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Inclusive Semileptonic B Decays at BABAR

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Abstract. We report updates on two analyses of inclusive semileptonic B decays based on a dataset of 89 million $B\overline{B}$ events recorded with the *BABAR* detector at the $\Upsilon(4S)$ resonance. Events are selected by fully reconstructing the decay of one B meson and identifying a charged lepton from the decay of the other $\overline{B}$ meson. In the first analysis, the measurement of the first and second moment of the hadronic mass distribution in Cabibbo-favored $\overline{B} \to X_c \ell \bar{\nu}$ decays allows for the determination of the nonperturbative parameters $\overline{\Lambda}$ and λ_1 of Heavy Quark Effective Theory (HQET) and $|V_{cb}|$. In the second analysis, the hadronic mass distribution is used to measure the inclusive charmless semileptonic branching fraction and to determine $|V_{ub}|$.

PACS. 13.20.He Decays of beauty mesons – 12.39.Hg Heavy quark effective theory

1 Introduction

The principal motivation for flavor physics is a comprehensive test of the Standard Model description of *CP* violation. Semileptonic B decays allow for the determination of $|V_{cb}|$ and $|V_{ub}|$, two elements of the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix. In the unitarity triangle, constraints derived from kaon decays and the overall normalization depend on $|V_{cb}|$, while the uncertainty in $|V_{ub}|$ dominates the error of the length of the side opposite the angle β. As this angle can be measured very cleanly in time-dependent *CP* asymmetries, the errors of $|V_{ub}|$ must be model independent, well understood, and small before any discrepancies between sides and angles could be interpreted as new physics. Currently, the error in $|V_{ub}|$ is dominated by theoretical uncertainties in inclusive B decays and the absence of model independent formfactor calculations in exclusive B decays [1].

The Cabibbo-favored decays $\overline{B} \to X_c \ell \bar{\nu}$ allow for high-statistics measurements of HQET parameters and quantitative tests of the consistency of the underlying theory. The large branching fraction allows for clean experimental measurements with high purity event tags and small systematic errors. The main difficulty in the determination of $|V_{ub}|$ is the large background from $\overline{B} \to X_c \ell \bar{\nu}$ decays, overlapping over most of the phase space. Selection cuts reduce this background by restricting the phase space, but lead to problems in the theoretical description.

The measurements [2] presented here are based on a sample of 89 million $B\overline{B}$ pairs collected near the $\Upsilon(4S)$ resonance by the *BABAR* detector [3]. The boosted center-of-mass system (CMS) at *BABAR* leads to a limited coverage of about 85% of the solid angle in the CMS. The very high luminosity opens alternative methods in the precise study of (semileptonic) B decays. Both analyses presented here use $\Upsilon(4S) \to B\overline{B}$ events, where one B meson decays hadronically and is fully reconstructed (B_{reco} candidate) and the semileptonic decay of the recoiling B meson is identified by the presence of an electron or muon. This approach results in a low overall event selection efficiency, but allows for the determination of the momentum, charge, and flavor of the B mesons. To reconstruct a large sample of B mesons, hadronic decays $B_{reco} \to \overline{D}Y^{\pm}, \overline{D}^{*}Y^{\pm}$ are selected, where the hadronic system Y consists of $n_1\pi^{\pm} n_2K^{\pm} n_3K_s^0 n_4\pi^0$, with $n_1 + n_2 \leq 5$, $n_3 \leq 2$, and $n_4 \leq 2$. The kinematic consistency of B_{reco} candidates is checked with the beam energy-substituted mass $m_{\rm ES} = \sqrt{s/4 - \boldsymbol{p}_B^2}$ and the energy difference $\Delta E = E_B - \sqrt{s}/2$, where $\sqrt{s}$ is the total energy and $(E_B, \boldsymbol{p}_B)$ denotes the momentum four-vector of the B_{reco} candidate in the CMS.

2 Cabibbo-favored Decays $\overline{B} \to X_c \ell \bar{\nu}$

Inclusive semileptonic B decays are calculated in the Heavy Quark Expansion (HQE), an Operator Product Expansion using HQET, allowing for the computation of, *e.g.,* the total semileptonic width Γ_{sl} in terms of $|V_{cb}|$ and a double series in Λ_{QCD}/m_b and $\alpha_s(m_b)$. Higher order corrections are parametrized in terms of expectation values of hadronic matrix elements. Other observables, *e.g.,* moments of the hadronic mass (squared) and lepton energy distributions, can be expressed in similar expansions with different dependences on the nonperturbative parameters. An overall fit to these moments together with Γ_{sl} thus

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provides a consistency check of the theory by comparing the predicted and measured moments and a determination of $|V_{cb}|$. The determination of the b quark mass m_b and the parameters λ_1, λ_2, ρ_1, etc. is one of the central topics of semileptonic B physics. Special emphasis is placed on the reduction of theoretical input and error estimates and to rely on data from various processes.

This analysis reports an update of the measurement of the moments $\langle m_X \rangle$ and $\langle m_X^2 \rangle$ of the mass distribution of the hadronic system X in a semileptonic B decay.

We select events by requiring a B_{reco} candidate and an identified lepton with momentum in the CMS $p^* > 900\,\mathrm{MeV}/c$, with a charge consistent for a primary B decay. We require that the charge imbalance of the event is not larger than one and obtain a data sample of about 7100 events.

We combine all remaining charged tracks and neutral showers into the hadronic system X. A neutrino candidate is reconstructed from the missing four-momentum $p_{miss} = p_{\Upsilon(4S)} - p_X - p_{B_{reco}}$, where all momenta are measured in the laboratory frame. We impose consistency of the measured p_{miss} with the neutrino hypothesis with the requirements $E_{miss} > 0.5\,\mathrm{GeV}$, $|\boldsymbol{p}_{miss}| > 0.5\,\mathrm{GeV}$, and $|E_{miss} - |\boldsymbol{p}_{miss}|| < 0.5\,\mathrm{GeV}$. A $2C$ kinematic fit—imposing four-momentum conservation, the equality of the masses of the two B mesons and forcing $p_\nu = 0$—improves the resolution of the m_X measurement to a width of about 350 MeV. Monte Carlo simulated event samples are used to calibrate the mass scale, determine efficiencies, and estimate backgrounds.

The resulting moments of the hadronic mass-squared distribution are shown as a function of the threshold lepton momentum p^*_{min} in Fig. 1a. A substantial rise of the moments towards lower momentum is visible, due to the enhanced contributions of high-mass charm states (phase-space suppressed at higher p^*_{min}). The main contributions to the systematic error are the simulation of the detector response and residual backgrounds. The uncertainty from the modeling of the X_c state is negligible compared to the other systematic errors.

Accounting for all correlations between the moments of different p^*_{min}, we determine $\overline{\Lambda}^{\overline{MS}} = 0.53 \pm 0.09\,\mathrm{GeV}$ and $\lambda_1^{\overline{MS}} = -0.36 \pm 0.09\,\mathrm{GeV}^2$ in the $\overline{MS}$ scheme [4]. The errors given do not include uncertainties due to terms $\mathcal{O}(1/m_B^3)$. For comparison, we also show in Fig. 1a the result of the hadronic mass measurement of DELPHI [5], fully consistent with our result. The CLEO result [6] of the first hadronic mass moment at $p^*_{min} = 1.5\,\mathrm{GeV}$ is also consistent with our measurement, but in combination with the mean photon energy from $b \to s\gamma$ [7] shows a different p^*_{min} dependence (see Ref. [8] for recent developments).

The calculations of Ref. [9] are used to fit all hadronic moments from *BABAR* in the $1S$ scheme, as this scheme exhibits better convergence of the series than other alternatives. We find $m_b^{1S} = 4.638 \pm 0.094_{exp} \pm 0.062_{dim\oplus BLM} \pm 0.065_{1/m_B^3}\,\mathrm{GeV}$ and $\lambda_1 = -0.26 \pm 0.06_{exp} \pm 0.04_{dim\oplus BLM} \pm 0.04_{1/m_B^3}\,\mathrm{GeV}^2$. In this fit, we take into acount all correlations between the experimental results, a significant improvement with respect to the approach of Ref. [9]. The fit also utilizes the semileptonic width $\Gamma_{sl} = (4.37 \pm 0.18) \times 10^{-11}\,\mathrm{MeV}$ (determined from *BABAR* data) and determines $|V_{cb}| = (42.10 \pm 1.04_{exp} \pm 0.52_{dim\oplus BLM} \pm 0.50_{1/m_B^3}) \times 10^{-3}$.

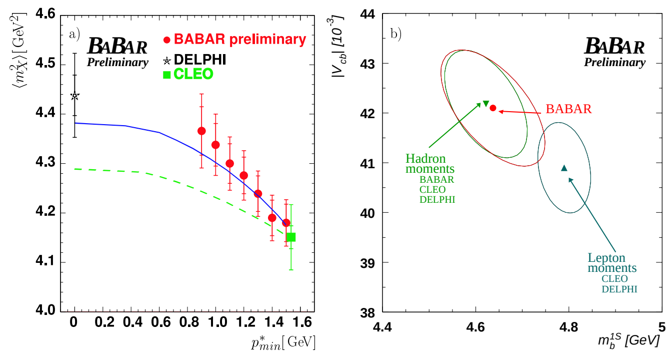

Fig. 1. (a) Measured moments $\langle m_X \rangle$ for different lepton threshold momenta p^*_{min}. The errors of the individual *BABAR* measurements are highly correlated. For comparison, the measurements by the DELPHI [5] and CLEO [6] collaborations are also shown. The solid curve is a fit to the *BABAR* data; the dashed curve is the prediction based on the CLEO results [6, 7]. (b) Constraints on the b quark mass and $|V_{cb}|$ from the combined fit to hadron moments and lepton moments, respectively.

We test the consistency of the HQE by combining the measurement of *BABAR* with the four lepton energy moments measured by the CLEO collaboration [10] and the hadronic mass moment measurement of the DELPHI collaboration [5]. In Fig. 1b, the fit results are shown separately for hadron mass and lepton energy moments. The $\Delta\chi^2 = 1$ contours of hadronic mass and lepton energy moments do not overlap. The largest errors in these measurements are due to the unknown higher order terms of order $1/m_B^3$.

3 Cabibbo-suppressed Decays $\overline{B} \to X_u \ell \bar{\nu}$

In the measurement of $\overline{B} \to X_u \ell \bar{\nu}$ decays, the large background from $\overline{B} \to X_c \ell \bar{\nu}$ decays is traditionally reduced by measuring the lepton spectrum at the "endpoint", beyond the kinematic cutoff for $\overline{B} \to X_c \ell \bar{\nu}$ decays. A disadvantage of this approach is that only about 10% of all charmless semileptonic decays are measured. This leads to significant extrapolation uncertainties, which can be reduced with information on the movement of the b quark inside the B meson obtained from the photon energy spectrum in $b \to s\gamma$ decays.

Here we use the invariant mass m_X of the hadronic system to separate $\overline{B} \to X_u \ell \bar{\nu}$ decays from the dominant $\overline{B} \to X_c \ell \bar{\nu}$ background [11]. This method offers a substantially larger acceptance than the endpoint measurement. As in the first analysis, 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 not associated with

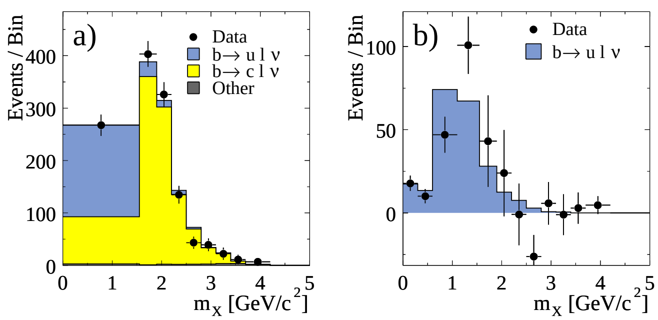

Fig. 2. The m_X distribution for $\overline{B} \to X\ell\bar{\nu}$ candidates: a) data (points) and fit components, and b) data and signal MC after subtraction of the $b \to c\ell\nu$ and the "other" backgrounds.

the B_{reco} candidate or the identified lepton. We require exactly one charged lepton with $p^* > 1\,\mathrm{GeV}/c$, charge conservation ($Q_X + Q_\ell + Q_{B_{reco}} = 0$), and $m^2_{miss} < 0.5\,\mathrm{GeV}^2$. We reduce the $\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}$ background with a partial reconstruction of the decay (the π^+_s from the $D^{*+} \to D^0\pi^+_s$ decay and the lepton). Furthermore, we veto events with charged or neutral kaons in the recoil $\overline{B}$.

In order to reduce experimental systematic errors, we determine the ratio of branching fractions R_u from N_u, the observed number of $\overline{B} \to X_u\ell\bar{\nu}$ candidates with $m_X < 1.55\,\mathrm{GeV}/c^2$, and $N_{sl} = 29982 \pm 233$, the number of events with at least one charged lepton:

$$R_u = \frac{\mathcal{B}(\overline{B} \to X_u\ell\bar{\nu})}{\mathcal{B}(\overline{B} \to X\ell\bar{\nu})} = \frac{N_u/(\varepsilon^u_{sel}\varepsilon^u_{m_X})}{N_{sl}} \times \frac{\varepsilon^{sl}_l \varepsilon^{sl}_{reco}}{\varepsilon^u_l \varepsilon^u_{reco}}.$$

Here $\varepsilon^u_{sel} = 0.326 \pm 0.6_{stat}$ is the efficiency for selecting $\overline{B} \to X_u\ell\bar{\nu}$ decays once a $\overline{B} \to X\ell\bar{\nu}$ candidate has been identified, $\varepsilon^u_{m_X} = 0.770 \pm 0.9_{stat}$ is the fraction of signal events with $m_X < 1.55\,\mathrm{GeV}/c^2$, $\varepsilon^{sl}_l/\varepsilon^u_l = 0.887 \pm 0.008_{stat}$ corrects for the difference in the efficiency of the lepton momentum cut for $\overline{B} \to X\ell\bar{\nu}$ and $\overline{B} \to X_u\ell\bar{\nu}$ decays, and $\varepsilon^{sl}_{reco}/\varepsilon^u_{reco} = 1.00 \pm 0.03_{stat}$ accounts for a possible efficiency difference in the B_{reco} reconstruction in events with $\overline{B} \to X\ell\bar{\nu}$ and $\overline{B} \to X_u\ell\bar{\nu}$ decays.

We extract N_u from the m_X distribution by a fit to the sum of three contributions: signal, background N_c from $\overline{B} \to X_c\ell\bar{\nu}$, and a background of $< 1\%$ from other sources. Fig. 2a shows the fitted m_X distribution. To minimize the model dependence, the first bin is extended to $m_X < 1.55\,\mathrm{GeV}/c^2$. We find 175 ± 21 signal events and 90 ± 5 background events in the region $m_X < 1.55\,\mathrm{GeV}$.

The dominant detector systematic errors are due to the uncertainty in photon detection and combinatorial background subtraction. We assess the theoretical uncertainties by varying the nonperturbative parameters in Ref. [12] within their errors, $\overline{\Lambda} = 0.48 \pm 0.12\,\mathrm{GeV}$ and $\lambda_1 = -0.30 \pm 0.11\,\mathrm{GeV}^2$, obtained from the results in Ref. [6] by removing terms proportional to $1/m^3_b$ and α^2_s from the relation between the measured observables and $\overline{\Lambda}$ and λ_1.

In summary, we have $R_u = (2.06 \pm 0.25 \pm 0.23 \pm 0.36) \times 10^{-2}$. Combining the ratio R_u with the measured inclusive semileptonic branching fraction of Ref. [13], we obtain $\mathcal{B}(\overline{B} \to X_u\ell\bar{\nu}) = (2.24 \pm 0.27 \pm 0.26 \pm 0.39) \times 10^{-3}$. With the average B lifetime of Ref. [14] we obtain $|V_{ub}| = (4.62 \pm 0.28 \pm 0.27 \pm 0.40 \pm 0.26) \times 10^{-3}$ based on Ref. [15]. The first error is statistical, the second systematic, the third gives theoretical (signal efficiency and the extrapolation of R_u to the full m_X range), and the fourth is the uncertainty in the extraction of $|V_{ub}|$ from the total decay rate. No error is assigned to the assumption of parton-hadron duality. This result is consistent with previous inclusive measurements, but has a smaller systematic error, primarily due to larger acceptance and higher sample purity. The results of exclusive measurements tend to have a lower central value, but with a slightly larger error.

4 Outlook

Both analyses presented here will benefit from higher statistics. By measuring higher moments of the hadronic mass, the lepton energy, and possibly other distributions, the analysis of $\overline{B} \to X_c\ell\bar{\nu}$ decays will gain sensitivity to higher order HQET parameters and thus reduce the theory dependent error in the determinations of $|V_{cb}|$ and $|V_{ub}|$. Independent measurements of $b \to s$ transitions are expected to provide another means of constraining the theoretical uncertainties.

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