Measurement of the CKM Matrix Element $|V_{ub}|$ with $B \to p\bar{e}\nu$ Decays

B. Aubert,1 R. Barate,1 D. Boutigny,1 J.-M. Gaillard,1 A. Hicheur,1 Y. Karyotakis,1 J. P. Lees,1 P. Robbe,1 V. Tisserand,1 A. Zghiche,1 A. Palano,2 A. Pomplii,2 J. C. Chen,3 N. D. Qi,3 G. Rong,3 P. Wang,3 Y. S. Zhu,3 G. Eigen,4 I. Ofte,4 M. Stupig,4 G. S. Abrams,5 A. W. Borgland,5 A. B. Breon,5 D. N. Brown,5 J. Button-Shafer,5 R. N. Cahn,5 E. Charles,5 M. S. Gill,5 A. V. Gritsan,5 Y. Gridsman,5 R. G. Jacobsen,5 R. W. Kadel,5 J. Kadyk,5 L. T. Kerth,5 Yu. G. Kolomensky,5 J. F. Kral,5 C. LeClere,5 M. E. Levi,5 G. Lynch,5 L. M. Mir,5 P. J. Oddone,5 T. J. Orimoto,5 M. Pripstein,5 N. A. Roe,5 A. Romosan,5 M. T. Ronan,5 V. G. Shelkov,5 A. V. Telnov,5 W. A. Wenzel,5 T. J. Harrison,6 C. M. Hawkes,6 D. J. Knowles,6 S. W. O’Neale,6 R. C. Penny,6 A. T. Watson,6 N. K. Watson,6 T. Deppermann,7 K. Goetzen,7 H. Koch,7 B. Lewandowski,7 M. Pelizaeus,7 K. Peters,7 H. Schmuecker,7 M. Steinke,7 N. R. Barlow,8 W. Bhimji,8 J. T. Boyd,8 N. Chevalier,8 P. J. Clark,8 W. N. Cottingham,8 C. Mackay,8 F. F. Wilson,8 C. Hearty,9 T. S. Mattison,9 J. A. McKenna,9 D. Thiessen,9 S. Jolly,10 P. Kyberd,10 A. K. McKenney,10 V. E. Blinov,11 A. D. Bukin,11 A. R. Buzlykaev,11 V. B. Golubev,11 V. N. Ivanchenko,11 A. A. Korol,11 E. A. Kravchenko,11 A. P. Onuchin,11 S. I. Serednyakov,11 Yu. I. Skovpen,11 A. N. Yushkov,11 D. Best,12 M. Chao,12 D. Kirkby,12 A. J. Lankford,12 M. Mandelkern,12 S. McMahan,12 R. K. Mommsen,12 D. P. Stoker,12 C. Buchanan,13 H. K. Hadavand,14 E. J. Hill,14 D. B. MacFarlane,14 H. P. Paar,14 Sh. Rahatlou,14 G. Raven,14 U. Schwanke,14 V. Sharma,14 J. W. Berryhill,15 C. Campagnari,15 B. Dahmes,15 N. Kuznetsova,15 S. L. Levy,15 O. Long,15 A. Lu,15 M. A. Mazur,15 J. D. Richman,15 W. Verkerke,15 J. Beringer,16 A. M. Eisner,16 M. Grothe,16 C. A. Heusch,16 W. S. Lockman,16 T. Pulliam,16 T. Schalk,16 R. E. Schmitz,16 B. A. Schumm,16 A. Seiden,16 M. Turri,16 W. Walkowiak,16 D. C. Williams,16 M. G. Wilson,16 J. Albert,17 E. Chen,17 G. P. Dubois-Felsmann,17 A. Dvoretskii,17 D. G. Hitlin,17 I. Narsky,17 F. C. Porter,17 A. Ryd,17 A. Samuel,17 S. Yang,17 J. Satyalekha,18 G. Mancinelli,18 B. T. Meadows,18 M. D. Sokoloff,18 T. Barillari,19 F. Blanc,19 P. Bloom,19 W. T. Ford,19 U. Nauenberg,19 A. Olivas,19 P. Rankin,19 J. Roy,19 J. G. Smith,19 W. C. van Hoek,19 L. Zhang,19 J. L. Harton,20 T. Hu,20 A. Soffer,20 W. H. Toki,20 R. J. Wilson,20 J. Zhang,20 D. Altenburg,21 T. Brandt,21 J. Brose,21 T. Colberg,21 M. Dickopp,21 R. S. Dubitsky,21 A. Hauke,21 H. M. Lackner,21 E. Mal,21 R. Müller-Pfeffernik,21 R. Negowits,21 S. Otto,21 K. R. Schubert,21 R. Schwierz,21 B. Spaan,21 L. Wilden,21 D. Bernard,21 G. R. Bouneaud,22 F. Brochard,22 J. Cohen-Tanugi,22 S. T’Jampens,22 Ch. Thiebaux,22 G. Vasileiadis,22 M. Verderi,22 A. Anjomshoa,23 R. Bernet,23 A. Khan,23 D. Lavin,23 F. Muheim,23 S. Playfer,23 J. E. Swain,23 J. Tinsley,23 M. Falbo,24 C. Borean,25 C. Bozzi,25 L. Piemontese,25 A. Sarti,25 E. Treadwell,26 F. Anulli,27 C. Baldini-Ferroli,27 A. Calcetta,27 R. de Sangro,27 D. Fulcic,27 G. Finocchiaro,27 P. Patteri,27 T. I. Peruzzi,27 C. Miccoli,27 A. Zallo,27 S. Bagnasco,28 A. Buzzo,28 R. Contr,28 G. Crosetti,28 M. Lo Vetere,28 M. Macri,28 M. R. Monge,28 S. Passaggio,28 F. C. Pastore,28 C. Patrignani,28 E. Robutti,28 A. Santroni,28 S. Tosi,28 S. Bailey,29 M. Morii,29 G. J. Grenier,30 U. Mallik,30 J. Cochran,31 H. B. Crawford,31 J. Lamsa,31 W. T. Meyer,31 S. Prell,31 E. I. Rosenberg,31 J. Yi,31 M. Davier,32 G. Grosdidier,32 A. Höcker,32 S. Laplace,32 F. Le Diberder,32 V. Lepeltier,32 A. M. Lutz,32 T. C. Petersen,32 S. Ptaszynski,32 M. H. Schune,32 L. Tantot,32 G. Wormser,32 R. M. Bionta,33 V. Brighlev,33 D. J. Lange,33 K. van Bibber,33 D. M. Wright,33 A. J. Bevan,34 J. R. Fry,34 E. Gabathuler,34 R. Gamet,34 M. George,34 M. Kay,34 D. J. Payne,34 R. J. Sloane,34 C. Touramanis,34 M. L. Aspinwall,35 D. A. Bowerman,35 P. D. Dauncey,35 U. Egede,35 I. Eschrich,35 G. W. Morton,35 J. A. Nash,35 P. Sanders,35 G. P. Taylor,35 J. J. Back,36 G. Bellod,36 P. Dixon,36 P. F. Harrison,36 H. W. Shorthouse,36 P. Strother,36 P. B. Vidal,36 G. Cowan,37 H. U. Flaecher,37 S. George,37 M. G. Green,37 A. Kurup,37 C. E. Marker,37 T. R. McMahon,37 S. Ricciardi,37 F. Salvatore,37 G. Vaitis,37 M. A. Winter,37 D. Brown,38 C. L. Davis,38 J. Allison,39 R. J. Barlow,39 A. C. Forti,39 P. A. Hart,39 F. Jackson,39 G. D. Lafferty,39 A. J. Lyon,39 N. Savvas,39 J. H. Weatherall,39 J. C. Williams,39 A. Farbin,40 A. Jawahery,40 V. Lillard,40 D. A. Roberts,40 G. Blaylock,41 C. Dallapiccola,41 K. T. Flood,41 S. S. Hertzbach,41 R. Koffer,41 V. B. Koptchev,41 T. Moore,41 H. Staengle,41 R. Willocq,42 G. Sciolla,42 F. Taylor,42 R. K. Yamamoto,42 M. Milek,43 P. M. Patel,43 F. Palombo,44 J. M. Bauer,45 L. Cremaldi,45 V. Eschenburg,45 R. Kroeger,45 J. Reidy,45 D. A. Sanders,45 D. J. Summers,45 H. Zhao,45 C. Hast,46 P. Taras,46 H. Nicholson,47 C. Cartaro,48 N. Cavallo,48 G. De Nardo,48 F. Fabozzi,48 C. Gatto,48 L. Lista,48 P. Paolucci,48 D. Piccolo,48 C. Sciacca,48 J. M. LoSecco,49
J. R. G. Alsmiller, T. A. Gabriel, B. Krau, J. Brau, R. Frey, M. Iwasaki, C. T. Potter, N. B. Sinv, D. Strom, E. Torrence, F. Colecchia, A. Dorigo, F. Galeazzi, M. Margoni, M. Morandin, M. Possco, M. Rotondo, F. Simonetto, R. Strölli, G. Tiozzo, C. Voci, M. Benayoun, B. Briand, J. Chauveau, P. David, Ch. de la Vaissière, L. Del Buono, O. Hammon, Ph. Lerniste, J. Ocariz, M. Pikv, L. Roos, J. Stark, P. F. Manfredi, V. Re, V. Speciali, L. Gladney, Q. H. Guo, J. Panetta, C. Angelini, G. Batignani, S. Bettarini, M. Bondioli, F.ucci, G. Calderini, E. Campagna, M. Carpinelli, F. Forti, M. A. Giorgi, A. Lusiani, G. Marchiori, F. Martinez-Vidal, M. Morganti, N. Neri, E. Paoloni, M. Rama, G. Rizzo, F. Sandrelli, G. Triggiani, J. Walsh, M. Haie, D. Judd, K. Paick, L. Turnbull, D. E. Wagoner, N. Danielson, P. Elmer, C. Lu, V. Miftakov, J. Olsen, A. J. S. Smith, A. Tumanov, E. V. Ozcan, L. Turnbull, A. M. Eichenbaum, V. Luth, Ch. de la Vaissière, P. F. Manfredi, Technische Universität Dresden, Institut für Kern- und Teilchenphysik, D-01062 Dresden, Germany

University of California at Santa Cruz, Institute for Particle Physics, Santa Cruz, CA 95064, USA

University of California at San Diego, La Jolla, CA 92093, USA

University of Cincinnati, Cincinnati, OH 45221, USA

University of Colorado, Boulder, CO 80309, USA

Colorado State University, Fort Collins, CO 80523, USA

Technische Universität Dresden, Institut für Kern- und Teilchenphysik, D-01062 Dresden, Germany

University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom

Ecole Polytechnique, LLR, F-91128 Palaiseau, France

University of Ferrara, Dipartimento di Fisica e INFN, I-44100 Ferrara, Italy

(Author List)

(Laboratoire de Physique des Particules, F-74941 Annecy-le-Vieux, France)

Università di Bari, Dipartimento di Fisica e INFN, I-70126 Bari, Italy

Institute of High Energy Physics, Beijing 100039, China

Institute for Particle Physics, University of Bergen, 5007 Bergen, Norway

Lawrence Berkeley National Laboratory and University of California, Berkeley, CA 94720, USA

University of Birmingham, Birmingham, B15 2TT, United Kingdom

University of Bristol, Bristol BS8 1TL, United Kingdom

University of British Columbia, Vancouver, BC, Canada V6T 1Z1

Brunei University, Uxbridge, Middlesex UB8 3PH, United Kingdom

Brookhaven National Laboratory, Upton, NY 11973, USA

University of California at Irvine, Irvine, CA 92617, USA

University of California at Los Angeles, Los Angeles, CA 90024, USA

University of California at San Diego, La Jolla, CA 92039, USA

University of California at Santa Barbara, Santa Barbara, CA 93106, USA

University of California at Santa Cruz, Institute for Particle Physics, Santa Cruz, CA 95064, USA

University of California at Santa Cruz, Instituto de Física y Cs. de la Tierra, Santa Cruz, CA 95064, USA

California Institute of Technology, Pasadena, CA 91125, USA

University of Cincinnati, Cincinnati, OH 45221, USA

University of Colorado, Boulder, CO 80309, USA

Colorado State University, Fort Collins, CO 80523, USA

(Barber Collaboration)
We present a measurement of the branching fraction for the rare decays $B \to \rho e\nu$ and extract a value for the magnitude of $V_{ub}$, one of the smallest elements of the Cabibbo-Kobayashi-Maskawa quark-mixing matrix. The results are given for five different calculations of form factors used to parametrize the hadronic current in semileptonic decays. Using a sample of 55 million $B\bar{B}$ meson pairs recorded with the BABAR detector at the PEP-II $e^+e^-$ storage ring, we obtain $B(B^0 \to \rho^- e^+\nu) = (3.29 \pm 0.42 \pm 0.47 \pm 0.60) \times 10^{-4}$ and $|V_{ub}| = (3.64 \pm 0.22 \pm 0.25_{-0.56}^{+0.39}) \times 10^{-3}$, where the uncertainties are statistical, systematic, and theoretical, respectively.

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Exclusive $b \to u\ell\nu$ decays can be used to determine $|V_{ub}|$, one of the smallest and least well-determined ele-
ments of the Cabibbo-Kobayashi-Maskawa quark-mixing matrix. The modes $B \to \rho \ell \nu$ have a comparatively large branching fraction, and a high fraction of events is found at large electron momenta. We determine both the branching fraction $B(B \to \rho \ell \nu)$ and $|V_{ub}|$ using form factors, which describe the hadronic current in the decay, to extrapolate the decay rates to the full range of lepton energies and to normalize $B$ to $|V_{ub}|$. Five different form-factor calculations are used, as given in Table I.

The data in this analysis were collected with the BABAR detector at the PEP-II asymmetric-energy $e^+e^-$ storage ring. The integrated luminosity of the sample recorded on the $\Upsilon$(4S) resonance in years 2000 and 2001 (“on-resonance”) is $50.5 \text{ fb}^{-1}$, corresponding to $55.2$ million $BB$ meson pairs. An additional $8.7 \text{ fb}^{-1}$ of data were taken $40 \text{ MeV}$ below the resonance (“off-resonance”). BABAR is a detector optimized for the asymmetric beam configuration at PEP-II. Charged-particle momenta are measured in a tracking system consisting of a 5-layer, double-sided silicon vertex tracker (SVT) and a 40-layer drift chamber (DCH) filled with a mixture of helium and isobutane, both operating in a 1.5-T superconducting solenoid. The electromagnetic calorimeter (EMC) consists of 6580 CsI(Tl) crystals arranged in barrel and forward endcap subdetectors. Particle identification is performed by combining information from ionization measurements in the SVT and DCH, energy deposits in the EMC, and the angle and number of Cherenkov photons measured by the DIRC (detector of internally reflected Cherenkov light).

We select decays in the modes $B^+ \to \rho^0 e^+\nu$, $B^0 \to \rho^- e^+\nu$, $B^+ \to \omega e^+\nu$, $B^+ \to \pi^0 e^+\nu$, and $B^0 \to \pi^- e^+\nu$, with $\rho^0 \to \pi^+\pi^-$, $\rho^- \to \pi^0\pi^-$, and $\omega \to \pi^0\pi^+\pi^-$. The inclusion of charge conjugate decays is implied throughout. The analysis is optimized for $B \to \rho \ell \nu$ decays, similar to that in Ref. [5]. Each signal event is sometimes reconstructed in one of the other modes; the $\pi$ and $\omega$ modes are included in order to estimate this crossfeed into the $\rho$ modes. Throughout this paper, all variables are expressed in the $T(4S)$ center-of-mass frame, except if stated otherwise. Two electron-energy regions are considered: $2.0 \leq E_e < 2.3 \text{ GeV}$ (low-$E_e$) and $2.3 \leq E_e < 2.7 \text{ GeV}$ (high-$E_e$). A large background to $b \to u e\nu$ decays comes from the more copious $b \to c e\nu$ decays. This background is kinematically suppressed in the high-$E_e$ region and dominates in the low-$E_e$ region. The low-$E_e$ region provides the background normalization in the high-$E_e$ region. The largest background in the high-$E_e$ region is continuum $e^+e^- \to q\bar{q}$ events. The off-resonance data are used to estimate its size.

Hadronic events are selected based on track and photon multiplicity and event topology. We use tracks originating from the interaction point with at least 12 hits in the DCH and a transverse momentum greater than $0.1 \text{ GeV}/c$. Signals in the EMC with $E_{lab} > 30 \text{ MeV}$ that are not associated with any track are considered as photons if the lateral moment of the shower energy distribution is smaller than 0.8. We select events with at least five tracks, or with at least four tracks and at least five photons. We require the ratio $H_2/H_0$ of Fox-Wolfram moments to be less than 0.4. This requirement keeps 85% of the $\rho \ell \nu$ signal; it rejects 55% of the non-$BB$ events.

Electrons are identified with a likelihood estimator using information from the DCH, EMC, and DIRC subdetectors [11]. The selection efficiency is around 90%, with a pion misidentification rate of less than 0.1%. We reject electrons from $J/\psi$ decays and from photon conversions.

Charged pion candidates are tracks not identified as kaons with high confidence based on DIRC and $dE/dx$ measurements. A $\pi^0$ is reconstructed from photon pairs with an invariant mass $120 < M_{\gamma\gamma} < 145 \text{ MeV}/c^2$.

To reconstruct $\rho^0$ mesons, we combine two oppositely-charged pions, and for $\rho^\pm$ a pion track and a $\pi^0$. To suppress combinatorial background we require that the pion with the higher momentum satisfies $p_\pi > 400 \text{ MeV}/c$ and the other $p_\pi > 200 \text{ MeV}/c$. For the $\omega$, we combine two oppositely-charged pions with a $\pi^0$. To suppress combinatorial background we require $p_\pi > 100 \text{ MeV}/c$ for each pion. In the mode $B \to \pi e\nu$ we require $p_\pi > 200 \text{ MeV}/c$.

The missing momentum in the event is given by

$$\vec{p}_{\text{miss}} = - \sum_{\text{tracks}} \vec{p}_i - \sum_{\text{photons}} \vec{p}_i ,$$

where the sums are over all accepted tracks and photons. We require $|\cos \theta_{\text{miss}}| < 0.9$, where $\theta_{\text{miss}}$ is the angle between $\vec{p}_{\text{miss}}$ and the beam axis. This rejects events with missing high-momentum particles close to the beam axis. We also compare the direction of $\vec{p}_{\text{miss}}$ with that of the neutrino inferred from $\vec{p}_\nu = \vec{p}_B - \vec{Y}$, where $Y$ is the $p + e$, $\omega + e$, or $\pi + e$ system. The latter is known to within an azimuthal ambiguity about the $B$ direction since only the magnitude of $\vec{p}_B$ is known. We use the smallest possible angle $\Delta \theta_{\text{min}}$ between the two directions and require $\cos \Delta \theta_{\text{min}} > 0.8$. Using the constraints $E_B = E_{\text{beam}}$ and $p_\nu^2 = (p_B - p_\nu)^2 = 0$, the angle between the

| Form factors | $\Gamma_{th} \text{ (ps}^{-1})$ | Error (%) | Reference |
|-------------|-----------------|-----------|-----------|
| Isgw2       | 14.2            | ±50       | 1         |
| Beyer/Melikhov | 16.0      | ±15       | 2         |
| Ukqcd       | 16.5            | +21, -14  | 3         |
| LCSR        | 16.9            | ±32       | 4         |
| Ligeti/Wise | 19.4            | ±29       | 5         |
is the direction of the electron and \( \vec{p}_{\text{total}} \) momentum of all tracks except the one that maximizes the sum of the longitudinal momenta of all particles; the angle \( \theta_{\text{thrust}} \) between the thrust axis of the \( Y \) system and the thrust axis of the rest of the event (the thrust axis is defined to be the direction that maximizes the sum of the longitudinal momenta of all particles); the angle \( \theta_{\text{thrust},Y} \) between the thrust of the \( Y \) system and the beam axis; the angle \( \theta_{\text{lep.}} \) between the thrust of the \( Y \) system and the beam axis; the angle \( \theta_{\text{rest}} \) between the thrust of the rest of the event and the thrust axis of the rest of the event; the angle \( \theta_{\text{min}} \) between the thrust of the rest of the event and the thrust axis of the rest of the event.

The signal events fulfill \( |\cos\theta_{BY}| \leq 1 \); allowing for detector resolution we require \( |\cos\theta_{BY}| < 1.1 \). After all other selection criteria, this requirement rejects more than 60% of the \( B \to c\bar{e}\nu \) and approximately 68% of the remaining continuum backgrounds, it retains 98% of the signal.

To further reduce the continuum background, we use a neural net with 14 event-shape variables: the sum of track and photon energies in nine cones centered on the lepton-momentum; the angle \( \theta_{\text{thrust}} \) between the thrust axis of the \( Y \) system and the thrust axis of the rest of the event; the angle \( \theta_{\text{thrust,Y}} \) between the thrust of the \( Y \) system and the beam axis; the angle \( \theta_{\text{lep.}} \) between the thrust of the \( Y \) system and the beam axis; the angle \( \theta_{\text{rest}} \) between the thrust of the rest of the event and the thrust axis of the rest of the event; the angle \( \theta_{\text{min}} \) between the thrust of the rest of the event and the thrust axis of the rest of the event.

The fit has nine free parameters: \( B(B^0 \to \rho^- e^+ \nu) \), \( B(B^0 \to \pi^- e^+ \nu) \), the normalization of the \( B \to u\bar{e}\nu \) background in the two electron-energy ranges (two parameters), and the normalization of the \( B \to c\bar{e}\nu \) background (five parameters, one for each mode). The rates of the \( \rho^0 \), \( \omega \), and \( \pi^0 \) channel are constrained by the isospin and quark model relations \( \Gamma(B^0 \to \rho^- e^+ \nu) = 2 \Gamma(B^+ \to \rho^0 e^+ \nu) \), \( \Gamma(B^+ \to \rho^0 e^+ \nu) = \Gamma(B^+ \to \omega e^+ \nu) \), and \( \Gamma(B^0 \to \pi^- e^+ \nu) = 2 \Gamma(B^+ \to \pi^0 e^+ \nu) \). The maximum-likelihood fit takes into account the statistical uncertainties in the on- and off-resonance data and in the probability distributions extracted from MC simulations.

The fit quality has been checked with a \( \chi^2 \) test, where bins in sparsely populated regions have been combined before the \( \chi^2 \) calculation. We obtain \( \chi^2 = 91 \) for 93 degrees of freedom for ISGW2, and similarly good fit quality for the other form-factor calculations. The signal yields extracted from the maximum-likelihood fit in the high-\( E_e \) region are 321 \pm 40 \( B^+ \to \rho^0 e^+ \nu \) events and 505 \pm 63 \( B^0 \to \rho^- e^+ \nu \) events. The resulting branching fractions \( B(B^0 \to \rho^- e^+ \nu) \) are shown in Fig. 1 for the ISGW2 model. A continuum-background contribution of 917 \pm 73 events in high-\( E_e \) and 1928 \pm 106 in low-\( E_e \) has been subtracted. Good agreement between data and the fit result is seen in each of these figures. The fits for the other form-factor calculations show the same level of agreement. The fit quality has been checked with a \( \chi^2 \) test, where bins in sparsely populated regions have been combined before the \( \chi^2 \) calculation. We obtain \( \chi^2 = 91 \) for 93 degrees of freedom for ISGW2, and similarly good fit quality for the other form-factor calculations. The signal yields extracted from the maximum-likelihood fit in the high-\( E_e \) region are 321 \pm 40 \( B^+ \to \rho^0 e^+ \nu \) events and 505 \pm 63 \( B^0 \to \rho^- e^+ \nu \) events. The resulting branching fractions \( B(B^0 \to \rho^- e^+ \nu) \) are shown in Fig. 2. The five fit parameters describing the \( b \to c\bar{e}\nu \) backgrounds agree with the known branching fractions \( \frac{\Gamma(B \to D\pi\nu)}{\Gamma(B \to D\pi\nu)} \) for \( B \to D\pi\nu \), \( B \to D^*\pi\nu \) backgrounds, and \( B \to D^{(*)}(\pi)\nu \) backgrounds agree with the predictions of the MC simulation. The fit result for the \( \pi^0 \) modes is \( B(B^0 \to \pi^- e^+ \nu) = (1.86 \pm 0.56_{\text{stat.}}) \times 10^{-4} \) for the ISGW2 model.
TABLE I: Summary of all contributions to the systematic uncertainty on the branching fraction \( B(B \to \rho e^+\nu) \).

| Contribution | \( \Delta B_{\rho}/B_{\rho} \) (\%) |
|--------------|----------------------------------|
| Tracking efficiency | ±5 |
| Tracking resolution | ±1 |
| \( \pi^0 \) efficiency | ±5 |
| \( \pi^0 \) energy scale | ±3 |
| \( b \to ce\nu \) background composition | +1.4, −1.7 |
| Resonant \( b \to ue\nu \) background composition | +6, −4 |
| Non-resonant \( b \to ue\nu \) background | ±9 |
| \( B \) lifetime | ±1 |
| Number of \( B\bar{B} \) pairs | ±1.6 |
| Misidentified electrons | < ±1 |
| Electron efficiency | ±2 |
| \( B(T(4S) \to B^+ B^-)/B(T(4S) \to B^0 \bar{B}^0) \) | < ±1 |
| Isospin and quark model symmetries | < ±1 |
| Fit method | +4, −6 |
| Total systematic uncertainty | ±14.4 |

FIG. 1: Continuum-subtracted data distributions (points with error bars) and fit projections (histograms) for \( M_{x\pi} \) (top plots) and \( \Delta E \) (bottom plots) for the \( B^0 \to \rho^- e^+\nu \) channel in the low-\( E_e \) (left plots) and high-\( E_e \) regions (right plots). The fit results are shown for the ISGW2 model. The histograms correspond to the true and crossfeed components of the signal (open histogram, above and below the dashed line, respectively), the background from other \( b \to ue\nu \) decays (dark shaded region), and \( b \to ce\nu \) and other backgrounds (light shaded region).

FIG. 2: The \( B^0 \to \rho^- e^+\nu \) branching fraction results using five different form-factor calculations. The uncertainties shown are statistical, systematic, and (for the combined result) theoretical, successively added in quadrature. The combined result is the average of the five form-factor results.

The composition of the resonant component of other \( b \to ue\nu \) decays has been varied by changing the branching fractions for individual resonances by ±50%, while keeping the total rate constant. Variations in the \( b \to ce\nu \) composition contribute much less to the total systematic error than variations in the \( b \to ue\nu \) component. Possible violations of the isospin and quark model constraints are discussed in Refs. [17] and [18]. Their contribution to the systematic error is determined by allowing a ±3% violation. Several fits were performed: fitting without the \( \omega \) mode, without the \( \pi \) mode (fixing \( B(B \to \pi e\nu) \) [19]), without the low-\( E_e \) region, and with different binning. We assign a systematic uncertainty for the fit method as half the largest resulting changes of the fit result. We have also varied the most important selection requirements and find that the changes in \( B(B \to \rho e\nu) \) are consistent with statistical variations as determined by a MC simulation.

A value of \( |V_{ub}| \) is determined by the relation

\[
|V_{ub}| = \frac{\sqrt{B(B^0 \to \rho^- e^+\nu)/(\Gamma_{th} \tau_{B^0})}}{10^{-4}},
\]

where \( \Gamma_{th} \) is the predicted form-factor normalization as given in Table I. The branching fractions are used separately for each form-factor calculation, as shown in Fig. 2. We use \( \tau_{B^0} = 1.542 \pm 0.016 \text{ ps} \) [10] for the \( B^0 \) lifetime. The results for \( |V_{ub}| \) are shown in Fig. 3. The combined result has been obtained as weighted average of the five form-factor results, where the weight is obtained from the theoretical uncertainty of each. The theoretical uncertainty on the combined result is estimated to be half of the full spread of all theoretical uncertainties.

In conclusion, we have measured the branching fraction

\[
B(B^0 \to \rho^- e^+\nu) = (3.29 \pm 0.42 \pm 0.47 \pm 0.60) \times 10^{-4}
\]

using isospin constraints and extrapolating to all electron energies according to five different form-factor calculations. The errors given are statistical, systematic, and theoretical, in the order shown. The value of \( |V_{ub}| \) determined by the same form-factor calculations is \( |V_{ub}| = (3.64 \pm 0.22 \pm 0.25 \pm 0.32) \times 10^{-3} \). Our results are slightly higher (22% for \( B \) and 13% for \( |V_{ub}| \)) than a previous \( B \to \rho e\nu \) result from CLEO [8], but agree within statistical errors.
FIG. 3: $|V_{ub}|$ determined using five different form-factor calculations. Only theoretical error bars are shown. The combined result is also shown at the bottom with statistical, systematic, and theoretical uncertainties successively added in quadrature. The combined result is the weighted average of the five form-factor results, where we have used only the theoretical uncertainties to calculate the weights.

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* Also with Università di Perugia, Perugia, Italy
† Also with Università della Basilicata, Potenza, Italy

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