Heavy Hadron Spectroscopy and Production at the Tevatron

Igor V. Gorelov[1] on behalf of the CDF and DØ Collaborations
Department of Physics and Astronomy,
University of New Mexico, MSC07 4220,
1919 Lomas Blvd. NE,
Albuquerque, NM 87131-0001, USA

Using data from $p\overline{p}$ collisions at $\sqrt{s} = 1.96\,\text{TeV}$ recorded by the CDF II and DØ detectors at the Fermilab Tevatron, we present recent results on charm and bottom hadrons. We the most recent CDF results on properties of the four bottom baryon resonant states $\Sigma_b^{(*)-}$, $\Sigma_b^{(*)+}$. New results on exotic $Y(4140)$ state observed by CDF are also reported. A precise measurement of production rates of the lowest lying bottom baryon, Λ_b^0, produced in the DØ detector is presented.

1 Measurement of the Masses and Widths of the Bottom Baryons $\Sigma_b^{(*)-}$ and $\Sigma_b^{(*)+}$ with the CDF II Detector

Baryons with a heavy quark Q as the "nucleus" and a light diquark $q_1 q_2$ as the two orbiting "electrons" are the helium atoms of QCD. The heavy quark in the baryon may be used as a probe of confinement which allows the study of non-perturbative QCD in a different regime from that of the light baryons.

A recent comprehensive review of the experimental and theoretical status of baryon spectroscopy with many useful references can be found in Ref. [1]. The resonant $\Sigma_b^{(*)}$ states have been discovered by CDF [2], and this study follows that first observation.

The $\Sigma_b^{(*)\pm}$ candidates are reconstructed in their exclusive decay modes to $\Lambda_b^0 \pi^{\pm}_{soft}$. The base state Λ_b^0 is reconstructed in its weak decay $\Lambda_b^0 \to \Lambda_c^+ \pi_b^-$ with the Λ_c^+ candidates found in the $\Lambda_c^+ \to pK^-\pi^+$ decay by fitting three tracks to a common vertex. The Λ_b^0 vertex is formed by a Λ_c^+ candidate combined with a fourth pion track, the π_b^-, having a transverse momentum above $1.5\,\text{GeV}/c$. Then the vertex is subjected to a three-dimensional kinematic fit. The Λ_b^0 signal in the invariant mass distribution $M(\Lambda_c^+\pi_b^-)$ amounts to approximately 16 300 candidates at the expected Λ_b^0 mass, with a signal to background ratio

[1] gorelov@fnal.gov

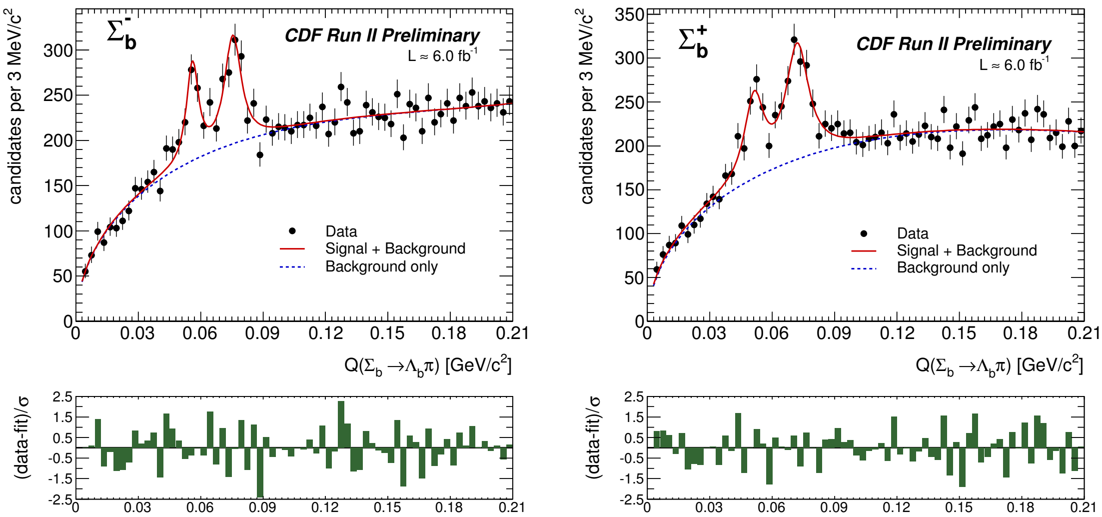


Figure 1: The Q-value spectra for $\Sigma_b^{(*)-}$ (left plot) and $\Sigma_b^{(*)+}$ (right plot) candidates, where $Q = M(\Lambda_b^0\pi^\pm) - M(\Lambda_b^0) - m_{\pi^\pm}$, are shown with the projection of the corresponding unbinned ML fit superimposed on the binned distribution. The pull distributions of the fit (bottom plots) are evenly distributed around zero with fluctuations of about a $\pm 2\sigma$ range.

around 1.8. To produce the spectra of $\Sigma_b^{(*)\pm} \to \Lambda_b^0 \pi_{soft}^\pm$ candidates, each $\Lambda_c^+\pi_b^-$ candidate from the Λ_b^0 signal region of $m(\Lambda_b^0) \in (5.561, 5.677)\,\mathrm{GeV}/c^2$ is combined with one of the tracks remaining in the event with transverse momentum above $200\,\mathrm{MeV}/c^2$ and with a pion mass hypothesis assigned. The analysis of the $\Sigma_b^{(*)\pm}$ signals is performed using the mass difference distributions $Q = m(\Lambda_b^0\pi_{soft}^\pm) - m(\Lambda_b^0) - m(\pi^\pm)$, where $m(\pi^\pm)$ is set to its world-average value [3]. The mass resolution of the $m(\Lambda_b^0 \to \Lambda_c^+\pi_b^-)$ signal and most of the systematic uncertainties cancel in the mass difference spectrum, yielding fine detector resolution in the Q-value scale. The experimental $\Sigma_b^{(*)-}$ and $\Sigma_b^{(*)+}$ Q-value distributions, each fitted with an individual unbinned maximum likelihood (ML) functions, are shown in Fig. 1. The projection of the corresponding unbinned ML fit is superimposed on each graph. The shape of the signal is modeled with a non-relativistic Breit-Wigner function convoluted with a Gaussian detector resolution. As the soft pion $\pi_{soft}^\pm$ is emitted in a P-wave, the Breit-Wigner width parameter is modified by the P-wave factor [4] $\Gamma = \Gamma_0 \cdot \left(p^*_{\pi_{soft}}/p^{*0}_{\pi_{soft}}\right)^3$. The background is described by an ordinary second order polynomial modulated by a kinematically motivated threshold factor, specifically $\sqrt{(Q+m_\pi)^2 - m_T{}^2} \cdot \mathcal{P}^2(Q; C, b_1, b_2)$. The left and right plots in Fig. 1 show clear signals of Σ_b^-, Σ_b^{*-} and Σ_b^+, Σ_b^{*+}, respectively. The significance of every peak is well above $6 \cdot \sigma$. The analysis results are arranged in Table 1.

In conclusion, the first observation [2] of the $\Sigma_b^{(*)\pm}$ bottom baryons has been confirmed.

State	Q-value, MeV/c^2	Absolute mass m, MeV/c^2	Width Γ, MeV/c^2
Σ_b^-	$56.2\,^{+0.6}_{-0.5}\,^{+0.1}_{-0.4}$	$5815.5\,^{+0.6}_{-0.5} \pm 1.7$	$4.3\,^{+3.1}_{-2.1}\,^{+1.0}_{-1.1}$
Σ_b^{*-}	$75.7 \pm 0.6\,^{+0.1}_{-0.6}$	$5835.0 \pm 0.6 \pm 1.8$	$6.4\,^{+2.2}_{-1.8}\,^{+0.7}_{-1.1}$
Σ_b^+	$52.0\,^{+0.9}_{-0.8}\,^{+0.1}_{-0.4}$	$5811.2\,^{+0.9}_{-0.8} \pm 1.7$	$9.2\,^{+3.8}_{-2.9}\,^{+1.0}_{-1.1}$
Σ_b^{*+}	$72.7 \pm 0.7\,^{+0.1}_{-0.6}$	$5832.0 \pm 0.7 \pm 1.8$	$10.4\,^{+2.7}_{-2.2}\,^{+0.8}_{-1.2}$
	Isospin mass splitting, MeV/c^2		
$m(\Sigma_b^+) - m(\Sigma_b^-)$	$-4.2\,^{+1.1}_{-0.9} \pm 0.1$		
$m(\Sigma_b^{*+}) - m(\Sigma_b^{*-})$	$-3.0 \pm 0.9 \pm 0.1$		

Table 1: Summary of the final results. For all the entries, the first uncertainty is the statistical one and the second is systematic. To extract the absolute masses, the best CDF mass measurement for Λ_b^0 [5] has been used.

The direct mass difference measurements have statistical precision a factor of $\gtrsim 2.3$ better than was previously reported [2] due to the larger dataset. The measurements are in good agreement with the previous results. The isospin mass splittings within the $I = 1$ triplets of Σ_b and Σ_b^* states have been extracted for the first time. The $\Sigma_b^{(*)-}$ states have higher mass values than their $\Sigma_b^{(*)+}$ partners following a pattern [6] common to most of the known isospin multiplets. These measurements favor the phenomenological explanation of this ordering due to higher masses of d-quarks than u-quarks and a larger electromagnetic contribution due to electrostatic Coulomb forces between quarks in $\Sigma_b^{(*)-}$ states than in the $\Sigma_b^{(*)+}$ ones. The natural widths of the $\Sigma_b^{\pm}$ and $\Sigma_b^{*\pm}$ states have been measured for the first time. The measurements are in agreement with theoretical expectations [7], within their experimental uncertainties. For further details on this analysis, please see [8].

2 Update on the $\Upsilon(4140)$ Near-Threshold Structure in $J/\Psi\phi$ Mass Spectrum of the $B^+ \to J/\Psi\phi K^+$ Decays

Recently, evidence has been reported by the CDF Collaboration for a narrow structure near the $J/\psi\phi$ threshold in exclusive $B^+ \to J/\psi\phi K^+$ decays produced in $p\overline{p}$ collisions at $\sqrt{s} = 1.96$ TeV [9]. A latest update [10] reports a preliminary confirmation of the signal in $M(J/\psi\phi)$ spectrum. The analysis is based on a larger sample of data comprising an integrated luminosity of $\sim 6\,\mathrm{pb}^{-1}$ accumulated by the CDF II detector. The specific data sample is collected by a dedicated three-level dimuon trigger recording $J/\psi \to \mu^+\mu^-$ events.

The $B^+ \to J/\psi\phi K^+$ candidates are reconstructed from $J/\psi \to \mu^+\mu^-$ candidates taken within $\pm 50\,\mathrm{MeV}/c^2$ around the mass of the J/ψ and $\phi \to K^-K^+$ candidates within a $\pm 7\,\mathrm{MeV}/c^2$ window at the ϕ mass combined further with the K^+ positive track. All five tracks are subjected to a $3D$ kinematic fit to a common vertex with $M(J/\psi)$ constrained to its PDG value.

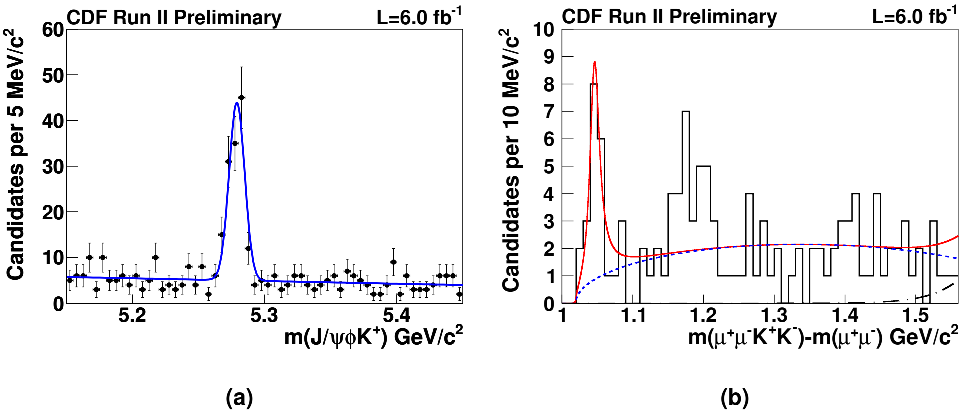


Figure 2: (a): The B^+ meson mass distribution $M(J/\psi\,\phi K^+)$ is shown with a fit to the data made with a Gaussian signal function and a linear background function. (b): The mass difference spectrum $\Delta M = M(\mu^+\mu^-K^-K^+) - M(\mu^+\mu^-)$ with the $\mu^+\mu^-K^-K^+$ combinations contained within $B^+ \to J/\psi\,\phi K^+$ candidates at $\pm 3\sigma$ around nominal $M(B^+)$ [3]; the background is predicted by the sum of the pure three-body phase space background contribution (dotted curve) and the B_s^0 meson contamination (fixed to 3.3, dash-dotted curve); the solid red curve is the total unbinned ML fit where the signal PDF is an S-wave Breit-Wigner convoluted with the resolution of $\sigma = 1.7\,\mathrm{MeV}/c^2$.

dE/dx and ToF measurements are used to identify three kaons contributing to the final state to further suppress the combinatorial background. The total transverse momentum p_T of the final candidate is required to be above $4\,\mathrm{GeV}/c$. The plot in Fig. 2a shows a prominent B^+ meson signal of $115 \pm 12\,(\mathrm{stat})$ events in the invariant mass spectrum $M(J/\psi\,\phi K^+)$. Selecting the B^+ candidates in $\pm 3\sigma$ mass range around its nominal mass the mass difference spectrum $\Delta M = M(\mu^+\mu^-K^-K^+) - M(\mu^+\mu^-)$ within final states of those B^+ candidates is examined. An enhancement near a threshold is seen at the Fig. 2b. The unbinned ML fit shown at the plot returns the signal position, width and its yield arranged in a Table 2. The fitted parameters are consistent with the previous results [9] on the $Y(4140)$ state. The p-value of the observed signal with respect to the background is determined using a statistical trials generation. It has been found to be $p \approx 2.3 \cdot 10^{-7}$ or $\approx 5.0 \cdot \sigma$ in Gaussian terms. In conclusion, the increased $B^+ \to J/\psi\,\phi K^+$ sample at CDF allows further investigation of the $Y(4140)$ structure and a preliminary observation of the signal is reported [10]. The mass and width are found to be consistent with the previous report [9].

Other experimental groups [11] [12] [13] do not confirm the observation of the $Y(4140)$ structure. Further investigation is needed and work is ongoing at CDF Collaboration to update the whole analysis on the full Run II data sample.

State	ΔM, MeV/c^2	M, MeV/c^2	Γ, MeV/c^2	N_{cands}	N_σ
$Y(4140)$	$1046.7^{+2.9}_{-3.0}$	$4143.4^{+2.9}_{-3.0} \pm 0.6$	$15.3^{+10.4}_{-6.1} \pm 2.5$	19 ± 6	$\approx 5.0 \cdot \sigma$
$\mathcal{B}(B^+ \to Y(4140)K^+) \cdot \mathcal{B}(Y(4140) \to J/\psi\,\phi)/\mathcal{B}(B^+ \to J/\psi\,\phi K^+) = 0.149 \pm 0.039 \pm 0.024$					

Table 2: Summary of the results found for the $Y(4140)$. On all the entries, the first uncertainty is the statistical one and the second is systematic. The absolute masses are extracted from the fitted ΔM and the world average $M(J/\psi)$ [3]. The measured relative branching ratio for $Y(4140)$ is presented in row 2.

3 Measurement of the Λ_b^0 Production Fraction $f(b \to \Lambda_b^0) \cdot \mathcal{B}(\Lambda_b^0 \to J/\Psi\Lambda^0)$ with the DØ Detector

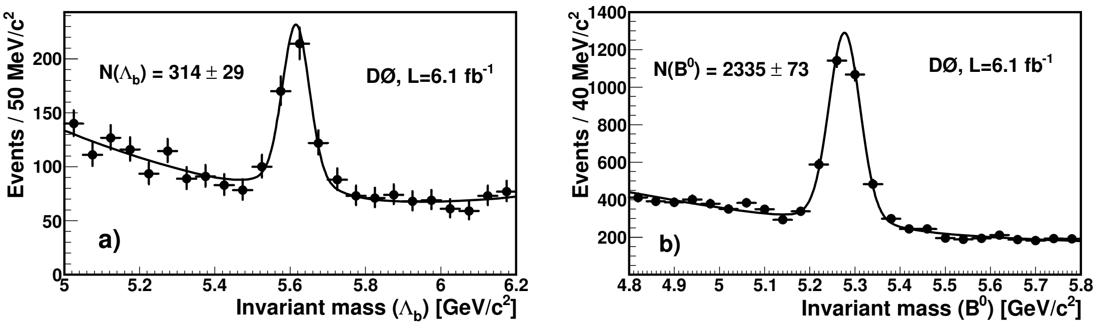
For the Λ_b^0, the lightest bottom baryon, only a few decay channels have been studied, and the uncertainties on its branching fractions are large, $\sim$ (30 − 60)%. Increasingly precise measurements of $f(b \to \Lambda_b^0) \cdot \mathcal{B}(\Lambda_b^0 \to J/\psi\,\Lambda^0)$ (where $f(b \to \Lambda_b)$ is the fraction of b quarks which hadronize to Λ_b^0 baryons) will allow better tests of models including PQCD and relativistic and nonrelativistic quark models which predict heavy baryon decays. Moreover, these measurements could help in the study of $b \to s$ transitions such as $\Lambda_b^0 \to \mu^+\mu^-\Lambda^0$ [14] [15], which are topologically similar to $\Lambda_b^0 \to J/\psi\,\Lambda^0$ where $J/\psi \to \mu^+\mu^-$.

DØ reports an improved measurement (relative to Ref. [16]) on the relative production fraction, specifically

$$\sigma_{\mathrm{rel}} = \frac{f(b \to \Lambda_b^0) \cdot \mathcal{B}(\Lambda_b^0 \to J/\psi\,\Lambda^0)}{f(b \to B^0) \cdot \mathcal{B}(B^0 \to J/\psi\,K_S^0)} = \frac{N(\Lambda_b^0)}{N(B^0)} \cdot \frac{\mathcal{B}(\Lambda_b^0 \to J/\psi\,\Lambda^0)}{\mathcal{B}(B^0 \to J/\psi\,K_S^0)} \cdot \frac{\mathcal{B}(K_S^0 \to \pi^+\pi^-)}{\mathcal{B}(\Lambda^0 \to p\pi^-)} \cdot \epsilon\,,$$

where $\epsilon = 2.37 \pm 0.05$ (MC stat.) is the relative detection efficiency of the well-measured $B^0 \to J/\psi\,K_S^0$ reference signal in denominator with respect to the $\Lambda_b^0 \to J/\psi\,\Lambda^0$ in the numerator. From this measurement one can extract $f(b \to \Lambda_b^0) \cdot \mathcal{B}(\Lambda_b^0 \to J/\psi\,\Lambda^0)$ with a significantly improved precision compared to the current world average [3]. The study is based on $\int \mathcal{L}\,dt \approx 6.1\,\mathrm{fb}^{-1}$ of $p\overline{p}$ collisions collected with the DØ detector between 2002 and 2009. The invariant mass distributions of the Λ_b^0 and B^0 candidates passing the analysis criteria are shown in Fig. 3a and Fig. 3b correspondingly. To extract the yields of the observed Λ_b^0 and B^0 hadrons, an unbinned ML fit is applied to each mass distribution assuming a double Gaussian function for each signal and a second order polynomial distribution for their backgrounds. The fits yield $N(\Lambda_b^0 \to J/\psi\,\Lambda^0) = 314 \pm 29$ events and $N(B^0 \to J/\psi\,K_S^0) = 2335 \pm 73$ events. In summary, the DØ Collaboration has obtained the production fraction multiplied by the branching fraction for the decay $\Lambda_b^0 \to J/\psi\,\Lambda^0$ relative to that for the decay $B^0 \to J/\psi\,K_S^0$ to be

$$\sigma_{\mathrm{rel}} = 0.345 \pm 0.034(\mathrm{stat}) \pm 0.033(\mathrm{syst}) \pm 0.003\,(\mathrm{PDG})\,.$$



(a) (b)

Figure 3: Invariant mass distribution in data for (a) $\Lambda_b^0 \to J/\psi\,\Lambda^0$ and (b) $B^0 \to J/\psi\,K_S^0$ decays. Fit results are superimposed.

The measurement is the most precise to date and exceeds the precision of the current value reported as the world average, 0.27 ± 0.13 [3]. Using the PDG value [3], $f(b \to B^0) \cdot \mathcal{B}(B^0 \to J/\psi\,K_S^0) = (1.74 \pm 0.08) \times 10^{-4}$, one extracts

$$f(b \to \Lambda_b^0) \cdot \mathcal{B}(\Lambda_b^0 \to J/\psi\,\Lambda^0) = [6.01 \pm 0.60(\text{stat}) \pm 0.58(\text{syst}) \pm 0.28\,(\text{PDG})] \times 10^{-5}$$

which can be compared directly to the world average value of $(4.7 \pm 2.3) \times 10^{-5}$ [3]. This result represents a reduction by a factor of ~ 3 of the uncertainty with respect to the previous measurement [16]. For further details on this analysis, please see [17].

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