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B spectroscopy at the Tevatron

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We present the latest results on B hadron spectroscopy from the CDF and DØ experiments at the Tevatron. Both experiments have observed the B_c^- meson in the $B_c^- \to J/\psi\pi^-$ decay, and measured its mass. Also, CDF and DØ have reported the observation of excited B_s mesons and the first direct observation of the Ξ_b^- and Ω_b^- baryons.

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1. Introduction

An important part of the physics program of the Tevatron experiments, CDF [1] and DØ [2], is the observation and measurement of b-hadron properties. For this matter the Tevatron is an excellent place to study b-hadron physics since all species (B^-, B^0, B_s, B_c^-, Λ_b, *etc.* [1]) are produced in large quantities. However, level of background due to the total inelastic cross section in $p\bar{p}$ collisions compared to the cross section of $b\bar{b}$ is huge as well. This leads to the necessity for dedicated triggers to select a higher purity of b events, as well as the use of multivariate techniques to discriminate signal from background at the analysis level.

In this contribution, the observation of the B_c^- meson in a fully decay channel is reported, as well as the measurement of its mass. In addition, the first observations of excited B_s mesons, and the Ξ_b^- and Ω_b^- baryons are presented.

2. B_c mass measurement

The B_c^- is a special meson in which two heavy quarks, c and b, are combined to make a particle. Both quarks can decay weakly and in fact the measured lifetime [3] of the B_c^- is of a short nature, more a c-like meson lifetime than a b-like. This makes the reconstruction of this meson experimentally challenging, and in addition to its short lifetime, its production rate is very low, making even more difficult to obtain sufficient statistics to measure its properties.

To measure the B_c^- mass, CDF and DØ have reconstructed this meson in the exclusive decay channel $B_c^- \to J/\psi\pi^-$, follow by $J/\psi \to \mu^+\mu^-$. Both experiments optimize the B_c^- selection on data using $B^- \to J/\psi K^-$ decays, which has a similar topology to $B_c^- \to J/\psi\pi^-$. Figure 1 shows the invariant mass distribution of $J/\psi\pi^-$ decays reconstructed in CDF and DØ experiments. In a dataset corresponding to 1.3 fb^{-1} of integrated luminosity DØ has observed [4] a B_c^- signal with a significance higher than five standard deviations above background, and has measured its mass to be $M(B_c^-) = 6300 \pm 14$ (stat) ± 5 (syst) MeV/c^2.

CDF reconstructs [5] the B_c^- meson in a dataset corresponding to an integrated luminosity of 2.4 fb^{-1}. A signal of 108 ± 15 candidates is observed, with a significance that exceeds 8σ. The mass of the B_c^- meson is measured to be 6275.6 $\pm$ 2.9 (stat.) $\pm$ 2.5 (syst.) MeV/c^2.

3. Excited B_s mesons

Quark models predict the existence of four P-wave ($L = 1$) states in the $\bar{b}s$ system: two broad resonances (B_{s0}^* and $B_s^{'}$) and two narrow resonances (B_{s1} and B_{s2}^*) [6, 7]. The narrow B_s excited resonances are commonly called as B_s^{**} and they are shown in Fig. 2. The B_s^{**} resonances decay via D-wave processes ($L = 2$), and if the mass of the B_{sJ} ($J = 1,2$) is large enough, the main decay channel should be $B_{sJ} \to B^*K$, since the $B_s\pi$ channel is forbidden by isospin conservation.

The CDF and DØ experiments look for the decays $B_s^{**} \to B^{*+}K^-$ followed by $B^{*+} \to B^+\gamma$ (γ is not detected) and $B^+ \to J/\psi K^+$ (CDF and DØ) or $B^+ \to D^0\pi^+$ (CDF). The invariant mass difference $M(BK) - M(B) - M(K)$ is shown in Fig. 3. CDF measures [8] $M(B_{s1}) = 5829.4 \pm 0.2$ (stat) ± 0.6 (syst) GeV/c^2 and $M(B_{s2}^*) = 5839.6 \pm 0.4$ (stat) ± 0.5 (syst) GeV/c^2 in 1.0 fb^{-1} of

[1] Charge conjugation is always assumed.

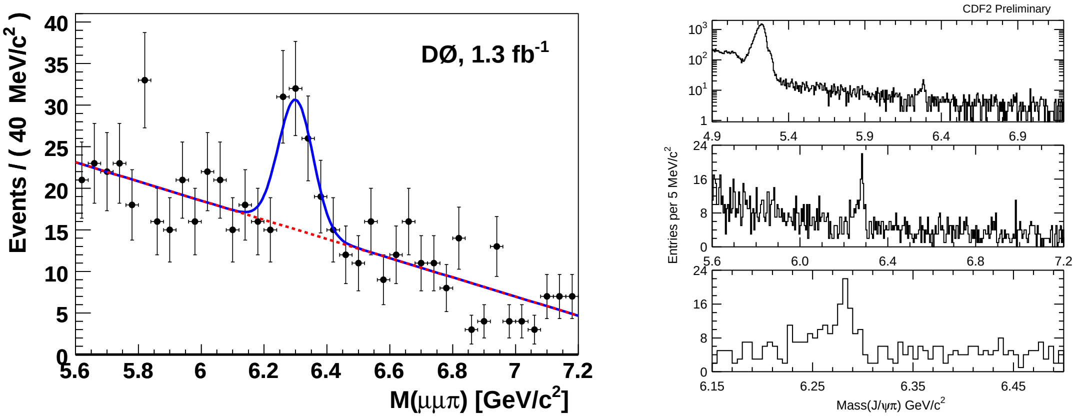

Figure 1: $J/\psi\pi$ invariant mass distribution of B_c^- candidates in D0 (left) and a projection of the unbinned maximum likelihood fit to the distribution is shown overlaid. Right plots shows the B_c^- reconstruction in CDF. Signal in three different mass regions is shown.

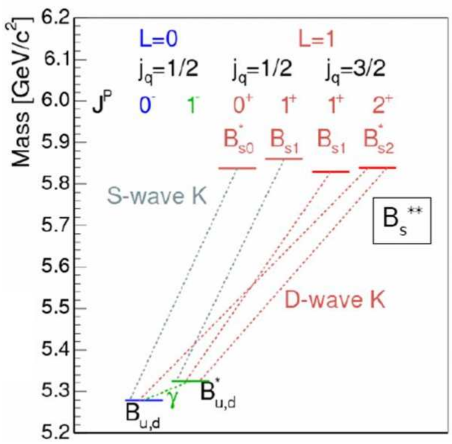

Figure 2: The spectroscopy of the $\bar{b}s$ system. J^P denotes the spin-parity of the state and L the orbital angular momentum.

data, while DØ finds [9] $M(B^*_{s2}) = 5839.6 \pm 1.1$ (stat) ± 0.7 (syst) GeV/c^2 in 1.3 fb^{-1} of integrated luminosity.

4. Ξ_b^- baryon observation

In the quark model the Ξ_b^- is formed by the combination of a b, d, and s quark, and it is expected to have $J^P = 1/2^+$ although I, J or P have yet to be measured. Evidence for the Ξ_b^- has been inferred from an excess of same sign $\Xi^\pm \ell^\pm$ events in jets which are interpreted as $\Xi_b^- \to \Xi^- \ell^- \bar{\nu}_\ell X$ [10]. From this decay mode, the average lifetime of the Ξ_b^- is measured to be $1.42^{+0.28}_{-0.24}$ ps [11]. These semileptonic decays of the Ξ_b^- did not allow for a mass measurement, but theoretical calculations predict the Ξ_b^- mass in the range $5.7 - 5.8$ GeV [12].

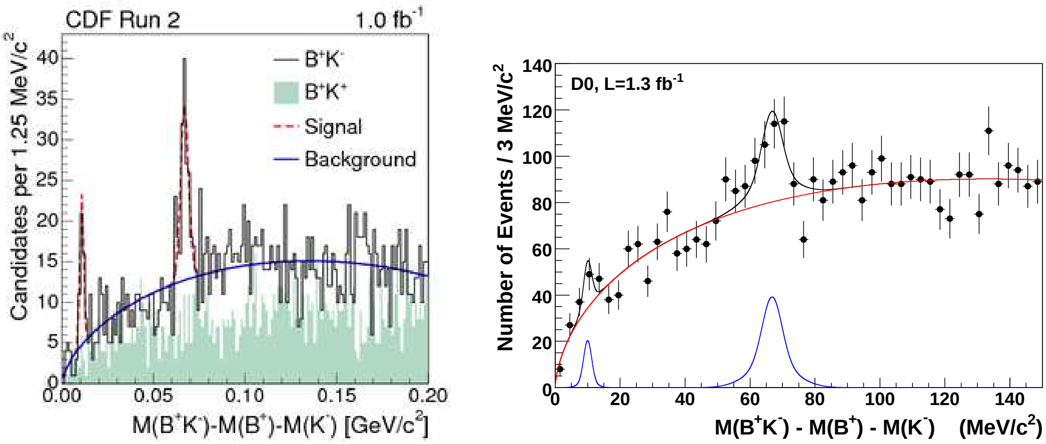

Figure 3: Invariant mass difference for the B_s^{**} candidates in DØ (right) and CDF (left).

The CDF and DØ experiments searched for the Ξ_b^- baryon in the decay channel $\Xi_b^- \to J/\psi\Xi^-$, followed by $J/\psi \to \mu^+\mu^-$, and $\Xi^- \to \Lambda\pi^-$, where Λ decays to $p\pi^-$. DØ optimizes selection criteria based on signal Monte Carlo events and background from wrong-sign combination events $J/\psi(\Lambda\pi^+)$, while CDF optimizes based on $B^- \to J/\psi K^-$ decays. Figure 4 shows the Ξ_b^- observation in DØ data. Different cross-checks such as trying to reconstruct the signal by using sideband events from J/ψ and Ξ^- signals, or from wrong-sign combinations ($J/\psi(\Lambda\pi^+)$), are performed to make sure that the observed signal is not due to artifacts of the analysis. In a data sample of 1.3 fb^{-1} of integrated luminosity DØ collaboration observes [13] 15.2 ± 4.4 Ξ_b^- events and measures the Ξ_b^- mass to be 5.774 ± 0.011 (stat.) ± 0.015 (syst.) GeV/c^2. DØ also determines its $\sigma \times \mathscr{B}$ relative to that of the Λ_b to be 0.28 ± 0.09 (stat.)$^{+0.09}_{-0.08}$ (syst.). The statistical significance of the signal was found to be 5.5σ.

The CDF experiment observes [14] 17.5 ± 4.3 Ξ_b^- signal events with mass of 5792.9 ± 2.5(stat) $\pm$ 1.7(syst) MeV/c^2, and a signal significance of 7.7σ. These events are reconstructed in a data sample of 1.9 fb^{-1} of integrated luminosity. An updated measurement of the Ξ_b^- mass from CDF was presented in this conference [21].

5. Ω_b^- baryon observation

In the quark model the Ω_b^- is composed of a b quark and two s quarks. Nothing is experimentally known about this particle, but it is expected to have $J^P = 1/2^+$, a mass between 5.94 – 6.12 GeV/c^2 and a lifetime such that $0.55 < \tau(\Omega_b^-)/\tau(B^0) < 1.10$ [15].

The CDF and DØ have searched for the Ω_b^- in the decay channel $\Omega_b \to J/\psi\Omega^-$ followed by $J/\psi \to \mu^+\mu^-$, $\Omega^- \to \Lambda K^-$ and $\Lambda \to p\pi^-$. DØ reconstructs $\Omega_b^- \to J/\psi\Omega^-$ decays in the same data in which the Ξ_b^- is observed. A similar procedure to the reconstruction of $\Xi_b^- \to J/\psi\Xi^-$ decays is applied, but in the $\Omega^- \to \Lambda K^-$ reconstruction, kinematic variables associated with daughter particle momenta, vertices, and track qualities are combined using Boosted Decision Trees (BDT) [16, 17]. The ΛK^- mass distribution before and after the BDT selection is shown in Fig. 6. A blind optimization for the $J/\psi + \Omega^-$ combinations is performed by using signal Monte Carlo events compared

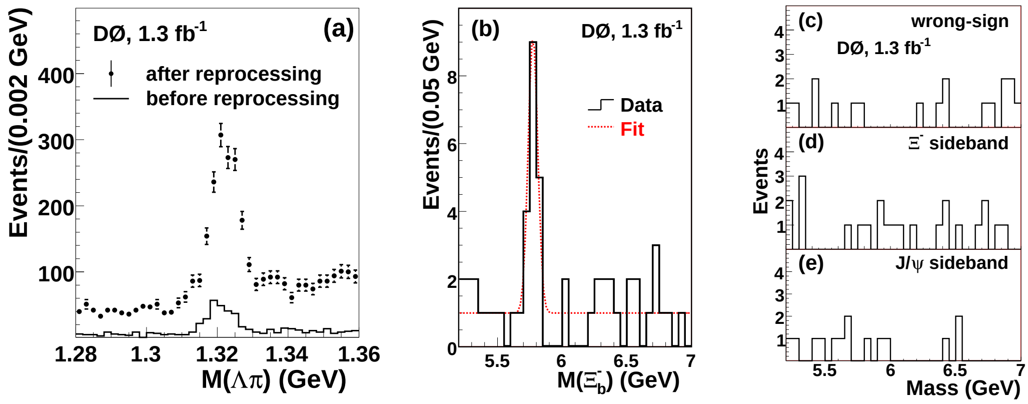

Figure 4: Ξ_b^- observation in DØ . (a) Invariant mass distributions of the $\Lambda\pi^-$ pair before and after data reprocessing. The reprocessing significantly increases the Ξ^- yield. (b) The $M(\Xi_b^-)$ distribution of the Ξ_b^- candidates after all selection criteria. The dotted curve is an unbinned likelihood fit to the model of a constant background plus a Gaussian signal. The $(\mu^+\mu^-)\Lambda\pi$ mass distributions for (c) the wrong-sign background, (d) the Ξ^- sideband, and (e) the J/ψ sideband events. The mass $M(J/\psi\,\Lambda\pi) - M(\mu^+\mu^-) + M_{\text{PDG}}(J/\psi)$ is plotted for (c) and (d) while the mass $M(\mu^+\mu^-\Xi^-) - M(\Lambda\pi^-) + M_{\text{PDG}}(\Xi^-)$ is plotted for (e).

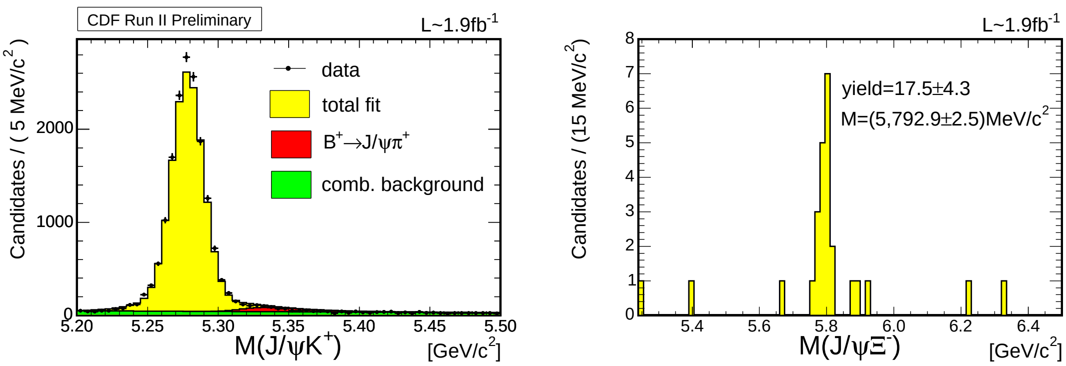

Figure 5: Ξ_b^- reconstruction in CDF. $B^- \to J/\psi K^-$ decays after signal optimization (left), and Ξ_b^- candidates after apply selection criteria (right).

to background from wrong-sign combinations $(J/\psi + (\Lambda(p\pi^-)K^+))$. From this optimization a $p_T(J/\psi\Omega^-) > 6$ GeV criterion is imposed, in addition to a requirement that the uncertainty on the boost-corrected decay length of the Ω_b^- candidates is less than 0.03 cm.

Figure 7(a) shows the invariant mass distribution of $J/\psi + \Omega^-$ combinations. The mass is corrected event per event by calculating $M(\Omega_b^-) = M(J/\psi\,\Omega^-) - M(\mu^+\mu^-) - M(\Lambda K^-) + \hat{M}(J/\psi) + \hat{M}(\Omega^-)$. Here $M(J/\psi\,\Omega^-)$, $M(\mu^+\mu^-)$, and $M(\Lambda K^-)$ are the reconstructed masses while $\hat{M}(J/\psi)$ and $\hat{M}(\Omega^-)$ are taken from Ref. [18]. This calculation improves the mass resolution of the MC Ω_b^- events from 0.080 GeV to 0.034 GeV.

By performing an unbinned likelihood fit of a Gaussian plus a flat background to data, DØ measures [19] the Ω_b^- mass to be $6.165 \pm 0.010\,(\text{stat.}) \pm 0.013\,(\text{syst.})$ GeV. The significance of the

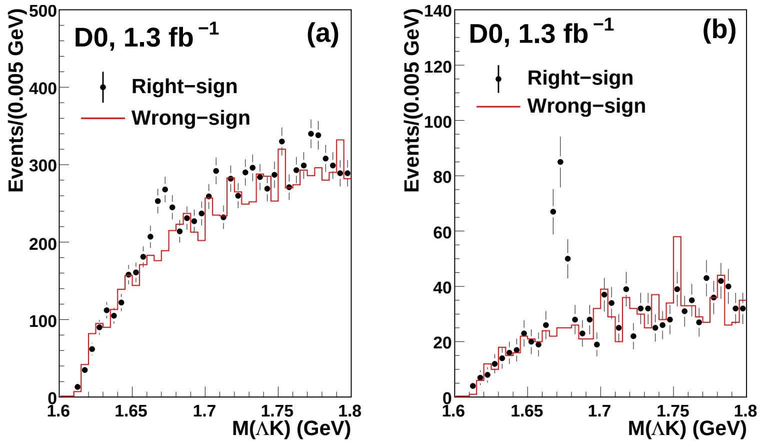

Figure 6: The invariant mass distribution of the ΛK pair before (a) and after (b) the BDT selection. Filled circles are from the right-sign ΛK^- events while the histogram is from the wrong-sign ΛK^+ events without any additional normalization.

observed signal is 5.4σ, and the number of observed events is $17.8 \pm 4.9\,(\text{stat.}) \pm 0.8\,(\text{syst.})$. In addition DØ calculates the Ω_b^- production rate relative to that of the Ξ_b^-. By using the reported Ξ_b^- events and the observed Ω_b^- yield, DØ estimates

$$\mathscr{R} = \frac{f(b \to \Omega_b^-)}{f(b \to \Xi_b^-)} \cdot \frac{Br(\Omega_b^- \to J/\psi\,\Omega^-)}{Br(\Xi_b^- \to J/\psi\,\Xi^-)}$$

to be $\mathscr{R} = 0.80 \pm 0.32\,(\text{stat.})^{+0.14}_{-0.22}\,(\text{syst.})$. Here $f(b \to \Omega_b^-)$ and $f(b \to \Xi_b^-)$ are the fractions of b quarks that hadronize to form Ω_b^- and Ξ_b^-, respectively. The systematic uncertainty includes contributions from the signal yields as well as the efficiency ratio. Using a theoretical estimate for $\Gamma(\Omega_b^- \to J/\psi\,\Omega^-)/\Gamma(\Xi_b^- \to J/\psi\,\Xi^-) = 9.8$ [20], the central values of $\tau(\Xi_b^-) = 1.42^{+0.28}_{-0.24}$ ps [18], the $\mathscr{R}$ value above, and $\tau(\Omega_b^-)$ in the range of $0.83 - 1.67$ ps [15], we obtain $f(b \to \Omega_b^-)/f(b \to \Xi_b^-) \approx 0.07 - 0.14$.

DØ performs many different cross checks to validate the observation of the Ω_b^-. Figure 7(b) shows the same analysis procedure on control samples where no signal should be present. The analysis procedure is also applied to many different b-hadron decays in Monte Carlo events with more than ten times statistics than that observed on data for each of studied decays,and no signal is found. Tighter cuts in $p_T(\Omega_b^-)$ reduces background and increases the signal significance to more than 6σ. In addition, an independent cut based analysis (no BDT used) reproduces the signal but with lower statistical significance due to the better discrimination power of the BDT in the Ω^- selection.

For the CDF Ω_b^- observation, I refers the reader to a dedicated CDF contribution to this conference [21] which presents CDF's result.

6. Conclusions

The Tevatron experiments, DØ and CDF, are performing very exciting analyses on b-hadron spectroscopy with the data accumulated during Run II of the Tevatron. Many of these results are

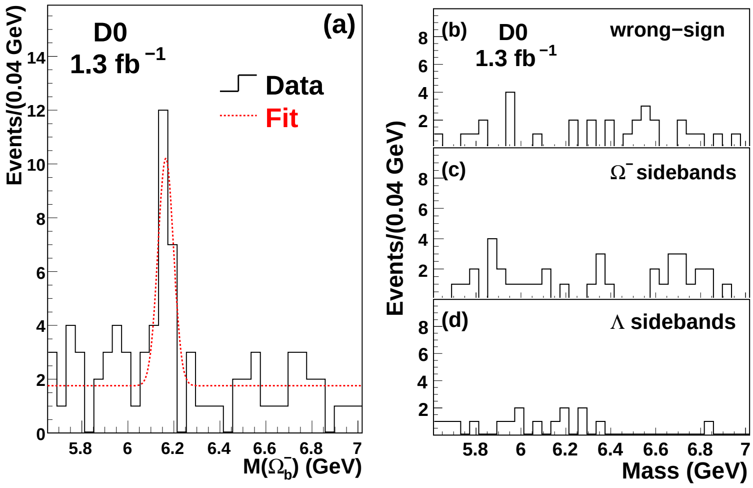

Figure 7: (a) The $M(\Omega_b^-)$ distribution of the Ω_b^- candidates after all selection criteria. The dotted curve is an unbinned likelihood fit to the model of a constant background plus a Gaussian signal. The mass distributions for the wrong-sign background (b), the Ω^- sideband events (c), and the Λ sideband events (d).

the first observations of particles like the excited B_s mesons, the Ξ_b^- and Ω_b^- baryons. In addition some properties of the b-hadrons are also measured, giving valuable information for comparisons with theoretical predictions.

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