D AND B MESON SPECTROSCOPY, NEW STATES, BARYONS AT THE TEVATRON

Michal Kreps on behalf of the CDF and DØ Collaborations
Universität Karlsruhe (TH), Postfach 6980, 76128 Karlsruhe, Germany

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Abstract

We review recent results in heavy quark hadron spectroscopy at the Tevatron. With increasing data samples, the Tevatron experiments start to uncover information on the spectroscopy of b-hadrons. Most important are the first observations of the narrow B_s^{**0} as well as $\Sigma_b^{\pm}$, $\Sigma_b^{*\pm}$ and Ξ_b^- baryons. In addition we present updated results on the narrow B^{**0} and B_c mesons.

1 Introduction

Heavy mesons consisting of a light quark and a heavy anti-quark form an interesting laboratory for studying QCD, the theory of strong interaction. They are a close analogue to the hydrogen atom and play a similar role for the study of QCD as hydrogen does for QED. The heavy anti-quark ($\overline{b}$ or $\overline{c}$) takes the role of the source of a static color potential, in which the light quark (u, d or s) is located. Similarly, the heavy quark baryons with a single heavy quark can in first order be viewed in the same picture, only having a light diquark in the static color field of the heavy quark. If the diquark picture isn't correct, then one would arrive at an object similar to the helium atom with a heavy quark generating the potential in which two light quarks are located. Special case is the B_c meson, which is the only one composed by two distinct heavy quarks. The interplay of the two heavy quarks, which decay through the weak interaction, is important for our understanding of decays of the heavy quark hadrons.

Heavy quark hadrons can be used to test QCD in regions where perturbation calculations cannot be used and many different approximations to solve the QCD have been developed. Just a few examples of them are heavy quark effective theory, non-relativistic and relativistic potential models or lattice QCD. While a large amount of information for c-hadrons exist[1], the spectroscopy of b-hadrons was almost unknown up to recently. In this paper we review recent measurements in the sector of heavy quark hadrons by the CDF and DØ experiments at the Tevatron collider. It is currently the only place where information about excited b-mesons and b-baryons can be obtained. Charge-conjugate modes are implied throughout this paper unless otherwise stated.

2 Mass measurement of the B_c meson

Up to recently the B_c meson was observed only in its semileptonic decay modes[2, 3]. While semileptonic decay modes have in general large branching fractions, the precision of the mass measurement is rather limited due to the undetected neutrino. With increasing amount of data at the Tevatron, search in the fully reconstructed decay modes becomes feasible. The decay mode in which the B_c search is done is $B_c \rightarrow J/\psi\pi^+$. The CDF collaboration obtained evidence for $B_c \rightarrow J/\psi\pi^+$ decay[4] using 360 pb^{-1} of data.

This measurement[5] of the $B_c \rightarrow J/\psi\pi^+$ decay is based on the data selection developed on the high statistics $B^+ \rightarrow J/\psi K^+$ decay. Its main feature is the huge background suppression at a high

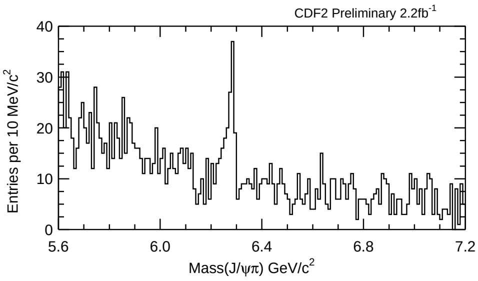

Figure 1: *Invariant mass distribution of the $B_c \to J/\psi\pi^+$ candidates observed by the CDF experiment.*

signal efficiency. After the final selection we observe around 19700 $B^+ \to J/\psi K^+$ signal events on 2.2 fb^{-1} of data. Application of the same selection on $J/\psi\pi^+$ sample yields to the invariant mass distribution shown in Fig. 1. A clear signal at a mass around 6270 MeV/c^2 is visible. To extract the mass and the number of B_c signal candidates an unbinned maximum likelihood fit is used. The signal is described by a Gaussian and the background by a empirical function. The fit returns 87 ± 13 signal events with a B_c mass of $6274.1 \pm 3.2(\text{stat}) \pm 2.6(\text{sys})$ MeV/c^2. The statistical significance exceeds 8σ. The measurement is compatible with existing predictions (see Ref.[5]), with an experimental uncertainty smaller than theory uncertainties.

3 Orbitally excited heavy quark mesons

The bound states of a heavy b anti-quark with a light u or d quark are generically referred to as B mesons. The states with a light s quark are analogous and are referred to as a B_s. The ground states with $J^P = 0^0$ and $J^P = 1^-$ are well established[1], but spectroscopy of the excited states has not been well studied. The first excited state of the B (B_s) meson is predicted to occur when a light quark has an orbital angular momentum of $L = 1$. Those states are collectively known as B^{**0} (B_s^{**0}). Combining the spin of the light quark with its orbital momentum yields two isodoublets with a total spin of light quark $J_l = 1/2$ and $J_l = 3/2$. The doublet $J_l = 1/2$ contains two states, B_0^{*0} with total spin $J = 0$ and B_1^0 with $J = 1$. The members of the doublet with $J_l = 3/2$ are B_1^0 with $J = 1$ and B_2^{*0} with $J = 2$. The $J_l = 1/2$ states decay to $B^{(*)}\pi$ via an S-wave transition. Consequently, these states are expected to be very broad and difficult to observe at the Tevatron. The $J_l = 3/2$ states decay to $B^{(*)+}\pi^-$ via a D-wave transition and are expected to be narrow. The decay $B_1^0 \to B^+\pi^-$ is forbidden by angular momentum and parity conservation, while both $B_2^{*0} \to B^+\pi^-$ and $B_2^{*0} \to B^{*+}\pi^-$ decays are allowed. The B_s^{**0} system has the same structure, except of the π^- changed to a K^- in the decay. The decay of B_s^{**0} to $B_s\pi^0$ is forbidden by isospin conservation.

Both Tevatron experiments perform studies of the narrow B^{**0} [6] and B_s^{**0} [7] states in the $B^+\pi^-$ and B^+K^- final states. The decays to B^* are included implicitly as B^* decays to $B^+\gamma$ with γ undetected in both experiments. The missing γ will shift the reconstructed mass by the mass difference between B^* and B^+. The B^+ is reconstructed in the $J/\psi K^+$ final state by both experiments. In addition, the $\overline{D}^0\pi^+$ mode is used by CDF in the B_s^{**0} search and the $\overline{D}^0 3\pi$ mode is added to the previous two for B^{**0} studies. The invariant mass difference of $B^+\pi^-$ and B^+K^- combinations obtained by CDF are shown in Fig. 2 and by DØ in Fig. 3. For the first time experiments are able to observe the two B^{**0} states as two separate peaks. The measured masses are listed in Table 1. In addition to the masses, the CDF experiment measures for the first time also the width of the B_2^{*0} state to be $\Gamma(B_2^{*0}) = 22.1^{+3.6}_{-3.1}(\text{stat})^{+3.5}_{-2.6}(\text{sys})$ MeV. Both experiments observe for the first time the B_{s2}^{*0} state with a statistical significance larger than 5σ. The CDF experiment observes in addition the B_{s1}^0 state, which wasn't seen before, with a

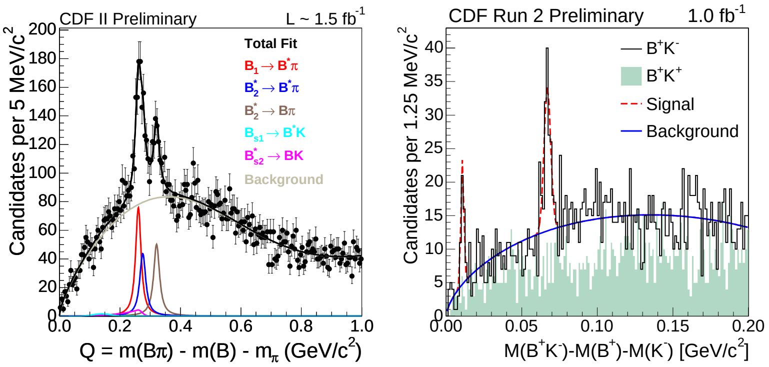

Figure 2: *Invariant mass difference distribution for* $B^+\pi^-$ *(left) and* B^+K^- *(right) combinations observed by the CDF experiment.*

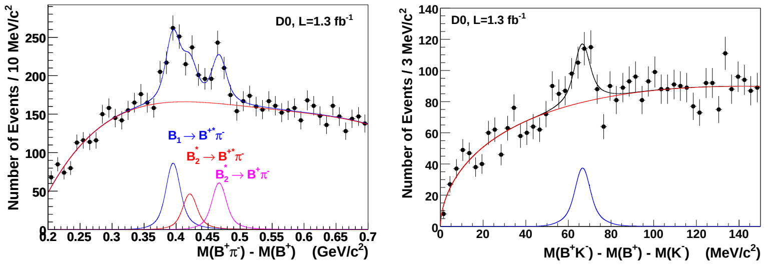

Figure 3: *Invariant mass difference distribution for* $B^+\pi^-$ *(left) and* B^+K^- *(right) combinations observed by the DØ experiment.*

statistical significance of more than 5σ.

The DØ experiment performs also a mass measurement of the $D_{s1}^-(2536)$ state[8]. The measurement is done in the context of extraction of the branching fraction of the decay $B_s \to D_{s1}^-(2536)\mu^+\nu X$. In Fig. 4 the invariant mass distribution of the $D^{*+}K_s^0$ combinations coming from semileptonic B_s decays is shown. A very clean signal is obtained, which allows for a precise mass measurement. For completeness, the branching fraction of the decay $B_s \to D_{s1}^-(2536)\mu^+\nu X$ is measured to be $\mathcal{B}(B_s \to D_{s1}^-(2536)\mu^+\nu X) = (0.86 \pm 0.16(\mathrm{stat}) \pm 0.13(\mathrm{sys}) \pm 0.09(\mathrm{ext}))\%$.

4 Observation of $\Sigma_b^\pm$ and $\Sigma_b^{*\pm}$ baryons

With increasing data samples collected at the Tevatron accelerator, searches for yet unobserved b-baryons begin to be feasible. The first of such searches was performed by the CDF experiment, which searched for the $\Sigma_b^\pm$ baryon and its spin excited partner $\Sigma_b^{*\pm}$[9]. A general theoretical expectations are the mass difference $M(\Sigma_b) - M(\Lambda_b^0) - M(\pi) = 40-70\,\mathrm{MeV}/c^2$ with $M(\Sigma_b^*) - M(\Sigma_b) = 10-40\,\mathrm{MeV}/c^2$. A small difference on the level of 5 MeV/c^2 is expected between the masses of Σ_b^+ and Σ_b^-. Both the Σ_b and the Σ_b^* are expected to be narrow with a natural width of around 8 and 15 MeV/c^2 with $\Lambda_b^0\pi$ being the dominant decay mode.

The CDF search is based on 1 fb^{-1} of data using fully reconstructed Λ_b^0 baryons. The Λ_b^0 is reconstructed in the $\Lambda_c^+\pi^-$ decay mode with $\Lambda_c^+ \to pK^-\pi^+$. In total around 3200 Λ_b signal events are reconstructed. In the sample used for the $\Sigma_b^\pm$ search 90 % of events are Λ_b^0 baryons. The search is performed for the charged $\Sigma_b^\pm$'s only, as the neutral one decays by emission of π^0, which is extremely difficult to detect at the CDF experiment.

The selected Λ_b^0 candidates are then combined with charged pions to form $\Sigma_b^\pm$ candidates. After

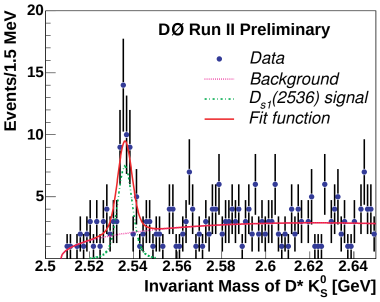

Figure 4: *Invariant mass difference distribution for* $D^{*+}K_s^0$ *combinations observed by the DØ experiment.*

Table 1: *Masses of the orbitally excited heavy quark mesons. All values are in* MeV/c^2 *with first uncertainty being statistical and second systematical.*

state	CDF	DØ
B_1^0	$5725.3^{+1.6}_{-2.1}\,^{+0.8}_{-1.1}$	$5720.6 \pm 2.4 \pm 1.4$
B_2^{*0}	$5739.9^{+1.7}_{-1.8}\,^{+0.5}_{-0.6}$	$5746.8 \pm 2.4 \pm 1.7$
B_{s1}^0	$5829.4 \pm 0.2 \pm 0.6$	-
B_{s2}^{*0}	$5839.0 \pm 0.4 \pm 0.5$	$5839.6 \pm 1.1 \pm 0.7$
$D_{s1}^-(2536)$	-	$2535.7 \pm 0.6 \pm 0.5$

choosing the selection of candidates, the background is estimated while keeping the signal region blinded. The background consists of three basic components, which are combinatorial background, Λ_b^0 hadronization and hadronization of mis-reconstructed B mesons. Relative fractions of these components are taken from the fit of the Λ_b^0 invariant mass distribution. The shape of the combinatorial background is determined using the upper sideband of the Λ_b^0 invariant mass distribution. For the hadronization of mis-reconstructed B mesons, the fully reconstructed $B^0 \to D^-\pi^+$ in the data are used. The shape of the largest component, Λ_b^0 hadronization, is determined using a PYTHIA Monte Carlo sample. The observed invariant mass difference distribution is shown in Fig. 5. To extract the signal yields and positions of the peaks, an unbinned maximum likelihood fit is performed. The data are described by a previously determined background shape together with Breit-Wigner functions convoluted with a resolution function for each peak. Due to the low statistics, difference $M(\Sigma_b^{*+}) - M(\Sigma_b^+)$ is constrained to be the same as $M(\Sigma_b^{*-}) - M(\Sigma_b^-)$. The values obtained in the fit are summarized in Table 2 and the fit projection is shown in Fig. 5.

To estimate the significance of the observed signal, the fit is repeated with an alternative hypothesis and the difference in the likelihoods is used. Three different alternative hypotheses were examined, namely the null hypothesis, using only two peaks instead of four and leaving each single peak separately out of the fit. As a result we conclude that the null hypothesis can be excluded by more than five standard deviations. The fit favors four peaks against two and except of the Σ_b^+ peak, each peak has a significance above three standard deviations.

5 Observation of the Ξ_b^- baryon

The latest state observed by the Tevatron experiments is the Ξ_b^- baryon[10], a state with quark content dsb. The mass of the Ξ_b^- is expected to be around 5.8 GeV/c^2. The decay is dominated by the weak decay of the b quark. The LEP experiments observed excess in $\Xi^- l^- \nu_l X$ events, which

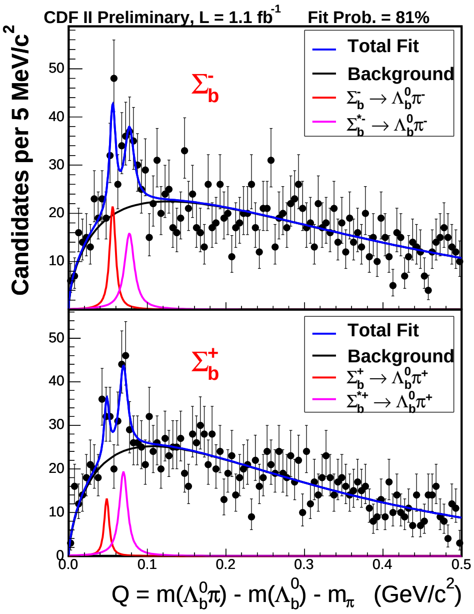

Figure 5: *Projection of the fit result of the* $\Sigma_b^\pm$ *invariant mass difference distribution. The points with error bars represent the data. The blue line corresponds to the result of the fit, the background is shown by the black line while the signals are represented by the red and magenta curves.*

was attributed to the Ξ_b baryon and the lifetime $\tau = 1.39^{+0.34}_{-0.28}$ ps was deduced[1]. Suitable decay modes for the search at the Tevatron are $\Xi_b^- \to J/\psi\Xi^-$, which can be used by both CDF and DØ and the $\Xi_b \to \Xi_c\pi$, $\Xi_b \to D\Lambda$, $\Xi_b \to \Lambda_c K\pi$ decay modes accessible at the CDF experiment. The presented search uses the decay mode $\Xi_b^- \to J/\psi\Xi^-$ which has the advantage of a J/ψ in the final state leading to clean trigger signature. A disadvantage of the used decay mode is that only the Ξ_b^- is accessible as the Ξ_b^0 contains π^0 in the decay chain.

A complication in the study of the Ξ_b^- state comes from having a Ξ in the final state, which decays through the weak interaction to Λ and π with a subsequent decay of $\Lambda \to p\pi$. As both Ξ and Λ have long lifetime, their decay vertices are significantly displaced from the production point. This requires a special treatment of the track reconstruction comparing to the usual tracks used in b-hadron studies. In addition the Ξ^- is charged and travels several centimeters in the magnetic field which adds to the complexity of the analysis as the bending of the Ξ^- is significant.

Table 2: *Result of the fit to the* Σ_b *invariant mass difference distribution.*

Parameter	Value
$Q(\Sigma_b^+)$ (MeV/c^2)	$48.5^{+2.0}_{-2.2}\,^{+0.2}_{-0.3}$
$Q(\Sigma_b^-)$ (MeV/c^2)	$55.9 \pm 1.0 \pm 0.2$
$M(\Sigma_b^*) - M(\Sigma_b)$ (MeV/c^2)	$21.2^{+2.0}_{-1.9}\,^{+0.4}_{-0.3}$
Σ_b^+ events	$32^{+13}_{-12}\,^{+5}_{-3}$
Σ_b^- events	$59^{+15}_{-14}\,^{+9}_{-4}$
Σ_b^{*+} events	$77^{+17}_{-16}\,^{+10}_{-6}$
Σ_b^{*-} events	$69^{+18}_{-17}\,^{+16}_{-5}$

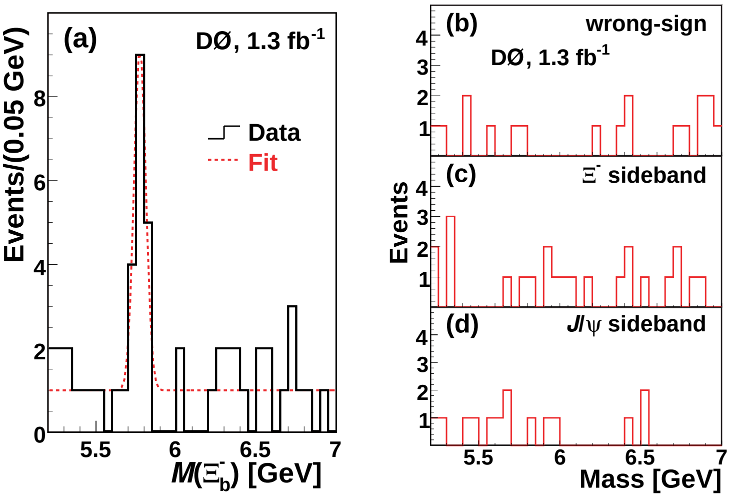

Figure 6: *Invariant mass distribution of the* Ξ_b^- *candidates observed by the DØ experiment (left) and invariant mass of the various background samples (right).*

On the other hand there is a possibility to gain in precision of the secondary vertex resolution by tracking Ξ^- in the silicon detector close to the interaction region. The CDF experiment chosed this approach, leading to improvements in the precision of the Ξ^- impact parameter measurement as well as in determination of the Ξ_b^- secondary vertex position.

Both experiments use the momenta of the Ξ_b^- candidate and its daughters, vertex quality along with the Ξ_b^- decay vertex displacement to select final candidates. The DØ experiment develops the selection based on the signal from simulated events and background from wrong-sign data. The invariant mass distribution of selected candidates is shown in Fig. 6. The CDF collaboration uses a data only approach. As the Ξ^- is tracked in the silicon detector, one can treat it as an ordinary track. In such an approach, the decay $\Xi_b^- \to J/\psi\Xi^-$ is similar to the decay $B^+ \to J/\psi K^+$. This allows to reuse the selection developed on $B^+ \to J/\psi K^+$ decays for the B_c search. The observed invariant mass distribution is shown in Fig. 7. In both experiments a clear signal with a mass slightly below 5.8 GeV/c^2 is visible.

To extract the mass and number of signal events, both experiments perform an unbinned maximum likelihood fit. They obtain the number of signal events $N_s = 14.8 \pm 4.3(\text{stat})^{+1.9}_{-0.4}(\text{sys})$ (DØ) and $N_s = 17.5 \pm 4.3(\text{stat})$ (CDF). The statistical significance of the signal is 5.2σ and 7.7σ for the DØ and CDF experiment respectively. The measured masses are $5774 \pm 11(\text{stat}) \pm 15(\text{sys})$ MeV/c^2 (DØ) and $5792.9 \pm 2.5(\text{stat}) \pm 1.7(\text{sys})$ MeV/c^2 (CDF) are in good agreement between the two experiments.

Several cross checks were done by both experiments to strengthen the interpretation of the observed signal as a Ξ_b^- state. The DØ experiment made a detailed examination of the wrong-sign combinations together with the Ξ^- and J/ψ sideband events with no signal observed in any of these (see Fig. 6). In addition the proper decay length distribution from data was compared to the one expected for a typical weakly decaying b-hadron and good consistency was observed. The CDF experiment used its unique opportunity to trigger on events with displaced vertices and searched also for the $\Xi_b^- \to \Xi_c^0\pi^-$ decay mode. Also here evidence for the signal is seen with the mass at same position as in $\Xi_b^- \to J/\psi\Xi^-$. Thus one can conclude that the observed signal is due to the $\Xi_b \to J/\psi\Xi$ decay.

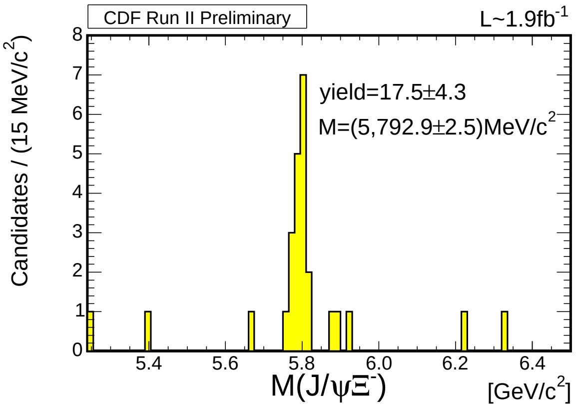

Figure 7: *Invariant mass distribution of the* Ξ_b^- *candidates observed by the CDF experiment.*

6 Conclusions

Heavy quark states provide an interesting laboratory for testing various approaches to the non-perturbative regime of QCD. The Tevatron experiments have made large effort to improve our knowledge of the b-hadrons. Roughly one and half year ago only few b-mesons were known. The B_c meson was seen only in a semileptonic decay mode with a large uncertainty on the mass measurement. Orbitally excited mesons were not observed (B_s^{**0}) or could not be seen as distinct peaks (B^{**0}). In the b-baryon sector, only Λ_b^0 was directly observed with little information on Ξ_b obtained by the LEP experiments from the excess in $\Xi^- l^- \nu_l X$ events.

Since then the effort of the CDF and DØ collaborations provided new important data. It started with the observation of fully reconstructed $B_c \to J/\psi\pi^+$ decay at CDF, which allowed for a precise mass measurement. Both experiments contributed to studies of the orbitally excited B and B_s mesons. From those studies both $J_l = 3/2$ states of the B_s^{**0} have been observed for the first time. Also the $J_l = 3/2$ states of the B^{**0} have been for the first time seen as two separate peaks. On the side of b-baryons, $\Sigma_b^\pm$ and $\Sigma_b^{*\pm}$ as well as Ξ_b^- were observed starting a new era in the study of b-baryons.

To conclude, due to the effort of the Tevatron experiments our knowledge of the b-hadrons was increased considerably, but lot of room to improve our knowledge on the properties of already observed hadrons still exists. On the side of unobserved hadrons, the next focus should be on the η_b search, the last unobserved meson containing a b quark. Also an observation of the Ξ_b^0, which should be possible at CDF, would strengthen the interpretation of the signal attributed to Ξ_b^-. Last, an observation of the Ω_b would be a nice completion of the Tevatron program on spectroscopy of b-hadrons. With more data coming and the well understood detector we believe that at least some of those searches will be successful.

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