Abstract

Weak decays of heavy flavored hadrons are sensitive probes of several facets of the Standard Model. In particular the experimental study of $B$ meson semileptonic decays is starting to pin down the quark mixing parameters in the Cabibbo Kobayashi Maskawa matrix. In addition, some features of the non–perturbative regime of the strong interaction are probed by these decays. New results from the CLEO experiment at the CESR $e^+e^-$ collider, based on a data sample of up to 3.5 fb$^{-1}$ provide crucial information on both of these aspects of heavy flavor phenomenology.

---

1Talk presented at the 4th International Workshop on B Physics at Hadron Machines
1 Introduction

Weak decays of heavy flavored hadrons are an excellent laboratory to study the Standard Model. In particular B meson decays provide a wealth of information on the quark mixing elements. While the next generation of high luminosity facilities have a good chance to measure CP asymmetries in these decays and perhaps shed some light on the puzzling and fundamental phenomenon of CP violation, good progress in measuring some parameters describing quark mixing has been achieved.

In the framework of the Standard Model the gauge bosons, $W^\pm$, $\gamma$ and $Z^0$ couple to mixtures of the physical $d$, $s$ and $b$ states. This mixing is described by the Cabibbo-Kobayashi-Maskawa (CKM) matrix:

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}. \quad (1)$$

A commonly used approximate parameterization was originally proposed by Wolfenstein [1]. It reflects the hierarchy between the magnitude of matrix elements belonging to different diagonals. The 3 diagonal elements and the 2 elements just above the diagonal are real and positive. It is defined as:

$$V_{CKM} = \begin{pmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}. \quad (2)$$

$B$ decays probe several of these matrix elements. The study of semileptonic decays allows the measurement of $|V_{cb}|$ and $|V_{ub}|$. In addition, the ratio $B(B \to \rho(\omega)\gamma)/B(B \to K^*\gamma)$ is considered a promising avenue to measure the ratio $V_{td}/V_{ts}$ [2].

The Standard Model parameterization of the quark mixing via the CKM matrix element accommodates a complex phase, and therefore offers a natural way to model the intriguing phenomenon of CP violation. So far this violation has been measured only in neutral $K$ decays, and yet it may very well be at the origin of the matter dominated universe that exists now.

The CKM matrix must be unitary and the relation between elements of different rows dictated by this property can be graphically represented as so called ‘unitarity triangles’. Fig. [3] shows the most promising of the triangles:
the angles $\alpha$, $\beta$ and $\gamma$ are all related to the single phase in the CKM matrix element. The study of $B$ decays will eventually allow the measurements of all the three angles. Thus, it will pose a serious challenge to the Standard Model description of CP violation and perhaps shed some light on phenomenology beyond the Standard Model.

The statistical accuracy corresponding to the present data sample accumulated with the CLEO detector, about $3.5 \text{ fb}^{-1}$ for the results presented in this paper, is not yet sufficient to probe CP violation in $B$ decays or to measure rare decays like $B \to \rho\gamma$ accurately, but is adequate to give extremely valuable information on the matrix elements $V_{cb}$ and $V_{ub}$. These data allow us to put better constraints on the fundamental parameters in two major ways. On one hand, the measurements reported in this paper provide new information that reduces the experimental errors on the parameters. On the other hand, the experimental data provide constraints to the theoretical models that are needed to relate measured observables to the fundamental parameters of the Standard Model.

In addition, heavy flavored meson decays are a laboratory to probe the strong interaction in different dynamical domains. $B$ meson decays probe a regime not fully amenable to perturbative QCD calculations, but suitable for the application of effective theories derived from QCD in some asymptotic conditions. In particular, an approach that has generated a lot of interest in the last few years is the so called ‘Heavy Quark Effective Theory’ (HQET) \cite{3}, where the asymptotic behavior corresponds to taking the limit $m_Q \to \infty$. New data shedding some light on the hadronic matrix element will be discussed.

2 The Cabibbo Kobayashi Maskawa Matrix and $B$ meson semileptonic decays

The CKM parameters $|V_{cb}|$ and $|V_{ub}|$ have been studied extensively by the CLEO collaboration through the study of semileptonic decays $B \to X\ell\bar{\nu}$. The experimental study of semileptonic decays has addressed both inclusive measurements, where the recoiling hadronic state is not identified, and exclusive measurements, where the recoiling hadron is reconstructed through one of its decay channels.
Inclusive decays have provided several interesting results. Most notably the study of the end–point of the lepton spectrum, where no charmed hadron final states are kinematically allowed, has provided the first conclusive evidence of a non zero value of $|V_{ub}|$.

Exclusive decays provide complementary information. In particular the semileptonic channel more extensively studied so far is $B \rightarrow D^* \ell \bar{\nu}$. This channel is attractive from an experimental point of view because the slow $\pi$ emitted in the decay $D^* \rightarrow D \pi$ provides a unique signature of this hadronic final state. In addition, a sharpened attention to this decay has been prompted by the suggestion from HQET that its study provides a ‘model independent’ method to determine $|V_{cb}|$. The arguments for this claim will be discussed below.

### 2.1 The CKM element $|V_{cb}|$ and the decay $B \rightarrow D \ell \bar{\nu}$

The decay $B \rightarrow D \ell \bar{\nu}$ is interesting for several reasons. Analyses similar those for the decay $B \rightarrow D^* \ell \bar{\nu}$ provide ways to understand the systematic uncertainty in the extraction of the parameter $|V_{cb}|$.

The hadronic matrix element involved in this decay, the main source of uncertainty in extracting $|V_{cb}|$ from the experimental data, is probed effectively by the differential decay width $d\Gamma/dq^2$:

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2}{24\pi^2} |V_{cb}|^2 \frac{K^3 M_B^2}{M_D^2} f_+(q^2) |\text{.} \tag{3}$$

where $M_B$ and $M_D$ are the $B$ and $D$ meson momenta respectively, $q^2$ is the invariant mass of the lepton-neutrino pair and $K$ is the $D$ momentum in the $B$ rest frame and is given by:

$$K = \frac{M_B}{2} \left\{ \left[ 1 - \frac{M_D^2 - q^2}{M_B^2} \right] - 4 \frac{M_D^2 q^2}{M_B^4} \right\}^{1/2} \tag{4}.$$

$f_+(q^2)$ is the form factor describing the hadronic interaction and must be extracted from theory. Most quark model calculations assume a $q^2$ dependence for the form factor and predict the normalization at a given kinematic point. The normalization factor is calculated either at $q^2 = 0$ or $q^2 = q_{\text{max}}^2$. In general the arbitrariness of the assumed $q^2$ dependence is a reason for some
concern, but in this specific decay the $q^2$ range is not very big and therefore we would not expect a strong model dependence.

CLEO has recently studied the decay $B \to D\ell\bar{\nu}$ with two different techniques [6]. In the first method only the lepton and the $D$ candidates in the final state are found, using the decay $D^+ \to K^-\pi^+\pi^+$. Because the $B\bar{B}$ pairs are produced nearly at rest, the missing mass squared $MM^2$ is calculated as:

$$MM^2 = E^2_\nu - \vec{p}_\nu^2 \approx (E_B - E_D - E_\ell)^2 - (\vec{p}_\ell + \vec{p}_D)^2.$$  

(5)

Here the approximation consists of assuming $\vec{p}_B \approx 0$, relying upon the low magnitude of the $B$ momentum because of the vicinity of the $\Upsilon(4S)$ to the threshold for $B\bar{B}$ meson production. The second approach exploits the hermeticity of the CLEO II detector and infers the $\bar{\nu}$ momentum from a full reconstruction of the semileptonic decay. Stringent cuts need to be applied in this case to ensure that no other sources of missing 4-momentum, like additional $\nu$'s or $K_L$'s, are present in the event.

In the former analysis, the $MM^2$ distribution of candidate events containing a $D^\pm$ and an opposite sign lepton is studied in 6 different $q^2$ bins GeV$^2$/c$^2$, evenly spaced between 0 and 12 GeV$^2$/c$^2$. Fig. 2 shows the $K^-\pi^+\pi^+$ invariant mass for the interval $2 < q^2 < 4$ GeV$^2$/c$^2$.

One of the crucial elements of this analysis is an accurate background estimate. Several sources are subtracted directly, using independent control samples. In particular, a major background is the decay $B \to D^{*+}X\ell\bar{\nu}$, where the $D^{*+}$ decays into the final state $D^+\pi^0$. This component is subtracted by measuring the $MM^2$ distribution for identified $B \to D^{*+}X\ell\bar{\nu}$ decays, rescaled by the ratio in detection and reconstruction efficiency for the two channels. The data sample remaining after direct background subtraction has two components: the signal final state $B^0 \to D^+\ell\bar{\nu}$ and final states of the kind $B \to D^+X\ell\bar{\nu}$, where $X$ is a hadronic final state not coming from the $D^*$ mode discussed above. This last background is subtracted by fitting its contribution with the shape given by a Monte Carlo simulation. The results of the fit in several $q^2$ bins is shown in Fig. 4. Note that in different $q^2$ bins the relative weight of signal and background is quite different. Therefore the study of the $MM^2$ in different $q^2$ regions is quite effective in isolating the signal from this last background contribution.

The second technique reconstructs the $\nu$ four–vector by summing all the charged track and photon momenta in the event. Since the total energy in
the event is equal to the center of mass energy and the total momentum is zero, the \( \nu \) is assumed to have energy equal to the difference between center of mass energy and total reconstructed energy and momentum equal and opposite to the reconstructed momentum. In order to achieve adequate resolution, stringent event selection criteria are applied to avoid smearing due to additional undetected neutral particles or particles outside the detector acceptance. Consistency between the reconstructed energy and momentum is required. Once \( \vec{p}_\nu \) is estimated, the \( B \) meson candidate can be reconstructed with the usual procedure for exclusive hadronic final states, as shown in Fig. 3.

The \( MM^2 \) technique gives a branching fraction of \((1.75 \pm 0.25 \pm 0.20)\%\), the \( \nu \) reconstruction technique gives \((1.89 \pm 0.22 \pm 0.35)\%\) with a combined (preliminary) branching fraction of \((1.78 \pm 0.20 \pm 0.24)\%\). The statistical errors in these two techniques are essentially uncorrelated, while the systematic error is strongly correlated.

The \( q^2 \) distribution for the \( MM^2 \) method is shown in Fig. ?? The intercept at \( q^2 = 0 \) is proportional to \( |V_{cb} f_+(0)| \). The curve is fitted to the functional form:

\[
f_+(q^2) = \frac{f_+(0)}{1 - q^2/M_V^2},
\]

where \( f_+(0) \) is the normalization at \( q^2 = 0 \), and \( M_V \) is the mass of the pole. The quark model calculations predict \( f_+(0) \), and the pole corresponds the vector meson exchanged in the t-channel, in this case the \( B^* \). The data are fitted including both \( f_+(0) \) and \( M_V \) as fit parameters, except in the case of the model developed by Demchuck et al. [7], where the mass of the pole is a definite prediction of the theory. The results and a comparison with different models [8], [9], [7] are given in Table 1. Even if this study considers only a restricted set of models, the limited range of \( q^2 \) spanned by this decay makes the results quite general.

The first errors in the average value of \( |V_{cb}| \) is the quadrature of the statistical and systematic errors in the data and the fact that the fraction of neutral \( B^0 \bar{B}^0 \) final state produced at the \( \Upsilon(4S) \) is known only as \( 0.49 \pm 0.05 \) [10]. The second error is due only to model dependence.

The same data can be used to extract \( |V_{cb}| \) with a different method, inspired by HQET. In this approach the relevant dynamical variable is the
velocity transfer \( w \), related to \( q^2 \) by:

\[
w = \frac{M_B^2 + M_D^2 - q^2}{2M_B M_D}.
\]

The point \( w = 1 \) corresponds to the situation where the \( B \) decays to a \( D \) at rest in the \( B \) frame. Fig. 5 shows the experimental data for \( |\mathcal{F}(w)V_{cb}| \). In particular it can be seen that it is difficult to ascertain the curvature of the Isgur-Wise universal function because of the low statistics at the points close to \( w = 1 \) and thus the uncertainty in the extraction of \( |V_{cb}| \) must reflect this additional uncertainty [10]. The fit to these data gives \( \mathcal{F}(1) = (3.46 \pm 0.42 \pm 0.46) \times 10^{-2} \).

In addition to the measurement discussed in this paper, the parameter \( |V_{cb}| \) has been studied experimentally with several different methods. Many groups have reported their findings for the branching fraction \( \mathcal{B}(B \to D^*\ell\bar{\nu}) \) [11] and related their measurement to several different theoretical models to extract their estimate of \( |V_{cb}| \). In addition this decay can be studied with the HQET method discussed above [3]. This approach has a special interest from the point of view of HQET theorists because Luke’s theorem [12] states that for \( w = 1 \), the mass dependent corrections vanish to first order and therefore the first non–zero term occurs with power \( 1/m_Q^2 \). This implies that for a well behaved perturbative expansion, these corrections should play a minor role and thus allow an extraction of \( |V_{cb}| \) prone to smaller theoretical uncertainty. Lastly, the inclusive semileptonic decay can be related to \( |V_{cb}| \) [10]. The average values of \( |V_{cb}| \) obtained with these techniques are shown in Fig. 6. The average value \( |V_{cb}| = 0.0381 \pm 0.0021 \), corresponding to the value for the \( CKM \) parameter \( A = 0.784 \pm 0.043 \), has been obtained by adding statistical and systematic errors in the various estimates linearly and then adding the different methods in quadrature. This procedure is by no means rigorous but it should give a conservative estimate of the final errors.

2.2 The CKM parameter \(|V_{ub}|\) and charmless semileptonic decays

The first evidence of a non-zero \( |V_{ub}| \) was obtained by CLEO I [4], by studying inclusive semileptonic decays. They reported an excess of leptons beyond the kinematic endpoint for the decay \( B \to D\ell\bar{\nu} \). This result was quickly
confirmed by ARGUS [14] and then studied in more detail and with better statistical accuracy by CLEO II [15]. There are two crucial issues that make the extraction of $|V_{ub}|$ from experimental data trickier than the extraction of $|V_{cb}|$. First of all, in this case we have the possibility of light hadronic systems recoiling against the lepton–$\bar{\nu}$ pair. Therefore the $q^2$ domain spanned by these decays is much bigger and the assumed $q^2$ dependence of the form factors strongly affects the predicted rate $\gamma_u$ and fraction of high momentum leptons $f_u(p)$. In addition, there is some uncertainty on the composition of the hadronic system recoiling against the lepton-$\bar{\nu}$ pair.

Consequently models that focus on a few exclusive hadronic final states are not likely to give reliable predictions for $\gamma_u$, as it is quite unlikely that the whole Dalitz plot is dominated by the low lying resonances. On the contrary, ‘inclusive’ models, like the one proposed by Altarelli et al. (ACCMM) [16], based upon a quark-hadron duality picture, become more relevant when several final states are involved. The importance of the theoretical uncertainty in the extraction of this parameter is illustrated by the fact that the CLEO II estimate of $|V_{ub}/V_{cb}|$ changed by a factor of two depending upon the model used [15]. The theoretical uncertainty in the extraction of this parameter is closely related to the $q^2$ dependence of the form factors, as shown by Artuso [17], by comparing the ACCMM and ISGW [18] predictions for the $q^2$ distributions. Recently N. Isgur and D. Scora have revised the ISGW model, aiming at making it more realistic at high $q^2$ and using some constraints on the form factors derived from HQET. This model, referred to as ISGW II [19], is now much closer to ACCMM in several respects. In particular, Fig. 7 shows the the predicted $q^2$ distribution of events with leptons in the momentum range of 2.4 to 2.6 GeV/c (the interval adopted in the CLEO II analysis leading to the most precise value of $|V_{ub}|$ available so far). It can be seen that the $q^2$ distribution predicted by ISGW II is much softer than the one expected by ISGW.

It is obvious that in order to reduce the errors on the estimate of the parameter $|V_{ub}|$ it is necessary to enlarge the set of experimental observables. In particular the study of exclusive channels is the necessary first step to check in more detail different theoretical predictions. CLEO has recently measured the branching fractions for exclusive charmless semileptonic decays involving a $\pi$, $\rho$ or $\omega$ meson in the final state [20]. Both charged and neutral $B$ decays have been studied. The experimental technique adopted relies again upon the $\bar{\nu}$ energy and momentum estimates from the rest of the event. The $\bar{\nu}$
The invariant mass squared is calculated from the reconstructed $E_{\text{miss}}$ and $\vec{p}_{\text{miss}}$ as $M_{\text{miss}}^2 = E_{\text{miss}}^2 - \vec{p}_{\text{miss}}^2$ and the selection criterion $M_{\text{miss}}^2/2E_{\text{miss}} < 300\text{ MeV}$ is subsequently applied. This approach allows to reconstruct these decays with the techniques developed to study exclusive $B$ meson decays. Fig. 8 shows the beam constrained invariant mass $M_{\text{cand}}$, evaluated as:

$$M_{\text{cand}}^2 = E_{\text{beam}}^2 - (\vec{p}_\nu + \vec{p}_l + \vec{p}(\pi \text{ or } \rho))^2.$$  \hspace{1cm} (8)

In the study of hadronic final states involving $\pi\pi$ in the final system it is often difficult to prove that this system is indeed prevalently $\rho$. CLEO addresses this question by plotting the $\pi^0\pi^0$ summed mass spectrum, as shown in Fig. 9. They also show the $\pi^0\pi^0$ case, which cannot be $\rho$. In the latter case they see a flat background, while the former distribution show some peaking at the expected nominal resonance mass. On the other hand the $3\pi$ spectrum show little evidence of resonant $\omega$. There is clearly the need for more statistics, but this analysis is performed under the assumption that the resonant component is dominant.

The five modes $B^- \rightarrow \pi^0\ell\bar{\nu}$, $B^- \rightarrow \rho^0\ell\bar{\nu}$, $B^- \rightarrow \omega^0\ell\bar{\nu}$, $\bar{B}^0 \rightarrow \pi^+\ell\bar{\nu}$, $\bar{B}^0 \rightarrow \rho^+\ell\bar{\nu}$ are fitted simultaneously, using the constraints following from isospin:

$$\Gamma(\bar{B}^0 \rightarrow \pi^+\ell\bar{\nu}) = \Gamma(B^- \rightarrow \pi^0\ell\bar{\nu}),$$ \hspace{1cm} (9)

$$\Gamma(\bar{B}^0 \rightarrow \rho^+\ell\bar{\nu}) = 2\Gamma(B^- \rightarrow \rho^0\ell\bar{\nu}) = 2\Gamma(B^- \rightarrow \omega^0\ell\bar{\nu}).$$ \hspace{1cm} (10)

The analysis yields the branching fractions $B(\bar{B}^0 \rightarrow \pi^+\ell\bar{\nu}) = (1.8 \pm 0.4 \pm 0.3 \pm 0.2) \times 10^{-4}$ and $B(\bar{B}^0 \rightarrow \rho^+\ell\bar{\nu}) = (2.5 \pm 0.4^{+0.5}_{-0.7} \pm 0.5) \times 10^{-4}$. The ratio between the partial widths to vector and pseudoscalar final state is interesting because it provides a useful consistency check of the soundness of the assumptions adopted by different phenomenological models. Table 2 shows a comparison between the theoretical ratio $\Gamma(B \rightarrow \rho\ell\bar{\nu})/\Gamma(B \rightarrow \pi\ell\bar{\nu})$ predicted by a variety of quark model calculations [19], [9], [8], [13] and the corresponding measured values, using the same model to estimate the efficiency corrections. It can be seen that for some models there is a quite significant discrepancy between the predicted and measured value. In particular the Korner and Schuler (KS) model has only a 0.5% likelihood to be consistent with the data.

Fig. 10 summarizes our present knowledge of the parameter $|V_{ub}/V_{cb}|$, both from the exclusive and inclusive analyses. For the inclusive analysis results from CLEO I [4] and ARGUS [14] have been included in the average.
The KS model has been excluded from the average as their prediction of the pseudoscalar to vector ratio is inconsistent with the data. In addition, the ISGW model has been replaced by the updated ISGW II model. The spread in the $|V_{ub}/V_{cb}|$ estimates related to model dependence is now narrowed compared to previous analyses. It should be noted that the models adopted are now much more similar in their estimate of the $q^2$ dependence of the form factors used and an experimental confirmation of the correctness of this predicted dependence is eagerly awaited. Furthermore, new approaches, based either on QCD sum rule techniques \cite{21}, \cite{22} or on lattice QCD \cite{23} provide new theoretical perspectives on these decay. Nonetheless at the present time the model dependence still dominates the errors. A conservative estimate gives:

$$\frac{|V_{ub}|}{|V_{cb}|} = 0.080 \pm 0.015, \quad (11)$$

which corresponds to the constraint:

$$\rho^2 + \eta^2 = (0.36 \pm 0.07)^2. \quad (12)$$

Fig. 11 shows the constraints to the unitarity triangle deriving from the values of $|V_{cb}|$ and $|V_{ub}|$ reported in this paper together with the constraints coming from $B^0\bar{B}^0$ mixing and $CP$ violation in the $K^0\bar{K}^0$ system ($\epsilon$) \cite{24}. The width of the $\epsilon$ band is mostly affected by the uncertainties in the Wolfenstein parameter $A$, the top quark mass $m_t$, the charm quark mass $m_c$ and the correction factor for the vacuum insertion approximation $f_K$. The width of the $B^0\bar{B}^0$ mixing band is dominated by the uncertainty on the $B$ meson decay constant $f_B$ here taken to be in the range $240\, MeV > f_B > 160\, MeV$.

### 3 Factorization test with the decay $\bar{B}^0 \rightarrow D^+ \ell \bar{\nu}$

The role of factorization in theoretical predictions on exclusive hadronic decays is multifaceted and has indeed been debated at length. In the early theoretical studies of hadronic heavy flavor decays \cite{25}, factorization was used as an \textit{ansatz}, by assuming that in energetic two body decays direct formation of hadrons by a quark current is a useful approximation and that the two currents ‘factorize’, i.e. the Hamiltonian can be expressed as a product of two currents, one which couples a meson in the final state with the decaying
one and the other which produces the second meson out of the vacuum \[25\], \[26\]. For instance, \(B \rightarrow D\pi\) could be expressed as:

\[
< D^+\pi^- | O | B^0 > = \frac{G_F}{\sqrt{2}} V_{ub} V_{cd}^* c_1 < \bar{u}_L \gamma^\mu d_L | 0 > < D^+ | \bar{b}_L \gamma_\mu c_L | B >
\]

(13)

There is no good reason why factorization should hold in all two-body hadronic \(B\) decays. However, some arguments based on color transparency, originally proposed by Bjorken \[27\], and later by Dugan and Grinstein \[28\], make it plausible that decays involving one heavy and one light meson in the final state factorize. This is because the time scale of interaction between two mesons in the final state is too short to allow appreciable gluon exchange between them. Dugan and Grinstein base their arguments on perturbative QCD. The soundness of their approach has been questioned by Aglietti \[29\]. Therefore, precise experimental tests of factorization in hadronic \(B\) decays is quite valuable to disentangle this very complex issue.

A factorization test proposed by Bjorken is based on the observation that if Eq. 13 is valid, then we can relate the amplitude \(< D^+ | \bar{b}_L \gamma_\mu c_L | B >\) to the corresponding matrix element in semileptonic \(B\) decays. This implies:

\[
\frac{\mathcal{B}(\bar{B}^0 \rightarrow D^+h^-)}{d\mathcal{B}/dq^2(\bar{B}^0 \rightarrow D^+\ell\bar{\nu})|_{q^2=m_{h^-}^2}} = 6\pi^2 c_1^2 f_{h^-}^2 |V_{ud}|^2
\]

(14)

here \(c_1\) is a calculable short distance QCD correction and \(f_{h^-}\) is the light meson decay constant.

We can use the measured differential decay width \(d\mathcal{B}/dq^2\) reported in this paper with the exclusive branching fractions for \(\bar{B}^0 \rightarrow D^+\pi^-\) and \(\bar{B}^0 \rightarrow D^+\rho^-\) \[30\] and use the known \(f_\pi\) and \(f_\rho\) to extract an experimental estimate of the parameter \(c_1\). The experimental data can be compared with QCD calculations to assess the applicability of factorization to these hadronic decays. The results of this comparison are shown in Table 3. It can be seen that the agreement is quite satisfactory.

4 Conclusions

\(B\) decays continue to provide a wealth of information on the Standard Model. In particular, the detailed study of \(B\) meson semileptonic decays has given
new insights on the quark mixing parameters and on properties of the strong interactions when heavy quarks are involved in the decay. More detailed studies are forthcoming with the increased luminosity planned for the CLEO upgrade and, later, with the $e^+e^-$ $B$ factories and dedicated $B$ experiments at hadron machines. Therefore most of the uncertainties related to model dependence will be disentangled and the Standard Model will have to withstand one of its more substantial challenges.

5 Acknowledgements

The author would like to acknowledge the contribution of CLEO and CESR scientists and technical staff to obtain the data presented in this paper. Many thanks are due to C. Sachrajda, G. Martinelli and N. Uraltsev for inspiring discussion during the Beauty ’96 conference. F. Ferroni deserves gratitude for the impeccable organization and the unforgettable visit to the Hadrian Villa and P. Schlein for his indefatigable work towards this conference series. Lastly Sheldon Stone should be thanked for his insightful comments and Julia Stone should be thanked for nice breaks provided to my evening writing.

References

[1] L. Wolfenstein Phys. Rev. Lett. 51, 1945 (1983).

[2] A. Ali, in $B$ Decays, 2nd edition revised, ed. S. Stone, World Scientific, Singapore (1994).

[3] N. Isgur and M. B. Wise, “Heavy Quark Symmetry,” in $B$ Decays, 2nd edition revised, ed. S. Stone, World Scientific, Singapore (1994); N. Isgur and M. B. Wise, Phys. Rev. D42 2388 (1990); N. Isgur and M. B. Wise, Phys. Lett. B232, 113 (1989); ibidem B237, 527 (1990); M. B. Voloshin and M. A. Shifman, Sov. J. Nucl.Phys. 45, 292 (1987); ibidem 47, 511 (1988); H. D. Politzer and M. B. Wise, Phys. Lett. 206B, 681 (1988) 681; ibidem B208, 504 (1988); E. Eichten and B. Hill, Phys. Lett. B234, 511 (1990); H. Georgi, Phys. Lett. 240B, 447 (1990); B. Grinstein, Nucl. Phys. B339, 253 (1990); A. F. Falk, H. Georgi, B. Grinstein and M. B. Wise, Nucl. Phys. B343, 1 (1990).
[4] R. Fulton et al., (CLEO) Phys. Rev. Lett. 64, 16 (1990).

[5] M. Neubert, Phys. Lett. B264, 455 (1991).

[6] T. Bergfeld et al., (CLEO) CLEO-CONF 96-3, ICHEP-96 PA05-78 (1996).

[7] N. B. Demchuk, I. L. Grach, I. M. Narodetski, S. Simula, “Heavy-to-heavy and heavy-to-light weak decay form factors in the light-front approach: the exclusive $0^-$ to $0^-$ case,” INFN-ISS 95/18, hep-ph/9601369 (1996).

[8] J. G. Korner and G. A. Schuler Z. Phys. C38, 511 (1988); ibid, (erratum) C41 690 (1989).

[9] M. Wirbel, B. Stech and M. Bauer Z. Phys. C29, 637 (1985); M. Bauer and M. Wirbel, Z. Phys. C42, 671 (1989).

[10] S.L. Stone, in B Decays, 2nd edition revised, ed. S. Stone, World Scientific, Singapore (1994).

[11] B. Barish et al., (CLEO) Phys. Rev. D51, 1014 (1995); D. Bortoletto et al., (CLEO) Phys. Rev. Lett. 16, 1667 (1989); H. Albrecht et al., (ARGUS) Z. Phys. C57, 533 (1993); D. Buskulic et al., (ALEPH) Phys. Lett. B359, 236 (1995); P. Abreu et al., (DELPHI) CERN-PPE/96-11 (1996).

[12] M. E. Luke, Phys. Lett. B252, 447 (1990).

[13] D. Melikhov, Phys. Lett. B380, 363 (1996).

[14] H. Albrecht, et al., Phys. Lett. B234, 409 (1990).

[15] J. Bartelt et al., Phys. Rev. Lett. 71, 4111 (1993).

[16] G. Altarelli, N. Cabibbo, G. Corbo and L. Maiani Nuclear Phys. B207, 365 (1982).

[17] M. Artuso, Phys. Lett. B311, 307 (1993).

[18] N. Isgur, D. Scora, B. Grinstein, and M. B. Wise, Phys. Rev. D39, 799 (1989).
[19] Daryl Scora and Nathan Isgur, *Phys.Rev.* D52, 2783 (1995).

[20] J.P. Alexander *et al.*, (CLEO) Cornell Preprint CLNS 96–1419 (1996).

[21] I. Bigi, M. Shifman, N. Uraltsev, A. Vainshtein, *Phys.Lett.* B328, 431 (1994).

[22] P. Ball, *Phys.Rev.* D48, 3190 (1993).

[23] C. Sachrajda, these proceedings and references therein.

[24] S. Stone, “Prospect for B-physics in the next decade”, to be published in the proceedings of the NATO Advanced Study Institute on Techniques and Concepts in High-energy Physics, 9th, St. Croix, U.S. Virgin Is., 1996.

[25] M. Bauer, B. Stech and M. Wirbel *Z. Phys.* C34, 103 (1987).

[26] A. De Andrea *et al.*, *Phys. Lett.* B318, (549) 1993.

[27] J. Bjorken, *Nucl. Phys.* B (Proc. Suppl.) 11, 325 (1989).

[28] M. Dugan and B. Grinstein, *Phys. Lett.* B255, 583 (1991).

[29] U. Aglietti, *Phys. Lett.* B292, 424 (1992).

[30] T. Browder and K. Honscheid, in *B Decays*, 2nd edition revised, ed. S. Stone, World Scientific, Singapore (1994); and references therein.
| Model          | $f_+(0)$ prediction | $|V_{cb}f_+(0)| \times 10^4$ | $|V_{cb}| \times 10^4$ |
|---------------|---------------------|-----------------------------|--------------------------|
| WSB           | 0.70                | 25.7 ± 1.4 ± 1.7            | 37.3 ± 2.0 ± 2.5         |
| KS            | 0.69                | 25.7 ± 1.4 ± 1.7            | 36.7 ± 2.0 ± 2.5         |
| Demchuk et al.| 0.68                | 24.8 ± 1.1 ± 1.6            | 36.4 ± 1.6 ± 2.4         |

Table 1: Results of $\bar{B}^o \to D^+\ell^-\bar{\nu}$ analysis.

| Model       | $\mathcal{B}(B \to \pi\ell\nu)$ $\times 10^4$ | $\mathcal{B}(B \to \rho\ell\nu)$ $\times 10^4$ | $\Gamma(\rho)/\Gamma(\pi)$ predicted | $\Gamma(\rho)/\Gamma(\pi)$ predicted |
|-------------|-----------------------------------------------|-----------------------------------------------|---------------------------------------|---------------------------------------|
| ISGW II     | 2.0 ± 0.5 ± 0.3                              | 2.2 ± 0.4$^{+0.4}_{-0.6}$                      | 1.1$^{+0.3+0.2}_{-0.3-0.3}$            | 1.47                                 |
| WSB         | 1.8 ± 0.5 ± 0.3                              | 2.8 ± 0.5$^{+0.5}_{-0.8}$                      | 1.6$^{+0.7+0.3}_{-0.5-0.4}$            | 3.51                                 |
| KS          | 1.9 ± 0.5 ± 0.3                              | 1.9 ± 0.3$^{+0.4}_{-0.5}$                      | 1.0$^{+0.5+0.2}_{-0.3-0.3}$            | 4.55                                 |
| Melikhov†   | 1.8 ± 0.4 ± 0.3 ± 0.2                        | 2.8 ± 0.5$^{+0.5}_{-0.8}$ ± 0.4                | 1.6$^{+0.7+0.3}_{-0.5-0.4}$ ± 0.11     | 1.53±0.15                           |

† The 3rd error arises from uncertainties in the estimated form-factors.

Table 2: Results from exclusive semileptonic $b \to u$ transitions

| $h^-$ | $f_h$(MeV) | $d\mathcal{B}/dq^2$ | $\mathcal{B}(\bar{B}^o \to D^+h^-)$ | $c_1^2$(exp) | $c_1^2$(th) |
|-------|-----------|----------------------|---------------------------------------|--------------|-------------|
| $\pi^-$ | 131.7 ± 0.2 | 0.35 ± 0.04 ± 0.04 | 0.29 ± 0.04 ± 0.03 | 0.85 ± 0.20 | 1.06-1.32  |
| $\rho^-$ | 215.0 ± 4.0 | 0.33 ± 0.04 ± 0.04 | 0.81 ± 0.11 ± 0.12 | 0.94 ± 0.24 | 1.06-1.32  |

Table 3: Results of factorization tests.
Figure 1: The CKM triangle shown in the $\rho - \eta$ plane. The left side is determined by $|V_{ub}/V_{cb}|$ and the right side can be determined using mixing in the neutral $B$ system. The angles can be found by making measurements of CP violation in $B$ decays.
Figure 2: Invariant $K^-\pi^+\pi^+$ mass spectra from CLEO for events with an opposite sign lepton in the interval $4 > q^2 > 2$ and for different $MM^2$ slices.
Figure 3: Beam constrained mass spectrum for $\bar{B}^0 \rightarrow D^+ \ell \bar{\nu}$ with the $\bar{\nu}$ reconstruction analysis. The white area represents the signal events, the hatched area represents the combinatoric background, the crosshatched area represents the $D^{*+} \ell^- \bar{\nu}$ and the shaded area represents all the remaining backgrounds.
Figure 4: The $q^2$ distribution for $\bar{B}^0 \to D^+ \ell \bar{\nu}$ from the $MM^2$ analysis.
Figure 5: Measured values of $|\mathcal{F}(\bar{w})V_{cb}|$, $\mathcal{F}(\bar{w})$, where $\bar{w}$ represents the measured Lorentz invariant $w$. The results from the $\nu$ reconstruction analysis are shown as solid dots and the missing mass analysis ones as asterisks. The combined results are shown as the solid line. Note that the curve shown is not a fit to the data. The dashed line denotes as measured in $B \to D^*\ell\nu$ decays.
Figure 6: Results of four different methods used to evaluate $|V_{cb}|$, and the resulting average. The horizontal lines show the values, the statistical errors out to the thin vertical lines, and the systematic errors added on linearly out to the thick vertical lines.
Figure 7: $q^2$ distribution, for charmless semileptonic $B$ decays in the model of Altarelli et al. (ACCMM) and the original ISGW model shown on top, and the new ISGW II model shown on the bottom. The areas reflect the predicted widths, but the vertical scale is arbitrary. The high $q^2$ tails on the ISGW and ISGW II models arise from the $\pi\ell\nu$ final state.
Figure 8: The $B$ candidate mass distributions, $M_{\text{cand}}$, for the sum of the scalar $\pi^+\ell\nu$ and $\pi^0\ell\nu$ (top) and the vector modes ($\rho$ and $\omega$)$\ell\bar{\nu}$ (bottom). The points represent the data after continuum and fake background subtractions. The unshaded histogram is the signal, while the dark shaded shows the $b \rightarrow cX$ background estimate, the cross-hatched show the estimated $b \rightarrow u\ell\nu$ feed–down. For the $\pi$ (vector) modes, the light-shaded and hatched histograms are $\pi \rightarrow \pi$ (vector$\rightarrow$vector) and vector$\rightarrow \pi$ ($\pi \rightarrow$vector) cross–feeds, respectively. The inserts show the lepton momentum spectra for the events in the $B$ mass peak (the arrows indicate the momentum cuts).
Figure 9: Mass distributions for $\pi^+\pi^-$ plus $\pi^+\pi^0$ (left), $3\pi$ (upper right) and $\pi^0\pi^0$ (lower right), for events which are candidates $B \rightarrow X\ell\bar{\nu}$ decays which satisfy all the other $B$ candidate cuts including a cut on the $B$ mass. The shading is the same as on the previous figure. The arrows indicate the mass range used in the analysis.
Figure 10: Values of $|V_{ub}/V_{cb}|$ obtained from the exclusive $\pi \ell \nu$ and $\rho \ell \nu$ analyses combined, taking $|V_{cb}| = 0.0381$, and results from the inclusive endpoint analysis. The best estimate combining all models except KS is also given.
Figure 11: The regions in $\rho-\eta$ space (shaded) consistent with measurements of CP violation in $K^0_L$ decay ($\epsilon$), $|V_{ub}/V_{cb}|$ in semileptonic $B$ decay, $B^0_d$ mixing, and the excluded region from limits on $B^0_S$ mixing. The allowed region is defined by the overlap of the 3 permitted areas, and is where the apex of the CKM triangle sits.