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STUDIES OF B STATES AT THE TEVATRON

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Abstract

The Tevatron is an excellent place to study B hadrons. In this article the latest results of the DØ and CDF collaborations on orbitally excited B^0 and B_s mesons, the B_c mass, η_b production, Λ_b lifetime and Σ_b baryons are presented.

1 Introduction

The large $b\bar{b}$ production rate and the possibility to create all types of B hadrons makes the Tevatron a unique place for studies of B states. On the other hand the huge inelastic cross section and the hadronic environment are experimental challenges.

The analysis of B hadron states allows us to study QCD at a non-perturbative scale and to tune our models of bound quark states. The techniques to calculate such states range from potential models to non-relativistic QCD and lattice QCD. In heavy quark effective theory [1] (HQET) a system of b and light quarks is treated in first order as a light quark in a static color field of an infinitely heavy b quark. This approach is for example used to explain the spectrum of orbitally excited B^0 and B_s mesons [2].

2 B**

The bound system of a $\bar{b}$ and d quark[1] with orbital angular momentum of $L = 1$ between the two quarks is called B^{**} or B_J. In the approximation of infinite heavy quark mass the spins of the two quarks decouple so that the sum j_q of the light quark spin and the orbital angular momentum becomes a characterizing quantum number of the B^{**}. Together with the heavy quark spin there are four possible spin combinations. The two $j_q = 1/2$ states can decay via S-wave. Therefore they are expected to be broad and very difficult to distinguish from combinatorial background. Because the two $j_q = 3/2$ states can only decay via D-wave, they are expected to be narrow and observable in the experiment.

The B_2^* with $J^P = 2^+$ can decay to $B^+\pi^-$ and $B^{*+}\pi^-$ while the B_1 with $J^P = 1^+$ can only decay to $B^{*+}\pi^-$. Because the photon from the decay $B^{*+} \to B^+\gamma$ is not detected, three peaks in the reconstructed B^{**} mass spectrum are expected.

DØ observes these three peaks in the B^{**}-B^+ candidate mass difference spectrum (Fig. 1 left) in a data sample of 1 fb^{-1} where the B^+ is reconstructed in the decay mode $J/\psi K^+$ [3]. CDF utilizes the decay $B^+ \to D^0\pi^+$ in addition to the $J/\psi K^+$ mode for the B^+ reconstruction, but has analyzed only 370 pb^{-1} of data so far [4]. The distribution of the Q value, which is the remaining kinetic energy of the B^{**} candidate decay, is shown in Fig. 1 (right) for the $D^0\pi^+$ mode. The extracted masses and mass differences of $m(B_1) = 5720.8 \pm 2.5 \pm 1.1$ MeV/c^2 (DØ), $m(B_1) = 5734 \pm 3 \pm 2$ MeV/c^2 (CDF) and $m(B_2^*) - m(B_1) = 25.2 \pm 3.0 \pm 1.1$ MeV/c^2 (DØ), $m(B_2^*) - m(B_1) = 4 \pm 6 \pm 2$ MeV/c^2 (CDF) are not in good agreement.

[1] Charge conjugate states are always implied in this article.

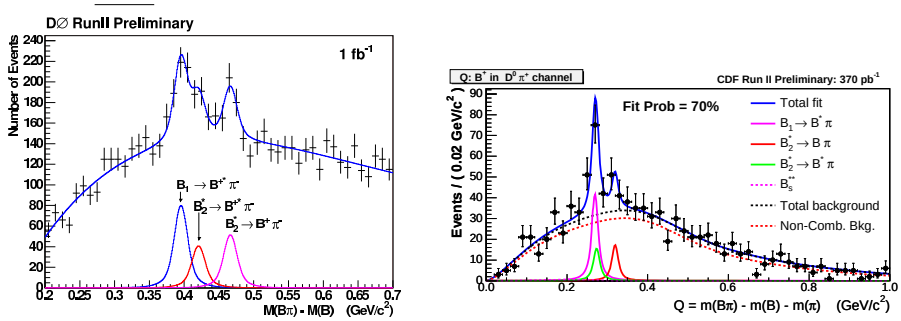

Figure 1: *Mass difference of B^{**} candidates in the B^+ decay mode $J/\psi K^+$ from DØ (left) and Q value of B^{**} candidates in the B^+ decay mode $D^0\pi^+$ from CDF (right)*

3 $\mathbf{B_s^{**}}$

For the B_s^{**} or B_{sJ} states the same structure of two narrow and two broad states as for the B^{**} is expected. The d quark in the B^{**} is just replaced by an s quark. Because the decay $B_s^{**} \to B_s\pi$ violates isospin conservation the B_s^{**} dominantly decays to $B^{(*)+}K^-$. Like in the B^{**} analyses the photon from the B^{*+} decay is not detected which leads to a shift of about 46 MeV/c^2 in the reconstructed mass. DØ uses a sample of 16k $B^+ \to J/\psi K^+$ while CDF uses 31k $B^+ \to J/\psi K^+$ and 27k $B^+ \to D^0\pi^+$. Fig. 2 shows the Q distribution from both experiments for 1 fb^{-1} of data.

The signal measured by DØ is the first direct observation of the B_{s2}^* state [5]. It is confirmed by CDF [6] and the extracted masses of $m(B_{s2}^*) = 5839.1 \pm 1.4 \pm 1.5\,\mathrm{MeV/c^2}$ (DØ) and $m(B_{s2}^*) = 5839.64 \pm 0.30 \pm 0.14 \pm 0.5\,\mathrm{MeV/c^2}$ (CDF), where the last error is due to the uncertainty of the B^+ mass [7], are in good agreement. In addition CDF observes for the first time the B_{s1} state and measures its mass as $m(B_{s1}) = 5829.41 \pm 0.21 \pm 0.14 \pm 0.6$ MeV/c^2.

As can be seen in Fig. 2 there is no peak in the background of wrong sign charge combinations. The significance of the B_{s1} signal was evaluated with toy experiments to be well above five standard deviations.

4 $\mathbf{B_c}$

The B_c is an extraordinary particle because it is the only meson with two distinct heavy quarks. However, experimentally it is challenging because its production rate is about three orders of magnitude smaller than the rate of

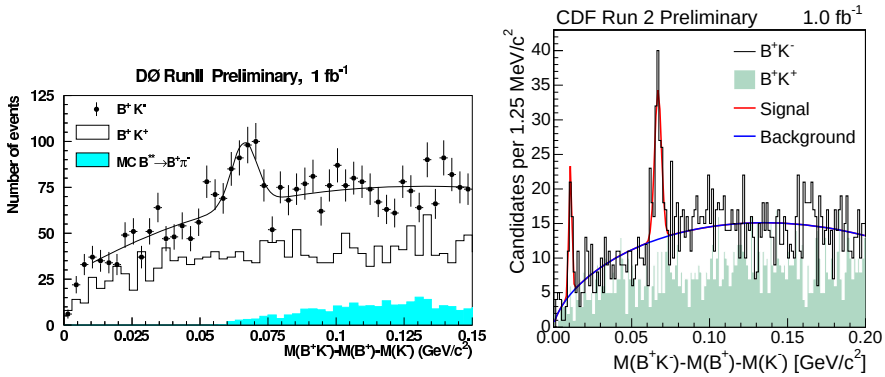

Figure 2: *Q value distribution of B_s^{**} candidates from DØ (left) and from CDF (right).*

B^+ or B^0. It was first observed by DØ and CDF in semileptonic decays. Due to the inclusive reconstruction the precision of the B_c mass measurement was limited.

Therefore CDF looks in 1.1 fb^{-1} of data for fully reconstructed $B_c^+ \to J/\psi\pi^+$ [8]. With selection cuts optimized on the kinematically very similar high statistics $B^+ \to J/\psi K^+$ sample an excess with a significance of more than six standard deviations is observed in the invariant mass spectrum (Fig. 3). An unbinned fit yields a mass of $m(B_c) = 6276.5 \pm 4.0 \pm 2.7$ MeV/c^2. The precision of this measurement challenges theoretical calculations like the recent lattice QCD prediction [9] of $m(B_c) = 6304 \pm 12^{+18}_{-0}$ MeV/c^2.

5 η_b

While the $b\bar{b}$ vector mesons are well known the pseudo-scalar $b\bar{b}$ state, the η_b, is not observed yet. CDF searches for this last missing meson ground state in the decay channel $\eta_b \to J/\psi J/\psi$ [10]. This mode has an experimentally clean signature but on the other hand the predicted branching ratio is low [11]. Only 0.2 to 20 visible events are expected per fb^{-1}.

With cuts optimized for a search no significant signal is observed in the $J/\psi J/\psi$ mass spectrum (Fig. 4 left). Therefore a limit is determined with tighter cuts to ensure well understood efficiencies (Fig. 4 middle and right). The 95% confidence level limit on the visible η_b cross section times branching ratio relative to inclusive J/ψ from b decays is $\sigma(p\bar{p} \to \eta_b X; |y(\eta_b)| <$

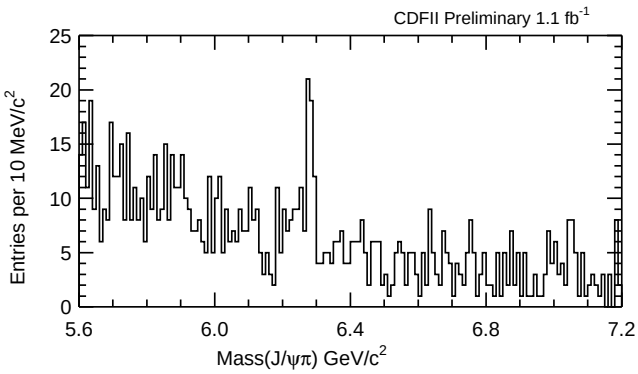

Figure 3: *Invariant mass spectrum of B_c candidates from CDF.*

$0.6, p_T(\eta_b) > 3.0$ GeV/c) $\cdot BR(\eta_b \to J/\psi J/\psi)/\sigma(p\bar{p} \to b \to J/\psi X; |y(J/\psi)| < 0.6, p_T(J/\psi) > 3.0$ GeV/c) $< 5.0 \times 10^{-3}$. Using the $b \to J/\psi X$ cross section measurement [12] this translates into $\sigma(p\bar{p} \to \eta_b X; |y(\eta_b)| < 0.6, p_T(\eta_b) > 3.0$ GeV/c) $\cdot BR(\eta_b \to J/\psi J/\psi) \cdot [BR(J/\psi \to \mu\mu)]^2 < 2.6$ pb.

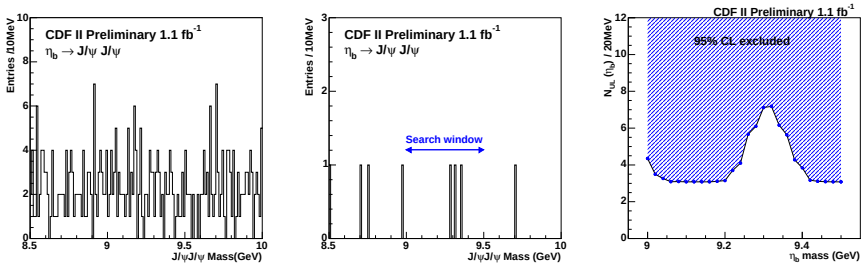

Figure 4: *Invariant mass spectrum of η_b candidates with cuts for a search (left) and for a limit determination (middle) and limit on the number of η_b particles (right).*

6 Λ_b

In the spectator model the lifetime of the Λ_b is expected to be equal to the lifetime of the B^0. When interactions between the weakly decaying b quark and

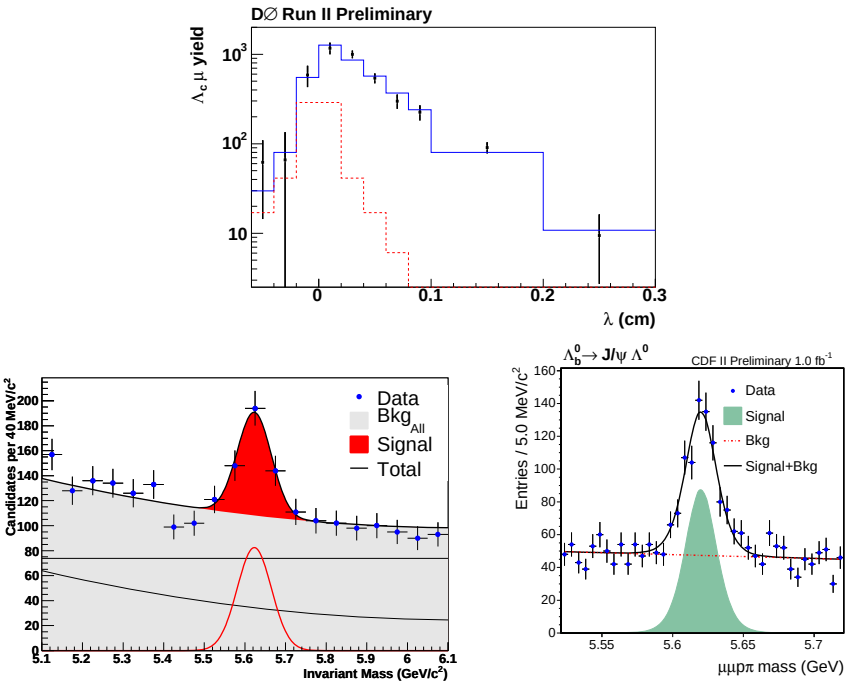

Figure 5: *Visible proper decay length distribution of* $\Lambda_b^0 \to \Lambda_c^+ \mu^- X$ *candidates from DØ (top) and invariant mass spectrum of fully reconstructed* Λ_b *candidates from DØ (bottom left) and CDF (bottom right).*

the spectator quarks are taken into account NLO QCD calculations predict a 10% to 20% lower lifetime for Λ_b [13].

DØ measures in 1.3 fb^{-1} of data the Λ_b lifetime in the semileptonic decay mode $\Lambda_b^0 \to \Lambda_c^+ \mu^- X$ with $\Lambda_c^+ \to K_s^0 p$ [14]. From a fit to the visible proper decay length (Fig. 5 top) which takes into account the missing momentum and a contribution from $c\bar{c}$ events, a lifetime of $\tau(\Lambda_b) = 1.28^{+0.12}_{-0.11} \pm 0.09$ ps is extracted.

Both Tevatron experiments also measure the Λ_b lifetime in fully reconstructed decays $\Lambda_b^0 \to J/\psi \Lambda^0$ [15, 16]. As a cross check the B^0 lifetime was measured in a high statistics sample of kinematically similar $B^0 \to J/\psi K_s^0$ decays and the results are in good agreement with the world average. With a sample of 170 Λ_b baryons (Fig. 5 bottom left) DØ measures in 1.2 fb^{-1} of data a lifetime of $\tau(\Lambda_b) = 1.298 \pm 0.137 \pm 0.050$ ps. Both DØ measurement

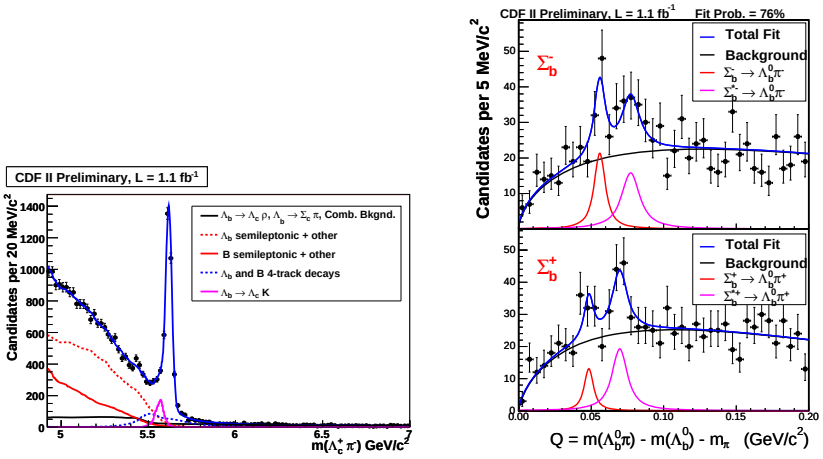

Figure 6: *Invariant mass spectrum of* $\Lambda_b^0 \to \Lambda_c^+\pi^-$ *candidates (left) and Q value distribution of* $\Sigma_b^{(*)}$ *candidates from CDF (right).*

agree well with the 2006 world average of 1.230 ± 0.074 ps and with the NLO QCD calculations. Using 500 Λ_b particles in 1 fb^{-1} (Fig. 5 bottom right) CDF measures a lifetime of $\tau(\Lambda_b) = 1.59 \pm 0.08 \pm 0.03$ ps. This result is 3.2 standard deviations above the world average and consistent with the DØ result in the same decay channel at a level of 1.7 standard deviations.

7 Σ_b

So far the Λ_b was the only directly observed b baryon. At an about 200 MeV/c^2 higher mass the next b baryon is expected, the Σ_b, an isospin 1 particle with a b and two light quarks. The mass splitting between the spin 3/2 Σ_b^* and the spin 1/2 Σ_b ground state is predicted to be 10 to 40 MeV/c^2.

Using 3000 fully reconstructed hadronic decays $\Lambda_b^0 \to \Lambda_c^+\pi^-$ with $\Lambda_c^+ \to pK^-\pi^+$ (Fig 6 left) CDF searches for charged $\Sigma_b^{(*)}$ in the decay mode $\Sigma_b^{(*)\pm} \to \Lambda_b^0\pi^{\pm}$ [17]. After unblinding the signal region four peaks with a significance of more than five standard deviations are observed (Fig 6 right). The measured masses of $m(\Sigma_b^-) = 5816^{+1.0}_{-1.0} \pm 1.7$ MeV/c^2, $m(\Sigma_b^+) = 5808^{+2.0}_{-2.3} \pm 1.7$ MeV/c^2, $m(\Sigma_b^{*-}) = 5837^{+2.1}_{-1.9} \pm 1.7$ MeV/c^2 and $m(\Sigma_b^{*+}) = 5816^{+1.6}_{-1.8} \pm 1.7$ MeV/c^2 are consistent with the theoretical predictions.

8 Summary

The Tevatron allows a broad spectrum of very competitive or even unique studies of B states. Among the impressive results of the DØ and CDF collaborations are the most precise mass measurements of B^{**}, B_s^{**}, B_c and Σ_b. Moreover, the individual B_s^{**} states and the Σ_b baryon were observed for the first time. With an increasing amount of collected data further improvements of the precision, which may for example resolve the discrepancy in the measured Λ_b lifetime, can be expected. Also new discoveries or limits challenging theoretical predictions, one candidate being the η_b, can be anticipated.

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