The following full text is a publisher's version.

For additional information about this publication click this link.
http://repository.ubn.ru.nl/handle/2066/128276

Please be advised that this information was generated on 2020-09-21 and may be subject to change.
Determinations of $|V_{ub}|$ from Inclusive Semileptonic $B$ Decays with Reduced Model Dependence

22 Colorado State University, Fort Collins, Colorado 80523, USA
23 Institut für Physik, Universität Dortmund, D-44221 Dortmund, Germany
24 Institut für Kern- und Teilchenphysik, Technische Universität Dresden, D-01062 Dresden, Germany
25 Ecole Polytechnique, LLR, F-91128 Palaiseau, France
26 University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom
27 Dipartimento di Fisica and INFN, Università di Ferrara, I-44100 Ferrara, Italy
28 Laboratori Nazionali di Frascati dell’INFN, I-00044 Frascati, Italy
29 Dipartimento di Fisica e INFN, Università di Genova, I-16146 Genova, Italy
30 Harvard University, Cambridge, Massachusetts 02138, USA
31 Physikalisches Institut, Universität Heidelberg, Philosophenweg 12, D-69120 Heidelberg, Germany
32 Imperial College London, London, SW7 2AZ, United Kingdom
33 University of Iowa, Iowa City, Iowa 52242, USA
34 Iowa State University, Ames, Iowa 50011-3160, USA
35 Institut für Experimentelle Kernphysik, Universität Karlsruhe, D-76021 Karlsruhe, Germany
36 Laboratoire de l’Accélérateur Linéaire, F-91898 Orsay, France
37 Lawrence Livermore National Laboratory, Livermore, California 94550, USA
38 University of Liverpool, Liverpool L69 72E, United Kingdom
39 Queen Mary, University of London, E1 4NS, United Kingdom
40 Royal Holloway and Bedford New College, University of London, Egham, Surrey TW20 0EX, United Kingdom
41 University of Louisville, Louisville, Kentucky 40292, USA
42 University of Manchester, Manchester M13 9PL, United Kingdom
43 University of Maryland, College Park, Maryland 20742, USA
44 University of Massachusetts, Amherst, Massachusetts 01003, USA
45 Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
46 McGill University, Montréal, Québec H3A 2T8, Canada
47 Dipartimento di Fisica and INFN, Università di Milano, I-20133 Milano, Italy
48 University of Mississippi, University, Mississippi 38677, USA
49 Physique des Particules, Université de Montréal, Montréal, Québec H3C 3J7, Canada
50 Mount Holyoke College, South Hadley, Massachusetts 01075, USA
51 Dipartimento di Scienze Fisiche e INFN, Università di Napoli Federico II, I-80126, Napoli, Italy
52 NIKHEF, National Institute for Nuclear Physics and High Energy Physics, NL-1009 DB Amsterdam, The Netherlands
53 University of Notre Dame, Notre Dame, Indiana 46556, USA
54 Ohio State University, Columbus, Ohio 43210, USA
55 University of Oregon, Eugene, Oregon 97403, USA
56 Dipartimento di Fisica and INFN, Università di Padova, I-35131 Padova, Italy
57 Laboratoire de Physique Nucléaire et de Hautes Energies, Universités Paris VI et VII, F-75252 Paris, France
58 University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA
59 Dipartimento di Fisica and INFN, Università di Perugia, I-06100 Perugia, Italy
60 Dipartimento di Fisica, Scuola Normale Superiore, and INFN, Università di Pisa, I-56127 Pisa, Italy
61 Prairie View A&M University, Prairie View, Texas 77446, USA
62 Princeton University, Princeton, New Jersey 08544, USA
63 Dipartimento di Fisica and INFN, Università di Roma La Sapienza, I-00185 Roma, Italy
64 University of Rostock, D-18051 Rostock, Germany
65 Rutherford Appleton Laboratory, Didcot, Oxon, OX11 0QX, United Kingdom
66 DSM/Dapnia, CEA/Saclay, F-91191 Gif-sur-Yvette, France
67 University of South Carolina, Columbia, South Carolina 29208, USA
68 Stanford Linear Accelerator Center, Stanford, California 94309, USA
69 Stanford University, Stanford, California 94305-4060, USA
70 State University of New York, Albany, New York 12222, USA
71 University of Tennessee, Knoxville, Tennessee 37996, USA
72 University of Texas at Austin, Austin, Texas 78712, USA
73 University of Texas at Dallas, Richardson, Texas 75083, USA
74 Dipartimento di Fisica Sperimentale and INFN, Università di Torino, I-10125 Torino, Italy
75 Dipartimento di Fisica and INFN, Università di Trieste, I-34127 Trieste, Italy
76 IFIC, Universitat de Valencia-CSIC, E-46071 Valencia, Spain
77 Vanderbilt University, Nashville, Tennessee 37235, USA
78 University of Victoria, Victoria, British Columbia V8W 3P6, Canada
79 Department of Physics, University of Warwick, Coventry CV4 7AL, United Kingdom
80 University of Wisconsin, Madison, Wisconsin 53706, USA
81 Yale University, New Haven, Connecticut 06511, USA
(Received 1 February 2006; published 8 June 2006)
We report two novel determinations of $|V_{ub}|$ with reduced model dependence, based on measurements of the mass distribution of the hadronic system in semileptonic $B$ decays. Events are selected by fully reconstructing the decay of one $B$ meson and identifying a charged lepton from the decay of the other $B$ meson from $Y(4S) \to BB$ events. In one approach, we combine the inclusive $B \to X_s \ell \bar{\nu}$ rate, integrated up to a maximum hadronic mass $m_X < 1.67 \text{ GeV}/c^2$, with a measurement of the inclusive $B \to X_s \gamma$ photon energy spectrum. We obtain $|V_{ub}| = (4.43 \pm 0.38_{\text{stat}} \pm 0.25_{\text{syst}} \pm 0.29_{\text{theo}}) \times 10^{-3}$. In another approach we measure the total $B \to X_s \ell \bar{\nu}$ rate over the full phase space and find $|V_{ub}| = (3.84 \pm 0.70_{\text{stat}} \pm 0.30_{\text{syst}} \pm 0.10_{\text{theo}}) \times 10^{-3}$. 

The measurement of the element $V_{ub}$ of the Cabibbo-Kobayashi-Maskawa quark-mixing matrix [1] plays a critical role in testing the consistency of the standard model description of CP violation. The uncertainties in existing measurements [2,3] are dominantly due to uncertainties in the $b$-quark mass $m_b$ and the modeling of the Fermi motion of the $b$ quark inside the $B$ meson [4]. In this Letter, we present two techniques to extract $|V_{ub}|$ from inclusive $B \to X_s \ell \bar{\nu}$ [5] decays where these uncertainties are significantly reduced. Neither method has been previously implemented experimentally.

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 $m_X$ [6]. A technique utilizing weight functions had been proposed previously by Neubert [4]. The calculations of LLR are accurate up to corrections of order $\alpha_s^2$ and $[\Lambda m_b/(\zeta m_b)]^2$, where $\zeta$ is the experimental maximum hadronic mass up to which the $B \to X_s \ell \bar{\nu}$ decay rate is determined and $\Lambda \approx \Lambda_{\text{QCD}}$. This method combines the hadronic mass spectrum, integrated below $\zeta$, with the high-energy end of the measured differential $B \to X_s \gamma$ photon energy spectrum via the calculations of LLR.

An alternative method [7] to reduce the model dependence is to measure the $B \to X_d \ell \bar{\nu}$ 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 $\alpha_s^2$. We extract the $B \to X_d \ell \bar{\nu}$ rate from the hadronic mass spectrum up to $\zeta = 2.5 \text{ GeV}/c^2$ which corresponds to about 96% of the simulated hadronic mass spectrum.

The measurements presented here are based on a sample of $88.9 \times 10^6 BB$ pairs collected near the $Y(4S)$ resonance by the BABAR detector [8] at the PEPII asymmetric-energy $e^+e^-$ storage rings operating at SLAC. The analysis uses $Y(4S) \to BB$ events in which one of the $B$ mesons decays hadronically and is fully reconstructed ($B_1$) and the other decays semileptonically ($B_{sl}$). To reconstruct a large sample of $B$ mesons, we follow the procedure described in Ref. [2] in which 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 $B_1$ candidates.

We use Monte Carlo (MC) simulations of the BABAR detector based on GEANT4 [9] to optimize selection criteria and to determine signal efficiencies and background distributions. Charmless semileptonic $B \to X_s \ell \bar{\nu}$ decays are simulated as a combination of resonant three-body decays ($X_s = \pi, \rho, \omega, \eta, \eta')$ [10], and decays to nonresonant hadronic final states $X_s$ [11] for which the hadronization is performed by JETSET4.12. The effect of Fermi motion is implemented in the simulation using an exponential function [11] with the parameters $m_b = 4.79 \text{ GeV}/c^2$ and $\lambda_1 = -0.24 \text{ GeV}^2/c^4$ [13]. The simulation of the $B \to X \ell \bar{\nu}$ background uses a heavy quark effective theory parameterization of form factors for $B \to D^* \ell \bar{\nu}$ [14] and models for $B \to D \pi \ell \bar{\nu}$, $D^* \pi \ell \bar{\nu}$ [15], and $B \to D_s \ell \bar{\nu}$ [10] decays.

Semileptonic $B_{sl}$ candidates are identified by the presence of at least one electron or muon with momentum $p_\ell > 1 \text{ GeV}/c$ in the $B_{sl}$ rest frame. For charged $B_\ell$ candidates, we require the charge of the lepton to be consistent with a primary decay, and for neutral $B_\ell$ candidates, both charge-flavor combinations are retained and the average $B^0 \bar{B}^0$ mixing rate [16] is used to determine the primary lepton yield. Electrons (muons) are identified [17] (Ref. [8]), with a 92% (60–75%) average efficiency and a hadron misidentification rate ranging between 0.05% and 0.1% (1–3%).

The hadronic system $X$ in the $B \to X \ell \bar{\nu}$ decays is reconstructed from charged tracks and energy depositions in the calorimeter that are not associated with the $B_\ell$ candidate or the identified lepton. The neutrino four-momentum $p_\nu$ is estimated from the missing momentum four-vector $p_{\text{miss}} = p_{Y(4S)} - p_X - p_\ell$, where all momenta are measured in the laboratory frame and $p_{Y(4S)}$ refers to the $Y(4S)$ momentum.

To select $B \to X_s \ell \bar{\nu}$ candidates we require exactly one lepton with $p_\ell > 1 \text{ GeV}/c$ in the event, charge conservation ($Q_X + Q_\ell + Q_{B_1} = 0$), and a missing four-momentum consistent with a neutrino hypothesis, i.e., missing mass consistent with zero ($-1.0 < m_{\text{miss}}^2 < 0.5 \text{ GeV}^2/c^4$), $|p_{\text{miss}}| > 0.3 \text{ GeV}/c$, and $|\cos \theta_{\text{miss}}| < 0.95$, where $\theta_{\text{miss}}$ is the polar angle of the missing momentum three-vector $p_{\text{miss}}$. These criteria suppress the majority of $B \to X_s \ell \bar{\nu}$ decays that contain additional neutrinos or an undetected $K_S^0$ meson. Additionally we reject events with charged or neutral kaons (reconstructed as $K_S^0 \to \pi^+ \pi^- \pi^0$ decays) in the decay products of the $B_{sl}$. We suppress $B \to D^* \ell \bar{\nu}$...
backgrounds by partial reconstruction of charged and neutral $D^*$ mesons via identification of charged and neutral slow pions. 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 $p_T^\ell = 0$. The resulting $m_X$ resolution is $\sim 250$ MeV/$c^2$ on average.

The extraction of $|V_{ub}|/|V_{ts}|$ from the selected events starts from the equation [6]

$$|V_{ub}|/|V_{ts}| = \left[ 6\alpha (1 + H_{\text{mix}}^0) C_{(0)}^2 \pi I_0(\xi) + I_1(\xi) \right]^{1/2} \delta R_u(\xi), \tag{1}$$

where $\delta R_u(\xi)$ is the partial charmless semileptonic decay rate extracted from the number of $B \rightarrow X_u \ell \bar{\nu}$ events up to a limit $\xi$ in the $m_X$ spectrum. $H_{\text{mix}}^0$ accounts for interferences between electromagnetic penguin operator $O_7$ with $O_2$ and $O_8$ [18], and $C_{(0)}^0$ is the effective Wilson coefficient. The terms $I_0(\xi)$ and $I_1(\xi)$ are determined by multiplying the photon energy spectrum $d\Gamma / dE_\gamma$ in $B \rightarrow X_s \gamma$ decays [13] with weight functions [6] and integrating. The weights are zero below a minimum photon energy $E_\gamma = m_B/2 - \xi/4$.

In terms of measurable quantities, $\delta R_u(\xi)$ is

$$\delta R_u(\xi) = \frac{N_u(\xi) f(\xi) B(B \rightarrow X_u \ell \bar{\nu}) e_{u}^{\text{rec}} / e_{u}^{\text{true}}}{N_d e_u(\xi)}. \tag{2}$$

Here, $N_u(\xi)$ is the number of reconstructed $B \rightarrow X_u \ell \bar{\nu}$ events with $m_X < \xi$, $f(\xi)$ accounts for migration in and out of the region below $\xi$ due to finite $m_X$ resolution, $B(B \rightarrow X \ell \bar{\nu})$ is the total inclusive semileptonic branching fraction, and $e_u(\xi)$ is the efficiency for selecting $B \rightarrow X_u \ell \bar{\nu}$ decays once a $B \rightarrow X \ell \bar{\nu}$ decay has been identified with a hadronic mass below $\xi$. $N_d$ is the number of observed fully reconstructed $B$ meson decays with a charged lepton with momentum above 1 GeV/$c$, $e_{u}^{\text{rec}} / e_{u}^{\text{true}}$ corrects for the difference in the efficiency of the lepton momentum selection for $B \rightarrow X \ell \bar{\nu}$ and $B \rightarrow X_u \ell \bar{\nu}$ decays, and $e_{u}^{\text{rec}} / e_{u}^{\text{true}}$ accounts for the difference in the efficiency of reconstructing a $B$, in events with a $B \rightarrow X \ell \bar{\nu}$ and $B \rightarrow X_u \ell \bar{\nu}$ decay. By measuring the ratio of $B \rightarrow X_u \ell \bar{\nu}$ events to all semileptonic $B$ decays many systematic uncertainties cancel out.

We derive $N_u(\xi)$ from the $m_X$ distribution with a binned $\chi^2$ fit to four components: data, $B \rightarrow X_u \ell \bar{\nu}$ signal MC simulations, $B \rightarrow X_s \ell \bar{\nu}$ background MC simulations, and a small MC background from other sources (misidentified leptons, $B \rightarrow X \tau \bar{\nu}_\tau$, and charm decays), fixed relative to the $B \rightarrow X_u \ell \bar{\nu}$ component. $N_u(\xi)$ is determined after the subtraction of the fitted background contributions. For all four contributions, the combinatorial background is determined, separately in each bin of the $m_X$ distribution, with unbinned maximum likelihood fits to distributions of the beam energy-substituted mass $m_{\text{ES}} = \sqrt{s/4 - p_B^2}$ of the $B$ candidate, where $\sqrt{s}$ is the $e^+ e^-$ center-of-mass energy. The $m_{\text{ES}}$ fit uses an empirical description of the combinatorial background shape [19] with a signal shape [20] peaking at the $B$ meson mass. The combinatorial background varies from 5% (low $m_X$ bins) to 25% (high $m_X$ bins). The fitted $m_X$ distributions are shown in Fig. 1(a) before and in Fig. 1(b) after subtraction of backgrounds. The $m_X$ bins are 300 MeV/$c^2$ wide except that one bin is widened such that its upper edge is at $\xi$.

We extract $N_d = (3.253 \pm 0.024) \times 10^4$ from an unbinned maximum likelihood fit to the $m_{\text{ES}}$ distribution of all events with $p_T^\ell > 1$ GeV/$c$. The efficiency corrections $e_{u}^{\text{rec}} / e_{u}^{\text{true}} = 0.82 \pm 0.02_{\text{stat}}$, as well as $e_u(\xi)$ and $f(\xi)$ (see Table I) are derived from simulations, where we also find $e_{u}^{\text{rec}} / e_{u}^{\text{true}}$ in agreement with one, assigning a 3% uncertainty.

We study three categories of systematic uncertainties in the determination of $|V_{ub}|$: uncertainties in the signal extraction, the simulation of physics processes, and the theoretical description. The quoted uncertainties have been determined for a value of $\xi = 1.67$ GeV/$c^2$ where the total uncertainty on $|V_{ub}|$ is found to be minimal.

Experimental uncertainties in the signal extraction arise from imperfect description of data by the detector simulation. We assign 0.5% (0.5%, 0.8%) for the particle identification of electrons ($\mu$, $K^\pm$), 0.7% for the reconstruction efficiency of charged particles, and 0.8% for the resolution and reconstruction efficiency of neutral particles. An additional 0.9% uncertainty is due to imperfect simulation of $K^0_L$ interactions. By changing the function describing the signal shape in $m_{\text{ES}}$ to a Gaussian function and switching from an unbinned to a binned fit method we derive an uncertainty of 2.2%. An uncertainty of 0.8% is determined by letting the contribution from other sources (see above) to the $m_X$ spectrum float freely in the minimum-$\chi^2$ fit. The uncertainties on the inclusive $B \rightarrow X_s \gamma$ photon energy

![FIG. 1](https://example.com/figure1.png)  

FIG. 1 (color online). The $m_X$ distributions (without combinatorial backgrounds) for $B \rightarrow X_s \ell \bar{\nu}$ candidates: (a) data (points) and fit components after the minimum-$\chi^2$ fit, and (b) data and signal MC simulations after subtraction of the $B \rightarrow X_s \ell \bar{\nu}$ and other backgrounds. The upper edge of the eighth bin is chosen to be at $m_X = 2.5$ GeV/$c^2$. This fit result, with $\chi^2 = 10.2$ for 11 degrees of freedom, is used to extract the number of signal events below 2.5 GeV/$c^2$.  

221801-5
the resonant final states have been varied by an uncertainty of 0.5%. The branching fractions of the nonresonant final states has been varied by 20% resulting in an uncertainty of 5.4%. Theoretical uncertainties in the measurement via the full rate are taken from Ref. [23] to be 1.2% (QCD) and 2.2% (HQE). Table II provides a summary of the uncertainties for $\zeta = 1.67$ GeV/c² and for $\zeta = 2.5$ GeV/c².

Finally, we present two different determinations of $|V_{ub}|$. First, using the weighting technique with the photon energy spectrum in $B \rightarrow X_s \gamma$ decays from Ref. [13], the hadronic mass spectrum up to a value of $\zeta = 1.67$ GeV/c², we find $|V_{ub}|/|V_{ts}| = 0.107 \pm 0.009_{\text{stat}} \pm 0.006_{\text{syst}} \pm 0.007_{\text{theo}}$. If we assume the Cabibbo-Kobayashi-Maskawa matrix is unitary then $|V_{ub}| = |V_{ub}| \times [1 \pm 0(1\%)]$ and, taking $|V_{cb}|$ from Ref. [24], we derive

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

where the first error is the statistical uncertainty from $\bar{B} \rightarrow X_s \ell \bar{\nu}$ and from $B \rightarrow X_s \gamma$ added in quadrature, the second (third) is systematic (theoretical). Second, we determine $|V_{ub}|$ from a measurement of the full $m_X$ spectrum, i.e., up to a value of $\zeta = 2.5$ GeV/c², and find $|V_{ub}| = (3.84 \pm 0.70_{\text{stat}} \pm 0.30_{\text{syst}} \pm 0.10_{\text{theo}}) \times 10^{-3}$, using the average $B$ lifetime of $\tau_B = (1.604 \pm 0.012)$ ps [16,25].

The weighting technique is expected to break down at low values of $\zeta$, since only a small fraction of the phase space is used. Figure 2 illustrates the dependence of the result, and its statistical and theoretical uncertainties, on variations of $\zeta$ and also compares it with the value of $|V_{ub}|$ determined from the full rate. The weighting technique

![FIG. 2 (color online). $|V_{ub}|$ as a function of $\zeta$ with the LLR method (left) and for the determination with the full rate measurement (right). The error bars indicate the statistical uncertainty. They are correlated between the points and get larger for larger $\zeta$ due to larger background from $\bar{B} \rightarrow X_s \ell \bar{\nu}$. The total shaded area illustrates the theoretical uncertainty; the inner light shaded (yellow online) area indicates the perturbative share of the uncertainty. The arrow indicates $\zeta = 1.67$ GeV/c².](image)
appears to be stable down to $\zeta \sim 1.4 \text{ GeV}/c^2$. The current uncertainties on the $B \to X_s \gamma$ photon energy spectrum limit the sensitivity with which the behavior at high $\zeta$ can be probed.

The above results are consistent with previous measurements [2,3] but have substantially smaller uncertainties from $m_B$ and the modeling of Fermi motion. Both techniques are based on theoretical calculations that are distinct from other calculations normally employed to extract $|V_{ub}|$ and, thus, provide a complementary determination of $|V_{ub}|$.

We wish to thank Adam Leibovich, Ian Low, and Ira Rothstein for their help and support. We are grateful for the excellent luminosity and machine conditions provided by our PEP-II colleagues, and for the substantial dedicated effort from the computing organizations that support BABAR. The collaborating institutions wish to thank SLAC for its support and kind hospitality. This work is supported by DOE and NSF (USA), NSERC (Canada), NFR (Norway), MIST (Russia), and PPARC (United Kingdom). Individuals have received support from the A.P. Sloan Foundation, Research Corporation, and Alexander von Humboldt Foundation.

\section*{References}

[5] Charge conjugation is implied throughout the Letter.
[25] The impact of the uncertainty of the relative fraction of produced neutral and charged $B$ mesons is negligible.