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Lifetime Difference and CP-Violating Phase in the B_s^0 System

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From an analysis of the decay $B_s^0 \to J/\psi\phi$ we obtain the width difference between the light and heavy mass eigenstates, $\Delta\Gamma \equiv (\Gamma_L - \Gamma_H) = 0.17 \pm 0.09$ (stat) ± 0.02 (syst) ps^{-1} and the CP-violating phase $\phi_s = -0.79 \pm 0.56$ (stat) $^{+0.14}_{-0.01}$ (syst). Under the hypothesis of no CP violation ($\phi_s \equiv 0$), we obtain $1/\overline{\Gamma} = \overline{\tau}(B_s^0) = 1.52 \pm 0.08^{+0.01}_{-0.03}$ ps and $\Delta\Gamma = 0.12^{+0.08}_{-0.10} \pm 0.02$ ps^{-1}. The data sample corresponds to an integrated luminosity of 1.1 fb^{-1} accumulated with the D0 detector at

the Tevatron.

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In the standard model (SM), the light (L) and heavy (H) eigenstates of the mixed B_s^0 system are expected to have a sizeable mass and decay width difference, $\Delta M \equiv M_H - M_L$ and $\Delta\Gamma \equiv \Gamma_L - \Gamma_H$. The CP-violating phase, defined as the the relative phase of the off-diagonal elements of the mass and decay matrices in the B_s^0 - $\overline{B}_s^0$ basis, is predicted to be small. Thus, to a good approximation the two mass eigenstates are expected to be CP eigenstates. New phenomena may alter the CP-violating mixing phase ϕ_s, leading to a reduction of the observed $\Delta\Gamma$ compared to the SM prediction [1] $\Delta\Gamma_{SM}$: $\Delta\Gamma = \Delta\Gamma_{SM} \times \cos\phi_s$. While the mass difference has recently been measured to high precision [2, 3], the CP-violating phase remains unknown.

The decay $B_s^0 \to J/\psi\phi$, proceeding through the quark process $b \to c\bar{c}s$, gives rise to both CP-even and CP-odd final states. It is possible to separate the two CP components of the decay $B_s^0 \to J/\psi\phi$, and thus to measure the lifetime difference, through a study of the time-dependent angular distribution of the decay products of the J/ψ and ϕ mesons. Moreover, with a sizeable lifetime difference, there is sensitivity to the mixing phase through the interference terms between the CP-even and CP-odd waves.

In Ref. [4] we presented an analysis of the decay chain $B_s^0 \to J/\psi\phi$, $J/\psi \to \mu^+\mu^-$, $\phi \to K^+K^-$ based on the first ≈450 pb^{-1} of $p\bar{p}$ data at a center-of-mas energy of 1.96 TeV collected with the D0 detector [5]. In that analysis, we extracted three parameters characterizing the B_s^0 system and its decay $B_s^0 \to J/\psi\phi$: the average lifetime, $\overline{\tau} = 1/\overline{\Gamma}$, where $\overline{\Gamma} \equiv (\Gamma_H + \Gamma_L)/2$; $\Delta\Gamma/\overline{\Gamma}$; and the relative rate of the decay to the CP-odd states at time zero. Here we present new results, based on a two-fold increase in statistics. In addition to $\overline{\tau}$ and $\Delta\Gamma$, we extract for the first time the CP-violating phase ϕ_s. We also measure the magnitudes of the decay amplitudes, and their relative phases.

The data, collected between June 2002 and January 2006, correspond to an integrated luminosity of 1.1 fb^{-1}. The selected events include two reconstructed muons of opposite charge, with a transverse momentum greater than 1.5 GeV and pseudorapidity $|\eta| < 2$. Each muon is required to be detected as a track segment in at least one of the three layers of the muon system, and to be matched to a central track. One muon is required to have segments both inside and outside the toroid magnet. We require the events to satisfy a muon trigger that does not include a cut on the impact parameter.

To select the B_s^0 candidate sample, we set the minimum values of momenta in the transverse plane for B_s^0, ϕ, and K meson candidates at 6.0 GeV, 1.5 GeV, and 0.7 GeV, respectively. J/ψ candidates are accepted if

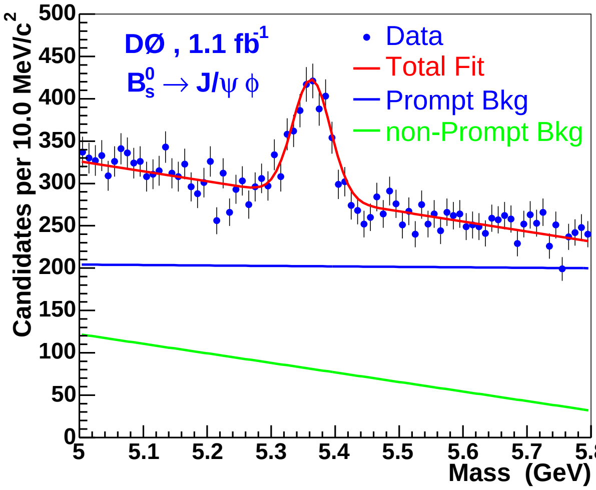

FIG. 1: The invariant mass distribution of the $(J/\psi, \phi)$ system for B_s^0 candidates. The curves are projections of the maximum likelihood fit (see text).

the invariant mass of the muon pair is in the range 2.9 – 3.3 GeV. For events in the central rapidity region (an event is considered to be central if the higher p_T muon has $|\eta_{\mu 1}| < 1$), we require the transverse momentum of the J/ψ meson to exceed 4 GeV. Successful candidates are constrained to the world average mass of the J/ψ meson [6]. Decay products of the ϕ candidates are required to satisfy a fit to a common vertex and to have an invariant mass in the range 1.01 – 1.03 GeV. We require the $(J/\psi, \phi)$ pair to be consistent with coming from a common vertex, and to have an invariant mass in the range 5.0 – 5.8 GeV. In the case of multiple ϕ meson candidates, we select the one with the highest transverse momentum. Monte Carlo (MC) studies show that the p_T spectrum of the ϕ mesons coming from B_s^0 decay is harder than the spectrum of a pair of random tracks from hadronization. We define the signed decay length of a B_s^0 meson L_{xy}^B as the vector pointing from the primary vertex to the decay vertex projected on the B_s^0 transverse momentum. To reconstruct the primary vertex, we select tracks with $p_T > 0.3$ GeV that are not used as decay products of the B_s^0 candidate, and apply a constraint to the average beam spot position. The proper decay length, ct, is defined by the relation $ct = L_{xy}^B \cdot M_{B_s^0}/p_T$ where $M_{B_s^0}$ is the measured mass of the B_s^0 candidate. The distribution of the proper decay length uncertainty $\sigma(ct)$ of B_s^0 mesons peaks around 25 μm. We accept events with $\sigma(ct) < 60$ μm. The invariant mass distribution of the accepted 23343 candidates is shown in Fig. 1. The curves are projections of the maximum likelihood fit, described below. The fit assigns 1039±45 (stat) events to the B_s^0 decay.

We perform a simultaneous unbinned maximum likelihood fit to the proper decay length, three decay angles, and mass. The likelihood function $\mathcal{L}$ is given by:

$$\mathcal{L} \;=\; \prod_{i=1}^{N}[f_{sig}\mathcal{F}^{i}_{sig} + (1-f_{sig})\mathcal{F}^{i}_{bck}], \qquad (1)$$

where N is the total number of events, and f_{sig} is the fraction of signal in the sample. The function $\mathcal{F}^{i}_{sig}$ describes the distribution of the signal in mass, proper decay length, and the decay angles, and $\mathcal{F}^{i}_{bck}$ is the product of the background mass, proper decay length, and angular probability density functions. Background is divided into two categories. "Prompt" background is due to directly produced J/ψ mesons accompanied by random tracks arising from hadronization. This background is distinguished from "non-prompt" background, where the J/ψ meson is a product of a B hadron decay while the tracks forming the ϕ candidate emanate from a multi-body decay of the same B hadron or from hadronization.

The time evolution of the angular distribution of the products of the decay of *flavor untagged* B^0_s mesons, i.e., summed over B^0_s and $\overline{B}^0_s$, expressed in terms of the linear polarization amplitudes A_x and their relative phases δ_i is [1]:

$$\frac{d^3\Gamma(t)}{d\cos\theta\; d\varphi\; d\cos\psi} \propto 2|A_0(0)|^2\,\mathcal{T}_+\,\cos^2\psi(1-\sin^2\theta\cos^2\varphi)+\sin^2\psi\{|A_\parallel(0)|^2\,\mathcal{T}_+\,(1-\sin^2\theta\sin^2\varphi)+|A_\perp(0)|^2\,\mathcal{T}_-\,\sin^2\theta\}$$

$$+\frac{1}{\sqrt{2}}\sin 2\psi |A_0(0)||A_\parallel(0)|\cos(\delta_2-\delta_1)\;\mathcal{T}_+\;\sin^2\theta\sin 2\varphi$$

$$+\left\{\frac{1}{\sqrt{2}}|A_0(0)||A_\perp(0)|\cos\delta_2\sin 2\psi\sin 2\theta\cos\varphi\right.$$

$$\left.-|A_\parallel(0)||A_\perp(0)|\cos\delta_1\sin^2\psi\sin 2\theta\sin\varphi\right\}\frac{1}{2}\left(e^{-\Gamma_H t}-e^{-\Gamma_L t}\right)\sin\phi_s\;. \qquad (2)$$

where $\mathcal{T}_{+/-} = \frac{1}{2}\left((1\pm\cos\phi_s)e^{-\Gamma_L t} + (1\mp\cos\phi_s)e^{-\Gamma_H t}\right)$.

In the coordinate system of the J/ψ rest frame (where the ϕ meson moves in the x direction, the z axis is perpendicular to the decay plane of $\phi \to K^+K^-$, and $p_y(K^+) \geq 0$), the transversity polar and azimuthal angles (θ, φ) describe the direction of the μ^+, and ψ is the angle between $\vec{p}(K^+)$ and $-\vec{p}(J/\psi)$ in the ϕ rest frame.

We model the acceptance in the three angles by fits using polynomial functions, with parameters determined using Monte Carlo simulations. We have used the *SVV_HELAMP* model in the EvtGen generator [7], interfaced to the Pythia program [8]. Simulated events were reweighted to match the kinematic distributions observed in the data.

The lifetime distribution shape of the background is described as a sum of a prompt component, simulated as a Gaussian function centered at zero, and a non-prompt component, simulated as a superposition of one exponential for the negative *ct* region and two exponentials for the positive *ct* region, with free slopes and normalization. The mass distributions of the backgrounds are parametrized by first-order polynomials. The distributions in the transversity polar and azimuthal angles are parametrized as $1 + X_{2x}\cos^2\theta + X_{4x}\cos^4\theta$ and $1+Y_{1x}\cos(2\varphi)+Y_{2x}\cos^2(2\varphi)$, respectively. For the background dependence on the angle ψ, we use the function $1 + Z_{2x}\cos^2(\psi)$. We also allow for a background term analogous to the interference term of the CP-even waves, with one free coefficient. For each of the above background functions we use two separate sets of parameters for the prompt and non-prompt components.

Our results for the hypothesis of CP conservation and for the case of free ϕ_s, are presented in Table I. For the CP-violating phase, which has a four-fold ambuguity discussed below, the fit value closest to the SM prediction of -0.03 [1] is $\phi_s = -0.79 \pm 0.56$. Figures 2 – 5 show the fit projections on the angular distributions and the proper decay length. Figure 6 shows the $\Delta\ln(\mathcal{L}) = 0.5$ error ellipse contour (corresponding to the confidence level of 39%) in the plane $(\Delta\Gamma,\, \phi_s)$. As seen from Eq. 2, the sign of $\sin\phi_s$ is reversed with the simultaneous reversal of the signs of $\cos\delta_1$ and $\cos\delta_2$. For the case $\cos\delta_1 < 0$ and $\cos\delta_2 > 0$, our measurement correlates two possible solutions for ϕ_s with the two signs of $\Delta\Gamma$: $\phi_s = -0.79\pm0.56$, $\Delta\Gamma > 0$, and $\phi_s = 2.35\pm0.56$, $\Delta\Gamma < 0$. For the case $\cos\delta_1 > 0$ and $\cos\delta_2 < 0$ the two solutions are $\phi_s = 0.79 \pm 0.56$, $\Delta\Gamma > 0$, and $\phi_s = -2.35 \pm 0.56$, $\Delta\Gamma < 0$.

TABLE I: Maximum likelihood fit results. Sign ambiguities are discussed in the text.

Observable	CP conserved	free ϕ_s
$\Delta\Gamma$ (ps^{-1})	$0.12^{+0.08}_{-0.10}$	$0.17^{+0.09}_{-0.09}$
$\frac{1}{\bar{\Gamma}} = \overline{\tau}$ (ps)	$1.52^{+0.08}_{-0.08}$	1.49 ± 0.08
ϕ_s	$\equiv 0$	-0.79 ± 0.56
$\lvert A_0(0)\rvert^2 - \lvert A_\parallel(0)\rvert^2$	0.38 ± 0.05	0.37 ± 0.06
$A_\perp(0)$	0.45 ± 0.05	0.46 ± 0.06
$\delta_1 - \delta_2$	2.6 ± 0.4	2.6 ± 0.4
δ_1	–	3.3 ± 1.0
δ_2	–	0.7 ± 1.1

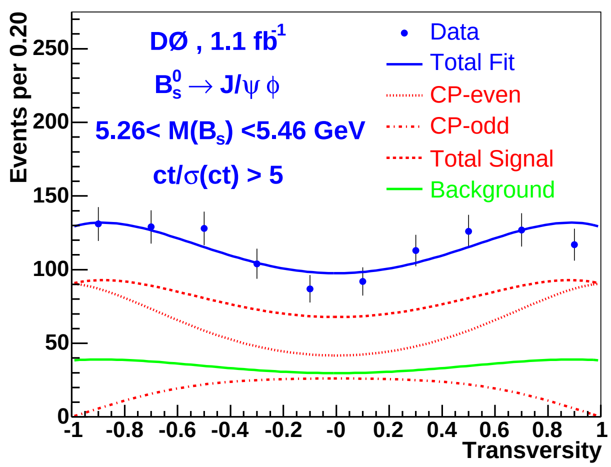

FIG. 2: The transversity polar angle distribution for the signal-enhanced subsample: $ct/\sigma(ct) > 5$ and signal mass range. The curves show: the signal contribution, dotted (red); the background, light solid (green); and total, solid (blue) [color online].

We perform a test using pseudo-experiments with similar statistical sensitivity, generated with the same parameters as obtained in this analysis under the condition of no CP violation. When fits allowing for CP violation are performed, $\approx 50\%$ of the experiments have a fitted $\cos(\phi_s)$ less than the measured value. About 80% of experiments have the statistical uncertainty of ϕ_s greater than that for data.

We verify the procedure by performing fits on MC samples passed through the full chain of detector simulation, event reconstruction, and maximum likelihood fitting. We assign systematic uncertainties due to the statistical precision of this procedure test. We also repeat the fits to the data with the parameters describing the acceptance varied by $\pm 1\sigma$.

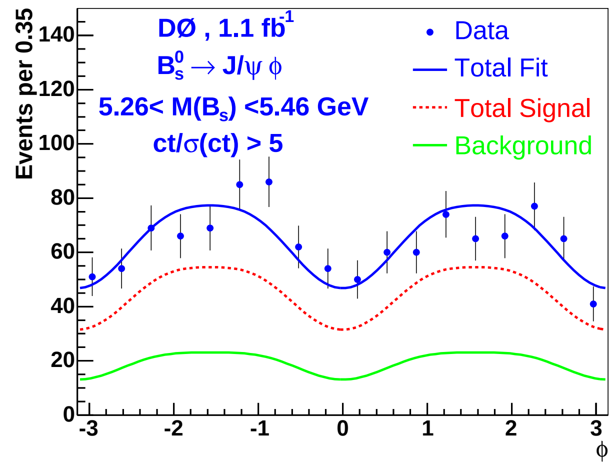

FIG. 3: The transversity asimuthal angle distribution for the signal-enhanced subsample: $ct/\sigma(ct) > 5$ and signal mass range. The curves show: the signal contribution, dotted (red); the background, light solid (green); and total, solid (blue) [color online].

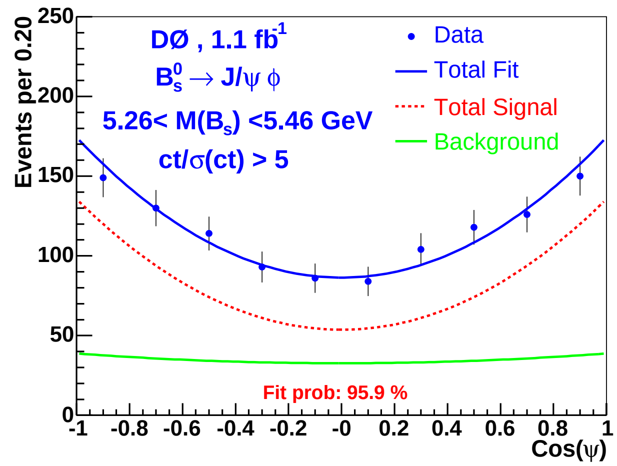

FIG. 4: The ψ angle distribution for the signal-enhanced subsample: $ct/\sigma(ct) > 5$ and signal mass range. The curves show: the signal contribution, dotted (red); the background, light solid (green); and total, solid (blue) [color online].

Uncertainties from the data processing reflect the stability of the results with respect to different versions of the track and vertex reconstruction algorithms. The "interference" term in the background model accounts for the collective effect of various physics processes. However, its presence may be partially due to the detector acceptance effects. Therefore, we interpret the difference between fits with and without this term as a systematic uncertainty associated with the background model. Effects of the imperfect detector alignment are estimated using a modified geometry of the the silicon microstrip tracker, with silicon sensors moved within the known uncertainty. The effects of systematic uncertainties are listed in Table II.

From a fit to the CP-conserving time-dependent angu-

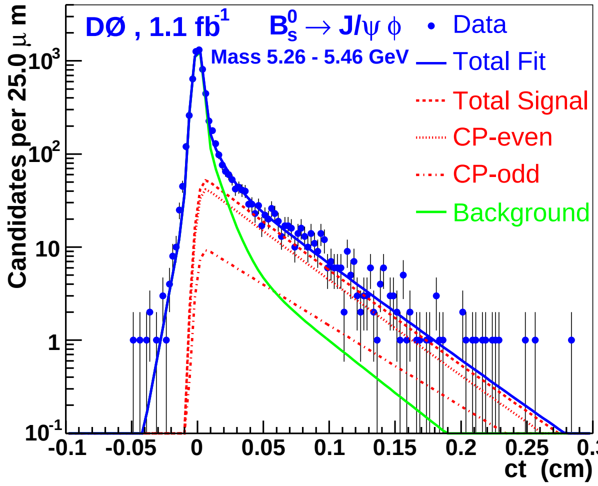

FIG. 5: The proper decay length, ct, of the B_s^0 candidates in the signal mass region. The curves show: the signal contribution, dashed (red); the CP-even (dotted) and CP-odd (dashed-dotted) contributions of the signal, the background, light solid(green); and total, solid (blue) [color online].

TABLE II: Sources of systematic uncertainty in the results of the analysis of the decay $B_s^0 \to J/\psi\phi$.

Source	$c\tau(B_s^0)$ μm	$\Delta\Gamma$ ps^{-1}	$R_\perp$	ϕ_s
Procedure test	± 2.0	± 0.02	± 0.01	–
Acceptance	± 0.5	± 0.001	± 0.003	± 0.01
Reco. algorithm	$-8.0, +1.3$	$+0.001$	± 0.01	-0.01
Background model	$+1.0$	$+0.01$	-0.01	$+0.14$
Alignment	± 2.0	–	–	–
Total	$-8.8, +3.3$	± 0.02	± 0.02	$-0.01, +0.14$

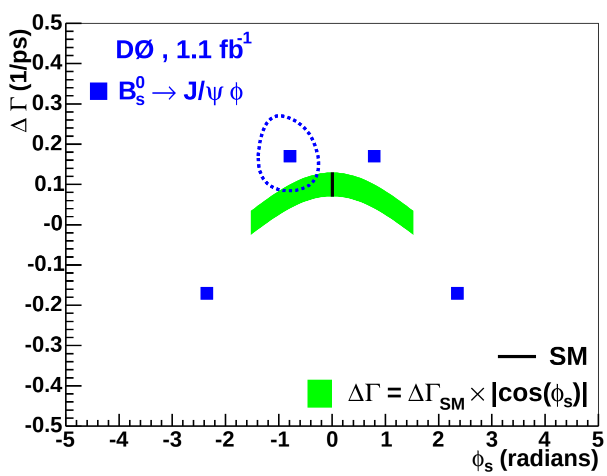

FIG. 6: The $\Delta\ln(\mathcal{L}) = 0.5$ contour (error elipse) in the plane ($\Delta\Gamma$, ϕ_s) for the fit to the $B_s^0 \to J/\psi\phi$ data. Also shown is the band representing the relation $\Delta\Gamma = \Delta\Gamma_{SM} \times |(\cos(\phi_s)|$, with $\Delta\Gamma_{SM} = 0.10 \pm 0.03$ ps^{-1} [10]. The 4-fold ambiguity is discussed in the text.

lar distribution of the untagged decay $B_s^0 \to J/\psi\phi$, we obtain the average lifetime of the B_s^0 system, $\overline{\tau}(B_s^0) = 1.52 \pm 0.08$ (stat) $^{+0.01}_{-0.03}$ (syst) ps and the width difference between the two mass eigenstates, $\Delta\Gamma = 0.12^{+0.08}_{-0.10}$ (stat) ± 0.02 (syst) ps^{-1}.

Allowing for CP violation in B_s^0 mixing, we provide the first direct constraint on the CP-violating phase, $\phi_s = -0.79 \pm 0.56$ (stat) $^{+0.14}_{-0.01}$ (syst).

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