

B States at the Tevatron

M. Paulini (representing the CDF and D0 Collaboration)

Carnegie Mellon University, Department of Physics, Pittsburgh, Pennsylvania, U.S.A.

The CDF and D0 experiments have produced a wealth of heavy flavour physics results since the beginning of Run II of the Fermilab Tevatron. We review recent measurements of B hadron states including excited B states (B^{**} , B_s^{**}) and the B_c^+ meson. We also summarize the discoveries of the Σ_b baryon states and the Ξ_b^- baryon.

1. Introduction

The past decade has seen an overwhelming amount of exciting heavy flavour physics results [1] from the e^+e^- B factory experiments BaBar and Belle as well as from the CDF and D0 experiments operating at the Tevatron $p\bar{p}$ collider. Traditionally, B physics has been the domain of e^+e^- machines operating on the $\Upsilon(4S)$ resonance or the Z^0 pole. But the UA1 Collaboration has already shown that B physics is feasible at a hadron collider environment (see for example Ref. [2]). The first signal of fully reconstructed B mesons at a hadron collider has been published by the CDF Collaboration in 1992 [3]. CDF found a handful of $B^+ \rightarrow J/\psi K^+$ events in a data sample of 2.6 pb^{-1} taken during the Tevatron Run0 at the end of the 1980's. This era was followed by a successful B physics program during the Tevatron 1992-1996 Run I data taking period (for example, for a review of B physics results from CDF in Run I see Ref. [4]). With the development of high precision silicon vertex detectors, the study of B hadrons has become an established part of the physics program at hadron colliders including the future LHC experiments Atlas and CMS or the dedicated B physics experiment LHCb.

In many cases, the measurements performed at the Tevatron Collider are complementary to the B factories. In particular, all B hadron states are produced at the Tevatron. Besides the neutral B^0 and the charged B^+ which are the only products at the $\Upsilon(4S)$ resonance, the Tevatron is also the source of B mesons containing s - or c -quark: B_s^0 and B_c^- . In addition, baryons containing bottom quarks such as the Λ_b^0 , Ξ_b^- or Σ_b^- are produced at the Tevatron. An additional bonus of B physics measurements at the Tevatron is the enormous cross section for b quark production in $p\bar{p}$ collisions. The cross section for the production of $B^0\bar{B}^0$ or B^+B^- pairs at the $\Upsilon(4S)$ resonance is about 1 nb, while $\sigma(p\bar{p} \rightarrow b)$ is, with $\sim 20 \mu\text{b}$ in the central detector region, several orders of magnitude larger.

In this review we discuss recent results on B hadron states from the Fermilab Tevatron. After an introduction of the Tevatron Collider and the CDF and D0 experiments in Sec. 2, we summarize the spectroscopy of excited B states (B^{**} , B_s^{**}) and discuss the B_c^- meson in Sec. 3. In Section 4 we report about the recent discoveries of the Σ_b baryon states and the Ξ_b^- baryon.

Other interesting B physics topics from the Tevatron have been presented at this conference in Ref. [5–7]

2. Experimental Equipment

With a centre-of-mass energy of 1.96 TeV, the Fermilab Tevatron operates in Run II with a bunch crossing time of 396 ns generated by 36×36 $p\bar{p}$ bunches. The luminous region of the Tevatron beam has an RMS of ~ 30 cm along the beam-line (z -direction) with a transverse beam-width of about 25-30 μm . The initial Tevatron luminosity steadily increased from 2002 to 2008 with a peak luminosity of $31 \cdot 10^{31} \text{ cm}^{-2}\text{s}^{-1}$ reached by the Tevatron in spring 2008. The total integrated luminosity delivered by the Tevatron to CDF and D0 at the time of this conference is $\sim 4.1 \text{ fb}^{-1}$ with about 3.5 fb^{-1} recorded to tape by each collider experiment. However, most results presented in this review use about 1-3 fb^{-1} of data. The features of the CDF and D0 detectors are described elsewhere in References [9] and [8], respectively.

The total inelastic $p\bar{p}$ cross section at the Tevatron is about three orders of magnitude larger than the b quark production cross section. The CDF and D0 trigger system is therefore the most important tool for finding B decay products. First, CDF and D0 both exploit heavy flavour decays with leptons in the final state. Identification of dimuon events down to very low momentum is also possible, allowing for efficient $J/\psi \rightarrow \mu^+\mu^-$ triggers. As a consequence, both experiments are able to fully reconstruct B decay modes involving J/ψ 's. In addition, both experiments use inclusive lepton triggers designed to accept semileptonic $B \rightarrow \ell\nu_\ell X$ decays. D0 has an inclusive muon trigger with excellent acceptance, allowing the accumulation of very large samples of semileptonic decays. In addition, the CDF detector has the ability to select events based upon track impact parameter. The Silicon Vertex Trigger gives CDF access to purely hadronic B decays. This hadronic track trigger is the first of its kind operating successfully at a hadron collider. With a fast track trigger at Level 1, CDF finds track pairs in the COT with $p_T > 1.5 \text{ GeV}/c$. At Level 2, these tracks are linked into the silicon vertex detector and cuts on the track impact parameter (e.g. $d > 100 \mu\text{m}$) are applied. With these different B trigger strategies,

the Collider experiments are able to trigger and reconstruct large samples of heavy flavour hadrons.

3. B Meson States

A physicist comes typically first into contact with the discussion of states in quantum mechanics while studying the hydrogen atom. The spectroscopy of the H-atom is explained as transitions between the various energy levels of the hydrogen atom. This prime example of quantum mechanics allows to draw parallels to the spectroscopy of B hadrons. The hydrogen atom consists of a heavy nucleus in form of the proton which is surrounded by the light electron. The spectroscopy of the hydrogen atom studies the interaction between the proton and electron which is based on the electromagnetic Coulomb interaction and described through QED in its ultimate form. In analogy, a B hadron consists of a heavy bottom quark surrounded by either a light anti-quark to form a B meson or by a di-quark pair to form a bottom baryon. The interaction between the b quark and the other quark(s) in a B hadron is based on the strong interaction or Quantum Chromodynamics (QCD). It is often stated that heavy quark hadrons are the hydrogen atom of QCD. The study of B hadron states is thus the study of (non-perturbative) QCD which provides sensitive tests of potential models, HQET and all aspects of QCD including lattice gauge calculations.

3.1. Orbitally Excited B Mesons

Until a couple of years ago, excited meson states containing b quarks have not been studied well. Only the stable 0^- ground states B^+ , B^0 and B_s^0 and the excited 1^- state B^* had been firmly established. Quark models predict the existence of two wide (B_0^* and B_1^*) and two narrow (B_1^{0*} and B_2^{0*}) bound P -states [10]. The wide states decay through a S -wave and therefore have a large width of a couple of hundred MeV/c^2 , which makes it difficult to distinguish such states from combinatoric background. The narrow states decay through a D -wave ($L = 2$) and thus should have a small width of around $10 \text{ MeV}/c^2$ [11, 12]. Almost all previous observations [13, 14] of the narrow states B_1 and B_2^{0*} have been made indirectly using inclusive or semi-exclusive B decays which prevented the separation of both states and a precise measurement of their properties. In contrast, the masses, widths and decay branching fractions of these states are predicted with good precision by theoretical models [11, 12].

B_1^0 and B_2^{0*} candidates are reconstructed in the following decay modes: $B_1^0 \rightarrow B^{*+}\pi^-$ with $B^{*+} \rightarrow B^+\gamma$ and $B_2^{0*} \rightarrow B^{*+}\pi^-$ with $B^{*+} \rightarrow B^+\gamma$ as well as $B_2^{0*} \rightarrow B^+\pi^-$. In both cases the soft photon from

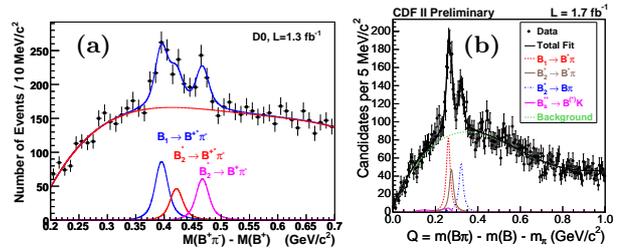


Figure 1: Result of the fit to the B^{**} mass difference (a) $\Delta m = m(B\pi) - m(B)$ from D0 and (b) $Q = m(B\pi) - m(B) - m(\pi)$ from CDF.

the B^* decay is not observed resulting in a shift of about $46 \text{ MeV}/c^2$ in the mass spectrum. D0 reconstructs B^+ candidates in the fully reconstructed mode $B^+ \rightarrow J/\psi K^+$ with $J/\psi \rightarrow \mu^+\mu^-$ while CDF selects B^+ mesons in addition through the $B^+ \rightarrow D^0\pi^+$ and $D^0\pi^+\pi^+\pi^-$ mode with $D^0 \rightarrow K^-\pi^+$. The CDF analysis [15] is based on 1.7 fb^{-1} of data resulting in a $B^+ \rightarrow J/\psi K^+$ signal of 51 500 events as well as 40 100 and 11 000 candidates in the $D^0\pi^+$ and $D^0\pi^+\pi^+\pi^-$ channel, respectively. The D0 measurement [16] employs 1.3 fb^{-1} of Run II data and finds a signal peak of $23\,287 \pm 344$ events attributed to the decay $B^+ \rightarrow J/\psi K^+$.

D0 presents their measured mass distribution as $\Delta m = m(B\pi) - m(B)$ as shown in Figure 1(a), while CDF plots $Q = m(B\pi) - m(B) - m(\pi)$ as displayed in Fig. 1(b). Clear signals for the narrow excited B states are observed: CDF reconstructs a total of about 1250 B^{**} candidates while D0 observes a total of $662 \pm 91 \pm 140$ candidates for the narrow B^{**} states. The measured masses are reported as $m(B_1^0) = (5720.6 \pm 2.4 \pm 1.4) \text{ MeV}/c^2$ and $m(B_2^{0*}) = (5746.8 \pm 2.4 \pm 1.7) \text{ MeV}/c^2$ from D0, while CDF quotes $m(B_1^0) = (5725.3^{+1.6+1.4}_{-2.2-1.5}) \text{ MeV}/c^2$ and $m(B_2^{0*}) = (5740.2^{+1.7+0.9}_{-1.8-0.8}) \text{ MeV}/c^2$. Both results are in agreement.

3.2. Orbitally Excited B_s Mesons

The properties of $|b\bar{s}\rangle$ excited meson states and the comparison with the properties of excited states in the $|b\bar{u}\rangle$ and $|b\bar{d}\rangle$ systems provides good tests of various models of quark bound states. These models [10, 11, 17] predict the existence of two wide resonances (B_{s0}^0 and B_{s1}^*) and two narrow (B_{s1}^0 and B_{s2}^{0*}) bound P -states. The wide states decay through an S -wave and therefore have a large width of a couple of hundred MeV/c^2 . This makes it difficult to distinguish such states from combinatoric background. The narrow states decay through a D -wave ($L = 2$) and therefore should have a small width of around $1 \text{ MeV}/c^2$ [12]. If the mass of the orbitally excited B_s^{**} is large enough, then the main decay channel should be through $B^{(*)}K$ as the $B_s^0\pi$ decay mode is

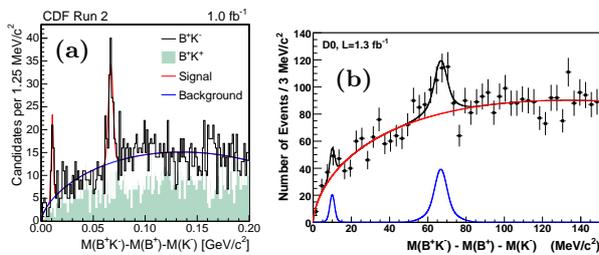


Figure 2: Result of the fit to the B_s^{**} mass difference $Q = m(BK) - m(B) - m(K)$ from (a) CDF and (b) D0.

not allowed by isospin conservation. Previous observations [13] of the narrow B_s^{**} P -states have been made indirectly preventing the separation of both states.

B_{s1}^{0*} and B_{s2}^{0*} candidates are reconstructed in the following decay modes: $B_{s1}^{0*} \rightarrow B^{*+}K^-$ with $B^{*+} \rightarrow B^+\gamma$ and $B_{s2}^{0*} \rightarrow B^{*+}K^-$ with $B^{*+} \rightarrow B^+\gamma$ as well as $B_{s2}^{0*} \rightarrow B^+K^-$. In both cases the soft photon from the B^* decay is not reconstructed resulting in a shift in the mass spectrum. D0 selects B^+ candidates in the fully reconstructed mode $B^+ \rightarrow J/\psi K^+$ with $J/\psi \rightarrow \mu^+\mu^-$ while CDF reconstructs B^+ mesons in addition through the $B^+ \rightarrow D^0\pi^+$ mode with $D^0 \rightarrow K^-\pi^+$. The CDF and D0 measurements are based on 1.0 and 1.3 fb^{-1} of Run II data, respectively. The CDF analysis [18] finds $\sim 31\,000$ $B^+ \rightarrow J/\psi K^+$ events and $\sim 27\,200$ candidates in the $B^+ \rightarrow D^0\pi^+$ channel. The D0 measurement [19] uses a signal of $20\,915 \pm 293 \pm 200$ B^+ events from the decay $B^+ \rightarrow J/\psi K^+$. Both experiments present their measured mass distribution in the quantity $Q = m(BK) - m(B) - m(K)$ as displayed in Figure 2(a) and (b).

A clear signal at $Q \sim 67$ MeV/c^2 is observed by CDF and D0 (see Fig. 2), which is interpreted as the B_{s2}^{0*} state. CDF reconstructs 95 ± 23 events in the peak at $Q = (67.0 \pm 0.4 \pm 0.1)$ MeV/c^2 while D0 reports $125 \pm 25 \pm 10$ events at $Q = (66.7 \pm 1.1 \pm 0.7)$ MeV/c^2 . In addition, CDF observes 36 ± 9 events in a peak at $Q = (10.7 \pm 0.2 \pm 0.1)$ MeV/c^2 which is the first observation of this state interpreted as B_{s1}^{0*} . A similar structure in the Q value distribution from D0 has a statistical significance of less than 3σ . The measured masses are reported as $m(B_{s2}^{0*}) = (5839.6 \pm 1.1 \pm 0.7)$ MeV/c^2 from D0, while CDF quotes $m(B_{s1}^{0*}) = (5829.4 \pm 0.7)$ MeV/c^2 and $m(B_{s2}^{0*}) = (5839.6 \pm 0.7)$ MeV/c^2 , where the statistical and systematic errors are added in quadrature. The results from CDF and D0 are in good agreement.

3.3. B_c^- Meson Properties

The B_c^- meson with a quark content $|b\bar{c}\rangle$ is a unique particle as it contains two heavy quarks that can each decay via the weak interaction. This means transitions of the b or c quark contribute to the decay width of this meson. The B_c^- decay can occur via the b quark

in a $b \rightarrow c$ transition with a J/ψ in the final state (hadronic $J/\psi X$ or semileptonic $J/\psi\ell\nu X$) or via the \bar{c} quark in a $\bar{c} \rightarrow \bar{s}$ transition with a \bar{B}_s^0 in the final state (hadronic $\bar{B}_s^0 X$ or semileptonic $\bar{B}_s^0\ell\nu X$). In addition, the $b\bar{c}$ quark pair can annihilate into a W boson with a lepton or quark pair coupling to the W for a $B_c^- \rightarrow \ell^-\bar{\nu}_\ell$ or $B_c^- \rightarrow q\bar{q}X$ transition. The decays of both heavy quarks suggest copious decay modes and an expected lifetime much shorter than that of other B mesons. The lifetime of the B_c^- meson is thus predicted from theory to be around 0.5 ps (see Ref. [7]) while a measurement of the B_c^- mass tests potential model predictions as well as lattice QCD calculations.

The mass of the B_c^- meson has been predicted using a variety of theoretical techniques. Non-relativistic potential models [20] have been used to predict a mass of the B_c^- in the range 6247-6286 MeV/c^2 , and a slightly higher value is found for a perturbative QCD calculation [21]. Recent lattice QCD determinations provide a B_c^- mass prediction of $(6304 \pm 12_{-0}^{+18})$ MeV/c^2 [22]. Precision measurements of the properties of the B_c^- meson are thus needed to test these predictions.

CDF and D0 both use fully reconstructed $B_c^- \rightarrow J/\psi(\rightarrow \mu^+\mu^-)\pi^-$ decays for a precise measurement of the B_c^- mass. CDF first published their analysis [24] where the B_c^- selection is optimized on the signal yield of $B^- \rightarrow J/\psi K^-$ and the obtained selection criteria are directly transferred to the $J/\psi\pi^-$ data for an unbiased selection. The obtained $J/\psi\pi^-$ invariant mass distribution of B_c^- candidates is shown in Figure 3. A signal of 108 ± 15 events with a significance greater than 8σ is observed. The mass of the B_c^- meson is measured to be $(6275.6 \pm 2.9 \pm 2.5)$ MeV/c^2 . To test the background reduction process, the D0 analysis [23] uses a well-understood signal sample of $B^- \rightarrow J/\psi K^-$ data. After the final selection the $J/\psi\pi^-$ invariant mass distribution of B_c^- candidates shown in Figure 4 is obtained. An unbinned likelihood fit yields a signal of 54 ± 12 events corresponding to a significance of 5.2σ . The extracted B_c^- mass value is reported as $(6300 \pm 14 \pm 5)$ MeV/c^2 . In comparison to the theoretical predictions [20-22], it is obvious that the experimental measurements, especially the CDF result with small uncertainties, start to challenge the theoretical models and lattice QCD predictions.

4. Heavy b -Baryon States

The QCD treatment of quark-quark interactions significantly simplifies if one of the participating quarks is much heavier than the QCD confinement scale Λ_{QCD} . In the limit of $m_Q \rightarrow \infty$, where m_Q is the mass of the heavy quark, the angular momentum and flavour of the light quark become good quantum numbers. This approach, known as Heavy Quark Effective Theory (HQET), thus views a baryon made

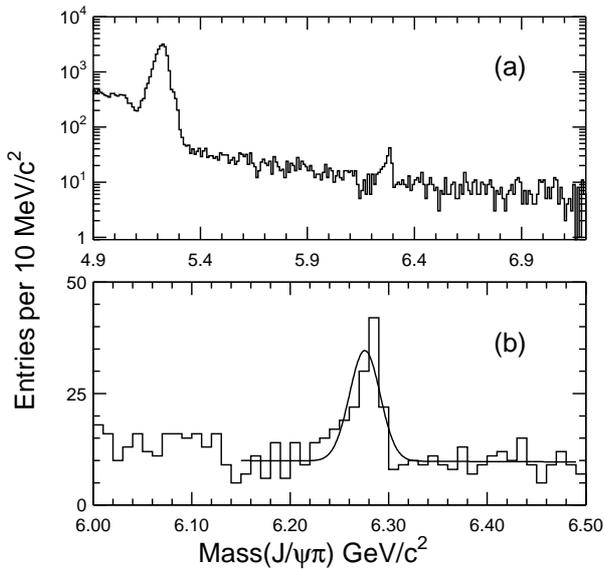


Figure 3: (a) The invariant mass distribution of $J/\psi \pi^-$ combinations from CDF. (b) Identical to (a), but in a narrower mass range around the B_c^- mass. The projection of the fit to the data is indicated by the curve overlaid in (b).

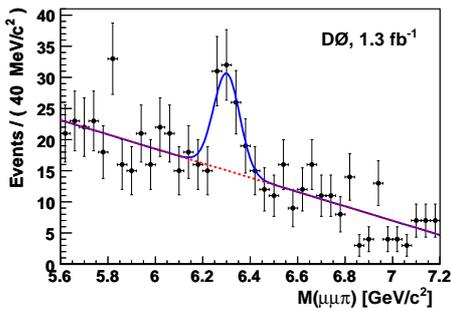


Figure 4: $J/\psi \pi^-$ invariant mass distribution of B_c^- candidates after the final D_0 selection. A projection of the unbinned maximum likelihood fit is overlaid.

out of one heavy quark and two light quarks as consisting of a heavy static color field surrounded by a cloud corresponding to the light di-quark system. In $SU(3)$ the two quarks are in di-quark form $\bar{3}$ and 6 according to the decomposition $3 \otimes 3 = \bar{3} \oplus 6$, leading to a generic scheme of baryon classification. Di-quark states containing quarks in an antisymmetric flavour configuration, $[q_1, q_2]$, are called Λ -type whereas states with di-quarks containing quarks in a flavour symmetric state, $\{q_1, q_2\}$, are called Σ -type.

4.1. Observation of Σ_b and Σ_b^* Baryons

Until recently only one bottom baryon, the Λ_b^0 , has been directly observed. The $\Sigma_b^{(*)}$ baryon has quark content $\Sigma_b^{(*)+} = |buu\rangle$ and $\Sigma_b^{(*)-} = |bdd\rangle$. In the Σ -type ground state, the light di-quark system has

isospin $I = 1$ and $J^P = 1^+$. Together with the heavy quark, this leads to a doublet of baryons with $J^P = \frac{1}{2}^+$ (Σ_b) and $J^P = \frac{3}{2}^+$ (Σ_b^*). The ground state Σ -type baryons decay strongly to Λ -type baryons by emitting pions. In the limit $m_Q \rightarrow \infty$, the spin doublet $\{\Sigma_b, \Sigma_b^*\}$ would be exactly degenerate since an infinitely heavy quark does not have a spin interaction with a light di-quark system. As the heavy quark is not infinitely massive, there will be a small mass splitting between the doublet states and there is an additional isospin splitting between the $\Sigma_b^{(*)-}$ and $\Sigma_b^{(*)+}$ states [25]. There exist a number of predictions for the masses and isospin splittings of these states using HQET, non-relativistic and relativistic potential models, $1/N_c$ expansion, sum rules and lattice QCD calculations [25, 26].

The CDF collaboration has accumulated the world's largest data sample of Λ_b^0 baryons using the CDF displaced track trigger. Using a 1.1 fb^{-1} data sample of fully reconstructed $\Lambda_b^0 \rightarrow \Lambda_c \pi^-$ candidates, CDF searches for the decay $\Sigma_b^{(*)\pm} \rightarrow \Lambda_b^0 \pi^\pm$. The CDF analysis [27] reconstructs a Λ_b^0 yield of approximately 2800 candidates in the signal region $m(\Lambda_b^0) \in [5.565, 5.670] \text{ GeV}/c^2$. To separate out the resolution on the mass of each Λ_b^0 candidate, CDF searches for narrow resonances in the mass difference distribution of $Q = m(\Lambda_b^0 \pi) - m(\Lambda_b^0) - m(\pi)$. Unless explicitly stated, Σ_b refers to both the $J = \frac{1}{2}$ (Σ_b^\pm) and $J = \frac{3}{2}$ ($\Sigma_b^{*\pm}$) states while the analysis distinguishes between $\Sigma_b^{(*)+}$ and $\Sigma_b^{(*)-}$. There is no transverse momentum cut applied to the pion from the Σ_b decay, since these tracks are expected to be very soft. The result of the $\Sigma_b^{(*)}$ search in the $\Lambda_b^0 \pi^+$ and $\Lambda_b^0 \pi^-$ subsamples is displayed in Figure 5. The top plot shows the $\Lambda_b^0 \pi^+$ subsample, which contains $\Sigma_b^{(*)+}$, while the bottom plot shows the $\Lambda_b^0 \pi^-$ subsample, which contains $\Sigma_b^{(*)-}$. The final fit results for the Σ_b measurement are summarized in Table I. The absolute Σ_b mass values are calculated using a CDF measurement of the Λ_b^0 mass [28], which contributes to the systematic uncertainty. The mass splitting $\Delta_{\Sigma_b^*}$ between Σ_b^* and Σ_b has been set in the fit to be the same for Σ_b^+ and Σ_b^- .

Table I Final results for the Σ_b measurement. The first uncertainty is statistical and the second is systematic. The absolute Σ_b mass values are calculated using a CDF measurement of the Λ_b^0 mass [28].

State	Yield	Q or $\Delta_{\Sigma_b^*}$ [MeV/ c^2]	Mass [MeV/ c^2]
Σ_b^+	32_{-12}^{+13+5}	$Q_{\Sigma_b^+} = 48.5_{-2.2-0.3}^{+2.0+0.2}$	$5807.8_{-2.2}^{+2.0} \pm 1.7$
Σ_b^-	59_{-14}^{+15+9}	$Q_{\Sigma_b^-} = 55.9 \pm 1.0 \pm 0.2$	$5815.2 \pm 1.0 \pm 1.7$
Σ_b^{*+}	77_{-16-6}^{+17+10}	$\Delta_{\Sigma_b^*} = 21.2_{-1.9-0.3}^{+2.0+0.4}$	$5829.0_{-1.8-1.8}^{+1.6+1.7}$
Σ_b^{*-}	69_{-17-5}^{+18+16}		$5836.4 \pm 2.0_{-1.7}^{+1.8}$

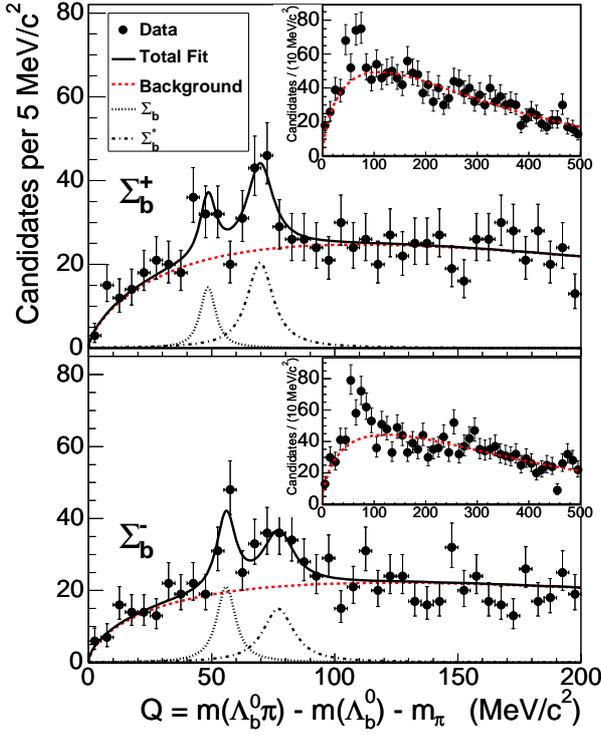


Figure 5: The $\Sigma_b^{(*)}$ fit to the $\Lambda_b^0\pi^+$ and $\Lambda_b^0\pi^-$ subsamples. The top plot shows the $\Lambda_b^0\pi^+$ subsample, which contains $\Sigma_b^{(*)+}$, while the bottom plot shows the $\Lambda_b^0\pi^-$ subsample, which contains $\Sigma_b^{(*)-}$. The insets show the expected background plotted on the data for $Q \in [0, 500]$ MeV/c^2 , while the signal fit is shown on a reduced range of $Q \in [0, 200]$ MeV/c^2 .

4.2. Observation of the Ξ_b^- Baryon

The Ξ_b baryons with a quark content of $\Xi_b^- = |bds\rangle$ and $\Xi_b^0 = |bud\rangle$ decay weakly through the decay of the b quark and are expected to have a lifetime similar to the typical B hadron lifetime of about 1.5 ps. Possible decay modes of the Ξ_b^0 include $\Xi_b^0 \rightarrow \Xi_c^0\pi^0$ or $J/\psi\Xi^0 (\rightarrow \Lambda\pi^0)$. Both decays involve the reconstruction of neutral pions which are difficult to achieve at CDF and D0. However, the Ξ_b^- can decay through $\Xi_b^- \rightarrow J/\psi\Xi^-$ followed by $\Xi^- \rightarrow \Lambda\pi^-$ with $\Lambda \rightarrow p\pi^-$ and $J/\psi \rightarrow \mu^+\mu^-$ which is the mode in which CDF and D0 search for the Ξ_b^- baryon.

A schematic of the decay topology is shown in Figure 6 from where the challenges in the Ξ_b^- reconstruction become apparent. The Ξ_b^- baryon travels an average of distance of $c\tau(\Xi_b^-) \sim 450 \mu\text{m}$ and then decays into a J/ψ and Ξ^- which has a $c\tau(\Xi^-) = 4.9 \text{ cm}$ traversing parts of the silicon detector. Furthermore, the Ξ^- decays into a Λ which has a $c\tau(\Lambda) = 7.9 \text{ cm}$ often decaying in the inner layers of the main tracker. This brings significant challenges for the reconstruction of the Ξ_b^- decay products and their track reconstruction. The D0 analysis [29] based on 1.3 fb^{-1}

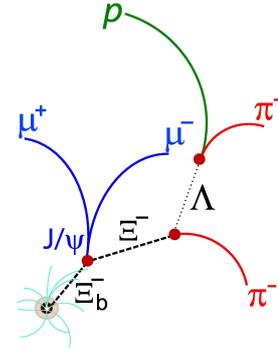


Figure 6: Schematic of the $\Xi_b^- \rightarrow J/\psi\Xi^-$ decay topology.

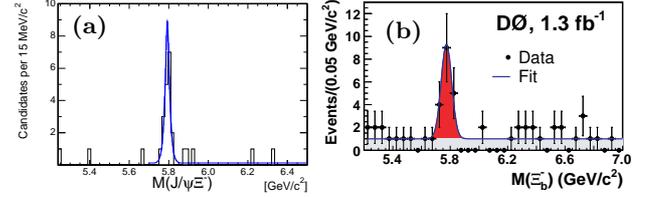


Figure 7: The $J/\psi\Xi^-$ invariant mass distribution from (a) CDF and (b) D0 that satisfy the selection requirements including fits to the data overlaid.

of data runs a special re-processing of the dimuon datasets to improve the efficiency of reconstructing high impact parameter tracks in the track pattern recognition. The event selection is based on wrong-sign data and guided by Ξ_b^- Monte Carlo events. On the other hand, CDF develops a dedicated silicon-only tracking algorithm to reconstruct the charged Ξ^- tracks in its silicon tracker. The CDF event selection [30] based on 1.9 fb^{-1} data uses a $B^- \rightarrow J/\psi K^-$ control sample where the selection criteria are developed. The K^- is then replaced in the data analysis by the Ξ^- for an unbiased event selection.

Both experiments observe significant Ξ_b^- signals as can be seen in the $J/\psi\Xi^-$ invariant mass distribution in Figure 7. D0 finds $15.2 \pm 4.4_{-0.4}^{+1.9}$ Ξ_b^- signal event with a Gaussian significance of 5.2σ and reports a mass of $m(\Xi_b^-) = (5744 \pm 11 \pm 15) \text{ MeV}/c^2$ [29]. CDF observes 17.5 ± 4.3 Ξ_b^- signal event with a Gaussian significance of 7.7σ and measures a Ξ_b^- mass of $m(\Xi_b^-) = (5792.9 \pm 2.5 \pm 1.7) \text{ MeV}/c^2$ [30]. In addition, D0 verifies that the lifetime of the Ξ_b^- candidates is compatible with a B hadron like lifetime.

5. Conclusion

We review recent result on heavy quark physics focusing on Run II measurements of B hadron states at the Fermilab Tevatron. A wealth of new B physics measurements from CDF and D0 has been available. These include the spectroscopy of excited

B states (B^{**} , B_s^{**}) and the observation of the Σ_b and Ξ_b^- baryons. During the preparation of this manuscript, D0 announced the observation of another heavy b baryon [31], the double strange Ω_b^- baryon with quark content $|bss\rangle$. With the same dataset used for the Ξ_b^- observation, D0 reconstructs $\Omega_b^- \rightarrow J/\psi\Omega^-$ followed by $\Omega^- \rightarrow \Lambda K^-$ and obtains a mass measurement of $m(\Omega_b^-) = (6165 \pm 10 \pm 13) \text{ MeV}/c^2$ based on a Ω_b^- signal of $17.8 \pm 4.9 \pm 0.8$ events corresponding to a significance of 5.4σ .

Acknowledgments

I would like to thank the organizers of this stimulating meeting, especially Elisabetta Barberio, for an excellent conference. I am grateful to my colleagues from the CDF and D0 collaboration for their help in preparing this talk. I also would like to thank my family, Ann, Emma, Helen, Tiger and Snowflake, a constant source of inspiration and support, for their continuous understanding about the life of a traveling physicist. This work was supported in part by the U.S. Department of Energy under Grant No. DE-FG02-91ER40682.

References

- 1 C. Amsler *et al.* [Particle Data Group], Phys. Lett. B **667**, 1 (2008).
- 2 N. Ellis and A. Kernan, Phys. Rept. **195** (1990) 23.
- 3 F. Abe *et al.* [CDF Collaboration], Phys. Rev. Lett. **68** (1992) 3403.
- 4 M. Paulini, Int. J. Mod. Phys. A **14** (1999) 2791 [arXiv:hep-ex/9903002].
- 5 I. Bertram, these proceedings.
- 6 J. Boudreau, these proceedings.
- 7 H. Evans, these proceedings.
- 8 V. M. Abazov *et al.* [D0 Collaboration], Nucl. Instrum. Meth. A **565**, 463 (2006) [arXiv:physics/0507191].
- 9 D. E. Acosta *et al.* [CDF Collaboration], Phys. Rev. D **71**, 032001 (2005) [arXiv:hep-ex/0412071].
- 10 E. J. Eichten, C. T. Hill and C. Quigg, Phys. Rev. Lett. **71** (1993) 4116 [arXiv:hep-ph/9308337].
- 11 D. Ebert, V. O. Galkin and R. N. Faustov, Phys. Rev. D **57**, 5663 (1998) [Erratum-ibid. D **59**, 019902 (1999)] [arXiv:hep-ph/9712318].
- 12 N. Isgur, Phys. Rev. D **57** (1998) 4041. M. Di Pierro and E. Eichten, Phys. Rev. D **64** (2001) 114004 [arXiv:hep-ph/0104208].
- 13 R. Akers *et al.* [OPAL Collaboration], Z. Phys. C **66** (1995) 19.
- 14 P. Abreu *et al.* [DELPHI Collaboration], Phys. Lett. B **345** (1995) 598. D. Buskulic *et al.* [ALEPH Collaboration], Z. Phys. C **69** (1996) 393. R. Barate *et al.* [ALEPH Collaboration], Phys. Lett. B **425** (1998) 215. A. A. Affolder *et al.* [CDF Collaboration], Phys. Rev. D **64** (2001) 072002.
- 15 T. Aaltonen *et al.* [CDF Collaboration], arXiv:0809.5007 [hep-ex].
- 16 V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. Lett. **99**, 172001 (2007) [arXiv:0705.3229 [hep-ex]].
- 17 A. F. Falk and T. Mehen, Phys. Rev. D **53** (1996) 231 [arXiv:hep-ph/9507311].
- 18 T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. Lett. **100**, 082001 (2008) [arXiv:0710.4199 [hep-ex]].
- 19 V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. Lett. **100**, 082002 (2008) [arXiv:0711.0319 [hep-ex]].
- 20 E. J. Eichten and C. Quigg, Phys. Rev. D **49**, 5845 (1994) [arXiv:hep-ph/9402210]. W. K. Kwong and J. L. Rosner, Phys. Rev. D **44**, 212 (1991). S. Godfrey, Phys. Rev. D **70**, 054017 (2004) [arXiv:hep-ph/0406228].
- 21 N. Brambilla, Y. Sumino and A. Vairo, Phys. Rev. D **65**, 034001 (2002) [arXiv:hep-ph/0108084].
- 22 I. F. Allison, C. T. H. Davies, A. Gray, A. S. Kronfeld, P. B. Mackenzie and J. N. Simone [HPQCD Collaboration and Fermilab Lattice Collaboration and UKQCD Collaboration], Phys. Rev. Lett. **94**, 172001 (2005) [arXiv:hep-lat/0411027].
- 23 V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. Lett. **101**, 012001 (2008) [arXiv:0802.4258 [hep-ex]].
- 24 T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. Lett. **100**, 182002 (2008) [arXiv:0712.1506 [hep-ex]].
- 25 J. L. Rosner, Phys. Rev. D **75** (2007) 013009 [arXiv:hep-ph/0611207].
- 26 D. P. Stanley and D. Robson, Phys. Rev. Lett. **45**, 235 (1980).
- 27 T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. Lett. **99**, 202001 (2007) [arXiv:0706.3868 [hep-ex]].
- 28 D. Acosta *et al.* (CDF Collaboration), Phys. Rev. Lett. **96**, 202001 (2006).
- 29 V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. Lett. **99**, 052001 (2007) [arXiv:0706.1690 [hep-ex]].
- 30 T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. Lett. **99**, 052002 (2007) [arXiv:0707.0589 [hep-ex]].
- 31 V. M. Abazov *et al.* [D0 Collaboration], arXiv:0808.4142 [hep-ex].