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Measurements of $|V_{cb}|$ and $|V_{ub}|$ at *BABAR*

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Abstract

We report on new measurements of the Cabibbo-Kobayashi-Maskawa matrix elements $|V_{cb}|$ and $|V_{ub}|$ with inclusive and exclusive semileptonic B decays, highlighting the recent precision measurements with the *BABAR* detector at the PEP-II asymmetric-energy B Factory at SLAC.

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1 Introduction

The stringent tests of the Standard Model are currently not limited by the measurements of the CP-Violation parameter sin 2β [1] but by the measured ratio of the CKM matrix elements $|V_{ub}|/|V_{cb}|$, which determines the length of the left side of the Unitary Triangle.

The semileptonic B meson decays to charm and charmless mesons are the primary tool for measuring the CKM matrix elements $|V_{cb}|$ and $|V_{ub}|$ because of their simple theoretical description at the parton level. Their relatively large decay rates are proportional to $|V_{cb}|^2$ or $|V_{ub}|^2$, depend on the quark masses m_b and m_c, and allow us to probe the impact of strong interactions on the bound quark.

The semileptonic B meson decays can also be used to achieve a precision measurement of $f_{00} \equiv \mathcal{B}(\Upsilon(4S) \rightarrow B^0\overline{B}^0)$, which allows to reduce systematic uncertainty on many analyses. We measured f_{00} using a novel method, which does not require the knowledge of $\tau(B^+)/\tau(B^0)$ nor rely on isospin symmetry [2]. The f_{00} value is important for measuring absolute $\Upsilon(4S)$ branching fractions and for measuring $|V_{cb}|$. Experimental studies of the semileptonic B meson decays can be broadly categorized into inclusive and exclusive measurements.

2 $|V_{cb}|$ Measurements

The CKM matrix element $|V_{cb}|$ can be extracted from the semileptonic B decay rate by correcting the strong interaction effects in the parton-level calculations. The semileptonic B decay rate is determined from its semileptonic branching fraction and the average B lifetime measurements. The perturbative and non-perturbative QCD corrections and their uncertainties can be calculated in the Heavy Quark Expansion (HQE) [3]. In the kinetic-mass scheme, these expansions in $1/m_b$ and $\alpha_s(m_b)$ have six parameters to order $\mathcal{O}(1/m_b^3)$: the two running kinetic masses of b and c quarks, $m_b(\mu)$ and $m_c(\mu)$, and four non-perturbative parameters: $\mu_\pi^2(\mu)$, $\mu_G^2(\mu)$, $\rho_D^3(\mu)$, and $\rho_{LS}^3(\mu)$, the expectation value of kinetic, chromomagnetic, Darwin, and spin-orbit operators, respectively. All these parameters depend on the scale μ separating short-distance from long-distance QCD effects; the calculations are performed for $\mu = 1$ GeV [4].

We measured the inclusive $B \rightarrow X_c\ell\nu$ branching fraction and the six heavy quark parameters from a fit to the moments of the hadronic mass and electron energy distribution in semileptonic B decays, obtaining $|V_{cb}| = (41.4 \pm 0.4 \pm 0.4 \pm 0.6) \times 10^{-3}$, $\mathcal{B}(B \rightarrow X_c e\nu) = (10.61 \pm 0.16 \pm 0.06)\%$, $m_c = (1.18 \pm 0.07 \pm 0.06 \pm 0.02)$ GeV, $m_b = (4.61 \pm 0.05 \pm 0.04 \pm 0.02)$ GeV, $\mu_\pi^2 = (0.45 \pm 0.04 \pm 0.04 \pm 0.01)$ GeV^2, $\mu_G^2 = (0.27 \pm 0.06 \pm 0.03 \pm 0.02)$ GeV^2, $\rho_D^3 = (0.20 \pm 0.02 \pm 0.02 \pm 0.00)$ GeV^3, and $\rho_{LS}^3 = (-0.09 \pm 0.04 \pm 0.07 \pm 0.01)$ GeV^3, where the errors refer to contributions from the experimental errors on the moment measurements and the HQE, and other theoretical uncertainties derived from Refs. [6]. The fit results are fully compatible with independent estimates of $\mu_G^2 = (0.35 \pm 0.07)$ GeV^2, based on the $B^* - B$ mass splitting [6], and of $\rho_{LS}^3 = (-0.15 \pm 0.10)$ GeV^3, from the heavy-quark sum rules [7]. This is to date the most precise measurement of both $|V_{cb}|$ and the b-quark mass.

The CKM matrix elements $|V_{cb}|$ can also be extracted from the exclusive semileptonic $\overline{B}^0 \rightarrow D^{*+}\ell^-\overline{\nu}_\ell$ as a function of w, where w is the product of the four velocities of the $\overline{B}^0$ and D^{*+}, and corresponds to the relativistic boost γ of the D^{*+} in the $\overline{B}^0$ rest frame. By extrapolating the differential decay rate of $\overline{B}^0 \rightarrow D^{*+}\ell^-\overline{\nu}_\ell$ to the kinematic limit $w \rightarrow 1$, we extract the product of $|V_{cb}|$ and the axial form factor $\mathcal{A}_1(w = 1)$. We combined this measurement with a lattice QCD calculation [8] of $\mathcal{A}_1(1) = \mathcal{F}(1) = 0.919\,^{+0.030}_{-0.035}$ to determine $|V_{cb}| = (38.7 \pm 0.3 \pm 1.7\,^{+1.5}_{-1.3}) \times 10^{-3}$ [9], where the errors represents the statistical, the systematic, and the uncertainty in $\mathcal{A}_1(1)$, respectively.

3 $|V_{ub}|$ Measurements

The inclusive decay rate $B \to X_u \ell \nu$ is directly proportional to $|V_{ub}|^2$ and can be calculated using HQE; however, the extraction of $|V_{ub}|$ is a challenging task due to a large background from $B \to X_c \ell \nu$ decays.

We have extracted $|V_{ub}|$ using the following techniques: a) the measurement of the lepton spectrum above 2.0 GeV/c, i.e. near the kinematic endpoint for $B \to X_c \ell \nu$ decays [10], resulting in $|V_{ub}| = (4.44 \pm 0.25\, ^{+0.42}_{-0.38} \pm 0.22) \times 10^{-3}$; b) the measurement of the lepton spectrum combined with q^2, the momentum transfer squared [11], resulting in $|V_{ub}| = (3.95 \pm 0.26\, ^{+0.58}_{-0.42} \pm 0.25) \times 10^{-3}$; c) the measurement of the hadron mass distribution below 1.7 GeV/c^2 and $q^2 > 8$ GeV$^2/c^4$ in events tagged by the full reconstruction of a hadronic decay on the second B meson [12], resulting in $|V_{ub}| = (4.65 \pm 0.34\, ^{+0.46}_{-0.38} \pm 0.23) \times 10^{-3}$. In all of the above measurements, the errors are due to experimental, shape function, and theoretical uncertainties.

We have also measured $|V_{ub}|$ in the exclusive semileptonic $B \to \pi \ell \nu$ decays based on three different methods: a) in untagged events, in which the neutrino momentum is inferred from the missing momentum, i.e. the four-momentum is inferred from the difference between the four-momentum of the colliding-beam particles and sum of the four-momenta of all detected particles in the event. This measurement is performed separately in five intervals of q^2 and leads to an independent measurement of the shape of the form factor. The results agree well with predictions from lattice QCD and light-cone sum rules [13], resulting in $|V_{ub}| = (3.82 \pm 0.14 \pm 0.22 \pm 0.11\, ^{+0.88}_{-0.52}) \times 10^{-3}$ from $B \to \pi \ell \nu$, where the errors are statistical, systematic, the form factor shape, and the form factor normalization; b) measurement of $B^0 \to \pi^- \ell^+ \nu$ decays uses events in which the signal B meson recoils against a B meson that has been reconstructed in a semileptonic decay $\overline{B}^0 \to D^{(*)+} \ell^- \overline{\nu}_\ell$ [14], resulting in $|V_{ub}| = (3.3 \pm 0.4 \pm 0.2\, ^{+0.8}_{-0.4}) \times 10^{-3}$; c) measurements of $B^0 \to \pi^- \ell^+ \nu$ and $B^+ \to \pi^0 \ell^+ \nu$ decays in $\Upsilon(4S) \to B\overline{B}$ events tagged by a fully reconstructed hadronic B decay in three regions of q^2 [15], resulting in $|V_{ub}| = (3.7 \pm 0.3 \pm 0.2\, ^{+0.8}_{-0.5}) \times 10^{-3}$, where the errors of the last two results are statistical, systematic, and the form factor normalization uncertainties, respectively.

4 Conclusion

Precision measurements of the CKM matrix elements $|V_{cb}|$ and $|V_{ub}|$ would significantly improve the constraints on the Standard Model. The current experimental precision of $|V_{cb}|$ is about 2% and the precision of $|V_{ub}|$ is about 8%, which is dominated by theory uncertainties.

In the next few years, much larger $B\overline{B}$ data sample will become available from the B Factories [16], PEP-II [17], and KEKB [18]. We can expect significant improvements in statistics, in our understanding of the experimental and theoretical uncertainties, leading to higher precision of $|V_{cb}|$ and $|V_{ub}|$.

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