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Measurements of moments of the hadronic mass distribution in semileptonic *B* decays

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We report a measurement of the first four moments of the hadronic mass distribution in $\overline{B}\to X_c\ell^-\overline{\nu}$ decays. The measurements are based on 89 million $\Upsilon(4S)\to B\overline{B}$ events where the hadronic decay of one of the B mesons is fully reconstructed and a charged lepton from the decay of the other B meson is identified. The moments are presented for minimum lepton momenta ranging from 0.9 to 1.6 GeV in the B rest frame. It is expected that such measurements will lead to improved determinations of $|V_{cb}|$ and $|V_{ub}|$.

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In this paper we report measurements of the first four moments $\langle M_X^n\rangle$, with $n=1-4$, of the hadronic mass distributions in $\overline{B}\to X_c\ell^-\overline{\nu}$ decays [1]. The moments are presented as a function of $p^*_{\min}$, the lower limit on the charged lepton momentum, which we vary between 0.9 and 1.6 GeV.

Moments of inclusive distributions and rates for semileptonic and rare B decays can be related via operator product expansions (OPE) [2] to fundamental parameters of the standard model, such as the Cabibbo-Kobayashi-Maskawa matrix elements $|V_{cb}|$ and $|V_{ub}|$ [3] and the heavy quark masses m_b and m_c. These expansions in $1/m_b$ and the strong coupling constant α_s involve nonperturbative quantities that can be extracted from moments of inclusive distributions. We

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plan to use measurements of the hadron mass and lepton energy moments [4] to improve the determination of $|V_{cb}|$ from the semileptonic decay rate [5].

The measurement presented here is based on a sample of 89 million $B\overline{B}$ pairs collected on the $\Upsilon(4S)$ resonance by the *BABAR* detector [6] at the PEP-II asymmetric-energy e^+e^- storage ring operating at SLAC. We use Monte Carlo (MC) simulations of the *BABAR* detector based on GEANT4 [7] to determine background distributions and to correct for detector acceptance effects. The simulations of $\overline{B}\to X_c\ell^-\overline{\nu}$ decays use a parametrization of form factors for $\overline{B}\to D^*\ell^-\overline{\nu}$ [8], and models for $\overline{B}\to D\ell^-\overline{\nu}$, $D^{**}\ell^-\overline{\nu}$ [9] and $\overline{B}\to D\pi\ell^-\overline{\nu}$, $D^*\pi\ell^-\overline{\nu}$ [10].

The analysis uses $\Upsilon(4S)\to B\overline{B}$ events in which one of the B mesons decays to hadrons and is fully reconstructed (B_{reco}) and the semileptonic decay of the recoiling $\overline{B}$ mesons (B_{recoil}) is identified by the presence of an electron or muon. While this approach results in a low overall event selection efficiency, it allows for the determination of the momentum, charge, and flavor of the B mesons. To obtain a large sample of B mesons, many exclusive hadronic decays are reconstructed [11]. The kinematic consistency of these B_{reco} candidates is checked with two variables, the beam-energy-substituted mass $m_{\mathrm{ES}}=\sqrt{s/4-\vec{p}_B^{\,2}}$ and the energy difference $\Delta E=E_B-\sqrt{s}/2$. Here $\sqrt{s}$ is the total energy in the center of mass frame (c.m.), $\vec{p}_B$ and E_B denote the c.m. momentum and c.m. energy of the B_{reco} candidate. We require $\Delta E=0$ within three standard deviations as measured for each mode. For a given B_{reco} decay mode, the purity is estimated as the signal fraction in events with $m_{\mathrm{ES}}>5.27$ GeV. For events with one high-momentum lepton the purity is approximately 70%.

Semileptonic decays are identified by the presence of one and only one electron or muon above a minimum momentum p^*_{min} measured in the rest frame of the B_{recoil} meson recoiling against the B_{reco}. Electrons are selected [12] with 92% average efficiency and a hadron misidentification rate ranging between 0.05% and 0.1%. Muons are identified [6] with an efficiency ranging between 60% ($p_{\mathrm{lab}}=1$ GeV) and 75% ($p_{\mathrm{lab}}>2$ GeV) and a hadron misidentification rate between 1% and 3%. Efficiencies and misidentification rates are estimated from selected samples of electrons, muons, pions, and kaons. We impose the condition $Q_bQ_\ell<0$, where Q_ℓ is the charge of the lepton and Q_b is the charge of the b-quark of the B_{reco}. This condition is fulfilled for primary leptons, except for $B^0\overline{B}^0$ events in which flavor mixing has occurred. We require the total observed charge of the event to be $|Q_{\mathrm{tot}}|=|Q_{\mathrm{B_{reco}}}+Q_{\mathrm{B_{recoil}}}|\leqslant 1$, allowing for a charge imbalance in events with low momentum tracks or photon conversions.

The hadronic system X in the decay $\overline{B}\to X\ell^-\overline{\nu}$ is reconstructed from charged tracks and energy depositions in the calorimeter that are not associated with the B_{reco} candidate or the charged lepton. Depending on particle identification information the charged tracks are assigned either the $K^\pm$ or $\pi^\pm$ mass. Procedures are implemented to eliminate fake

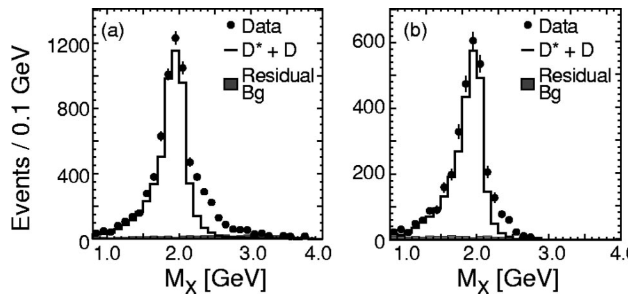

FIG. 1. M_X distributions after subtraction of the B_{reco} background, for (a) $p^*_{\mathrm{min}}=0.9$ GeV, and (b) $p^*_{\mathrm{min}}=1.6$ GeV. The Monte Carlo prediction for decays to D and D^* is indicated by the open histogram, the small residual background by the solid histogram.

charged tracks, low-energy beam-generated photons, and energy depositions in the calorimeter from charged and neutral hadrons.

The neutrino four-momentum p_ν is estimated from the missing four-momentum $p_{\mathrm{miss}}=p_{\Upsilon(4S)}-p_{B_{\mathrm{reco}}}-p_X-p_\ell$, where all momenta are measured in the laboratory frame. The measured p_{miss} is an important indicator of the quality of the reconstruction of X. We impose the following criteria: $E_{\mathrm{miss}}>0.5$ GeV, $|\vec{p}_{\mathrm{miss}}|>0.5$ GeV, and $|E_{\mathrm{miss}}-|\vec{p}_{\mathrm{miss}}||<0.5$ GeV. The mass of the hadronic system M_X is determined by a kinematic fit that imposes four-momentum conservation, the equality of the masses of the two B mesons, and constrains $p_\nu^2=0$. We require the fit to converge, thus ensuring that the abovementioned constraints are fulfilled. The resulting mean resolution in M_X is 350 MeV.

The background is dominated by combinatorial background in the B_{reco} sample. To estimate this background we fit the observed m_{ES} distribution to a sum of an empirical function [13] describing the combinatorial background from both continuum and $B\overline{B}$ events and a narrow signal function [14] peaked at the B meson mass. This fit is performed separately for several bins in M_X, thus accounting for changes in background as a function of M_X. For $p^*_{\mathrm{min}}=0.9$ GeV and $m_{\mathrm{ES}}>5.27$ GeV, we find a total of 7114 signal events above a combinatorial background of 2102 events. Figure 1 shows

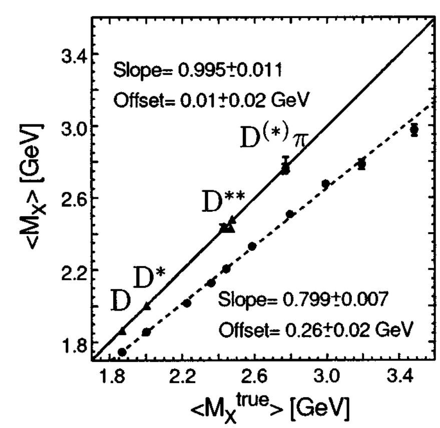

FIG. 2. Results of the $\langle M_X\rangle$ calibration procedure. The calibration data and fit results are shown by the lower dashed line (circles), the verification by the upper solid line (triangles).

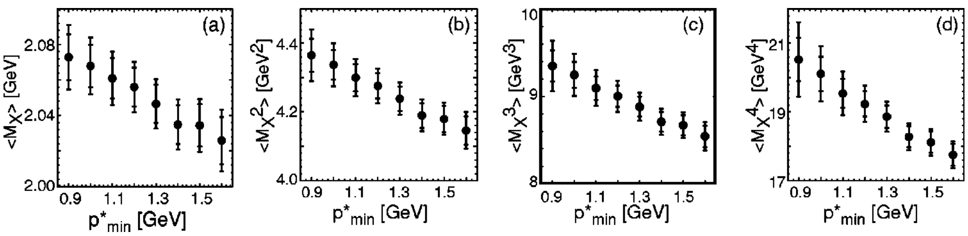

FIG. 3. Measured moments (a) $\langle M_X\rangle$, (b) $\langle M_X^2\rangle$, (c) $\langle M_X^3\rangle$, and (d) $\langle M_X^4\rangle$ for different lepton momenta, $p^*_{\rm min}$. The bars indicate the statistical and total errors. The individual moments are highly correlated.

M_X distributions after $B_{\rm reco}$ background subtraction. The dominant contributions are from the lowest mass mesons, (D^+,D^0) and (D^{*+},D^{*0}), but there are clear indications for higher mass states.

The residual background, estimated from MC simulation, is due to hadron misidentification, $\tau^\pm$ leptons, $\overline{B}\to X_u\ell^-\overline{\nu}$ decays, and secondary leptons from semileptonic decays of $D^{(*)}$ and D_s mesons, either from $B^0\overline{B}^0$ mixed events or produced in $b\to c\overline{c}s$ transitions.

To extract unbiased moments $\langle M_X^n\rangle$, we need to correct for effects that can distort the mass distributions (see also [15]). We use observed linear relationships between the measured $\langle M_X^n\rangle$ and generated $\langle M_X^{n\ \rm true}\rangle$ values from MC simulations in bins of $M_X^{n\ \rm true}$ (see Fig. 2) to calibrate the measurement of M_X^n on an event-by-event basis. Since any radiative photon is included in the measured hadron mass and our definition of M_X does not include these photons, we employ PHOTOS [16] to simulate QED radiative effects and correct for their impact (less than 5%) on the moments as part of the calibration procedure.

To verify this procedure, we apply the calibration to the measured masses for individual hadronic states in simulated $\overline{B}\to X_c\ell^-\overline{\nu}$ decays, and compare their calibrated mass moments to the true mass moments. The result of this test is also shown in Fig. 2 for M_X, indicating that the calibration reproduces the true moments over the full mass range. Corresponding curves are obtained for M_X^2, M_X^3, and M_X^4. We observe no significant mass bias after calibration. The MC-based calibration procedure has also been validated on a data sample of partially reconstructed $D^{*+}\to D^0\pi^+$ decays [11] where we identity the low-momentum π^+. This serves only as a tag and allows us to select an inclusive event sample for which the true hadronic mass is known.

Detailed studies show that the slope and offset of the calibration curves vary slightly as a function of the multiplicity of the hadron system and as a function of $E_{\rm miss}-|\vec{p}_{\rm miss}|$. Thus, instead of one universal calibration curve for all data, we split the data into three bins in multiplicity and three bins in $E_{\rm miss}-|\vec{p}_{\rm miss}|$, and derive a total of nine calibration curves, one for each subsample.

We estimate and subtract the contribution to the moments from residual backgrounds and then correct the result by a factor $\mathcal{C}_n$ for the effect of detection and selection efficiencies. We can express the fully corrected hadronic mass moment $\langle M_X^n\rangle$ as

$$\langle M_X^n\rangle=\frac{\langle M_X^n\rangle_{\rm calib}^{\rm DATA}-f_{\rm bg}\cdot\langle M_X^n\rangle_{\rm calib}^{\rm MCbg}}{1-f_{\rm bg}}\times\mathcal{C}_n, \qquad (1)$$

where $\langle M_X^n\rangle_{\rm calib}^{\rm DATA}$ and $\langle M_X^n\rangle_{\rm calib}^{\rm MCbg}$ are the calibrated moments of the data and the residual background. The factor $f_{\rm bg}$ denotes the size of the residual background relative to the data.

Decays to higher mass final states usually generate higher multiplicities and are more strongly affected by the requirements on $E_{\rm miss}$ and $|\vec{p}_{\rm miss}|$ due to limited efficiency. In addition, the different decay modes have different spin configurations and thus different angular distributions. The correction factor $\mathcal{C}_n$ in Eq. (1) accounts for these effects. It is determined by MC simulation, and is found to be within 1% of unity.

The hadronic mass moments $\langle M_X^n\rangle$ obtained after background subtraction, correction for $\overline{B}\to X_u\ell^-\overline{\nu}$ decays, and mass calibration are presented in Fig. 3 as a function of $p^*_{\rm min}$. The measurements are highly correlated. The numerical results and the full correlation matrix for the four sets of $p^*_{\rm min}$ dependent moment measurements can be found in [17]. The four moments increase as $p^*_{\rm min}$ decreases due to the presence of higher mass charm states. Fits to the $p^*_{\rm min}$ dependence assuming constant moments are inconsistent with our results, with χ^2 probabilities less than 0.4%.

Table I shows the four measured moments and their principal errors for $p^*_{\rm min}=0.9$ GeV and $p^*_{\rm min}=1.6$ GeV. The main sources of systematic errors are the precision in the modeling of the detector efficiency and particle reconstruction, the subtraction of the combinatorial background of the $B_{\rm reco}$ sample, the residual background estimate, and the uncertainties in the modeling of the hadronic states. The uncertainty related to the detector modeling and event reconstruction has been estimated by MC simulations of the track and photon efficiencies. Resolutions, fake rates, and background rates have been studied in detail by varying the adjustments to the MC simulation that are introduced to improve the agreement with data. The track efficiency was found to be 0.8% higher in MC compared to data and the systematic error assumes an uncertainty of 3.5%, independent of energy, polar angle, and multiplicity. For photons, the relative energy resolution was broadened by 3% to 1.6% for energies between 30 and 600 MeV. The uncertainty in the combinatorial $B_{\rm reco}$ background subtraction is estimated by varying the lower limit of the signal region in the $m_{\rm ES}$ distribution. The error due to the subtraction of the residual background is dominated by the uncertainties (typically 30% [18]) in the rate of $D^{(*)}$ and D_s production via $b\to c\overline{c}s$ transitions. The uncertainty related to the modeling of the semileptonic B decays is estimated by varying the branching fractions, in particular those for the high mass resonant and nonresonant states. Uncertainties in

TABLE I. Results for $\langle M_X^n \rangle$ for the two extreme values of $p^*_{\min}$, with statistical and systematic errors and details on the major contributions to the systematic uncertainties.

	$p^*_{\min}$ (GeV)	$\langle M_X^n \rangle$(GeV^n)	Detector response	$B_{\rm reco}$ background	Residual background	$\overline{B} \to X_c \ell^- \overline{\nu}$ model	Radiative corrections
$n=1$	0.9	$2.073 \pm 0.013 \pm 0.013$	0.009	0.004	0.008	0.002	0.003
	1.6	$2.026 \pm 0.013 \pm 0.012$	0.010	0.004	0.002	0.002	0.004
$n=2$	0.9	$4.366 \pm 0.049 \pm 0.058$	0.034	0.023	0.039	0.009	0.009
	1.6	$4.146 \pm 0.042 \pm 0.036$	0.031	0.009	0.007	0.007	0.013
$n=3$	0.9	$9.35 \pm 0.18 \pm 0.23$	0.15	0.05	0.16	0.01	0.03
	1.6	$8.54 \pm 0.12 \pm 0.11$	0.10	0.02	0.01	0.01	0.04
$n=4$	0.9	$20.53 \pm 0.63 \pm 0.90$	0.58	0.31	0.58	0.13	0.14
	1.6	$17.75 \pm 0.32 \pm 0.23$	0.19	0.06	0.02	0.08	0.09

the radiative corrections, especially effects not included in PHOTOS, are estimated by removing photons above a variable energy limit from the hadronic system X.

To test the stability of the moment measurements, the data are divided into several independent subsamples: $B^\pm$ and B^0, decays to electrons and muons, different run periods, positive and negative $E_{\rm miss} - |\vec{p}_{\rm miss}|$, and high and low purity $B_{\rm reco}$ modes. No significant variations are observed.

In summary, we have performed a measurement of the first four moments $\langle M_X^n \rangle$ of the hadronic mass distribution in semileptonic B decays. For $p^*_{\min} = 1.5$ GeV, our measurement of $\langle M_X^2 \rangle = 4.18 \pm 0.04(\text{stat.}) \pm 0.03(\text{syst.})$ GeV^2 agrees well with the single result from CLEO [19]. The selection of events with one fully reconstructed hadronic B decay, the kinematic fit, and calibration of the hadronic mass in the semileptonic decay of the second B decay have led to moment measurements with comparable statistical and systematic errors. The results do not depend on assumptions for branching fractions and mass distributions for higher mass hadronic states. The measured moments increase significantly as the limit on the lepton momentum, $p^*_{\min}$, is lowered, as expected for increasing contributions from higher mass states. The set of moments presented here can be used to test the applicability of the OPE to semileptonic and rare B decays. Combining them with the measured semileptonic decay rate is expected to result in a significantly improved determination of $|V_{cb}|$ [4,5].

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[1] Charge conjugation is implied throughout this Rapid Communication.

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