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Recent CLEO CKM Results[1]

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Abstract. I report B physics results from the CLEO collaboration, highlighting measurements of the Cabibbo-Kobayashi-Maskawa matrix elements $|V_{cb}|$ and $|V_{ub}|$. I report a recent measurement of $|V_{ub}|$ through study of the q^2 dependence of $\bar{B} \to \pi\ell\bar{\nu}$ and $\bar{B} \to \rho\ell\bar{\nu}$. I also describe new measurements of the inclusive semileptonic branching fraction $\mathscr{B}(\bar{B} \to Xe\bar{\nu})$ and of moments of the hadronic invariant mass spectrum in $\bar{B} \to X\ell\bar{\nu}$, with impact on $|V_{cb}|$.

INTRODUCTION

CLEO's recent measurements of the Cabibbo-Kobayashi-Maskawa matrix elements $|V_{ub}|$ and $|V_{cb}|$ are still competitive in the era of B Factory statistics because these measurements are systematically and theoretically limited, and CLEO's well-understood detector and analysis techniques bring added value to the world knowledge of these couplings in semileptonic B decays. Along with $|V_{td}|$ and $|V_{ts}|$ inferred from measurements of B mixing, $|V_{ub}|$ and $|V_{cb}|$ form an important part of the *B CP* puzzle: the sides of the Unitarity Triangle. Combined with measurements of the angles from the *CP*-violating phases, will the Unitarity Triangle hold together or indicate the presence of new physics? Precise measurements of $|V_{ub}|$ and $|V_{cb}|$ are required for this test.

EXCLUSIVE $|\mathbf{V_{ub}}|$ MEASUREMENT

Recently CLEO measured $|V_{ub}|$ in the exclusive modes $\bar{B} \to [\pi/\rho/\omega/\eta]\ell\bar{\nu}$ [1]. The neutrino is reconstructed from the missing energy and momentum of the event, taking advantage of CLEO's large solid angle (95%). Tracks reconstructed from hits in the drift chamber and silicon are combined with neutral showers in the calorimeter to form missing energy and momentum estimates. Considerable effort is made to remove spurious tracks and showers from hadronic interactions, in order to give the best estimate of the neutrino energy and momentum. When the neutrino candidate is combined with a lepton and light meson candidate, energy and momentum conservation leads to signal peaks in $\Delta E = E - E_{\text{beam}}$ and the B candidate invariant mass $M_{m\ell\nu}$, 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. We find clear signals for π and ρ/ω and a 3.2 sigma significance for $\eta\ell\bar{\nu}$. The branching fractions are given in Table 1.

Signals for π (Fig. 1a) and ρ are extracted separately in three q^2 bins. The differential decay rate for $\pi\ell\bar{\nu}$,

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2}{24\pi^3}|V_{ub}|^2 p_\pi^3 \left|f_+(q^2)\right|^2 ,$$

[1] The following article has been submitted to the Proceedings of Beauty 2003. After it is published, it will be found at `http://proceedings.aip.org`.

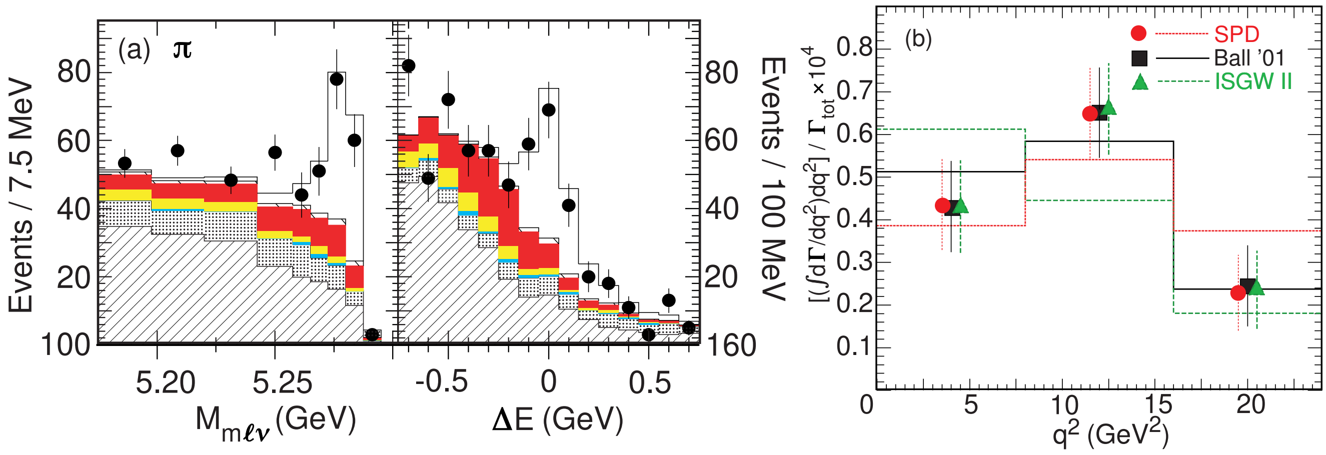

FIGURE 1. Exclusive $B \to \pi \ell \bar{\nu}$: (a) projections of ML fit to $M_{m\ell\nu}$ and ΔE and (b) fit to $d\Gamma/dq^2$.

TABLE 1. Branching fractions for exclusive $b \to u\ell\bar{\nu}$ modes. In order, the errors given are statistical, systematic, due to the π form factor, and due to ρ form factors. For $\eta\ell\bar{\nu}$, the last error is due to the η form factor.

Mode	BF $\times 10^4$
$B^0 \to \pi^- \ell^+ \nu$	$1.33 \pm 0.18 \pm 0.11 \pm 0.01 \pm 0.07$
$B^0 \to \rho^- \ell^+ \nu$	$2.17 \pm 0.34\ ^{+0.47}_{-0.54} \pm 0.01 \pm 0.41$
$B^+ \to \eta \ell^+ \nu$	$0.84 \pm 0.31 \pm 0.10 \pm 0.09$

includes a form factor f_+ which encodes the hadronic physics for the $B \to \pi$ transition. For $\rho\ell\bar{\nu}$, which has a vector meson in the final state, there are two additional form factors. Given form factors from theory, we extract $|V_{ub}|$ from a fit to $d\Gamma/dq^2$ (Fig. 1b). Combining $\bar{B} \to \pi\ell\bar{\nu}$ and $\bar{B} \to \rho\ell\bar{\nu}$ results we find

$$|V_{ub}| = (3.17 \pm 0.17|_{\rm st}\ ^{+0.16}_{-0.17}|_{\rm sy}\ ^{+0.53}_{-0.39}|_{\rm th} \pm 0.03|_{\rm ff}) \times 10^{-3},$$

where the quoted errors are, in order, statistical, experimental systematic, and theoretical from form factor normalization and shape. This result uses form factors from Lattice QCD ($q^2 > 16$ GeV^2) and light cone sum rules ($q^2 > 16$ GeV^2) where each are most reliable. In a test of $\bar{B} \to \pi\ell\bar{\nu}$ form factors, ISGW2 [2] is disfavored (Fig. 1b).

By binning in q^2, this analysis has relaxed the theoretical assumption on the shape of the form factor made in earlier analyses. The theoretical uncertainty on the form factor normalization currently limits the precision of the $|V_{ub}|$ extraction. In the future, unquenched Lattice QCD calculations [3] can improve the $\bar{B} \to \pi\ell\bar{\nu}$ form factor in a limited region of q^2. We find good agreement between measurements of $|V_{ub}|$ using inclusive techniques [4, 5, 6] and other exclusive measurements [7, 8].

INCLUSIVE $|\mathbf{V_{cb}}|$ MEASUREMENT

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) [9], the inclusive semileptonic decay rate is expanded in a double 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.

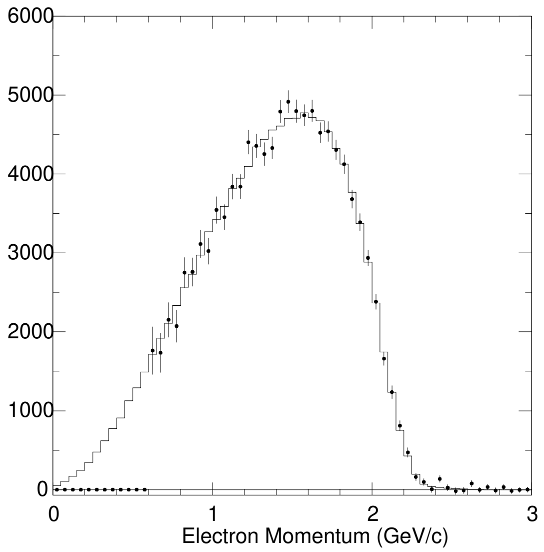

FIGURE 2. Unfolded primary $\bar{B} \to Xe\bar{\nu}$ electron spectrum measured using a high momentum lepton tag. The line shows a fit to exclusive $\bar{B} \to Xe\bar{\nu}$ decays, used to extrapolate below the cut at 600 MeV/c. (Preliminary)

From the B-B^* mass difference, $\lambda_2 = 0.128 \pm 0.010\ \mathrm{GeV}^2$. 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, allowing extraction of λ_1 and $\bar{\Lambda}$ from two or more spectral measurements.

Inclusive Semileptonic Branching Fraction

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. [10], 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 $(10.88 \pm 0.08 \pm 0.33)\%$, in agreement with measurements from LEP and B Factory data [11]. The spectrum of electrons above 600 MeV/c is also obtained (Fig. 2), from which spectral moments will be measured.

Extraction of $|V_{cb}|$ using the Heavy Quark Expansion

Using CLEO's new inclusive branching fraction of $(10.8 \pm 0.3)\%$, subtracting a 1% relative contribution from $b \to u\ell\bar{\nu}$, and the PDG average B^0 and B^+ lifetimes [12], we find the semileptonic decay rate $\Gamma_c^{SL} = (0.44 \pm 0.02) \times 10^{-10}$ MeV. Using the HQET expansion for the decay rate and HQET parameters $\bar{\Lambda}$ and λ_1 from CLEO measurements of the moments of the $B \to X_s\gamma$ photon spectrum [13] and $\bar{B} \to X\ell\bar{\nu}$ hadronic mass spectrum [14], we obtain $|V_{cb}| = 0.0411 \pm 0.0005|_{\bar{\Lambda},\lambda_1} \pm 0.0007|_{\Gamma} \pm 0.0009|_{HQE}$. The overall precision of 3% is limited by theoretical uncertainties from the unknown $\mathcal{O}(1/M^3)$ heavy quark expansion parameters. There is an unquantifiable error from the parton-hadron duality assumption of the inclusive approach.

Spectral Moments as a test of HQE

It is essential to test the heavy quark expansion and the assumption of parton-hadron duality implicit in inclusive determinations of $|V_{cb}|$. Previously CLEO published an analysis of the lepton energy spectral moments in $\bar{B} \to X_c\ell\bar{\nu}$ with a cut at 1.5 GeV [15], showing good agreement with HQET expectations and the hadronic mass and $B \to X_s\gamma$

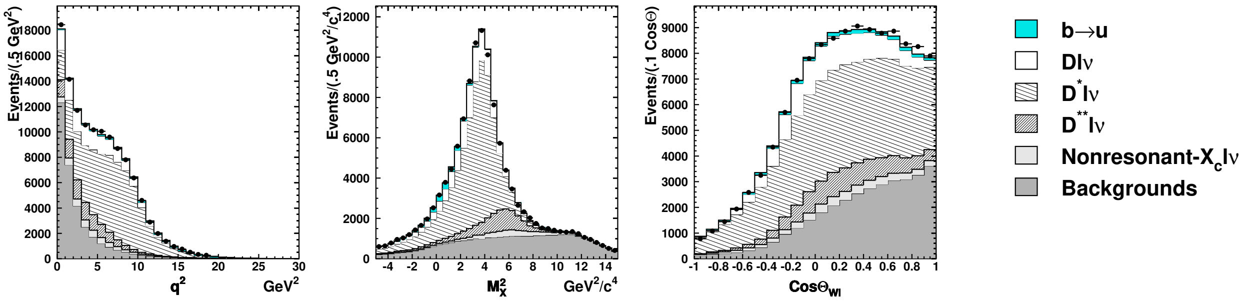

FIGURE 3. Projections of likelihood fit to differential decay rate. For the three independent kinematic variables we have chosen q^2, M_X^2, and $\cos\theta_{W\ell}$, the helicity angle of the virtual W decay.

TABLE 2. Hadronic recoil mass moments versus the lepton energy cut. The errors on the entries in the table are the statistical, detector systematics, and model dependence, respectively.

$E_\ell^{\rm min}$ Cut (GeV)	$\langle M_X^2 - \bar{M}_D^2 \rangle$ (GeV$^2/c^4$)
1.0	$0.456 \pm 0.014 \pm 0.045 \pm 0.109$
1.1	$0.422 \pm 0.014 \pm 0.031 \pm 0.084$
1.2	$0.393 \pm 0.013 \pm 0.027 \pm 0.069$
1.3	$0.364 \pm 0.013 \pm 0.030 \pm 0.054$
1.4	$0.332 \pm 0.012 \pm 0.027 \pm 0.055$
1.5	$0.293 \pm 0.012 \pm 0.033 \pm 0.048$

photon spectrum analyses. At Lepton Photon 2003, CLEO presented new preliminary results from an analysis of the hadronic invariant mass spectrum in $\bar{B} \to X_c \ell \bar{\nu}$ [16].

Like the exclusive $|V_{ub}|$ measurement, we use the neutrino reconstruction technique to estimate the neutrino energy and momentum. Combined with a lepton (electron or muon) candidate with $p > 1.0$ GeV$/c$ we can reconstruct the hadronic invariant mass recoiling against the lepton and neutrino:

$$M_X^2 = M_B^2 + q^2 - 2E_{\rm beam}(E_\ell + E_\nu) + 2|\vec{p}_B||\vec{q}|cos\theta_{Bq},$$

where $q^2(\vec{q})$ is the lepton-neutrino (virtual W) invariant mass squared (momentum). Only the last term in the exact equation for M_X^2 is unknown; fortunately because it is small in the $\Upsilon(4S)$ rest frame, the approximation from neglecting this term is adequate.

We fit the three-dimensional differential decay rate to contributions from $\bar{B} \to D\ell\bar{\nu}$, $\bar{B} \to D^*\ell\bar{\nu}$, $\bar{B} \to D^{**}\ell\bar{\nu}$, $\bar{B} \to X_c\ell\bar{\nu}$, and $\bar{B} \to X_u\ell\bar{\nu}$ (Fig. 3), allowing contributions from fake lepton, $e^+e^- \to q\bar{q}$, and $b \to c \to \ell$ backgrounds, which are estimated using data and Monte Carlo simulation. From the fit results we extract the first and second moments of the hadronic recoil mass. The first moment $\langle M_X^2 - \bar{M}_D^2 \rangle$ is computed as a function of the minimum lepton energy cut $E_\ell^{\rm min}$, varied between 1.0 and 1.5 GeV (Table 2). The first moment is plotted versus the lepton energy cut in Fig. 4, overlayed with results from a similar analysis of *BABAR* [17] and expectations from HQET given the CLEO measurement of $\langle E_\gamma \rangle$ in $B \to X_s\gamma$. The dotted lines show the range of uncertainty from $1/M^3$ terms in the heavy quark expansion.

There is good agreement with theory and between experiments, which use complementary techniques. *BABAR* uses a reconstructed B tag with smaller systematic but larger statistical uncertainty, while without the B tag, CLEO has higher efficiency but larger backgrounds and attendant systematic uncertainties, notably from $e^+e^- \to q\bar{q}$.

CONCLUSION

CLEO's direct contributions to beauty physics are nearing an end, but recent measurements of CKM matrix elements $|V_{cb}|$ and $|V_{ub}|$ are still among the best available. In the future CLEO's contribution to flavor physics and the test of the CKM paradigm for *CP*-violation will come from measurements at charm threshold [18].

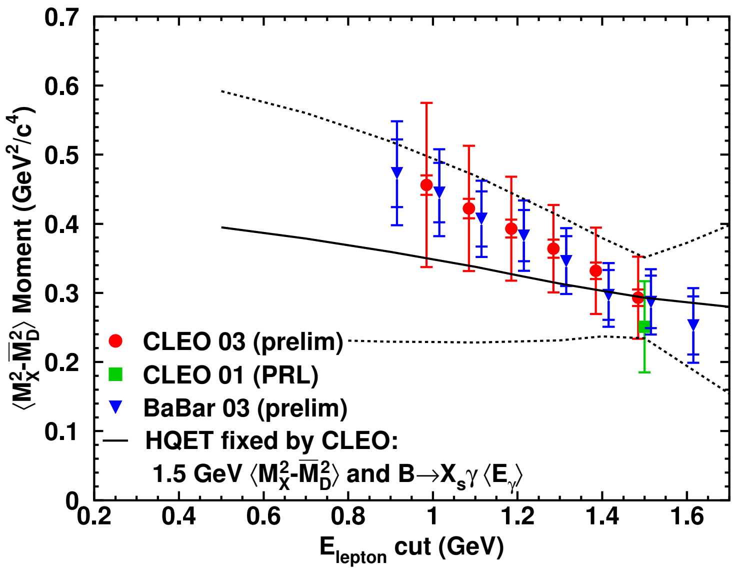

FIGURE 4. Hadronic recoil mass moments versus the lepton energy cut. For both CLEO and *BABAR*, the inner (outer) error bars give the statistical (total) uncertainty. N.B., there is substantial correlation among the points as the lepton energy cut is varied. The CLEO 01 point corresponds to [14].

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