Inclusive $|V_{ub}|$ measurements at BABAR

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We present two inclusive measurements of Cabibbo-Kobayashi-Maskawa (CKM) matrix element $|V_{ub}|$: one uses the lepton energy spectrum ($E_l$) and the other uses the invariant mass of the hadronic system ($m_X$) to discriminate signal ($B \to X_u \ell \nu$) and background ($B \to X_c \ell \nu$) events in $B \to X \ell \nu$ transitions. Both analyses are based on data samples collected by the BABAR detector at the PEP-II asymmetric-energy B Factory at SLAC.

The element $|V_{ub}|$ of the CKM matrix plays a central role in tests of the unitarity of this matrix: it’s extraction, based on tree level decays, gives results that are independent of new physics contributions. We report the determination of $|V_{ub}|$ from two different measurements of the inclusive charmless semileptonic $B$ branching fraction, $\mathcal{B}(B \to X_u \ell \nu)$, using $E_l$ spectrum (endpoint) and the $m_X$ spectrum on the recoil of fully reconstructed $B$ mesons respectively.

The selection of $B \to X_u \ell \nu$ events is hampered by the presence of a large $B \to X_c \ell \nu$ background: $E_l$ and $m_X$ spectra are used to discriminate the two different transitions. The endpoint analysis is sensitive to approximately 10% of the $E_l$ spectrum while the acceptance for the $m_X$ approach is larger: ≃ 70% of the $m_X$ spectrum is selected by analysis cuts. The extrapolation of the measured rates to the full phase space introduces theoretical uncertainties\(^1\)\(^2\). Results also depend on the shape function (SF) modeling of $b$ quark Fermi motion inside the $B$ meson.

Both measurements are based on data recorded by the BABAR detector at the PEP-II asymmetric-energy $e^+e^-$ storage ring at SLAC. The endpoint analysis data sample consists of about 23 million $B\bar{B}$ pairs (21 fb\(^{-1}\)) collected at the $\Upsilon(4S)$ resonance (ON-peak), with an additional sample of 2.6 fb\(^{-1}\) recorded about 40 MeV below the $\Upsilon(4S)$ peak (OFF-peak), while the $m_X$ measurement uses a data sample of about 88 million $B\bar{B}$ pairs (82 fb\(^{-1}\)) ON-peak.

Monte Carlo (MC) simulations of the BABAR detector based on GEANT 4\(^3\) are used to optimize selection criteria and to determine signal efficiencies and background shapes. To simulate $B \to X_u \ell \nu$ transitions three models are employed: $B \to D^{(*)} \ell \nu$ decay is modeled following a parametrization of form factors based on HQET\(^5\); for $B \to D^{(*)} \ell \nu$ decays and higher mass charm meson states $B \to D^{(*)} \pi \ell \nu$, the ISGW2 model is used; nonresonant decays, $B \to D^{(*)} \pi \ell \nu$, are modeled according to a prescription by Goity and Roberts\(^7\). In the endpoint analysis the MC simulation of $B \to X_u \ell \nu$ events is based on the ISGW2 model: the hadrons $X_u$ are represented by single particles or resonances with masses up to 1.5 GeV/c\(^2\) and nonresonant contributions are not included. In the $m_X$ analysis $B \to X_u \ell \nu$ transitions are simulated with an hybrid model which is a mixture of resonant and nonresonant components. The Fermi motion of the $b$ quark inside the $B$ meson is implemented in the nonresonant component using the SF parameterization described in \[8\], and the fragmentation is handled by Jetset 7.4\(^9\).

1 Endpoint analysis

For this analysis, electron candidates are selected in the momentum range from 1.5 to 3.5 GeV/c in the $\Upsilon(4S)$ rest frame with a solid angle defined by the electromagnetic calorimeter acceptance.

The inclusive electron spectrum for charmless semileptonic $B$ decays, measured in the $\Upsilon(4S)$ rest frame in the momentum range of 2.3–2.6 GeV/c, is used to extract $\mathcal{B}(B \to X_u \ell \nu)$. To suppress low-multiplicity QED processes and continuum processes consisting of nonresonant $e^+e^-\to q\bar{q}$ production ($q = u,d,s,c$) at least three charged tracks per event are required and a cut on the ratio of Fox-Wolfram moments $H_2/H_0 < 0.4$\(^10\) is applied. The missing momentum four-vector $p_{miss} = p_t - p_{B_{ch}} - p_X - p_{\ell}$, where all momenta are measured in the laboratory frame and $p_{\ell}$ refers to the four-momentum of the initial state of the colliding beams, can be used to select semileptonic events: $|p_{miss}|$ is requested to be larger than 1 GeV/c, to point into the detector fiducial volume and the angle between the electron candidate and the missing momentum is required to be greater than $\pi/2$. Candidate electrons are rejected if, when paired with an opposite-sign electron, the invariant mass of the pair is consistent with the $J/\psi$ mass (3.05 < $M_{e^+e^-}$ < 3.15 GeV/c\(^2\)). For the selection criteria described above, the detection efficiency for charmless semileptonic decays in the electron momentum interval of 1.5–2.6 GeV/c ranges from ~0.4 to ~0.25.

The raw spectrum of the highest momentum electron after the subtraction of continuum background (determined from OFF resonance data sample) is shown in Fig. 1. Also

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\(^1\)Charge-conjugate states are implied throughout this paper.

\(^2\)The results presented are depending on the parton-duality to which no error is assigned.
To determine the charmless semileptonic branching fraction $\Delta B(\Delta p)$, the fraction $f_\mu(\Delta p)$ of the spectrum that falls into the momentum interval $\Delta p$ is needed. The CLEO collaboration has recently used the measurement of the inclusive photon spectrum from $b \to s \gamma$ transitions [11] to derive $f_\mu(\Delta p)$ for $B \to X_{e\nu}$ transition. They quote a value of $f_\mu(\Delta p) = 0.074 \pm 0.014 \pm 0.009$ for the interval $\Delta p$ from 2.3 to 2.6 GeV/c. Relying on the CLEO measurement, the result presented here translates into a total branching ratio of $\mathcal{B}(B \to X_{e\nu}) = (2.05 \pm 0.27_{\text{exp}} \pm 0.46_{\mu}) \cdot 10^{-3}$. We extract $|V_{ub}|$ from the measured inclusive charmless semileptonic branching fraction with the relation in [15] and the average $B$ lifetime of $\tau_B = 1.608 \pm 0.012$ ps [15] and find

$$|V_{ub}| = (4.43 \pm 0.29_{\text{exp}} \pm 0.25_{\text{OPE}} \pm 0.50_{\mu} \pm 0.35_{\gamma}) \cdot 10^{-3}(3)$$

Here the first error is the combined statistical and systematic error, and the second refers to the uncertainty on the extraction of $|V_{ub}|$ from relation in [15]. The third one is taken from the CLEO analysis and is related to the experimental determination of $f_\mu$. The last error accounts for uncertainties related to assumption that $b \to s \gamma$ transition can be used for shape function modeling in $B \to X_{e\nu}$ transition.

2 \hspace{1cm} |V_{ub}| measurement using the recoil of fully reconstructed $B$ mesons

This analysis is based on $B \bar{B}$ events in which one of the $B$ meson decays in a fully reconstructed hadronic final state ($B_{\text{reco}}$) and the other one is identified as decaying semileptonically by the presence of an electron or a muon. The full reconstruction of one of the two $B$ mesons reduces the overall efficiency, but allows to reconstruct both the neutrino and the hadronic system ($X$), to determine the flavour and to separate charged and neutral $B$ mesons. In order to reduce systematic uncertainties due to efficiency determination we extract the branching ratio $R_{\text{ref}} = \mathcal{B}(\bar{B} \to X_{e\nu})/\mathcal{B}(\bar{B} \to X_{\mu\nu})$ after measuring the number of events with one identified lepton.

To fully reconstruct a large sample of $B$ mesons, hadronic $B$ decays of the type $B_{\text{reco}} \to D^{(*)}\gamma Y$ are selected. $Y$ represents a collection of hadrons with a total charge of $\pm 1$, composed of $n_1 \pi^+ n_2 K^* n_3 K^0 \eta n_4 \eta' n_5$, where $n_1 + n_2 < 6$, $n_3 < 3$, and $n_4 < 3$. The kinematic consistency of a $B_{\text{reco}}$ candidate with a $B$ meson decay is checked using two variables, the beam energy-substituted mass $m_{\text{RES}} = \sqrt{s/4 - p_B^2}$ and the energy difference, $\Delta E = E_B - \sqrt{s}/2$. Here $\sqrt{s}$ refers to the total energy in the $Y(4S)$ center of mass frame, and $p_B$ and $E_B$ denote the momentum and energy of the $B_{\text{reco}}$ candidate in the same frame, respectively. In events with more than one reconstructed $B$ decay, the decay mode with highest purity is selected.

Semileptonic $\bar{B}$ decays, $\bar{B} \to X_{e\nu}$, recoiling against the $B_{\text{reco}}$ candidate are identified by an electron or muon candidate with a minimum momentum ($p^*$) greater than 1 GeV/c.
in the $B$ rest frame. Correlation between the charge of the prompt leptons and the flavor of the $B_{\text{reco}}$ is imposed ($B^0 - \bar{B}^0$ mixing rate is used to extract the prompt lepton yield in case of neutral candidates).

The hadron system $X$ in the decay $B \rightarrow X\ell\bar{v}$ is made of charged tracks and neutral energy depositions in the calorimeter that are not associated with the $B_{\text{reco}}$ candidate and not identified as a lepton. The mass of the hadronic system is determined by a kinematic fit that imposes four-momentum conservation, the equality of the masses of the two $B$ mesons, and forces $p^2_{\text{miss}} = 0$.

The selection of $B \rightarrow X_{\nu}\ell\bar{v}$ decays is tightened by requiring exactly one charged lepton with $p^\nu > 1$ GeV/c, charge conservation ($Q_B + Q_\ell + Q_{b_{\text{reco}}} = 0$), and missing mass consistent with zero ($p^2_{\text{miss}} < 0.5$ GeV$^2$/c$^2$). These criteria improve the resolution in $m_X$ and suppress the dominant $B \rightarrow X_{\nu}\ell\bar{v}$ decays, many of which contain additional neutrinos or undetected $K_L$. We suppress the $B^0 \rightarrow D^{*+}\ell^-\nu$ background with a partial reconstruction in which only the slow pion from the $D^{*+} \rightarrow D\pi^+$ decay and the lepton are reconstructed. We veto events with charged or neutral kaons in the $X$ system to reduce the background from $\bar{B} \rightarrow X_{\nu}\ell\bar{v}$ decays. The impact of the selection criteria on the $m_X$ distribution is illustrated on MC in Fig 2. We determine $R_{d/s/l}$ from $N_{d/s/l}$, the observed number of $b \rightarrow u$ events, and $N_{sl}$, the number of events with at least one charged lepton:

$$R_{d/s/l} = \frac{B(B \rightarrow X_{\nu}\ell\bar{v})}{B(B \rightarrow X\ell\bar{v})} = \frac{N_{d/s/l}/(e^{\nu}_{d/s/l}e^{\nu}_{m_{X}})}{N_{sl}/e^{\nu}_{l}e^{\nu}_{l}} \times \frac{e^{l}_{l}e^{\nu}_{l}}{e^{l}_{l}e^{l}_{l}}$$

(4)

Here $e^{\nu}_{m_{X}} = (34.2 \pm 0.6)$% is the efficiency for selecting $\bar{B} \rightarrow X_{\nu}\ell\bar{v}$ decays with all analysis requirements, $e^{\nu}_{m_{X}} = (73.3 \pm 0.9)$% is the fraction of signal events with $m_X < 1.55$ GeV/c$^2$, $e^{l}_{l}/e^{l}_{l} = 0.887 \pm 0.008$ corrects for the difference in the efficiency due to the lepton momentum cut for $\bar{B} \rightarrow X\ell\bar{v}$ and $\bar{B} \rightarrow X_{\nu}\ell\bar{v}$ decays, and $e^{l}_{l}/e^{l}_{l} = 1.00 \pm 0.04$ accounts for a possible efficiency difference in the $B_{\text{reco}}$ reconstruction in events with $\bar{B} \rightarrow X\ell\bar{v}$ and $\bar{B} \rightarrow X_{\nu}\ell\bar{v}$ decays.

We derive $N_{d/s/l}$ from a fit to the $m_{X}$ distribution shown in Fig 2. The fit uses an empirical description [13] of the combinatorial background from continuum and $BB$ events, together with a narrow signal [14] peaked at the $B$ meson mass. The residual background in $N_{d/s}$ from misidentified leptons and semileptonic charm decays amounts to 6.8% and has been subtracted. We obtain $N_{d}$ from the $m_X$ distribution with a $\chi^2$ fit to the sum of three contributions: signal, background $N_{e}$ from $\bar{B} \rightarrow X_{\nu}\ell\bar{v}$, and a background of less than 1% from other sources (misidentified leptons, secondary $\tau$ and charm decays).

In each bin of the $m_X$ distribution, the combinatorial $B_{\text{reco}}$ background is subtracted on the basis of a fit to the $m_{ES}$ distribution. Figure 3a shows the $m_X$ distribution with the results of the fit superimposed. The fit reproduces well the data having a $\chi^2/\nu f = 7.6/6$. In the fit, the first bin is chosen to contain all events with $m_X$ less than 1.55 GeV/c$^2$ while the other bins are chosen in order to separate the contribution from each resonant $\bar{B} \rightarrow X_{\nu}\ell\bar{v}$ mode. The $m_X$ cut, set at 1.55 GeV/c$^2$, has been optimized minimizing the total error. Figure 3b shows the $m_X$ distribution after background subtraction with finer binning. Table 1 summarizes the results of fits with different requirements on $m_X$, for electrons and muons, for neutral and charged $B_{\text{reco}}$ candidates, and for different ranges of the $B_{\text{reco}}$ purity, $P$. The results are all consistent within the uncorrelated statistical errors.

We have performed extensive studies to determine systematic uncertainties. We use events with charged and neutral kaons in the recoil of the $B_{\text{reco}}$ candidate as a control sample to assess that the background from $\bar{B} \rightarrow X_{\nu}\ell\bar{v}$ events is properly described. The relative systematic error ($\Delta_p$) due to the selection criteria related to the reconstruction of particles in the event is $\Delta_p = 8.5\%$. The uncertainty of the $B_{\text{reco}}$ combinatorial background subtraction is estimated by varying the signal shape function ($\Delta_s = 3.8\%$). The impact of the binning is studied by changing the binning for $m_X > 1.55$ GeV/c$^2$ ($\Delta_m = 2.9\%$). The branching fractions of $B \rightarrow D^{\pm}\ell\nu$ and of inclusive and exclusive $D$ mesons decays are varied within the world aver-
The first error is statistical, the second refers to the exper-
imental systematic uncertainty, the third gives the theoretical
uncertainty on the extrapolation of \( R_{u/d} \) to the full \( m_\tau \)
range, and the last error combines quadratically the pertur-
ba
tive and nonperturbative uncertainties in the extraction of
\( |V_{ub}| \) from the total decay rate.

### 3 Conclusions

Two different approaches for the extraction of \( |V_{ub}| \) CKM
matrix element have been presented. The analysis based on
\( m_\tau \) gives currently the most precise determination of \( |V_{ub}| \).

This is primarily due to specific advantages of this tech-
nique: large phase-space acceptance and high purity of the
sample (signal over background ratio \( \sim 1.7 \)). The two re-
results are consistent and they are in agreement with previous
inclusive measurements [15].

### References

1. N. Cabibbo, Phys. Rev. Lett. 10, 531 (1963); M. Kobayashi and T. Maskawa, Prog. Th. Phys. 49, 652
(1973).
2. M. Battaglia et al., “The CKM matrix and the unitarity triangle,” arXiv:hep-ph/0304132 (2002)
3. The BABAR Collaboration, B. Aubert et al., Nucl. Instrum. Methods. A479, 1 (2002).
4. S. Agostinelli et al. [GEANT4 Collaboration], SLAC-PUB-9350, CERN-IT-2002-003 (2002)
5. I.I. Bigi, M. Shifman, and N.G. Uraltsev, Annu. Rev. Nucl. Part. Sci. 47, 591 (1997); J. E. Duboscq et al. [CLEO Collaboration], Phys. Rev. Lett. 76, 3898
(1996).
6. D. Scora and N. Isgur, Phys. Rev. D 52, 2783 (1995).
7. J.L. Goity and W. Roberts, Phys. Rev. D51, 3459
(1995).
8. F. De Fazio and M. Neubert, JHEP 9906, 017 (1999).
9. T. Sjöstrand, Comput. Phys. Commun. 82, 74 (1994).
10. G.C. Fox and S. Wolfram, Phys. Rev. Lett. 41, 1581
(1978).
11. The CLEO Collaboration, A. Bornheim et al., hep-ex/0202019 (2002).
12. B. Aubert et al. [BABAR Collaboration], Phys. Rev. D 67, 031101 (2003).
13. H. Albrecht et al. [ARGUS Collaboration], Z. Phys. C 48, 543 (1990).
14. T. Skwarnicki [Crystal Ball Collaboration], DESY F31-86-02.
15. K. Hagiwara et al. [Particle Data Group Collaboration], Phys. Rev. D 66, 010001 (2002).
16. M. Althoff et al. [TASSO Collaboration], Z. Phys. C 27, 27 (1985). W. Bartel et al. [JADE Collaboration],
Z. Phys. C 20, 187 (1983). V. Luth et al., Phys. Lett. B 70, 120 (1977).
17. D. Cronin-Hennessy et al. [CLEO Collaboration], Phys. Rev. Lett. 87:251808, 2001.
18. R. Barate et al. [ALEPH Collaboration], Eur. Phys. J. C 6, 555 (1999); M. Acciarri et al. [L3 Collaboration],
Phys. Lett. B 436, 174 (1998); P. Abreu et al. [DELPHI Collaboration], Phys. Lett. B 478, 14 (2000);
B. Huhrens et al. [CLEO Collaboration], Phys. Rev. D 61, 052001 (2000); G. Abbiendi et al. [OPAL
Collaboration], Eur. Phys. J. C 21, 399 (2001); A. Bornheim et al. [CLEO Collaboration], Phys. Rev. Lett. 88, 231803 (2002).

### Table 1. Fit results for several data samples.

| Sample | \( N_u \) | \( N_e \) | \( N_\mu \) | \( R_{u/d} \) (%) |
|--------|------|----|--------|-------------|
| \( m_\tau < 1.55 \text{ GeV}/c^2 \) | 32210 ± 233 | 167 ± 21 | 99 ± 6 | 1.97 ± 0.25 |
| \( m_\tau < 1.40 \text{ GeV}/c^2 \) | 32210 ± 233 | 134 ± 19 | 64 ± 4 | 1.77 ± 0.25 |
| \( m_\tau < 1.70 \text{ GeV}/c^2 \) | 32210 ± 233 | 191 ± 26 | 70 ± 11 | 2.11 ± 0.29 |
| Neutral \( \phi_{\mu} \) | 11852 ± 133 | 76 ± 13 | 21 ± 3 | 2.46 ± 0.33 |
| Charged \( \phi_{\mu} \) | 20583 ± 191 | 91 ± 16 | 77 ± 5 | 1.68 ± 0.30 |

| Charge | \( \phi_{\mu} \) | \( \phi_{\text{el}} \) |
|--------|-----|-----|
| \( \leq 0 \% \) | 1182 ± 172 | 82 ± 15 |
| \( \geq 0 \% \) | 14122 ± 172 | 125 ± 8 |

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| \( \leq 0 \% \) | 1182 ± 172 | 82 ± 15 |
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