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We measure the mean lifetime $\tau = 2/(\Gamma_L + \Gamma_H)$ and the decay-width difference $\Delta\Gamma = \Gamma_L - \Gamma_H$ of the light and heavy mass eigenstates of the $B_s^0$ meson, $B_{sL}^0$ and $B_{sH}^0$, in $B_s^0 \rightarrow J/\psi\phi$ decays using 1.7 $\text{fb}^{-1}$ of data collected with the CDF II detector at the Fermilab Tevatron $p\bar{p}$ collider. Assuming $CP$ conservation, a good approximation for the $B_s^0$ system in the standard model, we obtain $\Delta\Gamma = 0.076^{+0.059}_{-0.063}(\text{stat}) \pm 0.006(\text{syst})\ \text{ps}^{-1}$ and $\tau = 1.52 \pm 0.04(\text{stat}) \pm 0.02(\text{syst})$ ps, the most precise measurements to date. Our constraints on the weak phase and $\Delta\Gamma$ are consistent with $CP$ conservation.

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In the standard model (SM), the mass and flavor eigenstates of the $B_s^0$ meson differ. This gives rise to particle-antiparticle oscillations [1], which proceed in the SM through weak interaction processes, and whose phenomenology depends on the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix. The time ($t$) evolution of $B_s^0$ mesons is governed by the Schrödinger equation

$$i\frac{d}{dt}\begin{pmatrix} |B_s^0(t)\rangle \\ |\bar{B}_s^0(t)\rangle \end{pmatrix} = \left(\mathbf{M} - \frac{i}{2}\mathbf{\Gamma}\right)\begin{pmatrix} |B_s^0(t)\rangle \\ |\bar{B}_s^0(t)\rangle \end{pmatrix},$$

with mass matrix $\mathbf{M}$ and decay matrix $\mathbf{\Gamma}$. The mass difference, $\Delta m = m_H - m_L \approx 2|M_{12}|$, between the heavy and light mass eigenstates, $B_{sH}^0$ and $B_{sL}^0$, determines the frequency of $B_s^0$ oscillations, a quantity precisely measured in Ref. [2]. The mean lifetime, $\tau = 2/(\Gamma_L + \Gamma_H)$, is expected to be equal to the mean $B^0$ lifetime within 1% [3]. The decay-width difference, $\Delta\Gamma = \Gamma_L - \Gamma_H$, is predicted in the SM to be $0.096 \pm 0.039\ \text{ps}^{-1}$ [4] and was first measured by the CDF Collaboration [5] and, recently, by the D0 Collaboration with higher precision [6]. It depends on the $CP$-violating weak phase difference between the $B_s^0$-$\bar{B}_s^0$ mixing amplitude and the amplitudes of the subsequent $B_s^0$ and $\bar{B}_s^0$ decays to common final states, $\phi_s = \arg(-M_{12}/\Gamma_{12})$, via the relation $\Delta\Gamma = 2|\Gamma_{12}|\cos(\phi_s)$. While the SM expectation, $\phi_s^{\mathrm{SM}} = 4 \times 10^{-3}$ [4], is small, contributions from new physics processes to $B_s^0$ mixing can lead to a significantly different value of the phase, $\phi_s = \phi_s^{\mathrm{SM}} + \phi_s^{\mathrm{NP}}$. The same new physics contribution $\phi_s^{\mathrm{NP}}$ would be present in the relative phase between mixing and $b \to c\bar{c}s$ quark transitions, $2\beta_s = 2\beta_s^{\mathrm{SM}} - \phi_s^{\mathrm{NP}}$, in which the SM contribution is defined in terms of CKM matrix elements by $\beta_s^{\mathrm{SM}} = \arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*) \approx 0.02$ [4]. Since both $\phi_s^{\mathrm{SM}}$ and $\beta_s^{\mathrm{SM}}$ are significantly smaller than the current experimental resolution, we can approximate $2\beta_s = -\phi_s^{\mathrm{NP}} = -\phi_s$. Thus the measurement of a sizable value of $2\beta_s$ inconsistent with zero would indicate new physics. In the case of a nonzero $|\Gamma_{12}|$, an analysis of time-dependent decay rates of $B_s^0$ mesons to two vector mesons becomes sensitive to the weak phase $2\beta_s$, even without information on the $B_s^0$ flavor at production, because of the interference between $CP$ eigenstates.

In this Letter, we present the measurement of the $B_s^0$ meson mean lifetime $\tau$ and decay-width difference $\Delta\Gamma$ using $B_s^0 \to J/\psi\phi$ decays followed by $J/\psi \to \mu^+\mu^-$ and $\phi \to K^+K^-$ decays. Charge-conjugate modes are implied throughout this Letter. We also extract information about the weak phase $2\beta_s$. The final state is a mixture of $CP$-even and $CP$-odd states that are distinguished using the angular distributions of the decay products. Since the $B_s^0$ is a pseudoscalar and the $J/\psi$ and $\phi$ are vector mesons, the orbital angular momentum between the two decay products can have the magnitudes $\ell = 0$, 1, or 2. The final state is $CP$-even in $S$- and $D$-wave decays and $CP$-odd in $P$-wave decays. The angular distributions are expressed in terms of three angles, $\theta_T$, $\phi_T$, and $\psi_T$, defined in the transversity basis [7]. The angles $\theta_T$ and $\phi_T$ are the polar and azimuthal angles of the $\mu^+$ in the rest frame of the $J/\psi$, where the $x$ axis is defined by the momentum direction of the $B_s^0$ and the $xy$ plane by the $\phi \to K^+K^-$ decay plane with a positive $y$ component of the $K^+$ momentum. The angle $\psi_T$ is the polar angle of the $K^+$ with respect to the opposite of the $B_s^0$ flight direction in the $\phi$ rest frame.

The data were collected by the CDF II detector at the Fermilab Tevatron $p\bar{p}$ collider between February 2002 and January 2007, and correspond to an integrated luminosity of 1.7 $\mathrm{fb}^{-1}$. The CDF II detector [8] consists of a magnetic spectrometer surrounded by electromagnetic and hadronic calorimeters and muon detectors. The tracking system is composed of a silicon microstrip detector [9] surrounded by an open-cell drift chamber (COT) [10]. We detect muons in planes of multiwire drift chambers and scintillators [11] in the pseudorapidity range $|\eta| \le 1.0$. Charged particle identification is provided by the time-of-flight system [12], complemented by the ionization-energy-loss measurement in the COT ($dE/dx$). Events with $J/\psi \to \mu^+\mu^-$ decays used in this analysis were recorded using a dimuon trigger, which required two oppositely charged COT tracks matched to muon chamber track segments with a dimuon mass between 2.7 and 4.0 $\mathrm{GeV}/c^2$.

In the offline analysis, $B_s^0 \to J/\psi\phi$ decays are reconstructed following the procedure described in Ref. [5]. We train an artificial neural network (ANN) to separate $B_s^0$ decays from the combinatorial background, which is the dominant one. We model the signal with simulated events and use data from $B_s^0$ mass sidebands (see Fig. 1) to model the combinatorial background. The input variables to the ANN are kinematic quantities, vertex fit quality parameters, and particle-identification information obtained from the muon system, the time-of-flight detector, and the $dE/dx$ measurements. The requirement on the ANN output is selected by maximizing the significance $S/\sqrt{S+B}$ on data where $S$ ($B$) is the number of signal (background) events in a $\pm 20$ $\mathrm{MeV}/c^2$ window around the $B_s^0$ mass peak position. The selected sample contains about 2500 $B_s^0 \to J/\psi\phi$ decays. The resulting mass distribution is shown in Fig. 1.

To extract $\tau$ and $\Delta\Gamma$, we perform an unbinned maximum likelihood fit with probability density functions (PDFs) depending on mass, lifetime, and transversity angles.

For the PDFs of the background, we use empirical models with floating fit parameters determined from the data. The background has a prompt component and a nonprompt component. The mass PDF is parametrized by a straight-line function for each component. The lifetime distribution is described by a $\delta$ function at $t = 0$ for the prompt component, a positive exponential for the long-lived nonprompt component, and a negative and positive exponential for mismeasured candidates. All lifetime components are convolved with a Gaussian to account for the lifetime resolution estimated on a candidate-by-candidate basis. Because correlations among the three angles are negligible, we factorize the angular PDF as a product of polynomials in $\cos^2(\theta_T)$, $\cos(2\phi_T)$, and $\cos(\psi_T)$. The an-

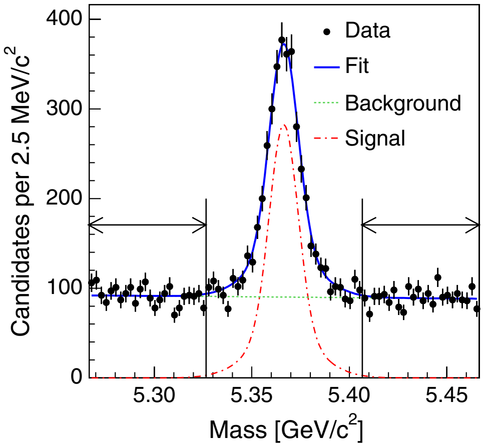

FIG. 1 (color online). Invariant $J/\psi\phi$ mass distribution with fit projection overlaid. The arrows indicate the sideband regions.

gular distributions of prompt and nonprompt background events agree within uncertainties, and are chosen to be identical in the likelihood function.

For the signal, the mass distribution is described by the sum of two Gaussians. The lifetime and the angles $\vec{\rho} = (\cos(\theta_T), \phi_T, \cos(\psi_T))$ are correlated for $B_s^0$ signal events. The lifetime-angular distribution without acceptance effects is given by

$$\frac{d^4P(\vec{\rho},t)}{d\vec{\rho}dt} \propto |A_0|^2 f_1(\vec{\rho})\mathcal{T}_+ + |A_\parallel|^2 f_2(\vec{\rho})\mathcal{T}_+ + |A_\perp|^2 f_3(\vec{\rho})\mathcal{T}_- + |A_0||A_\parallel| f_5(\vec{\rho})\cos(\delta_\parallel)\mathcal{T}_+ + |A_\parallel||A_\perp| f_4(\vec{\rho})\cos(\delta_\perp - \delta_\parallel)\sin(2\beta_s)(e^{-\Gamma_H t} - e^{-\Gamma_L t})/2 + |A_0||A_\perp| f_6(\vec{\rho})\cos(\delta_\perp)\sin(2\beta_s)(e^{-\Gamma_H t} - e^{-\Gamma_L t})/2, \tag{1}$$

where

$$\begin{aligned}
\mathcal{T}_\pm &= [(1 \pm \cos(2\beta_s))e^{-\Gamma_L t} + (1 \mp \cos(2\beta_s))e^{-\Gamma_H t}]/2,\\
f_1(\vec{\rho}) &= 2\cos^2(\psi_T)(1 - \sin^2(\theta_T)\cos^2(\phi_T)),\\
f_2(\vec{\rho}) &= \sin^2(\psi_T)(1 - \sin^2(\theta_T)\sin^2(\phi_T)),\\
f_3(\vec{\rho}) &= \sin^2(\psi_T)\sin^2(\theta_T),\\
f_4(\vec{\rho}) &= -\sin^2(\psi_T)\sin(2\theta_T)\sin(\phi_T),\\
f_5(\vec{\rho}) &= \sin(2\psi_T)\sin^2(\theta_T)\sin(2\phi_T)/\sqrt{2},\\
f_6(\vec{\rho}) &= \sin(2\psi_T)\sin(2\theta_T)\cos(\phi_T)/\sqrt{2}.
\end{aligned} \tag{2}$$

The quantities $A_0$, $A_\perp$, and $A_\parallel$ are the linear polarization amplitudes at $t = 0$, and $\delta_\perp$ and $\delta_\parallel$ are the strong phases of $A_\perp$ and $A_\parallel$ relative to $A_0$, respectively.

The lifetime-angle distribution is invariant under each of the two transformations ($2\beta_s \to -2\beta_s$, $\delta_\perp \to \delta_\perp + \pi$) and ($\Delta\Gamma \to -\Delta\Gamma$, $2\beta_s \to 2\beta_s + \pi$). Because of this fourfold ambiguity, this measurement is insensitive to the sign of both $2\beta_s$ and $\Delta\Gamma$.

The signal lifetime terms are convolved with the same Gaussian resolution function used for the background, which employs the candidate-by-candidate lifetime uncertainty. To account for different distributions of the lifetime uncertainty between signal and background, their PDFs are included in the likelihood. These PDFs are derived from sideband-subtracted signal events and from sideband events, respectively.

The angular distribution of $B_s^0$ decays described in Eq. (1) is modified by detector acceptance as well as trigger and selection efficiencies. This effect is taken into account with an acceptance function $\epsilon(\vec{\rho})$ derived from simulated $B_s^0 \to J/\psi\phi$ decays. The factor $\epsilon(\vec{\rho})$ is described by a three-dimensional histogram with 20 bins in each of the angles.

We consider possible systematic uncertainties due to the signal mass model, the lifetime resolution model, the $\mathcal{O}(3\%)$ contamination by $B^0 \to J/\psi K^*$ decays misreconstructed and selected as $B_s^0$ candidates not included in the background model, the acceptance description, the silicon detector alignment, and the model for the angular distribution of the background. The largest systematic uncertainty for $\Delta\Gamma$ is caused by $B^0$ mesons reconstructed as $B_s^0$ mesons. The largest contributions to the systematic uncertainty on $\tau$ are the lifetime resolution model and the silicon detector alignment. The dominant source of systematic uncertainties on the amplitudes is the angular background model.

Under the assumption of $CP$ conservation ($2\beta_s = 0$), we obtain

$$\begin{aligned}
\tau &= 1.52 \pm 0.04 \pm 0.02\ \text{ps},\\
\Delta\Gamma &= 0.076^{+0.059}_{-0.063} \pm 0.006\ \text{ps}^{-1},\\
|A_0|^2 &= 0.531 \pm 0.020 \pm 0.007,\\
|A_\perp|^2 &= 0.239 \pm 0.029 \pm 0.011,\\
|A_\parallel|^2 &= 0.230 \pm 0.026 \pm 0.009.
\end{aligned}$$

The first uncertainties are statistical, the second ones systematic. We do not quote a point estimate of the strong phase $\delta_\parallel$ because its likelihood profile is nonparabolic due to a symmetry point at $\delta_\parallel = \pi$ which makes an uncertainty estimate unreliable. This analysis is insensitive to the second strong phase $\delta_\perp$ if $2\beta_s = 0$ [see Eq. (1)]. The invariant mass, proper decay time, and angular distributions with fit projections overlaid are shown in Figs. 1–3. The measured mean lifetime is compatible with the $B^0$ lifetime [13] as predicted by theory [3]. The measured

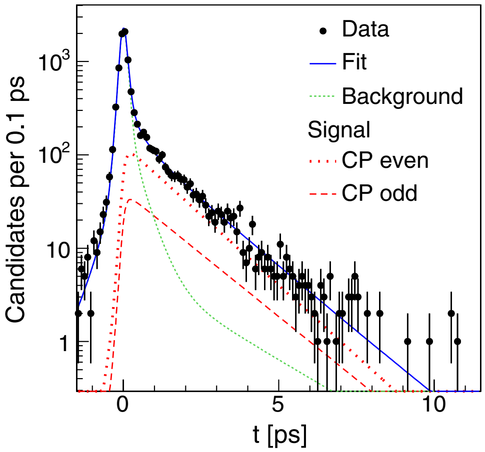

FIG. 2 (color online). Lifetime distribution with fit projection overlaid.

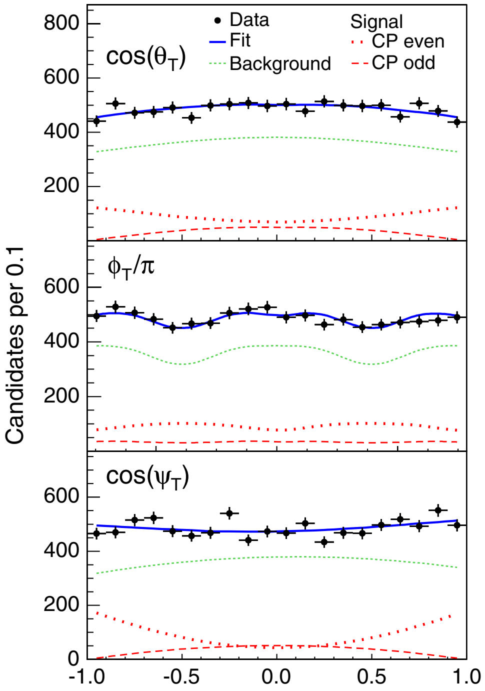

FIG. 3 (color online). Angular distributions with fit projection overlaid.

amplitudes are consistent with the ones observed in $B^0 \to J/\psi K^*$ decays [14] as expected under the assumption of SU(3) flavor symmetry.

For the constraints on the *CP*-violating phase, we construct a 90% (95%) confidence level region in the $2\beta_s$-$\Delta\Gamma$ plane using the likelihood-ratio ordering of Feldman and Cousins [15]. We choose this method instead of a point estimate because it is not affected by the bias we observe in simulated experiments. The bias is of the order of the statistical uncertainty for input values of $\Delta\Gamma$ or $2\beta_s$ close to zero, which are near to the SM expectation. The bias can be understood from Eq. (1). If $2\beta_s$ approaches zero, the two terms proportional to $\sin(2\beta_s)$ vanish, and this analysis becomes insensitive to $\delta_\perp$. The same effective loss of degrees of freedom in the fit occurs when $\Delta\Gamma$ approaches zero and multiple degenerate solutions for $2\beta_s$ and $\delta_\perp$ exist.

To obtain the likelihood-ratio distribution for given values of $\Delta\Gamma$ and $2\beta_s$, we use experiments simulated with values for all other parameters determined by a fit to data [16]. We checked that alternate choices of these values do not affect the coverage properties of our algorithm. Systematic uncertainties are not included in the algorithm, since they are all negligible.

The resulting confidence region is shown in Fig. 4. Since both $B_s^0$ mass eigenstates have the same angular distribution at $2\beta_s = \pm\pi/2$, the sensitivity on $\Delta\Gamma$ decreases towards this value. For the SM expectation ($\Delta\Gamma \approx 0.1$ ps$^{-1}$ and $2\beta_s \approx 0$), we find the probability to get an equal or greater likelihood ratio than the one observed in data to be $p = 22\%$, corresponding to an agreement at 1.2 Gaussian standard deviations.

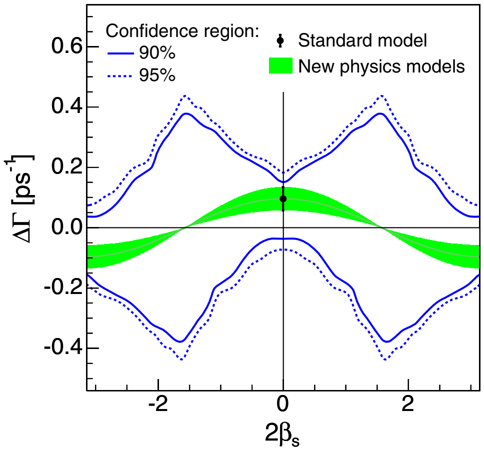

FIG. 4 (color online). Regions at the 90% and 95% confidence level in the $2\beta_s$-$\Delta\Gamma$ plane compared with the SM prediction and the region allowed in new physics models given by $\Delta\Gamma = 2|\Gamma_{12}|\cos(\phi_s)$ [4].

In summary, we report the measurement of the mean lifetime, the width difference, and the amplitudes in $B_s^0 \to J/\psi\phi$ decays assuming *CP* conservation. This measurement improves the precision of the current best measurement [6] by 30%–50%. It is in good agreement with previous results and the SM expectation. In addition we derive constraints on $\Delta\Gamma$ and the *CP*-violating phase $2\beta_s$. Our data are consistent with the SM expectation of $2\beta_s \approx 0$, but sizable values allowed within new physics models cannot be ruled out.

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