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Properties of Heavy B Hadrons

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We review recent measurements of heavy B hadron states including masses and lifetimes of the B_c^- meson as well as excited B states (B^{**}, B_s^{**}). We discuss properties of the B_s^0 meson such as lifetime, lifetime difference $\Delta\Gamma_s/\Gamma_s$ and CP violation in $B_s^0 \to J/\psi\phi$ decays. We also summarize new measurements of the masses and lifetimes of bottom baryons including the Λ_b^0 baryon, the Σ_b baryon states as well as the Ξ_b^- and Ω_b^- baryons.

1. INTRODUCTION

Hadrons containing bottom quarks can be classified according to their J^P quantum numbers. There are the ground state 0^- mesons such as the neutral $\bar{B}^0$ meson with quark content $|b\bar{d}\rangle$, the charged B^- ($|b\bar{u}\rangle$), the $\bar{B}_s^0$ ($|b\bar{s}\rangle$) and the B_c^- meson which contains a bottom and charm quark ($|b\bar{c}\rangle$). In addition, there are excited vector states with spin-1 such as the 1^- states $\bar{B}^{*0}$ ($|b\bar{d}\rangle$), B^{*-} ($|b\bar{u}\rangle$), $\bar{B}_s^{*0}$ ($|b\bar{s}\rangle$), the 1^+ states $\bar{B}_1^0$ ($|b\bar{d}\rangle$), $\bar{B}_{s1}^0$ ($|b\bar{s}\rangle$) and the $J^P = 2^+$ states $\bar{B}_2^{*0}$ ($|b\bar{d}\rangle$), $\bar{B}_{s2}^{*0}$ ($|b\bar{s}\rangle$). Also, there exist bound $|b\bar{b}\rangle$ mesons such as the $J^P = 1^-$ states $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$ and the $\Upsilon(4S)$ resonance which is the source of $\bar{B}^0/B^-$ mesons at the KEKB and PEP-II e^+e^- B factories with the Belle and *BABAR* experiments. The 0^- state η_b ($|b\bar{b}\rangle$), recently discovered at *BABAR* [1], is discussed in detail in Ref. [2] contributed to this conference.

In addition to B mesons states, there exist baryons containing b quarks. The lowest baryon state is the Λ_b^0 with quark content $|bdu\rangle$. Other bottom baryons with $J^P = 1/2^+$ are the Ξ_b^- ($|bds\rangle$) as well as the Σ_b^- ($|bdd\rangle$) and the Σ_b^+ ($|buu\rangle$) plus their $3/2^+$ excited states Σ_b^{*-} ($|bdd\rangle$) and Σ_b^{*+} ($|buu\rangle$). In this paper, a heavy B hadron is defined as all B states outlined above except for the B^0 and B^- mesons. Since the properties of $|b\bar{b}\rangle$ states are covered by another presentations at this conference [2, 3], we shall focus on B_s^0, B_c^- mesons and excited B states (generically called B^{**}, B_s^{**}) as well as bottom baryons including the Λ_b^0 baryon, the Σ_b baryon states plus the Ξ_b^- and Ω_b^-.

After defining "heavy B hadron", we explain what is meant by "properties" of B hadrons. Under properties we understand masses, lifetimes and decay properties of heavy B hadrons. This brings us to the question of "why study B hadron states"? A physicist typically first comes into contact with the discussion of states while studying the hydrogen atom in quantum mechanics. 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 us to draw parallels to the study and spectroscopy of B hadrons. The hydrogen atom consists of a heavy nucleus in the form of the proton which is surrounded by a light electron. The spectroscopy of the hydrogen atom studies the interaction between proton and electron, based on the electromagnetic Coulomb interaction. These are described by Quantum Electrodynamics in its ultimate form. In analogy, a B hadron consists of a heavy bottom quark surrounded either by a light anti-quark, to form a B meson or 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, providing sensitive tests of potential models, heavy quark effective theory (HQET) and all aspects of QCD, including lattice gauge calculations.

1.1. B Hadron Lifetimes

In the spectator model of B hadron decay, the b quark decays like a free particle. The other (anti-)quark(s) in the hadron act as pure spectators without influencing the b quark decay. In such a simple weak decay picture, the lifetimes of all B hadrons would be equal. In reality, the strong force in the form of gluons, coupling to the quarks, as well as final state interactions, influence the pure weak decay. Measurements of B hadron lifetimes thus study the

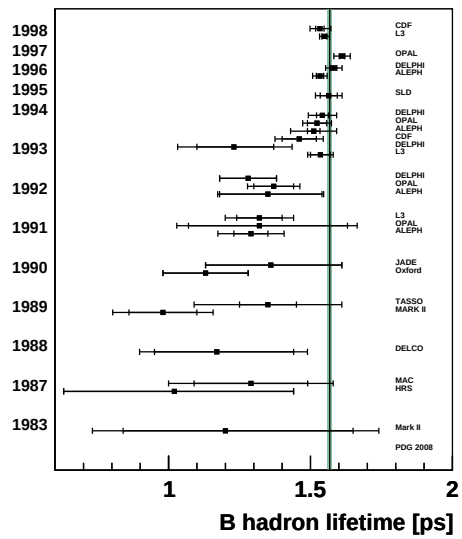

Figure 1: History of measurements of the average B hadron lifetime.

interplay between the strong and weak interaction. Predictions of B hadron lifetimes are provided in the heavy quark expansion (HQE) which in turn allows us to expand the inclusive decay width Γ_B in powers $1/m_b$ of the bottom quark mass

$$\Gamma_B \sim |V_{CKM}|^2 \sum_n c_n(\mu) \left(\frac{1}{m_b}\right)^n \langle H_b|O_n|H_b\rangle. \tag{1}$$

In HQE short distance effects contained in the Wilson coefficients $c_n(\mu)$, evaluated in perturbation theory, are separated from long distance physics represented by the matrix element $\langle H_b|O_n|H_b\rangle$ to be computed through non-perturbative QCD sum rules, operator product expansion methods or lattice QCD calculations. In HQE the order $\mathcal{O}(1/m_b^2)$ distinguishes meson versus baryon decays while spectator effects of order $\mathcal{O}(1/m_b^3)$ differentiate between the lifetimes of B^0, B^+ and B_s^0 mesons. These calculations allow for precise predictions of B hadron lifetimes where many can be found in the literature. Reference [4] only quotes a few of them. Most of these predictions can be summarized in form of the following estimates for B hadron lifetime ratios

$$\frac{\tau(B^+)}{\tau(B^0)} = 1.06 \pm 0.02, \qquad \frac{\tau(B_s^0)}{\tau(B^0)} = 1.00 \pm 0.01, \qquad \frac{\tau(\Lambda_b^0)}{\tau(B^0)} = 0.88 \pm 0.05. \tag{2}$$

Measurements of B hadron lifetimes thus test the validity of HQE, a technique which is also used to supply input for the extraction of elements of the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix.

Since history always provides guidance, Figure 1 shows the history of measurements of the average B hadron lifetime which starts with the first measurement of the average lifetime of bottom hadrons [5] in 1983. The Mark II detector measured $\tau_b = (1.20^{+0.45}_{-0.36} \pm 0.30)$ ps which is within large errors in agreement with the current average B hadron lifetime as determined by the Particle Data Group (PDG) [6]. However, Figure 1 indicates that all early measurements of bottom hadron lifetimes appear to obtain low central values compared to the current world average until the availability of precision measurements pined down the current world average. Such an effect seems to repeat itself in other B hadron lifetime measurements as we shall see later.

2. Experimental Environment

The producers of hadrons containing b quarks are currently the KEKB and PEP-II e^+e^- colliders together with the Belle and *BABAR* experiments, as well as the Fermilab Tevatron where the CDF and D0 experiments are operating.

At the Fermilab Tevatron all B hadrons are produced. Besides the B^0 and B^+ meson, which are the only bottom hadrons produced at the B factories operating at the $\Upsilon(4S)$ resonance, the Tevatron is a source for B_s^0 and B_c^- mesons as well as baryons containing b quarks such as the Λ_b^0, Σ_b or Ξ_b^-. It has been common believe that the study of B_s^0 properties is the domain of the CDF and D0 experiments operating at the Tevatron.

However, it has recently become possible to produce B_s^0 events in sufficiently large numbers in e^+e^- collisions at the $\Upsilon(5S)$ resonance which can decay into pairs of $B_s^0\bar{B}_s^0$, $B_s^{*0}\bar{B}_s^0$ or $B_s^{*0}\bar{B}_s^{*0}$. The KEKB collider operating at the $\Upsilon(5S)$ resonance at a center-of-mass energy of $\sim$10.87 GeV has delivered a dataset to the Belle detector in 2005 and 2006 totaling an integrated luminosity of (23.6 ± 0.3) fb^{-1}. From a study [7] of 161 ± 15 reconstructed decays $B_s^0 \to D_s^-\pi^+$, Belle has reported the measurement of the branching fraction $\mathcal{B}(B_s^0 \to D_s^-\pi^+) = [3.67^{+0.35}_{-0.33}\,(\text{stat.})^{+0.43}_{-0.42}\,(\text{syst.}) \pm 0.49\,(f_s)] \times 10^{-3}$, where the largest systematic error, which is due to the uncertainty in the production fraction $f_s = N_{B_s^{(*)}\bar{B}_s^{(*)}}/N_{b\bar{b}}$, is quoted separately. The obtained branching fraction is compatible with the CDF result [6, 8] and is slightly higher than $\mathcal{B}(B^0 \to D^-\pi^+)$ by $1.3\,\sigma$. In addition, Belle observes $6.7^{+3.4}_{-2.7}$ signal events from decays $B_s^0 \to D_s^\mp K^\pm$ and measures the branching ratio $\mathcal{B}(B_s^0 \to D_s^\mp K^\pm) = [2.4^{+1.2}_{-1.0}\,(\text{stat.}) \pm 0.3\,(\text{syst.}) \pm 0.3\,(f_s)] \times 10^{-4}$ with a significance of $3.5\,\sigma$.

After a successful 1992-1996 Run I data taking period of the Fermilab Tevatron (for a review of B physics results from e.g. CDF in Run I see Ref. [9]), the Tevatron operates in Run II at a centre-of-mass energy of 1.96 TeV with a bunch crossing time of 396 ns generated by 36×36 $p\bar{p}$ bunches. The initial Tevatron luminosity steadily increased from 2002 to 2008 with a peak luminosity of $> 30 \cdot 10^{31}$ cm^{-2}s^{-1} reached in 2008. The total integrated luminosity delivered by the Tevatron to CDF and D0 at the time of this conference is $\sim$4.5 fb^{-1} with about 3.7 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 [10] and [11], respectively. For the remainder of this paper, we will focus on results from the Tevatron experiments CDF and D0.

3. PROPERTIES OF B_s^0 MESONS

In the neutral B_s^0 system there exist two flavour eigenstates, the $B_s^0 = |\bar{b}s\rangle$ and $\bar{B}_s^0 = |b\bar{s}\rangle$. The time evolution of these states is governed by the Schrödinger equation

$$i\frac{d}{dt}\begin{pmatrix} |B_s^0(t)\rangle \\ |\bar{B}_s^0(t)\rangle \end{pmatrix} = \left[\mathbf{M} - \frac{i}{2}\mathbf{\Gamma}\right]\begin{pmatrix} |B_s^0(t)\rangle \\ |\bar{B}_s^0(t)\rangle \end{pmatrix} \qquad \text{with } \mathbf{M} = \begin{pmatrix} M_0 & M_{12} \\ M_{12}^* & M_0 \end{pmatrix} \quad \text{and } \mathbf{\Gamma} = \begin{pmatrix} \Gamma_0 & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_0 \end{pmatrix}, \tag{3}$$

where $\mathbf{M}$ is the mass matrix and $\mathbf{\Gamma}$ is the decay matrix. The mass eigenstates B_s^H and B_s^L are admixtures of the flavour eigenstates B_s^0 and $\bar{B}_s^0$:

$$|B_s^H\rangle = p\,|B_s^0\rangle - q\,|\bar{B}_s^0\rangle, \qquad |B_s^L\rangle = p\,|B_s^0\rangle + q\,|\bar{B}_s^0\rangle, \quad \text{with } \frac{q}{p} = \frac{V_{tb}^* V_{ts}}{V_{tb} V_{ts}^*}. \tag{4}$$

The fact that the mass eigenstates are not the same as the flavour states causes oscillations between the B_s^0 and $\bar{B}_s^0$ states with a frequency proportional to the mass difference of the mass eigenstates, $\Delta m_s = m_H - m_L \sim 2\,|M_{12}|$. In the standard model (SM) particle-antiparticle oscillations are explained in terms of second-order weak processes involving virtual massive particles that provide a transition amplitude between the B_s^0 and $\bar{B}_s^0$ states. The decay width difference between the mass eigenstates $\Delta\Gamma_s = \Gamma_L - \Gamma_H \sim 2\,|\Gamma_{12}|\cos\phi_s$ is related to the CP phase $\phi_s = \arg(-\mathrm{M}_{12}/\Gamma_{12})$. Assuming no CP violation in the B_s^0 system, which is justified in the standard model where the CP phase is expected to be small ($\phi_s^{\mathrm{SM}} \sim 0.004$ [12]), the B_s^0 mass eigenstates are also CP eigenstates where Γ_L is the width of the CP even state corresponding to the short lived state in analogy to the kaon system where the short-lived state (K_S^0) is CP even. Γ_H is the width of the CP odd state corresponding to the long lived B_s^0 state.

Thus the experimental observables describing the B_s^0 system are the masses m_H and m_L of the B_s^0 mass eigenstates accessible through a measurement of the mass difference Δm_s in B_s^0-$\bar{B}_s^0$ oscillations. Other experimental quantities are the width difference $\Delta\Gamma_s$, the total decay width $\Gamma_s = (\Gamma_H + \Gamma_L)/2 = 1/\tau_s$, which is related to the mean B_s^0 lifetime τ_s, as well as the CP phase ϕ_s.

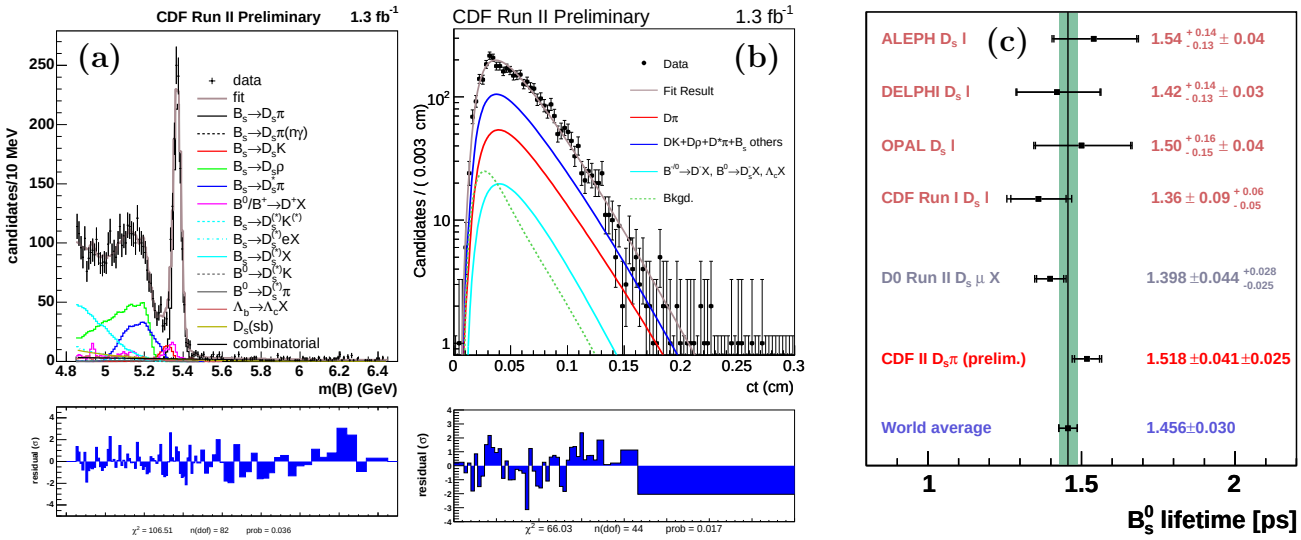

Figure 2: (a) Mass fit of events reconstructed as $B_s^0 \to D_s^-(\phi\pi^-)\pi^+$ in the CDF measurement of the flavour specific B_s^0 lifetime and (b) projection of the corresponding lifetime fit results. (c) Summary of B_s^0 flavour specific lifetime measurements.

3.1. Measurements of the B_s^0 Meson Lifetime

In the light of a substantial width difference $\Delta\Gamma_s$, the B_s^0 system contains short- and long-lived components similar to the kaon system and various B_s^0 decay channels will have different proportions of the B_s^H and B_s^L eigenstates. Lifetime measurements of different final states have therefore different meaning and can be broken down into several categories. First, there are flavour specific decays, such as semileptonic $B_s^0 \to D_s^-\ell^+\nu$ or $B_s^0 \to D_s^-\pi^+$ decays, which have equal fractions of B_s^L and B_s^H at proper time zero from where both components will evolve with their specific lifetimes $\tau_H = 1/\Gamma_H$ and $\tau_L = 1/\Gamma_L$. Fitting a single exponential to such a decay distributions measures the flavour specific lifetime

$$\tau(B_s^0)_{\text{flav.spec.}} = \frac{1}{\Gamma_s}\frac{1+\left(\frac{\Delta\Gamma_s}{2\Gamma_s}\right)^2}{1-\left(\frac{\Delta\Gamma_s}{2\Gamma_s}\right)^2}. \tag{5}$$

Second, there is the CP specific lifetime measured in decays that are assumed to be either CP even or CP odd. For example, the exclusive decay $B_s^0 \to K^+K^-$ is expected to be CP even within 5% and measures the lifetime of the light mass eigenstate $\tau_L = 1/\Gamma_L$. In 2006, CDF reported a preliminary measurement of $\tau(B_s^0) = (1.53\pm0.18\pm0.02)$ ps from $B_s^0 \to K^+K^-$. Finally, there are decays into a mixed CP final state where it is possible to disentangle the final state CP components. For example, an angular analysis can be used to decompose the CP components in the exclusive decay $B_s^0 \to J/\psi\phi$ which is expected to be dominated by the CP even state and its lifetime.

3.1.1. B_s^0 Flavour Specific Lifetime

CDF presented a new measurement of the B_s^0 flavour specific lifetime at this conference. In a data sample of $\sim$1.3 fb^{-1} of $p\bar{p}$ collisions, CDF reconstructs B_s^0 candidates through its decay $B_s^0 \to D_s^-\pi^+$ followed by $D_s^- \to \phi\pi^-$ with $\phi \to K^+K^-$. This sample yields more than 1100 fully reconstructed B_s^0 candidates as shown in Fig. 2(a). In addition, this sample also includes about 2000 partially reconstructed B_s^0 candidates that contribute to the fit of the lifetime distribution shown in Fig. 2(b). CDF obtains the flavour specific lifetime $\tau(B_s^0) = (1.518 \pm 0.041 \pm 0.027)$ ps. The ratio of this result and the world average B^0 lifetime [6] yields $\tau(B_s^0)/\tau(B^0) = 0.99 \pm 0.03$ in good agreement with theoretical predictions. Note, using the 2008 PDG mean B_s^0 lifetime [6] results in $\tau(B_s^0)/\tau(B^0) = 0.95 \pm 0.02$. A compilation of all B_s^0 flavour specific lifetime measurements to date is given in Fig. 2(c) and the world averaged flavour specific B_s^0 lifetime including the new CDF result is determined to be $\tau(B_s^0) = (1.456 \pm 0.030)$ ps [13].

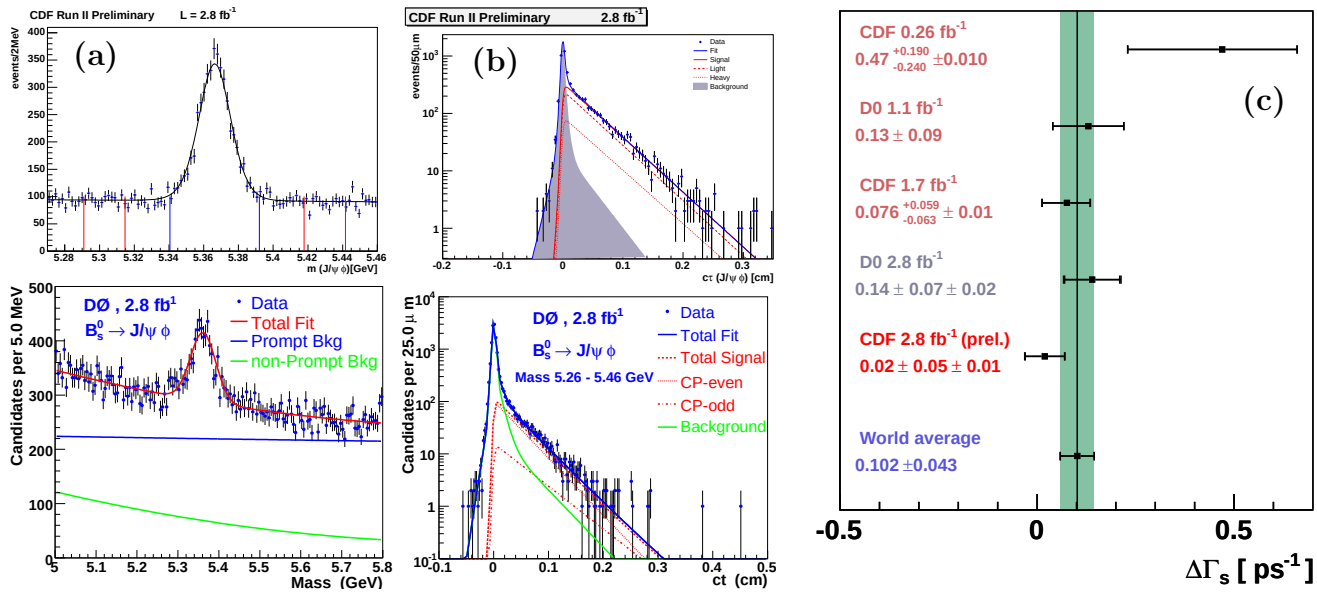

Figure 3: (a) Invariant mass distribution of $B_s^0 \to J/\psi\phi$ from CDF (top) and D0 (bottom). (b) Corresponding lifetime distributions with fit projections overlaid from CDF (top) and D0 (bottom). Note the difference in the large CP even and the much smaller CP odd contributions. (c) Compilation of various $\Delta\Gamma_s$ measurements.

3.1.2. B_s^0 Lifetime from $B_s^0 \to J/\psi\phi$ and Measurement of $\Delta\Gamma_s$

The decay $B_s^0 \to J/\psi\phi$ is the transition of the spin-0 pseudo-scalar B_s^0 into two spin-1 vector particles. The orbital angular momenta of the vector mesons, J/ψ and ϕ, can be used to distinguish the CP even S-wave ($L = 0$) and D-wave ($L = 2$) final states from the CP odd P-wave ($L = 1$) final state. Typically the set of decay angles $\vec{\rho} = (\cos\theta_T, \phi_T, \cos\psi_T)$ defined in the transversity basis (see e.g. Ref. [14]) is used to disentangle the CP mixture of the $J/\psi\phi$ final state. Such an angular decomposition reveals that the decay is dominated by the CP even state.

The experimental situation with respect to measurements of the mean B_s^0 lifetime $\tau_s = 2/(\Gamma_H + \Gamma_L)$ from $B_s^0 \to J/\psi\phi$ assuming no CP violation is as follows: The D0 collaboration has published [15] a result based on 2.8 fb^{-1} of data, while the CDF collaboration updated their published result [14] based on 1.35 fb^{-1} for this conference with a preliminary result using 2.8 fb^{-1} of data. The D0 analysis identifies 1967 ± 65 $J/\psi\phi$ signal events [15] as shown in Figure 3(a) while CDF finds 3166 ± 56 B_s^0 signal events in 2.8 fb^{-1} of data. With these events D0 measures a mean B_s^0 lifetime $\tau_s = (1.53 \pm 0.06 \pm 0.01)$ ps and quotes $\Delta\Gamma_s = (0.14 \pm 0.07 \pm 0.02)$ ps^{-1} assuming no CP violation in the B_s^0 decay. The corresponding numbers from the preliminary CDF analysis are $\tau_s = (1.53 \pm 0.04 \pm 0.01)$ ps and $\Delta\Gamma_s = (0.02 \pm 0.05 \pm 0.01)$ ps^{-1}. As can be seen in the lifetime distributions of Fig. 3(b), the lifetime distribution is mainly CP even while the CP odd component is much smaller. A compilation of various measurement of $\Delta\Gamma_s$ is shown in Figure 3(c). The preliminary CDF result mentioned above is not yet included in the world average of $\Delta\Gamma_s = (0.102 \pm 0.043)$ ps^{-1} [13]. When these direct measurements of $\Delta\Gamma_s$ are combined with the B_s^0 flavour specific lifetime measurements discussed in Sec. 3.1.1, a constrained result of $\Delta\Gamma_s = (0.067^{+0.031}_{-0.035})$ ps^{-1} is obtained [13].

3.2. CP Violation in $B_s^0 \to J/\psi\phi$

In analogy to measurements of the time dependent CP asymmetry in neutral B^0 decays into e.g. $B^0 \to J/\psi K_S^0$ accessing the CP violating phase $\sin(2\beta)$ which arises through the interference between decay and mixing, the application of flavour tagging to $B_s^0 \to J/\psi\phi$ events measures the corresponding phase in B_s^0 decays. This phase, which is responsible for CP violation in $B_s^0 \to J/\psi\phi$ in the standard model, is in analogy to the phase $\sin(2\beta)$ called $\sin(2\beta_s^{SM})$ and is defined as $\beta_s^{SM} = \arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*)$. In the context of the standard model, this phase is expected to be small and global fits of experimental data constrain it to $2\beta_s^{SM} \sim 0.04$ [12, 13]. Measuring such

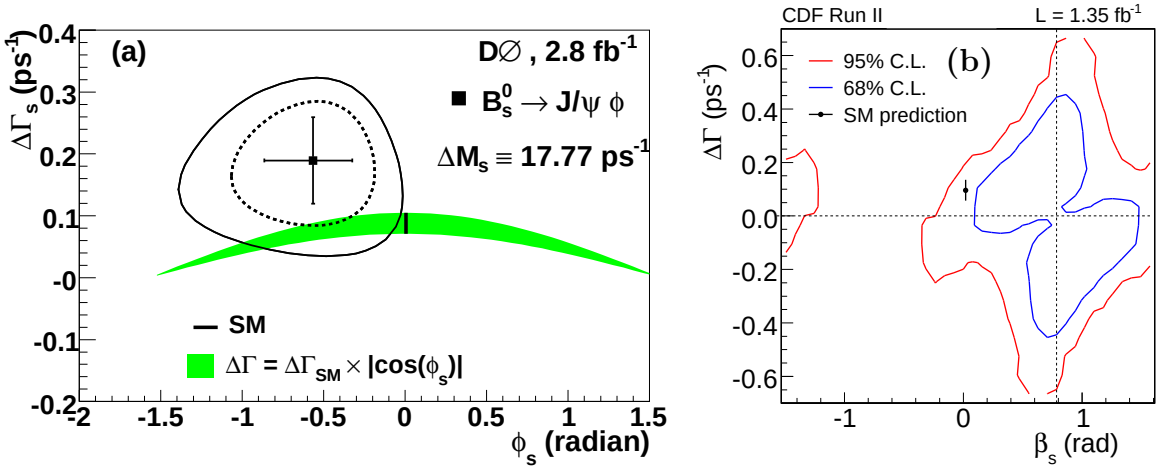

Figure 4: Confidence level regions in plane of $\Delta\Gamma_s$ versus $\beta_s^{J/\psi\phi}$ in flavour-tagged $B_s^0 \to J/\psi\phi$ analysis from (a) the 2.8 fb^{-1} result from D0 and (b) the 1.35 fb^{-1} result from CDF. Note the transformation $2\beta_s^{J/\psi\phi} = -\phi_s^{J/\psi\phi}$.

a small value of $\sin(2\beta_s^{SM})$ is currently beyond the experimental reach at the Tevatron. However, new physics may contribute significantly larger values to the CP violating phase in $B_s^0 \to J/\psi\phi$ decays [12, 16, 17]. In this case, the observed CP phase would be modified by a phase ϕ_s^{NP} due to new physics processes, and can be expressed as $2\beta_s^{J/\psi\phi} = 2\beta_s^{SM} - \phi_s^{NP}$. If $\phi_s^{NP} \gg 2\beta_s^{SM} \Rightarrow \phi_s^{NP} \gg \phi_s$, we expect $\Delta\Gamma_s = 2\,|\Gamma_{12}|\cos\phi_s \sim 2\,|\Gamma_{12}|\cos(2\beta_s^{J/\psi\phi})$. We can then make the approximation for the observed quantities $2\beta_s^{J/\psi\phi} = -\phi_s^{J/\psi\phi}$. The current interest in measuring CP violation in $B_s^0 \to J/\psi\phi$ is therefore a search for enhanced CP violation through new physics processes.

At the 2008 winter conferences both Tevatron experiments presented tagged, time dependent angular analyses of $B_s^0 \to J/\psi\phi$ decays. Due to the non-parabolic behaviour of the log-likelihood function, no meaningful point estimates for $\beta_s^{J/\psi\phi}$ can be quoted and both experiments construct their results as confidence level regions in the plane of $\Delta\Gamma_s$ versus $\beta_s^{J/\psi\phi}$. The D0 results [15] based on 2.8 fb^{-1} of data is shown in Figure 4(a) while the CDF result from 1.35 fb^{-1} of data [18] is displayed in Figure 4(b). Both experiments observe a mild inconsistency with the SM prediction $2\beta_s^{SM} \sim 0.04$. Interestingly, the CDF and D0 inconsistencies with the standard model both point in the same direction. Assuming the SM prediction, CDF quotes a probability of 15% to observe a likelihood ratio equal or higher than the one observed in data which corresponds to about $1.5\,\sigma$. Using constraints on the strong phases, D0 finds a p-value of 6.6% corresponding to a $1.8\,\sigma$ inconsistency with the SM hypothesis [15].

There are two new results on CP violation in $B_s^0 \to J/\psi\phi$ presented at this conference. First, D0 released their data without a constraint on the strong phases allowing for a combination of the CDF and D0 likelihoods obtained in their flavour-tagged $B_s^0 \to J/\psi\phi$ time-dependent analyses. The combined result is shown in Figure 5(a) and restricts $\beta_s^{J/\psi\phi}$ to the interval $[0.14, 0.73] \cup [0.83, 1.42]$ at 90% confidence level (CL). The consistency of the combined result gives a p-value of 3.1% corresponding to a $2.2\,\sigma$ discrepancy with the SM prediction. Second, CDF released an update of their published analysis [18] using 2.8 fb^{-1} of data. The new result again shown as a confidence region in the plane of $\Delta\Gamma_s$ versus $\beta_s^{J/\psi\phi}$, as displayed in Figure 5(b), confirms the trend of the published result. CDF finds that the p-value at the SM expected value is 7% corresponding to a $\sim 1.8\,\sigma$ discrepancy with the standard model. Furthermore, CDF determines that the projected one-dimensional range for $\beta_s^{J/\psi\phi}$ is confined to the interval $\beta_s^{J/\psi\phi} \in [0.28, 1.29]$ at 68% CL.

The updated CDF analysis was obtained with a suboptimal dataset which did not allow the use of particle identification for the entire data selection and restricted the application of same side kaon flavour tagging to the first half of the data. To estimate the future reach of this analysis, CDF's expected sensitivity of measuring a value of $\beta_s^{J/\psi\phi} = 0.40$ for various integrated luminosities ranging from 1.35 fb^{-1} up to 10 fb^{-1} of data is shown in Figure 5(c). With about 5 fb^{-1} of data, the probability to measure an assumed value of $\beta_s^{J/\psi\phi} = 0.40$ is about 50% which puts some excitement on awaiting further updates of the measurement of $\beta_s^{J/\psi\phi}$ in $B_s^0 \to J/\psi\phi$ from the Tevatron.

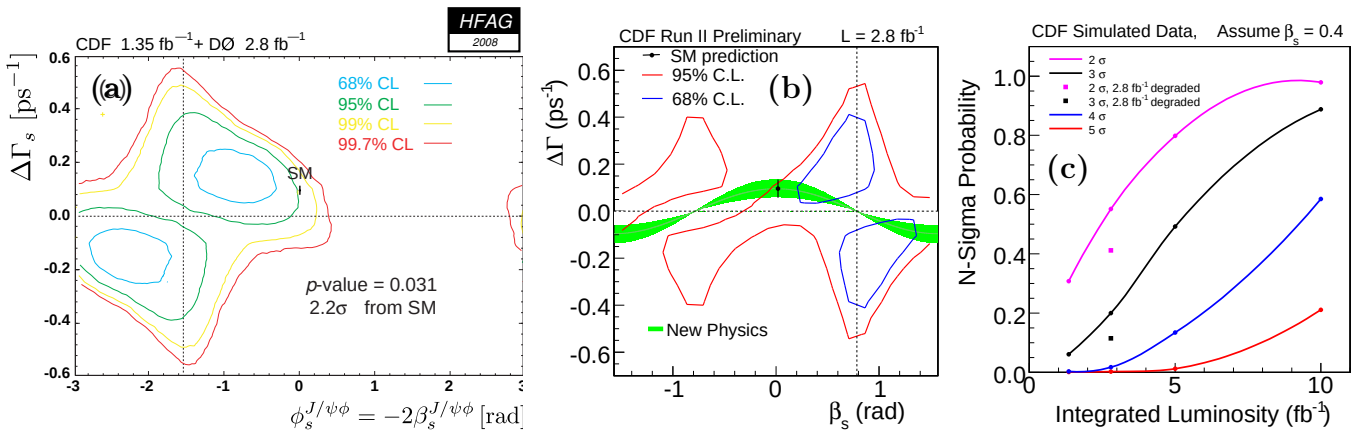

Figure 5: Confidence regions in the plane of $\Delta\Gamma_s$ versus $\beta_s^{J/\psi\phi}$ from (a) combination of CDF and D0 likelihoods obtained from their flavour-tagged $B_s^0 \to J/\psi\phi$ analyses and (b) the CDF preliminary update of the $B_s^0 \to J/\psi\phi$ analysis based on 2.8 fb^{-1}. (c) CDF expected sensitivity to $\beta_s^{J/\psi\phi} = 0.40$ for various integrated luminosities from 1.35 fb^{-1} to 10 fb^{-1} of data.

4. PROPERTIES OF OTHER HEAVY B MESONS

4.1. Orbitally Excited B Mesons

Until a couple of years ago, excited meson states containing b quarks had not been studied well. Only the stable $J^P = 0^-$ 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 [19]. The wide states decay via an 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 via a D-wave transition ($L = 2$) and thus should have a small width of $\sim$10 MeV/c^2 [20, 21]. Almost all previous observations [22, 23] of the narrow states B_1^0 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 [20, 21].

B_1^0 and B_2^{*0} candidates are reconstructed in the following decay modes: $B_1^0 \to B^{*+}\pi^-$ with $B^{*+} \to B^+\gamma$ and $B_2^{*0} \to B^{*+}\pi^-$ with $B^{*+} \to B^+\gamma$ as well as $B_2^{*0} \to B^+\pi^-$. In both cases the soft photon from the B^{*+} decay is not observed resulting in a shift of about 46 MeV/c^2 in the mass spectrum. D0 reconstructs B^+ candidates in the fully reconstructed mode $B^+ \to J/\psi K^+$ with $J/\psi \to \mu^+\mu^-$, while CDF selects B^+ mesons in addition through the $B^+ \to D^0\pi^+$ and $D^0\pi^+\pi^+\pi^-$ mode with $D^0 \to K^-\pi^+$. The CDF analysis [24] is based on 1.7 fb^{-1} of data resulting in a $B^+ \to J/\psi K^+$ signal of $\sim$ 51 500 events as well as 40 100 and 11 000 candidates in the $D^0\pi^+$ and $D^0\pi^+\pi^+\pi^-$ channels, respectively. The D0 measurement [25] employs 1.3 fb^{-1} of Run II data and finds a signal peak of 23 287 $\pm$ 344 events attributed to the decay $B^+ \to J/\psi K^+$.

D0 presents their measured mass distribution as $\Delta m = m(B\pi) - m(B)$ as shown in Figure 6(a), while CDF plots $Q = m(B\pi) - m(B) - m(\pi)$ as displayed in Fig. 6(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 $m(B_1^0) = (5720.6 \pm 2.4 \pm 1.4)$ MeV/c^2 and $m(B_2^{*0}) = (5746.8 \pm 2.4 \pm 1.7)$ MeV/c^2 from D0, while CDF quotes $m(B_1^0) = (5725.3^{+1.6+1.4}_{-2.2-1.5})$ MeV/c^2 and $m(B_2^{*0}) = (5740.2^{+1.7+0.9}_{-1.8-0.8})$ MeV/c^2. Both results are in modest agreement.

4.2. Orbitally Excited Strange B Mesons

The properties of $|b\bar{s}\rangle$ excited meson states, referred to as B_s^{**}, 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 [19, 20, 26]. These

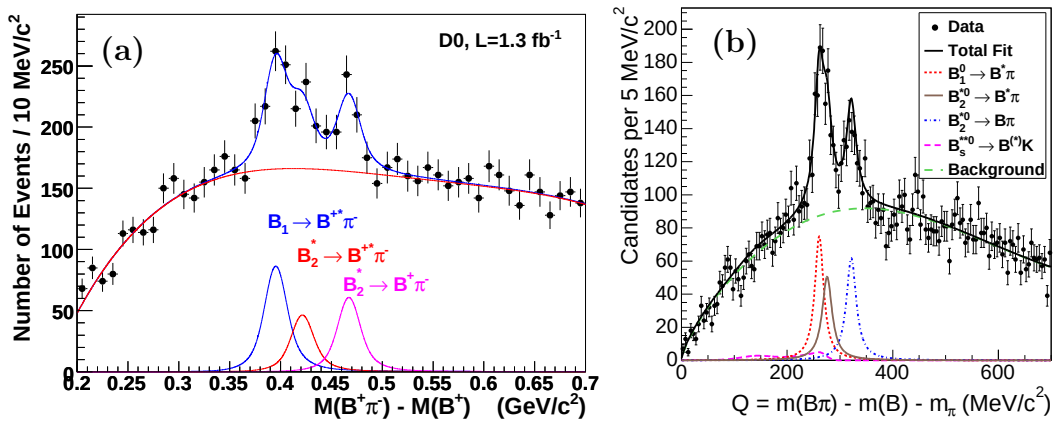

Figure 6: Fit to the B^{**} mass difference (a) $\Delta m = m(B\pi) - m(B)$ from D0 and (b) $Q = m(B\pi) - m(B) - m(\pi)$ from CDF.

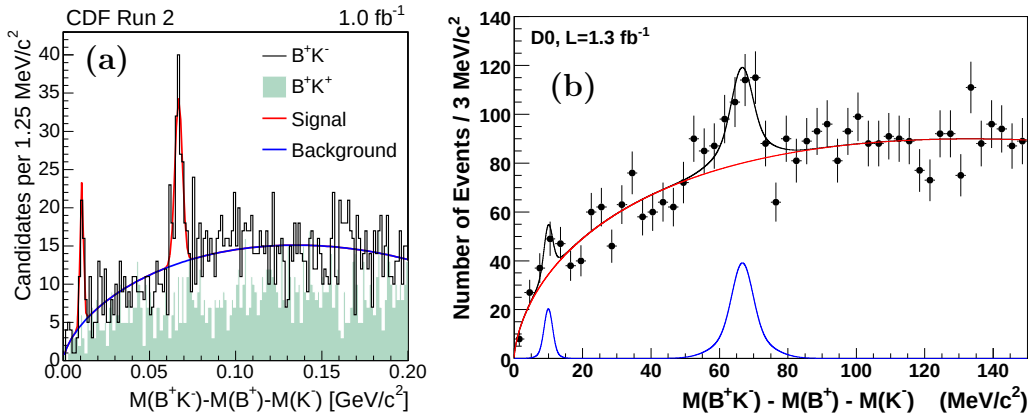

Figure 7: Result of the fit to the B_s^{**} mass difference $Q = m(BK) - m(B) - m(K)$ from (a) CDF and (b) D0.

models predict the existence of two wide resonances (B_{s0}^* 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 thus have a large width of order 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 order 1 MeV/c^2 [21] varying with predicted mass. 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 not allowed by isospin conservation. Previous observations [22] 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: $B_{s1}^0 \to B^{*+}K^-$ with $B^{*+} \to B^+\gamma$ and $B_{s2}^{*0} \to B^{*+}K^-$ with $B^{*+} \to B^+\gamma$ as well as $B_{s2}^{*0} \to B^+K^-$. 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 $B^+ \to J/\psi K^+$ with $J/\psi \to \mu^+\mu^-$, while CDF reconstructs B^+ mesons in addition through the $B^+ \to D^0\pi^+$ mode with $D^0 \to K^-\pi^+$. The CDF and D0 measurements are based on 1.0 and 1.3 fb^{-1} of Run II data, respectively. The CDF analysis [27] finds $\sim$31 000 $B^+ \to J/\psi K^+$ events and $\sim$27 200 candidates in the $B^+ \to D^0\pi^+$ channel. The D0 measurement [28] uses a signal of $20\,915 \pm 293 \pm 200$ B^+ events from the decay $B^+ \to J/\psi K^+$. Both experiments present their mass distributions in the quantity $Q = m(BK) - m(B) - m(K)$ as displayed in Figure 7(a) and (b).

A clear signal at $Q \sim 67$ MeV/c^2 is observed by CDF and D0 (see Fig. 7), 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

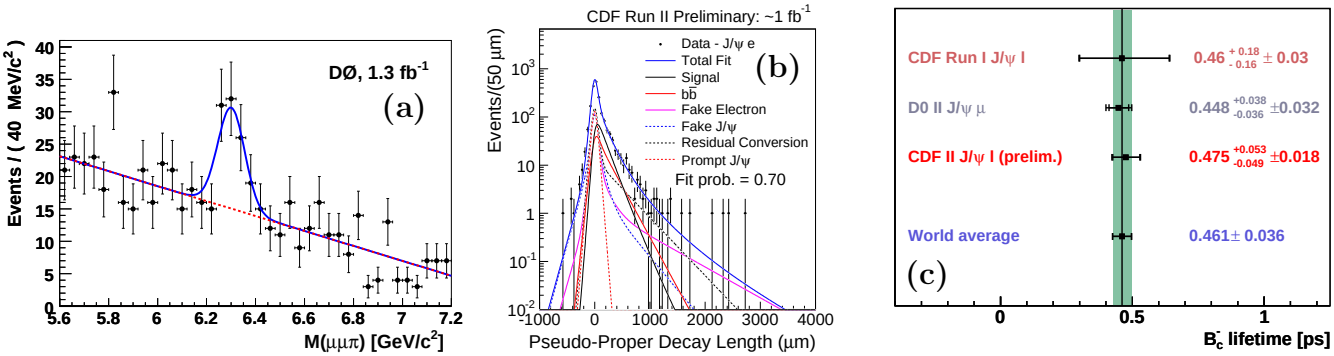

Figure 8: (a) $J/\psi\,\pi^-$ invariant mass distribution of B_c^- candidates from D0. (b) Lifetime distribution from $B_c^- \to J/\psi e^- X$ with fit results overlaid from CDF. (c) Compilation of B_c^- lifetime measurements.

statistical significance of less than $3\,\sigma$. 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.

4.3. 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 $b \to c$ transition with a J/ψ in the final state (hadronic $J/\psi X$ or semileptonic $J/\psi \ell \nu X$ which is the mode in which the B_c^- meson was discovered by CDF in Run I [29]) or via the $\bar{c}$ quark in a $\bar{c} \to \bar{s}$ 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 $B_c^- \to \ell^- \bar{\nu}_\ell$ or $B_c^- \to q\bar{q}X$ 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 [35], while a measurement of the B_c^- mass tests potential model predictions as well as lattice QCD calculations.

4.3.1. Mass of the B_c^- Meson

The mass of the B_c^- meson has been predicted using a variety of theoretical techniques. Non-relativistic potential models [30] 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 [31]. Recent lattice QCD determinations provide a B_c^- mass prediction of $(6304 \pm 12^{+18}_{-0})$ MeV/c^2 [32]. Precision measurements of the properties of the B_c^- meson are thus needed to test these predictions.

CDF and D0 both use fully reconstructed $B_c^- \to J/\psi\,(\to \mu^+\mu^-)\,\pi^-$ decays for a precise measurement of the B_c^- mass. CDF first published their analysis [33], based on 2.4 fb^{-1} of data, where the B_c^- selection is optimized on the signal yield of $B^- \to J/\psi K^-$ and the obtained selection criteria are directly transferred to the $J/\psi\pi^-$ data for an unbiased selection. A signal of 108 ± 15 events with a significance greater than $8\,\sigma$ 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 [34], based on 1.3 fb^{-1} of data, uses a well-understood signal sample of $B^- \to J/\psi K^-$ data. After the final selection the $J/\psi\,\pi^-$ invariant mass distribution of B_c^- candidates from D0 is obtained as shown in Figure 8(a). An unbinned likelihood fit yields a signal of 54 ± 12 events corresponding to a significance of $5.2\,\sigma$. The extracted B_c^- mass value is reported as $(6300 \pm 14 \pm 5)$ MeV/c^2. Combining both results yields a world average B_c^- mass of $m(B_c^-) = (6276 \pm 4)$ MeV/c^2. In comparison to the theoretical predictions [30–32], it is obvious that the experimental measurements, especially the CDF result with small uncertainties, start to challenge the predictions of theoretical models and lattice QCD calculations.

4.3.2. Lifetime of the B_c^- Meson

As discussed above, the decay of a B_c^- meson can occur via a $b \to c$ transition, a $\bar{c} \to \bar{s}$ transition or a $b\bar{c}$ quark pair annihilation into a W boson leading to an expected lifetime of order (0.5 ± 0.1) ps [35], only one third that of other B mesons. Due to the large branching fraction, CDF and D0 both use the semileptonic decay $B_c^- \to J/\psi \ell^- \nu X$ with $J/\psi \to \mu^+\mu^-$ for their measurement of the B_c^- lifetime. The main issue in using a B_c^- semileptonic decay is to control the backgrounds since no B_c^- mass peak can be reconstructed. Since the event signature is two muons forming the J/ψ meson plus a third lepton, the background sources are fake J/ψ's, fake leptons, or uncorrelated real J/ψ's and leptons from $b\bar{b}$ events where the J/ψ is from one b quark while the lepton is from the other b quark jet. In the $J/\psi e^-$ channel, which is only used by CDF, there is an additional background of electrons from residual photon conversions $\gamma \to e^+e^-$ within the detector material. CDF and D0 estimate the backgrounds with Monte Carlo or based on data depending on the analysis approach. The D0 analysis [36], using 1.3 fb^{-1} of data, identifies 881 ± 80 $J/\psi\mu X$ signal candidates and measures the B_c^- lifetime as $\tau(B_c^-) = (0.448^{+0.038}_{-0.036} \pm 0.032)$ ps.

In a preliminary analysis, based on 1 fb^{-1} of data, CDF analyzes both the $J/\psi\mu$ and $J/\psi e$ final state in the $J/\psi\ell$ invariant mass range between 4-6 GeV/c^2, in which the B_c^- signal is expected to lie. The CDF lifetime distribution with the various background sources indicated is shown in Figure 8(b) for the $J/\psi e$ mode. Combining the electron and muon channel, CDF measures $\tau(B_c^-) = (0.475^{+0.053}_{-0.049} \pm 0.018)$ ps. A compilation of both measurements together with an older CDF Run I result is displayed in Figure 8(c) and a world average B_c^- lifetime of $\tau(B_c^-) = (0.461 \pm 0.036)$ ps is determined in good agreement with theoretical predictions.

5. PROPERTIES OF BOTTOM BARYONS

The QCD treatment of quark-quark interactions significantly simplifies if one of the participating quarks is much heavier than the QCD confinement scale $\Lambda_{\rm QCD}$. In the limit of $m_Q \to \infty$, 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, thus views a baryon made 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. For baryons with a bottom quark, this classification gives the ground state Λ_b^0 baryon with quark content $|bdu\rangle$ and the Σ_b baryons with quark content $\Sigma_b^{(*)+} = |buu\rangle$ and $\Sigma_b^{(*)-} = |bdd\rangle$. If one of the light quarks is a strange quark, we classify the bottom baryon as a cascade Ξ_b baryon and the double strange bottom baryon is the Ω_b^- with quark content $|bss\rangle$.

5.1. The Λ_b^0 Lifetime Story

The mass of the ground state bottom baryon, the Λ_b^0 ($|bdu\rangle$), has been established for quite some time with the current mass value $m(\Lambda_b^0) = (5620.2 \pm 1.6)$ MeV/c^2 [6]. However, the lifetime of the Λ_b^0 baryon has been puzzling the community for a long time. The situation of Λ_b^0 lifetime measurements as of 2006 is summarized in Figure 9(a). A world average lifetime of $\tau(\Lambda_b^0) = (1.230 \pm 0.074)$ ps is quoted by the PDG in 2006 based on several LEP measurements, one CDF Run I measurement and the first Run II measurement with 0.25 fb^{-1} from D0 [37] using the decay mode $\Lambda_b^0 \to J/\psi\Lambda^0$. The 2006 world average Λ_b^0 lifetime translates into a lifetime ratio $\tau(\Lambda_b^0)/\tau(B^0) = 0.804 \pm 0.049$. This number is on the low side of theoretical predictions which are in the range of 0.88 ± 0.05. This introduces the long-standing puzzle that the Λ_b^0 lifetime is measured smaller than theoretical predictions.

Then in 2007, the D0 experiment updated its measurement of the Λ_b^0 lifetime from $J/\psi\Lambda^0$ with 1.2 fb^{-1} of data [38] measuring $\tau(\Lambda_b^0) = (1.218^{+0.130}_{-0.115} \pm 0.042)$ ps resulting in a lifetime ratio $\tau(\Lambda_b^0)/\tau(B^0) = 0.811^{+0.096}_{-0.087} \pm 0.034$. In the same year D0 released another measurement [39] of the Λ_b^0 lifetime using semileptonic decays $\Lambda_b^0 \to \mu^-\bar{\nu}\Lambda_c^+X$. In

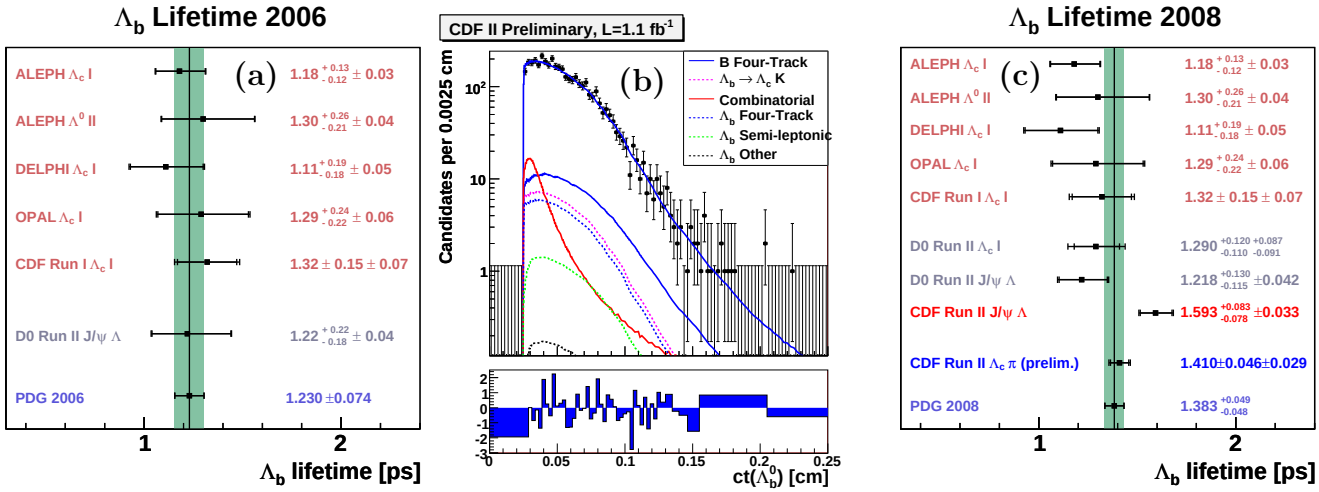

Figure 9: (a) Summary of Λ_b^0 lifetime measurements as of 2006. (b) Λ_b^0 lifetime fit of CDF data using $\Lambda_b^0 \to \Lambda_c^+\pi^-$ and (c) compilation of Λ_b^0 lifetime measurements as of 2008.

1.2 fb^{-1} of $p\bar{p}$ collision data, D0 identifies 4437 ± 329 signal candidates and measures $\tau(\Lambda_b^0) = (1.290^{+0.119+0.087}_{-0.111-0.091})$ ps. Both D0 results are in good agreement with the 2006 world average Λ_b^0 lifetime. In the same year in 2007, CDF published a measurement of the Λ_b^0 lifetime in the exclusive decay $\Lambda_b^0 \to J/\psi\Lambda^0$ using 1.2 fb^{-1} of data [40]. The resulting $\tau(\Lambda_b^0) = (1.593^{+0.083}_{-0.078} \pm 0.033)$ ps was the single most precise measurement of $\tau(\Lambda_b^0)$ but is $3.2\,\sigma$ higher than the 2006 world average. This surprising fact is also evident when forming a ratio with the world average B^0 lifetime yielding $\tau(\Lambda_b^0)/\tau(B^0) = 1.041 \pm 0.057$ larger than one! This result was a big surprise and further measurements were needed to resolve the situation.

New in 2008 is a preliminary CDF measurement of the Λ_b^0 lifetime using fully reconstructed $\Lambda_b^0 \to \Lambda_c^+\pi^-$ decays with $\Lambda_c^+ \to pK^+\pi^-$. With a dataset of 1.2 fb^{-1}, CDF obtains a clean sample of about 3000 fully reconstructed Λ_b^0 signal events. From the lifetime distribution shown in Figure 9(b), CDF measures $\tau(\Lambda_b^0) = (1.410 \pm 0.046 \pm 0.029)$ ps and reports a lifetime ratio $\tau(\Lambda_b^0)/\tau(B^0) = 0.922 \pm 0.039$ in good agreement with theoretical predictions. This measurement is as precise as and in good agreement with the current world average of the Λ_b^0 lifetime $\tau(\Lambda_b^0) = (1.383^{+0.049}_{-0.048})$ ps determined for the PDG 2008 edition [6] without including the new preliminary CDF result. The situation of Λ_b^0 lifetime measurements is summarized in Figure 9(c) where it can be seen that the new CDF result is also in agreement within one standard deviation with the 2007 measurement of $\tau(\Lambda_b^0)$ from CDF. It appears that the longstanding puzzle surrounding the Λ_b^0 lifetime has been resolved.

5.2. 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 $m_Q \to \infty$, 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 resulting in an additional isospin splitting between the $\Sigma_b^{(*)-}$ and $\Sigma_b^{(*)+}$ states [41]. There exist a number of predictions for the masses and isospin splittings of these states using HQET, non-relativistic and relativistic potential models, $1/\mathrm{N}_c$ expansion, sum rules and lattice QCD calculations [41, 42].

The CDF collaboration has accumulated a large data sample of Λ_b^0 baryons using the CDF displaced track trigger. Using a 1.1 fb^{-1} data set of fully reconstructed $\Lambda_b^0 \to \Lambda_c^+\pi^-$ candidates, CDF searches for the decay $\Sigma_b^{(*)\pm} \to \Lambda_b^0\pi^\pm$.

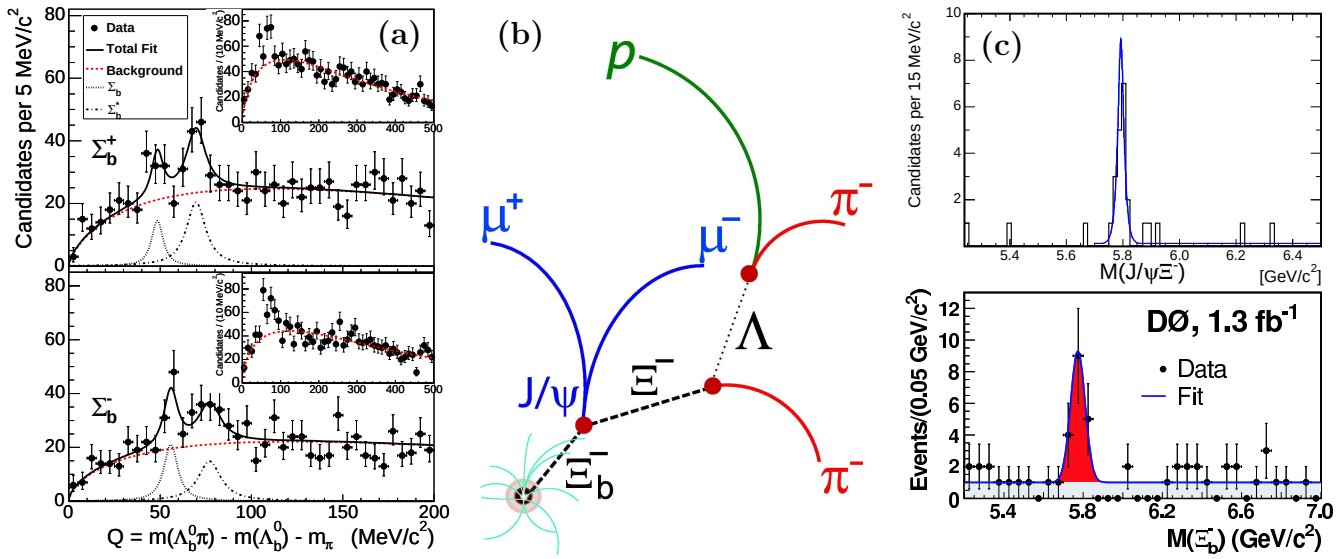

Figure 10: (a) The $\Sigma_b^{(*)}$ fit to the $\Lambda_b^0\pi^+$ and $\Lambda_b^0\pi^-$ subsamples. The top plot shows the $\Lambda_b^0\pi^+$ data, which contain $\Sigma_b^{(*)+}$, while the bottom plot shows the $\Lambda_b^0\pi^-$ subsample, which contains $\Sigma_b^{(*)-}$. (b) Schematic of the $\Xi_b^- \to J/\psi\,\Xi^-$ decay topology. (c) The $J/\psi\,\Xi^-$ invariant mass distribution from CDF (top) and D0 (bottom) including fits to the data overlaid.

Table I: Final results for the $\Sigma_b^{(*)}$ mass measurements. The first uncertainty is statistical and the second is systematic. The absolute $\Sigma_b^{(*)}$ mass values are calculated using a CDF measurement of the Λ_b^0 mass [44].

State	Yield	Q or $\Delta_{\Sigma_b^*}$ [MeV/c^2]	Mass [MeV/c^2]
Σ_b^+	32^{+13+5}_{-12-3}	$Q_{\Sigma_b^+} = 48.5^{+2.0+0.2}_{-2.2-0.3}$	$5807.8^{+2.0}_{-2.2} \pm 1.7$
Σ_b^-	59^{+15+9}_{-14-4}	$Q_{\Sigma_b^-} = 55.9 \pm 1.0 \pm 0.2$	$5815.2 \pm 1.0 \pm 1.7$
Σ_b^{*+}	77^{+17+10}_{-16-6}	$\Delta_{\Sigma_b^*} = 21.2^{+2.0+0.4}_{-1.9-0.3}$	$5829.0^{+1.6+1.7}_{-1.8-1.8}$
Σ_b^{*-}	69^{+18+16}_{-17-5}		$5836.4 \pm 2.0^{+1.8}_{-1.7}$

The CDF analysis [43] reconstructs a Λ_b^0 yield of approximately 2800 candidates in the signal region $m(\Lambda_b^0) \in [5.565, 5.670]$ 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, $\Sigma_b^{(*)}$ refers to both the $J = \frac{1}{2}$ ($\Sigma_b^{\pm}$) 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 $\Sigma_b^{(*)}$ 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 10(a). 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. The final fit results for the $\Sigma_b^{(*)}$ measurement are summarized in Table I. The absolute $\Sigma_b^{(*)}$ mass values are calculated using a CDF measurement of the Λ_b^0 mass [44], 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^-.

5.3. Observation of the Ξ_b^- Baryon

The Ξ_b baryons with a quark content of $\Xi_b^- = |bds\rangle$ and $\Xi_b^0 = |bus\rangle$ 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 $\Xi_b^0 \to \Xi_c^0\pi^0$ or $J/\psi\,\Xi^0\,(\to \Lambda^0\pi^0)$. Both decays involve the reconstruction of neutral pions which

is difficult to achieve at CDF and D0. However, the Ξ_b^- can decay through $\Xi_b^- \to J/\psi\Xi^-$ followed by $\Xi^- \to \Lambda^0\pi^-$ with $\Lambda^0 \to p\pi^-$ and $J/\psi \to \mu^+\mu^-$. This is the decay mode in which CDF and D0 search for the Ξ_b^- baryon.

A schematics of the decay topology is shown in Figure 10(b) from where the challenges in the Ξ_b^- reconstruction become apparent. The Ξ_b^- baryon travels an average distance of $c\tau(\Xi_b^-) \sim 450$ μm and then decays into a J/ψ and Ξ^- which has a $c\tau(\Xi^-) = 4.9$ cm traversing parts of the silicon detector. Furthermore, the Ξ^- decays into a Λ^0 which has a $c\tau(\Lambda^0) = 7.9$ 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 [45] based on 1.3 fb^{-1} 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 algorithm. 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 [46] based on 1.9 fb^{-1} of data uses a $B^- \to J/\psi K^-$ 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 10(c). D0 finds $15.2 \pm 4.4^{+1.9}_{-0.4}$ Ξ_b^- signal event with a Gaussian significance of $5.2\,\sigma$ and reports a mass of $m(\Xi_b^-) = (5774 \pm 11 \pm 15)$ MeV/c^2 [45]. CDF observes 17.5 ± 4.3 Ξ_b^- signal event with a Gaussian significance of $7.7\,\sigma$ and measures a Ξ_b^- mass of $m(\Xi_b^-) = (5792.9 \pm 2.5 \pm 1.7)$ MeV/c^2 [46]. In addition, D0 verifies that the lifetime of the Ξ_b^- candidates is compatible with a B hadron like lifetime.

Soon after this conference, the D0 collaboration announced the observation of another heavy bottom baryon [47], the double strange Ω_b^- baryon with quark content $|bss\rangle$. With the same dataset as used for the Ξ_b^- observation based on 1.3 fb^{-1} of $p\bar{p}$ collisions, D0 reconstructs $\Omega_b^- \to J/\psi\Omega^-$ followed by $\Omega^- \to \Lambda^0 K^-$ and obtains a mass measurement of $m(\Omega_b^-) = (6165 \pm 10 \pm 13)$ MeV/c^2 based on an Ω_b^- signal of $17.8 \pm 4.9 \pm 0.8$ events. The significance of the observed signal is $5.4\,\sigma$ corresponding to a probability of 6.7×10^{-8} of it arising from background fluctuation.

6. CONCLUSION

We have reviewed recent result on heavy B hadron properties focusing on Run II measurements from the Fermilab Tevatron which offers a rich heavy flavour program. A wealth of new results on properties of heavy B hadron states from CDF and D0 has been available. These include measurements of the lifetime and decay width difference $\Delta\Gamma_s$ in B_s^0 meson decays, updates on CP violation in $B_s^0 \to J/\psi\phi$ decays which continue to show an intriguing discrepancy with the standard model prediction. In addition, the Belle collaboration used B_s^0 mesons produced at the $\Upsilon(5S)$ resonance to obtain competitive branching ratio measurements for B_s^0 decays. We also reviewed recent results on the mass and lifetime of the B_c^- meson. With respect to bottom baryons, the puzzle of the Λ_b^0 lifetime measurements being lower than theoretical predictions appears to be solved. New heavy bottom baryons have been established, the $\Sigma_b^{(*)}$ states as well as the Ξ_b^- and Ω_b^- baryon. We expect more results from the Tevatron which will accumulate more data until the end of Run II currently scheduled to conclude in 2010. With the onset of the Large Hadron Collider in 2009, more exciting result on heavy B hadron properties are expected, especially from the LHCb experiment.

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