PROCEEDINGS OF SCIENCE

Inclusive Measurements of $|V_{ub}|$ from BaBar

Giuseppe Della Ricca*
(on behalf of the BABAR Collaboration)
Università di Trieste and INFN Trieste, Italy
E-mail: `giuseppe.della-ricca@ts.infn.it`

The Cabibbo-Kobayashi-Maskawa (CKM) matrix element V_{ub} is a fundamental parameter of the Standard Model, representing the coupling of the b quark to the u quark. It is one of the smallest and least known elements of the CKM matrix. With the increasingly precise measurements of decay-time-dependent CP asymmetries in B-meson decays, in particular the angle β [1, 2], improved measurements of the magnitude of V_{ub} will allow for stringent experimental tests of the Standard Model mechanism for CP violation [3]. The extraction of $|V_{ub}|$ is a challenge, both theoretically and experimentally. Theoretically, the weak decay rate for $b \to ue\nu$ can be calculated at the parton level. It is proportional to $|V_{ub}|^2$ and m_b^5, where m_b is the b-quark mass. To relate the B-meson decay rate to $|V_{ub}|$, the parton-level calculations have to be corrected for perturbative and non-perturbative QCD effects. These corrections can be calculated using various techniques: heavy quark expansions (HQE) [4] and QCD factorization [5]. They make use of specific assumptions and are affected by different uncertainties. It is therefore important to make redundant measurements by using several experimental techniques, and different theoretical frameworks. Experimentally, the principal challenge is to separate the signal $B \to X_u e\nu$ decays 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 addition, exploiting the available kinematic variables which discriminate between rare charmless semileptonic decays and the much more abundant decays involving charmed mesons, gives different sensitivities to the underlying theoretical calculations and assumptions. In inclusive measurements, the most common kinematic variables discussed in the literature, each having its own advantages, are the lepton energy (E_ℓ), the hadronic invariant mass (M_X), and the leptonic invariant mass squared (q^2).

In this letter we present three different determinations of $|V_{ub}|$, based on the analysis of semileptonic B decays collected with the BABAR detector at the PEP-II e^+e^- storage ring. Charmless semileptonic B decays are selected: *(a)* in the electron momentum interval of $2.0-2.6\,\mathrm{GeV}/c$ [6]; *(b)* using measurements of the electron energy and the invariant mass squared of the electron-neutrino pair [7]; *(c)* in kinematic regions where the dominant background from semileptonic B decays to charm is reduced by requirements on the hadronic mass M_X and the momentum transfer q^2 ($M_X < 1.7$ GeV/c^2 and $q^2 > 8$ GeV$^2/c^4$) [8].

International Europhysics Conference on High Energy Physics
July 21st - 27th 2005
Lisboa, Portugal

*Speaker.

PoS(HEP2005)211

1. Measurement of the Inclusive Electron Spectrum in Charmless Semileptonic B Decays Near the Kinematic Endpoint and Determination of |Vub|

In the rest frame of the B meson, the kinematic endpoint of the electron spectrum is about 2.3 GeV$/c$ for the dominant $B \to X_c e\nu$ decays and about 2.6 GeV$/c$ for $B \to X_u e\nu$ decays. The spectrum above 2.3 GeV$/c$ is dominated by electrons from $B \to X_u e\nu$ transitions, and this allows for a relatively precise measurement, largely free from $B\bar{B}$ background, in a 300 MeV$/c$ interval that covers approximately 10% of the total electron spectrum for charmless semileptonic B decays. BABAR measured the inclusive electron momentum spectrum in charmless semileptonic B decays, averaged over charged and neutral B mesons, near the kinematic endpoint, determining the partial branching fractions in five overlapping momentum intervals [6]. The upper limit is fixed at 2.6 GeV$/c$, while the lower limit varies from 2.0 GeV$/c$ to 2.4 GeV$/c$. The data set used corresponds to an integrated luminosity of 80.4 fb^{-1}, collected at the $\Upsilon(4S)$ resonance. The charmless semileptonic B decays are select requiring an electron with momentum $p_e > 1.1$ GeV$/c$. For a given interval, Δp, in the electron momentum, BABAR has determined the inclusive partial branching fraction of $B \to X_u e\nu$. From the largest momentum interval, 2.0–2.6 GeV$/c$, the partial branching fraction is $\Delta\mathscr{B}(B \to X_u e\nu) = (0.572 \pm 0.041_{stat} \pm 0.065_{syst}) \times 10^{-3}$, where the first error is statistical and the second is the total systematic error. The value of $|V_{ub}|$ is extracted from the equation $|V_{ub}| = [\Delta\mathscr{B}/(\Delta\zeta \ \ \tau_B)]^{1/2}$, where $\Delta\zeta$ is the normalized partial rate [9], and $\tau_B = 1.604 \pm 0.023\,\text{ps}$ [10]. The values used for the heavy quark parameters in the evaluation of $\Delta\zeta$, $m_b = 4.59 \pm 0.05$ GeV and $\mu_\pi^2 = 0.21 \pm 0.05$ GeV^2 [11], are based on the BABAR analyses of the inclusive photon spectrum in $B \to X_s\gamma$ decays [12], and of the moments of the hadron mass and lepton energy spectra in $B \to X_c\ell\nu$ decays [13], translated to the shape-function scheme of Ref. [14]. BABAR obtained $|V_{ub}| = (4.44 \pm 0.25_{exp} + (^{+0.42}_{-0.38})_{SF} \pm 0.22_{th}) \times 10^{-3}$. Here the first error represents the total experimental uncertainty, the second refers to the uncertainty on the determination of the shape function parameters [14], and the third combines the stated theoretical uncertainties in the extraction of $|V_{ub}|$, including uncertainties from the subleading shape functions [15], weak annihilation effects [16], and various scale matching uncertainties. No additional uncertainty due to the theoretical assumption of quark-hadron duality has been assigned.

2. Determination of |Vub| from Measurements of the Electron and Neutrino Momenta in Inclusive Semileptonic B Decays

In this analysis, BABAR selected semileptonic $\bar{B} \to X_u e\bar{\nu}$ decays using a novel approach based on simultaneous requirements for the electron energy, E_e, and the invariant mass squared of the $e\bar{\nu}$ pair, q^2 [7]. The neutrino 4-momentum is reconstructed from the visible 4-momentum and knowledge of the e^+e^- initial state. The dominant charm background is suppressed by selecting a region of the q^2-E_e phase space where correctly reconstructed $\bar{B} \to X_c e\bar{\nu}$ events are kinematically excluded. The data set used consists of 88.4 million $B\bar{B}$ pairs collected at the $\Upsilon(4S)$ resonance, corresponding to an integrated luminosity of 81.4 fb^{-1}. Hadronic decays containing an identified electron with energy 2.1 GeV $< E_e <$ 2.8 GeV, whose maximum kinematically allowed hadronic mass squared $s_\mathrm{h}^\mathrm{max}(E_e, q^2)$, for a given E_e and q^2, is less than 3.5 GeV^2, are selected. With additional requirements to improve the quality of the neutrino reconstruction and suppress contributions from $e^+e^- \to q\bar{q}$ continuum events, BABAR measured the partial branching ratio $\Delta\mathscr{B}(\bar{B} \to X_u e\bar{\nu}, \tilde{E} > 2.0\ \text{GeV}, \tilde{s}_\text{h}^\text{max} < 3.5\ \text{GeV}^2) = (3.54 \pm 0.33_{stat} \pm 0.34_{syst}) \times 10^{-4}$, where $\tilde{E}_e$ and $\tilde{s}_\text{h}^\text{max}$ are the true (generated) values in the B meson rest frame, and the uncertainties are statistical and systematic, respectively. The value of $|V_{ub}|$ is extracted using the equation $|V_{ub}| = [\Delta\mathscr{B}/(\Delta\zeta\ \tau_B)]^{1/2}$ described above [9]. The values used for the heavy quark parameters in the evaluation of $\Delta\zeta$, $m_b = 4.61 \pm 0.08$ GeV and $\mu_\pi^2 = 0.15 \pm 0.07$ GeV^2, are based on fits to the BABAR analysis of the $\bar{B} \to X_c\ell\bar{\nu}$ $b \to cl\nu$ moments [13], translated to the shape-function scheme. BABAR found $|V_{ub}| = (3.95 \pm 0.26_{exp} + (^{+0.58}_{-0.42})_{SF} \pm 0.25_{th}) \times 10^{-3}$ for $\tilde{E}_e > 2.0$ GeV, where the errors represent experimental, heavy quark parameters, and theoretical uncertainties, respectively. The latter include estimates of the effects of subleading shape functions [15], variations in the matching scales used in the calculation, and weak annihilation [16], as above. No uncertainty is assigned for possible quark-hadron duality violation.

3. Measurement of the Partial Branching Fraction for Inclusive Charmless Semileptonic B Decays and Extraction of |Vub|

Theoretical studies indicate that it is possible to reduce the theoretical error on the extrapolation by applying simultaneous cuts on M_X and q^2 in inclusive $\bar{B} \to X_u\ell\bar{\nu}$ decays [17]. In fact, while the M_X distribution has a large usable fraction of events, of the order of 70%, but depends on the shape function describing the Fermi motion of the b quark inside the B meson, the q^2 distribution is less sensitive to non-perturbative effects and less dependent on the calculation. Unfortunately, only a small fraction of events (about 20%) is usable with a pure q^2 selection. The study presented in [17] shows that a combined cut on M_X and q^2 may mitigate the drawbacks of the two methods while retaining good statistical and systematic sensitivities. BABAR performed a study of charmless semileptonic decays and a measurement of the $|V_{ub}|$ CKM matrix element, on the recoiled B candidate opposite of a fully reconstructed B hadronic decay, by using the combined information of the M_X-q^2 distribution to discriminate signal and background and to minimize the theoretical uncertainties [8]. Using a total integrated luminosity of 210.7 fb^{-1} collected on the $\Upsilon(4S)$ resonance, BABAR measured the partial branching fraction of charmless semileptonic decays $\Delta\mathscr{B}(\bar{B} \to X_u\ell\bar{\nu}, M_X < 1.7\ \text{GeV}/c^2, q^2 > 8\ \text{GeV}^2/c^4) = (0.87 \pm 0.09_{stat} \pm 0.09_{syst} \pm 0.01_{th}) \times 10^{-3}$. Using the partial decay model from Ref. [9], taking the shape function parameters from the BABAR analysis of $\bar{B} \to X_c\ell\bar{\nu}$ moments [13], BABAR found: $|V_{ub}| = (4.65 \pm 0.24_{stat} \pm 0.24_{syst} + (^{+0.46}_{-0.38})_{SF} \pm 0.23_{th}) \times 10^{-3}$, where the errors are due to statistics, experimental systematics, shape function parameters and theoretical systematics, respectively.

4. Conclusions

The $|V_{ub}|$ measurements from Refs. [6, 7, 8] presented here are summarized in Table 1. For comparison, the result of Ref. [6] obtained using the shape function parameters based on the BABAR analysis of the moments of the hadron mass and lepton energy spectra in $B \to X_c\ell\nu$ decays [13] is also shown. The results are in good agreement with earlier measurements, given the experimental and theoretical uncertainties. The improvement in precision can be attributed to both the improvements in the experimental techniques, higher statistics and improved background estimates, as well as to the significant advances in the theoretical understanding of the shape functions and in the extraction of the shape function parameters from inclusive spectra and moments.

Ref. [6]	$\|V_{ub}\| = (4.44 \pm 0.25_{exp} + (^{+0.42}_{-0.38})_{SF} \pm 0.22_{th}) \times 10^{-3}$
Ref. [6]$^{(*)}$	$\|V_{ub}\| = (4.30 \pm 0.24_{exp} + (^{+0.75}_{-0.59})_{SF} \pm 0.21_{th}) \times 10^{-3}$
Ref. [7]	$\|V_{ub}\| = (3.95 \pm 0.26_{exp} + (^{+0.58}_{-0.42})_{SF} \pm 0.25_{th}) \times 10^{-3}$
Ref. [8]	$\|V_{ub}\| = (4.65 \pm 0.34_{exp} + (^{+0.46}_{-0.38})_{SF} \pm 0.23_{th}) \times 10^{-3}$

Table 1: Summary of the $|V_{ub}|$ measurements from Refs. [6, 7, 8]. The result of Ref. [6], obtained taking the same input values for the shape function parameters as the ones used in the other two references, is shown for comparison on the second row, and is indicated with Ref. [6]$^{(*)}$.

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