td}|, 10^3 |V_{ts}|) &= (1.009 \pm 0.031, 8.2 \pm 0.6, 40.0 \pm 2.7), \\ (|V_{cd}|, |V_{cs}|) &= (0.220 \pm 0.005, 0.995 \pm 0.016), \\ (|V_{ud}|, |V_{us}|) &= (0.97417 \pm 0.00021, 0.2248 \pm 0.0006), \\ (f_\pi, f_K) &= (130.2 \pm 1.7, 155.6 \pm 0.4) \text{ MeV}, \\ (f_D, f_{D_s}) &= (203.7 \pm 4.7, 257.8 \pm 4.1) \text{ MeV}. \end{aligned} \quad (9)$$

In addition, we use

$$a_1^{M_{(c)}} = 1.1 \pm 0.1, \quad (10)$$

which depends on the effective Wilson coefficients ( $c_1^{eff}, c_2^{eff}$ ) = (1.168, -0.365) and the effective color number  $N_c^{eff}$ . In Eq. (10),  $N_c^{eff}$  has been taken to be 3 as the central value, and ranging from 2 to  $\infty$  [8] for the error to account for the non-factorizable effects in the generalized factorization. Since  $\Lambda_b \rightarrow pM$  have been tested to be insensitive to the non-factorizable effects [7], we adopt the values of  $a_{1,4,6}$  from Ref. [8] with  $N_c^{eff} = 3$ . Note that the initial inputs for the  $\Lambda_b \rightarrow (p, \Lambda_c)$  and  $\Lambda_c \rightarrow \Lambda$  form factors defined in Eq. (7) are chosen from Refs. [5,13].

There can be two issues for the simultaneous extractions of  $|V_{ub}|$  and  $|V_{cb}|$  in the exclusive  $\Lambda_b$  decays. First, when the non-leptonic and semileptonic decays are all included in the global fit, there are some possible uncertainties from the data correlations, which should be avoided or estimated. According to the “CONSTRAINED FIT INFORMATION” in the PDG [1],  $\mathcal{B}(\Lambda_b \rightarrow \Lambda_c^+ \pi^-, \Lambda_c^+ K^-)$  and  $\mathcal{B}(\Lambda_b \rightarrow p\pi^-, pK^-)$  are 94% and 83% correlated, respectively. Moreover,  $\mathcal{B}(\Lambda_b \rightarrow \Lambda_c^+ \ell \bar{\nu}_\ell)$  has 14% correlations with the individual value of  $\mathcal{B}(\Lambda_b \rightarrow \Lambda_c^+ \pi^-)$  and  $\mathcal{B}(\Lambda_b \rightarrow \Lambda_c^+ K^-)$ . As a result, we adopt  $\mathcal{B}(\Lambda_b \rightarrow \Lambda_c^+ \pi^-) = (4.57_{-0.30}^{+0.31} \pm 0.23) \times 10^{-3}$  observed in Ref. [15] and rescaled in the PDG [1], instead of the weighted average one with other data, to minimize its correlation with  $\mathcal{B}(\Lambda_b \rightarrow \Lambda_c^+ \ell \bar{\nu}_\ell)$ . We also use three different scenarios with or without including  $\mathcal{B}(\Lambda_b \rightarrow \Lambda_c^+ K^-, pK^-)$

**Table 1**  
Inputs of the experimental data.

	branching ratios	experimental data
	$\mathcal{R}_{ub/cb}$	$(0.95 \pm 0.08) \times 10^{-2}$ [14]
I1	$10^2 \mathcal{B}(\Lambda_b \rightarrow \Lambda_c \ell \bar{\nu}_\ell)$	$6.2_{-1.3}^{+1.4}$ [1]
	$\frac{\mathcal{B}(\Lambda_b \rightarrow \Lambda_c \ell \bar{\nu}_\ell)}{\mathcal{B}(\Lambda_c \rightarrow \Lambda \ell \bar{\nu}_\ell)}$	$1.7 \pm 0.4$ [1]
	$10^6 \mathcal{B}(\Lambda_b \rightarrow p\pi^-)$	$4.1 \pm 0.8$ [1]
I2	$10^3 \mathcal{B}(\Lambda_b \rightarrow \Lambda_c \pi^-)$	$4.6 \pm 0.4$ [15,1]
	$10^4 \mathcal{B}(\Lambda_b \rightarrow \Lambda_c D^-)$	$4.6 \pm 0.6$ [1]
	$10^6 \mathcal{B}(\Lambda_b \rightarrow pK^-)$	$4.9 \pm 0.9$ [1]
I3	$10^4 \mathcal{B}(\Lambda_b \rightarrow \Lambda_c K^-)$	$3.6 \pm 0.3$ [1]
	$10^2 \mathcal{B}(\Lambda_b \rightarrow \Lambda_c D_s^-)$	$1.1 \pm 0.1$ [1]

in the fit to estimate the uncertainties. Second, the recently updated data for  $\mathcal{B}(\Lambda_c^+ \rightarrow pK^-\pi^+)$  would help to data fitting as  $\Lambda_c^+$  is one of the final states. In Table 1, we have used the revised  $\mathcal{R}_{ub/cb}$  value from Ref. [14], in which the correction is around 5%. Although  $\mathcal{B}(\Lambda_b \rightarrow \Lambda_c^+ K^-)$  has an unknown correction from  $\mathcal{B}(\Lambda_c^+ \rightarrow pK^-\pi^+)$  [16], it has been excluded in one of the fitting scenarios. On the other hand, it is found that  $\mathcal{B}(\Lambda_b \rightarrow \Lambda_c^+ \pi^-, \Lambda_c^+ D_s^-)$  and  $\mathcal{B}(\Lambda_b \rightarrow \Lambda_c^+ \ell \bar{\nu}_\ell, \Lambda_c^+ D^-)$  are free from  $\mathcal{B}(\Lambda_c^+ \rightarrow pK^-\pi^+)$ , whose examinations rely on the measurements in Refs. [15,17,10]. Accordingly, the nine data points in Table 1 are classified into three types of inputs, being denoted as I1, I2, and I3, where I1 is for the semileptonic decays, while I2 and I3 for the non-leptonic ones with  $q = (d, s)$ . There can be three scenarios for the extractions. In the first scenario (S1), we perform the global fit with the six data points in I1 and I2 of Table 1, such that there is no correlation in the calculation, leading to

$$\begin{aligned} |V_{ub}| &= (3.7 \pm 0.3) \times 10^{-3}, \\ (a_1^M, a_1^{M_{(c)}}) &= (1.14 \pm 0.07, 0.98 \pm 0.06), \\ \chi^2/d.o.f &= 2.7/4 \simeq 0.7, \end{aligned} \quad (11)$$

where *d.o.f* denotes as the degrees of freedom. Note that  $\chi^2/d.o.f \simeq 0.7$  in Eq. (11) presents a very good fit. In addition,  $a_1^M$  and  $a_1^{M_{(c)}}$  fitted with the slight deviations from the central value and smaller errors than the initial one imply the well-controlled non-factorizable effects. Our fitting results for S1 are summarized in Table 2, where we have also shown those from LHCb and LQCD.

As shown in Table 2, we obtain  $|V_{cb}| = (45.9 \pm 2.7) \times 10^{-3}$  in S1, which agrees with the value of  $(42.2 \pm 0.8) \times 10^{-3}$  in Eq. (1) from the inclusive  $B$  decays. Furthermore, our result of  $|V_{ub}| = (3.7 \pm 0.3) \times 10^{-3}$  in Eq. (11) is nearly identical to that of  $(3.72 \pm 0.19) \times 10^{-3}$  in Eq. (1) from the exclusive  $B$  decays, but higher than  $(3.27 \pm 0.15 \pm 0.16 \pm 0.06) \times 10^{-3}$  from LHCb [4]. Compared to  $|V_{cb}| = (39.5 \pm 0.8) \times 10^{-3}$  from the exclusive  $B$  decays, adopted by LHCb, our extracted value of  $|V_{cb}|$  has a larger uncertainty. Nonetheless, we still get  $|V_{ub}|$  with the error compatible to that of LHCb. This is due to the fact that the measured  $\mathcal{B}(\Lambda_b \rightarrow pM, \Lambda_c M_{(c)})$  are involved in the fitting, which reduce the theoretical uncertainties from  $\Lambda_b \rightarrow (p, \Lambda_c)$  transition form factors to be 2 times smaller than the value of  $0.68 \pm 0.07$  in Refs. [5, 4]. It can be demonstrated by  $R_{FF} = (0.67 \pm 0.03, 0.68 \pm 0.07)$  from the fitting and the initial LQCD inputs, respectively, where the nearly identical values of  $R_{FF}$  show that LQCD calculation is also suitable for the two-body  $\Lambda_b$  decays that proceed at the

**Table 2**  
Fitting results for the three scenarios of S1, S2, and S3, in comparison with the LHCb and LQCD ones.

	S1	S2	S3	LHCb [4]	LQCD [5]
$10^3  V_{ub} $	$3.7 \pm 0.3$	$3.6 \pm 0.2$	$3.7 \pm 0.4$	$3.27 \pm 0.15 \pm 0.16 \pm 0.06$	–
$10^3  V_{cb} $	$45.9 \pm 2.7$	$44.8 \pm 2.0$	$45.6 \pm 3.7$	–	–
$\frac{ V_{ub} }{ V_{cb} }$	$0.081 \pm 0.008$	$0.080 \pm 0.006$	$0.081 \pm 0.011$	$0.083 \pm 0.004 \pm 0.004$	–
$\mathcal{F}(\Lambda_b \rightarrow \Lambda_c)_{q^2 > 0 \text{ GeV}^2}$	$31.16 \pm 0.62$	$31.25 \pm 0.63$	$31.22 \pm 0.63$	–	$31.19 \pm 1.33$
$\mathcal{F}(\Lambda_b \rightarrow \Lambda_c)_{q^2 > 7 \text{ GeV}^2}$	$12.17 \pm 0.06$	$12.18 \pm 0.06$	$12.18 \pm 0.06$	–	$12.17 \pm 0.27$
$\mathcal{F}(\Lambda_b \rightarrow p)_{q^2 > 0 \text{ GeV}^2}$	$37.99 \pm 4.36$	$37.90 \pm 4.10$	$37.37 \pm 4.44$	–	$37.41 \pm 6.89$
$\mathcal{F}(\Lambda_b \rightarrow p)_{q^2 > 15 \text{ GeV}^2}$	$18.11 \pm 0.82$	$18.08 \pm 0.76$	$17.90 \pm 0.84$	–	$17.92 \pm 1.85$
$R_{FF} \equiv \frac{\mathcal{F}(\Lambda_b \rightarrow \Lambda_c)_{q^2 > 7 \text{ GeV}^2}}{\mathcal{F}(\Lambda_b \rightarrow p)_{q^2 > 15 \text{ GeV}^2}}$	$0.67 \pm 0.03$	$0.67 \pm 0.03$	$0.68 \pm 0.03$	$0.68 \pm 0.07$	$0.68 \pm 0.07$
$10^4 \mathcal{B}(\Lambda_b \rightarrow p\mu\bar{\nu}_\mu)$	$5.2 \pm 1.1$	$4.9 \pm 0.8$	$5.1 \pm 1.3$	$4.1 \pm 1.0$	–

low  $q^2$  regions, which have never been tested previously. It is interesting to note that the connection of the fitted values of  $|V_{ub}|$  and  $|V_{cb}|$  causes  $|V_{ub}|/|V_{cb}| = 0.081 \pm 0.008$ , being nearly the same as the value from the LHCb extraction. We also predict  $\mathcal{B}(\Lambda_b \rightarrow p\mu\bar{\nu}_\mu) = (5.2 \pm 1.1) \times 10^{-4}$ , which is slightly larger than  $(4.1 \pm 1.0) \times 10^{-4}$  by the extrapolation from the data at  $q^2 > 15 \text{ GeV}^2$ .

In the second scenario (S2), we fit with all data points from I1, I2 and I3 in Table 1 with the correlations. Note that  $\mathcal{B}(\Lambda_b \rightarrow \Lambda_c K^-)$  also mixes with the unknown contribution from  $\mathcal{B}(\Lambda_c^+ \rightarrow pK^- \pi^+)$ . As a result, we are able to test possible deviations caused by the correlations as well as the new result from  $\Lambda_c^+ \rightarrow pK^- \pi^+$ . Furthermore, we only use the three data points from the semileptonic processes in I1 as the third scenario (S3). In this scenario, there is no need to introduce the factorization. However, from Table 2 we find that the fitted results in S3 are very close to those in S1, indicating that the correlations and the effect of  $\Lambda_c^+ \rightarrow pK^- \pi^+$  are insensitive to the fit. We also see that, even without the factorization assumption, the central value of  $|V_{ub}|$  in S3 is almost the same as those in S1 and S2, except the larger errors. This implies that the global fit with the additional non-leptonic decays reduces the uncertainties but without violating the outcome of the factorization.

#### 4. Conclusions

We have performed the first simultaneous  $|V_{ub}|$  and  $|V_{cb}|$  extractions in the exclusive  $\Lambda_b$  decays. In addition to the ratio of  $\mathcal{B}(\Lambda_b \rightarrow p\mu\bar{\nu}_\mu)_{q^2 > 15 \text{ GeV}^2}$  to  $\mathcal{B}(\Lambda_b \rightarrow \Lambda_c^+ \mu\bar{\nu}_\mu)_{q^2 > 7 \text{ GeV}^2}$  measured by LHCb, the branching fractions of  $\Lambda_b \rightarrow (p, \Lambda_c)\mu\bar{\nu}_\mu$ ,  $\Lambda_b \rightarrow pM$  and  $\Lambda_b \rightarrow \Lambda_c M_{(c)}$  with  $M_{(c)} = \pi^-(D^-)$  have been included in the global fit, which help to eliminate the theoretical uncertainties from the  $\Lambda_b \rightarrow (p, \Lambda_c)$  transition form factors, calculated in the LQCD model. We have obtained  $|V_{ub}| = (3.7 \pm 0.3) \times 10^{-3}$ , which

is larger than the LHCb value of  $(3.27 \pm 0.15 \pm 0.16 \pm 0.06) \times 10^{-3}$  extracted from the  $\Lambda_b$  decays also, but almost identical to that of  $(3.72 \pm 0.19) \times 10^{-3}$  from the exclusive  $B$  decays. In addition, our extracted result of  $|V_{cb}| = (45.9 \pm 2.7) \times 10^{-3}$  is close to  $(42.2 \pm 0.8) \times 10^{-3}$  from the inclusive  $B$  decays. We have predicted  $\mathcal{B}(\Lambda_b \rightarrow p\mu\bar{\nu}_\mu) = (5.2 \pm 1.1) \times 10^{-4}$ , in comparison with the extrapolated value of  $(4.1 \pm 1.0) \times 10^{-4}$  from the partial branching ratio of  $\Lambda_b \rightarrow p\mu\bar{\nu}_\mu$  at  $q^2 > 15 \text{ GeV}^2$ .

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#### References

- [1] C. Patrignani, et al., Particle Data Group, Chin. Phys. C 40 (2016) 100001.
- [2] Y.K. Hsiao, C.Q. Geng, Eur. Phys. J. C 77 (2017) 714.
- [3] D. Bigi, P. Gambino, S. Schacht, Phys. Lett. B 769 (2017) 441; D. Bigi, P. Gambino, S. Schacht, J. High Energy Phys. 1711 (2017) 061.
- [4] R. Aaij, et al., LHCb Collaboration, Nat. Phys. 11 (2015) 743.
- [5] W. Detmold, C. Lehner, S. Meinel, Phys. Rev. D 92 (2015) 034503.
- [6] K.A. Olive, et al., Particle Data Group, Chin. Phys. C 38 (2014) 090001.
- [7] Y.K. Hsiao, C.Q. Geng, Phys. Rev. D 91 (2015) 116007.
- [8] A. Ali, G. Kramer, C.D. Lu, Phys. Rev. D 58 (1998) 094009.
- [9] Y.K. Hsiao, P.Y. Lin, C.C. Lih, C.Q. Geng, Phys. Rev. D 92 (2015) 114013.
- [10] R. Aaij, et al., LHCb Collaboration, Phys. Rev. Lett. 112 (2014) 202001.
- [11] A.K. Leibovich, Z. Ligeti, I.W. Stewart, M.B. Wise, Phys. Lett. B 586 (2004) 337.
- [12] T. Feldmann, M.W.Y. Yip, Phys. Rev. D 85 (2012) 014035, Erratum: Phys. Rev. D 86 (2012) 079901.
- [13] S. Meinel, Phys. Rev. Lett. 118 (2017) 082001.
- [14] Y. Amhis, et al., Averages of  $b$ -hadron,  $c$ -hadron, and  $\tau$ -lepton properties as of summer 2016, arXiv:1612.07233 [hep-ex].
- [15] R. Aaij, et al., LHCb Collaboration, J. High Energy Phys. 1408 (2014) 143.
- [16] R. Aaij, et al., LHCb Collaboration, J. High Energy Phys. 1404 (2014) 087.
- [17] T. Aaltonen, et al., CDF Collaboration, Phys. Rev. D 79 (2009) 032001.