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Determination of $|V_{cb}|$ and Related Results from *BABAR*

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Abstract

The CKM matrix element amplitude $|V_{cb}|$ was determined using the data collected by the BABAR detector. The partial branching fraction, lepton-energy moments, and hadron-mass moments were measured in inclusive semileptonic decays $B \to X_c \ell \nu$. A global fit to a Heavy-Quark-Expansion calculation allowed precise determination of $|V_{cb}|$, m_b, m_c, $\mathcal{B}(B \to X_c \ell \nu)$ and four non-perturbative parameters.

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1 Introduction

Accurate determination of $|V_{cb}|$, the CKM matrix element that governs the $b \to c$ weak transition, is an important basis for testing the unitarity of the CKM matrix. Semileptonic decays of the B mesons provide the best access to this quantity as the leptonic current can be cleanly factored out. Heavy Quark Expansion (HQE) has become a useful theoretical tool for calculating the QCD corrections needed for the prediction of the experimental observables such as the inclusive rate $\Gamma(B \to X_c \ell \nu)$, where X_c refers to any hadronic system with a charm quark. In addition, the moments of the lepton energy (E_ℓ) and charmed hadron mass (m_X) distributions can be calculated using HQE provided that the quantity in question is integrated over a large region of the phase space to ensure quark-hadron duality.

The expansion is performed in terms of $1/m_b$ and $\alpha_s(m_b)$, with a mass scale parameter μ (typically 1 GeV) separating the short- and long-distance QCD effects. While the former is perturbatively calculable given m_b, m_c, and α_s, the latter is not, and we are left with parameters representing the expectation values of the non-perturbative operators that appear in the expansion. The measurement presented here determines $|V_{cb}|$, m_b, m_c, the branching fraction $\mathcal{B}(B \to X_c \ell \nu)$, and four non-perturbative parameters by a global fit to the lepton-energy and hadron-mass moments.

2 Measurement

We measured, in the BABAR data, the following eight moments:

$$M_0^\ell = \frac{\int d\Gamma}{\Gamma_B}, \quad M_1^\ell = \frac{\int E_\ell d\Gamma}{\int d\Gamma}, \quad M_i^\ell = \frac{\int (E_\ell - M_1^\ell)^i d\Gamma}{\int d\Gamma} \quad (i = 2, 3), \tag{1}$$

$$M_i^X = \frac{\int m_X^i d\Gamma}{\int d\Gamma} \quad (i = 1, 2, 3, 4), \tag{2}$$

where Γ_B is the total B decay rate and $d\Gamma$ is the differential $B \to X_c \ell \nu$ decay rate. The integrations are done in the phase-space region in which E_ℓ is greater than an energy threshold E_{cut}.

2.1 Measurement of the lepton-energy moments

The lepton-energy moments were measured [1] using electrons found in the BABAR data that correspond to $47.4\,\text{fb}^{-1}$ on the $\Upsilon(4S)$ resonance and $9.1\,\text{fb}^{-1}$ below. We selected the events containing two electrons: one with a large center-of-mass momentum identified the event as a likely $\Upsilon(4S) \to B\bar{B}$ decay; the other was used to measure the lepton energy spectrum. The charge and angular correlations between the two electrons were used to separate the conribution of the primary $B \to X_c e \nu$ decays from the other sources. After correcting for the experimental efficiencies and for the Bremsstrahlung in the detector material, four moments M_i^ℓ were calculated with E_{cut} varying between 0.6 and 1.5 GeV. Corrections were applied for the difference between the $\Upsilon(4S)$ and B rest frames, for the effect of the final state photon radiation, and for the $B \to X_u \ell \nu$ decays.

2.2 Measurement of the hadron-mass moments

The hadron-mass moments were measured [2] in $81\,\text{fb}^{-1}$ of on-peak BABAR data. We selected the events in which a B meson was fully reconstructed in a hadronic decay channel. The remaining part of the event contains another B meson, whose flavor and momentum are known by the

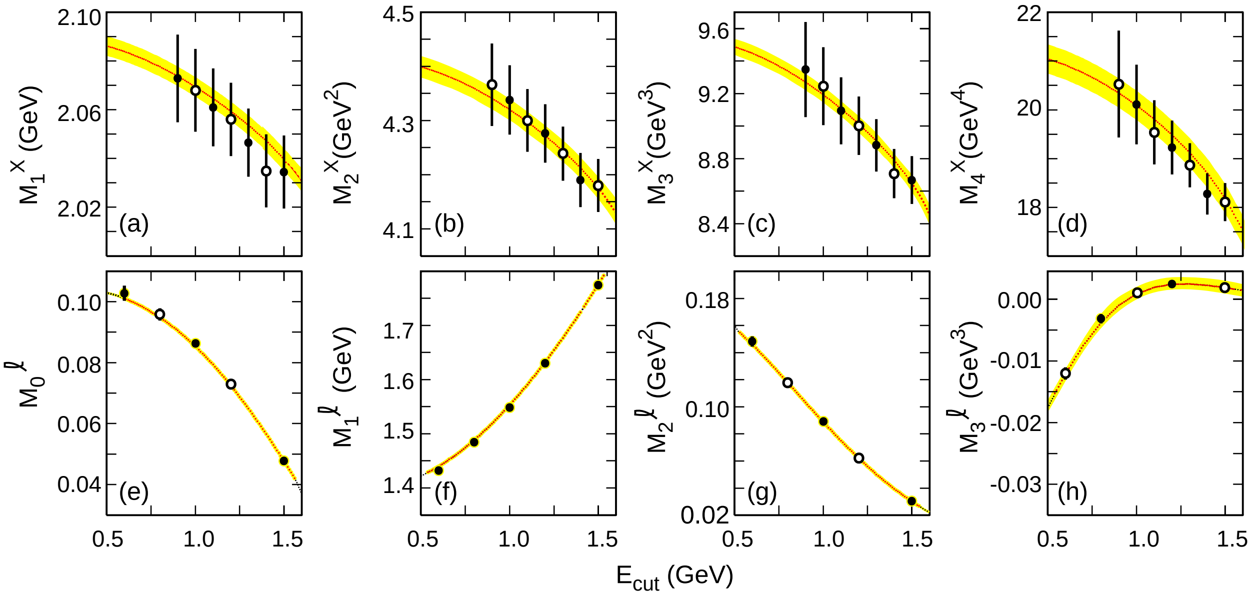

Figure 1: Results of the HQE fit. The points and the error bars are the measured moments and their experimental errors. The curves and the bands are the fit results and the theoretical errors.

conservation laws. In this recoil-B sample, we searched for a lepton accompanied by a missing 4-momentum compatible with a neutrino. The invariant mass of the hadronic system was determined by a kinematic fit assuming the 4-momentum conservation, the B meson mass, and zero neutrino mass. Residual downward bias in the measured mass, due mainly to the undetected particles, was corrected using Monte-Carlo simulation. Four moments M_i^X were calculated with $E_{\rm cut}$ varying between 0.9 and 1.6 GeV.

2.3 Fit to the HQE prediction

The HQE fit [3] used the calcuation in the kinetic mass scheme by Gambino and Uraltsev [4]. It contains four non-perturbative paramters: μ_π^2, μ_G^2, ρ_D^3, and ρ_{LS}^3. They represent the expectation values of the kinetic, chromomagentic, Darwin, and spin-orbit operators, respectively.

The eight moments, with varying $E_{\rm cut}$, provided 48 data points, some of which are heavily correlated. The full error matrix was calculated for both the statistical and systematic experimental errors. For the theoretical uncertainties, the dependencies on the $\mu_{\pi,G}^2$ and $\rho_{D,LS}^3$ parameters were varied by $\pm 20\%$ and $\pm 30\%$, respectively. The theoretical errors were assumed to be fully correlated among each moment at different $E_{\rm cut}$, but uncorrelated between different moments. These assumptions and the sizes of the theoretical uncertainties were varied to confirm that the fit results were stable.

The result of the nominal fit is shown in Fig. 1. The χ^2 is 15 for 20 degrees of freedom. Fits were repeated using E_ℓ and m_X moments separately. The results, shown in Fig. 2, are consistent with the nominal fit. We conclude from these observations that the HQE calculation describes the experimental data very well.

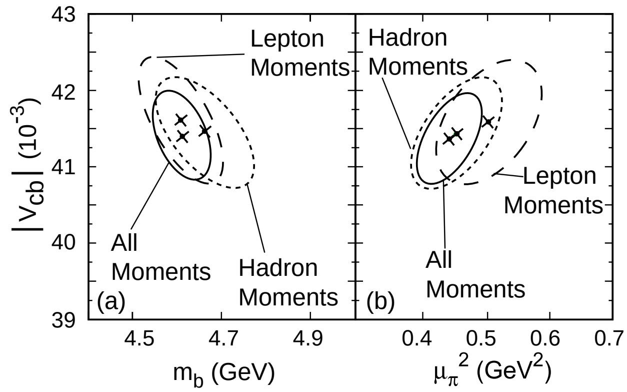

Figure 2: One-sigma contours of the HQE fits using all moments, lepton-energy moments only, and hadron-mass moments only.

The numerical results obtained from the fit are:

$$
\begin{aligned}
|V_{cb}| &= (41.4 \pm 0.4_{\rm exp} \pm 0.4_{\rm HQE} \pm 0.6_{\rm th}) \times 10^{-3}, \\
\mathcal{B}(B \to X_c \ell \nu) &= (10.61 \pm 0.16_{\rm exp} \pm 0.06_{\rm HQE})\%, \\
m_b^{\rm kin}(1\,{\rm GeV}) &= (4.61 \pm 0.05_{\rm exp} \pm 0.04_{\rm HQE} \pm 0.02_{\alpha_s})\,{\rm GeV}, \\
m_c^{\rm kin}(1\,{\rm GeV}) &= (1.18 \pm 0.07_{\rm exp} \pm 0.06_{\rm HQE} \pm 0.02_{\alpha_s})\,{\rm GeV}, \\
\mu_\pi^2 &= (0.45 \pm 0.04_{\rm exp} \pm 0.04_{\rm HQE} \pm 0.01_{\alpha_s})\,{\rm GeV}^2, \\
\mu_G^2 &= (0.27 \pm 0.06_{\rm exp} \pm 0.03_{\rm HQE} \pm 0.02_{\alpha_s})\,{\rm GeV}^2, \\
\rho_D^3 &= (0.20 \pm 0.02_{\rm exp} \pm 0.02_{\rm HQE} \pm 0.00_{\alpha_s})\,{\rm GeV}^3, \\
\rho_{LS}^3 &= (-0.09 \pm 0.04_{\rm exp} \pm 0.07_{\rm HQE} \pm 0.01_{\alpha_s})\,{\rm GeV}^3.
\end{aligned}
$$

The last error on $|V_{cb}|$ accounts for the uncalculated theoretical corrections to the semileptonic decay rate. The kinetic quark masses obtained above can be translated into the $\overline{\rm MS}$ masses:

$$\overline{m}_b(\overline{m}_b) = 4.22 \pm 0.06\,{\rm GeV}, \quad \overline{m}_c(\overline{m}_c) = 1.33 \pm 0.10\,{\rm GeV}.$$

These results represent one of the most accurate experimental determination of the heavy quark masses.

3 Summary

We determined $|V_{cb}|$, m_b, m_c, $\mathcal{B}(B \to X_c \ell \nu)$, and four non-perturbative parameters by a global fit to the lepton-energy and hadron-mass moments. The HQE fit found an excellent agreement and consistency between the theory and the data, giving us confidence in the validity of the application. Our fit used no external constraints on the HQE parameters, an improvement over the previous HQE-based measurements [5] in which some or all the parameters were either fixed or constrained.

References

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