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B Hadron Properties at the Tevatron: Lifetime, B_c, excited states

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The Tevatron provides physics rich in B hadrons to CDF and D0. Both experiments have measured the lifetimes of the Λ_b, B_s, and B_c hadrons, measured the B_c mass, and observed B^0 and B_s excited states. As the Tevatron delivers more data, improvements in hardware and analysis techniques are implemented to make the most of the unique B data available at the $p\bar{p}$ collider. This proceeding presents the results of measurements of B hadron properties from CDF and D0. Included are the lifetimes of select B hadrons, properties of the B_c meson, and the observation of excited states.

12th International Conference on B-Physics at Hadron Machines
September 7-11, 2009
Heidelberg, Germany.

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PoS(BEAUTY 2009)044

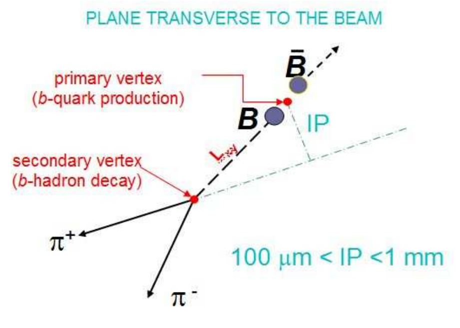
1. Introduction, Triggers, Final States

The Tevatron $p\bar{p}$ collider at Fermilab copiously produces B hadrons, many of which are not accessible at other high energy physics experiments. These data are used to make new measurements of B hadron properties.

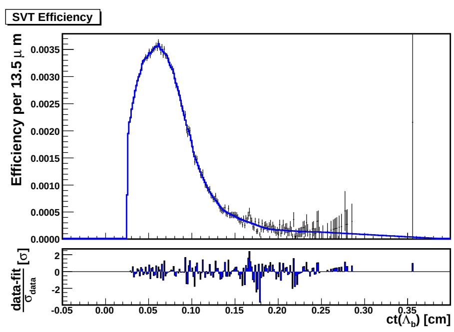
The high rate data delivered by the Tevatron consists primarily of B hadrons and an even higher rate of background from inelastic collisions. Thus, CDF and D0 must have efficient and smart triggers to both improve S/B and handle the high event rate. In addition, for these analyses, it is imperative to have good mass resolution to maximize S/B and excellent vertex resolution which translates directly into lifetime resolution[1].

Both CDF and D0 select on di-muon final states, most often to identify events with J/ψ candidates. These analyses typically use dedicated di-muon triggers that require two tracks that pass loose criteria, where at least one track is associated with a muon segment in the muon detector system. Semi-leptonic final states consist of at least one electron or muon. The single muon trigger at D0 requires a track with a matched muon segment or calorimeter energy deposition consistent with a minimum ionizing particle. Neither the di-muon or single lepton triggers introduce any lifetime bias to analyses.

Additionally, final states with all hadronic particles are analyzed at CDF. These analyses rely on displaced vertex track triggers. A schematic of a displaced vertex is shown in Figure 1(a). These triggers are extremely valuable because they substantially increase statistics and allow for several measurements in many channels that would otherwise be inaccessible. Displaced vertex trigger identification is limited to the impact parameter IP range 120 μm to 1000 μm, thus biasing the lifetime of the measurement. In order to account for the lifetime bias, the displaced vertex trigger efficiency for each process must be measured. An example of the trigger efficiency is shown for $\Lambda_b \to \Lambda_c \pi$ in Figure 1(b) [2].



(a) Schematic of displaced vertex trigger



(b) Displaced vertex trigger efficiency distribution for $\Lambda_b \to \Lambda_c \pi$

Figure 1: Displaced vertex trigger at CDF

2. Measuring Lifetimes

At CDF and D0, lifetime measurements are made by measuring the transverse momentum

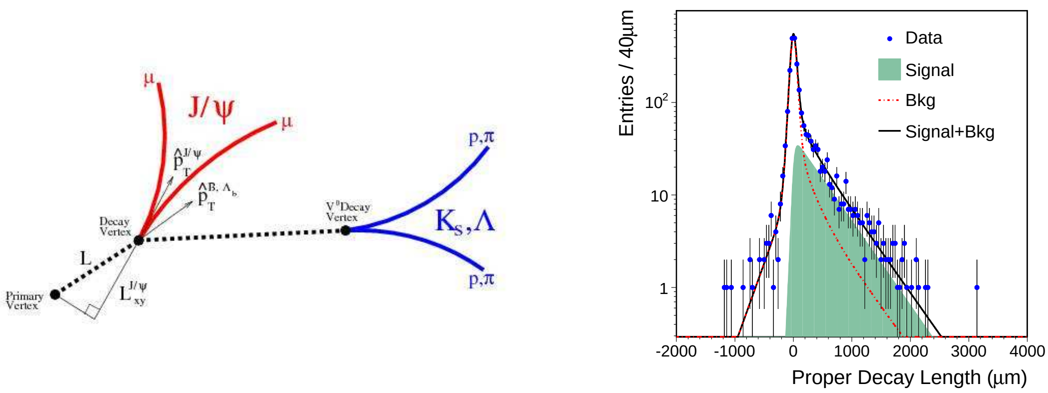
p_T and the transverse decay length L_{xy} of the particle of interest, which will be referred to as the "parent particle". The lifetime measured in the parent particle's rest frame, called proper decay length (PDL), is expressed as $ct = \frac{mL_{xy}}{p_T}$, where m is the mass of the parent particle. When the parent particle can not be completely reconstructed, such as when a neutrino is part of the decay, the L_{xy} and p_T of only the reconstructed particles can be measured. The "pseudo" or "visible" PDL is $ct^* = \frac{mL_{xy}(\text{reconstructed particles})}{p_T(\text{reconstructed particles})}$. The actual PDL can be extracted after including a "K-factor", which is an estimate of the ratio between the observed p_T of the reconstructed particles and the actual p_T of the parent particle, $K = \frac{p_T(\text{reconstructed particles})}{p_T(\text{parent particle})}$. The PDL is then $ct = K \cdot ct^*$.

3. Measurements of *B* Hadron Lifetimes

Lighter, non-b quarks in *B* hadrons are sometimes modeled as spectators to the weak force mediated *B* decay. In this model, all *B* hadrons are expected to have the same lifetime. Heavy Quark Effective Theory (HQET) [3] predicts differences in the lifetimes due to the non-trivial role of the "spectator" quarks. Thus, measurements of *B* hadron lifetimes provide a valuable tool to test HQET.

3.1 Λ_b Lifetime Measurements

Using ~ 1 fb^{-1} of data collected at CDF, the Λ_b lifetime is measured using the decay $\Lambda_b \to J/\psi\Lambda$. A major challenge of this analysis is the long lifetime of the Λ which decays to $p\pi$, as shown in Figure 2(a). To avoid a lifetime bias from the Λ's long lifetime, the CDF analysis uses the $J/\psi \to \mu\mu$ candidates to determine the Λ_c decay vertex. The J/ψ candidates are then associated with the Λ candidates which are reconstructed from $p\pi$ candidates with a common vertex. The analysis procedure was developed using $B^0 \to J/\psi K_s^0$ candidates because of their similar decay topology and larger yield. The resulting PDL distribution is shown in Figure 2(b) giving $c\tau(\Lambda_b) = 477.6^{+25.0}_{-23.4}$ (stat) $\pm$ 9.9 (syst) μm [4]. For comparison, using 1.2 fb^{-1} of data, D0 measures $c\tau(\Lambda_b) = 365.1^{+39.1}_{-34.7}$ (stat) $\pm$ 12.7 (syst) μm [5] in this decay mode.

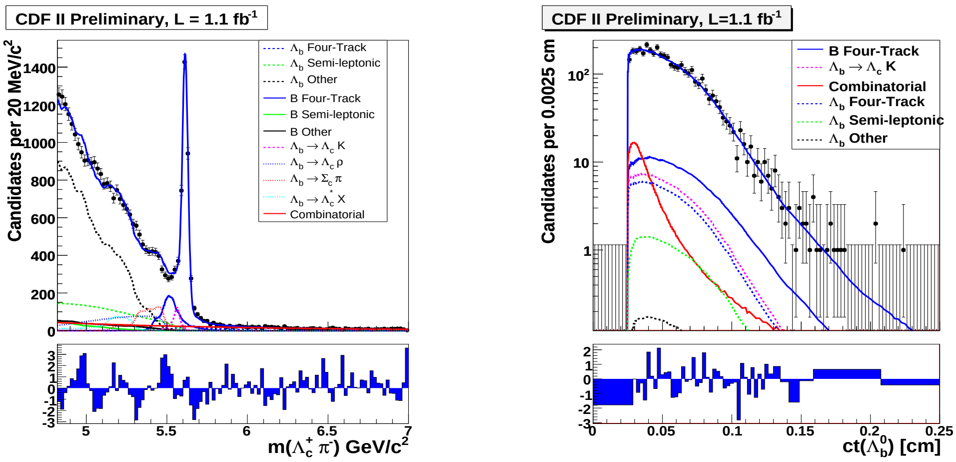


(a) $\Lambda_b \to J/\psi\Lambda$ decay schematic

(b) $\Lambda_b \to J/\psi\Lambda$ *ct* projection

Figure 2: $\Lambda_b \to J/\psi\Lambda$ at CDF

CDF also measures the Λ_b lifetime using $\Lambda_b \to \Lambda_c^+\pi^-$ decays where the $\Lambda_c^+ \to p^+K^-\pi^+$. This is an all hadronic final state that relies on displaced vertex triggers. To account for the lifetime bias introduced by the displaced vertex trigger, the trigger efficiency distribution is determined from Monte Carlo (Section 1, Figure 1(b)). Only fully reconstructed Λ_b candidates with reconstructed invariant mass $5.565 < M(\Lambda_c^+\pi^-) < 5.67$ GeV$/c^2$ are considered, yielding 2927 ± 58 events as shown in Figure 3(a). Fitting the data with an exponential convoluted with the trigger efficiency curve and the detector resolution function yields $c\tau(\Lambda_b) = 420.1 \pm 13.7$ (stat) $\pm$ 10.6 (syst) μm, as shown in Figure 3(b) [2]. Compared to Figure 2(b), the effect of the displaced vertex trigger is evident in Figure3(b).



(a) $\Lambda_b \to \Lambda_c\pi$ reconstructed invariant mass distribution

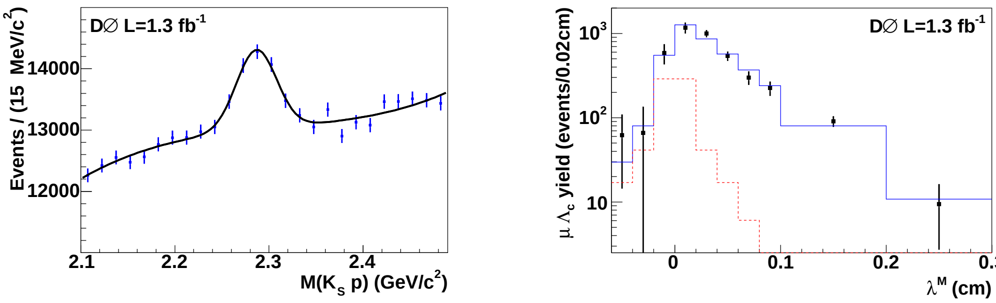
(b) $\Lambda_b \to \Lambda_c\pi$ PDL distribution

Figure 3: $\Lambda_b \to \Lambda_c\pi$ mass and proper decay length at CDF

The lifetime of the Λ_b is measured at D0 by reconstructing the semi-leptonic decay $\Lambda_b \to \mu\nu\Lambda_c^+X$, where $\Lambda_c^+ \to K_s^0 p^+$ [6]. Since the Λ_b is not fully reconstructed, a K-factor is determined and applied, as described in Section 2. Figure 4(a) shows the $K_s^0 p^+$ reconstructed invariant mass distribution for all selected Λ_b^0 candidates. The $\mu\Lambda_c$ yield is measured by fitting the $K_S^0 p^+$ invariant mass in bins of visible PDL λ^M, shown in Figure 4(b), yielding a total of 4437 ± 329 (stat) Λ_b candidates. After performing a lifetime fit, $c\tau(\Lambda_b^0)$ is determined to be $386.7^{+35.7}_{-32.9}$ (stat)$^{+26.1}_{-27.3}$ (syst) μm [6].

3.2 B_s Lifetime

CDF measures the B_s lifetime using the fully reconstructed mode $B_s \to D_s^-(\to \phi\pi^-)\pi^+$ and the partially reconstructed modes $B_s \to D_s^-\rho^+(\to \pi^+\pi^0)$, $B_s \to D_s^-K^+$, and $B_s \to D_s^{*-}\pi^+$. Including the partially reconstructed modes effectively doubles the statistics. The reconstructed invariant mass distributions of the partially and fully reconstructed modes are in Figure 5(a). Under the B_s mass peak are the fully reconstructed modes, while the partially reconstructed modes are in the lower tail of the mass distribution. The lifetime measured from the partially reconstructed modes must be accounted for using a K-factor, shown in Figure 5(b) and described in

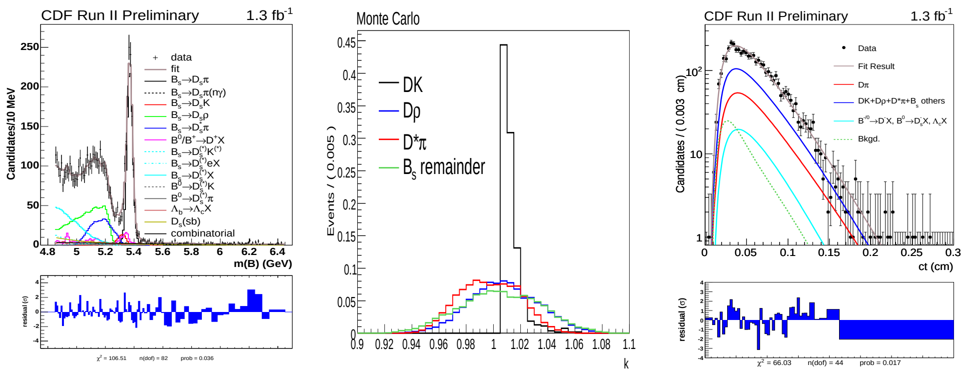


(a) $M(K_s^0 p^+)$ for selected Λ_b^0 candidates

(b) Measured Visible PDL

Figure 4: $\Lambda_b \rightarrow \Lambda_C \pi$ distributions from D0

Section 2. To correct for the lifetime bias from the displaced vertex trigger (see Section 1), the trigger efficiency distribution is measured using Monte Carlo and applied during the fit of the data. The resulting PDL distribution is shown in Figure 5(c), and the $c\tau(B_s)$ is determined to be $c\tau(B_s) = 455.0 \pm 12.2$ (stat) ± 8.2 (syst) μm[7].



(a) B_s reconstructed invariant mass distributions

(b) K-factor for partially reconstructed B_s modes

(c) B_s PDL distribution

Figure 5: $B_s \rightarrow D_s^- \pi^+$ at CDF

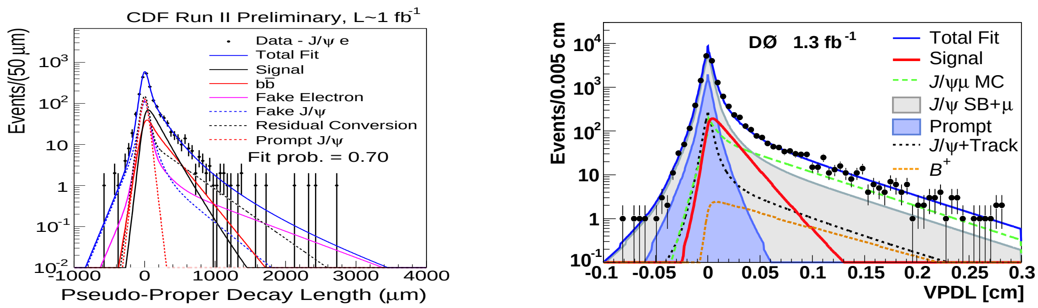
4. B_c Properties

The B_c meson is particularly interesting because it contains two different heavy quarks, a c-quark and a b-quark, providing a testing ground for QCD. Thus far at the Tevatron, B_c mesons have been observed only via decays $B_c \rightarrow J/\psi + X$, including $B_c \rightarrow J/\psi\mu + X$, $B_c \rightarrow J/\psi e + X$, and $B_c \rightarrow J/\psi\pi$.

4.1 B_c Lifetime

Since the B_c meson contains two different heavy quarks, its lifetime is expected to be shorter than the lifetimes of other B hadrons because each quark can decay, thus affecting the lifetime of the meson. The lifetime of the B_c meson is measured at CDF using both $B_c \to J/\psi\mu + X$ and $B_c \to J/\psi\ e\nu + X$ decays [8], and D0 uses only $B_c \to J/\psi\ \mu\nu + X$ decays [9]. X represents neutrinos and other unmeasured particles.

Events are triggered on J/ψ candidates at CDF and on single muons at D0. The primary challenge of this analysis is the multitude of backgrounds. These include backgrounds due to a fake lepton produced with a real J/ψ, J/ψ background events produced with a third lepton, $b\bar{b}$ events where one b-quark produces a J/ψ and the other produces a lepton, and prompt J/ψ production in association with an additional lepton. Figure 6(a) shows the pseudo PDL in the $B_c \to J/\psi e\nu$ mode as measured by CDF; Figure 6(b) shows the visible PDL in the $B_c \to J/\psi\mu\nu + X$ mode as measured by D0. CDF measures $c\tau_\mu = 179.1^{+32.6}_{-27.2}$ (stat) μm and $c\tau_e = 121.7^{+18.0}_{-16.3}$ (stat) μm, with a combined result of $c\tau = 142.5^{+15.8}_{-14.8}$ (stat) $\pm\, 5.5$ (syst) μm [8]. The B_c PDL measured by D0 is $c\tau = 134.3^{+11.4}_{-10.8}$ (stat) $\pm\, 9.59$ (syst) μm [9].



(a) $B_c \to J/\psi e\nu$ pseudo PDL distribution from CDF

(b) $B_c \to J/\psi\mu\nu$ visible PDL distribution from D0

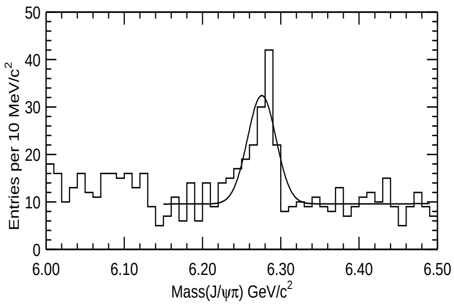
Figure 6: $B_c \to J/\psi l + X$ pseudo (visible) proper decay length distributions

4.2 B_c Mass

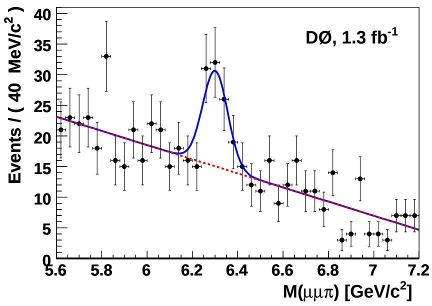
The mass of the B_c meson is measured using the decay $B_c^+ \to J/\psi\pi^+$ at both CDF and D0. The primary backgrounds are combinatorial and Cabibbo-suppressed $B_c^+ \to J/\psi K^+$. The CDF analysis optimizes the selection criteria using $B^+ \to J/\psi K^+$ candidates with $80 < ct < 300$ μm. Using 2.4 fb^{-1} of data, CDF observes a signal of 108 ± 15 B_c candidates with a significance greater than 8σ and measures the B_c mass to be 6275.6 ± 2.9 (stat) $\pm\, 2.5$ (syst) MeV$/c^2$, as shown in Figure 7(a) [10]. Using 1.3 fb^{-1} of data, D0 observes 54 ± 12 B_c candidates with a significance of 5.2σ and measures the B_c mass to be $M(B_c) = 6300 \pm 14$ (stat) $\pm\, 5$ (syst) MeV$/c^2$, as shown in Figure 7(b) [11].

5. Excited States

Heavy-light quark mesons such as B^0 and B_s mesons are expected to have orbitally excited states analogous to the excitation of hydrogen atoms in QED. Four orbitally excited states with L=1 are expected for B^0 (B_s) mesons. Two of the states have total angular momentum of the light quark j=$\frac{1}{2}$. These states are S-wave decays with broad resonances. The other two orbitally excited



(a) M($J/\psi\pi$) from CDF



(b) M($\mu\mu\pi$) from D0

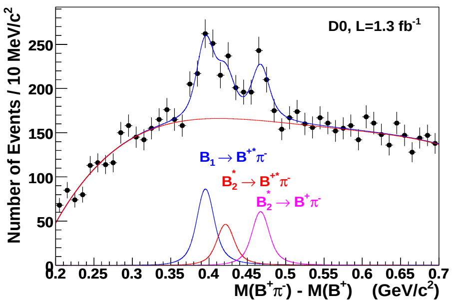
Figure 7: $B_c \to J/\psi\pi$ invariant mass spectra for candidate events

states have j=$\frac{3}{2}$. These states are D-wave decays which have narrow resonances and are expected to be observed at CDF and D0. These states are referred to as B_1 (B_{s1}) for J=1 and B_2^* (B_{s2}^*) for J=2.

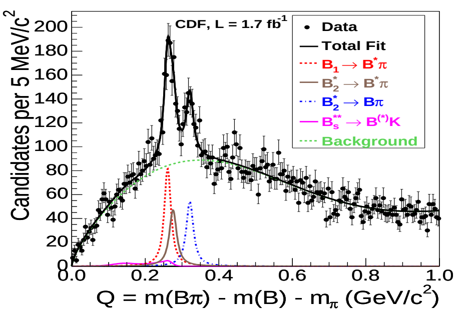
The B^0 orbitally excited (L=1) excited state B_1 decays via $B_1 \to B^{*+}(\to B^+\gamma)\pi^-$, while the B_2^* state decays via $B_2^* \to B^+\pi^-$ and $B_2^* \to B^{*+}(\to B^+\gamma)\pi^-$.

At D0, B^+ particles are reconstructed using $B^+ \to J/\psi(\to \mu\mu)K^+$ decays. Using 1.3 fb^{-1} of data, D0 measures $M(B_1) = 5720.6 \pm 2.4$ (stat) $\pm$ 1.4(syst) MeV/c^2 and $M(B_2^*) = 5746.8 \pm 2.4$ (stat) $\pm$ 1.7(syst) MeV/c^2, where the mass difference $M(B^+\pi^-) - M(B^+)$ distribution is shown in Figure 8(a) [12].

At CDF, B^+ particles are triggered using the di-muon trigger for $B^+ \to J/\psi(\to \mu\mu)K^+$ and using the displaced vertex trigger for $B^+ \to D^0(3)\pi^+$, $D^0 \to K^+\pi^-$. Using 1.7 fb^{-1} of data, the mass difference $Q = m(B\pi) - m(B) - m_\pi$ distribution is shown in Figure 8(b) [13]. The mass of the B_1 state is found to be $M(B_1) = 5725.3^{+1.6}_{-2.2}$ (stat)$^{+1.4}_{-1.5}$(syst) MeV/c^2. The B_2^* mass is measured to be $M(B_2^*) = 5740.2^{+1.7}_{-1.8}$ (stat)$^{+0.9}_{-0.8}$(syst) MeV/c^2 with a width of $\Gamma(B_2^*) = 22.7^{+3.8}_{-3.2}$ (stat)$^{+3.2}_{-10.2}$(syst) MeV/c^2 [13].



(a) Mass difference for excited B^0 candidates at D0



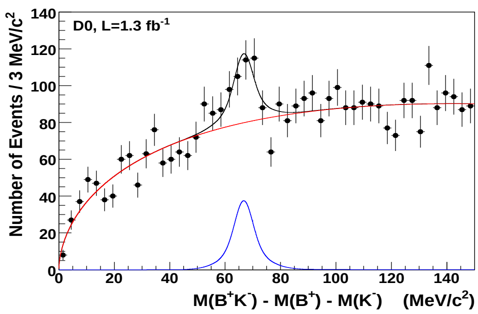
(b) Mass difference for excited B^0 candidates at CDF

Figure 8: Mass difference distributions for excited B^0 candidates

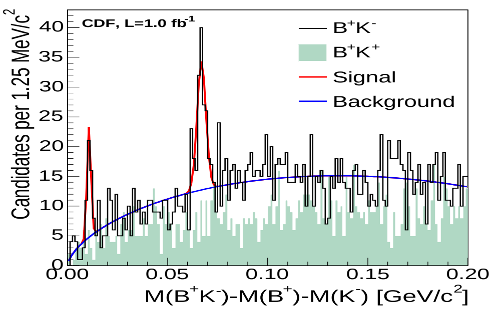
The excited B_s state B_{s1} decays via $B_{s1} \to B^{*+}(\to B^+\gamma)K^-$. The B_{s2}^* state decay modes are $B_{s2}^* \to B^+K^-$ and $B_{s2}^* \to B^{*+}(\to B^+\gamma)K^-$. B^+ candidates are reconstructed using the same decay channels that were used in the excited B^0 meson analysis. D0 observes the B_s excited state B_{s2}^*

where $B^*_{s2} \to B^+(\to J/\psi K^+)K^-$ with a significance of 4.8σ. The mass is measured to be $M(B^*_{s2}) = 5839.6 \pm 1.1$ (stat) ± 0.7(syst) MeV$/c^2$, as shown in Figure 9(a)[14].

The CDF analysis observes both j=$\frac{3}{2}$ excited B_s states, as shown in the mass difference distribution in Figure 9(b) [15]. Both the B_{s1} state and the B^*_{s2} are observed with significance greater than 5σ. The mass of the B_{s1} state is measured to be $M(B_{s1}) = 5829.4 \pm 0.7$ MeV/c^2, and the mass of the B^*_{s2} is measured to be $M(B^*_{s2}) = 5839.6 \pm 0.7$ MeV/c^2 [15].



(a) Mass difference distribution for B_{s1} and B^*_{s2} candidates at D0



(b) Mass difference distribution for B_{s1} and B^*_{s2} candidates at CDF

Figure 9: Mass difference distributions for excited B_s states

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