B_s^0 mixing and decays at the Tevatron

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This short review reports on recent results from CDF and DØ experiments at the Tevatron collider on B_s^0 mixing and the lifetimes of B_s^0 and Λ_b.

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1. Introduction

Due to the large $b\bar{b}$ cross section at 1.96 TeV $p\bar{p}$ collisions, the Tevatron collider at Fermilalb is currently the largest source of b-hadrons and provides a very rich environment for the study of b-hadrons. It is also the unique place to study high mass b-hadrons such as B_s^0, B_c, b-baryons and excited b-hadrons states.

CDF and DØ are both symmetric multipurpose detectors [1, 2]. They are essentially similar and consist of vertex detectors, high resolution tracking chambers in a magnetic field, finely segmented hermitic calorimeters and muons momentum spectrometers, both providing a good lepton identification. They have fast data acquisition systems with several levels of online triggers and filters and are able to trigger at the hardware level on large track impact parameters, enhancing the potential of their physics programs.

2. B_s^0 mixing

The B^0-$\bar{B}^0$ mixing is a well established phenomenon in particle physics. It proceeds via a flavor changing weak interaction in which the flavor eigenstates B^0 and $\bar{B}^0$ are quantum superpositions of the two mass eigenstates B_H and B_L. The probability for a B^0 meson produced at time $t = 0$ to decay as B^0 or $\bar{B}^0$ at proper time $t > 0$ is an oscillatory function with a frequency Δm, the difference in mass between B_H and B_L. Oscillation in the B_d^0 system is well established experimentally with a precisely measured oscillation frequency Δm_d. The world average value is $\Delta m_d = 0.507 \pm 0.005$ ps^{-1} [3]. In the B_s^0 system, the expected oscillation frequency value within the standard model (SM) is approximately 35 times faster than Δm_d. In the SM, the oscillation frequencies Δm_d and Δm_s are proportional to the fundamental CKM matrix elements $|V_{td}|$ and $|V_{ts}|$ respectively, and can be used to determine their values. This determination, however, has large theoretical uncertainties, but the combination of the Δm_s measurement with the precisely measured Δm_d allows the determination of the ratio $|V_{td}|/|V_{ts}|$ with a significantly smaller theoretical uncertainty.

Both DØ and CDF have performed B_s^0-$\bar{B}_s^0$ mixing analysis using 1 fb^{-1} of data [4, 5, 6]. The strategies used by the two experiments to measure Δm_s are very similar. They schematically proceed as follows: the B_s^0 decay is reconstructed in one side of the event and its flavor at decay time is determined from its decay products. The B_s^0 proper decay time is measured from the the difference between the B_s^0 vertex and the primary vertex of the event. The B_s^0 flavor at production time is determined from information in the opposite and/or the same-side of the event. finally, Δm_s is extracted from an unbinned maximum likelihood fit of mixed and unmixed events, which combines, among other information, the decay time, the decay time resolution and b-hadron flavor tagging. In the following only the latest CDF result is presented.

2.1. B_s^0 signal yields

The CDF experiment has reconstructed B_s^0 events in both semileptonic $B_s^0 \to D_s^{-(\star)}\ell^+\nu_\ell X$ ($\ell = e$ or μ) and hadronic $B_s^0 \to D_s^-(\pi^+\pi^-)\pi^+$ decays. In both cases the D_s^- is reconstructed in the channels $D_s^- \to \phi\pi^-$, $D_s^- \to K^{\star 0}K^-$ and $D_s^- \to \pi^-\pi^+\pi^-$ with $\phi \to K^+K^-$ and $K^{\star 0} \to K^+\pi^-$. Additional partially reconstructed hadronic decays, $B_s^0 \to D_s^{\star -}\pi^+$ and $B_s^0 \to D_s^-\rho^+$ with unreconstructed γ and π^0 in $D_s^{\star -} \to D_s^-(\phi\pi^-)\gamma/\pi^0$ and $\rho^+ \to \pi^+\pi^0$ decay modes, have also been used. The signal yields are 61,500 semileptonic decays, 5,600 fully reconstructed and 3,100 partially reconstructed hadronic decays. This correponds to an effective statistical increase in the number of reconstructed events of 2.5 compared to the first CDF published analysis [5]. This improvement was obtained mainly by using particle identification in the event selection, by using the artificial neural network (ANN) selection for hadronic modes and by loosening the kinematical selection. Figure 1 shows the distributions of the invariant masses of the $D_s^+(\phi\pi^+)\ell^-$ pairs $m_{D_s\ell}$ and of the $\bar{B}_s^0 \to D_s^+(\phi\pi^+)\pi^-$ decays including the contributions from the partially reconstructed hadronic decays.

2.2. B_s^0 proper decay time reconstruction

The proper decay time of the reconstructed B_s^0 events is determined from the transverse decay length L_{xy} which corresponds to the distance between the primary vertex and the reconstructed B_s^0 vertex projected onto the transverse plane to the beam axis. For

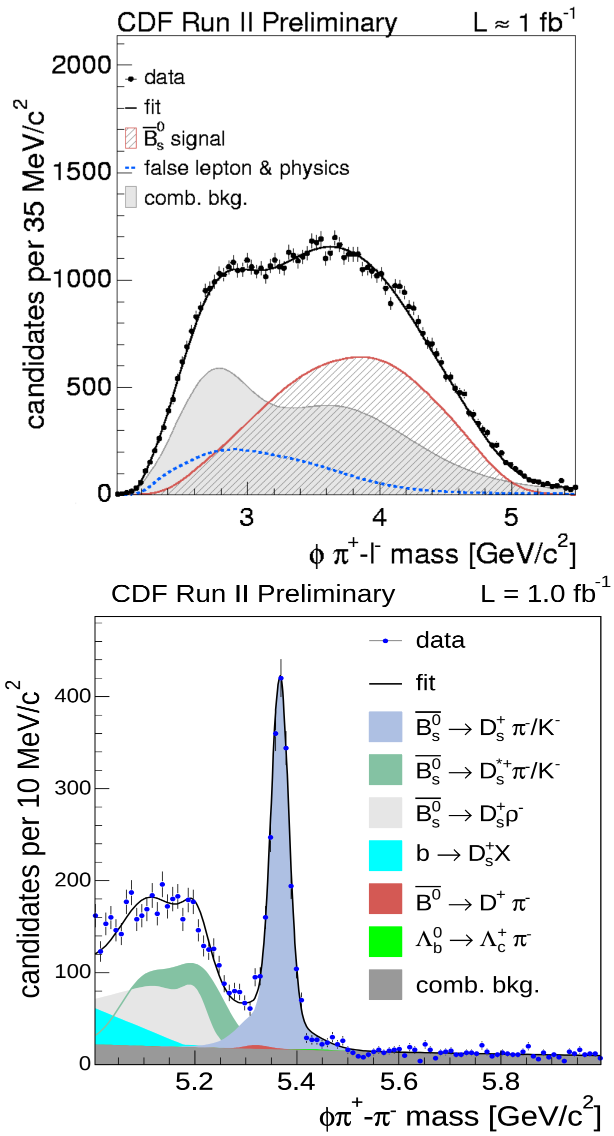

Figure 1: The invariant mass distributions for the $D_s^+(\phi\pi^+)\ell^-$ pairs (upper plot) and for the $\bar{B}_s^0 \to D_s^+(\phi\pi^+)\pi^-$ decays (bottom plot) including the contributions from the partially reconstructed hadronic decays.

the fully reconstructed B_s^0 decay channels the proper decay time is well defined and is given by:

$$t = L_{xy}\frac{M(B_s^0)}{P_T(B_s^0)}$$

For the partially reconstructed B_s^0 decay channels it is given by:

$$t = L_{xy}\frac{M(B_s^0)}{P_T(D_s\ell(\pi))} \times K, \quad K = \frac{P_T(D_s\ell(\pi))}{P_T(B_s^0)}$$

The K-factor takes into account the missing particles[1] in the event. It's distribution for different B_s^0 decay channels is obtained from Monte Carlo simulation. For illustration, figure 2 shows the K-factor distributions obtained by CDF in semileptonic and partially reconstructed hadronic decays. The proper time resolution which is one of the critical parameters for Δm_s measurement, has contributions from the uncertainty on L_{xy} and from the momentum of the missing decay products. For the fully reconstructed decay modes, the mean proper decay time resolution obtained is 87 fs, which corresponds to the quarter of an oscillation period at $\Delta m_s = 17.8$ ps^{-1}. For the partially reconstructed hadronic and semileptonic decays, the average proper decay time resolutions are $\sigma_t = 97$ fs and $\sigma_t = 168$ fs respectively.

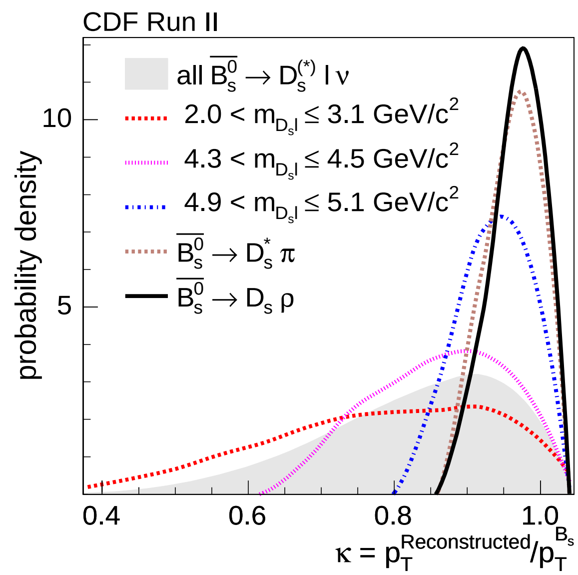

Figure 2: The distribution of the correction factor K in semileptonic and partially reconstructed hadronic decays from Monte Carlo simulation.

2.3. Flavor tagging

The flavor of the B_s^0 at the decay time is determined precisely from its decay products. At production time, the flavor of the B_s^0 is determined using both opposite-side and the same-side b-flavor tagging techniques. The opposite-side tagging exploits the fact that b quarks are dominently produced in $b\bar{b}$ pairs in hadron colliders. Same side tagging relies on the charges and the identity of associated particles produced in the fragmentation of the b quark that produces the reconstructed B_s^0. The effectiveness, $Q \equiv \epsilon\mathcal{D}^2$, of these techniques is quantified with

[1] Neutrino, π^0 and γ.

an efficiency ϵ, the fraction of signal candidates with a flavor tag, and a dilution $\mathcal{D} = 1 - 2\omega$, where ω is the probablity of mistagging.

The taggers used in the opposite-side of the event are the charge of the lepton (e and μ), the jet charge and the charge of identified kaons. The information from these taggers are combined in an ANN. The use of an ANN improves the combined opposite-side tag effectiveness by 20% ($Q = 1.8 \pm 0.1\%$) compared to the previous analysis [5]. The dilution is measured in data using large samples of kinematically similar B_d^0 and B^+ decays.

The same-side flavor tags rely on the identification of the charge of the kaon produced from the left over $\bar{s}$ in the process of B_s^0 fragmentation. Any nearby charged particle to the reconstructed B_s^0, identified as a kaon, is expected to be correlated to the B_s^0 flavor, with a K^+ correlated to a B_s^0 and K^- correlated to $\bar{B}_s$. An ANN is used to combine particle-identification likelihood based on information from the dE/dx and from the Time-of-Flight system, with kinematic quantities of the kaon candidate into a single variable. The dilution of the same side tag is estimated using Monte Carlo simulated data samples. The predicted effectiveness of the same-side flavor tag is Q=3.7% (4.8%) in the hadronic (semileptonic) decay sample. The use of ANN increased the Q value by 10% compared to the previous analysis [5].

If both a same-side tag and an opposite-side tag are present, the information from both tags are combined assuming they are independent.

2.4. Δm_s measurement

An unbinned maximum likelihood fit is used to search for B_s^0 oscillations in the reconstructed B_s^0 decays samples. The likelihood combines masses, decay time, decay-time rsolution, and flavor tagging information for each reconstructed B_s^0 candidate, and includes terms for signal and each type of background. The technique used to extract Δm_s from the unbinned maximum likelihood fit, is the amplitude scan method [7] which consists of multiplying the oscillation term of the signal probablity density function in the likelihood by an amplitude $\mathcal{A}$, and fit its value for different Δm_s values. The oscillation amplitude is expected to be consistent with $\mathcal{A} = 1$ when the probe value is the true oscillation frequency, and consitent with $\mathcal{A} = 0$ when the probe value is far from the true oscillation frequency. Figure 3 shows the fitted value of the amplitude as function of the oscillation frequency for the combination of semileptonic and hadronic B_s^0 candidates.

The sensitivity is 31.3 ps^{-1} for the combination[2]

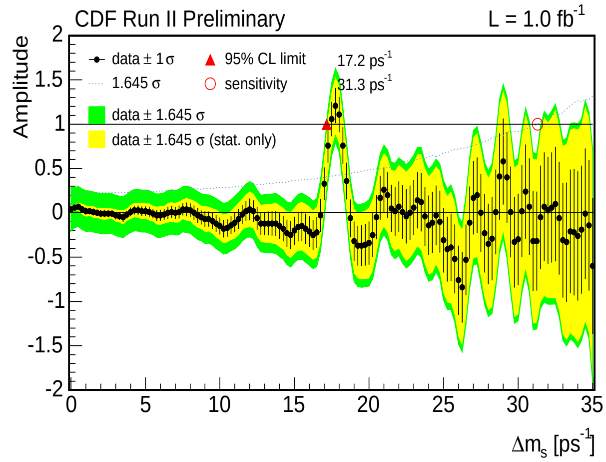

Figure 3: The measured amplitude values and uncertainties versus the B_s^0-$\bar{B}_s^0$ oscillation frequency Δm_s.

of all hadronic and semileptonic decay modes. At $\Delta m_s = 17.75$ ps^{-1}, the observed amplitude $\mathcal{A} = 1.21 \pm 0.20$ (stat.) is consistent with unity and $\mathcal{A}/\sigma_{\mathcal{A}} = 6.05$ where $\sigma_{\mathcal{A}}$ is the statistical uncertainty on $\mathcal{A}$. This shows that the amplitude is inconsistent with zero and that the data are compatible with B_s^0-$\bar{B}_s^0$ oscillations with that frequency. The significance of the signal is evaluated using the logarithm likelihood ratio $\Lambda \equiv \log\left[\mathcal{L}^{\mathcal{A}=0}/\mathcal{L}^{\mathcal{A}=1}(\Delta m_s)\right]$. Figure 4 shows Λ as function of Δm_s. At the minimum $\Delta m_s = 17.77$ ps^{-1}, $\Lambda = -17.26$. The significance of the signal is the probability that randomly tagged data would produce a value of Λ lower than -17.26 at any Δm_s value. This probability has been determined to be 8×10^{-8} which correponds to a significance of 5.4 σ.

The Δm_s value is determined from the fit for oscillation frequency at amplitude value $\mathcal{A} = 1$. The fit result is $\Delta m_s = 17.77 \pm 0.10\,(\text{stat.}) \pm 0.07\,(\text{sys.})\ \text{ps}^{-1}$. The systematic error is completely dominated by the time scale uncertainty.

The measured B_s^0-$\bar{B}_s^0$ oscillation frequency is used to determine the ratio $|V_{td}/V_{ts}|$. If one uses as inputs $m_{B_d^0}/m_{B_s^0} = 0.98390$ [8] with negligeable uncertainty, $\Delta m_d = 0.507 \pm 0.005$ ps^{-1} [3] and $\xi = 1.21^{+0.047}_{-0.035}$ [9], one finds:

$$
\begin{aligned}
|V_{td}/V_{ts}| &= \xi\sqrt{\frac{\Delta m_d m_{B_s^0}}{\Delta m_s m_{B_d^0}}} \\
&= 0.2060 \pm 0.0007(\text{exp})^{+0.0081}_{-0.006}(\text{theor})
\end{aligned}
$$

[2] 19.3 ps^{-1} for the semileptonic decays alone and 30.7 ps^{-1} for the hadronic decays alone.

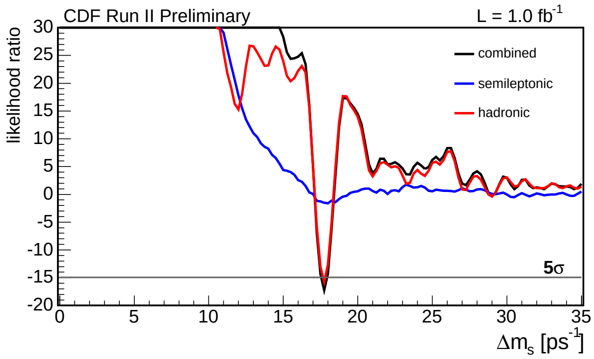

Figure 4: The logarithm of the ratio of likelihoods $\Lambda \equiv \log\left[\mathcal{L}^{\mathcal{A}=0}/\mathcal{L}^{\mathcal{A}=1}(\Delta m_s)\right]$, versus the oscillation frequency. The horizontal line indicates the value $\Lambda = -15$ that corresponds to a probability of 5.7×10^{-7} (5σ) in the case of randomly tagged data.

3. b-hadrons lifetime measurements at the Tevatron RunII

Lifetime measurements of b-hadrons provide important information on the interactions between heavy and light quarks. These interactions are responsible for lifetime hierarchy among b-hadrons observed experimentally:

$$\tau(B^+) \geq \tau(B_d^0) \simeq \tau(B_s^0) > \tau(\Lambda_b) \gg \tau(B_c)$$

Currently most of the theoretical calculations of the light quark effects on b hadrons lifetimes are performed in the framework of the Heavy Quark Expansion (HQE) [10] in which the decay rate of heavy hadron to an inclusive final state f is expressed as an expansion in $\Lambda_{\rm QCD}/m_b$. At leading order of the expansion, light quarks are considered as spectators and all b hadrons have the same lifetime. Differences between meson and baryon lifetimes arise at $\mathcal{O}(\Lambda^2_{\rm QCD}/m_b^2)$ and splitting of the meson lifetimes appears at $\mathcal{O}(\Lambda^3_{\rm QCD}/m_b^3)$.

Both CDF and DØ have performed a number of b-hadrons lifetimes measurements for all b-hadrons species. Most of these measurements are already included in the world averages and are summarised in [11]. In this note focus will be on the latest results on B_s^0 and Λ_b measurements from CDF and DØ .

3.1. B_s^0 lifetime measurements

In the standard model the light B_L and the heavy B_H mass eigenstates of the mixed B_s^0 system are expected to have a sizebale decay width difference of order $\Delta\Gamma_s = \Gamma_L - \Gamma_H = 0.096 \pm 0.039$ ps^{-1} [12]. If CP violation is neglected, the two B_s^0 mass eigenstates are expected to be CP eigenstates, with B_L being the CP even state and B_H being the CP odd state.

Various B_s^0 decay channels have a different proportion of B_L and B_H eigenstates:

- Flavor specific decays, such as $B_s^0 \to D_s^+\ell^-\bar{\nu}_\ell$ and $B_s^0 \to D_s^+\pi^-$ have equal fractions of B_L and B_H at $t = 0$. The fit to the proper decay length distributions of these decays with a single signal exponential lead to a flavor specific lifetime:

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

- Fully exclulsive $B_s^0 \to J/\psi\phi$ decays are expected to be dominated by CP even state and its lifetime.

3.1.1. B_s^0 lifetime measurements in flavor specific modes

Both CDF and DØ have measured B_s^0 lifetime in the semileptonic decays $B_s^0 \to D_s^+\ell^-\bar{\nu}_\ell$. Results based on respectively 360 and 400 pb^{-1} were presented at the FPCP06 conference last year [13, 14]. These are:

$$\begin{aligned}\tau^{\rm D\O}_{B_s}(fs) &= 1.398 \pm 0.044({\rm stat})^{+0.028}_{-0.025}({\rm sys})\ {\rm ps}\\ \tau^{\rm CDF}_{B_s}(fs) &= 1.381 \pm 0.055({\rm stat})^{+0.052}_{-0.046}({\rm sys})\ {\rm ps.}\end{aligned}$$

The DØ measurement provides the world best B_s^0 lifetimes measurement in the flavor specific decays.

CDF has also measured B_s^0 lifetime in the fully hadronic modes, $B_s^0 \to D_s^+\pi^-$ and $B_s^0 \to D_s^+\pi^+\pi^-\pi^-$. To date the analysis is based only on 360 pb^{-1}. The B_s^0 lifetime is extracted from a simultaneous fit to the mass and decay length distributions of the two decay modes. Figure 5 shows the distribution of the proper decay length and fits to the B_s^0 candidates. The measured B_s^0 lifetime is [15] $\tau^{\rm CDF}_{B_s} = 1.60 \pm 0.10({\rm stat}) \pm 0.02({\rm sys})$ ps. These measurements in the semileptonic and the hadronic decay modes will soon be updated with 1 fb^{-1} of data.

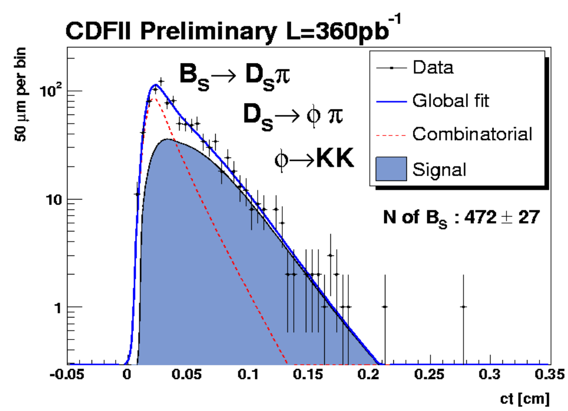

Figure 5: Proper decay length distribution of the B_s^0 candidates, with the fit result superimposed. The shaded region represents the signal.

3.1.2. B_s^0 lifetime measurements in $B_s^0 \to J/\psi\phi$

DØ experiment has performed a new B_s^0 mean lifetime measurement in $B_s^0 \to J/\psi\phi$ decay mode. The analysis uses a data set of 1.1 fb^{-1} and extracts three parameters, the average B_s^0 lifetime $\bar{\tau}(B_s^0) = 1/\Gamma_s$, the width difference between the B_s^0 mass eigenstates $\Delta\Gamma_s$ and the CP-violating phase ϕ_s, through a study of time-dependent angular distribution of the decay products of the J/ψ and ϕ mesons. Figure 6 shows the distribution of the proper decay length and fits to the B_s^0 candidates. From a fit to the CP-conserving time-dependent angular distributions of untagged decay $B_s^0 \to J/\psi\phi$, the measured values of the average lifetime of the B_s^0 system and the width difference between the two B_s^0 mass eigenstates are [16]:

$$\begin{aligned} \tau_{B_s}^{D\O} &= 1.52 \pm 0.08(\text{stat})^{+0.01}_{-0.03}(\text{sys})\ \text{ps} \\ \Delta\Gamma_s &= 0.12^{+0.08}_{-0.10}(\text{stat}) \pm 0.02(\text{sys})\ \text{ps}^{-1} \end{aligned}$$

Allowing for CP-violation in B_s^0 mixing, DØ provides

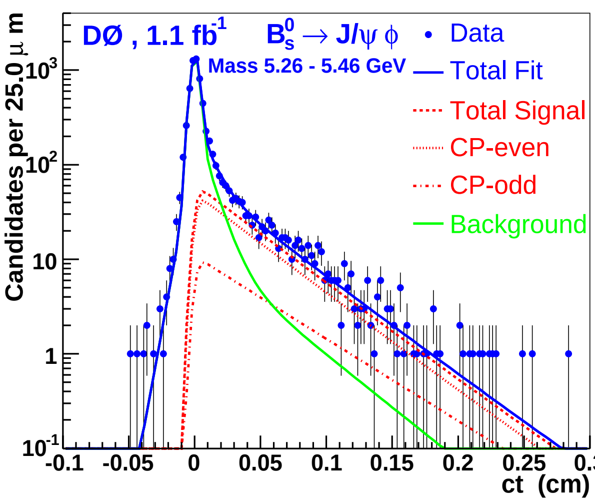

Figure 6: The proper decay length, ct, of the B_s^0 candidates in the signal mass region. The curves show: the signal contribution, dashed (red); the CP-even (dotted) and CP-odd (dashed-dotted) contributions of the signal, the background, light solid (green); and total, solid (blue).

the first direct constraint on the CP-violating phase, $\phi_s = -0.79 \pm 0.56(\text{stat})^{+0.14}_{-0.01}(\text{sys})$, value compatible with the standard model expectations.

3.2. Λ_b lifetime measurements

Both CDF and DØ have measured the Λ_b lifetime in the golden decay mode $\Lambda_b \to J/\psi\Lambda$. Similar analysis procedure have been used by the two experiments, on respectively 1 and 1.2 fb^{-1} of data. . The Λ_b lifetime was extracted from an unbinned simultaneous likelihood fit to the mass and proper decay lenghts distributions. To cross check the validity of the method similar analysis were performed on the kinematically similar decay $B^0 \to J/\psi K_s$. Figure 7 shows the proper decay time distributions of the $J/\psi\Lambda$ pair samples from CDF and DØ. The Λ_b lifetime values extracted from the maximum likelihood fit to these distributions are [17, 18]: $\tau_{\Lambda_b}^{CDF} = 1.580 \pm 0.077(\text{stat}) \pm 0.012(\text{sys})$ ps and $\tau_{\Lambda_b}^{D\O} = 1.218^{+0.130}_{-0.115}(\text{stat}) \pm 0.042(\text{sys})$ ps.

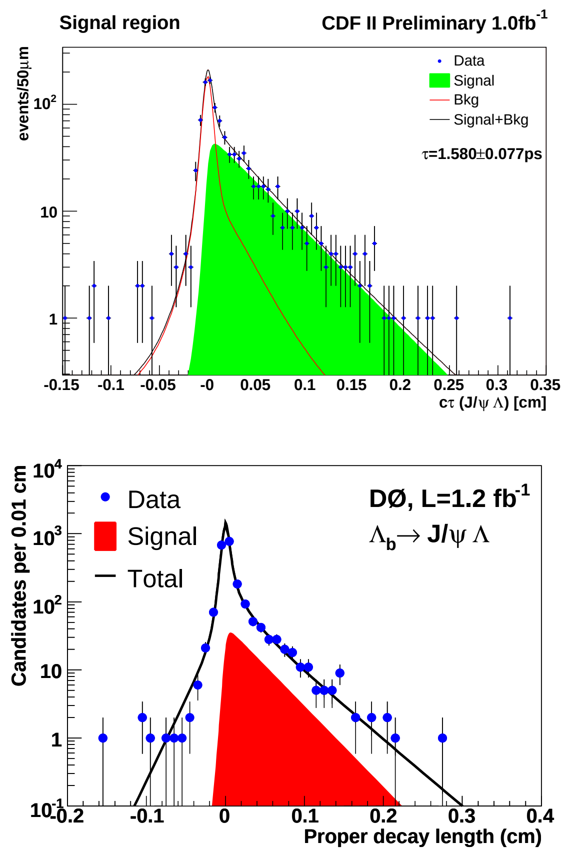

Figure 7: Proper decay length distribution of the Λ_b candidates from CDF (upper plot) and DØ (bottom plot), with the fit result superimposed. The shaded regions represent the signal.

The CDF measured value is the single most precise measurement of the Λ_b lifetime but is 3.2 σ higher than the current world average [3] ($\tau_{\Lambda_b}^{W.A.} = 1.230 \pm 0.074$ ps). The DØ result however is consistent with the world average value. The CDF and DØ $B^0 \to J/\psi K_s$ measured lifetimes are: $\tau_{B^0}^{CDF} = 1.551 \pm 0.019(\text{stat}) \pm 0.011(\text{sys})$ ps and $\tau_{B^0}^{D\O} = 1.501^{+0.078}_{-0.074}(\text{stat}) \pm 0.05(\text{sys})$ ps. Both are compatible with the world average value [11] ($\tau_{B^0}^{W.A.} = 1.527 \pm 0.008$ ps). One needs more experimental input to conclude about the difference between the CDF and the DØ/world average Λ_b lifetime values. One of the Λ_b decay modes that can be exploited is the fully hadronic $\Lambda_b \to \Lambda_c^+ \pi^-$, with $\Lambda_c^+ \to pK^-\pi^+$. CDF has in this decay mode about 3000 reconstructed events which is 5.6 more than in $\Lambda_b \to J/\psi\Lambda$.

Recently, the DØ experiment has performed a new measurement of the Λ_b lieftime in the semileptonic decay channel $\Lambda_b \to \Lambda_c^+ \mu^- \bar{\nu}_\mu X$, with $\Lambda_c^+ \to K_s p$ [19]. This measurement is based on 1.2 fb^{-1} of data. As this is a partially reconstructed decay mode the proper decay time is corrected by a kinematical factor $K = P_T(\Lambda_c^+ \mu^-)/P_T(\Lambda_b)$, estimated from Monte Carlo simulation. The Λ_b lifetime is not determined from the usually performed unbinned maximum likelihood fit, but is extracted from the number of $K_s p \mu^-$ events in bins of their visible proper decay length (VPDL). Figure 8 shows the distribution of the number of $\Lambda_c^+ \mu^-$ as function of the VPDL with the result of the fit superimposed. The fitted Λ_b lifetime value is $\tau(\Lambda_b) = 1.28 \pm 0.12(\text{stat}) \pm 0.09(\text{sys})$ ps. This results is compatible with the lifetime value from $\Lambda_b \to J/\psi\Lambda$ and the world average.

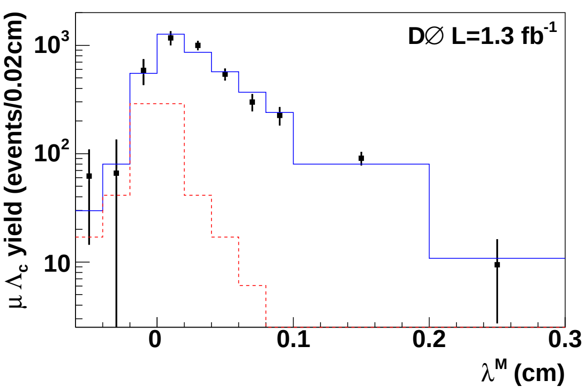

Figure 8: Measured yields in the VPDL bins and the result of the lifetime fit. The dashed line shows the $c\bar{c}$ contribution.

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