Measurements of $|V_{ub}|$ and $|V_{cb}|$ at Belle

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Abstract. Precise determinations of the magnitudes of the Cabibbo-Kobayashi-Maskawa (CKM) matrix elements $|V_{ub}|$ and $|V_{cb}|$ are crucial for testing the mechanism of CP violation in the Standard Model and searching for hints of New Physics in $B$ decays. In this article, we review recent Belle measurements of these two quantities.

1. Introduction

The magnitudes of the Cabibbo-Kobayashi-Maskawa (CKM) matrix elements $|V_{ub}|$ and $|V_{cb}|$ [1] are determined from semileptonic $B$ decays into charmed and charmless final states, respectively. In this paper, we review two recent Belle measurements: a determination of $|V_{cb}|$ based on inclusive observables in $B$ decays and a measurement of $B \to \pi \ell \nu$ using full reconstruction of the event kinematics.

The data used in this analyses were taken with the Belle detector [2] at the KEKB asymmetric energy $e^+e^-$ collider [3] operating at a center-of-mass energy near the $\Upsilon(4S)$ resonance. Belle is a large-solid-angle magnetic spectrometer that consists of a silicon vertex detector, a 50-layer central drift chamber, an array of aerogel threshold Čerenkov counters, a barrel-like arrangement of time-of-flight scintillation counters, and an electromagnetic calorimeter comprised of CsI(Tl) crystals located inside a super-conducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return located outside of the coil is instrumented to detect $K^0_L$ mesons and to identify muons.

The $|V_{cb}|$ analysis is based on 140 fb$^{-1}$ of integrated luminosity on the $\Upsilon(4S)$ resonance, or $152 \times 10^6 \ Upsilon(4S) \to BB$ events. The $B \to \pi \ell \nu$ measurement uses 531 fb$^{-1}$ or $576 \times 10^6 BB$ events. Additional data sets are taken at 60 MeV below the resonance to estimate the non-$BB$ (continuum) background. Monte Carlo simulated events are generated with EvtGen [4] and full detector simulation based on GEANT3 [5] is applied.

2. $|V_{cb}|$ from Inclusive Decays $B \to X_c \ell \nu$

Inclusive determinations of the CKM magnitude $|V_{cb}|$ rely on calculations of the semileptonic $B$ meson decay width in the frameworks of the Operator Product Expansion (OPE) and the Heavy Quark Effective Theory (HQET) [6, 7]. Predictions of this quantity depend on $|V_{cb}|$ and a number of non-perturbative heavy quark (HQ) parameters like quark masses and hadronic expectation values. These non-perturbative quantities have to be extracted from other inclusive observables in $B$ decays such as the lepton energy $E_\ell$ and hadronic mass $M_X^2$ moments in $B \to X_c \ell \nu$ and the photon energy $E_\gamma$ moments in $B \to X_s \gamma$ [6, 8, 9].
Table 1. Preliminary results of the global fit in the 1S and kinetic mass schemes [14]. The results for \( m_b \) are compatible after scheme translation.

| 1S scheme | kinetic scheme |
|-----------|---------------|
| \(| V_{cb} | = (41.49 \pm 0.52(\text{fit}) \pm 0.20(\tau_B)) \times 10^{-3} \) | \(| V_{cb} | = (41.93 \pm 0.65(\text{fit}) \pm 0.07(\alpha_s) \pm 0.63(\text{th})) \times 10^{-3} \) |
| \( m_b^{1S} = 4.729 \pm 0.048 \text{ GeV} \) | \( m_b^{\text{kin}} = 4.564 \pm 0.076 \text{ GeV} \) |
| \( \chi^2/\text{ndf.} = 5.7/17 \) | \( \chi^2/\text{ndf.} = 17.8/24 \) |

Belle has recently measured the moments of the electron energy and hadronic mass spectrum in \( B \to X_c \ell \nu \) decays [10, 11]. These analyses fully reconstruct the hadronic decay of one \( B \) meson using the modes \( B \to D^{(*)} \pi, \rho, a_1 \) (“tag side”) and identify the lepton from the decay \( B \to X_c \ell \nu \) within the remaining particles in the event (“signal side”). By fully reconstructing the event kinematics, backgrounds in the inclusive spectra are minimized and the resolution in \( M_X \) is greatly improved. To minimize the dependence on the \( B \to X_c \ell \nu \) model, the moments are calculated from the background subtracted spectra after the finite resolution in \( E_\ell \) respectively \( M_X^\gamma \) has been unfolded using the Singular Value Decomposition (SVD) algorithm [12].

Measurements of the partial branching fraction, the first three moments of the electron energy \( E_\ell \) and the first two moments of the hadronic mass squared \( M_X^\gamma \) spectrum in \( B \to X_c \ell \nu \) as well as the first two moments of the photon energy \( E_\gamma \) spectrum in \( B \to X_s \gamma \) [13] are used to perform a global analysis based on the theoretical expressions in the 1S [6] and kinetic mass schemes [8, 9]. As these calculations are completely independent, consistency is an important cross-check of our theoretical understanding. The preliminary results of this analysis [14] are shown in Table 1.

3. \(| V_{ub} | \) from the Decay \( B \to \pi \ell \nu \)

The differential \( B \to \pi \ell \nu \) decay width as a function of \( q^2 \), \( q^2 = (p_\ell + p_\nu)^2 \), is given by

\[
\frac{d\Gamma}{dq^2}(B \to \pi \ell \nu) = \frac{G_F^2 |V_{ub}|^2}{192 \pi^3 m_B^3} \lambda(q^2)^{3/2} |f_+(q^2)|^2 ,
\]

where \( \lambda(x) = (x + m_B^2 - m_\pi^2)^2 - 4m_B^2 m_\pi^2 \). Different theoretical approaches are available for determining the shape and the normalization of the form factor \( f_+(q^2) \): relativistic quark models (ISGW2 [15]), light cone sum rules for the region \( q^2 < 14 \text{ GeV}^2 \) (Ball-Zwicky [16]) and lattice QCD calculations for the region \( q^2 > 16 \text{ GeV}^2 \) (HPQCD [17], FNAL [18]).

As in the \( B \to X_c \ell \nu \) moment analyses described in the previous section, the recent Belle analysis of the decay \( B \to \pi \ell \nu \) [19] uses full reconstruction of the tag-side \( B \) meson. On the signal-side, the charged or neutral pion and the charged lepton (\( e \) or \( \mu \)) are reconstructed, and the signal yield is extracted from the peak around zero in the missing mass distribution. This technique allows to minimize (poorly known) backgrounds and the related systematic uncertainties. The \( B^0 \to \pi^- \ell^+ \nu \) and \( B^+ \to \pi^0 \ell^+ \nu \) branching fractions integrated over the whole \( q^2 \) range are measured to be \( (1.49 \pm 0.26(\text{stat}) \pm 0.06(\text{syst})) \times 10^{-4} \) and \( (0.86 \pm 0.17(\text{stat}) \pm 0.06(\text{syst})) \times 10^{-4} \), respectively. The partial branching fractions in bins of \( q^2 \) are used to calculate the value of \( |V_{ub}| \), Table 2.
Table 2. Values of $|V_{ub}|$ extracted from Ref. [19] using different form factor calculations.

| $q^2$ range | $|V_{ub}|$ $(10^{-3})$ |
|-------------|--------------------------|
| Ball-Zwicky [16] | $< 16$ GeV$^2$ | $3.56 \pm 0.29 (exp) \pm 0.47 (th) \pm 0.01 (\tau_{B^0})$ |
| HPQCD [17]    | $> 16$ GeV$^2$ | $3.52 \pm 0.49 (exp) \pm 0.48 (th) \pm 0.01 (\tau_{B^0})$ |
| FNAL [18]     | $> 16$ GeV$^2$ | $3.74 \pm 0.52 (exp) \pm 0.51 (th) \pm 0.01 (\tau_{B^0})$ |

4. Summary
We have reviewed two recent Belle measurements: The first analysis is a determination of the CKM magnitude $|V_{cb}|$ and the $b$-quark mass $m_b$ from different inclusive observables in $B$ decays. The results are given in Table 1. The precision achieved in $|V_{cb}|$ is about $1 - 2\%$. There is good consistency between the two independent theoretical calculations used in this analysis.

The second analysis searches for $B \rightarrow \pi \ell \nu$ decays in $\Upsilon(4S) \rightarrow B \bar{B}$ events in which the hadronic decay of one $B$ is fully reconstructed. The result in terms of the CKM magnitude $|V_{ub}|$ is given in Table 2. Experimentally, the precision of this measurement is limited only by the available $\Upsilon(4S)$ statistics.

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