

Recent Lifetime and Mixing Measurements at the Tevatron

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We present the latest B hadron lifetimes, B_s^0 mixing, and D^0 mixing measurements using up to 3.0 fb^{-1} of data collected by CDF and D0 experiments at Fermilab. The B_s^0 lifetime is measured from both $J/\psi\phi$ (CP admixture) and flavor specific channels, and the B_c lifetime is obtained from semileptonic channels. Following the B_s^0 oscillation frequency measurement at CDF in 2006, the D0 collaboration now observes B_s^0 oscillation at a significance of about 3σ . Since the first D^0 mixing evidence established at B factories in 2007, CDF has observed D^0 mixing at a significance of about 4σ level, the first time from hadron collider.

1. Introduction

Since the last FPCP conference in 2007, many interesting measurements have been carried at CDF and D0 experiments thanks to the smoothly operating Tevatron. By March 30 2008, the Tevatron has delivered about 4 fb^{-1} of integrated luminosity, while CDF and D0 recorded about 3.2 and 3.4 fb^{-1} separately. The measurements related to these proceedings use data from 1.0 fb^{-1} up to 2.8 fb^{-1} . The CDF and D0 experiments are described in detail in Ref. [1, 2]. For these proceedings, the recent B_s^0 and B_c lifetimes results, B_s^0 and D^0 mixing parameters will be presented.

2. Lifetimes measurement

In the frame work of the Heavy Quark Expansion Theory (HQET), the inclusive decay rate of B hadrons is given by [3]:

$$\Gamma = \frac{G_F^2 m_b^5}{192\pi^3} |V_{cb}|^2 \left[\Gamma_0 + \Gamma_2 \left(\frac{\Lambda_{QCD}}{m_b} \right)^2 + \Gamma_3 \left(\frac{\Lambda_{QCD}}{m_b} \right)^3 \right] \quad (1)$$

in the limit of $m_b \rightarrow \infty$ or a free quark model, all the B hadrons should have same lifetime, given by the first term of Eq. 1. The first correction arises from the kinetic and chromomagnetic operator which is at order of $(\Lambda_{QCD}/m_b)^2$, the second correction arises from weak annihilation or Pauli interference which is at order of $(\Lambda_{QCD}/m_b)^3$. Both theoretical and experimental uncertainties could be reduced if we measure the lifetime ratios of different B hadrons. Only the second correction will enter the lifetime ratio calculation. For example, Pauli interference will increase $\tau(B^+)/\tau(B^0)$ and $\tau(\Lambda_b)/\tau(B^0)$, and weak annihilation or scattering will reduce it. As a result, the lifetime ratios are not exactly unity for different B hadrons, and the precise measurements of the ratios can help test HQET at order of $(\Lambda_{QCD}/m_b)^3$. The current experimental situation for τ_{B^+}/τ_{B^0} , $\tau_{B_s^0}/\tau_{B^0}$ and $\tau_{\Lambda_b}/\tau_{B^0}$ are shown in Fig. 1, where one can see that the experimental result and theoretical prediction agree well for the B^+

case. For the B_s^0 case, there is still some discrepancy between the prediction and measurements, while for the Λ_b , the theoretical prediction range is large and the experimental results have large uncertainty at this time.

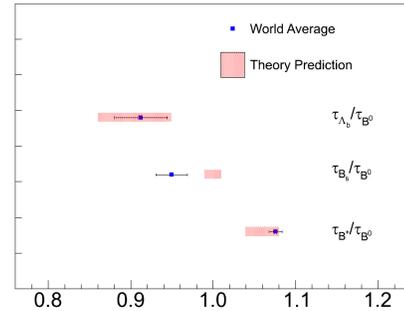


Figure 1: Current lifetime ratios for different B hadrons with theoretical predictions from Ref. [4].

2.1. B_s^0 lifetime measurements

The B_s^0 meson can decay directly or decay after it oscillates to \bar{B}_s^0 . Time evolution of an arbitrary system $a(t)|B_s^0\rangle + b(t)|\bar{B}_s^0\rangle$ is governed by the Schrödinger Equation

$$i \frac{d}{dt} \begin{pmatrix} a \\ b \end{pmatrix} = \left(M - i \frac{\Gamma}{2} \right) \begin{pmatrix} a \\ b \end{pmatrix}, \quad (2)$$

where M and Γ are mass and decay matrices. Two mass eigenstates B_L^0 and B_H^0 appear as a result of this mixing property. The eigenstates have different decay widths Γ_L and Γ_H . The average decay width is defined as $\Gamma = (\Gamma_L + \Gamma_H)/2$, while the decay width difference is $\Delta\Gamma = \Gamma_L - \Gamma_H$. $\Delta\Gamma$ also probes new physics since it's related to quantity ϕ_s by $\Delta\Gamma = 2|\Gamma_{12}|\cos(\phi_s)$, where $\phi_s = \arg(-M_{12}/\Gamma_{12})$, while Γ_{12} and M_{12} are matrix elements coming from the box diagram as shown in Fig. 2. New physics is likely to increase ϕ_s , so $\Delta\Gamma$ could be smaller than the Standard Model prediction.

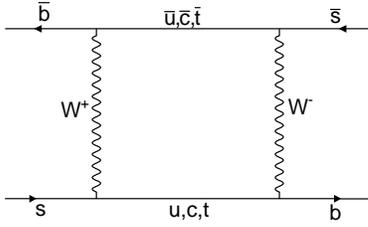


Figure 2: Feynman diagram for $B_s^0 - \bar{B}_s^0$ mixing.

2.1.1. Results from $B_s^0 \rightarrow J/\psi\phi$ channel

The data at CDF (1.7 fb^{-1}) and at D0 (2.8 fb^{-1}) were collected by di-muon triggers [1, 2] which preferentially selects events containing $J/\psi \rightarrow \mu^+\mu^-$ decays. An artificial neural network is trained to separate signal and combinatorial backgrounds at CDF, which yields about 2500 signal events, while a cut based selection procedure is used to select data at D0, giving about 2000 signal events. The mass projections from CDF and D0 are shown in Fig. 3 and Fig. 4.

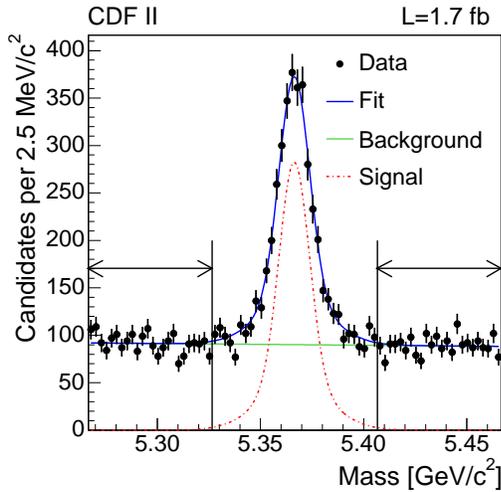


Figure 3: The invariant mass distribution of B_s^0 candidates from CDF

Since B_s^0 is a pseudo-scalar meson, J/ψ and ϕ are both vector mesons, the final states are admixtures of CP eigenstates, where S and D waves are CP even, P wave is CP odd. To separate the CP eigenstates, the angular distribution are used [5]. CP violation is predicted to be tiny in the Standard Model, so the CP phase is fixed to zero at CDF, while it's allowed to float at D0 with flavor tagging. To extract lifetime τ_s and decay width difference $\Delta\Gamma$, the final fit is done with an un-binned maximum likelihood method on mass, lifetime and angular variables.

The measured lifetime and decay width difference

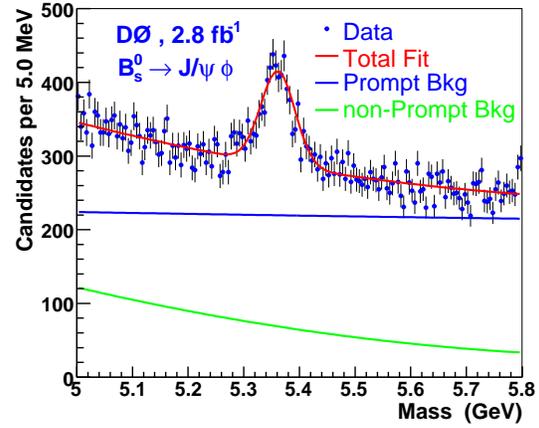


Figure 4: The invariant mass distribution of B_s^0 candidates from D0

results from CDF are [6]

$$\begin{aligned}\tau &= 1.52 \pm 0.04(\text{stat}) \pm 0.02(\text{syst}) \text{ ps} \\ \Delta\Gamma &= 0.08 \pm 0.06(\text{stat}) \pm 0.01(\text{syst}) \text{ ps}^{-1}\end{aligned}$$

where CP conservation is assumed, and the lifetime fit projection is shown in Fig. 5. At D0, the CP violation phase is allowed to float (with external constraint on strong phases from $B^0 \rightarrow J/\psi K^{*0}$), the results are [7]

$$\begin{aligned}\tau &= 1.52 \pm 0.05(\text{stat}) \pm 0.01(\text{syst}) \text{ ps} \\ \Delta\Gamma &= 0.19 \pm 0.07(\text{stat})_{-0.01}^{+0.02}(\text{syst}) \text{ ps}^{-1}\end{aligned}$$

The lifetime fit projection is shown in Fig. 6.

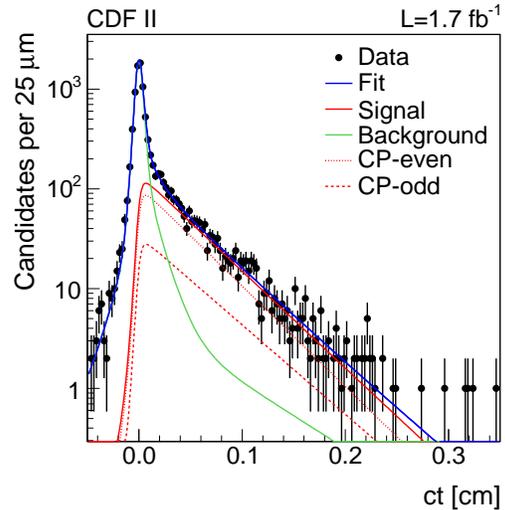


Figure 5: Proper decay time projection of the $B_s^0 \rightarrow J/\psi\phi$ fit at CDF. CP even fraction is dominant, and the slope difference of even and odd curves indicates decay width difference.

The systematic errors are controlled very well at both CDF and D0. Systematic errors considered at

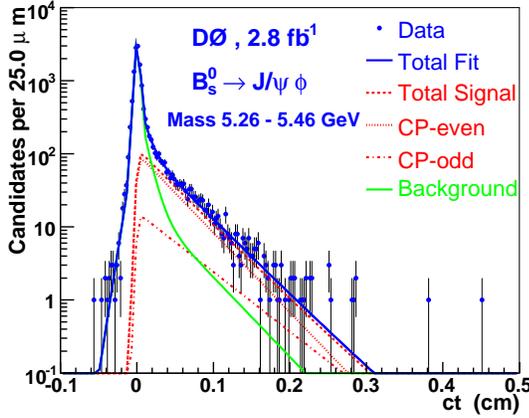


Figure 6: Proper decay time projection of the $B_s^0 \rightarrow J/\psi\phi$ fit at D0.

CDF include background angular distribution, mass model, lifetime resolution model, $B^0 \rightarrow J/\psi K^{*0}$ contamination, detector acceptance, and silicon detector alignment. Systematic errors considered at D0 include procedure test, acceptance, reconstruction algorithm, background model, and detector alignment.

2.1.2. Results from $B_s^0 \rightarrow D_s(\phi\pi)\pi X$ channel

This channel is different from $B_s^0 \rightarrow J/\psi\phi$, because it's flavor specific, i.e. B_s^0 can only decay into $D_s^-\pi^+X$, while \bar{B}_s^0 can only decay into $D_s^+\pi^-X$. By fitting the signal with one exponential function, the obtained lifetime is related to average decay width and decay width difference by

$$\tau(B_s^0)_{fs} = \frac{1}{\Gamma} \left(1 + \left(\frac{\Delta\Gamma}{2\Gamma} \right)^2 \right) / \left(1 - \left(\frac{\Delta\Gamma}{2\Gamma} \right)^2 \right) \quad (3)$$

assuming no CP violation. So it can be used to constrain Γ and $\Delta\Gamma$ in the global fit.

The result is obtained at CDF only, from both fully reconstructed $B_s^0 \rightarrow D_s\pi$ and partially reconstructed channels such as $B_s^0 \rightarrow D_s\rho(\pi^+\pi^0)$ where the π^0 is not reconstructed. In the partially reconstructed channels, a ‘‘K’’ factor is introduced to correct the proper decay time for missing mass and transverse momentum

$$ct = \frac{L_{xy} m_B^{rec}}{p_T} K$$

where L_{xy} is the projection of decay length in the $x-y$ plane, m_B^{rec} is reconstructed mass, p_T is reconstructed transverse momentum, and

$$K = \frac{m_B p_T}{m_B^{rec} p_T^{true}}$$

where m_B is the true mass and p_T^{true} is the true transverse momentum. The ‘‘K’’ factor distributions for different partially reconstructed channels are obtained from Monte Carlo and shown in Fig. 7.

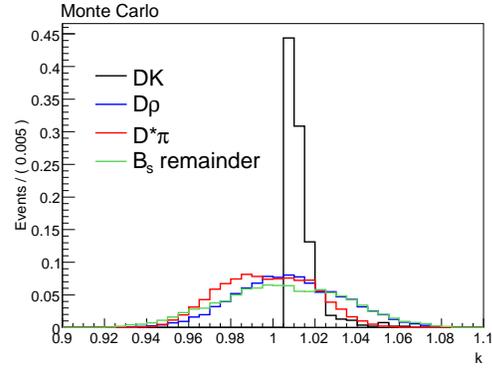


Figure 7: K factor distribution for each channel. The DK channel is fully reconstructed, but treated in the same way, since the K track is misidentified and a K factor is needed.

The data (1.3 fb^{-1}) were collected by displaced-vertex trigger [8] at CDF. The trigger takes the advantage of the long lifetime of B mesons and selects events within some impact parameter range ($120 \mu\text{m} \leq d_0 \leq 1000 \mu\text{m}$) with respect to the primary vertex. The trigger makes it possible to select B signal in large QCD backgrounds at CDF but also removes signal events which decay early. The lifetime bias is corrected using a trigger efficiency curve obtained from Monte Carlo.

The lifetime is extracted from a two-step fit. First a mass-only fit is done to extract relative fractions of various modes and backgrounds. The corresponding mass shapes are obtained from either Monte Carlo or data. A lifetime-only fit is performed with fractions fixed from the previous mass-only fit, where the lifetime is the only free parameter and the final result is [9]

$$\tau = 1.518 \pm 0.041(\text{stat}) \pm 0.025(\text{syst}) \text{ ps}$$

The lifetime results for control samples, such as $B^0 \rightarrow D^-(K^+\pi^-\pi^-\pi^+)\pi^+$, $B^0 \rightarrow D^{*-}(\bar{D}^0(K^+\pi^-\pi^-\pi^+)\pi^+$, and $B^+ \rightarrow \bar{D}^0(K^+\pi^-\pi^+)\pi^+$, all agree well with PDG values.

Fig. 8 compares this result with all published results from flavor specific channels. The previous PDG value is dominated by the D0 result in 2006 from B_s^0 semileptonic channels. This new result agrees with the PDG 2007 value, but the central value is higher.

2.2. B_c lifetime measurement

The doubly heavy B_c meson is an interesting QCD laboratory, where both b and c quarks can decay as well as annihilate. The lifetime is expected to be much shorter than light B mesons. Current theory predictions span from 0.47 ps to 0.59 ps [10], so experimental result with small uncertainty will be useful to constrain the theories.

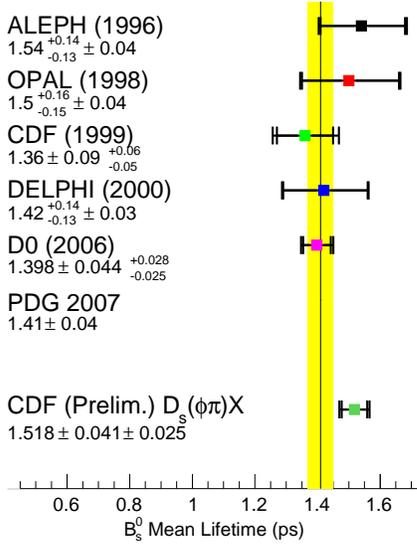


Figure 8: B_s^0 lifetime results from flavor specific channels.

Both CDF and D0 have measured the B_c lifetime from $B_c \rightarrow J/\psi l X$ semileptonic channels, and data are collected by the di-muon trigger. At CDF both $B_c \rightarrow J/\psi \mu X$ and $B_c \rightarrow J/\psi e X$ decays are reconstructed from 1.0 fb^{-1} data. At D0 only $B_c \rightarrow J/\psi \mu X$ is reconstructed from 1.3 fb^{-1} data. Because of the missing momentum of the neutrino, a “K” factor is also needed from Monte Carlo to correct the reconstructed lifetime value. Here the mass is taken from the measured value [11] instead of the reconstructed value, so the “K” factor takes the form

$$K = \frac{p_T(J/\psi l)}{p_T(B_c)}$$

The main challenge of the analysis is the various and dominant backgrounds which include: 1) fake J/ψ plus true lepton, 2) true J/ψ plus fake lepton, 3) true J/ψ and lepton from different b quarks, 4) prompt J/ψ background, 5) residual conversion (for electron channel only). At CDF, the shape of the proper decay time distributions of all backgrounds are modeled and calibrated carefully from either data or Monte Carlo, and the lifetime is extracted from a lifetime-only fit. At D0, the mass shape of signal and backgrounds are also modeled, and the lifetime is extracted from a mass-lifetime simultaneous fit.

The measured lifetime results at CDF from both muon and electron channels are [12]

$$c\tau = 179.1^{+32.6}_{-27.2}(\text{stat}) \mu\text{m} \text{ (muon channel)}$$

$$c\tau = 121.7^{+18.0}_{-16.3}(\text{stat}) \mu\text{m} \text{ (electron channel)}$$

and the combined result from two channels is given by

$$\tau(B_c) = 0.475^{+0.053}_{-0.049}(\text{stat}) \pm 0.018(\text{syst}) \text{ ps}$$

The same lifetime measured at D0 is [13]

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

The measured B_c lifetime values from CDF and D0 agree with each other well, and since the Tevatron is currently the only place which can produce B_c mesons, one can make a weighted world average with all the previous measurements from the Tevatron. The plot is shown in Fig. 9, and the weighted average is

$$\tau(B_c) = 0.459 \pm 0.037 \text{ ps}$$

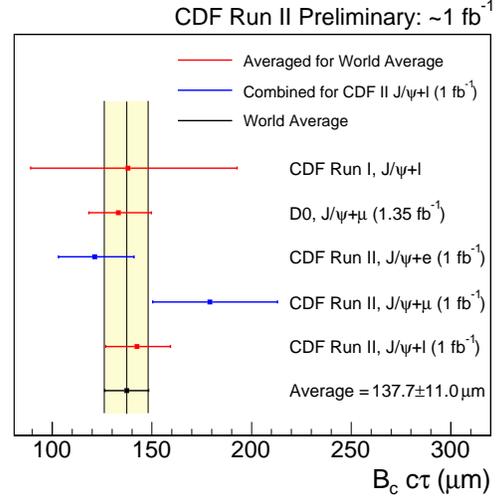


Figure 9: Comparison of B_c lifetime with CDF and D0 Run I results, and an weighted average (assuming no correlations among) those measurements.

3. B_s^0 Mixing

As shown in Fig. 2, B_s^0 oscillates through a box diagram. The oscillation frequency Δm_s is the mass difference of heavy and light eigenstates $\Delta m_s \equiv m_H - m_L$, which are related to the off diagonal element M_{12} of the mass matrix by

$$\Delta m_s = 2|M_{12}| \quad (4)$$

With the oscillation frequency from the B^0 system, one can take the ratio to cancel most of the theoretical uncertainties and get

$$\frac{\Delta m_s}{\Delta m_d} \propto \frac{|V_{ts}|^2}{|V_{td}|^2} \quad (5)$$

which is very important for constraining the CKM unitary triangle with measurements of other CKM matrix elements and some theory inputs.

The probability for a B_s^0 meson to mix or not as a function of time is proportional to

$$P(t)_{B_s^0 \rightarrow B_s^0, \bar{B}_s^0} \propto 1 \pm \cos \Delta m_s t \quad (6)$$

And one needs to identify the flavor of the meson at both production and decay time to see if it's mixed or unmixed. By reconstructing flavor specific channels, the flavor at decay time can be identical to the charge of the daughter particle. To identify the flavor at production time, two algorithms are generally used at the Tevatron. On the same side of the reconstructed B_s^0 meson, one looks at the charge of the kaon from fragmentation processes. On the opposite side, one can look at the charge of leptons from semileptonic decays or the jet charge of the other b quark. However, many things can dilute the tagging power, for example, the kaon mis-identification and low efficiency on the same side, mixing of neutral B mesons and sequential b decays on the opposite side. Thus, a dilution factor \mathcal{D} is introduced, and it modifies Eq. 6.

$$P(t)_{B_s^0 \rightarrow B_s^0, \bar{B}_s^0} \propto 1 \pm \mathcal{D} \cos \Delta m_s t \quad (7)$$

and $(1 + \mathcal{D})/2$ gives correct tagging probability.

Following the CDF measurement in 2006 with $\Delta m_s = 17.77 \pm 0.10(\text{stat}) \pm 0.07(\text{syst})$ ps, D0 now has a new measurement with 2.4 fb^{-1} data. The first 1.3 fb^{-1} belongs to Run IIa period and the other 1.1 fb^{-1} belongs to Run IIb when an additional silicon layer was installed at D0. Both hadronic and semileptonic decays are collected by inclusive single or di-muon triggers at D0. Most of the reconstructed channels and signal yields are listed in Tab. I, in addition, 1.2 fb^{-1} of $B_s^0 \rightarrow \mu^+ D_s^- (K_s^0 K^-)$ decays from Run IIa give about 600 signal events.

Table I Reconstructed channels and yields in B_s^0 mixing measurement

Channel	Run IIa	Run IIb	Total
$\mu^+ D_s^- (\phi \pi^-)$	28238 ± 339	16539 ± 239	44777 ± 415
$e^+ D_s^- (\phi \pi^-)$	1142 ± 83	548 ± 45	1663 ± 102
$\pi^+ D_s^- (\phi \pi^-)$	159 ± 13	90 ± 11	249 ± 17
$\mu^+ D_s^- (K^{*0} K^-)$	11649 ± 661	6449 ± 616	18098 ± 903

An amplitude A is introduced as shown in

$$P(t)_{B_s^0 \rightarrow B_s^0, \bar{B}_s^0} \propto 1 \pm A \mathcal{D} \cos \Delta m_s t \quad (8)$$

where A can be fitted by fixing Δm_s at different points, the true Δm_s value is indicated when the fitted A is consistent with unity, otherwise a sensitivity at 95% C.L. can be defined by the probe Δm_s value at which

$$1.645 \sigma_A(\Delta m_{sens}) = 1.0 \quad (9)$$

Individual amplitude scans vs. probe Δm_s were done separately for different channels and combined using COMBOS program [14]. The combined amplitude scan is shown in Fig. 10. The likelihood profile is

obtained from the combined amplitude scan using the formula [15]

$$\Delta \text{Ln} \mathcal{L} = -\text{Ln} \mathcal{L}(\Delta m_s) + \text{Ln} \mathcal{L}(\infty) = \frac{\frac{1}{2} - A_{fit}(\Delta m_s)}{\sigma_A^2} \quad (10)$$

and the profile is shown in Fig. 11. The measured Δm_s and its errors are derived by fitting a quadratic function to it, giving [16]

$$\Delta m_s = 18.53 \pm 0.93(\text{stat}) \pm 0.30(\text{syst}) \quad (11)$$

which has a total significance of 2.9σ .

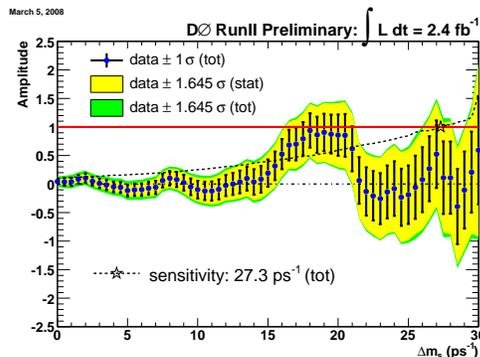


Figure 10: B_s^0 mixing combined amplitude scan.

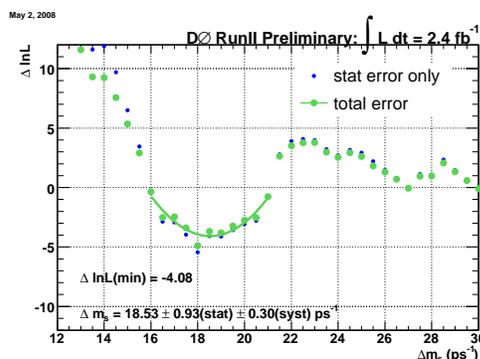


Figure 11: B_s^0 combined likelihood profile, which is done with statistical error and total error on amplitude A separately. An estimate of the Δm_s systematic error is obtained by subtracting, in quadrature, the error derived from statistical-error-only likelihood curve from that of the total-error curve.

4. D^0 Mixing

Since the discovery of charm quark in 1974, physicists have been trying to observe oscillations of the neutral charm meson. Unlike the kaon or B systems, the oscillation frequency in the charm system is predicted to be very small. In the Standard Model,

D^0 mixing occurs through two processes. The “long range” mixing can be estimated using strong interaction models. The “short range” process is negligible in the standard model, however, exotic weakly interacting particle from new physics could enhance the short-range process.

Recent D^0 mixing evidence has been found at the B factories in 2007. The *Belle* Collaboration found direct evidence by comparing the decay time distributions for D^0 decays to the CP -eigenstates K^+K^- and $\pi^+\pi^-$ with that for the CP -mixed state $K^-\pi^+$. The evidence found in the *BABAR* experiment is the decay rate difference of doubly-Cabibbo-suppressed (DCS) $D^0 \rightarrow K^+\pi^-$ decay and Cabibbo favored (CF) $D^0 \rightarrow K^-\pi^+$ decay. The ratio of decay rates can be approximated as a simple quadratic function of proper decay time and mean D^0 lifetime, with the assumption of CP conservation and a small value of $x = \Delta m/\Gamma$ and $y = \Delta\Gamma/2\Gamma$,

$$R(t/\tau) = R_D + \sqrt{R_D}y'(t/\tau) + \frac{x'^2 + y'^2}{4}(t/\tau)^4 \quad (12)$$

where R_D is the square of the ratio of DCS to CF amplitudes, x' and y' are linear combinations of x and y as

$$\begin{aligned} x' &= x \cos \delta + y \sin \delta \\ y' &= -x \sin \delta + y \cos \delta \end{aligned}$$

where δ is the strong phase difference between the DCS and CF amplitudes. In the absence of mixing, x' and y' are both zero.

At CDF, the same kind of evidence is found as in *BABAR*, but probed over a much wider D^0 decay time range. Events are selected with the displaced-vertex trigger using about 1.5 fb^{-1} data. The “right-sign” (RS) CF decay chain $D^{*+} \rightarrow \pi^+D^0$, $D^0 \rightarrow K^-\pi^+$, and the “wrong sign” (WS) decay chain $D^{*+} \rightarrow \pi^+D^0$, $D^0 \rightarrow K^+\pi^-$ are reconstructed. The relative charges of the two pions gives the “sign” of the decay chain and extra cuts are applied to reduce background to the WS signal from RS decays. The data are divided into 20 bins of t/τ ranging from 0.75 to 10.0 with bin size increasing from 0.25 to 2.0 to reduce statistical uncertainty at larger times. The ratio R is determined at each bin and a least-squares parabolic fit of the data is done with Eq. 12. The fit is shown in Fig. 12, and final results are shown in Table. II [17].

Table II Fit results for the $R(t/\tau)$ distribution

Fit type	$R_D(10^{-3})$	$y'(10^{-3})$	$x'^2(10^{-3})$	$\chi^2/d.o.f$
Unconstrained	3.04 ± 0.55	8.5 ± 7.6	-0.12 ± 0.35	19.2/17
Physically allowed	3.22 ± 0.23	6.0 ± 1.4	0	19.3/18
No mixing	4.15 ± 0.10	0	0	36.8/19

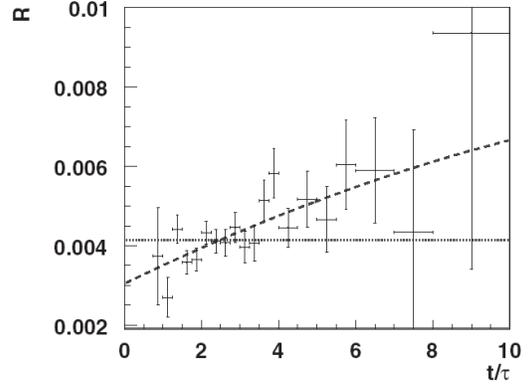


Figure 12: Ratio of prompt D^* “wrong sign” to “right sign” decays as a function of normalized proper decay time. The dashed curve is from a least-squares parabolic fit, the dotted line is the fit assuming no mixing

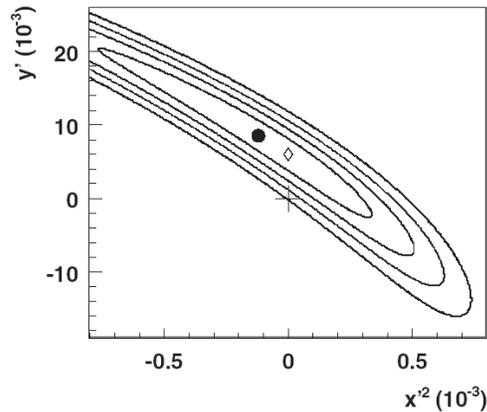


Figure 13: Bayesian probability contours in the $x'^2 - y'$ parameter space corresponding to one through four equivalent Gaussian standard deviations. The closed circle shows the unconstrained fit, the open diamond shows physically allowed fit ($x'^2 \geq 0$), the cross shows the no-mixing point.

To determine the consistency of the data with the no-mixing hypothesis, Bayesian contours are computed with likelihood and a flat prior. The contours are insensitive to modest changes in the prior, and shown in Fig. 13. The no-mixing point lies on the contour which excludes the region containing a probability of 1.5×10^{-4} , equivalent to 3.8 Gaussian standard deviations. Alternative procedures are also used to determine the probability for no mixing, and all give consistent results.

5. Summary

The most precise B_s^0 lifetime and decay width difference have been measured directly from the $B_s^0 \rightarrow J/\psi\phi$ channel from both CDF and D0 experiments.

The measured lifetime is also consistent with the value from B_s^0 flavor specific channel. Together, the recent results confirm the theory prediction that $\tau_s/\tau_d \sim 1$. The lifetime measurement result for the heavy B_c meson can provide good experimental input for the theory calculation which still has a huge uncertainty. The fast oscillation of B_s^0 mesons has been measured at CDF in 2006 and is now verified by the D0 experiment with results from combined channels. While D^0 mixing is predicted to be quite small in the Standard Model, the evidence has been found at CDF followed the first observation at B factories last year.

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