Selected Results on $b \to c\ell\nu$ from CLEO

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Recent results on semileptonic B-meson decays from the CLEO experiment are reported. Data on exclusive decay processes continue to improve, with a new study of $B \to D\ell\nu$ and the first results from updated measurements of $B \to D^*\ell\nu$. Inclusive measurements have entered a new phase, with the focus now being tests of the theory and determination of theoretical parameters used in the extraction of the CKM elements.

1 Introduction and Theoretical Background

Semileptonic processes continue to be one of the most powerful probes of heavy-flavor physics. In recent years studies of semileptonic B decays have focused increasingly on the determination of the CKM parameters V_{cb} and V_{ub}. Initially restricted to inclusive analyses, these measurements have evolved to concentrate on exclusive decays. The reasons for this have been twofold: growing data samples and improved experimental techniques have rendered the exclusive modes accessible, and the development and application of Heavy Quark Effective Theory (HQET) provide what many (not all) theorists believe is a superior route to the CKM couplings through exclusive measurements.

While the CKM measurements have become the principal objective, studies of semileptonic B decays provide excellent opportunities to learn about hadronic physics as well. In fact it is inescapable. To probe the dominant semileptonic decay $b \to c\ell\nu$ at the quark level, for example, we must disentangle that process from the obscuring (but interesting) effects of the strong interaction at the meson level. From the beginning of heavy-flavor studies this disentangling has been facilitated by theoretical *models*, beginning with spectator calculations,[1] and continuing with potential models.[2] In recent years we have begun to move beyond these phenomenological models to the application of QCD *theory*, with the development of HQET and the computational tools of the Operator Product Expansion (OPE).[3] The result is the ability to express a number of the observables of semileptonic B decays in a rigorous and systematic expansion in powers of α_s and Λ_{QCD}/m_Q, where m_Q is the heavy-meson mass.[4,5] The power of the procedure arises from the controlled corrections (none at order $1/m_Q$) and quantitatively estimable errors.

The parameters of the expansion are as follows:

$$\lambda_1 = -\langle B|\bar{b}_v(i\vec{D})^2 b_v|B\rangle, \text{ and} \tag{1}$$

$$\lambda_2 = \frac{1}{3}\langle B|\bar{b}_v\sigma_{\mu\nu}G^{\mu\nu}b_v|B\rangle, \tag{2}$$

where b_v is the heavy quark field and $G^{\mu\nu}$ is the chromomagnetic field operator. Intuitively, λ_1 and λ_2 can be thought of as the negative of the average momentum-squared of the b quark and the energy of the hyperfine interaction of the spin of the b with the light degrees of freedom, respectively. Introduction of a third parameter, $\bar{\Lambda}$, the energy of the light degrees of freedom, makes it possible to eliminate the quark mass m_b in favor of the meson masses m_B and m_B^*:

$$m_B = m_b + \bar{\Lambda} - \frac{\lambda_1}{2m_b} - d_M\frac{\lambda_2}{2m_b}, \tag{3}$$

where $d_P = 3$ and $d_V = -1$ are substituted for the pseudoscalar and vector meson states. The mass difference between the B and B^* mesons thus leads to $\lambda_2 \simeq 0.2$ GeV^2.

Determination of the theoretical parameters λ_1 and $\bar{\Lambda}$ requires detailed measurements of heavy-meson decays. In the absence of such data, their values have been guessed. This is tough, as is reflected by the range of values that have been used in the past: $\lambda_1 \simeq -0.1$ GeV^2 (spectator model), $\lambda_1 \simeq -0.6$ GeV^2 (QCD sum rules) and $\lambda_1 \geq -0.36$ GeV^2 (quantum mechanics), to give a few examples.

There is a clear challenge here for the experimenters. HQET/OPE allows the determination of $|V_{cb}|$ from inclusive semileptonic B decay, given the values of λ_1 and $\bar{\Lambda}$. It allows the determination of $|V_{cb}|$ from exclusive modes like $B \to D^*\ell\nu$, if we have λ_1. Both determinations depend on the validity of the theoretical approach. A program of testing the theory and measuring $\bar{\Lambda}$ and λ_1 is a *high* priority.

2 CLEO Measurements of Exclusive Semileptonic B Decays

Since it was brought into operation in 1989, the CLEO II detector has been used to make a series of increasingly precise measurements of semileptonic B decays. Highlights have included a study of $B \to D^*\ell\nu$,[6] which produced a measurement of $|V_{cb}| = (39.5 \pm 3.6) \times 10^{-3}$, where

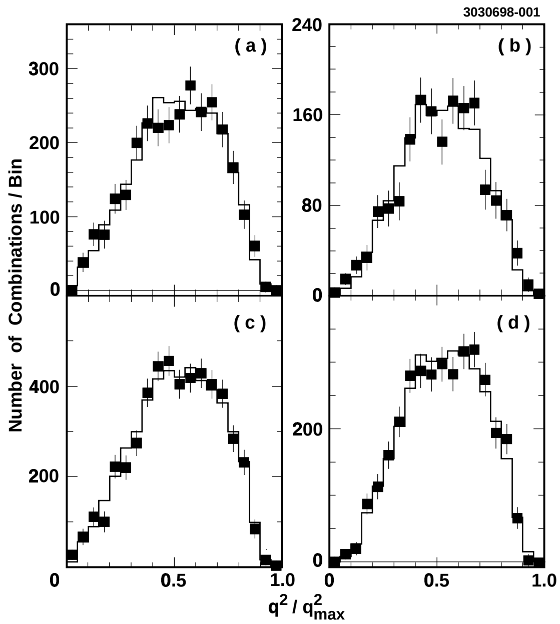

Figure 1: Background-subtracted $\widetilde{q}^2/q^2_{max}$ distributions for data (points with error bars) and the fit results for four different subsets of the CLEO II data sample: electrons (a and c) and muons (b and d), each for two generations of tracking code. Note that $\widetilde{q}^2$ is the estimated q^2 determined from the soft-pion and lepton four-momenta.

the combined statistical and systematic uncertainty is $\pm 9\%$. This effort continues, and an overall precision of $\pm 5\%$ is expected to be achieved with data collected by the end of CLEO II in early 1999. This determination is based on fitting the measured distribution in $d\Gamma/dq^2$ within the framework of HQET. To refine and test the validity of this approach, detailed measurements of $B \to D^*\ell\nu$, in particular of the ratios of the form factors, have been made. [7] These have generally supported HQET, although there is much room for improvement in the precision.

With the continuing growth of the CLEO II data sample, and the development of improved analysis procedures, efforts on $B \to D^*\ell\nu$ have been renewed. A first installment of this work has been presented to this conference, in the form of a new measurement of the q^2 distribution in $\bar{B}^0 = D^{*+}\ell^-\bar{\nu}$ based on the technique of partial reconstruction. [8] This measurement is complementary to and has higher efficiency than a full-reconstruction analysis. A total $B\bar{B}$ sample of 3.3 million events yields $\sim 25,000$ candidates. The resulting distributions are shown in Fig. 1, and the result of a fit constraining the form-factor ratios to CLEO's measurements gives

$$\hat{\rho}^2 = 0.54 \pm 0.05 \pm 0.10 \pm 0.02.$$

While this result is consistent with the world average, it is just barely so. With the completion of the updated analyses it is to be hoped that the picture will become more clear.

Although attention was initially entirely on $B \to D^*\ell\nu$, more recently there has also been work on $B \to D\ell\nu$. [9] The CKM measurement, $|V_{cb}| = (38.5 \pm 5.3) \times 10^{-3}$, is less precise than for the $B \to D^*\ell\nu$ analysis, but this mode represents an important piece of the puzzle and the consistency is encouraging.

CLEO has presented a new preliminary measurement of the exclusive semileptonic B decay to $D\ell\nu$. [10]. This is an independent analysis of the same data sample as was used for the published measurement (3.3 million $B\bar{B}$ events). In contrast with that analysis (full reconstruction with "neutrino detection"), this analysis has higher efficiency, different systematics, and better overall precision.

The approach is to select $D-\ell$ pairs from the decay of the same B meson, a sample that includes the processes $\bar{B} \to D\ell\bar{\nu}$, $\bar{B} \to D^*\ell\bar{\nu}$, $\bar{B} \to D^{**}\ell\bar{\nu}$, and $\bar{B} \to D^{(*)}\pi\ell\bar{\nu}$. Both charged and neutral $\bar{B}$'s are measured. The components are separated with the kinematic variable:

$$cos\theta_{B-D\ell} = \frac{E_B E_{D\ell} - m_B^2 - m_{D\ell}^2}{2|\vec{p_B}||\vec{p_{D\ell}}|} \qquad (4)$$

This quantity has physical values (-1 to 1) for correctly measured $D\ell\bar{\nu}$ signal, and is pushed to smaller values when more than the neutrino is missing. The resulting distributions include backgrounds from several sources: random $K\pi(\pi)$ combinations, $D-\ell$ combinations from different B's, non-signal $D-\ell$ descending from the same B, fake leptons, and continuum. The total background correction is approximately 50% for $D^0\ell$ combinations and approximately 75% for $D^+\ell$. The resulting samples consist of $\sim 3.2K$ $D^0\ell$ and $\sim 2.3K$ $D^+\ell$, and are shown in Fig. 2. These distributions are fitted to determine the contribution from each mode. The parameterizations in the fits are from the ISGW2 model [2] for $\bar{B} \to D\ell\bar{\nu}$ and $\bar{B} \to D^{**}\ell\bar{\nu}$, from calculations using CLEO's measured form factors for $\bar{B} \to D^*\ell\bar{\nu}$, and from the model of Goity and Roberts [11] for the nonresonant decays.

To extract branching fraction, form-factor and CKM information, the differential decay width is measured by fitting in eight bins of w, the standard kinematic variable of HQET,

$$w = \frac{(m_B^2 + m_D^2 - q^2)}{2m_B m_D}. \qquad (5)$$

The differential decay width is given by

$$\frac{d\Gamma}{dw} = \frac{G_F^2|V_{cb}|^2}{48\pi}(m_B + m_D)^2 m_D^3 (w^2-1)^{3/2} F_D(w)^2, \quad (6)$$

where $F_D(w)$ is the form factor. There is a practical complication in this measurement. The actual measured quantity is not w, but rather is an approximation $\widetilde{w}$, which is smeared by B motion and resolution effects. The

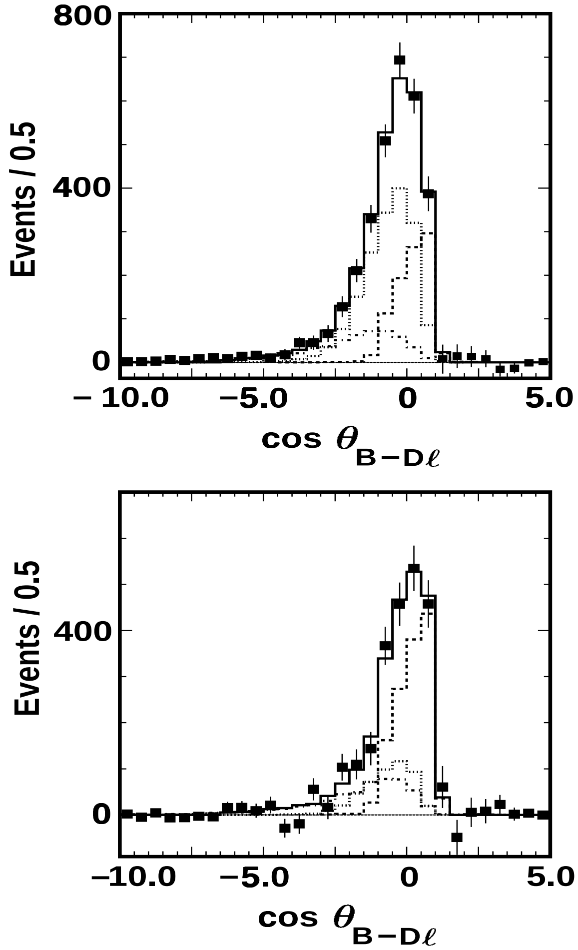

Figure 2: The $cos\theta_{B-D\ell}$ distribution for $B^- \to D^0 X\ell\bar{\nu}$ (top) and $\bar{B^0} \to D^+ X\ell\bar{\nu}$ (bottom). The data (solid squares) are overlaid with simulated $B \to D\ell\bar{\nu}$ decays (short-dashed histogram), $B \to D^*\ell\bar{\nu}$ decays (dotted histogram), $B \to D^{**}\ell\bar{\nu} + D^{(*)}\pi\ell\bar{\nu}$ decays (long dash-dotted histogram), and the total (solid histogram). Normalizations are provided by the fit.

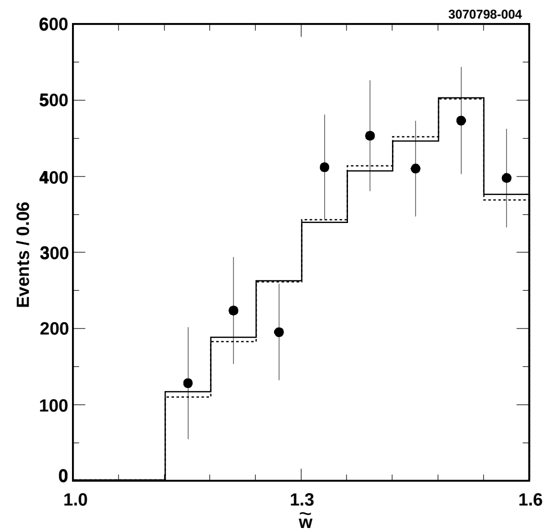

Figure 3: The sum of $B^- \to D^0\ell\bar{\nu}$ and $\bar{B}^0 \to D^+\ell\bar{\nu}$ yields as a function of $\widetilde{w}$, for the data (solid squares), and as computed using three form factors: linear expansion in w (dashed histogram), ISGW2 (dotted histogram) and following Boyd *et al.* (solid histogram).

distribution in $\widetilde{w}$ is shown in Fig. 3. The smearing of w into $\widetilde{w}$ is accounted for in the fitting procedure with a Monte Carlo-determined response matrix. The form factor is parameterized both in the usual way (linear, linear plus quadratic), and by alternative forms constrained by dispersion relations. [12,13] (For details on these see the contributed paper. [10]) The results of the fits are shown in Fig. 3.

There are several sources of systematic error that must be accounted for, including the B mass/momentum scale, the modeling of $D^{**}\ell\nu$ and $D^{(*)}\pi\ell\bar{\nu}$, and the $D^*\ell\nu$ form factors. The branching fractions are extracted by integrating $\frac{d\Gamma}{dw}$ over w and using B-lifetime data to be independent of the charged/neutral production fractions at the $\Upsilon(4S)$. The results are as follows:

$$\mathcal{B}(B^- \to D^0\ell\bar{\nu}) = (2.33 \pm 0.19 \pm 0.19 \pm 0.14)\% \quad (7)$$

$$\mathcal{B}(\bar{B^0} \to D^0\ell\bar{\nu}) = (2.25 \pm 0.18 \pm 0.18 \pm 0.13)\% \quad (8)$$

The uncertainties are statistical, systematic, and that associated with the input B lifetimes and D branching fractions. The values are consistent with previous measurements, and the precision is somewhat improved. A fit assuming a linear form factor gives a slope parameter $\rho^2_D = 0.81 \pm 0.14 \pm 0.09$. The value of $|V_{cb}|$ is also determined from the $\widetilde{w}$ distribution, with additional theoretical uncertainty due to the value of the form factor at $w = 1$. Using $F_D(1) = 1 \pm 0.1$, we find $|V_{cb}| = 0.048 \pm 0.006 \pm 0.003 \pm 0.001 \pm 0.005$, where the first three errors are the same as for the branching fraction, and the fourth is due to the theoretical uncertainty in $F_D(1)$. This result is somewhat larger than the previous measurement from $B \to D\ell\nu$. It is consistent with studies of $B \to D^*\ell\nu$, although with somewhat inferior precision.

3 CLEO Measurements of Inclusive Semileptonic B Decays

For most of the history of B-decay studies the only measurements of semileptonic decays were inclusive measurements. By virtue of enormous statistical power, they are still of great interest. CLEO II data have been used to determine the B semileptonic branching fraction of $(10.5 \pm 0.5)\%$, and the shapes of the primary and secondary lepton spectra, which are shown in Fig.4. [14] More precise measurements of the momentum spectrum and other details of $B \to X_c\ell\nu$ will continue to be a rich

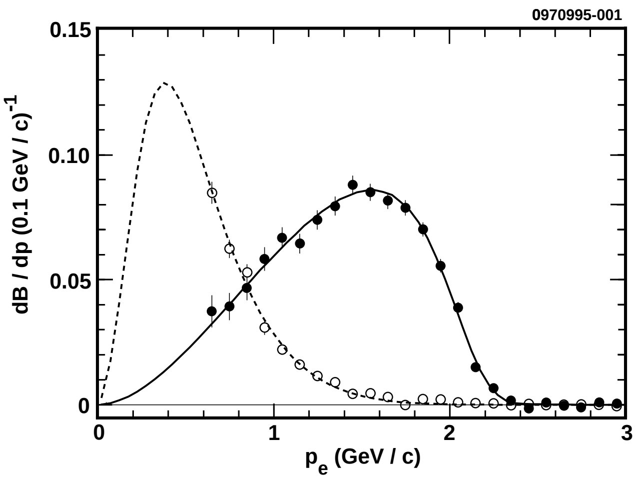

Figure 4: Primary ($B \to X_c e\nu$) and secondary ($B \to D \to Xe\nu$) electron spectra in $B\bar{B}$ events, from CLEO's lepton-tagged analysis.

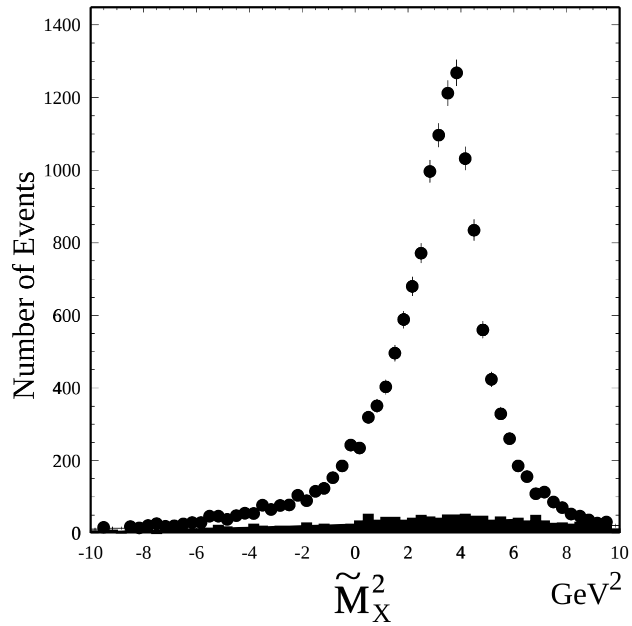

Figure 5: Measured $\widetilde{M_X^2}$ distributions, for on-resonance data (points) and scaled off-resonance data (shaded histogram).

source of information about the dynamics of B decay.

CLEO has presented a preliminary analysis of the moments of both the lepton-energy spectrum and the hadronic recoil mass-squared spectrum in $B \to X_c \ell\nu$.[15] The combination of HQET and the OPE provides quantitative predictions of these moments in terms of the theoretical parameters $\bar{\Lambda}$ and λ_1. By measuring the moments of both distributions, we have an opportunity to determine the values of the QCD parameters while making a consistency check of the theoretical framework. The ultimate goal is improved precision in determining $|V_{cb}|$.

CLEO has measured the first two moments of the recoil mass-squared distribution in semileptonic B decays without explicitly reconstructing the final state hadrons X_c. Like several of our recent measurements of semileptonic decays, this study is based on "detecting" the neutrino with careful determinations of missing momentum and energy. Events are chosen with leptons in the momentum range $1.5 - 2.4$ GeV$/c$. The missing mass is required to be consistent with a single neutrino, and events are restricted to those where this determination is reliable by demanding no extra leptons and a net charge of zero. Finally, events are required to be topologically consistent with $B\bar{B}$ to suppress continuum background. This investigation has been made with the full CLEO II data sample of 3.4 million $B\bar{B}$ events.

The objective is to determine the missing mass squared:

$$M_X^2 = (E_B - E_\ell - E_\nu)^2 - (\vec{p_B} - \vec{p_\ell} - \vec{p_\nu})^2 \qquad (9)$$

$$M_X^2 = M_B^2 + M_{\ell\nu}^2 - 2E_B E_{\ell\nu} + 2|\vec{p_B}||\vec{p_{\ell\nu}}|cos\theta_{\ell\nu,B} \quad (10)$$

Since we do not know the direction of the B momentum we must approximate by dropping the final term in Eq. 10:

$$\widetilde{M_X^2} = M_B^2 + M_{\ell\nu}^2 - 2E_B E_{\ell\nu} \qquad (11)$$

Fig. 5 shows the distributions of $\widetilde{M_X^2}$ for $\Upsilon(4S)$ decays and continuum events. Because of the smearing caused by the neglect of the last term in Eq. 10 and the resolution of the missing momentum and energy determinations, the expected shape of this distribution does not reveal the detailed structure: sharp resonant peaks on a nonresonant background. It nevertheless should yield the overall shape of the spectrum, and allow a precise determination of the moments.

Two methods are used to determine the moments from the background-subtracted $\widetilde{M_X^2}$ distribution. The distribution is fitted directly with Monte Carlo prediction of the contributions of expected $B \to X_c \ell\nu$ processes: $D\ell\nu$, $D^*\ell\nu$ and a mixture of charmed mesons of masses above that of D^* and nonresonant modes. The mixture of these that best fits the distribution is then used to determine the moments. The second procedure is to measure the moments of the raw distribution, and then to use Monte Carlo simulations to correct for experimental bias. In both cases the moments are computed about the square of the spin-averaged D/D^* mass, $\bar{M}_D^2 = (1.975\ GeV)^2$.

Results from the two procedures are quite consistent and have comparable errors. For what follows we use the averages computed with equal weighting: $\langle M_X^2 - \bar{M}_D^2 \rangle = (0.286 \pm 0.023 \pm 0.080)$ GeV^2 and $\langle (M_X^2 - \bar{M}_D^2)^2 \rangle = (0.911 \pm 0.066 \pm 0.309)$ GeV^2.

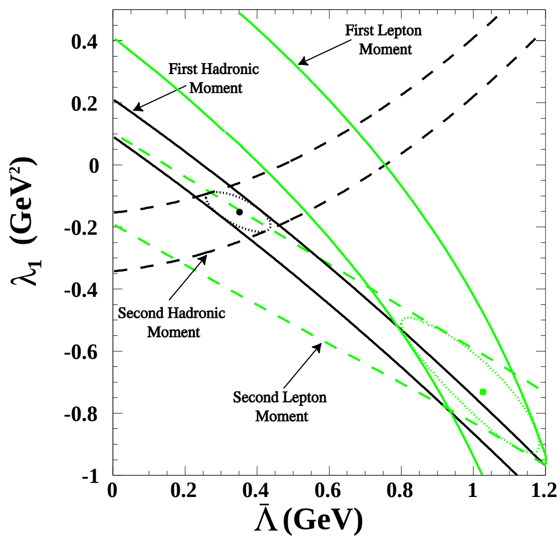

Figure 6: Bands in $\bar{\Lambda}-\lambda_1$ space defined by the measured first and second moments of the hadronic mass-squared and lepton energy. The intersections of the centerlines of the mass-squared and lepton-energy bands are shown as dots. The bands and ellipses represent one-sigma limits.

The HQET parameters are extracted from the moments by fitting to parameterizations due to Falk *et al.* and Gremm *et al.* [4] The resulting constraints on $\bar{\Lambda}$ and λ_1 are shown in Fig. 6. The best solution is given by $\bar{\Lambda}=(0.33\pm0.02\pm0.08)$ GeV and $\lambda_1=-(0.13\pm0.01\pm 0.06)$ GeV^2.

Voloshin [5] and Gremm *et al.* [16] have proposed the determination of $\bar{\Lambda}$ and λ_1 from the moments of the lepton-energy spectrum. Along with the analysis of the hadronic mass-squared moments, CLEO has presented preliminary measurements [15] of the lepton-energy moments, using the previously measured electron spectrum (Fig. 4). [14] This analysis is based on the first two moments, the mean lepton energy $\langle E_\ell\rangle$ and the spread about the mean $\langle (E_\ell-\langle E_\ell\rangle)^2\rangle$.

By necessity the lepton-energy spectrum is measured in the lab frame, with a minimum momentum requirement of 0.6 GeV/c. Corrections must be applied for electromagnetic radiative effects, experimental resolution (including radiation in the material of the detector), the boost from the B rest frame into the lab frame, and charmless decays $b\to u\ell\nu$. In addition, theoretical models must be used to correct for the unmeasured part of the spectrum.

The procedure for computing the true moments of the underlying B-decay spectrum from the data is first to calculate raw moments from the measured momentum spectrum, and then to apply Monte Carlo-determined corrections for each of the effects listed above (radiation, boost, etc.). Each correction is evaluated by calculating the moments for a simulated sample, then turning off the specific effect under study, and taking the changes in the moment values to be the corrections. In the course of this study it was verified that the procedure yields the true moments (which were known, since this was Monte Carlo) to excellent precision.

The results are quite sensitive to the momentum dependence of the detection efficiency and to the details of several physics backgrounds. We consider leptons from charmed mesons D^0, $D^\pm$ and D_s produced in "upper-vertex" processes ($b\to c\bar{c}s$), leptons from charmonium mesons from B decay, leptons from τ's from $B\to X\tau\nu$, semileptonic decays of Λ_c's from B decays, π^0 and η Dalitz decays, γ conversions, fake leptons, and secondary $b\to c\to s\ell\nu$ leptons. There are also small uncertainties in the procedures for correcting the raw moments as described above. Evaluation of systematic errors is not yet complete, and several have been estimated quite conservatively for this preliminary result. Overall, the largest single systematic uncertainty is that due to upper-vertex charm.

The preliminary results for the measured moments are as follows:

$$\langle E_\ell\rangle=(1.36\pm0.01\pm0.02)\ \mathrm{GeV, and} \quad (12)$$

$$\langle (E_\ell-\langle E_\ell\rangle)^2\rangle=(0.19\pm0.004\pm0.005)\ \mathrm{GeV}^2, \quad (13)$$

where all systematic errors have been combined in quadrature.

The constraints on λ_1 and $\bar{\Lambda}$ that are extracted from these moment measurements, following Voloshin, are sumperimposed on the results from the hadronic mass-squared moments in Fig. 6. Note that there is no common intersection among the one-sigma bands for the four inputs, and the disagreement appears to be outside the errors. Possible explanations for the disagreement include experimental error, the need to go beyond order $1/m_Q^2$ in the expansions, or perhaps a more serious problem with the theory.

Given values for $\bar{\Lambda}$ and λ_1, we can determine $|V_{cb}|$ from measurements of the B lifetime and semileptonic decays. If we were to accept the values and precision of the parameters as measured from the hadronic moments, we would find a value of $|V_{cb}|$ consistent with current determinations, and with a theoretical uncertainty of $\sim 2\%$. Substituting the values favored by the lepon moments, on the other hand, would result in a 4.5% (10%) increase in the $|V_{cb}|$ value from the exclusive (inclusive) data. Using the parameter values from the hadronic moments and

Eq. 3 to determine the b-quark mass, we would obtain $m_b = 4.97 \pm 0.10$ GeV where this is the pole mass in $\overline{MS}$ at one loop. Using the results from the lepton moments, the value for m_b would be lower by 0.7 GeV. Clearly we will benefit from further improvements in the precisions of both moments, full analyses of systematic errors, and a definitive test of the consistency of the theory with both the lepton spectrum and the recoil mass-squared distribution.

4 Conclusion

CLEO has continued to make significant progress in the study of exclusive $B \to X_c \ell \nu$. While new results are consistent with previous measurements, the level of consistency is not as stunning as has been the case in the past, and the completion of a new comprehensive analysis of $B \to D^* \ell \nu$ is eagerly anticipated. New directions for studying inclusive semileptonic decays are currently being developed. Preliminary tests of HQET/OPE calculations, and the determination of the parameters of the theory, are not yet conclusive, but seem to suggest that a conflict is brewing.

These studies will continue to be pursued aggressively. CLEO has more than doubled its $B\bar{B}$ data sample compared to the analyses reported here, and running continues with CESR luminosity now above $\sim 6 \times 10^{32}/(cm^2 s)$. Beginning in 1999 the next phase of the project will commence, as CESR Phase III and CLEO III will begin the push toward B-factory luminosity with a significantly upgraded detector.

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