B spectroscopy at the Tevatron

Eduard De La Cruz Burelo†
Physics Department
Centro de Investigacion y de Estudios Avanzados del IPN (CINVESTAV-IPN), Mexico City, Mexico.
E-mail: eduard@fnal.gov

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 $\Xi_b$ and $\Omega_b$ baryons.

Flavor Physics and CP Violation 2009
May 27 - June 1, 2009
Lake Placid, NY, USA

†Speaker.
†On behalf of CDF and DØ collaborations.
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 ($B^-, B^0, B_s, B_c^-, A_b$, 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 $\Xi_b^-$ and $\Omega_b^-$ 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) $\pm 5$ (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 $\pm$ 15 candidates is observed, with a significance that exceeds 8$\sigma$. 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 $b\bar{s}$ system: two broad resonances ($B_{s0}^*$ and $B_{s1}^*$) 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 $B_{sJ} K$ 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 [6, 7] $M(B_{s1}) = 5829.4 \pm 0.2$ (stat) $\pm 0.6$ (syst) $GeV/c^2$ and $M(B_{s2}^*) = 5839.6 \pm 0.4$ (stat) $\pm 0.5$ (syst) $GeV/c^2$ in 1.0 $fb^{-1}$ of

\(^1\) Charge conjugation is always assumed.
B spectroscopy at the Tevatron

Eduard De La Cruz Burelo

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 $M(B_{s2}^+) = 5839.6 \pm 1.1 \text{ (stat)} \pm 0.7 \text{ (syst)} \text{ GeV}/c^2$ in 1.3 fb$^{-1}$ of integrated luminosity.

4. $\Xi_b^-$ baryon observation

In the quark model the $\Xi_b^-$ 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 $\Xi_b^-$ has been inferred from an excess of same sign $\Xi^{\pm}\ell^\pm$ events in jets which are interpreted as $\Xi_b^- \rightarrow \Xi^- \ell^- \nu_\ell X$ [13]. From this decay mode, the average lifetime of the $\Xi_b^-$ is measured to be $1.42^{+0.28}_{-0.24}$ ps [13]. These semileptonic decays of the $\Xi_b^-$ did not allow for a mass measurement, but theoretical calculations predict the $\Xi_b^-$ mass in the range $5.7 - 5.8$ GeV [14].
The CDF and DØ experiments searched for the Ξ_b^- baryon in the decay channel Ξ_b^- → J/ψ Ξ^-, followed by J/ψ → µ^+ µ^-, and Ξ^- → Λ π^-, where Λ decays to pπ-. DØ optimizes selection criteria based on signal Monte Carlo events and background from wrong-sign combination events J/ψ(Λπ^+), while CDF optimizes based on B^- → J/ψ 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/ψ(Λπ^+)), 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 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 σ × BR relative to that of the Λ_b to be 0.28 ± 0.09 (stat.) ± 0.09 (syst.). The statistical significance of the signal was found to be 5.5σ.

The CDF experiment observes 17.5 ± 4.3 Ξ_b^- signal events with mass of 5792.9 ± 2.5(stat) ± 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 < τ(Ω_b^-) / τ(B^0) < 1.10 [15].

The CDF and DØ have searched for the Ω_b^- in the decay channel Ω_b^- → J/ψ Ω^- followed by J/ψ → µ^+ µ^-, Ω^- → Λ K^- and Λ → pπ^- . DØ reconstructs Ω_b^- → J/ψ Ω^- decays in the same data in which the Ξ_b^- is observed. A similar procedure to the reconstruction of Ξ_b^- → J/ψ Ξ^- decays is applied, but in the Ω^- → Λ 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/ψ + Ω^- combinations is performed by using signal Monte Carlo events compared
to background from wrong-sign combinations \((J/\psi + (\Lambda(p\pi^-)K^+))\). From this optimization a \(p_T(J/\psi\Omega^-) > 6 \text{ GeV}\) criterion is imposed, in addition to a requirement that the uncertainty on the boost-corrected decay length of the \(\Omega_b^-\) candidates is less than 0.03 cm.

Figure 4(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 \(\Omega_b^-\) 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 \(\Omega_b^-\) mass to be 6.165 ± 0.010 (stat.) ± 0.013 (syst.) GeV. The significance of the
observed signal is $5.4\sigma$, and the number of observed events is $17.8 \pm 4.9$ (stat.) $\pm 0.8$ (syst.). In addition DØ calculates the $\Omega_b^-$ production rate relative to that of the $\Xi_b^-$. By using the reported $\Xi_b^-$ events and the observed $\Omega_b^-$ yield, DØ estimates

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

to be $R = 0.80 \pm 0.32$ (stat.)$^{+0.14}_{-0.22}$ (syst.). Here $f(b \rightarrow \Omega_b^-)$ and $f(b \rightarrow \Xi_b^-)$ are the fractions of $b$ quarks that hadronize to form $\Omega_b^-$ and $\Xi_b^-$, respectively. The systematic uncertainty includes contributions from the signal yields as well as the efficiency ratio. Using a theoretical estimate for $\Gamma(\Omega_b^- \rightarrow J/\psi \Omega^-)/\Gamma(\Xi_b^- \rightarrow J/\psi \Xi^-) = 9.8$ [10], the central values of $\tau(\Xi_b^-) = 1.42^{+0.28}_{-0.24}$ ps [18], the $R$ value above, and $\tau(\Omega_b^-)$ in the range of $0.83 - 1.67$ ps [15], we obtain $f(b \rightarrow \Omega_b^-)/f(b \rightarrow \Xi_b^-) \approx 0.07 - 0.14$.

DØ performs many different cross checks to validate the observation of the $\Omega_b^-$. 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 $6\sigma$. 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 $\Omega^-$ selection.

For the CDF $\Omega_b^-$ observation, I refer 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 $\Omega_b$ 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 $\Omega^-$ sideband events (c), and the $\Lambda$ sideband events (d).

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

References


