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Permalink
https://escholarship.org/uc/item/8v53g0xk

Journal
Physical Review D - Particles, Fields, Gravitation and Cosmology, 69(11)

ISSN
1550-7998

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Publication Date
2004

DOI
10.1103/PhysRevD.69.111103

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Peer reviewed
Measurements of moments of the hadronic mass distribution in semileptonic B decays

In this paper we report measurements of the first four moments \( \langle M_X^n \rangle \), with \( n = 1 - 4 \), of the hadronic mass distri-
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 $B \bar{B}$ pairs collected on the $Y(4S)$ 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 $B \rightarrow X\ell^-\bar{\nu}$ decays use a parametrization of form factors for $B \rightarrow D^*\ell^-\bar{\nu}$ [8], and models for $B \rightarrow D \ell^-\bar{\nu}$, $D^{**}\ell^-\bar{\nu}$ [9] and $B \rightarrow D\pi\ell^-\bar{\nu}$, $D^*\pi\ell^-\bar{\nu}$ [10].

The analysis uses $Y(4S) \rightarrow B\bar{B}$ events in which one of the $B$ mesons decays to hadrons and is fully reconstructed ($B_{\text{reco}}$) and the semileptonic decay of the recoiling $B$ mesons ($B_{\text{recoil}}$) 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, energy depositions in the calorimeter from charged and neutral hadrons.

The neutrino four-momentum $p_\nu$ is estimated from the missing four-momentum $p_{\text{miss}} = p_{Y(4S)} - p_{B_{\text{reco}}} - p_{X} - p_{\ell}$, where all momenta are measured in the laboratory frame. The measured $p_{\text{miss}}$ is an important indicator of the quality of the reconstruction of $X$. We impose the following criteria: $E_{\text{miss}} > 0.5$ GeV, $|p_{\text{miss}}| > 0.5$ GeV, and $|E_{\text{miss}} - |p_{\text{miss}}|^2| < 0.5$ 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 $B_{\text{reco}}$ 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 $B\bar{B}$ 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 $p_{\text{miss}} = 0.9$ GeV and $m_{ES} > 5.27$ GeV, we find a total of 7114 signal events above a combinatorial background of 2102 events. Figure 1 shows the $M_X$ distributions after subtraction of the $B_{\text{reco}}$ background, for (a) $p_{\text{miss}} = 0.9$ GeV, and (b) $p_{\text{miss}} = 1.6$ 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.

FIG. 1. $M_X$ distributions after subtraction of the $B_{\text{reco}}$ background, for (a) $p_{\text{miss}} = 0.9$ GeV, and (b) $p_{\text{miss}} = 1.6$ 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 hadronic system $X$ in the decay $B \rightarrow X\ell^-\bar{\nu}$ is reconstructed from charged tracks and energy depositions in the calorimeter that are not associated with the $B_{\text{reco}}$ 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. 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).
$M_X$ distributions after $P_{\text{reco}}$ 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, $\bar{B}\to X_u\ell^+\bar{\nu}$ decays, and secondary leptons from semileptonic decays of $D^{(*)}$ and $D_s$ mesons, either from $B^0\bar{B}^0$ mixed events or produced in $b\to c\bar{c}\bar{s}$ transitions.

To extract unbiased moments $\langle M^n_X \rangle$, we need to correct for effects that can distort the mass distributions (see also [15]). We use observed linear relationships between the measured $\langle M^n_X \rangle$ and generated $\langle M^n_{X\text{true}} \rangle$ values from MC simulations in bins of $M^n_{X\text{true}}$ (see Fig. 2) to calibrate the measurement of $M^n_X$ 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 $\bar{B}\to X_u\ell^+\bar{\nu}$ 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 $M^n_{X_1}$, $M^n_{X_2}$, and $M^n_{X_3}$. We observe no significant mass bias after calibration. The MC-based calibration procedure has also been validated on a data sample, $P_{\text{reco}}$ background, and the systematic error assumes an uncertainty of 3.5%, independent of energy, polar angle, and multiplicity. In addition, the different decay modes have different spin configurations and thus different angular distributions. The correction factor $C_n$ 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 $\langle M^n_X \rangle$ obtained after background subtraction, correction for $\bar{B}\to X_u\ell^+\bar{\nu}$ decays, and mass calibration are presented in Fig. 3 as a function of $P_{\text{min}}^*$. The measurements are highly correlated. The numerical results and the full correlation matrix for the four sets of $P_{\text{min}}^*$ dependent moment measurements can be found in [17]. The four moments increase as $P_{\text{min}}^*$ decreases due to the presence of higher mass charm states. Fits to the $P_{\text{min}}^*$ dependence assuming constant moments are inconsistent with our results, with $\chi^2$ probabilities less than 0.4%.

Table I shows the four measured moments and their principal errors for $P_{\text{min}}^*=0.9$ GeV and $P_{\text{min}}^*=1.6$ 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 $B_{\text{reco}}$ 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 $B_{\text{reco}}$ background subtraction is estimated by varying the lower limit of the signal region in the $M_{B_{\text{reco}}}$ 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 $b\to c\bar{c}s$ 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 $p_{\text{min}}^n$, with statistical and systematic errors and details on the major contributions to the systematic uncertainties.

<table>
<thead>
<tr>
<th>$p_{\text{min}}^n$ (GeV)</th>
<th>$\langle M_X^n \rangle$ (GeV$^n$)</th>
<th>Detector response</th>
<th>$B_{\text{reco}}$ background</th>
<th>Residual background</th>
<th>$B \to X_s \ell^- \bar{\nu}$ model</th>
<th>Radiative corrections</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n = 1$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.9</td>
<td>2.073 ± 0.013 ± 0.013</td>
<td>0.009</td>
<td>0.004</td>
<td>0.008</td>
<td>0.002</td>
<td>0.003</td>
</tr>
<tr>
<td>1.6</td>
<td>2.026 ± 0.013 ± 0.012</td>
<td>0.010</td>
<td>0.004</td>
<td>0.002</td>
<td>0.002</td>
<td>0.004</td>
</tr>
<tr>
<td>$n = 2$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.9</td>
<td>4.366 ± 0.049 ± 0.058</td>
<td>0.034</td>
<td>0.023</td>
<td>0.039</td>
<td>0.009</td>
<td>0.009</td>
</tr>
<tr>
<td>1.6</td>
<td>4.146 ± 0.042 ± 0.036</td>
<td>0.031</td>
<td>0.009</td>
<td>0.007</td>
<td>0.007</td>
<td>0.013</td>
</tr>
<tr>
<td>$n = 3$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.9</td>
<td>9.35 ± 0.18 ± 0.23</td>
<td>0.15</td>
<td>0.05</td>
<td>0.16</td>
<td>0.01</td>
<td>0.03</td>
</tr>
<tr>
<td>1.6</td>
<td>8.54 ± 0.12 ± 0.11</td>
<td>0.10</td>
<td>0.02</td>
<td>0.01</td>
<td>0.01</td>
<td>0.04</td>
</tr>
<tr>
<td>$n = 4$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.9</td>
<td>20.53 ± 0.63 ± 0.90</td>
<td>0.58</td>
<td>0.31</td>
<td>0.58</td>
<td>0.13</td>
<td>0.14</td>
</tr>
<tr>
<td>1.6</td>
<td>17.75 ± 0.32 ± 0.23</td>
<td>0.19</td>
<td>0.06</td>
<td>0.02</td>
<td>0.08</td>
<td>0.09</td>
</tr>
</tbody>
</table>

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: $B^+$ and $B^0$, decays to electrons and muons, different run periods, positive and negative $E_{\text{miss}} - |p_{\text{miss}}|$, and high and low purity $B_{\text{reco}}$ 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 $p_{\text{min}}^* = 1.5$ GeV, our measurement of $\langle M_X^2 \rangle = 4.18 ± 0.04(\text{stat.}) ± 0.03(\text{syst.})$ 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, $p_{\text{min}}^*$, 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].

The authors are grateful for the excellent luminosity and machine conditions provided by our PEP-II colleagues, and for the substantial dedicated effort from the computing organizations that support BABAR. The collaborating institutions wish to thank SLAC for its support and kind hospitality. This work is supported by DOE and NSF (USA), NSERC (Canada), IHEP (China), CEA and CNRS-IN2P3 (France), BMBF and DFG (Germany), INFN (Italy), FOM (The Netherlands), NFR (Norway), MIST (Russia), and PPARC (United Kingdom). Individuals have received support from the A. P. Sloan Foundation, Research Corporation, and Alexander von Humboldt Foundation.

[1] Charge conjugation is implied throughout this Rapid Communication.
[17] See EPAPS Document No. E-PRVDAQ-69-R02411. A direct link to this document may be found in the online article’s