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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 $\Delta\Gamma \equiv (\Gamma_L - \Gamma_H) = 0.17 \pm 0.09(\mathrm{stat}) \pm 0.02(\mathrm{syst})\ \mathrm{ps}^{-1}$ and the CP-violating phase $\phi_s = -0.79 \pm 0.56(\mathrm{stat})^{+0.14}_{-0.01}(\mathrm{syst})$. Under the hypothesis of no CP violation ($\phi_s \equiv 0$), we obtain $1/\bar{\Gamma} = \bar{\tau}(B_s^0) = 1.52 \pm 0.08(\mathrm{stat})^{+0.01}_{-0.03}(\mathrm{syst})$ ps and $\Delta\Gamma = 0.12^{+0.08}_{-0.10}(\mathrm{stat}) \pm 0.02(\mathrm{syst})\ \mathrm{ps}^{-1}$. The data sample corresponds to an integrated luminosity of about 1.1 fb^{-1} accumulated with the D0 detector at the Fermilab Tevatron collider. This is the first direct measurement of the CP-violating mixing phase in the B_s^0 system.

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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 sizable 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 relative phase of the off-diagonal elements of the mass and decay matrices in the B_s^0-$\bar{B}_s^0$ 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] $\Delta\Gamma_{\mathrm{SM}}$: $\Delta\Gamma \approx \Delta\Gamma_{\mathrm{SM}} \times \cos\phi_s$. 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 sizable lifetime difference, there is sensitivity to the mixing phase through the interference terms between the CP-even and CP-odd waves.

Previous analyses [4,5] of the decay chain $B_s^0 \to J/\psi\phi$, $J/\psi \to \mu^+\mu^-$, $\phi \to K^+K^-$ extracted the average lifetime of the B_s^0 system $\bar{\tau} = 1/\bar{\Gamma}$, where $\bar{\Gamma} \equiv (\Gamma_H + \Gamma_L)/2$, and $\Delta\Gamma/\bar{\Gamma}$ under the assumption of CP conservation. Here we present new D0 results, based on a twofold increase in statistics. In addition to $\bar{\tau}$ 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 with the D0 detector [6] between June 2002 and January 2006, correspond to an integrated luminosity of about 1.1 fb^{-1}.

Events triggered by the presence of at least one muon are required to include two reconstructed muons of opposite charge, with a momentum in the plane transverse to the beam greater than 1.5 GeV and pseudorapidity $|\eta| < 2$. ($\eta = -\ln[\tan(\Theta/2)]$, and Θ is the polar angle with respect to the proton beam direction.) 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. At least one muon is required to have segments both inside and outside the toroid magnet.

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, 1.5, and 0.7 GeV, respectively. J/ψ candidates are accepted if the invariant mass of the muon pair is in the range 2.9–3.3 GeV. Successful candidates are constrained to the world average mass of the J/ψ meson [7]. 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/ψ, ϕ) 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 23 343 candidates is shown in Fig. 1. The curves are

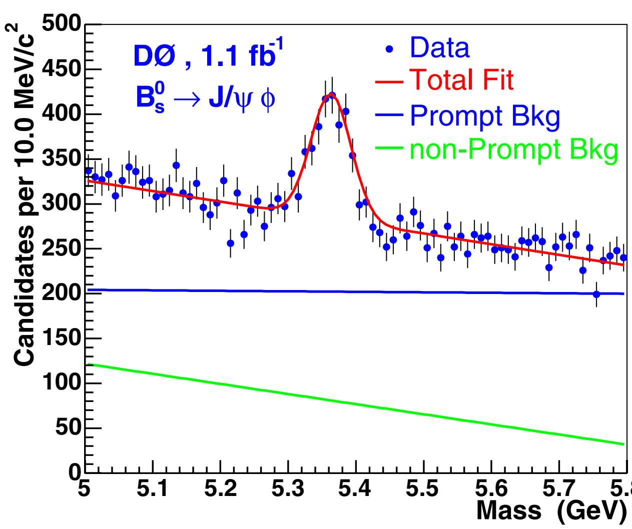

FIG. 1 (color online). The invariant mass distribution of the (J/ψ, ϕ) system for B_s^0 candidates. The curves are projections of the maximum likelihood fit (see text).

projections of the maximum likelihood fit, described below. The fit assigns 1039 $\pm$ 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

$$\mathcal{L} = \prod_{i=1}^{N} [f_{\rm sig}\mathcal{F}^i_{\rm sig} + (1 - f_{\rm sig})\mathcal{F}^i_{\rm bck}], \quad (1)$$

where N is the total number of events, and $f_{\rm sig}$ is the fraction of signal in the sample. The function $\mathcal{F}^i_{\rm sig}$ describes the distribution of the signal in mass, proper decay length, and the decay angles. For the signal mass distribution, we use a Gaussian function with free mean and width. The proper decay length distribution of the L or H component of the signal is parametrized by an exponential convoluted with a Gaussian function with the width taken from the event-by-event estimate of $\sigma(ct)$. $\mathcal{F}^i_{\rm bck}$ is the product of the background mass, proper decay length, and angular probability density functions. Background is divided into two categories. A "prompt" background is due to directly produced J/ψ mesons accompanied by random tracks arising from hadronization. This background is distinguished from a "nonprompt" background, where the J/ψ meson is a product of a B hadron decay while the tracks forming the ϕ candidate emanate from a multibody 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_s^0 mesons, i.e., summed over B_s^0 and $\bar{B}_s^0$, expressed in terms of the linear polarization amplitudes A_x and their relative phases δ_i is [8]

$$\begin{aligned}\frac{d^3\Gamma(t)}{d\cos\theta d\varphi d\cos\psi} \propto\ & 2|A_0(0)|^2\mathcal{T}_+\cos^2\psi(1-\sin^2\theta\cos^2\varphi) + \sin^2\psi\{|A_\parallel(0)|^2\mathcal{T}_+(1-\sin^2\theta\sin^2\varphi) + |A_\perp(0)|^2\mathcal{T}_-\sin^2\theta\} \\ & + \frac{1}{\sqrt{2}}\sin 2\psi|A_0(0)||A_\parallel(0)|\cos(\delta_2-\delta_1)\mathcal{T}_+\sin^2\theta\sin 2\varphi \\ & + \left\{\frac{1}{\sqrt{2}}|A_0(0)||A_\perp(0)|\cos\delta_2\sin 2\psi\sin 2\theta\cos\varphi - |A_\parallel(0)||A_\perp(0)|\cos\delta_1\sin^2\psi\sin 2\theta\sin\varphi\right\} \\ & \times\frac{1}{2}(e^{-\Gamma_H t} - e^{-\Gamma_L t})\sin\phi_s, \end{aligned} \quad (2)$$

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

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 and resolution 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 [9], interfaced to the PYTHIA program [10]. Simulated events were reweighted to match the kinematic distributions observed in the data.

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

Observable	*CP* conserved $\mathcal{L} \equiv \mathcal{L}_0$	Free ϕ_s $\mathcal{L} = \mathcal{L}_0 + 1.0$
$\Delta\Gamma(\text{ps}^{-1})$	$0.12^{+0.08}_{-0.10}$	0.17 ± 0.09
$\frac{1}{\bar\Gamma} = \bar\tau(\text{ps})$	1.52 ± 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	$\cdots$	3.3 ± 1.0
δ_2	$\cdots$	0.7 ± 1.1

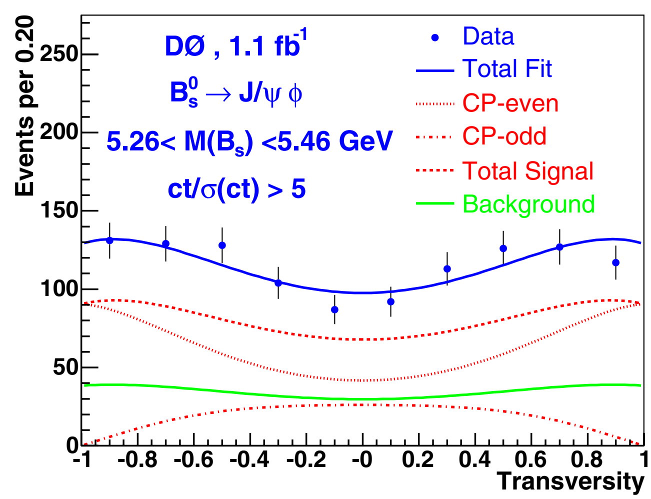

FIG. 2 (color online). The transversity polar angle distribution for the signal-enhanced subsample: $ct/\sigma(ct) > 5$ and signal mass range. The curves show the total signal contribution [dashed (red) curve], the *CP*-even (dotted curve) and *CP*-odd (dashed-dotted curve) contributions of the signal,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

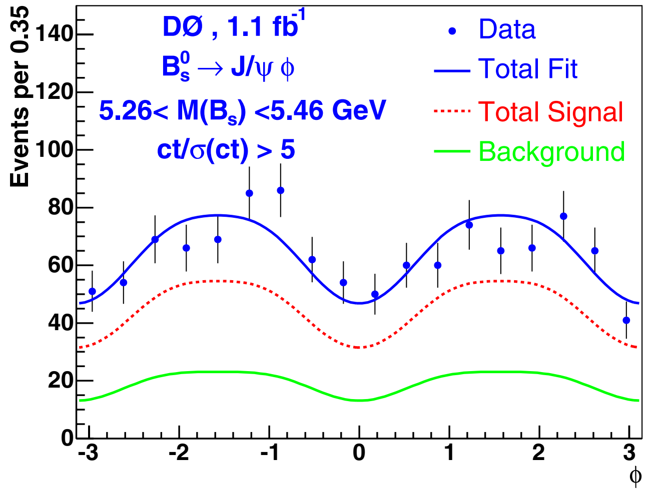

FIG. 3 (color online). The transversity azimuthal angle distribution for the signal-enhanced subsample: $ct/\sigma(ct) > 5$ and signal mass range. The curves show the signal contribution [dashed (red) curve], the background [light solid (green) curve], and the total [solid (blue) curve].

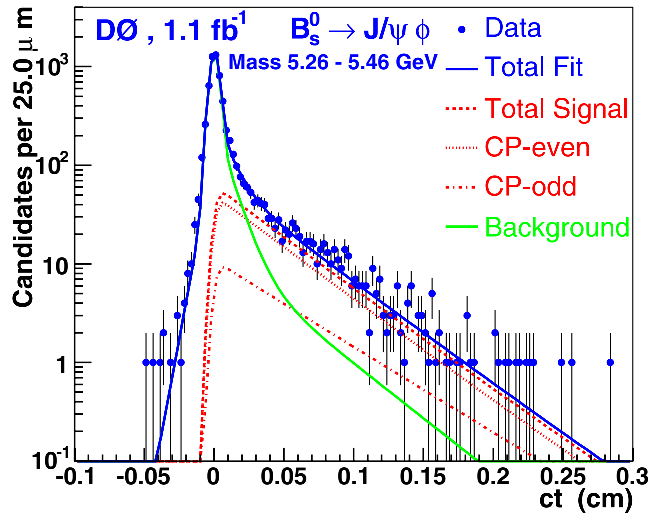

FIG. 5 (color online). The proper decay length ct of the B_s^0 candidates in the signal mass region. The curves show the signal contribution [dashed (red) curve], the CP-even (dotted curve) and CP-odd (dashed-dotted curve) contributions of the signal, the background [light solid (green) curve], and the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

The proper decay length distribution shape of the background is described as a sum of a prompt component, simulated as a Gaussian function centered at zero, and a nonprompt 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 nonprompt components.

Our results for the hypothesis of CP conservation and for the case of free ϕ_s are presented in Table I. Figures 2–5 show the fit projections on the angular distributions and the

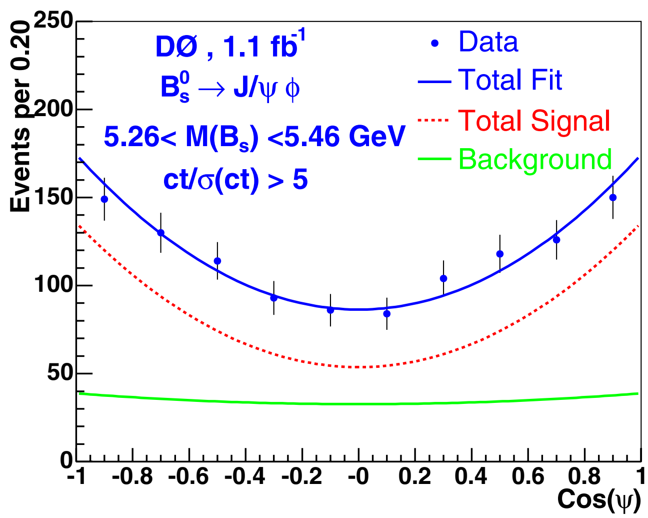

FIG. 4 (color online). The ψ angle distribution for the signal-enhanced subsample: $ct/\sigma(ct) > 5$ and signal mass range. The curves show the signal contribution [dashed (red) curve], the background [light solid (green) curve], and the total [solid (blue) curve].

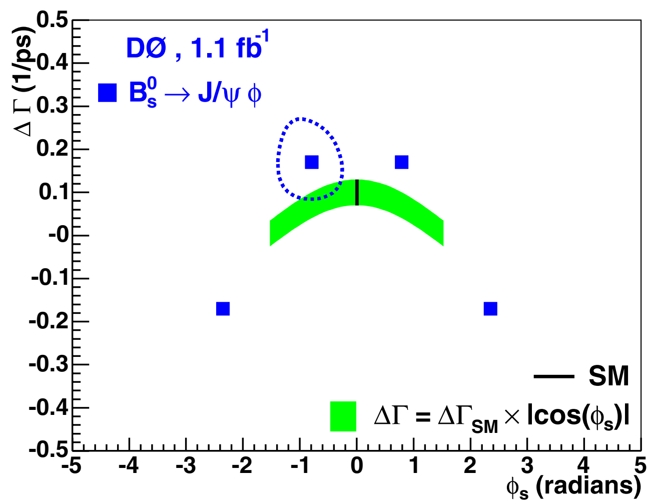

FIG. 6 (color online). The $\Delta\ln(\mathcal{L}) = 0.5$ contour (error ellipse) in the plane $(\Delta\Gamma, \phi_s)$ for the fit to the $B_s^0 \to J/\psi\phi$ data. Also shown is the band representing the relation $\Delta\Gamma = \Delta\Gamma_{SM} \times |(\cos(\phi_s)|$, with $\Delta\Gamma_{SM} = 0.10 \pm 0.03\ \text{ps}^{-1}$ [11]. The fourfold ambiguity is discussed in the text.

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	$\cdots$
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	$\cdots$	$\cdots$	$\cdots$
Total	-8.8, $+3.3$	± 0.02	± 0.02	-0.01, $+0.14$

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 $\cos\delta_2 > 0$, expected in the absence of final state interactions (cf. Table 1 in Ref. [8]), our measurement correlates two possible solutions for ϕ_s with the two signs of $\Delta\Gamma$: $\phi_s = -0.79 \pm 0.56(\text{stat})$, $\Delta\Gamma > 0$, and $\phi_s = 2.35 \pm 0.56$, $\Delta\Gamma < 0$. 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 $\phi_s = -2.35 \pm 0.56$, $\Delta\Gamma < 0$.

We perform a test using pseudoexperiments 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 the 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 repeat the fits to the data with the parameters describing the acceptance varied by $\pm 1\sigma$. 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 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 angular distribution of the untagged decay $B_s^0 \to J/\psi\phi$, we obtain the average lifetime of the B_s^0 system $\bar{\tau}(B_s^0) = 1.52 \pm 0.08(\text{stat})^{+0.01}_{-0.03}(\text{syst})$ ps and the width difference between the two mass eigenstates $\Delta\Gamma = 0.12^{+0.08}_{-0.10}(\text{stat}) \pm 0.02(\text{syst})$ ps^{-1}.

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

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