

Measurements of B Hadron Properties at the Tevatron

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Recent measurements of B hadron properties carried out in $\sqrt{s} = 1.96$ TeV $p\bar{p}$ collisions at the Tevatron are reviewed. Included are measurements of the B_c^+ meson lifetime, using $J/\psi + l + X$ final states, and the mass, using $J/\psi + \pi$ final states, a flavor specific measurement of the B_s^0 lifetime in $D_s + \pi + X$ decays, simultaneous measurements of τ_{B_s} and $\Delta\Gamma_{B_s}$ in $J/\psi + \phi$ decays, the first direct evidence and mass measurements of the Ξ_b^- baryon, and measurements of the polarization of 1S charmonium. For all measurements, charge conjugate modes are included.

1. INTRODUCTION

The measured properties of hadrons containing heavy quarks, b and c , test the predictions of quantum chromodynamics (QCD) in bound states that probe kinematic regions not seen in light hadrons. To carry out calculations, effective field theories have been developed for systems including a single heavy quark, heavy quark effective theory (HQET) [1], and two heavy quarks, nonrelativistic QCD (NRQCD) [2]. A number of tools have been adapted to work in the context of these effective field theories including lattice QCD (lQCD) [3], QCD sum rules [4], and the operator product expansion (OPE) [5]. The measured properties presented in this paper help in constraining some of the approaches used within the effective field theories.

The Tevatron, a $\sqrt{s} = 1.96$ TeV $p\bar{p}$ collider, provides collisions for two multipurpose detectors, the D0 detector and the upgraded Collider Detector at Fermilab (CDF II). Pairs $b\bar{b}$ production is the dominant source of b quarks with a cross section of $\sim 30 \mu\text{b}$ [6] compared to a total inelastic cross section of ~ 50 mb. All measurements presented in this paper use between 0.8 and 2.8 fb^{-1} of integrated luminosity of collisions measured by the D0 and CDF II detectors.

Throughout this paper charge conjugate modes are implied unless noted otherwise.

2. PROPERTIES OF THE B_c^+ MESON

The B_c^+ meson, the ground state meson consisting of a b and c quark, is unique among mesons since it both contains two heavy mesons and decays weakly. The doubly heavy nature of the B_c^+ allows for the application of NRQCD while calculating its properties, including the singular application of NRQCD to weak decay properties.

The B_c^+ decays through three tree level processes: decay of the c quark through a W leaving a B meson in the final state, decay of the b quark through a W leaving charmonium in the final state, and annihilation of the b and c quarks leaving $\tau + \bar{\nu}_\tau$ or $c + \bar{s}$ in the final state. While the decays of the c quark should be expected to have the largest branching fractions, channels involving the decay of the b quark can be more useful from an experimental perspective since the reconstruction of the J/ψ through the dimuon mode takes place at a higher efficiency than any modes involving a B_s^0 . Table I compares predictions for branching fractions of the B_c^+ to final states with J/ψ and B_s^0 .

2.1. Lifetime in $B_c^+ \rightarrow J/\psi + l^+ + X$ Decays

NRQCD predicts a B_c^+ lifetime that is short compared to the B^0/B^+ lifetimes. Calculations using QCD sum rules predict a lifetime of 0.47 ± 0.05 ps [10], while calculations using the optical theorem and OPE predict 0.52 ps [11]

Table I: Predicted B_c^+ branching fractions for decay channels that are candidates for experimental analysis.

Decay Mode	B_c Branching Fraction(%)		
	[7]	[8]	[9]
$B_s^0 + \pi^\pm$	16.4	3.9	1.56
$B_s^0 + e/\mu^\pm + \nu_{e/\mu}$	4.03	1.10	0.98
$J/\psi + \pi^\pm$	0.13	0.17	0.11
$J/\psi + e/\mu^\pm + \nu_{e/\mu}$	1.9	2.07	1.44

with a range of 0.4 – 0.7 ps depending on the value of the charm quark mass. The B_c lifetime was first measured in CDF Run I data and found to be $\tau_{B_c} = 0.46_{-0.16}^{+0.18}(stat.) \pm 0.03(syst.)$ ps [12].

D0 and CDF measure the B_c lifetime in the inclusive $B_c^\pm \rightarrow J/\psi(\mu\mu) + l^+ + X$ decay mode, which is expected to be dominated by semileptonic decays to $J/\psi + l^+ + \nu_l$ directly. D0 uses 1.3 fb^{-1} of $J/\psi + \mu + X$ events while CDF uses 1.0 fb^{-1} of $J/\psi + l^+ + X$ where l^+ can be a muon or electron. For both experiments, events are triggered on by the presences of the dimuon pair from the J/ψ decay.

The unmeasured particles in the inclusive decays require a correction to account for the missing momentum which can be modeled with a sample of simulated signal events and is defined as

$$K = \frac{p_T(J/\psi l)}{p(B_c) \cdot \hat{p}_T(J/\psi l)} \quad (1)$$

The missing momentum also implies a broad mass peak, so backgrounds are not estimated using mass sidebands. Instead, background are modeled using data and simulation and include: fake J/ψ plus third lepton, true J/ψ where the third lepton is faked by a hadron, true J/ψ and leptons that do not originate from the same decay, and prompt J/ψ plus a third lepton. The D0 measurement includes models of the mass distributions in a simultaneous fit of the lifetime and mass distributions, while the CDF measurement fits the lifetime distribution only.

D0 measures the lifetime with world best precision [13]:

$$\tau_{B_c} = 0.448_{-0.036}^{+0.038}(stat.) \pm 0.032(syst.) \text{ ps}$$

Systematic uncertainties limit further improvements in precision and are due to uncertainties in the mass and lifetime models used for the backgrounds. CDF measures the lifetime with similar precision [14]:

$$\tau_{B_c} = 0.476_{-0.049}^{+0.053}(stat.) \pm 0.018(syst.) \text{ ps}$$

For the CDF measurement, systematic uncertainties are limited by various tests of the background models using data. The results are summarized in Fig. 1 along with the CDF Run I measurement and a weighted average of

$$\tau_{B_c} = 0.459 \pm 0.037 \text{ ps}$$

The average result is in good agreement with predictions from NRQCD and provides already constraining information for theoretical predictions.

2.2. Mass in $B_c^+ \rightarrow J/\psi + \pi^+$ Decays

The mass of the B_c^+ meson can be estimated in NRQCD using lQCD, $M = 6304 \pm 12_{-0}^{+18} \text{ MeV}/c^2$ [15], and potential models, $M = 6247 - 6286 \text{ MeV}/c^2$ [16]. The mass of the B_c^+ was originally measured in the inclusive $B_c^+ \rightarrow J/\psi + l^+ + X$ mode in CDF Run I data to be $6400 \pm 390(stat.) \pm 130(syst.) \text{ MeV}/c^2$ [12].

Both CDF and D0 measure the B_c^+ mass in the exclusive $B_c^+ \rightarrow J/\psi + \pi^+$ decay mode, CDF with 2.4 fb^{-1} and D0 with 1.3 fb^{-1} of data. The choice of the exclusive mode allows for the first measurements of the B_c^+ mass from fits of

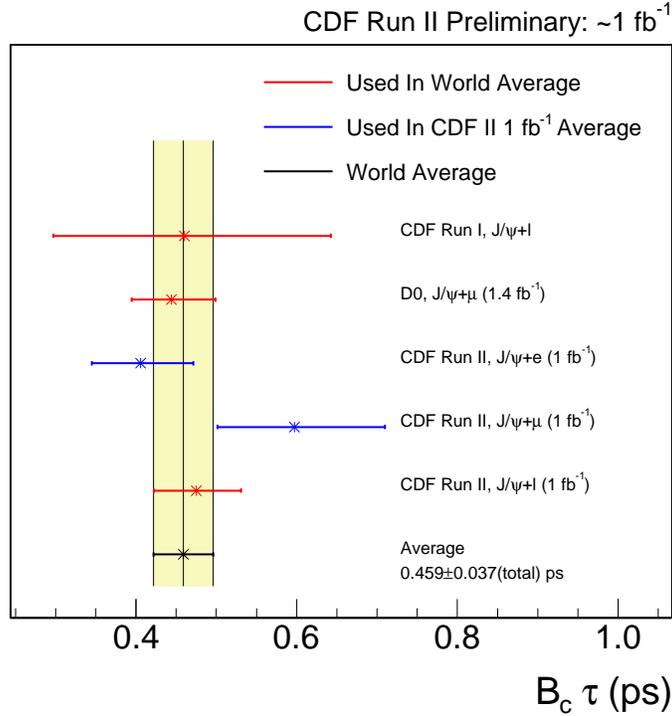


Figure 1: Average of B_c^+ lifetime measurements from the Tevatron. The world average is a weighted average of results assuming no correlation in the uncertainties.

a fully reconstructed mass peak. Both analysis are based on event selection optimized for use with $B^+ \rightarrow J/\psi + K^+$ decays. D0 carries out an additional stage of optimization using a sample of simulated signal events. Fig. 2 shows the reconstructed mass distributions for the CDF and D0 results. CDF obtains the world best measurement [17]:

$$M_{B_c} = 6275.6 \pm 2.9(\text{stat.}) \pm 2.5(\text{syst.}) \text{ MeV}/c^2$$

The further improvements in precision are limited by the systematic uncertainty which is dominated by the understanding of the detector resolution for mass measurements. D0 measures the mass as [18]

$$M_{B_c} = 6300 \pm 14(\text{stat.}) \pm 5(\text{syst.}) \text{ MeV}/c^2$$

The measurement are in agreement with each other, while the CDF result may suggest refinements to the calculation of the mass using lQCD.

3. LIFETIME OF THE B_s^0 MESON

The B_s^0 meson, the ground state meson consisting of b and s valence quarks, exhibits the behaviour of particle/antiparticle virtual transitions (mixing) which is seen in flavored neutral mesons. As a result of the mixing, the system has two mass eigenstates, B_L and B_H , each with its own lifetime. Measurements of the B_s^0 lifetime either differentiate the mass eigenstates and measure their lifetimes separately or measure a combination of the two lifetimes. One can define the average lifetime and lifetime difference as

$$\frac{1}{\tau_{B_s}} = \Gamma_s = (\Gamma_L + \Gamma_H)/2, \quad \Delta\Gamma_s = \Gamma_L - \Gamma_H \quad (2)$$

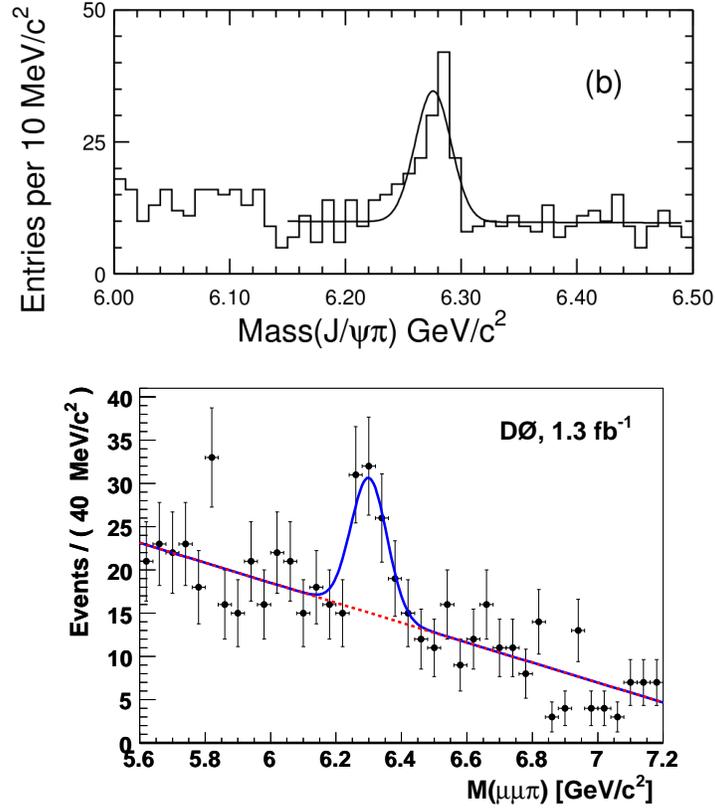


Figure 2: $J/\psi\pi$ mass distributions for B_c^+ mass measurements at CDF (top) and D0 (bottom).

For flavor specific measurements, where the flavor of the B_s^0 is determined by the final state particles, the mass eigenstates are not separately measured and the measured lifetime is [19]

$$(\tau_{B_s})_{fs} = \frac{1}{\Gamma_s} \frac{1 + (\frac{\Delta\Gamma_s}{2\Gamma_s})^2}{1 - (\frac{\Delta\Gamma_s}{2\Gamma_s})^2} \quad (3)$$

The theoretical estimates of lifetimes for ground state B mesons containing a light quark can be evaluated in the heavy quark expansion (HQE). Results are particularly precise for lifetime ratios, where many theoretical uncertainties cancel. The predicted lifetime ratio $\tau_{B_s}/\tau_{B_d} = 1.00 \pm 0.02$ [20] shows a 2.1σ difference from the world average measured value of 0.939 ± 0.021 [21] as of March 2007. The lifetime results in the following sections will greatly improve the world average and decide whether this discrepancy is significant.

3.1. Lifetime in $B_s^0 \rightarrow D_s^-(\pi^-\phi) + \pi^+ + X$ Decays

CDF measures the lifetime of the B_s^0 in the flavor specific mode $B_s^0 \rightarrow D_s^-(\pi^-\phi) + \pi^+ + X$, which includes the fully reconstructed $D_s^-(\pi^-\phi) + \pi^-$ and partially reconstructed $D_s^-(\pi^-\phi) + \rho^+$ and $D_s^{*-} + \pi^+$ final states. The partially reconstructed modes increase the statistics, improving the precisions, but require a K factor from a simulation of partially reconstructed states that models the missing momentum in those decay modes. The mass models for the decay modes are also determined with simulated events. The lifetime fit takes place in two steps: the mass distribution is fitted to constrain the fractions of the fully and partially reconstructed decay modes, and the fractions are propagated into the lifetime fit. The measured lifetime is the most precise flavor specific measurement to date [22]:

$$(\tau_{B_s})_{fs} = 1.518 \pm 0.041(stat.) \pm 0.025(syst.) ps$$

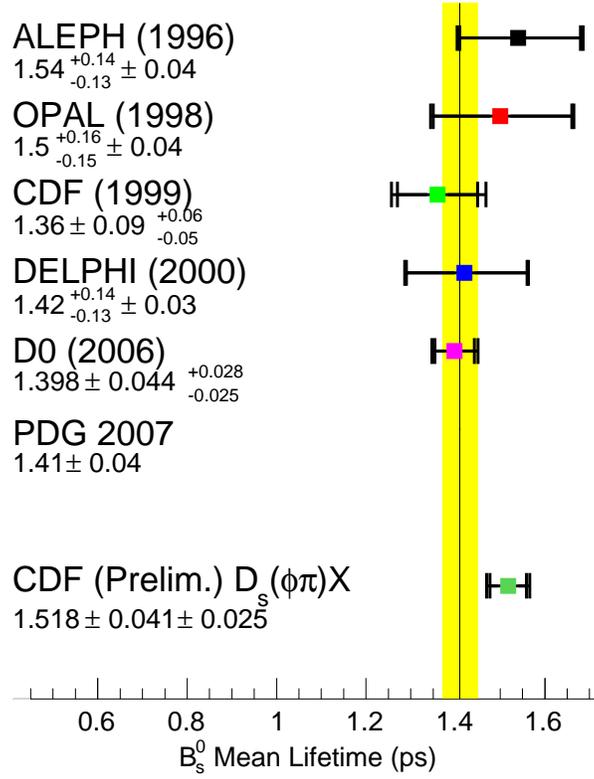


Figure 3: Comparison of flavor specific measurements of the B_s lifetime.

Fig. 3, which summarises measurements of the B_s lifetime in flavor specific modes, shows that this measurement has equal precision to the previous world average and will raise the average considerably.

3.2. Lifetime and $\Delta\Gamma_s$ in $B_s \rightarrow J/\psi + \phi$ Decays

The average B_s^0 lifetime and $\Delta\Gamma_s$ is measured using the decays $B_s^0 \rightarrow J/\psi + \phi$, where the heavy and light eigenstates can be identified. Since the heavy and light eigenstates are CP odd and even respectively if one neglects the small expected CP violation of these decays, CP of the decay products determines the mass eigenstate. In the decay of the pseudoscalar B_s^0 to the vectors J/ψ and ϕ , the CP of the final states is determined by the orbital angular configuration of the J/ψ and ϕ ; CP odd for P wave and CP even for S and D wave.

Both CDF and D0 measure the lifetime and $\Delta\Gamma_s$ using $1.7 fb^{-1}$ and $2.8 fb^{-1}$ respectively. In the CDF measurement the CP violating phase β_s is fixed to 0 while D0 allows it to float. The angular component of the fit is carried out using the transversity basis [23] and measures the mass eigenstate contributions. Fig. 4 shows the lifetime projections for the D0 and CDF fits. The fitted lifetime and $\Delta\Gamma_s$ from D0 are [23]

$$\begin{aligned}\tau_{B_s} &= 1.52 \pm 0.05(stat.) \pm 0.01(syst.) ps \\ \Delta\Gamma_s &= 0.19 \pm 0.07(stat.)^{+0.02}_{-0.01}(syst.) ps^{-1}\end{aligned}$$

and from CDF [24]

$$\begin{aligned}\tau_{B_s} &= 1.52 \pm 0.04(stat.) \pm 0.02(syst.) ps \\ \Delta\Gamma_s &= 0.08 \pm 0.06(stat.) \pm 0.01(syst.) ps^{-1}\end{aligned}$$

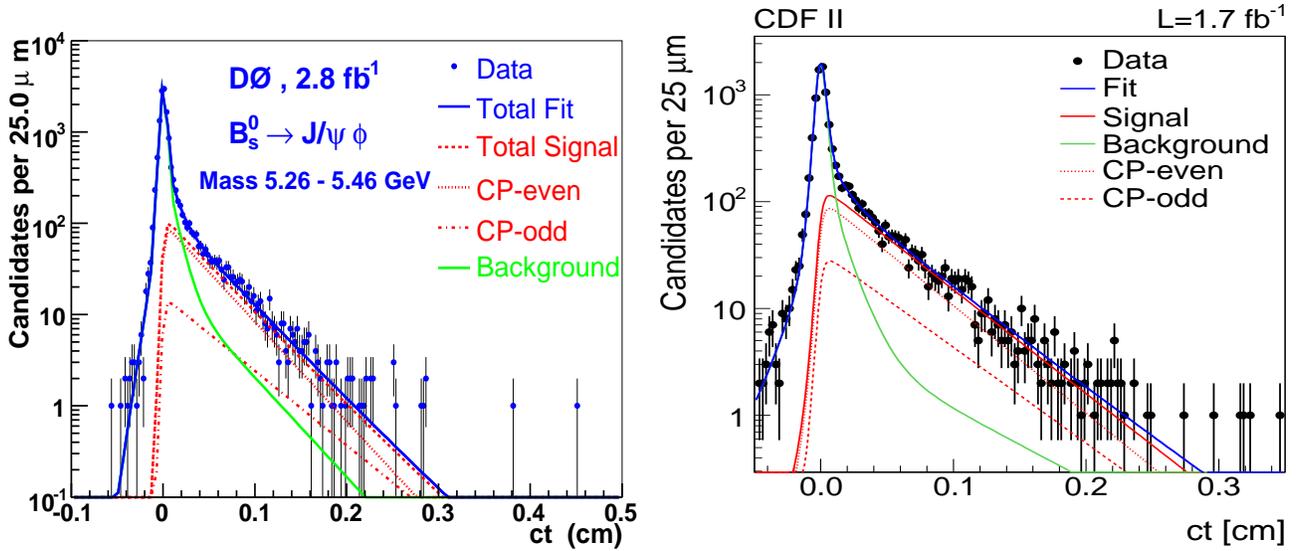


Figure 4: B_s^0 lifetime fit projections for measurements in the $J/\psi\phi$ channel at D0 (left) and CDF (right)

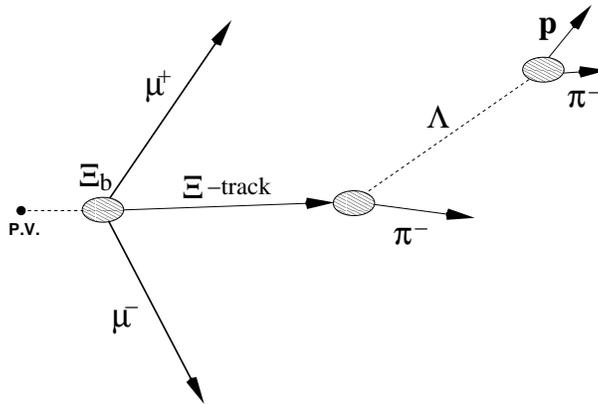


Figure 5: Decay topology for Ξ_b^- measurements.

Given the measured value of $\tau_{B_d} = 1.530 \pm 0.009$ [21], these results, including the flavor specific measurement, suggest the previous discrepancy in τ_{B_s}/τ_{B_d} was statistical, and $\tau_{B_s}/\tau_{B_d} = 1$ seems favored.

4. DIRECT OBSERVATION OF THE Ξ_b^- BARYON

Until recently, direct observation of baryons containing a b quark have been limited to the Λ_b (udb) baryon. The quark model predicts a charged baryon Ξ_b^- that is the dsb bound state. As an analog to $B_s^0 \rightarrow J/\psi\phi$ decays one will expect the Ξ_b^- to decay to a J/ψ and the doubly strange Ξ^- . CDF and D0 searched for the $\Xi_b^- \rightarrow J/\psi(\mu^+\mu^-) + \Xi^-(\Lambda\pi^-)$ decay chain (see Fig. 5) and measured the mass and relative production cross section of Ξ_b^- .

The selection of Ξ_b^- events is driven by the relative large decay lengths of the Ξ and Λ decay products, which are on the order of centimeters. For the D0 measurement which uses 1.3 fb^{-1} of data, large decay lengths are used by only selecting events where the Λ decay products have significantly large impact parameters with respect to the Ξ_b^- decay point. In the CDF analysis, the Ξ trajectory is reconstructed using hits in the silicon detectors, transforming a 5 track final state into a 3 track final state and reducing the backgrounds.

D0 made the first direct observation of Ξ_b^- with $15.2 \pm 4.4(\text{stat.})_{-0.4}^{+1.9}(\text{sys.})$ signal events at a significance of 5.5σ .

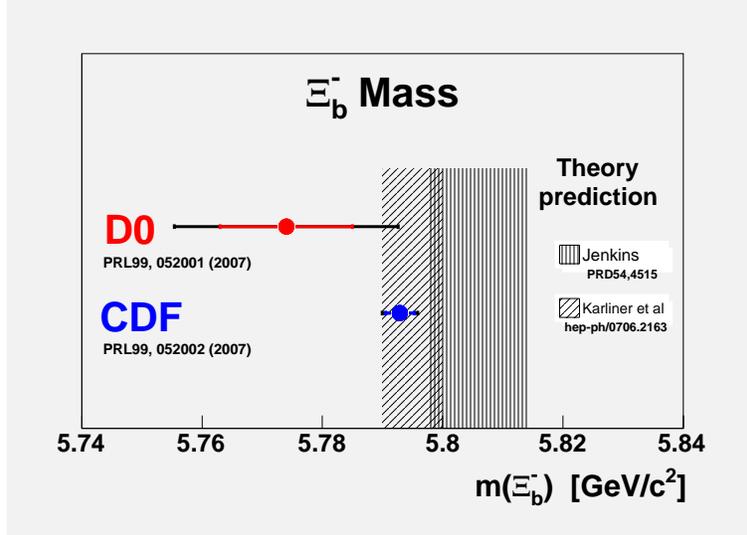


Figure 6: Comparison of Ξ_b^- mass measurements and theoretical predictions.

D0 measures the mass and relative cross section time branching ratio [25]:

$$M_{\Xi_b^-} = 5.774 \pm 0.011(stat.) \pm 0.015(syst.) \text{ GeV}/c^2$$

$$\frac{\sigma(\Xi_b^-) \times \mathcal{B}(\Xi_b^- \rightarrow J/\psi \Xi^-)}{\sigma(\Lambda_b) \times \mathcal{B}(\Lambda_b \rightarrow J/\psi \Lambda)} = 0.28 \pm 0.09(stat.)_{-0.08}^{+0.09}(syst.)$$

CDF observes 17.5 ± 4.3 signal events at a 7.7σ significance and measures the mass as well [26]:

$$M_{\Xi_b^-} = 5.793 \pm 0.003(stat.) \pm 0.007(syst.) \text{ GeV}/c^2$$

Fig. 6 shows the fitted mass results in comparison to theoretical predictions using hyperfine color interactions [27] and expansions in the heavy quark mass and number of colors [28]. The measured values are in good agreement at the low end of predicted values.

5. HEAVY QUARKONIUM POLARIZATION IN 1S STATES

The production of heavy quarkonium, $b\bar{b}$ and $c\bar{c}$ bound states, can be understood in the framework of NRQCD [29] where calculations of the total cross sections are in good agreement with previous charmonium results from CDF [6, 30]. The NRQCD approach to heavy quarkonium production predicts that for sufficiently large p_T the $J^{PC} = 1^{--}$ states should be transversely polarized [31]. Results from CDF Run I in charmonium [32] and bottomonium [33] do not show the predicted transverse polarization.

For measurements of the heavy quarkonium polarization, the polarization is parameterized using α :

$$\alpha = (\sigma_T - 2\sigma_L)/(\sigma_T + 2\sigma_L) \quad (4)$$

Here σ_T and σ_L are the transverse and longitudinal cross sections. For decays of the heavy quarkonium states to two muons, α is related to θ^* , the angle of the positive muon in the quarkonium center of mass frame with respect to the quarkonium direction in the lab frame:

$$\frac{dN}{d(\cos\theta^*)} \propto 1 + \alpha \cos^2\theta^* \quad (5)$$

The value of α can then be determined by studying the shape of the $\cos\theta^*$ distribution in heavy quarkonium decays.

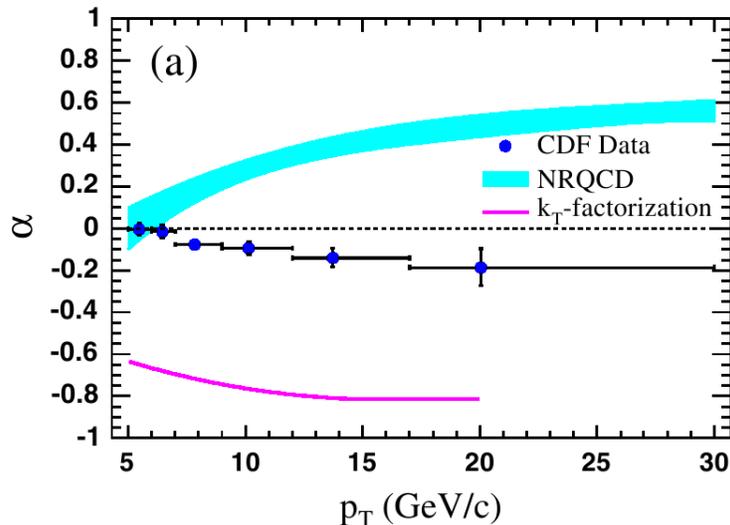


Figure 7: p_T dependence of the polarization parameter α in J/ψ production at CDF.

5.1. Polarization of the J/ψ

CDF measures the polarization of J/ψ and $\psi(2s)$ production as a function of $p_T > 5$ GeV/c using $\psi \rightarrow \mu\mu$ in 800 pb^{-1} of integrated luminosity. The J/ψ are chosen by reconstructing the dimuon mass and selecting events in a 3σ region around the central value. The background contribution is parameterized using events from J/ψ mass sidebands located 7σ from the signal region. The contribution of J/ψ from the decay of B hadrons is estimated by subtracting the distribution of events with negative ct , where there is only a contribution from prompt J/ψ production, from those with positive ct , where J/ψ are produced promptly and in B decays.

The distributions of $\cos\theta^*$ are fitted using templates that describe longitudinally and transversely polarized J/ψ . Fig. 7 shows the measured polarization parameter α as a function of the J/ψ p_T [34]. The polarization parameter α does not exhibit the transverse dominance predicted by NRQCD.

5.2. Polarization of the $\Upsilon(1S)$

D0 measures the polarization of $\Upsilon(1S)$ and $\Upsilon(2S)$ states in reconstructed dimuon pairs. As Fig. 8 illustrates, the Υ states overlap, leading to the importance of the mass fit in separating the contributions from the different states. The $\cos(\theta^*)$ for the transversely and longitudinally polarized states are model with simulated events that are reweighted to match the momentum distributions for Υ in data. The measured p_T dependent value of α [35] shown in Fig. 9 does agree with the CDF Run I measurement [33] and is in poor agreement with the theoretical prediction from NRQCD [36].

6. SUMMARY

The CDF and D0 experiments have measured a number of properties of hadrons containing heavy quarks that provide important feedback to the theoretical methods used in the study of these systems. The world best measurements of the lifetime and mass of the B_c^+ as well as the heavy quarkonium polarization test the abilities of various approaches in NRQCD to predict observables. The recent world best measurements of the B_s^0 lifetime greatly improve the precision and show good agreement with the predictions from *HQET*. The first direct observation of the Ξ_b^- suggests an exciting future in the study of baryons containing bottom quarks.

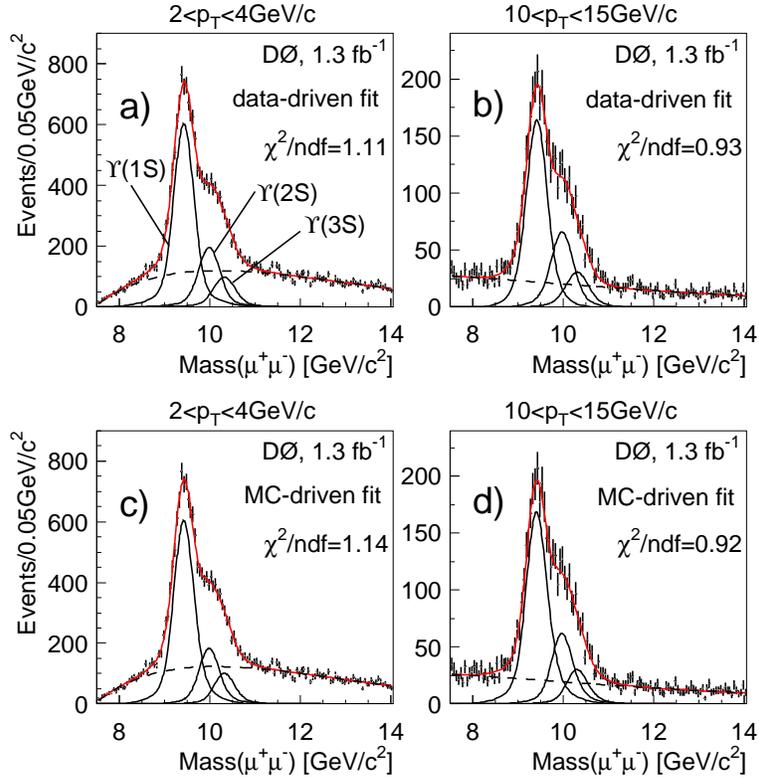


Figure 8: Examples of mass fits of Υ states decaying to two muons.

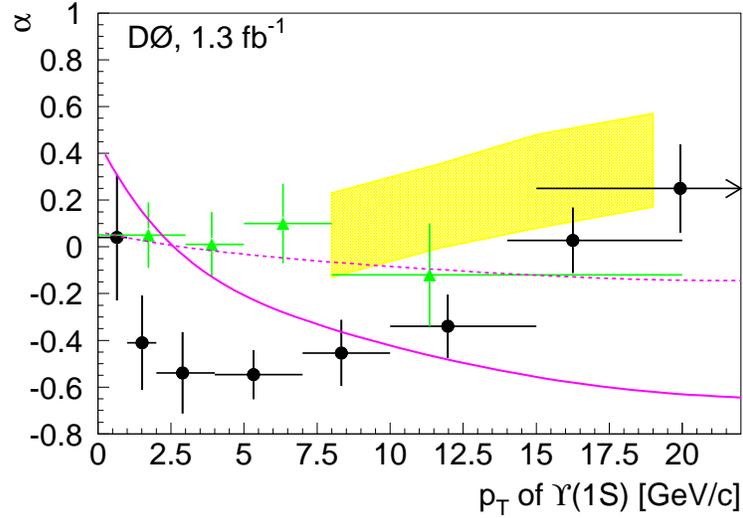


Figure 9: p_T dependence of the polarization parameter α in $\Upsilon(1S)$ production at D0.

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