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Study of the $B \to X_c \ell \nu$ Decays and Determination of $|V_{cb}|$

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We report studies of semileptonic decays, $B \to X_c \ell \nu$, based on a sample of 88 million $B\overline{B}$ events recorded with the BABAR detector. We have measured four moments of the electron energy and hadronic mass distributions and determined the inclusive branching fraction, the CKM matrix element $|V_{cb}|$, and other heavy quark parameters, using Heavy Quark Expansions in the kinetic mass scheme. In addition, we have studied a large sample of $B^0 \to D^{*-} \ell^+ \nu$ decays and extracted the decay form factors and $|V_{cb}|$.

1. Introduction

The CKM matrix element V_{cb}, the dominant coupling of the b quark to the charged weak current, is one of the fundamental parameters of the Standard Model. It determines the rate for $b \to c\ell\nu$ decays which at the parton level can be calculated accurately. This rate is proportional to $|V_{cb}|^2$ and depends also on b and c quark masses.

2. Inclusive Measurements

To relate inclusive semileptonic B-meson decay rate to $|V_{cb}|$, the parton-level calculations must be corrected for effects of strong interactions. Heavy-Quark Expansions (HQEs) [1] have become a powerful tool for calculating perturbative and non-perturbative QCD corrections and their uncertainties. We have chosen the kinetic-mass scheme [2,3] for expansions in $1/m_b$ and $\alpha_s(m_b)$, the strong coupling constant. To order $\mathcal{O}(1/m_b^3)$ there are six parameters: the running kinetic masses of the 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 values of the kinetic, chromomagnetic, Darwin, and spin-orbit operators, respectively. All these parameters depend on the scale μ separating short-distance from long-distance QCD effects.

We determine these HQE parameters from a fit to the moments of the hadronic-mass and electron-energy distributions in $B \to X_c \ell \nu$ decays, averaged over charged and neutral B mesons. The moments are measured as functions of a lower limit on the lepton energy E_{cut}.

The hadronic-mass distribution is measured in events tagged by the fully reconstructed hadronic decay of the second B meson [4]. The hadronic-mass moments are defined as $M_n^X(E_{cut}) = \langle m_X^n \rangle_{E_\ell > E_{cut}}$ with n = 1,2,3,4. The electron-energy distribution is measured in events tagged by a high-momentum electron from the second B meson [5]. We define the first energy moment as $M_1^\ell(E_{cut}) = \langle E_\ell \rangle_{E_\ell > E_{cut}}$ and higher order moments as $M_n^\ell(E_{cut}) = \langle (E_\ell - M_1^\ell(E_{cut}))^n \rangle_{E_\ell > E_{cut}}$ with $n = 2,3$. We fit also the partial branching ratio $M_0^\ell(E_{cut}) = \int_{E_{cut}}^{E_{max}} (d\mathcal{B}_{c\ell\nu}/dE_\ell)\, dE_\ell$.

All measured moments and the results of the least-square fit are shown in Fig. 1. The fit results (for the mass scale $\mu = 1$ GeV) are the following:

$$
\begin{aligned}
|V_{cb}| = (41.4 \pm 0.4_{exp} \pm 0.75_{HQE})\, 10^{-3} \;&;\; \mathcal{B}_{ce\nu} = (10.61 \pm 0.16_{exp} \pm 0.06_{HQE})\,\%;\\
m_b = (4.61 \pm 0.05_{exp} \pm 0.04_{HQE}) \text{ GeV}/c^2 \;&;\; m_c = (1.18 \pm 0.07_{exp} \pm 0.06_{HQE}) \text{ GeV}/c^2\,;\\
\mu_\pi^2 = 0.45 \pm 0.04_{exp} \pm 0.04_{HQE} \text{ GeV}^2 \;&;\; \mu_G^2 = 0.27 \pm 0.06_{exp} \pm 0.04_{HQE} \text{ GeV}^3;\\
\rho_D^3 = 0.20 \pm 0.02_{exp} \pm 0.02_{HQE} \text{ GeV}^3 \;&;\; \rho_{LS}^3 = -0.09 \pm 0.04_{exp} \pm 0.07_{HQE} \text{ GeV}^3;
\end{aligned}
$$

$$
m_b - m_c = (3.436 \pm 0.025_{exp} \pm 0.018_{HQE} \pm 0.010_{\alpha_s}) \text{ GeV}/c^2\,.
$$

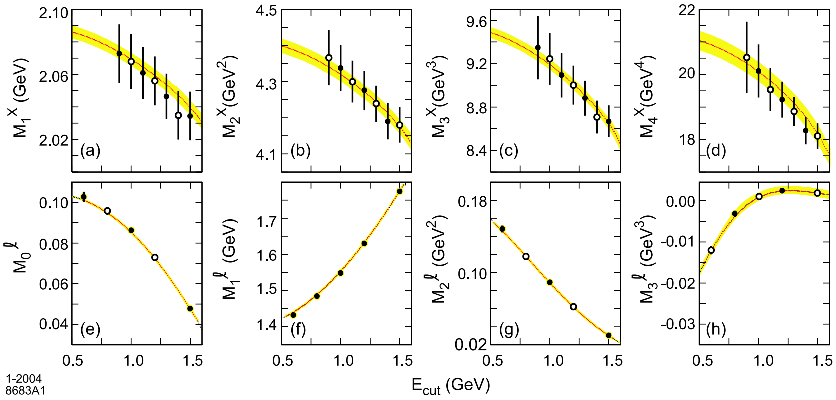

Fig. 1. Inclusive $B \to X_c e\nu$ decays: The measured hadronic-mass (a–d) and electron-energy (e–h) moments as a function of the cut-off lepton energy, E_{cut}, compared with the simultaneous fit result (line). Theoretical uncertainties are indicated as shaded bands. The solid data points show the measurements included in the fit. The vertical bars indicate the experimental errors. Moments for different E_{cut} are highly correlated. The χ^2 of the fit is 15 for 20 dof.

Beyond the statistical, systematic and HQE uncertainties that are included in the fit, the limited knowledge of the expression for the decay rate, including various perturbative corrections and higher-order non-perturbative corrections, introduces an additional error on $|V_{cb}|$, assessed to be 1.5% [3] and included in the stated HQE error. 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 [3], and of $\rho_{LS}^3 = (-0.15 \pm 0.10)$ GeV^3, from heavy-quark sum rules [7].

3. Exclusive $B^0 \to D^{*-}\ell^+\nu$ Decays

The differential decay rate of the decay $B^0 \to D^{*-}\ell^+\nu$ depends on three helicity amplitudes which are commonly expressed in terms of three form factors depending on w, the relativistic boost of the D^* in the B rest frame.

The $B^0 \to D^{*-}\ell^+\nu$ decays are selected using primarily two kinematic variables, the mass difference $\Delta m = M_{D^0\pi^-} - M_{D^0}$ and $\cos\theta_{B-D^*\ell}$, the angle between the momenta of the B and the $D^*\ell$ pair.

For a sample of about 20,000 selected $B^0 \to D^{*-}e^+\nu$ with subsequent $D^{*-} \to D^0\pi^-$, $D^0 \to K^-\pi^+$ decays an unbinned maximum likelihood fit to the observed four-dimensional decay distribution was performed, see Fig. 2. The fit assumes a linear dependence of the form factors on w with a slope ρ^2 and form factor ratios, R_1 and R_2 independent of w.

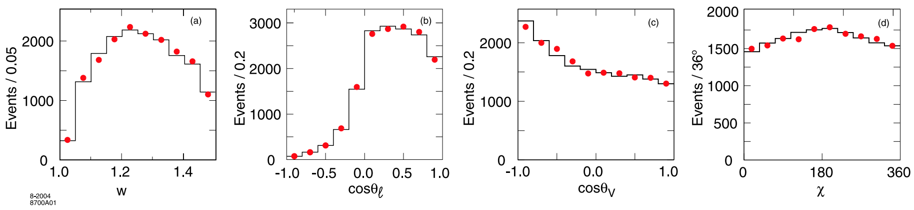

Fig. 2. Exclusive $D^{*+}e^-\nu$ decays: observed one-dimensional differential decay rates for the four variables: w (a); $\cos\theta_\ell$ (b), $\cos\theta_V$ (c), the helicity angles for leptons and hadrons; and χ, the angle between the $D\pi$ and $\ell\nu$ decay planes (d).

The results of the fit [8]

$$R_1 = 1.328 \pm 0.060_{stat} \pm 0.025_{syst} \;;\; R_2 = 0.920 \pm 0.048_{stat} \pm 0.013_{syst}$$
$$\rho^2 = 0.759 \pm 0.043_{stat} \pm 0.032_{syst} \;.$$

represent a significant improvement over previous measurements [9].

To extract $|V_{cb}|$ from exclusive $B^0 \to D^{*-}\ell^+\nu$ decays we integrate over the three decay angles and perform a least-squares fit to the observed w distribution. For this analysis we use 53,700 decays, including electrons and muons and several decay modes of the D^0 meson. We rely on Heavy Quark Effective Theory (HQET) to relate the differential decays rate $\mathrm{d}\Gamma/\mathrm{d}w$ to the product $|V_{cb}| \cdot \mathcal{A}_1$ at $w = 1$. We have adopted the form factor parameterization [10] with $R_1(w) \approx R_1(1) - 0.12(w - 1) + 0.05(w-1)^2$, $R_2(w) \approx R_2(1) + 0.11(w-1) - 0.06(w-1)^2$, $\mathcal{A}_1(w)/\mathcal{A}_1(1) \approx 1 - 8\rho^2_{\mathcal{A}_1} z + (53\rho^2_{\mathcal{A}_1} - 15)z^2 - (231\rho^2_{\mathcal{A}_1} - 91)z^3$, and $z = (\sqrt{w+1} - \sqrt{2})/(\sqrt{w+1} + \sqrt{2})$.

By extrapolation to $w = 1$ we extract [11]

$$\mathcal{A}_1(1)|V_{cb}| = (35.5 \pm 0.3_{stat} \pm 1.6_{syst}) \cdot 10^{-3},\ \rho^2_{\mathcal{A}_1} = 1.29 \pm 0.03_{stat} \pm 0.27_{syst}.$$

Using the lattice calculations [12] of $\mathcal{A}_1(1) = 0.919 \pm 0.035$ we obtain

$$|V_{cb}| = (38.7 \pm 0.3_{stat} \pm 1.7_{syst} \pm^{1.5}_{1.3}\ _{\mathcal{A}1}) \cdot 10^{-3}.$$

Integrating over the fitted w distribution we obtain:

$$\mathcal{B}_{D^{*-}\ell^{+}\nu} = (4.90 \pm 0.07_{stat} \pm 0.36_{syst})\%.$$

The dominant systematic error is due to the uncertainty in R_1 and R_2, for which we have used the earlier measurements by the CLEO Collaboration [9], $R_1(1) = 1.18 \pm 0.32$ and $R_2(1) = 0.71 \pm 0.21$. These values will be replaced in the future by the more precise BABAR results.

4. Conclusions and Outlook

With a significantly larger data sample and recent improvements in the theoretical calculation the BABAR Collaboration has succeeded in reducing the statistical and systematic error in the determination of $|V_{cb}|$. The extraction of $|V_{cb}|$ from exclusive decays still has sizable uncertainties. Currently the errors are dominated by the form factor uncertainties and theoretical estimation of the decay rate at zero recoil. We expect further improvement of experimental and theoretical accuracy in the near future.

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