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Studies of Orbitally Excited $D^{**}_{(s)}$ and B^{**} Mesons at CDF and DØ

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Abstract. Using a large data sample of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV recorded by the CDF and DØ detectors operating at the Fermilab Tevatron, the orbitally excited B mesons B_1 and B_2^* are observed directly as two separate states in fully reconstructed decays to $B^{(*)}\pi$. The masses and the mass differences between the states are presented. In the charm system, the orbitally excited D mesons D_1 and D_2^* are observed in fully reconstructed decays to $D^{(*)}\pi$. Measurements of the product branching rates of semileptonic decays $B \to \bar{D}^{**}\mu^+\nu_\mu X$ and their ratio are presented. We also present the observation of the semileptonic decays $B_s \to \mu\nu D_s^{**}$ where the excited D_s^{**} states are reconstructed in the mode $D_s^{**} \to D^* K_S^0$.

Keywords: Orbitally excited mesons, D^{**}, D_s^{**}, B^{**}, Heavy Quark Effective Theory
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THEORETICAL MOTIVATION

The D and B mesons are examples of a heavy-light quark bound state. The spectroscopy of these mesons may be predicted through application of Heavy Quark Effective Theory and the ideas behind it, particularly in the limit $m_{(c,b)} \to \infty$. In this limit, the excited states are described by the light degrees of freedom with spin-parity J_l^P. This leaves a degenerate doublet for each meson state, with the degeneracy broken by effects of the order $\Lambda_{QCD}/m_{(c,b)}$. These first excited states are known as the B^{**} and $D^{**}_{(s)}$ in the B and charm systems respectively. Measuring the properties of these mesons tests HQET.

The CDF and DØ detectors are described in detail in Ref [1] and Ref [2] respectively.

D^{**} mass measurement

CDF measures the masses and widths of the D_1^0 and D_2^{*0} states using two fully hadronic decay channels in 210 pb^{-1} of data [3]:[1]

- $D^{**} \to D^{*+}\pi^-, D^{*+} \to D^0\pi^+$
- $D^{**} \to D^+\pi^-$, with feed-down from $D^{*+} \to D^+\pi^0$ channel

The D^{**} invariant mass difference for both channels is shown in Figure 1. The wide D^{**} states are taken from the PDG [4]. The results are

[1] Charge conjugated states are always implied.

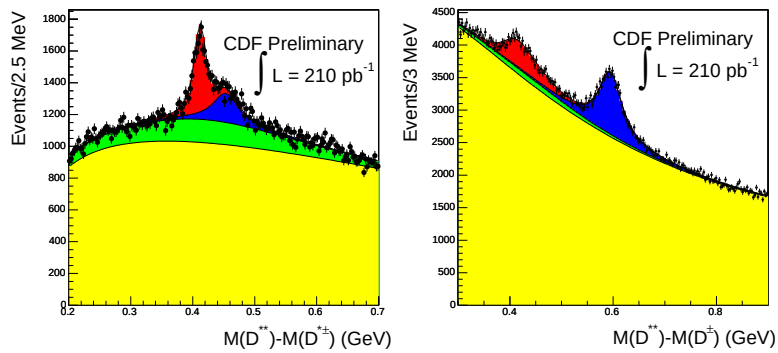

FIGURE 1. Right: invariant mass of $D^{*\pm}\pi^{\mp}$ combinations. Left: invariant mass of $D^{\pm}\pi^{\mp}$ combinations. D_1^0 contribution is shown in red, D_2^{*0} in blue, D^{**} wide states in green, and background in yellow.

- $M(D_1^0) = 2421.7 \pm 0.7(stat) \pm 0.6(syst), \Gamma(D_1^0) = 20.0 \pm 1.7 \pm 1.3$ MeV/c^2
- $M(D_2^{*0}) = 2463.3 \pm 0.6(stat) \pm 0.8(syst), \Gamma(D_2^{*0}) = 49.2 \pm 2.3 \pm 1.3$ MeV/c^2

D^{**} semileptonic branching rates

DØ measures the branching fractions of the decays $B \to \bar{D}_1^0(2420)\mu^+\nu_\mu X$ and $B \to \bar{D}_2^{*0}(2460)\mu^+\nu_\mu X$, and makes the first direct measurement of their ratio in 460 pb^{-1} of data [5]. The D^{**} invariant mass shown in Figure 2a is fit with the sum of two relativistic Breit-Wigners for the narrow states.

The branching fraction for the decays $B \to \bar{D}^{**}\mu^+\nu_\mu X$ are determined by normalization to the known value of the branching fraction for $\mathcal{B}(B \to D^{*-}\ell^+\nu X) = (2.75 \pm 0.19)\%$ [4]. To compare with theory, the fragmentation $\mathcal{B}(\bar{b} \to B)$ is included where B is either B^0 or $B^{\pm}$. The results for the D^{**} narrow branching fractions are

$$\mathcal{B}(\bar{b} \to B) \cdot \mathcal{B}(B \to (\bar{D}_1^0, \bar{D}_2^{*0})\mu^+\nu_\mu X) \cdot \mathcal{B}((\bar{D}_1^0, \bar{D}_2^{*0}) \to D^{*-}\pi^+) = (0.122 \pm 0.007(stat) \pm 0.015(syst))\%$$

$$\mathcal{B}(\bar{b} \to B) \cdot \mathcal{B}(B \to \bar{D}_1^0\mu^+\nu_\mu X) \cdot \mathcal{B}(\bar{D}_1^0 \to D^{*-}\pi^+) = (0.087 \pm 0.007(stat) \pm 0.014(syst))\%$$

$$\mathcal{B}(\bar{b} \to B) \cdot \mathcal{B}(B \to \bar{D}_2^{*0}\mu^+\nu_\mu X) \cdot \mathcal{B}(\bar{D}_2^{*0} \to D^{*-}\pi^+) = (0.035 \pm 0.007(stat) \pm 0.008(syst))\%$$

$$\frac{\mathcal{B}(B \to \bar{D}_2^{*0}\mu^+\nu_\mu X) \cdot \mathcal{B}(\bar{D}_2^{*0} \to D^{*-}\pi^+)}{\mathcal{B}(B \to \bar{D}_1^0\mu^+\nu_\mu X) \cdot \mathcal{B}(\bar{D}_1^0 \to D^{*-}\pi^+)} = 0.39 \pm 0.09(stat) \pm 0.12(syst)$$

Observation of D_s^{**}

DØ observes $B_s \to \mu\nu D_s^{**}$ through the decay channel $D_s^{**+} \to D^{*+}K_S^0$ with $D^{*+} \to D^0\pi^+, D^0 \to K^-\pi^+$ and $K_S^0 \to \pi^+\pi^-$ in 485 pb^{-1} of data. The significance of the signal

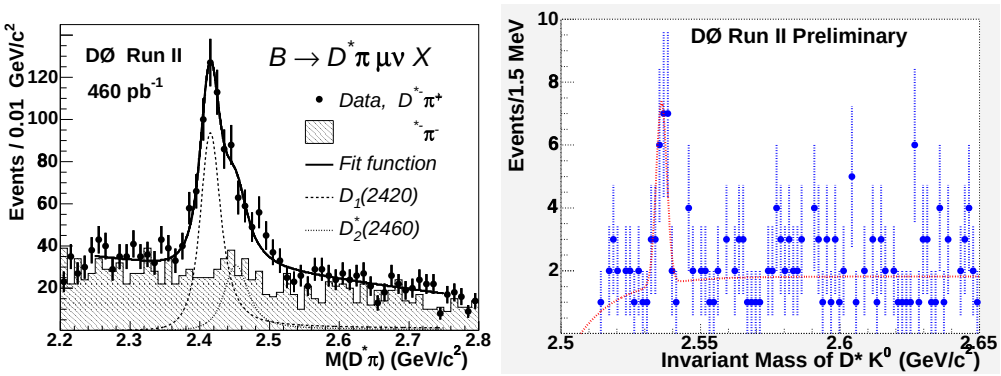

FIGURE 2. Right: The invariant mass $M(D^*\pi)$. Points correspond to $D^*\pi$ combinations with opposite charges and the hatched histogram corresponds to same charge combinations. Left: The invariant mass of D^*K_S, which shows evidence of the D_s^{**}.

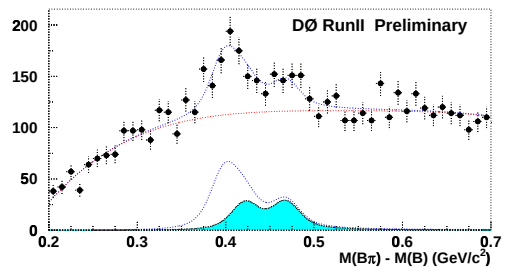

FIGURE 3. Mass difference $\Delta M = M(B\pi) - M(B)$ for exclusive B decays. The upper curve shows the total fit. The narrow B^{**} signal is shown separately, with the contribution from B_2^* shaded in.

shown in Figure 2b is greater than 3.0σ, an excess of 18.5 ± 5.5 events over background. The observation is only of one narrow state, the $D_{s1}^{\pm}(2536)$. This observation demonstrates the potential to measure production and spectroscopy of this state.

B^{**} mass measurement

Both CDF and DØ measured the narrow B^{**} states. DØ uses the fully reconstructed decays of $B^+ \to J/\psi K^+$, $B^0 \to J/\psi K^{*0}$, and $B^0 \to J/\psi K_S$ to reconstruct a mixture of B^{**0} and $B^{**\pm}$ states in 350 pb^{-1} of data [7]. The two narrow B^{**} states are fit by a relativistic Breit-Wigner convoluted with a Gaussian detector resolution function. With the widths of the two narrow states set equal, the results shown in Figure 3 are

- $M(B_1) = 5724 \pm 4(stat) \pm 7(syst)$ MeV/c^2
- $M(B_2^*) - M(B_1) = 23.6 \pm 7.7(stat) \pm 3.9(syst)$ MeV/c^2
- $\Gamma_1 = \Gamma_2 = 23 \pm 12(stat) \pm 9(syst)$ MeV/c^2

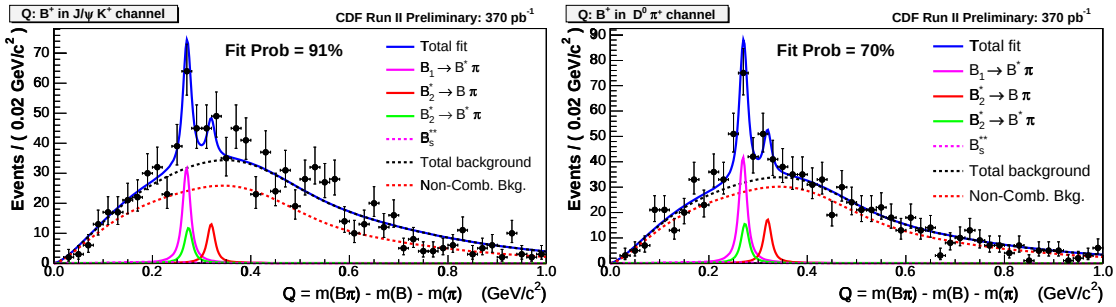

FIGURE 4. Right: Mass difference in the $B \to J/\psi K$ channel. Left: Mass difference in $B \to \bar{D}^0\pi$. Each narrow B^{**0} decay channel are shown separately. B_s^{**} contribution is estimated from Monte Carlo.

CDF uses the fully reconstructed decays of $B^+ \to J/\psi K^+$ and $B^+ \to \bar{D}^0\pi^+$ to reconstruct the B^{**0} states in 370 pb^{-1} of data [8]. Due to very different signal to background structure, B^{**0} events could not be added together and were fit simultaneously in both channels. Narrow B^{**0} states are fit with a non-relativistic Breit-Wigner convoluted with a double Gaussian detector resolution. The results shown in Figure 4 are

- $M(B_1^0) = 5734 \pm 3(stat) \pm 2(syst)$ MeV/c^2
- $M(B_2^{*0}) = 5738 \pm 5(stat) \pm 1(syst)$ MeV/c^2

CONCLUSIONS

All measurements agree well with HQET models. Many measurements are statistically limited, and will improve as more data is analyzed. The results are all interesting and competitive; the semileptonic branching fractions, for example, are an order of magnitude better than previous measurements.

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