Determination of $|V_{ub}|$ from Measurements of the Electron and Neutrino Momenta in Inclusive Semileptonic $B$ Decays

B. Aubert, R. Barate, D. Boutigny, F. Couderc, Y. Karyotakis, J. P. Lees, V. Poireau, V. Tisserand, A. Zaglache, E. Grauges, A. Palano, M. Pappagallo, A. Pompli, J. C. Chen, N. D. Qi, G. Rong, P. Wang, Y. S. Zhu, G. Eigen, I. Ofte, B. Stugu, G. S. Abrams, M. Battaglia, A. B. Breon, D. N. Brown, J. Button-Shafer, R. N. Cahn, E. Charles, T. C. Day, M. S. Gill, A. V. Gritsan, Y. Groysman, R. G. Jacobsen, R. W. Kadel, J. Kadyk, L. T. Kerth, Yu. G. Kolomensky, G. Kukartsev, G. Lynch, L. M. Mir, P. J. Oddone, T. J. Orimoto, M. Pripstein, N. A. Roe, M. T. Ronan, W. A. Wenzel, M. Barrett, K. E. Ford, T. J. Harrison, A. J. Hart, C. M. Hawkes, S. E. Morgan, A. T. Watson, M. Fritsch, K. Goetz, T. Held, H. Koch, B. Lewandowski, M. Pelizaevs, K. Peters, T. Schroeder, M. Steinke, J. T. Boyd, J. P. Burke, N. Chevalier, W. N. Cottonham, M. P. Kelly, T. Cuhadar-Donszelmann, B. G. Fulsom, C. Hearty, N. S. Knecht, T. S. Mattison, A. McKenna, A. Khan, P. Kyberd, M. Saleem, L. Teodorescu, A. E. Blinov, V. E. Blinov, A. D. Bukić, V. P. Druzhinin, V. B. Golubev, E. A. Kravchenko, A. O. Puncin, H. I. Serednyakov, Yu. I. Skovpen, E. P. Solodov, A. N. Yushkov, D. Best, M. Bondioli, M. Bruni, M. Chao, I. Eschrich, D. Kirkby, J. Lankford, M. Mandelkern, R. K. Momsen, W. Roethel, D. P. Stoker, C. Buchanan, B. L. Hartfiel, A. J. R. Weinstein, S. F. Doulas, J. W. Gary, O. Long, B. C. Shen, K. Wang, L. Zhang, D. del Re, H. K. Hadavand, E. J. Hill, D. B. MacFarlane, H. P. Paar, S. Rahatlou, V. Sharma, J. W. Berryhill, C. Campagnari, A. Cunha, B. Dahmes, T. M. Hong, M. A. Mazur, J. D. Richman, W. Verkerke, T. W. Beck, A. M. Eisner, C. J. Flacco, A. C. Heus, K. J. Roseberg, W. S. Lockman, G. Nesomi, T. Schalk, B. A. Schunn, A. Seiden, P. Spradlin, D. C. Williams, M. G. Wilson, J. Albert, E. Chen, G. P. Dubois-Felsmann, A. Dvoretzki, D. G. Hitlin, I. Narsky, T. Piatenko, F. C. Porter, A. Ryd, A. Samuel, R. Andreassen, S. Jayatilleke, G. Mancinelli, B. T. Meadows, M. D. Sokoloff, F. Blanc, P. Bloom, S. Chen, W. T. Ford, U. Nauenberg, A. Olivas, P. Rankin, W. O. Ruddick, J. G. Smith, K. A. Ulmer, S. R. Wagner, J. Zang, L. Zhong, C. Allen, E. Eckhart, A. Soffer, W. H. Toki, R. J. Wilson, Q. Zeng, D. Altenburg, E. Feltresi, A. Hauke, B. Spaan, T. Brandt, J. Brose, M. Dickopp, V. Klose, H. M. Lackner, R. Nogowski, S. Otto, A. Petzold, G. Schott, J. Schubert, K. R. Schubert, R. Schwierz, J. E. Sundermann, D. Bernard, G. R. Bonneau, P. Grenier, S. Schrenk, Ch. Thiebaux, G. Vasileiadis, M. Verderi, D. J. Bard, P. J. Clark, W. Gradl, F. Muheim, S. Playfer, Y. Xie, M. Andreotti, V. Azzolini, D. Bettoni, C. Bozzi, R. Calabrese, G. Cibinetto, E. Luppi, M. Negri, L. Piemontese, F. Anulli, R. Baldini-Ferroli, A. Calcaterra, R. de Sangro, G. Finocchiaro, P. Patteri, I. M. Peruzzi, M. Piccolo, A. Zallo, A. Buzzo, R. Capra, R. Contri, M. Lo Vetere, M. Macri, M. R. Monge, S. Passaggio, C. Patrignani, E. Robutti, A. Santroni, S. Tosi, S. Bailey, G. Brandenburg, K. S. Chaisanguanthum, M. Mori, E. Won, J. Wu, R. S. Dubitzky, U. Langenegger, J. Marks, S. Schenk, U. Wier, B. Whinney, D. A. Bowerman, P. D. Dauncey, U. Egede, R. L. Flack, J. R. Gaillard, G. W. Morton, J. A. Nash, M. B. Nikolich, G. P. Taylor, W. P. Vazquez, M. J. Charles, W. F. Mader, U. Mallik, A. K. Mohapatra, J. Cochran, H. B. Crawley, V. Eyges, W. T. Meyer, S. Prell, E. I. Rosenberg, A. E. Rubin, J. Yi, N. Arnaud, M. Davier, X. Giroux, G. Grosdidier, A. Höcker, F. Le Diberder, V. Lepeltier, A. M. Lutz, A. Oyanguren, T. C. Petersen, M. Pierini, S. Plaszczynski, S. Rodier, P. Roudeau, M. H. Schune, A. Stocchi, G. Wormser, C. H. Cheng, D. J. Lange, M. C. Simani, D. M. Wright, A. J. Bevan, C. A. Chavez, J. P. Coleman, J. I. Forster, J. R. Fry, E. Gabathuler, R. Gamet, K. A. George, D. E. Hutchcroft, R. J. Parry, D. J. Payne, K. C. Schofield, C. Tornamissi, C. M. Cormack, F. Di Lodovico, R. Sacco, C. L. Brown, G. Cowan, H. U. Flaecher, M. Green, D. A. Hopkins, P. S. Jackson, T. R. McMahon, S. Ricciardi, F. Salvatore, D. Brown, C. L. Davis, J. Allison, R. Barlow, R. J. Barlow, M. C. Hodgkinson, G. D. Lafferty, M. T. Naisbit, J. C. Williams, C. Chen, A. Farbin, W. D. Hulsbergen, A. Jawahery, D. Kovalskyi, C. K. Lai, V. Lillard, D. A. Roberts, G. Simi, G. Blaylock, C. Dallapiccola, S. Hertzbach.
We present a determination of the CKM matrix element $|V_{ub}|$ based on the analysis of semileptonic $B$ decays from a sample of 88 million $\Upsilon(4S)$ decays collected with the BABAR detector at the PEP-II $e^+e^-$ storage ring. Charmless semileptonic $B$ decays are selected using measurements of the electron energy and the invariant mass squared of the electron-neutrino pair. We obtain $|V_{ub}| = (4.41 \pm 0.30 \pm 0.47 \pm 0.28) \times 10^{-3}$, where the errors represent experimental uncertainties, heavy quark parameter uncertainties, and theoretical uncertainties, respectively.

Note: this document includes corrections to the original publication of this work [1]. These corrections, which affect the calculated efficiencies and quantities derived from them, will appear in an erratum.

PACS numbers: 13.20.He, 12.15.Hh, 14.40.Nd

The study of the weak interactions of quarks has played a crucial role in the development of the Standard Model (SM), which embodies our understanding of the fundamental interactions. The increasingly precise measurements of $CP$ asymmetries in $B$ decays allow stringent experimental tests of the SM mechanism for $CP$ violation via the complex phase in the Cabibbo-Kobayashi-Maskawa (CKM) matrix [2]. Improved determinations of $|V_{ub}|$, the coupling strength of the $b$ quark to the $u$ quark, will improve the sensitivity of these tests.

Two observables have been used to determine $|V_{ub}|$ from inclusive semileptonic $B$ decays: the endpoint of the lepton momentum spectrum [3] and the mass of the accompanying hadronic system [4]. In this paper, semileptonic $\bar{B} \rightarrow X_\ell e\bar{\nu}$ decays are selected 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, $q^2$ [5]. 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 $q^2\mathrm{E}_e$ phase space where correctly reconstructed $\bar{B} \rightarrow X_\ell e\bar{\nu}$ events are kinematically excluded. Background contamination in the signal region is due to resolution effects and is evaluated in Monte Carlo (MC) simulations. Theoretical calculations are applied to the measured $\bar{B} \rightarrow X_\ell e\bar{\nu}$ partial rate to determine $|V_{ub}|$, the precision of which is limited mostly by our current knowledge of the $b$-quark mass, $m_b$.

The data used in this analysis were collected with the BABAR detector [6] at the PEP-II asymmetric-energy $e^+e^-$ storage ring. The data set consists of 88.4 million $B\bar{B}$ pairs collected at the $\Upsilon(4S)$ resonance, corresponding to an integrated luminosity of 81.4 fb$^{-1}$ at $\sqrt{s} = 10.58$ GeV. An additional 9.6 fb$^{-1}$ of data were collected at center-of-mass energies 20 MeV below the $B\bar{B}$ threshold. Off-resonance data are used to subtract the non-$B\bar{B}$ contributions from the data collected at the $\Upsilon(4S)$ resonance. To do so, the off-resonance data are scaled according to the integrated luminosity and the energy dependence of the QED cross-section, and the particles are boosted to the $T(4S)$ resonance energy. Throughout this paper, all kinematic variables are given in the $T(4S)$ rest frame unless stated otherwise.

The simulation of charmless semileptonic $B$ decays used in optimizing the analysis and determining reconstruction efficiencies is based on the Heavy Quark Expansion (HQE) including $O(\alpha_s)$ corrections [7]. This calculation produces a continuous spectrum of hadronic masses, $m_X$. Subsequent hadronization is simulated using JETSET down to $2m_\pi$ [8]. Decays to low-mass hadrons ($\pi$, $\eta$, $\rho$, $\omega$, $\eta'$) are simulated separately using the ISGW2 model [9], and mixed with the non-resonant states so that the $m_X$, $q^2$ and $E_e$ spectral distributions correspond as closely as possible to the HQE calculation.

Hadronic events containing an identified electron with energy $2.1 \text{ GeV} < E_e < 2.8 \text{ GeV}$ are selected. Radiative Bhabha events rejected using the criteria given in Ref. [10] and electrons from $J/\psi \rightarrow e^+e^-$ decays are vetoed. The total visible 4-momentum, $p_{\text{vis}}$, is determined using charged tracks emanating from the collision point, identified pairs of charged tracks from $K^0_s \rightarrow \pi^+\pi^-$, $\Lambda \rightarrow p\pi^-$ and $\gamma \rightarrow e^+e^-$, and energy deposits in the electromagnetic calorimeter. Each charged particle is assigned a mass hypothesis based on particle identification information. Calorimeter clusters unassociated with a charged track and with a lateral energy spread consistent with electromagnetic showers are treated as photons.

Additional requirements are made to improve the quality of the neutrino reconstruction and suppress contributions from $e^+e^- \rightarrow q\bar{q}$ continuum events. We form the missing 4-momentum, $p_{\text{miss}} = p_{e^+e^-} - p_{\text{vis}}$, where $p_{e^+e^-}$ is the 4-momentum of the initial state. For each event we require (1) no additional identified $e$ or $\mu$; (2) $-0.95 < \cos\theta_{\text{miss}} < 0.8$, where $\theta_{\text{miss}}$ is the polar angle of the missing 3-momentum; (3) $0.0 \text{ GeV} < E_{\text{miss}} < 0.8 \text{ GeV}$, where $E_{\text{miss}}$ is the missing energy in the event; (4) $|p_{\text{miss}}| < 2.5 \text{ GeV}$ and (5) $|\cos\theta_T| < 0.75$, where $\theta_T$ is the angle between the electron momentum and the thrust vector of the remaining particles in the event.

The measured $|p_{\text{miss}}|$ differs from the true neutrino momentum due to additional particles that escape de-
tection. Therefore, a bias correction, \( p_\nu = p_{\text{miss}}(0.804 - 0.078/|p_{\text{miss}}|) \), is derived from the simulation. Since the resolution on \(|p_{\text{miss}}|\) is superior to that of \( E_{\text{miss}} \), we set \( p_\nu = (p_{e\nu}, p_\mu) \) and the resolution on \( B_{\nu} \), we set \( p_\nu = (p_{e\nu}, p_\mu) \) and the resolution on \( B_{\nu} \), we set \( p_\nu = (p_{e\nu}, p_\mu) \) and the resolution on \( B_{\nu} \), we set \( p_\nu = (p_{e\nu}, p_\mu) \) and the resolution on \( B_{\nu} \), we set \( p_\nu = (p_{e\nu}, p_\mu) \) and the resolution on \( B_{\nu} \), we set \( p_\nu = (p_{e\nu}, p_\mu) \) and the resolution on \( B_{\nu} \), we set \( p_\nu = (p_{e\nu}, p_\mu) \) and the resolution on \( B_{\nu} \), we set \( p_\nu = (p_{e\nu}, p_\mu) \) and the resolution on \( B_{\nu} \), we set \( p_\nu = (p_{e\nu}, p_\mu) \) and the resolution on \( B_{\nu} \), we set \( p_\nu = (p_{e\nu}, p_\mu) \) and the resolution on \( B_{\nu} \), we set \( p_\nu = (p_{e\nu}, p_\mu) \) and the resolution on \( B_{\nu} \), we set \( p_\nu = (p_{e\nu}, p_\mu) \) and the resolution on \( B_{\nu} \), we set \( p_\nu = (p_{e\nu}, p_\mu) \) and the resolution on \( B_{\nu} \), we set \( p_\nu = (p_{e\nu}, p_\mu) \) and the resolution on \( B_{\nu} \), we set \( p_\nu = (p_{e\nu}, p_\mu) \) and the resolution on \( B_{\nu} \), we set \( p_\nu = (p_{e\nu}, p_\mu) \) and the resolution on \( B_{\nu} \), we set \( p_\nu = (p_{e\nu}, p_\mu) \) and the resolution on \( B_{\nu} \), we set \( p_\nu = (p_{e\nu}, p_\mu) \) and the resolution on \( B_{\nu} \), we set \( p_\nu = (p_{e\nu}, p_\mu) \) and the resolution on \( B_{\nu} \), we set \( p_\nu = (p_{e\nu}, p_\mu) \) and the resolution on Solution Description

The quality of the neutrino reconstruction is evaluated using a control sample (\( D\ell\nu \)) consisting of the decays \( B^{-} \rightarrow D^{0}\ell\nu(X) \), where kinematic criteria result in the \( X \) system typically being no more than a \( \pi \) or \( \gamma \) from a \( D^{*} \rightarrow D^{0}X \) transition. The \( D^{0} \) is reconstructed in the \( K^{-}\pi^{+} \) decay mode and we require \(|p_{D^{0}}| > 0.5\) GeV and \( E_{\nu} > 1.4\) GeV. The \( D^{*}\ell \) combination must satisfy \(-2.5 < \cos\theta_{D^{*}\ell} < 1.1 \), where \( \cos\theta_{D^{*}\ell} = (2E_{\ell}E_{D^{0}} - m_{D^{0}}^{2} - m_{\ell}^{2})/(2E_{\ell}E_{D^{0}}) \) is the cosine of the angle between the vector momenta of the \( D^{0} \) and the \( D^{*}\ell \) system assuming the only missing particle in the \( D^{*} \) decay was a single neutrino. After the combinatorial background is subtracted using \( D^{0} \) mass sidebands, the selected sample consists primarily (\( \sim 95\% \)) of \( B^{-} \rightarrow D^{0}\ell\nu \) and \( B^{-} \rightarrow D^{*}\ell \nu \) decays. The control sample selection makes no requirements on the other \( B \) in the event, and can therefore be used to study the impact of the modeling of the other \( B \) on the neutrino reconstruction. Since the unreconstructed \( X \) system in the \( B^{-} \rightarrow D^{0}\ell\nu(X) \) decays carries away little energy, a good estimate (r.m.s. \( \sim 0.2 \) GeV) of the neutrino energy can be obtained from the known \( B^{-} \) energy and the measured \( D^{0} \) and \( \ell \) energies, \( E_{\nu}^{D^{0}\ell} \). A second estimate of the neutrino energy is constructed from the visible momentum as described previously. Subtracting the first estimate from the second gives the distribution shown in Fig. 1, where the criteria (1)–(5) described above have been imposed. We find good agreement between data and MC; the average (r.m.s.) is 0.066 GeV (0.366 GeV) for data and 0.072 GeV (0.365 GeV) for simulated events.

The \( D\ell\nu \) control sample is also used to improve the modeling of the \( B^{-} \rightarrow X_{e\ell}\nu \) decays. After relaxing the \( \cos\theta_{B^{-}D_{\ell}} \), requirements and subtracting continuum and combinatorial backgrounds, we perform a binned \( \chi^{2} \) fit to the \( D\ell\nu \) sample in the variables \(|p_{\ell}|, E_{\ell}, \cos\theta_{B^{-}D_{\ell}} \). The fit determines scale factors for the MC components \( B^{-} \rightarrow D\ell\nu \), \( B^{-} \rightarrow D^{*}\ell\nu \) and other contributions (85\% of which are decays to \( D^{*} \) states), while keeping the total \( B^{-} \rightarrow X_{e\ell}\nu \) branching fraction fixed to the measured value [11]. The fit increases the \( B^{-} \rightarrow D\ell\nu \) and \( B^{-} \rightarrow D^{*}\ell\nu \) branching fractions to 2.29\% and 6.02\% (2.48\% and 6.52\%) for neutral (charged) \( B \) mesons, respectively, while decreasing the remaining contributions. By design, these revised branching fractions respect isospin symmetry and are used in the determination of the background.

Two control samples are used to reduce the sensitivity of the efficiency and background estimates to details of the simulation: the \( D\ell\nu \) control sample described above, but with \( E_{\nu} > 2.0 \) GeV; and events satisfying the normal selection criteria but having \( s_{h}^{\text{max}} \) \( > 4.25 \) GeV\(^{2} \), a sample with < 5\% signal decays. Efficiencies \( e_{\text{data}} \) and \( e_{\text{MC}} \) are calculated separately in data and MC as the ratio of \( D\ell\nu \) candidates satisfying criteria (1)–(5) to the total \( D\ell\nu \) sample. The \( B^{-} \rightarrow X_{e\ell}\nu \) signal efficiency is multiplied by the ratio of these efficiencies to reduce sensitivity to details of the simulation. The \( s_{h}^{\text{max}} \) < 4.25 GeV\(^{2} \) sideband region is used to normalize the simulated \( s_{h}^{\text{max}} \) distribution to the data, reducing sensitivity to background normalization uncertainties.

We determine a partial branching fraction \( \Delta B(\tilde{E}, s_{h}^{\text{max}}) = B(\tilde{B}^{-} \rightarrow X_{e\ell}\nu) f_{u}, \) unfolded for detector effects. The acceptance, \( f_{u} \), is the fraction of \( \tilde{B}^{-} \rightarrow X_{e\ell}\nu \) decays in the region of interest, \( \tilde{E}_{e} > 2.0 \) GeV and \( s_{h}^{\text{max}} < 3.5 \) GeV\(^{2} \), where \( \tilde{E}_{e} \) and \( \tilde{s}_{h}^{\text{max}} \) are the true (generated) values in the \( B \) meson rest frame. Slightly lower values are accepted for \( \tilde{E}_{e} \) than for \( E_{\nu} \) to account for the boost of the \( B \) meson and to increase \( f_{u} \). The efficiency times acceptance for \( \tilde{B}^{-} \rightarrow X_{e\ell}\nu \) decays can be written as \( \epsilon_{u} = \epsilon_{\text{sig}} f_{u} + \epsilon_{\text{sig}}(1 - f_{u}) \), where \( \epsilon_{\text{sig}} \) is the efficiency for an event inside (outside) the region of interest to be reconstructed and pass our selection criteria. We calculate the partial branching fraction as follows:

\[
\Delta B = \frac{N_{\text{cand}} - M_{\text{bkg}} N_{\text{side}} M_{\text{side}}}{2 N_{\text{bkg}} c_{\ell,\text{MC}} c_{\ell,\text{sig}}} \left[ 1 + \frac{1 - f_{u} \epsilon_{\text{sig}}}{f_{u} \epsilon_{\text{sig}}} \right]^{-1}, \tag{1}
\]

where \( N_{\text{cand}} \) and \( N_{\text{side}} \) refer to the number of candidates in the signal and \( s_{h}^{\text{max}} \) sideband regions of the data, \( M_{\text{bkg}} \) and \( M_{\text{side}} \) refer to background in the signal re-

FIG. 1: The difference between the two neutrino energy estimates described in the text for continuum-subtracted data and simulated \( B\bar{B} \) events for the \( D\ell\nu \) control sample.
region and the yield in the sideband region in simulated events and $2N_{B\pi}$ is the number of $B$ mesons produced from $\Upsilon(4S) \to B\overline{B}$ decays. Since the resulting ratio of $\epsilon_{\text{sig}}/\epsilon_{\text{side}}$ is small, $\Delta B$ depends only weakly on the model used to determine $f_u$.

Fig. 2 shows the electron energy and $s_h^{\text{max}}$ distributions after cuts have been applied to all variables except the one being displayed. The discrepancy observed between data and MC for $E_e < 1.95\,\text{GeV}$ is covered by the systematic error on the $B \to X_e\pi$ modeling. The yields and efficiencies are given in Table I. We find

$$\Delta B(2.0, 3.5) = (4.41 \pm 0.42 \pm 0.42) \times 10^{-4}$$

where the uncertainties are statistical and systematic, respectively. Alternative values of $\Delta B$ are obtained using different electron energy requirements: $\Delta B(1.9, 3.5) = (5.29 \pm 0.44 \pm 0.72) \times 10^{-4}$ and $\Delta B(2.1, 3.5) = (3.68 \pm 0.43 \pm 0.36) \times 10^{-4}$.

![Fig. 2: The electron energy, $E_e$, and $s_h^{\text{max}}$ spectra in the $\Upsilon(4S)$ frame for continuum-subtracted data and simulated $B\overline{B}$ events satisfying all selection requirements except for the variable shown. The arrows denote the signal (and sideband) region in $E_e$ and $s_h^{\text{max}}$. Note that $E_e \neq E_c$ (see text).](image)

Systematic uncertainties are assigned for the modeling of the signal $B \to X_e\pi$ decays, background and detector response. The leading sources of uncertainty are listed in Table II. Uncertainties from the simulation of charged particle tracking, neutral reconstruction, charged particle identification, and the energy deposition by $K_L^0$ were evaluated from studies comparing data and simulation. Radiation in the decay process was simulated using

| Source | $\sigma(\eta_e)/\eta_e$ (%) | $\sigma(\Delta B)/\Delta B$ (%) |
|--------|---------------------------|-----------------------------|
| Tracking | $\pm 0.8$ | $\pm 1.5$ |
| Neutrals | $\pm 1.7$ | $\pm 3.4$ |
| Electron ID | $\pm 0.5$ | $\pm 1.0$ |
| Hadron ID | $\pm 1.0$ | $\pm 2.0$ |
| Bremsstrahlung | $\pm 1.0$ | $\pm 2.0$ |
| $K_L^0$ | $\pm 1.3$ | $\pm 2.6$ |
| $N_{B\pi}$ | $\pm 0.6$ | $\pm 1.1$ |
| Radiation | $\pm 1.9$ | $\pm 3.8$ |
| $B \to X_e\pi$ modeling | $\pm 2.5$ | $\pm 5.0$ |
| $B \to X_e\pi$ resonances | $\pm 2.2$ | $\pm 4.4$ |
| Statistical | $\pm 1.7$ | $\pm 9.3$ |
| Total experimental | $\pm 6.7$ | $\pm 13.3$ |
| Heavy quark parameters | $\pm 1.0$ | $\pm 1.5$ |
| Theoretical | $\pm 6.3$ | $\pm 1.5$ |

We extract $|V_{ub}| = |\Delta B/(\Delta\zeta \tau_B)|^{1/2}$ using $\tau_B = 1.604 \pm 0.023\,\text{ps}$ [17]. The normalized partial rate, $\Delta\zeta$, computed in units of $\Delta(\eta_e)^2$, is taken from Ref. [18], in which the leading terms in the HQE of the $B \to X_e\pi$ spectra are computed at next-to-leading order, and power corrections are included at $O(\alpha_S)$ for the lead-

| Source | $\sigma(\eta_e)/\eta_e$ (%) | $\sigma(\Delta B)/\Delta B$ (%) |
|--------|---------------------------|-----------------------------|
| Tracking | $\pm 0.8$ | $\pm 1.5$ |
| Neutrals | $\pm 1.7$ | $\pm 3.4$ |
| Electron ID | $\pm 0.5$ | $\pm 1.0$ |
| Hadron ID | $\pm 1.0$ | $\pm 2.0$ |
| Bremsstrahlung | $\pm 1.0$ | $\pm 2.0$ |
| $K_L^0$ | $\pm 1.3$ | $\pm 2.6$ |
| $N_{B\pi}$ | $\pm 0.6$ | $\pm 1.1$ |
| Radiation | $\pm 1.9$ | $\pm 3.8$ |
| $B \to X_e\pi$ modeling | $\pm 2.5$ | $\pm 5.0$ |
| $B \to X_e\pi$ resonances | $\pm 2.2$ | $\pm 4.4$ |
| Statistical | $\pm 1.7$ | $\pm 9.3$ |
| Total experimental | $\pm 6.7$ | $\pm 13.3$ |
| Heavy quark parameters | $\pm 1.0$ | $\pm 1.5$ |
| Theoretical | $\pm 6.3$ | $\pm 1.5$ |
ing shape function (SF) and at tree level for subleading SFs. The values used for the heavy quark parameters, \( m_b = 4.61 \pm 0.08 \text{ GeV} \) and \( \mu_h^2 = 0.15 \pm 0.07 \text{ GeV}^2 \), with a correlation coefficient of \(-0.4\), are based on fits to \( B \to X_c \ell \nu_\ell \) moments [19], translated to the shape-function scheme of Ref. [20].

We find \( |V_{ub}| = (4.41 \pm 0.30 \pm 0.05) \times 10^{-3} \) for \( \bar{E}_c > 2.0 \text{ GeV} \), where the errors represent experimental, heavy quark parameters, and theoretical uncertainties, respectively. The latter include estimates of the effects of subleading SFs [21], variations in the matching scales used in the calculation, and weak annihilation [22]. No uncertainty is assigned for possible quark-hadron duality violation. The determination of \( |V_{ub}| \) is limited primarily by our knowledge of \( m_b \). An approximate dependence is \( |V_{ub}(m_b)| = |V_{ub}(m_0)| (1 + 7(m_b - m_0)/m_0) \), where \( m_0 = 4.61 \text{ GeV} \). The sensitivity to higher moments of the SF is weak: the change in \( |V_{ub}| \) when varying \( \mu_h^2 \) from 0.03 to 0.35 GeV\(^2\) with \( m_b \) fixed is 2\%, and the impact of using alternative SF parameterizations [23] is < 2\%. The overall precision on the above result surpasses that of Refs. [3] and [4], but is comparable to determinations of \( |V_{ub}| \) which have become available while this paper was nearing completion [24].

**ACKNOWLEDGMENTS**

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), IHEP (China), CEA and CNRS-IN2P3 (France), BMF and DFG (Germany), INFN (Italy), FOM (The Netherlands), NFR (Norway), MIST (Russia), and PPARC (United Kingdom). Individuals have received support from CONACyT (Mexico), Marie Curie EIF (European Union), the A. P. Sloan Foundation, the Research Corporation, and the Alexander von Humboldt Foundation. Finally, we would like to thank the many theorists with whom we have had valuable discussions, and further thank M. Neubert, B. Lange and G. Paz for making available for our use a computer code implementing their calculations.

---

* Also with Università di Perugia, Dipartimento di Fisica, Perugia, Italy

† Deceased

[1] B. Aubert et al. (BaBar Collab.), Phys. Rev. Lett. 95, 111801 (2005).

[2] M. Kobayashi and T. Maskawa, Prog. Theor. Phys. 49, 652 (1973).

[3] R. Fulton et al. (CLEO Collab.), Phys. Rev. Lett. 64, 16 (1990); J. Bartelt et al., Phys. Rev. Lett. 31, 1141 (1993); A. Bornheim et al., Phys. Rev. Lett. 88, 231803 (2002); H. Albrecht et al. (ARGUS Collab.), Phys. Lett. B 234, 409 (1990); and Phys. Lett. B 255, 297 (1991).

[4] B. Aubert et al. (BaBar Collab.), Phys. Rev. Lett. 92, 071802 (2004); H. Kakuno et al. (BELLE Collab.), Phys. Rev. Lett. 92, 101801 (2004).

[5] R. Kowalewski and S. Menke, Phys. Lett. B 541, 29 (2002). We have modified the definition of \( s_{\text{max}} \) from that given in this reference.

[6] B. Aubert et al. (BaBar Collab.), Nucl. Instr. Methods Phys. Res., Sect. A 479, 1 (2002).

[7] F. De Fazio and M. Neubert, JHEP 06, 017 (1999).

[8] T. Sjostrand, Comput. Phys. Commun. 82, 74 (1994).

[9] N. Isgur, D. Scora, B. Grinstein and M. Wise, Phys. Rev. D 39, 799 (1989).

[10] B. Aubert et al. (BaBar Collab.), Phys. Rev. D 67, 031101 (2003).

[11] B. Aubert et al. (BaBar Collab.), Phys. Rev. D 69, 111104 (2004).

[12] E. Richter-Was, Phys. Lett. B 303, 163 (1993).

[13] E.S. Ginsberg, Phys. Rev. 142, 1035 (1966).

[14] J. Bartelt et al. (CLEO Collab.), Phys. Rev. Lett. 82, 3746 (1999).

[15] B. Aubert et al. (BaBar Collab.), “Measurement of the B → D∗ F Form Factors in the Semileptonic Decay B → D^{∗+} e^− \bar{\nu}^e”, Contribution to the 2004 International Conference on High Energy Physics, hep-ex/0409047 (2004).

[16] J. L. Goity and W. Roberts, Phys. Rev. D 51, 3459 (1995).

[17] S. Eidelman et al., Phys. Lett. B 592, 1 (2004).

[18] B.O. Lange, M. Neubert and G. Paz, “Theory of Charmless Inclusive B Decays and the Extraction of \( |V_{ub}| \)”, hep-ph/0504071 (2005).

[19] B. Aubert et al. (BaBar Collab.), Phys. Rev. Lett. 93, 011803 (2004).

[20] M. Neubert, Phys. Lett. B 612, 13 (2005).

[21] S.W. Bosch, M. Neubert and G. Paz, JHEP 0411, 073 (2004); M. Neubert, “Impact of four-quark shape functions on inclusive B decay spectra”, hep-ph/0411027 (2004).

[22] T.O. Meyer, “Limits on weak annihilation in inclusive charmless semileptonic B decays”, Cornell Univ. THESIS 05-1 (2005).

[23] A. Limosani and T. Nozaki, “Extraction of the b-quark shape function parameters using the Belle B → X_s\gamma photon energy spectrum”, hep-ex/0407052 (2004).

[24] The Heavy Flavor Averaging Group (EPS 2005 update): http://www.slac.stanford.edu/xorg/hfag/.