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SEMILEPTONIC B DECAYS AT THE B FACTORIES

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Recent results on inclusive and exclusive semileptonic B decays from B Factories are presented. The status and perspectives of the determination of the CKM matrix elements V_{ub} and V_{cb} with semileptonic B decays is discussed.

1 Introduction

Semileptonic B decays provide direct access to the CKM matrix elements V_{ub} and V_{cb}, whose ratio gives a measurement of the side of the Unitarity Triangle opposite the angle β.

The underlying theory of semileptonic B decays is at an advanced stage. The weak currents factorize in leptonic and hadronic parts which do not interact between each other. Moreover, the b quark mass is considerably larger than the scale Λ_{QCD} of hadronic physics. Therefore, a systematic expansion in Λ_{QCD}/m_b and α_s can be performed, contributions from perturbative and non-perturbative physics can be separated, and measurements of semileptonic B decays enable precise determinations of V_{cb} and V_{ub}.

Semileptonic B decays also probe the structure of B mesons, in analogy with neutrino deep inelastic scattering. Inclusive decays are sensitive to quantities such as the mass and momentum distribution of the b quark inside the B meson, whereas exclusive decays measure form factors for specific final states. As a consequence, dominant theoretical uncertainties which enter in the determination of V_{ub} and V_{cb} can be experimentally assessed and minimized.

Due to large data sets, B Factories are now performing precision measurements on high purity samples, such as events where one B from the $\Upsilon(4S)$ decay is fully or partially reconstructed, and the semileptonic decay of the other B is studied. As a consequence, partial rates

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for $\overline{B} \rightarrow X_u \ell \bar{\nu}$ transitions can be measured in regions of the phase space, previously considered inaccessible, where theoretical uncertainties are reduced.

A comprehensive review of V_{cb} and V_{ub} measurements is beyond the scope of this paper. In the following, after discussing the general framework of each measurement technique, we will present and discuss only the most recent determinations of V_{cb} and V_{ub} with inclusive (Sections 2 and 3) and exclusive (Sections 4 and 5) semileptonic B decays. The current status and outlook are summarized in Section 6.

2 Inclusive Semileptonic Decays with Charm

The rate for $\overline{B} \rightarrow X_c \ell \bar{\nu}$ decays is related to the free quark rate by Operator Product Expansion (OPE) techniques[1]. The resulting *Heavy Quarks Expansion* is double in powers of α_s and $1/m_b$, and can be written schematically as[2]

$$\Gamma_{sl} = \frac{G_F m_b^5}{192\pi^3} |V_{cb}|^2 (1 + A_{EW}) A_{pert}(\alpha_s) A_{non-pert}(1/m_b, 1/m_c, a_i) \tag{1}$$

where A_{EW} and A_{pert} represent electroweak and QCD perturbative corrections respectively. The non-perturbative QCD part $A_{non-pert}$ is expanded in terms of the heavy quark masses (m_b, m_c), with a_i as coefficients. The latter are matrix elements of operators, such as the kinetic energy and the chromomagnetic moment, which describe in principle universal properties of B mesons. In practice, the a_i parameters depend on the renormalization scale, on the chosen renormalization scheme, and their number is a function of the order of the $1/m_b$ expansion; four of them appear at order m_b^{-3}.

The Heavy Quark Expansion also predicts the moments of observables in $\overline{B} \rightarrow X_c \ell \bar{\nu}$ decays such as the lepton energy E_ℓ and the invariant mass of the hadronic final state m_X, in regions of phase space, as a function of the a_i parameters, m_b, m_c, and V_{cb}. Therefore, experimental determinations of these moments in different portions of the phase space allow a simultaneous measurement of the heavy quark parameters and masses, as well as V_{cb}. Such studies have been performed at the B Factories[3,4,5], CDF[6] and Delphi[7]. The resulting moments of the energy spectrum (0th-3rd) and of the squared hadronic mass spectrum (0th-2nd) have comparable statistical and systematic uncertainties.

Radiative $b \rightarrow s\gamma$ decays can also be used to determine the heavy quark parameters, since the energy spectrum of the photon, monoenergetic at the parton level, is smeared at the hadron level, by an amount which depends on the structure of the B meson. The same techniques used in semileptonic decays can be applied in this case as well. Moments can be computed and compared to experimental determinations[8,9,10,11]. The main limitation of these measurements is due to background subtraction, which is dominant at low ($E_\gamma < 1.9$GeV) energies.

The experimental determinations of the $b \rightarrow l\nu$ and $b \rightarrow s\gamma$ moments can be combined, by using the kinetic mass scheme, in a global fit to heavy quark parameters[12], which gives uncertainties of about 2% on $|V_{cb}|$, 1% on m_b and 10% on μ_π^2, the matrix element of the kinetic energy operator:

$$|V_{cb}| = (41.96 \pm 0.23 \pm 0.35 \pm 0.59) \cdot 10^{-3}$$
$$m_b = (4.59 \pm 0.04) GeV \qquad \mu_\pi^2 = (0.40 \pm 0.04) GeV^2 \qquad \rho = -0.26 \tag{2}$$

Since m_b and μ_π^2 contribute the dominant systematic uncertainty in the inclusive determination of V_{ub}, their precise measurement is crucial.

3 Inclusive Charmless Semileptonic Decays

In principle, $|V_{ub}|$ is related to the rate of inclusive charmless semileptonic decays by an expression equivalent to Eq. 1, which contains matrix elements of operators related to the ones entering in the $\overline{B} \to X_c \ell \bar{\nu}$ decay. If the full $\overline{B} \to X_u \ell \bar{\nu}$ decay rate were experimentally accessible, the resulting theory uncertainty would be of the order of 5% [13]. In practice the accessible rate is much reduced and the theoretical uncertainty increases considerably, since the overwhelming background (a factor 50) from $\overline{B} \to X_c \ell \bar{\nu}$ decays must be suppressed by stringent kinematic requirements. These cuts are all based on the u quark being much lighter than the c quark. As a consequence, the distributions of E_ℓ and q^2, the squared invariant mass of the lepton pair, extends to higher values for signal, whereas the m_X spectrum is concentrated at lower values. It is therefore possible to select regions of the phase space where the signal over background ratio is adequate. However, the resulting acceptances tend to be small (6%, 20%, up to 70% for typical requirements on E_ℓ, q^2 and m_X, respectively) and, if cuts are not carefully chosen, poorly known, since OPE breaks down and a shape function is needed to resum non-perturbative physics to all orders. This shape function depends on m_b and heavy quark parameters. Therefore, it is possible to determine its basic features from other processes, like $\overline{B} \to X_c \ell \bar{\nu}$ and $b \to s\gamma$ decays [a]. Indeed, most of the theoretical uncertainty in inclusive V_{ub} determinations is due to our imperfect knowledge of the shape function, m_b and the heavy quark parameters. Minimizing these uncertainties by maximizing the acceptance, *e.g.* by relaxing the cut on E_ℓ, is possible only if background knowledge is good. Otherwise, one can choose regions, e.g. at low m_X and high q^2, where shape function effects are expected to be small and OPE works well.

Several theory calculations [14,15,16,17] can be used to get acceptances in restricted regions of phase space. $|V_{ub}|$ is determined from the measurement of $\Delta\mathcal{B}(\overline{B} \to X_u \ell \bar{\nu})$, the charmless semileptonic partial branching fraction in the phase space region $\Delta\Phi$ defined by kinematic cuts, and $\zeta(\Delta\Phi)$, the rate (in $|V_{ub}|^2$ ps^{-1}) for the same phase space region predicted by theory:

$$|V_{ub}| = \sqrt{\frac{\Delta\mathcal{B}(\overline{B} \to X_u \ell \bar{\nu})}{\tau_b \cdot \zeta(\Delta\Phi)}} \tag{3}$$

where τ_b is the B meson lifetime. Measuring partial branching fractions allows to use and compare several models, and to update previous determinations as theory uncertainties and calculations improve.

3.1 Measurements near the Endpoint of the Lepton Energy Spectrum

Historically, the observation of events where the energy of the lepton exceeded the endpoint expected for $\overline{B} \to X_c \ell \bar{\nu}$ decays ($E_\ell > 2.3$ GeV) provided the first evidence for charmless semileptonic decays. As background knowledge improved, it has been possible [19,20,21] to relax the requirement on E_ℓ down to 2.0 GeV, or even 1.9 GeV (Belle), thereby increasing the acceptance and decreasing theory uncertainty. The typical signal-to-background ratio in these studies is about 1:10. Figure 1, left, shows the distribution of the electron momentum near the kinematic endpoint, after subtraction of backgrounds and corrections for efficiency and radiative effects, obtained by Babar on a sample of 88 million $B\overline{B}$ events. The resulting determination of $|V_{ub}|$, adjusted by HFAG [26] (see Section 3.3), is shown in Table 1 together with measurements from other experiments. The uncertainty on V_{ub} from endpoint measurements is at the 10% level, dominated by uncertainties on the shape function parameters, mostly a 40 MeV uncertainty on m_b.

3.2 Hadronic B tags

Other discriminating variables such as m_X and q^2 can be reconstructed experimentally by determining unambiguously which hadrons originate from the semileptonic decay of a B meson.

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[a] Some care must be taken when relating the heavy quark parameters determined in different processes, since the theoretical calculations are performed in different normalization schemes, and the order of the heavy quark expansion is not necessarily the same.

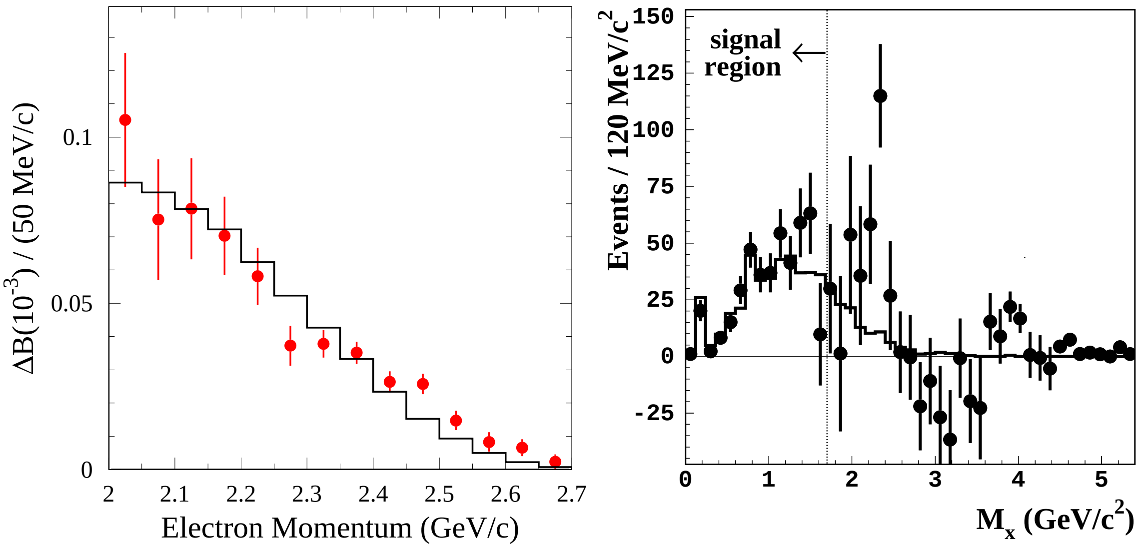

Figure 1: Left: Electron energy spectrum near the endpoint, obtained by Babar on a sample of 88×10^6 $B\overline{B}$ events. Data points, after background subtraction and correction for efficiency, bremsstrahlung and final state radiation, are compared to the Monte carlo simulation (histogram). Right: Distribution of m_X, obtained by Belle on a sample of 253×10^6 $B\overline{B}$ events. A B meson is reconstructed in a fully hadronic final state and a semileptonic decay of the second B is identified. Points represent data, after subtracting $\overline{B} \to X_c\ell\bar{\nu}$ and other backgrounds, the histogram is the fitted $\overline{B} \to X_u\ell\bar{\nu}$ contribution.

This difficult task for experiments running at the $\Upsilon(4S)$ peak can be solved by explicitly reconstructing the decay of a B meson in a fully hadronic final state, and studying the recoiling B, whose momentum and flavour are consequently known. If the recoiling B decays semileptonically, the only missing particle in the event is the neutrino, which can be reconstructed by using missing mass arguments. The experimental resolution on the discriminating variables can be increased by using a kinematic fit. This technique, pioneered by Babar [27], provides signal over background ratios of about 1 or more, at the expense of a very small ($\mathcal{O}(10^{-3})$) efficiency due to the full hadronic reconstruction. As datasets increase, inclusive measurements with hadronic B tags are expected to give the most precise determinations of $|V_{ub}|$. Figure 1, right, shows the m_X spectrum after background subtraction, resulting from an analysis by Belle [25]. The resulting V_{ub} measurement, adjusted by HFAG, is shown in Table 1, together with results from Babar. Results from the two experiments are comparable, with uncertainties at the 10% level, dominated by theory.

Shape function effects, which give the dominant contribution to the uncertainty in inclusive V_{ub} determinations, can be reduced by using theoretical calculations which relate the rate $\Delta\Gamma(\overline{B} \to X_u\ell\bar{\nu})$ to the photon energy spectrum in $b \to s\gamma$ decays. For instance, one can schematically write [28,29]

$$\Delta\Gamma(\overline{B} \to X_u\ell\bar{\nu}) = \frac{|V_{ub}|^2}{|V_{ts}|^2}\int W(E_\gamma)\frac{d\Gamma(b \to s\gamma)}{dE_\gamma}dE_\gamma, \tag{4}$$

where the integration is performed in an appropriate phase space region and the weight function $W(E_\gamma)$ is computed by theory with moderate uncertainty. The dependence on the shape function is therefore folded in the experimental measurement. A new Babar measurement [30], which uses this approach and calculations by Low, Leibovich and Rothstein [29], has been released just before this Conference. It is based on an analysis of the recoil of fully reconstructed B mesons on 88 million $B\overline{B}$ events. Figure 2 shows the spectrum of the hadronic invariant mass, before (left) and after (right) background subtraction. The partial rate $\Delta\Gamma(\overline{B} \to X_u\ell\bar{\nu})$ is determined by

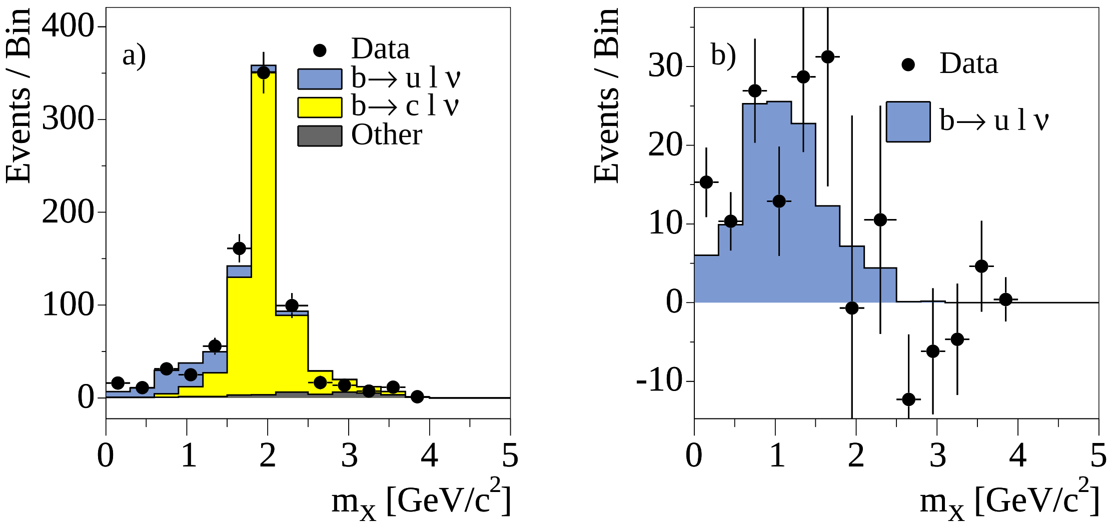

Figure 2: Distributions of m_X before (left) and after (right) subtraction of $\overline{B} \to X_c \ell \bar{\nu}$ and other backgrounds, obtained by Babar on a sample of $88{\times}10^6$ $B\overline{B}$ events. Semileptonic decays are identified in the recoil of a fully reconstructed hadronic B decay. Points are data, histograms represent signal and background contributions. The m_X spectrum after background subtraction is used to compute partial branching fractions as a function of the m_X cut, which are then combined with suitable integrations of the photon energy spectrum in $b \to s\gamma$ decays to obtain V_{ub}.

counting events below a cut on m_X, and V_{ub} is extracted by using the photon energy spectrum in $b \to s\gamma$ decays as measured by Babar [10]. Theory uncertainties increase as the m_X cut is decreased, since a region dominated by non-perturbative effects is selected. Experimental errors increase at higher m_X cuts due to background subtraction. The resulting optimal working point corresponds to $m_X < 1.67$ GeV, which gives a measurement of $|V_{ub}|$ (see Table 1) compatible with other determinations and 12% uncertainty. As expected, the impact of shape function parameters is small in this approach. The theory error results from neglecting high order terms in the $1/m_b$ expansion. A V_{ub} measurement over the full m_X spectrum is also shown in Table 1; as expected, the theory error decreases since the full phase space is used, but the statistical error increases.

3.3 Inclusive V_{ub}: Summary and Outlook

Table 1 shows a summary of inclusive V_{ub} measurements, together with the latest average from HFAG [26]. All measurements have been adjusted by HFAG so that the same theory framework [16] and shape function parameters and uncertainties (Eq. 2) are used. The total uncertainty on V_{ub} from inclusive measurements is 7.4%, dominated by theory. The uncertainty from limited knowledge of the shape function is about 4%. Experiments can help by determining shape function parameters with better accuracy, but it will be hard to go down 30 MeV on m_b. Other theoretical uncertainties, due to neglecting higher order terms and weak annihilation effects, contribute 5% to the uncertainty on V_{ub}. While the latter can be studied experimentally, the former will be difficult to improve. Other theory approaches, such as the Dressed Gluon Exponentiation by Andersen and Gardi [17], are also promising and worth to investigate.

Table 1: Experimental measurements of partial branching fractions $\Delta\mathcal{B}$ for inclusive $\overline{B} \to X_u \ell \bar{\nu}$ decays and $|V_{ub}|$, adjusted by HFAG as explained in the text. f_u is the space phase acceptance. The errors on V_{ub} refer to experimental and theoretical uncertainties, respectively. The $s_{\mathrm{h}}^{\max}$ variable is described elsewhere[18]. The P_+ variable is defined as $P_+ = E_X - |\vec{p}_X|$.

	accepted region	f_u	$\Delta\mathcal{B}[10^{-4}]$	$\lvert V_{ub}\rvert[10^{-3}]$
∗CLEO[19]	$E_e > 2.1$ GeV	0.19	$3.3 \pm 0.2 \pm 0.7$	$4.05 \pm 0.47 \pm 0.36$
∗BABAR[20]	$E_e > 2.0$ GeV	0.26	$5.3 \pm 0.3 \pm 0.5$	$4.25 \pm 0.30 \pm 0.31$
∗BELLE[21]	$E_e > 1.9$ GeV	0.34	$8.5 \pm 0.4 \pm 1.5$	$4.85 \pm 0.45 \pm 0.31$
∗BABAR[22]	$E_e > 2.0$ GeV, $s_{\mathrm{h}}^{\max} < 3.5\,\mathrm{GeV}^2$	0.19	$3.5 \pm 0.3 \pm 0.3$	$4.06 \pm 0.27 \pm 0.36$
∗BABAR[23]	$m_X < 1.7$ GeV$/c^2, q^2 > 8$ GeV$^2/c^2$	0.34	$8.7 \pm 0.9 \pm 0.9$	$4.79 \pm 0.35 \pm 0.33$
∗BELLE[24]	$m_X < 1.7$ GeV$/c^2, q^2 > 8$ GeV$^2/c^2$	0.34	$7.4 \pm 0.9 \pm 1.3$	$4.41 \pm 0.46 \pm 0.30$
BELLE[25]	$m_X < 1.7$ GeV$/c^2, q^2 > 8$ GeV$^2/c^2$	0.34	$8.4 \pm 0.8 \pm 1.0$	$4.68 \pm 0.37 \pm 0.32$
BELLE[25]	$P_+ < 0.66$ GeV	0.57	$11.0 \pm 1.0 \pm 1.6$	$4.14 \pm 0.35 \pm 0.29$
∗BELLE[25]	$m_X < 1.7$ GeV$/c^2$	0.66	$12.4 \pm 1.1 \pm 1.2$	$4.10 \pm 0.27 \pm 0.25$
BABAR[30]	$m_X < 1.67$ GeV & $b \to s\gamma$			$4.43 \pm 0.45 \pm 0.29$
BABAR[30]	$m_X < 2.5$ GeV & $b \to s\gamma$			$4.34 \pm 0.76 \pm 0.10$
Average of ∗	$\chi^2 = 6.3/6$, CL=0.40			$4.39 \pm 0.19 \pm 0.27$

4 Exclusive SL Decays with Charm

The technique of determining V_{cb} by using $B \to D^* l\nu$ decays is well established. The differential distribution can be written in terms of w, the D^* boost in the B rest frame, as

$$\frac{d\Gamma(B \to D^* l\nu)}{dw} = \frac{G_F^2 |V_{cb}|^2}{48\pi^3} (\mathcal{F}(w))^2 \mathcal{G}(w) \tag{5}$$

where $\mathcal{G}(w)$ is a phase space factor and $\mathcal{F}(w)$ is a form factor which would be 1 at $w = 1$ in the heavy quark limit. Lattice QCD can be used to compute effects due to finite quark masses, leading to [31] $\mathcal{F}(1) = 0.919^{+0.030}_{-0.035}$. The shape of $\mathcal{F}(w)$ cannot be predicted by theory, and is parameterized in terms of a slope ρ^2 and form factor ratios R_1 and R_2, (nearly) independent of w. The helicity amplitudes entering in the $B \to D^* l\nu$ decay are also function of the above parameters. These amplitudes, and therefore ρ^2 R_1 and R_2, can be determined by fitting the four-fold differential rate of $B \to D^* l\nu$ decays in terms of w and three angles which describe the decay kinematics. Figure 3 shows the result of the fit to the angular and w distributions obtained in a recent Babar measurement[32], where form factors are parameterized by using a prescription due to Caprini, Lellouch and Neubert[33]. The uncertainties on the resulting measurements

$$R_1 = 1.396 \pm 0.060 \pm 0.044, \quad R_2 = 0.885 \pm 0.040 \pm 0.026, \quad \rho^2 = 1.145 \pm 0.059 \pm 0.046,$$

are a factor 5 better than in previous determinations [34]. Consequently, the systematic uncertainty, due to form factor ratios, in the Babar exclusive V_{cb} determination[35] decreases approximately by the same amount. It is also interesting to note that the re-interpretation of the Babar exclusive V_{cb} measurement gives

$$|V_{cb}| = (37.6 \pm 0.3_{stat} \pm 1.3_{syst} \pm 1.4_{theory}) \times 10^{-3}, \tag{6}$$

which is about 2 standard deviations away from the published result [35]. Since $B \to D^* l\nu$ is a dominant background for charmless semileptonic decays, a reduction of the systematic uncertainty due to the better knowledge of the $B \to D^* l\nu$ form factor ratios is also observed in the endpoint measurement[20] of V_{ub}.

5 Exclusive Charmless SL Decays

The differential rates for exclusive charmless semileptonic decays in terms of q^2 is proportional to $|V_{ub}|^2$ times a form factor which is final state dependent. The absolute values of these form factors are predicted by using several theoretical frameworks (light-cone sum rules, lattice calculations, quark models); their dependence on q^2 can be checked experimentally, thereby allowing to discriminate different theoretical models. In brief, experiments search for semileptonic decays with a light meson $(\pi, \rho, \eta, \eta', \omega)$ in events where the other B is tagged via hadronic or semileptonic decays, or even in untagged events. The latter gives better efficiencies, but also higher backgrounds. No new results were released immediately before this Conference. A summary of determinations of exclusive charmless semileptonic branching fractions and V_{ub} is given elsewhere [26]. The uncertainty on the average value of $|V_{ub}|$, about 14%, is dominated by the normalization of the form factors, which contributes about 10%. The determinations of V_{ub} with inclusive and exclusive decays are in agreement at the present level of accuracy.

Heavy quark symmetry relates the form factors of $B \to \pi l\nu$ and $D \to \pi\ell\nu$ decays. A precise measurement of the latter represents a stringent test which can be used to calibrate theoretical calculations and increase the precision of V_{ub} determinations from $B \to \pi l\nu$ decays. A first step towards this goal is measuring the q^2 dependence of the hadronic form factor in $D \to K\ell\nu$ decays with great accuracy. A preliminary result obtained by Babar is shown for the first time at this Conference. A sample of $2{\times}10^5$ decays has been analysed, and the q^2 distribution, unfolded of detector effects, has been obtained and fit to two different ansätze (the pole and modified pole mass) for the form factor shape. Measurements of the mass and scale entering in these parameterizations give uncertainties which are at least a factor 2 better than previous determinations.

6 Conclusion

The study of semileptonic B decays is a very active area for both theory and experiment. Substantial progress has been obtained by applying HQE fits to inclusive $\overline{B} \to X_c\ell\bar{\nu}$ decays, resulting in precise measurements of $|V_{cb}|$ (2%), m_b (1%) and heavy quark parameters relevant also to charmless decays. Increased precision (7%) has been obtained in inclusive V_{ub} determinations, by improving the existing techniques, using a more comprehensive theoretical treatment, and improving the determination of the b quark mass.

New precision measurement of form factors in exclusive $B \to D^* l\nu$ decays allows to reduce systematic uncertainties in the determination of V_{cb} with exclusive decays and V_{ub} with inclusive

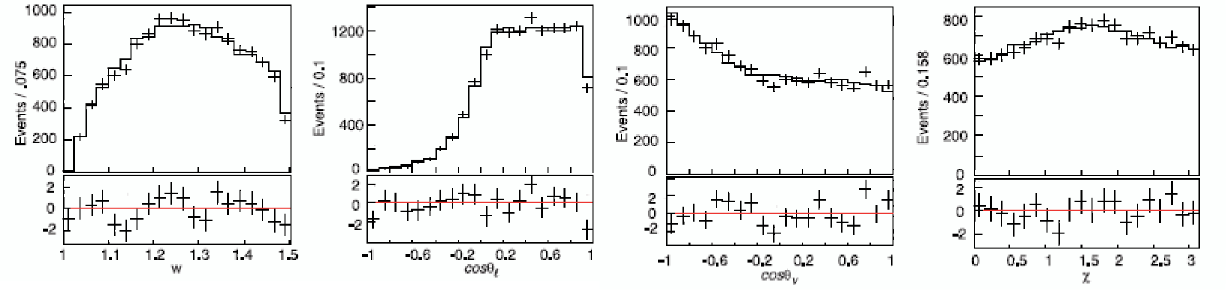

Figure 3: Background-subtracted data (points) overlaid on Monte Carlo (histograms) for the distributions of the four kinematic variables relevant in the $B \to D^* l\nu$ decay, as measured in the Babar form factor analysis on a sample of $86{\times}10^6$ $B\overline{B}$ events. Simulated events have been reweighted according to the best fit of the form factors. The bottom panel of each figure shows the pull (difference over error) plot. The line at zero is shown for comparison purposes only.

decays. Studies of exclusive charmless decays will improve as datasets increase. However, reducing the theoretical uncertainties to a level comparable with the statistical error and the inclusive determinations is challenging. In this respect, measurements of related processes such as semileptonic decays of charm mesons will increase confidence in theoretical calculations and uncertainties.

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