

**Determination of the  $b$ -quark mass and nonperturbative  
parameters in semileptonic and radiative penguin decays at  
*BABAR***

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**Abstract**

Knowing the mass of the  $b$ -quark is essential to the study of the structure and decays of  $B$  mesons as well as to future tests of the Higgs mechanism of mass generation. We present recent preliminary measurements of the  $b$ -quark mass and related nonperturbative parameters from moments of kinematic distributions in charmed and charmless semileptonic and radiative penguin  $B$  decays. Their determination from charmless semileptonic  $B$  decays is the first measurement in this mode. The data were collected by the *BABAR* detector at the PEP-II asymmetric-energy  $e^+e^-$ -collider at the Stanford Linear Accelerator Center at a center-of-momentum energy of 10.58 GeV.

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## 1. INTRODUCTION

An important goal of the  $B$ -physics program is the precise measurement of the CKM matrix [1] elements  $|V_{cb}|$  and  $|V_{ub}|$ . The most accurate determinations are obtained from semileptonic decays  $B \rightarrow X_c \ell \nu$  and  $B \rightarrow X_u \ell \nu$ , respectively. Generally, two different approaches can be used: The hadronic state  $X_{c,u}$  can be reconstructed either in specific exclusive modes, or inclusively by summing over all possible hadronic final states. The inclusive determinations rely on an Operator Product Expansion (OPE) in inverse powers of the  $b$ -quark mass  $m_b$  [2]. At second order in the expansion, two nonperturbative parameters arise, which describe the kinetic energy and the chromomagnetic moment of the  $b$  quark inside the  $B$  meson. In the kinetic scheme, they are denoted by  $\mu_\pi^2$  and  $\mu_G^2$ , respectively. Two more parameters arise at third order,  $\rho_D^3$  and  $\rho_{LS}^3$ . In the kinetic scheme, short- and long-distance contributions are separated by a hard cutoff  $\mu$  and the  $b$ -quark mass and nonperturbative parameters are given at  $\mu = 1 \text{ GeV}$ .

The mass  $m_b$  and the nonperturbative parameters can be determined from the study of kinematic distributions in semileptonic and radiative penguin  $B$  decays.

Precise measurements of  $m_b$  are needed both to reduce the uncertainty of inclusive determinations of  $|V_{ub}|$ , as well as for studying New Physics effects in the Higgs sector at future experiments.

Here, we present recent determinations of  $m_b$  and higher-order nonperturbative parameters from charm and charmless semileptonic and radiative penguin  $B$  decays at the  $BABAR$  experiment [3].

## 2. THE RECOIL METHOD

In all analyses presented,  $\Upsilon(4S) \rightarrow B\bar{B}$  decays are tagged by reconstructing one  $B$  meson ( $B_{\text{reco}}$ ) fully in hadronic modes,  $B_{\text{reco}} \rightarrow D^{(*)}Y^\pm$ . The  $Y^\pm$  system is composed of hadrons with a total charge of  $\pm 1$ ,  $Y^\pm = n_1\pi^\pm + n_2K^\pm + n_3K_S + n_4\pi^0$ , with  $n_1 + n_2 \leq 5$ ,  $n_3 \leq 2$ ,  $n_4 \leq 2$ . We test the kinematic consistency of  $B_{\text{reco}}$  candidates 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 invariant mass of the  $e^+e^-$  system and  $E_B$  and  $\vec{p}_B$  denote the energy and momentum of the  $B_{\text{reco}}$  candidate in the  $\Upsilon(4S)$  frame. We require  $\Delta E$  to be 0 within three standard deviations. In events with multiple  $B_{\text{reco}}$  candidates we retain the candidate reconstructed in the mode with highest purity as estimated from the ratio of signal over background for events with  $m_{\text{ES}} > 5.27 \text{ GeV}$  on Monte Carlo simulation (MC).

By fully reconstructing one of the  $B$  mesons in the event, the charge, flavor and momentum of the second  $B$  can be inferred. All particles that are not used in the reconstruction of the  $B_{\text{reco}}$  are assigned to the decay of the signal  $B$ . The efficiency to reconstruct a  $B_{\text{reco}}$  candidate is 0.3% (0.5%) for  $B^0\bar{B}^0$  ( $B^+B^-$ ) events.

We use fits to the  $m_{\text{ES}}$  distribution to subtract the combinatorial background from  $B\bar{B}$  events and the background from continuum ( $e^+e^- \rightarrow q\bar{q}$ ,  $q = u, d, s, c$ ) events. The backgrounds are modeled with a threshold function [4] and the signal is described by a Gaussian function joined with an exponential tail to describe photon energy loss [5]. Examples from the measurement in radiative penguin decays are shown in Fig. 1 (a) and (b).

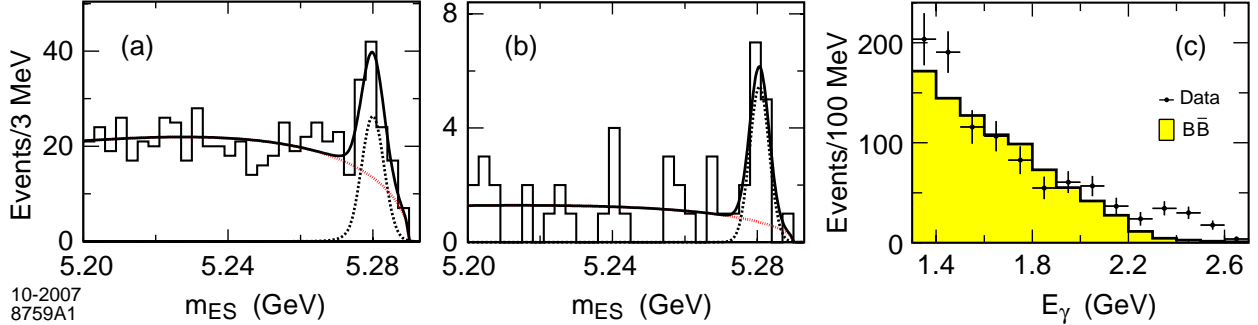


FIG. 1: Fits in  $B \rightarrow X_s \gamma$  to  $m_{ES}$  for two  $E_\gamma$  regions. The dashed curve shows the signal, the solid grey (red) curve the background as given by the fit. The solid black curve shows the sum of signal and background. (a)  $1.6 \text{ GeV} < E_\gamma < 1.7 \text{ GeV}$  for charged  $B$  events and (b)  $2.3 \text{ GeV} < E_\gamma < 2.4 \text{ GeV}$  for neutral  $B$  events. (c) The measured photon energy spectrum before subtraction of backgrounds. Points show the data spectrum, the shaded histogram shows the  $B\bar{B}$  backgrounds, where the shape is taken from MC.

### 3. RADIATIVE PENGUIN DECAYS

The first and second moments of the photon energy spectrum in radiative penguin decays,  $B \rightarrow X_s \gamma$ , are used for a preliminary determination of  $m_b$  and  $\mu_\pi^2$  [6]. The moments are extracted as a function of the lower cut on the photon energy,  $E_\gamma^{\min}$ , measured in the rest frame of the signal  $B$ . The full reconstruction of the second  $\bar{B}$  in the event results in an improved signal purity and different systematic uncertainties, but lower statistics, than alternative methods.

The measurement is based on a sample of 232 million  $B\bar{B}$  pairs. Events with a well reconstructed, high energy photon are selected if the photon is not compatible with originating from the decay of a  $\pi^0$  or  $\eta$ , or a  $\rho^\pm \rightarrow \pi^\pm \pi^0$  decay assuming that the second photon from the  $\pi^0$  decay was lost. Continuum background is suppressed by using a Fisher discriminant that makes use of the difference between event topologies in  $B\bar{B}$  and continuum events.

The  $E_\gamma$  spectrum is measured in bins of 100 MeV and is shown in Fig. 1 (c). The region  $1.3 \text{ GeV} < E_\gamma < 1.9 \text{ GeV}$  is used to normalize the backgrounds, the largest part of which consists of photons from unreconstructed  $\pi^0$  or  $\eta$  decays. The backgrounds are extrapolated into the signal region,  $E_\gamma > 1.9 \text{ GeV}$ , the shape of the backgrounds is taken from MC. The signal region contains  $119 \pm 22$   $B \rightarrow X \gamma$  events over an estimated background of  $145 \pm 9$  events. The measured photon spectrum is corrected for efficiency, which varies with  $E_\gamma$ , and resolution effects. First and second central moments,  $\langle E_\gamma \rangle$  and  $\langle E_\gamma^2 \rangle - \langle E_\gamma \rangle^2$ , as a function of  $E_\gamma^{\min}$  are extracted from the corrected spectrum. The moments for  $E_\gamma^{\min} \leq 2.0 \text{ GeV}$  are used to determine  $m_b = 4.46^{+0.21}_{-0.23} \text{ GeV}$  and  $\mu_\pi^2 = 0.64^{+0.39}_{-0.38} \text{ GeV}^2$  in the kinetic scheme with a correlation of  $\rho = -0.94$ .

### 4. CHARM SEMILEPTONIC B DECAYS

Moments of the hadronic mass and lepton energy spectra in  $B \rightarrow X_c \ell \nu$  decays are used for a preliminary extraction of  $m_b$ , the charm-quark mass  $m_c$ , nonperturbative parameters

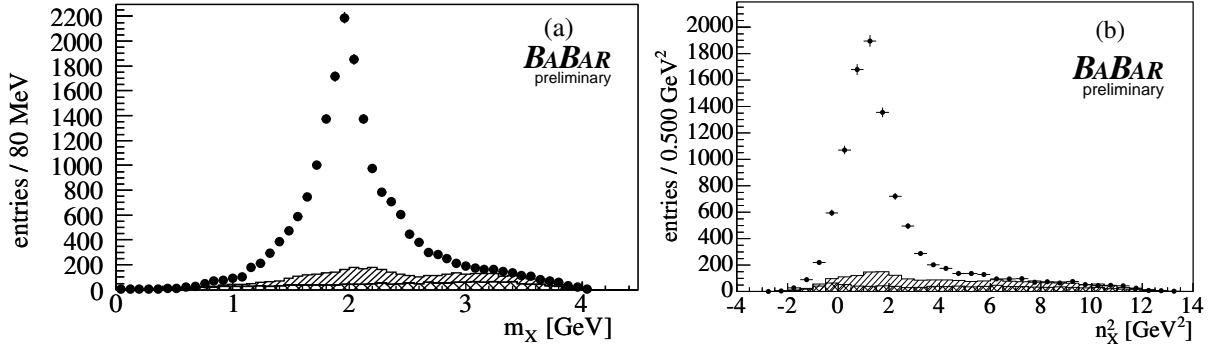


FIG. 2: (a) The measured hadronic mass spectrum and (b) the measured  $n_X$  spectrum for  $E_l > 0.8$  GeV in the  $B$  rest frame. Tag-side backgrounds are indicated by the hatched histogram, signal-side backgrounds by the cross-hatched histogram.

and  $|V_{cb}|$  [7]. We present moments of the hadronic mass  $\langle m_X^k \rangle$ ,  $k = 1..6$ , which use a larger data set than the previous measurement and new measurements of the mixed hadronic mass-energy moments  $\langle n_X^k \rangle$ ,  $k = 2, 4, 6$ .  $n_X$  is defined by  $n_X^2 = m_X^2 c^4 - 2\bar{\Lambda}E_X + \bar{\Lambda}^2$ , where  $m_X$  is the mass and  $E_X$  the energy of the inclusive  $X_c$  system in the  $B$  rest frame and  $\bar{\Lambda} = 0.65$  GeV. The mixed moments are expected to yield a more precise determination of higher order nonperturbative parameters. The moments are extracted as a function of a lower cut on the lepton energy between 0.8 GeV and 1.9 GeV in the signal  $B$  rest frame.

The measurement is based on a sample of 232 million  $B\bar{B}$  pairs. After reconstructing the  $B_{\text{reco}}$  and identifying the lepton, where both electrons and muons are used, the hadronic system is reconstructed from the remaining tracks and neutral energy depositions in the event. A kinematic fit imposing energy-momentum conservation and the missing energy and momentum in the event to be consistent with coming from one neutrino is performed to improve the resolution in the hadronic variables. The hadronic mass and mixed hadronic mass-energy spectra are shown in Fig. 2. The moments are extracted directly from the kinematically fitted hadronic masses and energies and are corrected for the effect of lost particles. The main contribution to the systematic uncertainties on the moments arise from the impact of the reconstruction efficiencies of neutral particles on the inclusive event reconstruction.

A combined fit is performed to hadronic mass moments, lepton energy moments [8] in  $B \rightarrow X_c \ell \nu$  decays and photon energy moments in  $B \rightarrow X_s \gamma$  decays [9] and yields  $m_b = (4.552 \pm 0.055)$  GeV,  $m_c = (1.070 \pm 0.085)$  GeV (correlation  $\rho_{m_b m_c} = 0.96$ ),  $\mu_\pi^2 = (0.471 \pm 0.070)$  GeV<sup>2</sup>,  $\mu_G^2 = (0.330 \pm 0.060)$  GeV<sup>2</sup>,  $\rho_D^3 = (0.220 \pm 0.047)$  GeV<sup>3</sup> and  $\rho_{LS}^3 = (-0.159 \pm 0.095)$  GeV<sup>3</sup> in the kinetic scheme.

## 5. CHARMLESS SEMILEPTONIC $B$ DECAYS

Moments of the hadronic mass spectrum in  $B \rightarrow X_u \ell \nu$  decays are used for a preliminary extraction of  $m_b$ ,  $\mu_\pi^2$  and  $\rho_D^3$ . Their determination in  $B \rightarrow X_u \ell \nu$  allows for a test of the theoretical framework used for the extraction of  $|V_{ub}|$  in the same channel in which  $|V_{ub}|$  is determined. The hadronic mass moments are measured with an upper cut on the hadronic

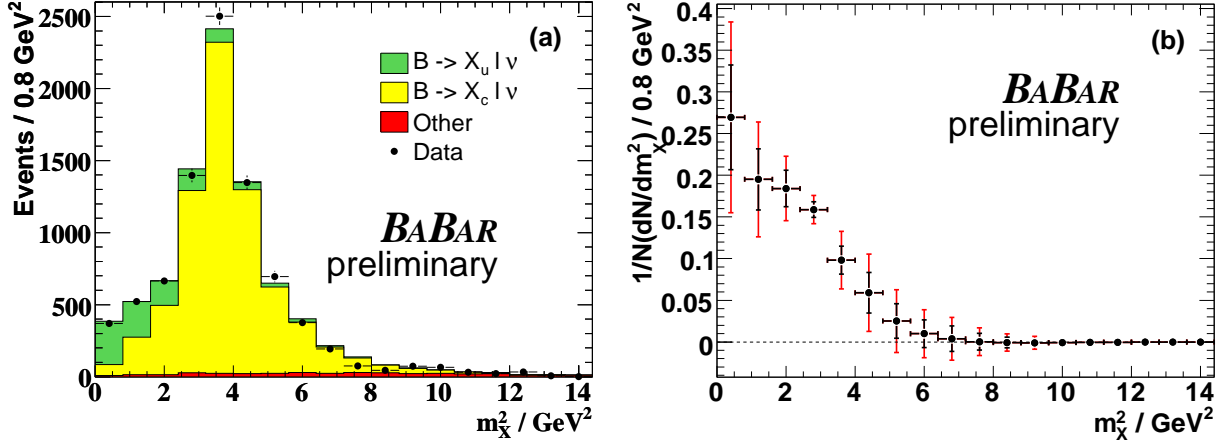


FIG. 3: (a) The measured hadronic mass spectrum before subtraction of  $B \rightarrow X_c \ell \nu$  and non-semileptonic backgrounds. (b) Unfolded hadronic mass spectrum in  $B \rightarrow X_u \ell \nu$ . The inner error bars show the statistical uncertainties only.

mass to reduce experimental uncertainties.

The measurement is based on a sample of 383 million  $B\bar{B}$  pairs. After reconstructing the  $B_{\text{reco}}$  and identifying the lepton, where both electrons and muons with a minimum energy of  $E_\ell = 1 \text{ GeV}$  in the  $B$  rest frame are used, the hadronic system is reconstructed from the remaining tracks and neutral energy depositions in the event. Vetos on identified  $K^\pm$ , reconstructed  $K_S$  and partially reconstructed  $D^{*\pm}$  are employed to suppress the dominant background from  $B \rightarrow X_c \ell \nu$  events. The remaining  $B \rightarrow X_c \ell \nu$  and non-semileptonic backgrounds are subtracted by a fit to the hadronic mass spectrum (Fig. 3 (a)). The full  $m_X^2$  region contains  $1027 \pm 176$  signal events. The background-subtracted spectrum is unfolded for detector acceptance, efficiency and resolution effects (Fig. 3 (b)) and the first and second and third central moments are extracted from the unfolded spectrum for  $m_X^2 < 6.4 \text{ GeV}^2$ :

$$\begin{aligned} \langle m_X^2 \rangle &= (1.96 \pm 0.34(\text{stat}) \pm 0.53(\text{syst})) \text{ GeV}^2 \\ \langle (m_X^2)^2 - \langle m_X^2 \rangle^2 \rangle &= (1.92 \pm 0.59(\text{stat}) \pm 0.87(\text{syst})) \text{ GeV}^4 \\ \langle (m_X^2)^3 - \langle m_X^2 \rangle^3 \rangle &= (1.79 \pm 0.62(\text{stat}) \pm 0.78(\text{syst})) \text{ GeV}^6 \end{aligned}$$

with correlation coefficients  $\rho_{12} = 0.99$ ,  $\rho_{23} = 0.94$  and  $\rho_{13} = 0.88$ . The main systematic uncertainties arise from the control of the  $B \rightarrow X_c \ell \nu$  background.

A fit of these moments to predictions in the kinetic scheme [10] yields

$$\begin{aligned} m_b &= (4.604 \pm 0.125(\text{stat}) \pm 0.193(\text{syst}) \pm 0.097(\text{theo})) \text{ GeV} \\ \mu_\pi^2 &= (0.398 \pm 0.135(\text{stat}) \pm 0.195(\text{syst}) \pm 0.036(\text{theo})) \text{ GeV}^2 \\ \rho_D^3 &= (0.102 \pm 0.017(\text{stat}) \pm 0.021(\text{syst}) \pm 0.066(\text{theo})) \text{ GeV}^3. \end{aligned}$$

with correlation coefficients  $\rho_{m_b \mu_\pi^2} = -0.99$ ,  $\rho_{\mu_\pi^2 \rho_D^3} = 0.57$  and  $\rho_{m_b \rho_D^3} = -0.59$ .

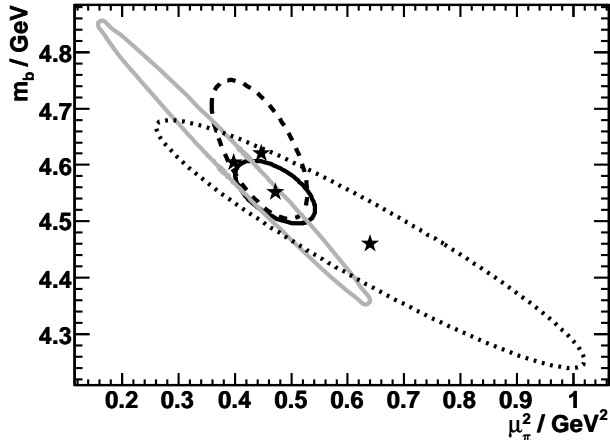


FIG. 4: Results from the recent BABAR analyses presented in the  $m_b$ - $\mu_\pi^2$  plane in the kinetic scheme. The dotted ellipse shows the result of the presented  $B \rightarrow X_s \gamma$  analysis [6], the dashed ellipse the result from  $B \rightarrow X_c \ell \nu$  decays [7, 8], the black solid ellipse the result from its combination with earlier  $B \rightarrow X_s \gamma$  measurements [9] and the solid grey ellipse the result from  $B \rightarrow X_u \ell \nu$  decays.

TABLE I: Results for  $m_b$  and  $\mu_\pi^2$  in the kinetic scheme and their correlations.

	$m_b / \text{GeV}$	$\mu_\pi^2 / \text{GeV}^2$	$\rho$
$B \rightarrow X_s \gamma$ [6]	$4.46^{+0.21}_{-0.23}$	$0.64^{+0.39}_{-0.38}$	-0.94
$B \rightarrow X_c \ell \nu$ [7, 8] and $B \rightarrow X_s \gamma$ [9]	$4.552 \pm 0.055$	$0.471 \pm 0.070$	-0.56
$B \rightarrow X_u \ell \nu$	$4.604 \pm 0.250$	$0.398 \pm 0.240$	-0.99

## 6. SUMMARY

We presented preliminary determinations of the  $b$ -quark mass  $m_b$  and nonperturbative parameters from charmed and charmless semileptonic and radiative penguin  $B$  decays at BABAR. The determination in charmless semileptonic  $B$  decays has been performed for the first time. The results for  $m_b$  and  $\mu_\pi^2$  are summarized in Table I and compared in Fig. 4. The determinations in the different channels are consistent within the quoted uncertainties and with earlier determinations [11].

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