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Semileptonic B decays in *BABAR*

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Recent results from *BABAR* on the determination of the CKM matrix elements $|V_{cb}|$ and $|V_{ub}|$ are presented.

1. Introduction

Semileptonic B decays to charm and charmless mesons are the primary tool where to measure the CKM matrix elements $|V_{cb}|$ and $|V_{ub}|$ because of their simple theoretical description at the parton level. Their relatively large decay rates are proportional to $|V_{cb}|^2$ and $|V_{ub}|^2$ and depend on the quark masses m_b, m_c. In recent years, tremendous progress has been made in the description of semileptonic and radiative decays in the framework of Heavy Quark Expansions (HQEs); calculations for their width and moments of inclusive observables with restrictions on the phase space are now available in different schemes through order $1/m_b^3$ and $\alpha_s^2\beta_0$.

2. Inclusive $|V_{cb}|$ measurement

Making use of HQEs it is possible to perform a combined fit to measured moments for which correlation matrices are published [1]. These include moments of the hadronic mass distribution $\langle M_X^n \rangle$ and moments of the lepton energy spectrum $\langle E_\ell^n \rangle$ in inclusive $B \to X_c \ell \bar{\nu}$ as well as moments of the photon energy spectrum $\langle E_\gamma^n \rangle$ in inclusive $B \to X_s \gamma$ decays for different minimum lepton and photon energies. HQEs express the semileptonic decay width Γ_{SL} as well as these moments in terms of the running kinetic quark masses $m_b(\mu)$ and $m_c(\mu)$. They depend on several non-perturbative parameters which therefore can be determined from a fit of the theoretical expressions to the experimental moment measurements.

In *BABAR*, hadron mass and energy moments for $B \to X_c \ell \bar{\nu}$ as a function of the minimum lepton energy have been measured [2,3]. They have been updated by taking into account recent improved measurements of the D_s and B branching fractions. In addition, the most recent results from two independent analyses on the photon energy spectrum in $B \to X_s \gamma$ decays as a function of the minimum photon energy have been taken into account [4,5].

The fit to the moment measurements (that includes also results from Belle, CDF, CLEO and DELPHI) is done using the HQE calculations in the kinetic scheme described in [6]. The fit results are summarised in the following:

$$|V_{cb}| = (41.96 \pm 0.23 \pm 0.35 \pm 0.59) \times 10^{-3},$$

where the first error includes statistical and systematic experimental uncertainties, the second the theoretical uncertainties from HQEs, and the third is due to the uncertainties in the expression of Γ_{SL}. For the other parameters:

$$\begin{aligned} m_c &= 1.142 \pm 0.037_{\mathrm{exp}} \pm 0.045_{\mathrm{HQE}}\ \mathrm{GeV} \\ \mu_\pi^2 &= 0.401 \pm 0.019_{\mathrm{exp}} \pm 0.035_{\mathrm{HQE}}\ \mathrm{GeV}^2 \end{aligned}$$

3. Exclusive $|V_{cb}|$ measurement

The determination of $|V_{cb}|$ from exclusive $B \to D^* \ell \nu$ decays can be greatly improved with a better measurement of $B \to D^*$ form factors. The hadronic weak current of said decay can be expressed in terms of two axial form factors A_1 and A_2, and one vector form factor V, which are functions of the B to D^* momentum transfer squared q^2. These form factors are usually characterized in terms of their ratio parameters R_1 and R_2, and a slope parameter ρ^2. 86×10^6 $B\overline{B}$ events collected with the *BABAR* detector were analyzed

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using an unbinned maximum likelihood method to extract the form factors from $B \to D^* e\nu$ decays [7]; in place of a linear parameterization of the q^2 dependence of the form factors, a higher-order polynomial was used. The Lorentz structure of the $B \to D^* \ell\nu$ decay amplitude can be expressed in terms of three helicity amplitudes which correspond to the three polarization states of the D^*. The full differential decay rate can be expressed in terms of four kinematic variables: the Lorentz-invariant w (the dot product of the B and D^* four-velocities) and three angles θ_ℓ (the angle between the direction of the lepton in the virtual W rest frame, and the direction of the virtual W in the B rest frame), θ_V (the angle between the direction of the D in the D^* rest frame) and χ (the dihedral angle between the plane formed by the DD and the plane formed by the $W - \ell$ system). Based on a sample of 16386 $B^0 \to D^{*-} e^+ \nu_e$ events, we obtain

$$\begin{aligned} R_1 &= 1.396 \pm 0.060 \pm 0.035 \pm 0.027, \\ R_2 &= 0.885 \pm 0.040 \pm 0.022 \pm 0.013, \\ \rho^2 &= 1.145 \pm 0.059 \pm 0.030 \pm 0.035, \end{aligned}$$

where the first error is statistical, the second Monte Carlo statistical, and the third systematic. These results allow a five-fold reduction in the largest source of systematic error in V_{cb} measurements based on $B \to D^* \ell\nu$ decays to be made. Using the measurements of R_1 and R_2 quoted above, it is possible to update the 2004 BABAR result [8] to find:

$$|V_{cb}| = (37.6 \pm 0.3_{\text{stat}} \pm 1.3_{\text{syst}}\ {}^{+1.5}_{-1.3(\text{theory})}) \times 10^{-3}.$$

The error due to the uncertainties in R_1 and R_2 is reduced from ${}^{+2.9\%}_{-2.6\%}$ to ±0.5%. The overall systematic error drops from ±1.7% to ±1.3%.

4. Inclusive $|V_{ub}|$ measurements

4.1. $|V_{ub}|$ from the inclusive electron spectrum near the kinematic endpoint

The principal challenge in this measurement is the separation of the signal $B \to X_u e\nu$ events from the 50 times larger $B \to X_c e\nu$ background. This can be achieved by selecting regions of phase space in which this background is highly suppressed. In the rest frame of the B meson, the kinematic endpoint of the electron spectrum is ~ 2.3 GeV/c for the dominant $B \to X_c e\nu$ decays and ~ 2.6 GeV/c for $B \to X_u e\nu$ decays. This allows for a relatively precise measurement, largely free from $B\overline{B}$ background, in a 300 MeV/c interval that covers approximately 10% of the total electron spectrum for charmless semileptonic B decays. In the $\Upsilon(4S)$ rest frame, the finite momenta of the B mesons cause additional spread of the electron momenta of ~ 200 MeV/c, extending the endpoints to higher momenta. BABAR has carried out this measurement on an integrated luminosity sample of 80.4 fb^{-1}, collected at the $\Upsilon(4S)$ resonance [9]. An additional sample of 9.5 fb^{-1} was recorded at a center-of-mass (c.m.) energy 40 MeV below the $\Upsilon(4S)$ resonance, and used to subtract the non-$B\overline{B}$ contributions from the main data sample. To determine the non-$B\overline{B}$ background, a χ^2 fit to the off-resonance data in the momentum interval of 1.1 to 3.5 GeV/c is performed. Hadronic B decays contribute to the background mostly via hadron misidentification and secondary electrons from decays of D, J/ψ and $\psi(2S)$ mesons. The total background is estimated by fitting the observed inclusive electron spectrum to the sum of the signal and individual background contributions, using MC simulated spectra and treating their relative normalization factors as free parameters in the fit. To extract the signal, a fit is performed simultaneously to the on- and off-resonance electron momentum spectra in the range from 1.1 to 3.5 GeV/c, in bins of 50 MeV/c. The lower part of the spectrum determines the relative normalization of the various background contributions, allowing for an extrapolation into the endpoint region above 2.0 GeV/c. The measurement of the $B \to X_c e\nu$ partial branching fraction in the range 2.0 to 2.6 GeV/c yields:

$$\Delta\mathcal{B} = (0.572 \pm 0.041 \pm 0.065) \times 10^{-3},$$

where the first error is statistical and the second is the total systematic error. This error also includes the observed dependence of the extracted signal on the choice of the shape function (SF) parameters. Based on the BNLP method [10], a value for $|V_{ub}|$ is obtained:

$$|V_{ub}| = (4.44 \pm 0.25 \ {}^{+0.42}_{-0.38} \pm 0.22) \times 10^{-3},$$

where the first error represents the total experimental uncertainty, the second refers to the uncertainty in the SF parameters from the combined fit to moments, and the third combines the stated theoretical uncertainties in the extraction of $|V_{ub}|$, including uncertainties from the subleading SFs, weak annihilation effects, and various scale-matching uncertainties.

4.2. $|V_{ub}|$ from inclusive semileptonic decays with reduced model dependence

The uncertainties in the existing measurements of $|V_{ub}|$ are dominated by the uncertainties in the b-quark mass m_b and the modeling of the Fermi motion of the b quark inside the $\overline{B}$ meson [11]. *BABAR* has recently presented two techniques to extract $|V_{ub}|$ from inclusive $\overline{B} \rightarrow X_u \ell \bar{\nu}$ decays where these uncertainties are significantly reduced [12]. Leibovich, Low, and Rothstein (LLR) have presented a prescription to extract $|V_{ub}|$ with reduced model dependence from either the lepton energy or the hadronic mass m_X [13]. The calculations of LLR are accurate up to corrections of order α_s^2 and $(\Lambda m_B/(\zeta m_b)/)^2$, where ζ is the experimental maximum hadronic mass up to which the $\overline{B} \rightarrow X_u \ell \bar{\nu}$ decay rate is determined and $\Lambda \approx \Lambda_{QCD}$. This method combines the hadronic mass spectrum, integrated below ζ, with the high-energy end of the measured differential $B \rightarrow X_s \gamma$ photon energy spectrum. An alternative method to reduce the model dependence is to measure the $\overline{B} \rightarrow X_u \ell \bar{\nu}$ rate over the entire m_X spectrum. Since no extrapolation is necessary to obtain the full rate, systematic uncertainties from m_b and Fermi motion are much reduced. Perturbative corrections are known to order α_s^2. The $\overline{B} \rightarrow X_u \ell \bar{\nu}$ rate is extracted from the hadronic mass spectrum up to $\zeta = 2.5$ GeV/c^2, which corresponds to about 96% of the simulated hadronic mass spectrum. The measurements presented here are based on a sample of 88.9 million $B\overline{B}$ pairs, in which one of the B mesons decays hadronically and is fully reconstructed and the other decays semileptonically. In this analysis method, charged and neutral hadrons are combined with an exclusively reconstructed D meson to obtain combinations with an energy consistent with a B meson. While this approach results in a low overall event selection efficiency, it allows for the precise determination of the momentum, charge, and flavor of the B candidates. The reconstruction of the mass of the hadronic system is improved by a kinematic fit that imposes four-momentum conservation, the equality of the masses of the two B mesons, and $p_\nu = 0$, where p_ν^2 is the neutrino four-momentum. The resulting m_X resolution is about 250 MeV/c on average. Two determinations of $|V_{ub}|$ are presented. First, using the LLR technique with the photon energy spectrum in $B \rightarrow X_s \gamma$ decays from Ref. [4], the hadronic mass spectrum up to a value of $\zeta = 1.67$ GeV/c^2, we find

$$|V_{ub}| = (4.43 \pm 0.38 \pm 0.25 \pm 0.29) \times 10^3,$$

where the first error is the statistical uncertainty from $\overline{B} \rightarrow X_u \ell \bar{\nu}$ and $B \rightarrow X_s \gamma$ added in quadrature, the second (third) is systematic (theoretical). Second, $|V_{ub}|$ is determined from the measurement of the full m_X spectrum, *i. e.* up to a value of $\zeta = 2.5$ GeV/c^2:

$$|V_{ub}| = (3.84 \pm 0.70 \pm 0.30 \pm 0.10) \times 10^3,$$

where the first error is statistical, the second systematic and the third theoretical.

5. Exclusive $|V_{ub}|$ measurement

$|V_{ub}|$ can be extracted from charmless semileptonic decays of B mesons with exclusively reconstructed final states, $B \rightarrow h_u \ell \nu$, where the hadronic state h_u represents a $\pi^\pm$, π^0, $\rho^\pm$, ρ^0. Exclusive decays allow for kinematic constraints and more efficient background suppression compared to inclusive decays, but must rely on theoretical form factor predictions. Using isospin symmetry, *BABAR* has measured the branching fractions[2] $\mathcal{B}(B \rightarrow \pi^- \ell^+ \nu)$ and $\mathcal{B}(B \rightarrow \rho^- \ell^+ \nu)$ as a function of the momentum transfer squared $q^2 = (p_\ell + p_\nu)^2$, and extracted $|V_{ub}|$ using recent form factor calculations based on light-cone sum rules (LCSR) and unquenched lattice QCD

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[2] Charge conjugation is implied throughout this paper.

(LQCD) [14]. These measurements are based on a sample of 83 million $B\overline{B}$ pairs. The signal yields are extracted by using the variables $\Delta E = (p_B \cdot p_{\mathrm{beams}} - s/2)/\sqrt{s}$ and $m_{ES} = \sqrt{(s/2) + (\vec{p}_B \cdot \vec{p}_{\mathrm{beams}})}$, where $\sqrt{s}$ is the mass of the $\Upsilon(4S)$, p_B and p_{beams} are the four-momenta of the B meson and of the colliding-beam particles. A binned extended maximum-likelihood fit to the ΔE vs. m_{ES} distributions was performed for the four signal modes simultaneously. The fit takes into account statistical fluctuations of both data and Monte Carlo samples. The relative proportions of the simulated signal and background samples were fitted to the data distributions in 5 GeV^2 or 10 GeV^2 intervals of q^2. Isospin relations were used to reduce the number of fit parameters to nine: five for the signal yields in the five q^2 intervals for $B \to \pi\ell\nu$ decays, three for the signal yields in the three q^2 intervals for $B \to \rho\ell\nu$ decays, plus one scale parameter, shared among all q^2 intervals and signal modes, to fit the overall normalization of the $B \to X_c\ell\bar{\nu}$ background. The fit yields, for the exclusive branching fraction calculations: $\mathcal{B}(B \to \pi^-\ell^+\nu) = (1.38 \pm 0.10 \pm 0.16 \pm 0.08) \times 10^{-4}$ and $\mathcal{B}(B \to \rho^-\ell^+\nu) = (2.14 \pm 0.21 \pm 0.48 \pm 0.28) \times 10^{-4}$, where the errors are statistical (data and simulation), experimental systematic, and uncertainties of the form factor shapes. For $\mathcal{B}(B \to \pi^-\ell^+\nu)$, the q^2 distribution agrees well with calculations based on LCSR and unquenched LQCD. Instead of averaging results based on different calculations, the measured form factor shape and normalization of LQCD2 [15] is chosen, and $|V_{ub}|$ calculated:

$$|V_{ub}| = (3.82 \pm 0.14 \pm 0.22 \pm 0.11 \ {}^{+0.88}_{-0.52}) \times 10^{-3},$$

where the additional fourth error reflects the uncertainty of the form-factor normalization.

6. Summary

New *BABAR* measurements of $|V_{cb}|$ and $|V_{ub}|$ from inclusive and exclusive semileptonic decays were obtained. Thanks to the improvements in experimental techniques, to the large sample of $B\overline{B}$ events collected, and the important progress in the theoretical description of semileptonic B decays, the value of $|V_{cb}|$ is now known at the 2% level from inclusive decays, with significant improvements also in the exclusive decays sector. With these measurements, our knowledge of $|V_{ub}|$ from inclusive decays is now at the 7% level.

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