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$|V_{cb}|$, $|V_{ub}|$, and HQET at CLEO

Karl M. Ecklund[1]

Floyd R. Newman Laboratory for Elementary-Particle Physics, Cornell University, Ithaca, New York, 14853

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Abstract. I report results from the CLEO collaboration on semileptonic B decays, highlighting measurements of the Cabibbo-Kobayashi-Maskawa matrix elements $|V_{cb}|$ and $|V_{ub}|$. I describe the techniques used to obtain the recent improvements in precision for these measurements, including the use of the $b \to s\gamma$ photon spectrum to reduce hadronic uncertainties in semileptonic B decays. I also report new measurements of $|V_{cb}|$ using the inclusive semileptonic branching fraction $\mathcal{B}(B \to Xe\nu)$ and of $|V_{ub}|$ through study of the q^2 dependence of $B \to \pi\ell\nu$ and $B \to \rho\ell\nu$.

PACS. 12.15.Hh Determination of Kobayashi-Maskawa matrix elements – 13.20.He Decays of bottom mesons

1 Introduction

The study of semileptonic B meson decays allows measurement of the Cabibbo-Kobayashi-Maskawa (CKM) matrix elements $|V_{cb}|$ and $|V_{ub}|$, providing important inputs to a test of the unitarity of the CKM matrix, which governs the weak charged current and gives rise to CP violation in the standard model. The rate for a b hadron to decay weakly to hadrons containing a c or u quark is proportional to $|V_{cb}|^2$ or $|V_{ub}|^2$ respectively. The absence of final-state interactions in semileptonic decay make the interpretation less dependent on hadronic matrix elements than fully hadronic B decays, although hadronic uncertainties still limit the precision of $|V_{ub}|$ and $|V_{cb}|$ measurements.

The current round of measurements from CLEO continues to test the hadronic calculations needed to disentangle weak matrix elements from strong interaction effects. For decays of B mesons to exclusive final states, the hadronic effects are expressed in terms of a form factor that depends only on the momentum transfer q^2 to the lepton neutrino pair. By measuring decay rates as a function of q^2 we have begun to test the form factors, particularly for $b \to u\ell\bar{\nu}$ transitions. In decays to inclusive final states, under the assumption of parton-hadron duality, quark-level calculations may be compared to inclusive measurements to extract CKM matrix elements. Measurement of spectral distributions in inclusive decays gives additional observables to overconstrain theory parameters and test how well the theory and parton-hadron duality works.

2 $|V_{cb}|$ Measurements

A measurement of $|V_{cb}|$ is possible using the inclusive semileptonic decay rate. The experimental inputs are the branching fraction for $\bar{B} \to X_c\ell\bar{\nu}$ and the B lifetime. The inclusive decay rate $\Gamma_c^{SL} = \gamma_c|V_{cb}|^2$, where γ_c comes from theory. Within the framework of heavy quark effective theory (HQET) [1], the inclusive semileptonic decay rate is expanded in a double

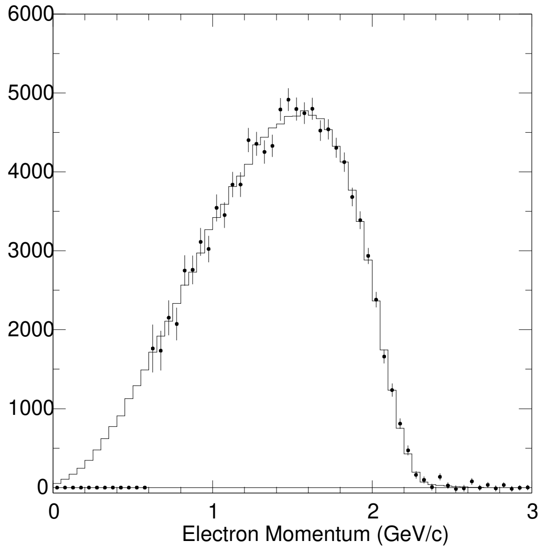

Fig. 1. Unfolded primary $B \to Xe^+\nu$ electron spectrum measured using a high momentum lepton tag. The line shows a fit to exclusive $B \to Xe^+\nu$ decays, used to extrapolate below the cut at 600 MeV/c. (Preliminary)

series in α_s^n and $1/M^n$, where M is the heavy quark mass. Hadronic effects enter both in the perturbative expansion and as expansion parameters, defined to be matrix elements of non-perturbative QCD operators. At $\mathcal{O}(1/M^2)$ there are two parameters: λ_1, which is proportional to the kinetic energy of the b quark in the B meson, and λ_2, which comes from the chromomagnetic operator. An additional parameter $\bar{\Lambda}$ relates the B meson mass to the b quark mass. From the B-B^* mass difference, $\lambda_2 = 0.128 \pm 0.010$ GeV^2. The other parameters can be estimated (*e.g.* in quark models) but they can also be measured using spectral moments in inclusive B decay. Moments, *e.g.* of the lepton energy spectrum, are also computed in HQET, al-

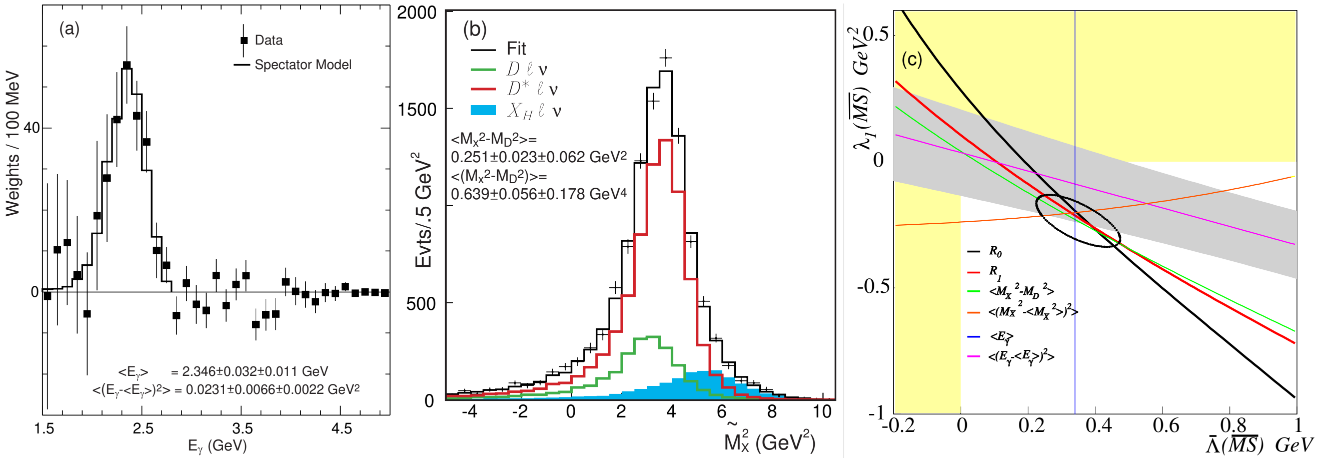

Fig. 2. $B \to X_s\gamma$ photon spectrum (a), $\bar{B} \to X_c\ell\bar{\nu}$ M_X^2 spectrum for $p_\ell > 1.5$ GeV/c (b), and constraints on HQET parameters (c) from CLEO moment measurements. As an illustration of theoretical uncertainties, the shaded band includes $\mathcal{O}(1/M^3)$ uncertainties for $\langle(E_\gamma - \langle E_\gamma\rangle)^2\rangle$.

lowing extraction of λ_1 and $\bar{\Lambda}$ from two or more spectral measurements.

CLEO has a new preliminary measurement of the inclusive semileptonic branching fraction using a high-momentum ($p > 1.5$ GeV/c) lepton tag. The analysis is an update of Ref. [2], where the lepton tag identifies a sample of B decays with high purity (98%). Additional electrons may come from the decay chain of the same B or from the decay of the other B meson in the event ($e^+e^- \to \Upsilon(4S) \to B\bar{B}$). Secondary electrons ($b \to c \to e$) and primary electrons are separated using kinematic and charge correlations, with a known correction from B^0-$\bar{B}^0$ mixing. The new semileptonic branching fraction is $10.88 \pm 0.08 \pm 0.33\%$. The spectrum of electrons above 600 MeV/c is also obtained (Fig. 1), from which spectral moments will be measured.

CLEO has recently measured spectral moments in inclusive semileptonic decay and in $B \to X_s\gamma$. These are used to extract HQET parameters and reduce the theoretical uncertainty in inclusive $|V_{cb}|$ measurements. CLEO measured the $B \to X_s\gamma$ photon spectrum and moments (Fig. 2a) in [3]. In [4], CLEO measured the moments of the hadronic mass distribution in $\bar{B} \to X_c\ell\bar{\nu}$ decays with $p_\ell > 1.5$ GeV/c (Fig. 2b). Combining the constraints on λ_1 and $\bar{\Lambda}$ from the first moments of the photon energy and hadronic mass spectra, we obtain a solution for λ_1 and $\bar{\Lambda}$ and extract $|V_{cb}| = (41.1 \pm 0.5_{\lambda_1,\bar{\Lambda}} \pm 0.7_\Gamma \pm 0.8_{HQET}) \times 10^{-3}$ using the new CLEO branching fraction and PDG2003 lifetime average as inputs. The uncertainties from unknown $\mathcal{O}(1/M^3)$ HQET parameters are dominant.

The lepton energy moments in $\bar{B} \to X_c\ell\bar{\nu}$ are also sensitive to the HQET parameters, and CLEO has measured the lepton spectrum [5] and normalized moments R [6] above 1.5 GeV. From all of the moment measurements, one can assemble the constraints on the HQET parameters λ_1 and $\bar{\Lambda}$. Figure 2c shows the remarkable consistency of these measurements, lending credibility to the inclusive $|V_{cb}|$ measurement.

At present the inclusive $|V_{cb}|$ measurement is more precise (3%) than that from $\bar{B} \to D^*\ell\bar{\nu}$, but with reliance on HQET for hadronic corrections. The first tests of HQET using spectral moments in inclusive B decays give us some confidence in the method, but additional tests with more inclusive moments are needed. This summer BaBar [7] and CLEO [8] presented a new analyses of the hadronic mass spectral moments with lepton energy as low as 0.9 GeV, in good agreement with previous measurements and expectations from HQET within the limits of $\mathcal{O}(1/M^3)$ uncertainties.

The agreement between inclusive and exclusive measurements is another test of our control of hadronic corrections. There is good agreement between inclusive and the world average exclusive $|V_{cb}|$ measurements [9], but the confidence level of the $\bar{B} \to D^*\ell\bar{\nu}$ world average is presently poor [10].

3 $|V_{ub}|$ Measurements

Measurements of $b \to u\ell\bar{\nu}$ have to contend with a 50–100 times larger background from $b \to c\ell\bar{\nu}$. Requiring a lepton energy above the endpoint for $b \to c\ell\bar{\nu}$ (≈ 2.3 GeV) is the easiest strategy to reduce background, but this cut near the edge of the spectrum introduces sensitivity to the motion of b quark in the B meson. The sensitivity is reduced by using the $b \to s\gamma$ photon spectrum [3], which is sensitive to the same hadronic effects at leading order [11–14].

CLEO measured the lepton spectrum from B decays in the endpoint region $E > 2.2$ GeV and extracted a partial branching fraction of $(2.30 \pm 0.15 \pm 0.35) \times 10^{-4}$ [15]. From the $b \to s\gamma$ photon spectrum, the fraction of $b \to u\ell\bar{\nu}$ events passing the lepton energy cut is $f_u = 0.130 \pm 0.024 \pm 0.015$. This gives $|V_{ub}| = (4.08 \pm 0.34_{\rm exp} \pm 0.44_{f_u} \pm 0.16_\Gamma \pm 0.24_{NLO}) \times 10^{-3}$, where the theoretical uncertainties are Γ, from [16,17], and NLO, from sub-leading terms relating hadronic effects in $b \to u\ell\bar{\nu}$ and $b \to s\gamma$.

In a contribution to this conference, CLEO has also measured $|V_{ub}|$ in the exclusive modes $\bar{B} \to [\pi/\rho/\omega/\eta]\ell\bar{\nu}$ [18], where kinematic constraints from the full reconstruction of the final state gives the needed suppression of $b \to c\ell\bar{\nu}$. The neutrino is reconstructed from the missing energy and momentum of the event, taking advantage of CLEO's large solid angle (95%). Combined with a lepton and light meson candidate, energy and momentum conservation leads to signal peaks in $\Delta E = E - E_{\rm beam}$ and the B candidate invariant mass $M_{m\ell\nu}$,

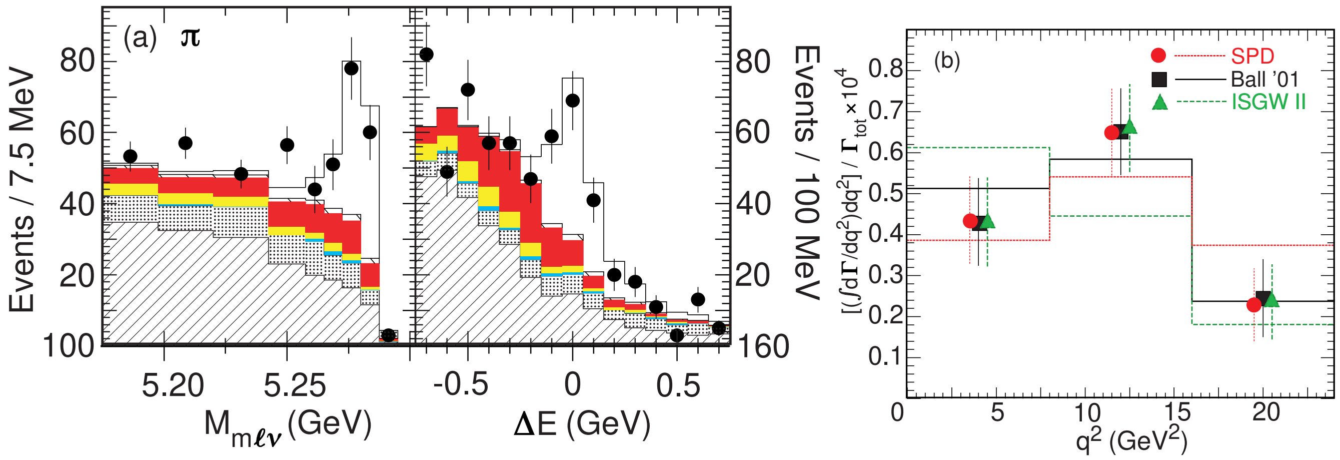

Fig. 3. Exclusive $\bar{B} \to \pi\ell\bar{\nu}$: (a) projections of ML fit to $M_{m\ell\nu}$ and ΔE and (b) fit to $d\Gamma/dq^2$.

with $S/B \approx 1$. We perform a simultaneous maximum likelihood fit in ΔE and $M_{m\ell\nu}$ to seven sub-modes: $\pi^\pm$, π^0, $\rho^\pm$, ρ^0, $\omega/\eta \to \pi^+\pi^-\pi^0$, and $\eta \to \gamma\gamma$. In the fit we use isospin symmetry to constrain the semileptonic widths $\Gamma^{SL}(\pi^\pm) = 2\Gamma^{SL}(\pi^0)$ and $\Gamma^{SL}(\rho^\pm) = 2\Gamma^{SL}(\rho^0) \approx 2\Gamma^{SL}(\omega)$, where the final approximate equality is inspired by constituent quark symmetry. Signals for π (Fig. 3a) and ρ are extracted separately in three q^2 bins. Given form factors from theory, we extract $|V_{ub}|$ from a fit to $d\Gamma/dq^2$ (Fig. 3b). Combining $\bar{B} \to \pi\ell\bar{\nu}$ and $\bar{B} \to \rho\ell\bar{\nu}$ results we find

$$|V_{ub}| = (3.17 \pm 0.17|_{\rm stat}\,{}^{+0.16}_{-0.17}|_{\rm syst}\,{}^{+0.53}_{-0.39}|_{\rm theo} \pm 0.03|_{\rm FF}) \times 10^{-3}.$$

This result uses form factors from Lattice QCD ($q^2 > 16\ \mathrm{GeV}^2$) and light cone sum rules ($q^2 > 16\ \mathrm{GeV}^2$) where each are most reliable. In a test of $\bar{B} \to \pi\ell\bar{\nu}$ form factors, ISGW2 [19] is disfavored (Fig. 3b).

We find good agreement between measurements of $|V_{ub}|$ using inclusive and exclusive techniques. The theoretical uncertainty on the form factor normalization currently limits the precision of the exclusive $|V_{ub}|$ measurement. In the future, unquenched Lattice QCD calculations can improve the $\bar{B} \to \pi\ell\bar{\nu}$ form factor in a limited region of q^2. Inclusive $b \to u\ell\bar{\nu}$ measurements can be further improved with increased $b \to s\gamma$ statistics and better phenomenological understanding of non-perturbative shape functions for the B meson [20–22]. Comparison between inclusive measurements that use kinematic cuts that are less dependent on hadronic effects (more inclusive and away from the endpoint region) will increase our confidence in inclusive $|V_{ub}|$ measurements. Since the principal background comes from $b \to c\ell\bar{\nu}$, better knowledge of the dominant semileptonic B decays will improve systematic errors for both inclusive and exclusive measurements.

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