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Measurements of Partial Branching Fractions for $\overline{B} \to X_u \ell \bar{\nu}$ and Determination of $|V_{ub}|$

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We present partial branching fractions for inclusive charmless semileptonic B decays $\overline{B} \to X_u \ell \bar{\nu}$, and the determination of the CKM matrix element $|V_{ub}|$. The analysis is based on a sample of 383 million $\Upsilon(4S)$ decays into $B\overline{B}$ pairs collected with the *BABAR* detector at the PEP-II e^+e^- storage rings. We select events using either the invariant mass M_X of the hadronic system, the invariant mass squared, q^2, of the lepton and neutrino pair, the kinematic variable P_+ or one of their combinations. We then determine partial branching fractions in limited regions of phase space: $\Delta\mathcal{B} = (1.18 \pm 0.09_{\text{stat.}} \pm 0.07_{\text{sys.}} \pm 0.01_{\text{theo.}}) \times 10^{-3}$ ($M_X < 1.55$ GeV/c^2), $\Delta\mathcal{B} = (0.95 \pm 0.10_{\text{stat.}} \pm 0.08_{\text{sys.}} \pm 0.01_{\text{theo.}}) \times 10^{-3}$ ($P_+ < 0.66$ GeV/c), and $\Delta\mathcal{B} = (0.76 \pm 0.08_{\text{stat.}} \pm 0.07_{\text{sys.}} \pm 0.02_{\text{theo.}}) \times 10^{-3}$ ($M_X < 1.7$ GeV/c^2, $q^2 > 8$ GeV^2/c^4). Corresponding values of $|V_{ub}|$ are extracted using several theoretical calculations.

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In the Standard Model the element V_{ub} of the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [1] plays a critical role in tests of the prediction of *CP* violation. Since the decay rate for charmless semileptonic decays, $\overline{B} \to X_u \ell \bar{\nu}$ [2], is proportional to $|V_{ub}|^2$, the best method to extract this quantity is to measure branching fractions for such decays. Experimentally, the principal challenge is to separate the rare $\overline{B} \to X_u \ell \bar{\nu}$ decays from the approximately 50 times larger $\overline{B} \to X_c \ell \bar{\nu}$ background. This can be achieved in regions of phase space where the background is suppressed. To relate the decay rate of the B meson to $|V_{ub}|$, parton level calculations have to be corrected for perturbative and non-perturbative QCD effects. A variety of QCD calculations are available to determine these corrections [3–5].

In this letter, we present measurements of partial branching fractions for inclusive charmless semileptonic decays, $\overline{B} \to X_u \ell \bar{\nu}$ [6]. $\Upsilon(4S) \to B\overline{B}$ events are tagged by the full reconstruction of a hadronic decay of one of the B mesons (B_{reco}). The semileptonic decay of the second B meson (B_{recoil}) is identified by the presence of an electron or a muon. This technique results in a low event selection efficiency but allows the determination of the momentum, charge, and flavor of the B mesons.

We use three kinematic variables to separate $\overline{B} \to X_u \ell \bar{\nu}$ decays from the dominant $\overline{B} \to X_c \ell \bar{\nu}$ background: M_X, the invariant mass of the hadronic system $X_{u,c}$; q^2, the invariant mass squared of the lepton-neutrino system; and $P_+ \equiv E_X - |\vec{P}_X|$, the light-cone component of the hadronic final state momentum along the jet direction [3, 4], where E_X and $\vec{P}_X$ are the energy and momentum of the hadronic system $X_{u,c}$ calculated in the B rest frame. We measure the fraction of partial rates of charmless semileptonic decays $\Delta R_{\text{u/sl}} = \Delta\mathcal{B}(\overline{B} \to X_u \ell \bar{\nu})/\mathcal{B}(\overline{B} \to X \ell \bar{\nu})$ in restricted phase space regions, corrected for resolution effects. The resulting partial branching fractions are used to calculate $|V_{ub}|$ following theoretical prescriptions.

The analysis uses a sample of 383 million $\Upsilon(4S)$ decays into $B\overline{B}$ pairs, corresponding to an integrated luminosity of $347.4 fb^{-1}$, collected with the *BABAR* detector [7]. Charmless semileptonic $\overline{B} \to X_u \ell \bar{\nu}$ decays are simulated as a combination of three-body decays ($X_u = \pi, \eta, \eta', \rho, \omega, \ldots$) [8] and decays to non-resonant hadronic final states X_u [9]. The motion of the b quark inside the B meson is modeled with the shape function parametrization given in Ref. [9]. The simulation of the $\overline{B} \to X_c \ell \bar{\nu}$ background uses an HQET parametrization of form factors for $B \to D^* \ell \nu$ [10, 11], and models for $\overline{B} \to D\pi \ell \bar{\nu}, D^*\pi \ell \bar{\nu}$ [12], and for $\overline{B} \to D \ell \bar{\nu}, D^{**} \ell \bar{\nu}$ [8]. The simulation of the hadronization is performed by `Jetset7.4` [13]. We use GEANT4 [14] to simulate the detector response.

To reconstruct a large sample of hadronically decaying B mesons, $B_{\text{reco}} \to \overline{D}^{(*)} Y^{\pm}$ are selected. Here, the system $Y^{\pm}$ consists of hadrons with a total charge of ± 1, composed of $n_1 \pi^{\pm}\, n_2 K^{\pm}\, n_3 K^0_S\, n_4 \pi^0$, where $n_1 + n_2 \leq 5$, $n_3 \leq 2$, and $n_4 \leq 2$. The kinematic consistency of B_{reco} candidates is checked with two variables, $m_{\text{ES}} = \sqrt{s/4 - \vec{p}_B^{\,2}}$ and $\Delta E = E_B - \sqrt{s}/2$. Here $\sqrt{s}$ is the total energy in the $\Upsilon(4S)$ center of mass frame, and $\vec{p}_B$ and E_B denote the momentum and energy of the B_{reco} candidate in the same frame. We require $\Delta E = 0$ within three standard deviations as measured for each decay mode. For each of the B_{reco} decays, the purity $\mathcal{P}$ is estimated on Monte Carlo (MC) as the ratio of signal over background events with $m_{\text{ES}} \geq 5.27\,\text{GeV}/c^2$. Only decays for which $\mathcal{P}$ exceeds 20% are retained. On average, we reconstruct at least one B candidate in 0.3% (0.5%) of the $B^0\overline{B}^0$ (B^+B^-) events. For events with more than one reconstructed B decay, the decay mode with the highest purity is selected.

We determine the number of B_{reco} candidates from an unbinned maximum likelihood fit to the m_{ES} distribution. The data are fit to the sum of three contributions: signal B_{reco} decays, combinatorial background from $B\overline{B}$ events, and continuum ($e^+e^- \to q\bar{q}$, $q = u, d, s, c$) events. A threshold function [15] is used to describe the combinatorial and continuum backgrounds. To obtain a good description of the signal m_{ES} distribution, we adopt the modified Gaussian function used in Ref. [16], which models both the peak and tail caused by photon energy loss. Fits to the m_{ES} distribution are shown in Fig. 1. Semileptonic decays $\overline{B} \to X \ell \bar{\nu}$ of the B_{recoil} candidate are identified by an electron or muon with momentum $p^*_\ell > 1\,\text{GeV}/c$ in the $\overline{B}$ rest frame. For charged B_{reco} candidates, we require the charge of the lepton to be consistent with a prompt semileptonic $\overline{B}$ decay. For neutral B_{reco} candidates, both charge-flavor combinations are retained and the known average B^0-$\overline{B}^0$ mixing rate [17] is used to extract the prompt lepton yield.

The hadronic system X in the decay $\overline{B} \to X \ell \bar{\nu}$ is reconstructed from charged tracks and energy depositions in the calorimeter that are not associated with

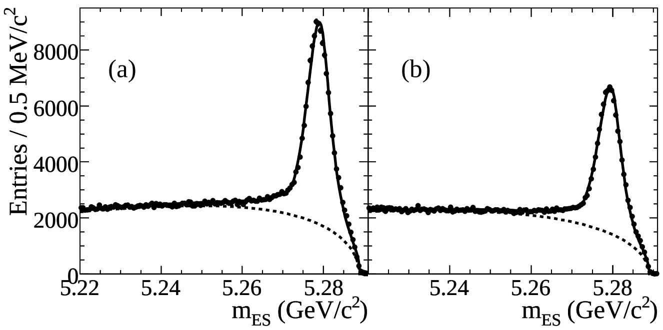

FIG. 1: The $m_{\rm ES}$ distribution for data (points with statistical errors) is shown together with the results of the fit (solid line) for selected semileptonic decays from B^+B^- events (a) and $B^0\overline{B}^0$ events (b). The dashed line shows the contribution from combinatorial and continuum background.

the $B_{\rm reco}$ candidate or the identified lepton. We reconstruct K^0_S by performing a mass-constrained fit to $\pi^+\pi^-$ pairs with an invariant mass in the range 0.473-0.523 GeV/c^2. The neutrino four-momentum p_ν is estimated from the missing momentum four-vector $p_{\rm miss} = p_{\Upsilon(4S)} - p_{B_{\rm reco}} - p_X - p_\ell$, where all momenta are measured in the laboratory frame and $p_{\Upsilon(4S)}$ refers to the $\Upsilon(4S)$ meson.

To select $\overline{B} \to X_u \ell \bar{\nu}$ candidates we require exactly one charged lepton with $p^*_\ell > 1\,{\rm GeV}/c$, charge conservation ($Q_X + Q_\ell + Q_{B_{\rm reco}} = 0$), and a missing mass consistent with zero ($m^2_{miss} < 0.5\,{\rm GeV}^2/c^4$). These criteria suppress the dominant $\overline{B} \to X_c \ell \bar{\nu}$ decays, many of which contain additional leptons or an undetected K^0_L meson. We suppress the $B \to D^* \ell \nu$ background by reconstructing the low momentum π^+ from the $D^{*+} \to D^0 \pi^+$ decay. Since the momentum of the π^+ is almost collinear with the D^{*+} momentum $p_{D^{*+}}$, we can approximate the D^{*+} energy as $E_{D^{*+}} \simeq m_{D^{*+}} \times E_\pi / 145\,{\rm MeV}/c^2$. Because the neutrino mass $m^2_\nu = (p_B - p_{D^{*+}} - p_\ell)^2$ is peaked at zero for background events, we require $m^2_\nu < -3\,{\rm GeV}^2/c^4$ for signal events. We reject events with charged kaons or K^0_S in the $B_{\rm recoil}$ to reduce the background from $\overline{B} \to X_c \ell \bar{\nu}$ decays.

To extract the distribution in the variables M_X, P_+, and the combination of M_X and q^2, we perform fits to the $B_{\rm reco}$ $m_{\rm ES}$ distributions for subsamples of events in individual bins for each of the variables, and subsequently separating the signal from the combinatorial and continuum backgrounds for the three distributions. The resulting distributions are presented in Fig. 2. To reduce the systematic uncertainties in the derivation of the branching fractions we determine the ratios of the partial branching fractions to the total semileptonic branching fraction. This is done for restricted regions of phase space, $M_X < 1.55$ GeV/c^2, $P_+ < 0.66$ GeV/c, and ($M_X < 1.7$ GeV/c^2, $q^2 > 8.0$ GeV$^2/c^4$). Specifically we define this ratio as

$$\frac{\Delta\mathcal{B}(X_u \ell \bar{\nu}_\ell)}{\mathcal{B}(X \ell \bar{\nu}_\ell)} = \frac{(N_u - N_u^{\rm out} - BG_u)/(\epsilon^u_{\rm sel}\epsilon^u_{\rm kin})}{(N_{\rm sl} - BG_{\rm sl})} \times \frac{\epsilon^{\rm sl}_\ell \epsilon^{\rm sl}_t}{\epsilon^u_\ell \epsilon^u_t}, \quad (1)$$

where N_u and BG_u are the measured signal events and the corresponding calculated background, and N_u^{out} refers to signal events that migrate from outside the kinematic region into the signal region. They are determined by a χ^2 fit to the measured spectra with the background shape determined from MC simulation. $N_{\rm sl} = 181074 \pm 706$ and $BG_{\rm sl} = 12185 \pm 78$ are the measured semileptonic events and the corresponding background. The efficiency $\epsilon^u_{\rm sel}$ denotes the fraction of selected $B_{\rm reco}$-tagged signal events with a high-energy lepton. The model-dependent efficiency $\epsilon^u_{\rm kin}$ accounts for the loss of selected events generated in the kinematic region that migrate outside this region. The efficiency of the tag and lepton selection, ϵ_t and ϵ_ℓ, differ slightly for the signal and the semileptonic samples, due to differences in the lepton momentum distribution and the multiplicity of the recoiling B meson. To convert the ratio in Eq. 1 to partial branching fractions, we use the total semileptonic branching fraction, $\mathcal{B}(\overline{B} \to X \ell \overline{\nu}_\ell) = (10.75 \pm 0.15)\%$ [17]. The resulting partial branching fractions for the three selected kinematic regions, along with parameters in Eq. 1, are listed in Table I.

We consider several sources of systematic uncertainties. Detector-related uncertainties take into account particle (e, μ, K) identification (efficiency, misidentification), charged particle tracking efficiency, photon reconstruction efficiency and K^0_L interactions. We estimate the error due to signal and background modeling. The signal modeling uncertainties are due to the modeling of exclusive charmless semileptonic decays and gluon splitting into $s\bar{s}$-quark pairs. We also calculate the errors associated with the uncertainties in the nonperturbative parameters and the functional form of the shape function. The background simulation depends on the B and D branching fractions and $B \to D^* \ell \nu$ form factors. We estimate the error due to $m_{\rm ES}$ fits, coming from the uncertainty in the parameterization ansatz. Finally, we estimate the error due to MC statistics. The fractional contribution of each uncertainty is shown in Table II together with the total error.

The results of the partial branching fractions are translated into $|V_{ub}|$ in the context of recent QCD calculations [3–5], including estimates of theoretical uncertainties (see Table I). The hadronic input parameters, the b-quark mass m_b, and the kinetic energy expectation value μ^2_π, are extracted from moment measurements in $B \to X_s \gamma$ and $\overline{B} \to X_c \ell \bar{\nu}$. Their values in the kinetic scheme [18] are $m_b = (4.59 \pm 0.04)$ GeV/c^2 and $\mu^2_\pi = (0.40 \pm 0.04)$ GeV^2/c^2 [19] and are translated into values in different schemes, as needed [3–5]. The partial branching fraction $\Delta\mathcal{B}(\overline{B} \to X_u \ell \bar{\nu})$ is related directly to

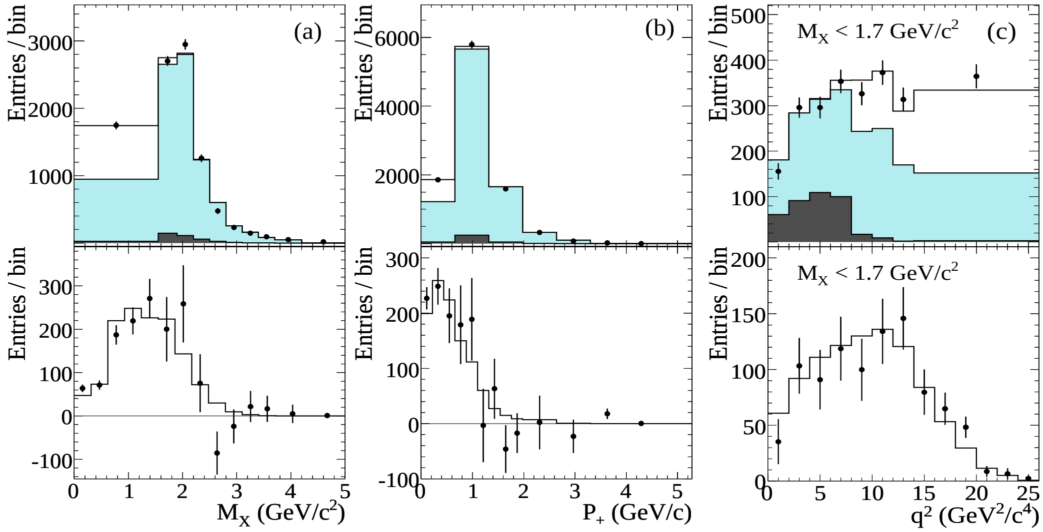

FIG. 2: Upper row: measured M_X (a), P_+ (b) and q^2 with $M_X < 1.7$ GeV/c^2 (c) spectra (data points). The result of the fit to the sum of three MC contributions is shown in the histograms: $\overline{B} \to X_u \ell \bar{\nu}$ decays generated inside (no shading) and outside (dark shading) the selected kinematic region, and $\overline{B} \to X_c \ell \bar{\nu}$ and other background (light shading). Lower row: corresponding spectra for $\overline{B} \to X_u \ell \bar{\nu}$ after $\overline{B} \to X_c \ell \bar{\nu}$ and other background subtraction; they have been rebinned in order to show the shape of the kinematic variables.

TABLE I: Summary of the measurements of the fitted numbers of events and efficiencies, $\Delta\mathcal{B}(\overline{B} \to X_u \ell \bar{\nu})$, and extracted $|V_{ub}|$ for the three kinematic cuts. The first error is statistical, the second systematic. For $\Delta\mathcal{B}$, the third error is due to the theoretical uncertainty on the signal efficiency; for the $|V_{ub}|$ values, it comes from the the theoretical uncertainty on $\Delta\zeta$. For Ref. [3] we use the exponential parametrization of the shape function.

	N_u	N_u^{out}	BG_u	$\epsilon^u_{\rm sel}\epsilon^u_{\rm kin}$	$\frac{\epsilon^{\rm sl}_\ell \epsilon^{\rm sl}_t}{\epsilon^u_\ell \epsilon^u_t}$	$\Delta\mathcal{B}(\overline{B} \to X_u \ell \bar{\nu})$ (10^{-3})	$\lvert V_{ub}\rvert$ (10^{-3})
M_X	803 ± 60	27 ± 2	923 ± 21	0.331 ± 0.003	0.76 ± 0.02	$1.18 \pm 0.09 \pm 0.07 \pm 0.01$	$4.27 \pm 0.16 \pm 0.13 \pm 0.30$ [3]
							$4.56 \pm 0.17 \pm 0.14 \pm 0.32$ [4]
P_+	633 ± 63	48 ± 5	1183 ± 27	0.344 ± 0.003	0.81 ± 0.02	$0.95 \pm 0.10 \pm 0.08 \pm 0.01$	$3.88 \pm 0.19 \pm 0.16 \pm 0.28$ [3]
							$3.99 \pm 0.20 \pm 0.16 \pm 0.24$ [4]
M_X, q^2	562 ± 55	32 ± 2	789 ± 9	0.373 ± 0.004	0.79 ± 0.03	$0.76 \pm 0.08 \pm 0.07 \pm 0.02$	$4.48 \pm 0.22 \pm 0.19 \pm 0.30$ [3]
							$4.53 \pm 0.22 \pm 0.19 \pm 0.25$ [4]
							$4.81 \pm 0.23 \pm 0.20 \pm 0.36$ [5]

$|V_{ub}|$ by the relation $|V_{ub}| = [\Delta\mathcal{B}(\overline{B} \to X_u \ell \bar{\nu})/\tau_b \Delta\zeta]^{1/2}$, where τ_b is the average B lifetime [17], and $\Delta\zeta$ is the prediction for the partial rate for $\overline{B} \to X_u \ell \bar{\nu}$ in the given phase-space region [3–5].

In summary, we have measured the branching fractions for inclusive charmless semileptonic B decays $\overline{B} \to X_u \ell \bar{\nu}$ in three overlapping regions of phase space. Relying on theoretical predictions, we extract values for the CKM matrix element $|V_{ub}|$ from our measured $\Delta\mathcal{B}$. The result, based on the hadronic mass spectrum, supersedes our previously published measurement [20], reducing the relative error by 40%. The statistical, systematic as well as theoretical errors are highly correlated. These values are in good agreement with the world average [17].

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TABLE II: Contributions to the systematic error on the measured $\Delta\mathcal{B}(\overline{B} \to X_u \ell\bar{\nu})$, shown in percent (%) for the three kinematic cuts, from detector, shape function (input parameters and functional form), exclusive $\mathcal{B}(\overline{B} \to X_u \ell\bar{\nu})$, gluon splitting, exclusive $\mathcal{B}(\overline{B} \to X_c \ell\bar{\nu})$, $B \to D^* \ell^- \overline{\nu}$ form factors, $\mathcal{B}(D)$, $m_{\rm ES}$ fit, MC statistics. The last column gives the total systematic error.

	Detector	Shape function	$\mathcal{B}(\overline{B} \to X_u \ell\bar{\nu})$ $X_u = \pi, \rho, \ldots$	Gluon splitting	$\mathcal{B}(\overline{B} \to X_c \ell\bar{\nu})$	$B \to D^* \ell^- \overline{\nu}$ form factors	$\mathcal{B}(D)$	$m_{\rm ES}$ fit	Monte Carlo statistics	Total
M_X	1.92	0.90	2.08	1.62	0.87	0.21	0.44	3.71	3.22	6.07
P_+	3.88	1.31	2.22	1.47	2.80	0.39	0.73	3.98	4.62	8.38
M_X, q^2	3.83	2.43	2.71	1.02	1.17	0.55	0.79	5.17	4.29	8.81

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