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Measurements of $|V_{ub}|$ and $|V_{cb}|$ from CLEO

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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 $|V_{ub}|$ and $|V_{cb}|$. I describe the techniques used to obtain the recent improvements in precision for these measurements, notably the use of the $b \to s\gamma$ photon spectrum to constrain non-perturbative hadronic effects in semileptonic B decays.

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1 Introduction

Measurements of semileptonic B meson decays are important in determining the Cabibbo-Kobayashi-Maskawa (CKM) matrix [1] elements $|V_{ub}|$ and $|V_{cb}|$, which in turn provide an important constraint on the Unitarity Triangle [2] that graphically represents the unitarity condition arising from the orthogonality relationship between the first and third columns of the CKM quark flavor-changing matrix. The ratio $\frac{|V_{ub}|}{|V_{cb}|}$ constrains the apex of the Unitarity Triangle in the ρ-η plane, where ρ and η are two of the four the Wolfenstein parameters which can represent the free parameters of the CKM matrix [3]. A significantly non-zero value for $|V_{ub}|$ implies a non-degenerate triangle with finite area. Because the area of the triangle is proportional to the amount of CP violation in weak flavor-changing decays, measurements of $|V_{ub}|$ help establish expectations for CP violation in B decays in the Standard Model, and improved measurements can test the consistency of the CKM paradigm for CP violation in the Standard Model. In overconstraining the Unitarity Triangle with measurements of B decays, $|V_{ub}|$ and $|V_{cb}|$ play an important role. As determinations of the height and base, respectively, $|V_{ub}|$ and $|V_{cb}|$ are complementary to measurements of the CKM phases like $\sin 2\beta$, which are interior angles of the unitarity triangle. Both side and angle measurements are needed.

Because semileptonic decays occur via a tree-level process, new physics contributions to the decay rate are insignificant, in contrast to a number of new physics scenarios which may contribute to the B_d^0 mixing phase. Should discrepancies among the constraints on the Unitarity Triangle appear, it will be most useful to have constraints which are insensitive to new physics contributions.

2 $|V_{cb}|$

There are two major approaches to determine the CKM matrix element $|V_{cb}|$. The $b \to c\ell\bar{\nu}$ decay rate is proportional to $|V_{cb}|^2$, so both techniques measure decay rates. In practice non-perturbative strong interaction effects limit the realized precision on $|V_{cb}|$. One approach is to focus on the exclusive decay mode $\bar{B} \to D^*\ell\bar{\nu}$, where heavy quark symmetry relations can be used to calculate the strong interaction form factor that enters the decay rate. A complementary approach takes advantage of a sum rule-like argument, comparing inclusive measurements summed over exclusive hadronic final states to calculations done at the quark level. In the inclusive measurements, there are also non-perturbative QCD corrections, but again these may be controlled by taking advantage of heavy quark symmetry relations. Besides the decay rate, other observables can be used to test our understanding of the QCD corrections. Because the understanding of non-perturbative QCD limits the precision of $|V_{cb}|$ determination, it is crucial to compare results obtained using exclusive and inclusive techniques, which each rely on those corrections but in different ways.

2.1 Exclusive $|V_{cb}|$ Measurement – $\bar{B} \to D^* \ell \bar{\nu}$

In studying the exclusive decay $\bar{B} \to D^* \ell \bar{\nu}$ in the framework of Heavy Quark Effective Theory (HQET) [4], it is useful to consider the kinematic variable $w = v_B \cdot v_{D^*} = \frac{m_B^2 + m_{D^*}^2 - q^2}{2 m_B m_{D^*}}$, which is linearly related to q^2, the mass of the virtual W. Because both the b and c quarks are heavy compared to the scale of QCD interactions, the non-relativistic scalar product of 4-velocities replaces q^2 as the relevant invariant in the limit M_b and $M_c \to \infty$.

The differential decay rate for $\bar{B} \to D^* \ell \bar{\nu}$ is given by

$$\frac{d\Gamma}{dw} = \frac{G_F^2}{48\pi^3} |V_{cb}|^2 [\mathcal{F}(w)]^2 \mathcal{K}(w), \tag{1}$$

where $\mathcal{K}(w)$ is a kinematic function of masses and w that depends only on the $V - A$ nature of the weak transitions, and $\mathcal{F}(w)$ represents the form factor describing the strong dynamics of the $B \to D^*$ transition [5]. HQET provides a normalization for the form factor at $w = 1$, the kinematic point where the c quark does not recoil in the parent B meson rest frame. In the infinite mass limit, the form factor is unity because the light degrees of freedom in the meson still see the same heavy source of color field unmoving in the meson rest frame. Corrections to the heavy quark symmetry limit occur first at order $1/M^2$ [6]; Lattice QCD [7] and QCD sum rules [8] give comparable values of $\mathcal{F}(1)$ at about 0.91 ± 0.04. The shape of the form factor is less determined. The most general Lorentz invariant form factor is simplified by heavy quark symmetry relations and consideration of only the nearly massless leptons e and μ. QCD dispersion relations may be used to constrain the shape [5]. Experimentally one measures the decay rate as a function of w and extrapolates to $w = 1$ to measure $\mathcal{F}(1)|V_{cb}|$.

Using this technique CLEO has recently measured $|V_{cb}|$ using $\bar{B} \to D^{*+} \ell \bar{\nu}$ and $\bar{B} \to D^{0*} \ell \bar{\nu}$ decays in a sample of 3.3×10^6 $B\bar{B}$ events collected in e^+e^- collisions just above threshold at the $\Upsilon(4S)$ [9]. Candidate D^*'s are reconstructed in the decay chains $D^{*+} \to D^0 \pi^+$ and $D^{*0} \to D^0 \pi^0$, and $D^0 \to K^- \pi^+$. Candidates are paired with electron or muon candidates, and the yield of $D^* \ell \bar{\nu}$ events is obtained using a maximum likelihood fit to the $\cos\theta_{B-D^*\ell}$ distribution, which allows kinematic separation of signal and background. The angle between the B and $D^* - \ell$ candidate may be reconstructed kinematically from 4-momentum conservation and the assumption that the missing 4-momentum is consistent with a neutrino:

$$\cos\theta_{B-D^*\ell} = \frac{2E_B E_{D^*\ell} - M_B^2 - M_{D^*\ell}^2}{2|\vec{p}_B||\vec{p}_{D^*\ell}|}. \tag{2}$$

Due to additional missing particles, the physics background $\bar{B} \to D^* X \ell \bar{\nu}$ can populate the unphysical regions in $\cos\theta_{B-D^*\ell}$ while signal events will peak in the interval $(-1, 1)$. In the fit other backgrounds are determined from data (e.g. mass sidebands) and Monte Carlo simulation. We fit in 10 w bins; representative fits are shown in Fig. 1. Given the $D^* \ell \bar{\nu}$ yields in 10 w bins, we extract $\mathcal{F}(1)|V_{cb}|$ and a form-factor slope parameter $\rho^2_{h_{A1}}$ using a χ^2 fit (Fig. 1). The best fit parameters are $\mathcal{F}(1)|V_{cb}| = (43.1 \pm 1.3 \pm 1.8) \times 10^{-3}$ and $\rho^2 = 1.61 \pm 0.09 \pm 0.21$, where the uncertainties are statistical and systematic respectively.

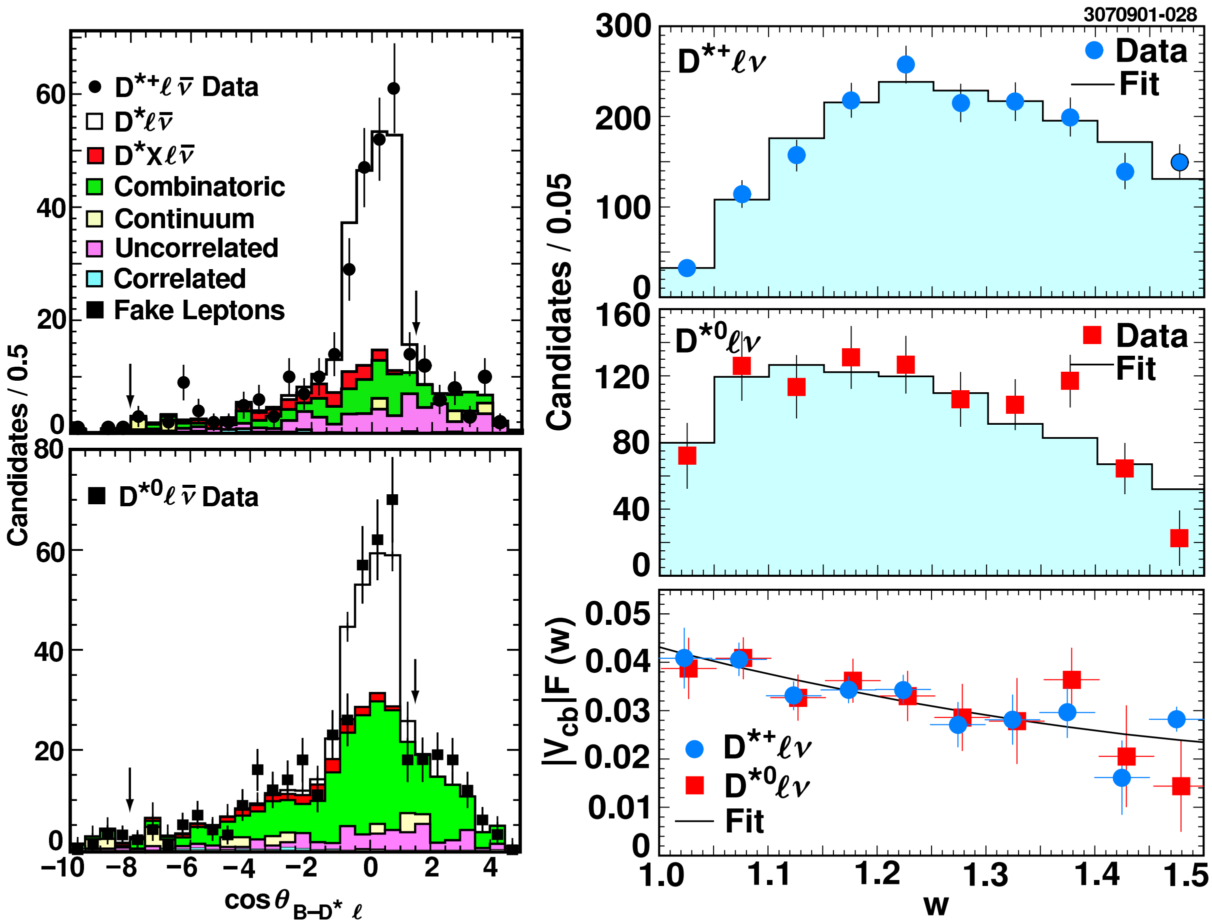

Figure 1: Left: Fits to $\cos\theta_{B-D^{*}\ell}$ for $D^{*+}\ell\bar{\nu}$ and $D^{*0}\ell\bar{\nu}$ for $1.10 \leq w < 1.15$. Right: Fit to observed yields of $D^{*+}\ell\bar{\nu}$ and $D^{*0}\ell\bar{\nu}$ in ten w bins. The points show the data and the lines show the predicted yields for the best fit. On the bottom the fit and efficiency corrected data are displayed as $\mathcal{F}(w)|V_{cb}|$ vs. w.

Using $\mathcal{F}(1) = 0.91 \pm 0.04$ this gives $|V_{cb}| = (47.4 \pm 1.4 \pm 2.0 \pm 2.1) \times 10^{-3}$. This value is somewhat larger than that found by experiments at LEP, and a global fit taking into account correlations between experiments has only a 5% confidence level [10]. CLEO is the only experiment that fits the data simultaneously for the poorly known $\bar{B} \to D^* X \ell \bar{\nu}$ backgrounds, finding a smaller contribution than that used by the LEP experiments. A 2σ fluctuation in this background would account for the difference between LEP and CLEO results.

2.2 Inclusive $|V_{cb}|$ Measurements – $b \to c\ell\bar{\nu}$

The complementary approach to determine $|V_{cb}|$ measures the inclusive semileptonic decay rate, which is proportional to $|V_{cb}|^2$. Again, heavy quark symmetry allows control of strong interaction effects. Within the framework of HQET the non-perturbative effects are handled using an operator product expansion (OPE) in inverse powers of the heavy quark mass M. HQET defines parameters $\bar{\Lambda}, \lambda_1$, and λ_2 that are matrix elements of non-perturbative operators. Observables like the semileptonic decay width and moments of inclusive decay spectra are expressed in terms of these parameters, as well as phase space factors and the coupling $|V_{cb}|$ we wish to determine. The degree to which we can constrain the HQET parameters determines the uncertainty of the $|V_{cb}|$ determination from the measurement of the decay width.

There are simple physical interpretations of the lowest order HQET parameters. One may think of $\bar{\Lambda}$ as the difference between the B meson mass and the b quark mass, expressing the energy of the light degrees of freedom in the meson. The parameters λ_1 and λ_2 enter the expansion at $\mathcal{O}(1/M^2)$ and are the kinetic energy of the b quark in the B meson and the hyperfine interaction of the b spin with the light degrees of freedom, respectively. The latter is determined from the B–B^* mass splitting to be 0.128 ± 0.010 GeV^2.

Recently the CLEO collaboration has measured the moments of the photon energy spectrum in $b \to s\gamma$ [11] and the first and second moments of the inclusive hadronic recoil mass [12] and lepton energy spectrum [13] in semileptonic decays. These spectral measurements can be compared to calculations to limit uncertainties on the HQET parameters, giving increased precision in the inclusive determination of $|V_{cb}|$.

2.2.1 $b \to s\gamma$ photon spectrum

At the parton level, the signal is the decay of a heavy quark to two (nearly) massless daughters. The spectrum is therefore expected to peak at $M_b/2$, with Doppler broadening due to the motion of the b quark in the B meson (easily related to λ_1) and of the B meson in the lab frame. Gluon radiation (or equivalently the production of hadronic states containing an s quark) also broaden the expected narrow peak. The signal is thus distinguished by a high energy (2–2.5 GeV) photon recoiling against a strange hadronic system. In e^+e^- production of B's, there are also substantial backgrounds from continuum production ($e^+e^- \to q\bar{q}$) of π^0's and initial state radiation ($e^+e^- \to q\bar{q}\gamma$).

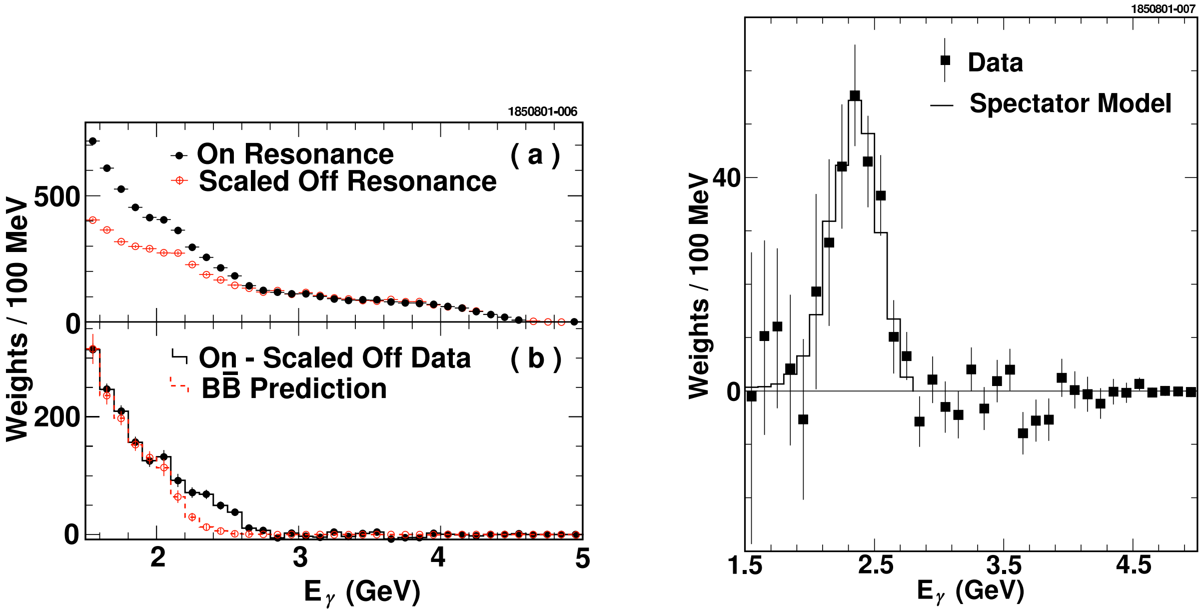

Figure 2: The left figure shows the inclusive photon spectrum (a) at the $\Upsilon(4S)$ and (b) in $B\bar{B}$ events. The background subtracted $b \to s\gamma$ spectrum is shown on the right.

Using a sample of 9.1 fb^{-1} (about 10^6 $B\bar{B}$ events), CLEO measures the inclusive photon spectrum on the $\Upsilon(4S)$ [11]. Large backgrounds from $e^+e^- \to q\bar{q}(\gamma)$ events are suppressed using event shape variables and signatures of B meson decays, either a lepton tag or a reconstructed $B \to X_s\gamma$ final state. The remaining backgrounds from $e^+e^- \to q\bar{q}(\gamma)$ are subtracted using a sizeable sample (4.4 fb^{-1}) of events below $B\bar{B}$ threshold. What remains includes backgrounds from B decays that are not $b \to s\gamma$, substantially from production of high momentum π^0's and η's. Monte Carlo is used to subtract the $B\bar{B}$ backgrounds which escape a π^0 and η veto. The Monte Carlo is normalized to the observed yield of high momentum π^0's and η's in the same data sample.

We obtain the first and second moments of the $b \to s\gamma$ photon spectrum (Fig. 2): $\langle E_\gamma \rangle = 2.346 \pm 0.032 \pm 0.011$ GeV and $\langle (E_\gamma - \langle E_\gamma \rangle)^2 \rangle = 0.0231 \pm 0.0066 \pm 0.0022$ GeV^2, where the uncertainties are statistical and systematic, respectively. From the first moment and the theoretical expression [14] we extract $\bar{\Lambda} = 0.35 \pm 0.08 \pm 0.10$ GeV. Here the uncertainties are experimental and theoretical, with a leading contribution from the variation of the unknown parameters that enter at $\mathcal{O}(1/M^3)$ in the operator produce expansion.

2.2.2 $b \to c\ell\bar{\nu}$ hadronic mass spectrum

The hadronic invariant mass spectrum in inclusive $\bar{B} \to X_c\ell\bar{\nu}$ also gives information about the HQET parameters. CLEO measures the recoil mass spectrum [12] by taking advantage of a hermetic detector (95% of the solid angle) to infer the neutrino 4-vector from missing energy and momentum measurements. The recoil mass is given exactly by $M_X^2 = M_B^2 + M_{\ell\nu}^2 - 2E_B E_{\ell\nu} + 2|p_B||p_{\ell\nu}|\cos\theta_{\ell\nu,B}$, where the last term is

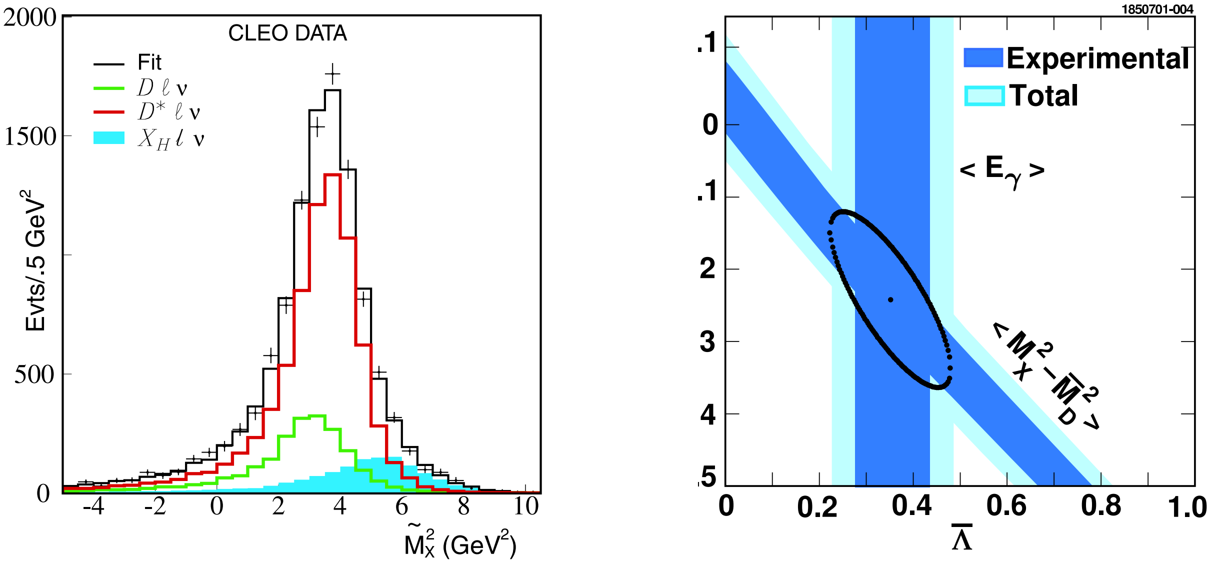

Figure 3: The observed $\widetilde{M_X^2}$ distribution in $\bar{B} \to X_c \ell \bar{\nu}$ (left) and constraints on the HQET parameters λ_1 and $\bar{\Lambda}$ (right) from the first moments of the photon energy in $b \to s\gamma$ and M_X^2 in $\bar{B} \to X_c \ell \bar{\nu}$.

uncalculable when the B direction is unknown and is therefore ignored. We measure $\widetilde{M_X^2} = M_B^2 + M_{\ell\nu}^2 - 2E_B E_{\ell\nu}$ for events with a lepton energy of at least 1.5 GeV. The hadronic invariant mass moments may be measured directly from the moments of the smeared $\widetilde{M_X^2}$ distribution (Fig. 3) after correcting for a small bias measured using a detailed Monte Carlo. Alternatively, consistent values are obtained by fitting $\widetilde{M_X^2}$ to components from $\bar{B} \to D^* \ell \bar{\nu}$, $\bar{B} \to D \ell \bar{\nu}$ and $\bar{B} \to X_H \ell \bar{\nu}$, where X_H represents resonant D^{**} and non-resonant $D^{(*)}\pi$ final states. The moments are insensitive to the composition of the X_H states used in the fit. We find $\langle M_X^2 - \overline{M_D}^2 \rangle = 0.251 \pm 0.023 \pm 0.062$ GeV^2 and $\langle (M_X^2 - \overline{M_D}^2)^2 \rangle = 0.639 \pm 0.056 \pm 0.178$ GeV^4. Here the moments are taken with respect to the spin-averaged $D^{(*)}$ meson mass.

Combined with theoretical expressions for the first hadronic mass moment, the measurement provides the constraint on the HQET parameters $\bar{\Lambda}$ and λ_1 shown in Fig. 3. In combination with the constraint from the first moment of the $b \to s\gamma$ photon spectrum, we determine $\lambda_1 = -0.238 \pm 0.071 \pm 0.078$ GeV^2, where the uncertainties are experimental and theoretical ($1/M^3$). These values for the HQET parameters may be combined with the theoretical expression for the semileptonic decay width and compared to measurements of the width from the $B \to X_c \ell \nu$ branching fraction from CLEO $(10.39 \pm 0.46)\%$ [15] and the B lifetime [16] to determine $|V_{cb}| = (40.4 \pm 0.5 \pm 0.9 \pm 0.8) \times 10^{-3}$. Here the uncertainties are due to $(\lambda_1, \bar{\Lambda})$, the measurement of the semileptonic width, and theory, respectively. This is a 3.2% measurement of $|V_{cb}|$ extracted assuming the validity of parton-hadron duality.

2.2.3 $b \to c\ell\bar{\nu}$ lepton energy spectrum

Finally because two HQET parameters have been extracted using two experimental measurements, it is extremely interesting to add additional constraints to test consistency. CLEO has recently measured moments of the lepton energy spectrum ($E_\ell > 1.5$ GeV) in semileptonic B decays [13]. Again a comparison to theory calculations [17] allows determination of HQET parameters.

CLEO measures the inclusive electron and muon spectra above 1.5 GeV, subtracting backgrounds using data and Monte Carlo. Backgrounds from $e^+e^- \to q\bar{q}$ are subtracted using data below the $\Upsilon(4S)$. Backgrounds from $\psi^{(\prime)} \to \ell\ell$ are vetoed, and Monte Carlo simulation is used to subtract a contribution that fails the veto cuts. Leptons from $b \to c \to \ell$ and $\tau \to \ell$ are also removed using simulation. The subtracted spectrum is corrected for efficiency, detector and final state radiation and the motion of the B in the lab frame. Figure 4 shows the spectrum for electrons and muons. We compute the generalized moments

$$R_0 = \frac{\int_{1.7\ \mathrm{GeV}} \frac{d\Gamma}{dE_\ell} dE_\ell}{\int_{1.5\ \mathrm{GeV}} \frac{d\Gamma}{dE_\ell} dE_\ell} \text{ and } R_1 = \frac{\int_{1.5\ \mathrm{GeV}} E_\ell \frac{d\Gamma}{dE_\ell} dE_\ell}{\int_{1.5\ \mathrm{GeV}} \frac{d\Gamma}{dE_\ell} dE_\ell}, \tag{3}$$

and compare to theoretical calculations to constrain λ_1 and $\bar{\Lambda}$. We find $R_0 = 0.6187(14)(16)$ and $R_1 = 1.7810(07)(09)$ GeV, where the uncertainties are statistical and systematic. The values of the HQET parameters are $\bar{\Lambda} = +0.39 \pm 0.07 \pm 0.12$ and $\lambda_1 = -0.25 \pm 0.05 \pm 0.14$, consistent with those obtained using moments of photon energy in $b \to s\gamma$ and hadronic mass in $b \to c\ell\bar{\nu}$.

Constraints from all CLEO moment measurements are shown in Fig. 4. The central values for all constraints are plotted. They all intersect near a common point with the exception of the second moment of the $b \to s\gamma$ photon spectrum, which is shown with a 1 σ band of the total uncertainty. This degree of agreement gives some confidence in the inclusive technique for determination of $|V_{cb}|$. The theoretical uncertainties due to unknown $\mathcal{O}(1/M^3)$ parameters are large and may potentially limit the precision. In principle, these may be self-consistently extracted from data given additional observables.

2.3 $|V_{cb}|$ Summary and Outlook

Two techniques have been used to measure $|V_{cb}|$ in semileptonic B decays. The exclusive measurement $\bar{B} \to D^*\ell\bar{\nu}$ gives an uncertainty below 7%, with a central value from CLEO which is larger than that obtained in the more precise (3.2%) inclusive measurement of $b \to c\ell\bar{\nu}$. The level of consistency for the CLEO exclusive and inclusive results is only at the 2 σ level. The world average for the exclusive $|V_{cb}|$ measurement is in very good agreement with the inclusive result.

There is room for improvement in future measurements using the large data samples at the B factories. The exclusive measurement relies on extrapolation to $w = 1$. Better experimental knowledge of the $B \to D^*$ form factor will improve that extrapolation. Reliance on HQET for form factor relations can be tested by measuring the form factor

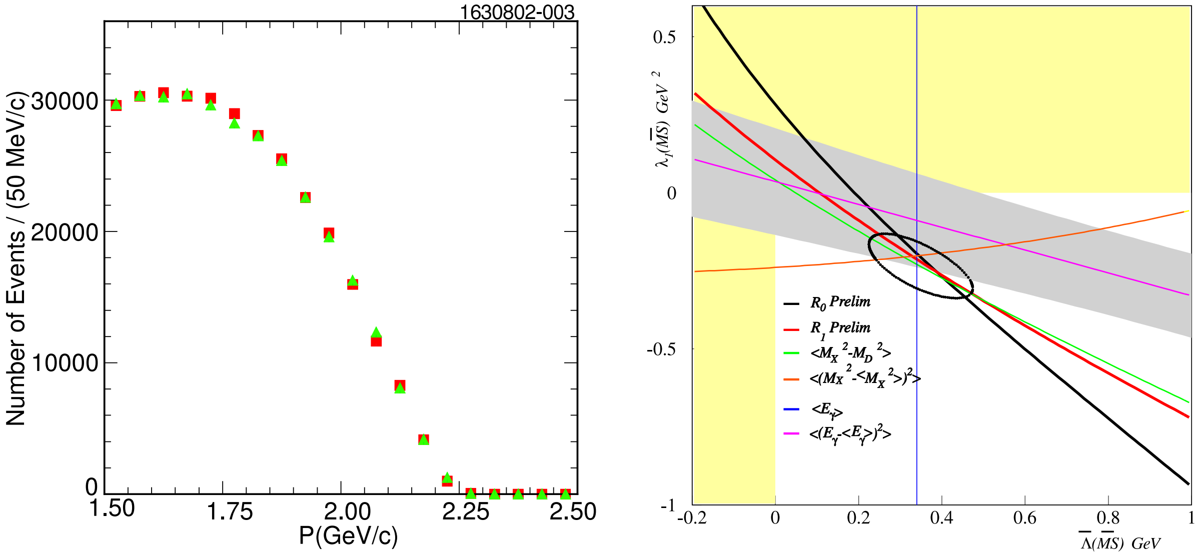

Figure 4: Spectrum for $b \to c\ell\bar{\nu}$ (left) and constraints on HQET parameters from moments of the $b \to s\gamma$ photon spectrum and moments of the $b \to c\ell\bar{\nu}$ hadronic mass and lepton energy spectra (right). The error ellipse comes from combination of only two of the constraints: $\langle E_\gamma \rangle$ from $b \to s\gamma$ and $\langle M_X^2 \rangle$ from $b \to c\ell\bar{\nu}$.

ratios R_1 and R_2 and checking symmetry relations with $\bar{B} \to D\ell\bar{\nu}$. Better understanding of backgrounds from $D^{**}\ell\bar{\nu}$ will hopefully resolve the 5% C.L. in combining LEP and CLEO results. The exclusive measurement is also limited by the theoretical uncertainty in $\mathcal{F}(1)$, which can be reduced in principle by unquenched lattice QCD calculations. The inclusive measurement can be improved with better measurements of the semileptonic width and the HQET parameters λ_1 and $\bar{\Lambda}$; statistical improvements, particularly for $b \to s\gamma$, will be possible at the B factories. The leading uncertainty comes from the $1/M^3$ terms in the OPE. Additional studies of inclusive decay spectra and better phenomenological understanding of the third order parameters will lead to greater confidence in the inclusive extraction of $|V_{cb}|$.

3 $|V_{ub}|$

The main experimental difficulty in the determination of $|V_{ub}|$ is suppression of the hundred-fold larger background from $b \to c\ell\bar{\nu}$. Two general approaches may be used to suppress the background. In one method, full reconstruction of exclusive final states (including the neutrino!) gives suppression. In inclusive techniques one makes kinematic cuts to enhance the $b \to u\ell\bar{\nu}$ signal over the $b \to c\ell\bar{\nu}$ background. A cut on the lepton energy above the endpoint for $b \to c\ell\bar{\nu}$ is a well-known and exploited kinematic cut. In both approaches the limitations from non-perturbative QCD are significant. For exclusive decays the limitation enters as poorly known, difficult- to-estimate form factors. In the inclusive approach the kinematic cuts introduce dependence on the non-perturbative parameters describing motion of the b quark inside the B meson and/or model dependence due to unknown distribution of decays in the kinematic variables. Like $|V_{cb}|$ measurements, because the main obstacles to interpretation are non-perturbative QCD parameters, it is important to use complementary techniques to assess the limits of our understanding.

3.1 Exclusive $|V_{ub}|$ Measurements

By "reconstructing" the neutrino 4-momentum using missing energy and momentum in a hermetic detector, CLEO observed the exclusive decays $\bar{B} \to \pi\ell\bar{\nu}$ and $\bar{B} \to \rho\ell\bar{\nu}$ [18]. The "neutrino reconstruction" technique defines the missing energy $E_{\rm miss} = 2E_{\rm beam} - \sum_i E_i$ and missing momentum $\vec{p}_{\rm miss} = -\sum_i \vec{p}_i$, assuming all daughters of the B decays apart from the neutrino are reconstructed. With the neutrino energy and momentum one reconstructs invariant mass and energy for each candidate; peaks in B candidate mass and $\Delta E = E_{\rm cand} - E_{\rm beam}$ are expected for signal events. CLEO uses isospin symmetry to combine charged and neutral modes in the π and ρ channels. ($\Gamma_{\pi^-} = 2\Gamma_{\pi^0}$ and $\Gamma_{\rho^-} = 2\Gamma_{\rho^0}$) From the observed events the branching fraction is measured: $\mathcal{B}(B^0 \to \pi^-\ell^+\nu) = (1.8 \pm 0.4 \pm 0.3 \pm 0.2) \times 10^{-4}$ and $\mathcal{B}(B^0 \to \rho^-\ell^+\nu) = (2.5 \pm 0.4^{+0.5}_{-0.7} \pm 0.5) \times 10^{-4}$.

A second analysis [19] is sensitive mainly to high momentum leptons ($p_\ell > 2.3$ GeV) and thus measured only $\bar{B} \to \rho\ell\bar{\nu}$, which has the harder lepton spectrum. The result, which is statistically independent from that in 1996, is $\mathcal{B}(B^0 \to \rho^-\ell^+\nu) = (2.69 \pm 0.41^{+0.35}_{-0.40} \pm 0.50) \times 10^{-4}$. In both analyses $|V_{ub}|$ is inferred from the decay rate $\Gamma = \mathcal{B}/\tau = \gamma_u|V_{ub}|^2$. The proportionality constant γ_u depends on kinematic factors and the decay form factors which are taken from Lattice QCD, quark models (e.g. ISGW2), or light cone sum rules. Combining both 1996 and 2000 CLEO results gives $|V_{ub}| = (3.25 \pm 0.14^{+0.21}_{-0.29} \pm 0.55) \times 10^{-3}$, where the uncertainties are statistical, systematic, and theoretical, mainly due to normalization of the form factors and partly due to the form factor shape. Since the time of this conference, CLEO presented preliminary results from an update of the 1996 analysis with increased statistics [20]. In the new analysis we are able to bin in q^2 and reduce the systematic uncertainty from the form factor shape.

3.2 Inclusive $|V_{ub}|$ Measurements

Inclusive measurements of $|V_{ub}|$ achieve the suppression of the $b \to c\ell\bar{\nu}$ background by selecting a region of phase space where the background is suppressed. A simple cut on lepton energy above the $b \to c\ell\bar{\nu}$ endpoint ($E_\ell > 2.3$ GeV) separates signal and background, but with a cost: the fraction of the $b \to u\ell\bar{\nu}$ spectrum measured is only 10%. This is important for two reasons. One would like the measurement to be as inclusive as possible to invoke parton-hadron duality, and one needs to know the efficiency of the cut precisely to extract $|V_{ub}|$ from the partial branching fraction. Other kinematic cuts are sensitive to more of the spectrum ($q^2 > 12$ GeV^2 is about 20% and $M_X < M_D$ is about 70%), but these are more difficult due to experimental resolution. The cut on lepton energy introduces another complication. Because the cut is near the endpoint, the fraction of events passing the cut is sensitive to Doppler broadening due to the motion

Source	Yield
N_{on}	8967
N_{off}	983
$N_{B\bar{B}}$	$6938 \pm 115 \pm 20$
$\bar{B} \to X_c \ell \bar{\nu}$	$4562 \pm 33 \pm 246$
Backgrounds	$474 \pm 22 \pm 67$
$\bar{B} \to X_u \ell \bar{\nu}$	$1901 \pm 122 \pm 256$

Table 1: Yields of leptons $2.2 < E_\ell < 2.6$.

of the b quark in the B meson, or in other words, the non-perturbative strong physics of the hadronic bound state. It was suggested by a number of authors that the $b \to s\gamma$ photon spectrum, which is sensitive to the same non-perturbative physics, can be used to measure this effect [21, 22, 23, 25]. Because the decays both involve heavy to light particle transitions, the same non-perturbative QCD effects smear both spectra, and the light cone shape functions are the same to leading order.

CLEO has recently measured the $b \to s\gamma$ photon spectrum (Sec. 2.2.1) and remeasured the lepton spectrum in B decays above 2.2 GeV [24]. Combined these analyses give a 15% measurement of $|V_{ub}|$. The lepton spectrum is measured above 1.5 GeV, and the region between 1.5 and 2.2 GeV is fit to control the $\bar{B} \to X_c \ell \bar{\nu}$ backgrounds in the 2.2–2.6 GeV signal region. Background from leptons in $e^+e^- \to q\bar{q}$ events (which tend to be more jet-like than $B\bar{B}$ events at threshold) is suppressed using event shape variables, and the remaining background is subtracted using data below the $\Upsilon(4S)$. Other backgrounds (e.g. from $\psi \to \ell\ell$) are subtracted using Monte Carlo. The yields of leptons from various sources are shown in Table 1. The partial branching fraction $\mathcal{B}(\bar{B} \to X_u \ell \bar{\nu}) = (2.30 \pm 0.15 \pm 0.35) \times 10^{-4}$ for $2.2 < E_\ell < 2.6$ is converted to a branching fraction without a lepton energy cut by dividing by the efficiency f_u for the lepton energy cut. The efficiency is determined to be $f_u = 0.130 \pm 0.024 \pm 0.015$ from analysis of the $b \to s\gamma$ photon energy spectrum. Then $|V_{ub}|$ is determined from the theory calculations for the decay rate in terms of $|V_{ub}|$ [26, 27]. We find $|V_{ub}| = (4.08 \pm 0.34 \pm 0.44 \pm 0.16 \pm 0.24) \times 10^{-3}$, where the uncertainties are due to uncertainties on the endpoint rate, the determination of f_u, theoretical uncertainties in the expression for the decay rate in terms of $|V_{ub}|$, and unknown higher order corrections to the shape function that differ between $b \to u\ell\bar{\nu}$ and $b \to s\gamma$.

It is appropriate to make two comments on the theoretical status of the $|V_{ub}|$ measurement from the lepton energy endpoint rate and $b \to s\gamma$ photon spectrum. Since the CLEO publication, there have been a number of theoretical investigations of the effects of sub-leading shape functions on the determination of f_u using the $b \to s\gamma$ photon spectrum [28]. The correspondence between the shape functions for $b \to u\ell\bar{\nu}$ and $b \to s\gamma$ is exact only at leading order in the twist expansion. The effects of higher twist terms were investigated and although they lead to a reduction in the value of f_u obtained from the $b \to s\gamma$ spectrum (and therefore an increase in the extracted $|V_{ub}|$ of order 10%), the resulting uncertainties on $|V_{ub}|$ are safely below the 10% level. A second concern is the

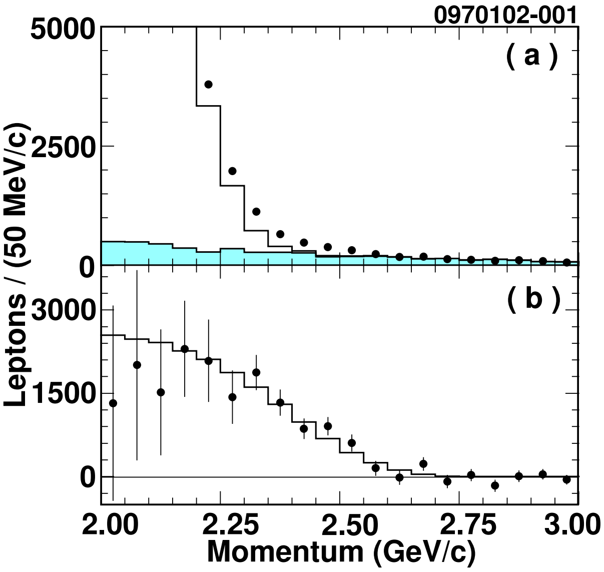

Figure 5: Lepton energy spectra from (a) $\Upsilon(4S)$ data (points), scaled off-resonance data (shaded histogram) and $b \to c\ell\bar{\nu}$ estimate (histogram). The subtracted spectrum is shown below (points) overlayed with expectations from $b \to u\ell\bar{\nu}$ (histogram).

effect of non-factorizable terms that may lead to light flavor-dependent contributions to $\bar{B} \to X_u \ell\bar{\nu}$ [29]. The so-called weak-annihilation term contributes at large q^2 and may have significant impact in the lepton energy endpoint region. The size of the contribution is not known presently, but the difference in endpoint rates or spectra for B^0 and B^+ decays would help clarify things in the future.

3.3 $|V_{ub}|$ Summary and Outlook

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 provide a form factor in a limited region of q^2 and experiments will have the statistics to bin in q^2 to extract the rate in this region. The inclusive $b \to u\ell\bar{\nu}$ measurement can be further improved with increased $b \to s\gamma$ statistics, and better phenomenological understanding of non-perturbative shape functions for the B meson. Comparison between inclusive measurements that use different kinematic cuts (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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