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# SEMILEPTONIC $B$ DECAYS AT *BABAR*

V.Azzolini [a]

*IFIC - Universitat de Valencia - CSIC , 46010 Valencia, Spain*

*Abstract.*We report on studies of charmless semileptonic decays based on the data collected at the $\Upsilon(4S)$ resonance using the the *BABAR* detector [1] at the Stanford Linear Accelerator Center. We present a number of inclusive methods to isolate $b \to u\ell\bar{\nu}$ decays and suppress the more abundant $b \to c\ell\bar{\nu}$ process and show results of measurements based on: the lepton energy and squared lepton-neutrino invariant mass, $E_\ell$ and $q^2$, the hadron invariant mass and squared lepton-neutrino invariant mass, $M_X$ and $q^2$. Exclusive charmless semileptonic decays have also been investigated. We report studies on $B \to \pi/\rho\ell\nu$ decay on untagged events, the $\bar{B} \to X_u\ell\bar{\nu}$ decay modes with hadronic tags, the $B^\pm \to \pi^0\ell^\pm\nu$ using semileptonic $B^- \to D^0\ell^-\,\overline{\nu}\,(X)$ tags and $B^0 \to \pi^-\,\ell^+\,\nu$ with semileptonic $\overline{B}^0 \to D^{(*)+}\ell^-\,\overline{\nu}$ s tags. From the measurements of partial and total branching fractions, the magnitude of the CKM element $|V_{ub}|$ is derived using several theoretical predictions and frameworks.

The principal physics goal of the *BABAR* experiment is to establish $CP$ violation in $B$ mesons and to test whether the observed effects are consistent with the predictions of the Standard Model (SM). $CP$ violating effects result in the SM from an irreducible phase in the Cabibbo-Kobayashi-Maskawa (CKM) matrix which describes the couplings of the charged weak current to quarks. An improved determination of the magnitude of the matrix element $|V_{ub}|$ , the coupling strength of the $b$ quark to the $u$ quark, will contribute critically to tests of the consistency of the measured angles of the unitarity triangle of the CKM matrix.

The precise determination of $|V_{ub}|$ is very difficult as, due to the large charmed backgrounds, we are forced to measure partial branching fractions and extrapolate them to the full phase space by relying on QCD based theoretical calculations. It is therefore important to make redundant measurements by using several experimental techniques, and different theoretical frameworks.

## 1 Inclusive Measurements

In inclusive measurements, three kinematic variables are discussed in the literature, each having its own advantages: the lepton energy ($E_\ell$), the hadronic invariant mass ($M_X$), and the leptonic invariant mass squared ($q^2$). The first measurements were restricted to the high end of the lepton spectrum where theoretical uncertainties are very large and therefore the extrapolation to the full spectrum becomes uncertain. Event selection based on $M_X$ and $q^2$ allows us to select larger portions of phase space, but the underlying theoretical assumptions need to be carefully evaluated.

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[a] e-mail: azzolini@slac.stanford.edu

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SLAC, Stanford University, Stanford, CA 94025

In the first analysis here presented, semileptonic $b \to ue\bar{\nu}$ 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, $q^2$ [b] [2]. The dominant charm background is suppressed by selecting a region of the $q^2$-$E_e$ phase space where correctly reconstructed $b \to ce\bar{\nu}$ events are kinematically excluded.

Hadronic events containing an identified electron with energy $2.1\ GeV < E_e < 2.8\ GeV$ are selected. The neutrino 4-momentum is reconstructed from the visible 4-momentum and knowledge of the $e^+e^-$ initial state.
The maximum kinematically allowed hadronic mass squared, for a given $E_e$ and $q^2$, is $s_h^{max} = m_B^2 + q^2 - 2m_B(E_e + q^2/4E_e)$ for $\pm 2E_e > \pm\sqrt{q^2}$; we require $s_h^{max} \approx m_{D^0}^2$. We determine a partial branching fraction $\Delta B(\tilde{E}, \tilde{s}_{\rm h}^{\rm max}) = B(\bar{B} \to X_u e\bar{\nu})f_u$, unfolded for detector effects. The acceptance, $f_u$, is the fraction of $\bar{B} \to X_u e\bar{\nu}$ decays in the region of interest, $\tilde{E}_e > 2.0\ GeV$ and $\tilde{s}_{\rm h}^{\rm max} < 3.5\ GeV$ (shown in Fig. 2 - [3]), where $\tilde{E}_e$ and $\tilde{s}_{\rm h}^{\rm max}$ are the generated values in the $B$ meson rest frame. We find $\Delta B(2.0, 3.5) = (3.54 \pm 0.33_{stat.} \pm 0.34_{syst.}) \times 10^{-4}$.

We extract $|V_{ub}| = [\Delta\mathcal{B}(\bar{B} \to X_u \ell\bar{\nu})/\Delta\zeta\ \tau_B]^{1/2}$ using $\tau_B = 1.604 \pm 0.023\,ps$ and the normalized partial rate,$\Delta\zeta$ as taken from Ref. [4]. The values used for the heavy quark parameters, $m_b = 4.61 \pm 0.08 GeV$ and $\mu_\pi^2 = 0.15 \pm 0.07 GeV$ are based on fits to *BABAR* $\bar{B} \to X_c \ell\bar{\nu}$ moments [5], translated to the Shape Function(SF) scheme of Ref. [6].

We find $|V_{ub}|(2.0, 3.5) = (3.95 \pm 0.26_{exp.}{}^{+0.58}_{-0.42}{}_{HQ} \pm 0.25_{theo.}) \times 10^{-3}$.

On the other hand, studies [7] indicate it is possible to reduce the theoretical error on the extrapolation by applying simultaneous cuts on $M_X$ and $q^2$ in inclusive $\bar{B} \to X_u \ell\bar{\nu}$. In fact, while the $M_X$ distribution has a large usable fraction of events, of the order of 70%, but depends on the SF, the $q^2$ distribution is less sensitive to non-perturbative effects but only a small fraction of events ($\sim 20\%$) is usable. We study the recoiled $B$ candidate opposite of a fully reconstructed $B$ in hadronic decay ($B_{reco}$), where are selected decays of the type $B \to \overline{D}\,Y$, where $D$ refers to a charm meson, and $Y$ is a collection of hadrons $(\pi^\pm, K^\pm, K_S^0, \pi^0)$ with a total charge of $\pm 1$ [c]. The kinematic consistency of a $B_{reco}$ candidate with a $B$ meson decay is checked using two variables, the beam-energy-substituted mass $m_{\rm ES} = \sqrt{s/4 - \vec{p}_B^{\,2}}$ and the energy difference, $\Delta E = E_B - \sqrt{s}/2$. Here $\sqrt{s}$ refers to 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. In order to extract the partial charmless semileptonic branching ratio, $\Delta BR(\bar{B} \to X_u \ell\bar{\nu})$, in a given region of the $M_X$-$q^2$ plane, we define as signal the events with true values of the kine-

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[b] hep-ex/0506036 - The data set used consists of 88.4 million $B\overline{B}$ pairs, corresponding to an integrated luminosity of $81.4\,\mathrm{fb}^{-1}$.

[c] hep-ex/0507017 - $211\,\mathrm{fb}^{-1}$.

matic variables in the chosen region, treating as background those that migrate from outside this region because of the resolution ((shown in Fig. 2 - [8]) and quote efficiences[d] only for those signal events. The partial branching fraction, in the signal region, is $\Delta BR(\bar{B} \rightarrow X_u\ell\bar{\nu}\ , M_X < 1.7GeV/c^2\ , q^2 > 8GeV^2/c^4\ ) = (0.87 \pm 0.13_{stat.+syst.} \pm 0.01_{theo}) \times 10^{-3}$.

To translate this into a measurement of $|V_{ub}|$ ;[e] we need the fraction of events inside the measurement region [f] as an external input; using the acceptance corrections calculated in the Bosch, Lange, Neubert and Paz [4, 10, 11] (BLNP) approach and by taking the SF parameters from [5], we find $|V_{ub}|^{BLNP}_{BABAR\ \bar{B}\rightarrow X_c\ell\bar{\nu}} = (4.65 \pm 0.34_{stat.+syst.}\ {}^{+0.46}_{-0.38}\ {}_{SF} \pm 0.23_{th}) \times 10^{-3}$, while with Bauer, Ligeti and Luke [12] (BLL) acceptances calculations, $|V_{ub}|^{BLL} = (4.82 \pm 0.36_{stat.+syst.} \pm 0.46_{theo.+SF}) \times 10^{-3}$.

In conclusion, the total error on $|V_{ub}|$ inclusive measurements is dominated by the experimental and theoretical uncertainties of the SF. The three approaches to measure inclusively $|V_{ub}|$ done at Babar show that no significantly changes occur changing the two sets of SF parameters coming from a fit to the photon energy spectrum and to the $\bar{B} \rightarrow X_c\ell\bar{\nu}$ moments. Being infact in good agreement, they give thus consistent results on $|V_{ub}|$ .

## 2 Exclusive Measurements

Alternatively the measurements of the $\bar{B} \rightarrow X_u\ell\bar{\nu}$ decay rates can be done exclusively, because this allow for kinematic constrains and more efficient background suppression, but must rely on theoretical form-factor predictions. We distinguish between them through the tagging method used: the hadronic tag, the semileptonic tag, and finally the untagged one.

In events in which the decay of one $B$ meson to a hadronic final state is fully reconstructed , the semileptonic decay, in $B^0 \rightarrow \pi^- \ell^+ \nu$ and $B^+ \rightarrow \pi^0\ell^+ \nu$, of the second $B$ is identified by the detection of a charged lepton and a pion [g]. The charmless meson in the semileptonic decay are reconstructed and the missing mass (see Fig. 3 - [13] ) is calculated assuming that the pion and the charged lepton are the only particles present in the recoil except for the undetected neutrino. Evaluating the signal yield from a fit to $m_{\rm ES}$ in three regions of the invariant mass squared of the lepton pair, we obtain the total branching fractions $BR(B^0 \rightarrow \pi^-\ell^+\nu\ ) = (1.14 \pm 0.27_{stat} \pm 0.17_{syst}) \times 10^{-4}$ and $BR(B^+ \rightarrow \pi^0\ell^+\nu\ ) = (0.86 \pm 0.22_{stat} \pm 0.11_{syst}) \times 10^{-4}$.

In the analyses using the semileptonic tag[h], we look for combinations of a $D^+$

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[d] They are computed on simulations based on the DFN model. [9].

[e] The partial rate for $\bar{B} \rightarrow X_u\ell\bar{\nu}$ can be related to $|V_{ub}|$ though the relation previously defined.

[f] referred to as "acceptance"

[g] hep-ex/0507085 - 211 fb$^{-1}$ .

[h] hep-ex/0506064 - 211 fb$^{-1}$ (hep-ex/0506065 - 81 fb$^{-1}$ ).

or $D^{*+}$ ($D^0$) meson and a charged lepton ($e^-$ or $\mu^-$) that are kinematically consistent with $\overline{B}^0 \rightarrow D^{(*)+}\ell^- \,\overline{\nu}$ ($B^- \rightarrow D^0\ell^- \,\overline{\nu}\,(X)$) decays. For each such $B$ candidate, we define the recoil side as the tracks and calorimeter clusters that are not associated with the candidate and search for a signature of a $B^0 \rightarrow \pi^- \,\ell^+ \,\nu$ ( $B^+ \rightarrow \pi^0\ell^+ \,\nu$ ) decay. We take advantage of the simple kinematics of the process to define discriminating variables like the cosine of $\theta_{BY}$ (see Fig. 2 - [14]) or of $\theta_{B\pi\ell}$ (Fig. 3 - [15])[i] , and extract the signal yield from their distributions in three bins of $q^2$. Finally we calculate the total and the partial branching fractions using the signal efficiencies predicted by a Monte Carlo (MC) simulation. From the signal yields and the efficiencies evaluated, we extract the following results for the total branching fraction as $B(B^0 \rightarrow \pi^-\ell^+\nu) = (1.03 \pm 0.25_{stat.} \pm 0.13_{syst.}) \times 10^{-4}$ and $B\,(B^+ \rightarrow \pi^0\ell^+\,\nu) = (1.80 \pm 0.37_{stat.} \pm 0.23_{syst.}) \times 10^{-4}$.

For the untagged approach we present a determination of total branching fraction from charmless semileptonic $B$ decays with exclusively reconstructed final states, $B \rightarrow h_u\ell\nu$, where the hadronic state $h_u$ represents a $\pi^{\pm}$, $\pi^0$, $\rho^{\pm}$, or $\rho^0$ and $\ell$ represents $e$ or $\mu$[j].
The neutrino four-momentum, is inferred from the difference between the net four-momentum of the colliding-beam particles, $p_{\rm beams}$ , and the sum of the four-momenta of all detected particles in the event. We discriminate against the remaining background using the variables $m_{\rm ES}$ and $\Delta E$ . Fig. 1 - [16] shows projections of the fitted $m_{\rm ES}$ vs $\Delta E$ distributions for each $q^2$ interval for $B \rightarrow \pi\ell\nu$ and $B \rightarrow \rho\ell\nu$ , respectively. Integrated over the whole $q^2$ range, we observe 396 $\pi^-\ell^+\nu$ , 137 $\pi^0\ell^+\nu$ , 95 $\rho^-\ell^+\nu$ , and 98 $\rho^0\ell^+\nu$ decays and the total branching fractions, $B(B^0 \rightarrow \pi^-\ell^+\nu) = (1.38 \pm 0.10_{stat.} \pm 0.16_{syst.} \pm 0.08_{FF}) \times 10^{-4}$ and $B(B^0 \rightarrow \rho^-\ell^+\nu) = (2.14 \pm 0.21_{stat.} \pm 0.48_{syst.} \pm 0.28_{FF}) \times 10^{-4}$.

In conclusion *BABAR* has produced in last months several and competitive total branching fraction exclusive measurements, that are consistent with previous measurements [17,18], but have higher statistical accuracy, are less dependent on theoretical form-factor predictions, and benefit from recent advances in theoretical calculations [19–21].

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[i] Referring to the $D^{(*)+}\ell^-$ system as the "$Y$" system, we first calculate the cosine of $\theta_{BY}$, the angle between $p^*_B$ and $p^*_Y$ and the cosine of $\theta_{B\pi\ell}$, the angle between $p^*_B$ and $p^*_{\pi\ell}$.

[j] hep-ex/0507003 - 76 fb$^{-1}$ .

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