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MOMENTS OF THE HADRONIC MASS DISTRIBUTION IN SEMILEPTONIC B MESON DECAYS

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We present a measurement of the first and second moments of the squared-mass distribution of charm hadrons in semileptonic decays of B mesons based on $\sim$ 180 pb^{-1} of data taken with the CDF II detector at the Fermilab Tevatron. For a minimum lepton momentum of 0.7 GeV/c in the B meson rest frame, we measure the first two moments of the $D^{**} \to D^{(*)}\pi$ component to be $\langle m^2_{D^{**}} \rangle = (5.83 \pm 0.16_{stat} \pm 0.08_{syst})$ (GeV/c^2)^2 and $\langle (m^2_{D^{**}} - \langle m^2_{D^{**}} \rangle)^2 \rangle = (1.30 \pm 0.69_{stat} \pm 0.22_{syst})$ (GeV/c^2)^4. Combining these values with known contributions from the D and D^* components, we obtain the overall charm hadron moments $\langle M^2_{X_c} \rangle - m^2_{\bar{D}} = (0.467 \pm 0.038_{stat} \pm 0.019_{syst} \pm 0.065_{BR})$(GeV/c^2)^2 and $\langle (M^2_{X_c} - \langle M^2_{X_c} \rangle)^2 \rangle = (1.05 \pm 0.26_{stat} \pm 0.08_{exp} \pm 0.10_{BR})$ (GeV/c^2)^4 where $m_{\bar{D}}$ is the spin-averaged D meson mass and the subscript "BR" denotes the uncertainty from the branching ratios used to combine the D, D^* and D^{**} components. From these moments we also determine the non-perturbative Heavy Quark Effective Theory parameters Λ and λ_1 in the pole and 1S mass schemes.

The most precise determination of the Cabibbo-Kobayashi-Maskawa matrix element $|V_{cb}|$ is achieved by measuring the semileptonic decay width of the B meson into charm $\Gamma_{sl} = \Gamma(B \to \ell\nu X_c)$ and relating Γ_{sl} to $|V_{cb}|$ through an operator product expansion (OPE) in Heavy Quark Effective Theory (HQET). [1,2] In this expansion in inverse powers of the B meson mass, non-perturbative parameters external to HQET enter in each term — one parameter Λ at order $1/m_B$, two parameters λ_1 and λ_2 at order $1/m^2_B$, etc. Experimental uncertainties in measuring Γ_{sl} are such that better knowledge of these non-perturbative parameters is required to substantially reduce the uncertainty on $|V_{cb}|$.

OPE in HQET also predicts the value of any weighted integral in the variable $s_H \equiv M^2_{X_c}$of the differential semileptonic width $d\Gamma_{sl}/ds_H$, as long as the weight function is smooth in s_H. This allows us to constrain the HQET parameters Λ, λ_1 and λ_2 by measuring the first two moments of the hadronic mass distribution $M_1 \equiv \langle M^2_{X_c} \rangle - m^2_{\bar{D}}$ and $M_2 \equiv \langle (M^2_{X_c} - \langle M^2_{X_c} \rangle)^2 \rangle$, where $m_{\bar{D}} \equiv 0.25 m_D + 0.75 m_{D^*}$ is the spin-averaged D meson mass.

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We separate the process $B^- \to X_c \ell^- \bar{\nu}$ (charge-conjugated processes are implicitly included throughout this paper) into three categories with $X_c = D^0$, D^{*0} and D^{**0} respectively. In terms of the differential width,

$$\frac{1}{\Gamma_{sl}}\frac{d\Gamma_{sl}}{ds_H} = \frac{\Gamma_0}{\Gamma_{sl}}\delta(s_H - m^2_{D_0}) + \frac{\Gamma_*}{\Gamma_{sl}}\delta(s_H - m^2_{D_0^*}) + (1 - \frac{\Gamma_0}{\Gamma_{sl}} - \frac{\Gamma_*}{\Gamma_{sl}})f^{**}(s_H), \quad (1)$$

where f^{**} is the mass distribution of the D^{**} component (defined as those X_c that decay as $D^{(*)+}\pi^-_{**}$) and Γ_0 and Γ_* are the partial semileptonic widths into D^0 and D^{*0} respectively. We explicitly assume that the difference between inclusive B^- semileptonic decays and the exclusive decays $B^- \to D^{(*)0}\ell^-\bar{\nu}_\ell$ is made up by decays of the type $B^- \to D^{(*)+}\pi^-\ell^-\bar{\nu}_\ell$. In this analysis, we only measure the shape of f^{**} and use Eq. 1 to obtain the overall semileptonic differential width $d\Gamma_{sl}/ds_H$.

We draw our data sample of $B \to D^{(*)+}\pi^-\ell^- X$ decays from $\sim$ 180 pb^{-1} of $p\bar{p}$ collisions ($\sqrt{s} = 1.96$ TeV) collected with the CDF II detector at the Fermilab Tevatron during the period February 2002 to August 2003. The relevant triggers require an electron or muon with transverse momentum $p_T \geq$4 GeV/c and a displaced track with an impact parameter of at least 120 μm with repsect to the beamline.

Tracks with $p_T \geq$0.4 GeV are used to reconstruct $\ell^- D^{*+}[\to D^0\pi^+_*]$ and $\ell^- D^+$ events in the $D^0 \to K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^-\pi^+$ and $D^+ \to K^-\pi^+\pi^+$ channels. With the exception of the $D^0 \to K^-\pi^+\pi^0$ channel, where the D^0 is reconstructed as a satellite $K\pi$ peak with an invariant mass of 1.50 to 1.70 GeV/c^2, the D^+ and D^0 mesons are required to fall in the mass range of 1.84 to 1.89 GeV/c^2. The $D^{*+}[\to D^0\pi^+_*]$ mesons are reconstructed with the requirement that $m(D^0\pi^+_*) - m(D^0)$ lies in the range 0.142 to 0.147 GeV/c^2 for the $K^-\pi^+$ and $K^-\pi^+\pi^+\pi^-$ modes and 0.142 to 0.155 for the $K^-\pi^+\pi^0$ satellite mode. The B vertex is reconstructed in three dimensions from the lepton and $D^{(*)+}$ meson.

After a $D^{(*)+}$ meson is found, an additional track (the π^-_{**}) of the opposite charge is sought to form the D^{**0}. The π^-_{**} is selected to pass within 2.5 standard deviations of the B meson vertex and at least three standard deviations away from the beamline. The selection has been optimized on a signal Monte Carlo sample based on the ISGW2 [4] and Goity-Roberts [5] decay models with background from wrong-sign $\pi^+_{**}\ell^-$ data.

A two-fold background subtraction is performed using data: sideband subtraction in the D^+ and $m(D^0\pi^+_*) - m(D^0)$ mass distributions removes the combinatorial background under the mass peaks; wrong sign $\pi^+_{**}\ell^-$ combinations account for background from the primary vertex. A further minor background of the type $B \to D^{(*)}D_s^{(*)}$ (amounting to $\sim$ 1% of the signal), in which the $D_s^{(*)}$ decays semileptonically, is subtracted according to Monte Carlo predictions.

We employ a detailed Monte Carlo simulation to correct for small biases to the observed $f^{**}(s_H)$ shape, this being the object of our analysis, and to calculate the relative contributions of the D^+ and D^{*+} sub-modes to f^{**}. Theoretical predictions of the moments are conventionally quoted for lower cutoffs in p^*_ℓ, the lepton momentum in the B rest-frame. Since p^*_ℓ is not directly measurable at CDF II, we use Monte Carlo simulation to correct our f^{**} distribution to a cut of $p_\ell^* > 0.7$ GeV. This particular value of the cut is chosen to minimize the correction. Dependency on the decay model is assessed and taken as a systematic uncertainty.

We compute the first two moments of the $f^{**}(s_H)$ distribution from the fully-corrected $D^{(*)+}\pi^-_{**}$ spectrum (Fig. 1). No assumptions are made regarding the rates or shapes of the various D^{**} components. We find $m_1 \equiv \langle m^2_{D^{**}} \rangle = (5.83 \pm 0.16_{stat} \pm 0.08_{syst})$ $(\mathrm{GeV/c^2})^2$ and $m_2 \equiv \langle (m^2_{D^{**}} - \langle m^2_{D^{**}} \rangle)^2 \rangle = (1.30 \pm 0.69_{stat} \pm 0.22_{syst})$ $(\mathrm{GeV/c^2})^4$ The correlation is $+61\%$.

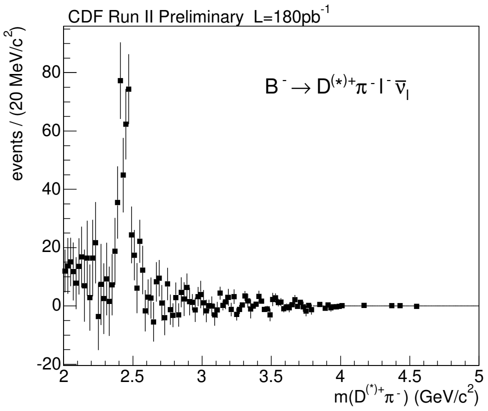

Fig. 1. The fully-corrected invariant mass distribution $m(D^{(*)+}\pi^-_{**})$ in $B^- \to D^{(*)+}\pi^-_{**}\ell^-\bar{\nu}_\ell$decays.

Using Eq. 1 with input from Particle Data Group [3] averages, we combine f^{**} with the D^0 and D^{*0} contributions to obtain the full moments $M_1 \equiv \langle M^2_{X_c} \rangle - m^2_{\bar{D}} = (0.467 \pm 0.038_{stat} \pm 0.019_{syst} \pm 0.065_{BR})$ $(\mathrm{GeV/c^2})^2$ and $M_2 \equiv \langle (M^2_{X_c} - \langle M^2_{X_c} \rangle)^2 \rangle = (1.05 \pm 0.26_{stat} \pm 0.08_{exp} \pm 0.10_{BR})$ $(\mathrm{GeV/c^2})^4$, where the subscript "BR" denotes the uncertainty from the branching ratios used in combining the three components. There is a correlation of $+69\%$ between M_1 and M_2.

From the moments we extract HQET parameters in the pole and 1S mass schemes. In the pole mass scheme $\Lambda = (0.397 \pm 0.078_{stat} \pm 0.027_{exp} \pm 0.064_{BR} \pm 0.058_{theory})$ GeV and $\lambda_1 = (-0.184 \pm 0.057_{stat} \pm 0.017_{exp} \pm 0.022_{BR} \pm 0.077_{theory})$ GeV^2 with a -79% correlation; in the 1S scheme, $m_b^{1S} \equiv m_\Upsilon/2 - \Lambda^{1S} = (4.654 \pm 0.078_{stat} \pm 0.027_{exp} \pm 0.064_{BR} \pm 0.089_{theory})$ GeV and $\lambda_1^{1S} = (-0.277 \pm 0.049_{stat} \pm 0.017_{exp} \pm 0.022_{BR} \pm 0.094_{theory})$ GeV^2 with a -77% correlation.

Statistical uncertainties dominate the measurements of m_1 and m_2. Uncertainties in semileptonic branching ratios become important when the overall moments M_1 and M_2 are calculated with Eq. 1. Finally, theoretical uncertanities become dominant in the extraction of the HQET parameters Λ and λ_1. Experimental systematics are smaller in all cases.

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