

Analysis of Decay-time Dependence of Angular Distributions  
in  $B_s^0 \rightarrow J/\psi \phi$  and  $B_d^0 \rightarrow J/\psi K^{*0}$  Decays  
and Measurement of the Lifetime Difference between  $B_s$  Mass Eigenstates

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We present measurements of the lifetimes and polarization amplitudes for  $B_s^0 \rightarrow J/\psi \phi$  and  $B_d^0 \rightarrow J/\psi K^{*0}$  decays. Lifetimes of the heavy (H) and light (L) mass eigenstates in the  $B_s^0$  system are separately measured for the first time by determining the relative contributions of amplitudes with definite  $CP$  as a function of the decay time. Using 203  $\pm 15$   $B_s^0$  decays we obtain  $\tau_L = (1.05^{+0.16}_{-0.13} \pm 0.02)$  ps and  $\tau_H = (2.07^{+0.58}_{-0.46} \pm 0.03)$  ps. Expressed in terms of the difference  $\Delta\Gamma_s$  and average  $\Gamma_s$ , of the decay rates of the two eigenstates, the results are  $\Delta\Gamma_s/\Gamma_s = (65^{+25}_{-33} \pm 1)\%$ , and  $\Delta\Gamma_s = (0.47^{+0.19}_{-0.24} \pm 0.01)$  ps<sup>-1</sup>.

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Particle-antiparticle oscillation occurs for both  $B_d^0$  and  $B_s^0$  mesons and gives rise, in each system, to two eigenstates with definite masses (heavy,  $m_H$  and light,  $m_L$ ) and widths ( $\Gamma_H$  and  $\Gamma_L$ ). In the Standard Model (SM), oscillation occurs due to second-order contributions from the weak interaction and depends on the Cabibbo-Kobayashi-Maskawa quark mixing matrix. Oscillation has been observed in the  $B_d^0$  system, and the mass difference ( $\Delta m \equiv m_H - m_L$ ) is

$\Delta m_d = (0.507 \pm 0.007) \text{ ps}^{-1}$  [1]. In the  $B_s^0$  system, no oscillation signal has been observed so far: the 95% CL limit for the mass difference is  $\Delta m_s > 14.4 \text{ ps}^{-1}$  [1]. In the SM, the decay width difference is proportional to the mass difference [2]. The ratio of the decay width difference  $\Delta\Gamma \equiv \Gamma_L - \Gamma_H$  to the average decay width  $\Gamma \equiv (\Gamma_L + \Gamma_H)/2$  is expected to be small (0.2% - 0.3%) [3] for the  $B_d^0$  system, but sizable for the  $B_s^0$  system [4]. Ref. [5] predicts  $\Delta\Gamma_s/\Gamma_s = (12 \pm 6)\%$ . The mass eigenstates in the  $B_s^0$  system are expected to be nearly  $CP$  eigenstates. The light mass eigenstate is expected to be  $CP$ -even and to have a larger decay width, and thus a shorter lifetime, than the heavy mass eigenstate [6]. By exploiting decays with known  $CP$  content, it is possible to measure the two decay widths separately.

The decays  $B_s^0 \rightarrow J/\psi \phi$  and  $B_d^0 \rightarrow J/\psi K^{*0}(892)$  are pseudoscalar to vector-vector transitions and are characterized by three amplitudes. These amplitudes correspond to transitions in which the  $J/\psi$  and  $\phi$  (or  $K^{*0}$ ) have a relative orbital angular momentum  $L$  of 0, 1, or 2. In the transversity basis [6], the decay amplitudes correspond to linear polarization states of the vector mesons. The  $L = 1$  decays take place via the decay amplitude  $A_\perp$  and correspond to a parity-odd (perpendicular) correlation between the transverse linear polarization states of the vector mesons. The other two decay amplitudes  $A_0$  and  $A_\parallel$  lead to decays corresponding to linear combinations of the parity-even  $L = 0$  and  $L = 2$  decays. In this analysis, the fully reconstructed decays  $B_s^0 \rightarrow J/\psi \phi$  (with  $J/\psi \rightarrow \mu^+ \mu^-$  and  $\phi \rightarrow K^+ K^-$ ) and  $B_d^0 \rightarrow J/\psi K^{*0}$  (with  $J/\psi \rightarrow \mu^+ \mu^-$  and  $K^{*0} \rightarrow K^+ \pi^-$ ) and their charge conjugates are used to measure the polarization amplitudes. The observed final state particles for the  $B_s^0$  and  $\bar{B}_s^0$  decays ( $\mu^+ \mu^- K^+ K^-$ ) have a definite  $CP$ , which depends on  $L$ , and a definite angular distribution. We determine the decay widths for the heavy and light  $B_s^0$  mass eigenstates by measuring the relative contribution of the  $CP$ -odd and  $CP$ -even decays to the observed angular distribution as a function of the decay time. The  $B_d^0$  decays provide a valuable control sample since they are expected to occur via similar (parity-odd and parity-even) decay amplitudes [6].

The analysis uses a portion of the data from Run II of the Tevatron  $p\bar{p}$  collider, corresponding to an integrated luminosity of about  $260 \text{ pb}^{-1}$ . The data were collected with the upgraded CDF detector [7], the most relevant components of which are described below. A five-layer double-sided silicon microstrip detector, SVX, provides track measurements at radii between 2.5 and 10.6 cm and allows for precise vertex reconstruction. A cylindrical drift chamber, COT, with eight alternating axial and stereo superlayers (each super-layer containing 12 sense wires) provides track measurements for charged particles between radii of 40 and 137 cm. The COT symmetry axis is the main axis of the cylindrical coordinate system used at CDF. Both tracking devices are immersed in a uniform axial 1.4 T magnetic field, allowing precision measurement of the momenta of charged particles in the radial direction  $p_T$ . Planar drift chambers located outside of calorimeters and additional steel absorbers are used to identify muons. Muons and charged hadrons are reconstructed in the central pseudorapidity region  $|\eta| < 1$ .

The three-level trigger system of CDF is used to select events of interest by requiring two oppositely charged particle tracks, each with  $p_T > 1.5 \text{ GeV}/c$  and matched to hits in the muon detector. About two million  $J/\psi \rightarrow \mu^+ \mu^-$  signal candidates were selected by requiring a reconstructed mass within  $80.0 \text{ MeV}/c^2$  of the  $J/\psi$  mass [1]. A  $B_s^0$  ( $B_d^0$ ) meson candidate is reconstructed by associating a  $J/\psi$  candidate with a pair of tracks, each with  $p_T > 0.4 \text{ GeV}/c$ , consistent with a  $\phi \rightarrow K^+ K^-$  ( $K^{*0} \rightarrow K^+ \pi^-$ ) decay. The  $K^+ K^-$  ( $K^+ \pi^-$ ) mass is required to be within  $6.5 \text{ MeV}/c^2$  ( $50.0 \text{ MeV}/c^2$ ) of the  $\phi$  ( $K^{*0}$ ) pole mass [1]. When both  $K^+ \pi^-$  and  $\pi^+ K^-$  particle assignments are kinematically viable in the  $K^{*0}$  reconstruction (no particle identification is used), the one giving the mass closest to the pole  $K^{*0}$  mass is chosen. This reduces the contribution from candidates with swapped particle assignment down to about 10% of the total signal. Background is suppressed by requiring  $p_T(B_{s,d}^0) > 6.0 \text{ GeV}/c$ ,  $p_T(\phi) > 2.0 \text{ GeV}/c$  and  $p_T(K^{*0}) > 2.6 \text{ GeV}/c$ . The more restrictive cut on  $p_T(K^{*0})$  is determined by an optimization procedure, and is a consequence of the larger combinatorial background underneath the  $K^{*0}$  peak.

We fit the  $B$  candidates subject to the constraint that the four tracks originate from a common point. In order to improve the mass resolution, the  $\mu^+ \mu^-$  mass is constrained to the  $J/\psi$  mass. To ensure only well measured vertices, a set of track and vertex quality requirements is applied [8]. In particular, all four tracks are required to have at least 3 measurements in the 5 axial layers of the silicon detector. The proper decay time,  $t$ , is determined from the radial distance  $l_T$  from the beam axis to the  $B$  meson decay vertex, signed relative to the direction of  $\vec{p}_T$  of the  $B$  candidate:  $ct = c(\vec{l}_T \cdot \vec{p}_T)M_B/p_T^2$ . The position of the beam axis is determined using data taken with an inclusive jet trigger. The radial profile of the beam is approximately Gaussian with an RMS of about  $30 \mu\text{m}$ .

The correlation between the linear polarization states of the vector mesons is determined from the angular distribution of the final-state decay products. In the transversity basis, two of the decay angles are defined in the rest frame of the  $J/\psi$ . For  $B_s^0$  (and  $\bar{B}_s^0$ ) decays, the  $\phi$  flight direction defines the positive transversity  $x$  axis, and the  $K^+ K^-$  system defines the  $x$ - $y$  plane with the  $y$  axis such that  $p_y(K^+) > 0$ . The  $z$  axis is defined to make a right-handed coordinate system. The transversity angles  $\theta$  and  $\varphi$  are the polar and azimuthal angles of the  $\mu^+$  momentum in this frame. The angle  $\psi$  is the helicity angle, specifying the direction of the  $K^+$  in the  $\phi$  rest frame relative to the direction opposite to the  $J/\psi$  flight direction in that same frame. The angular definitions carry over for the  $B_d^0$  decays with the  $K$  used to define the helicity angle.

In the  $B_d^0$  system, the mass eigenstates are not  $CP$  eigenstates, and the observed decays are flavor-specific with the charge of the  $K$  meson identifying whether the decay is that of a  $B_d^0$  or a  $\bar{B}_d^0$ . Summing over initially produced  $B_d^0$  and  $\bar{B}_d^0$  yields a differential decay rate [9] which is insensitive to first order to a lifetime difference [3]:

$$\begin{aligned} \frac{d^4\mathcal{P}(\vec{\rho}, t)}{d\vec{\rho}dt} &\propto \left[ |A_0|^2 \cdot f_1(\vec{\rho}) + |A_{\parallel}|^2 \cdot f_2(\vec{\rho}) + |A_{\perp}|^2 \cdot f_3(\vec{\rho}) \right. \\ &\quad \pm \text{Im}(A_{\parallel}^* A_{\perp}) \cdot f_4(\vec{\rho}) + \text{Re}(A_0^* A_{\parallel}) \cdot f_5(\vec{\rho}) \\ &\quad \left. \pm \text{Im}(A_0^* A_{\perp}) \cdot f_6(\vec{\rho}) \right] e^{-\Gamma_d t}. \end{aligned}$$

Here the upper (lower) sign is used for  $K^+\pi^-(K^-\pi^+)$  in the final state and  $\Gamma_d \equiv 1/\tau_{B_d^0}$ . The functions  $f_i(\vec{\rho})$  depend on the transversity variables  $\vec{\rho} \equiv \{\cos\theta, \varphi, \cos\psi\}$  and are given explicitly in Ref. [9].

In the  $B_s^0$  system, the SM expectation is that  $CP$  violation due to mixing is small, and the mass eigenstates are nearly  $CP$  eigenstates. Ignoring  $CP$  violation due to mixing, and summing the distributions for initially produced  $B_s^0$  and  $\bar{B}_s^0$  mesons, the interference terms between the  $CP$ -even and  $CP$ -odd amplitudes cancel, leaving:

$$\begin{aligned} \frac{d^4\mathcal{P}(\vec{\rho}, t)}{d\vec{\rho}dt} &\propto |A_0|^2 e^{-\Gamma_L t} \cdot f_1(\vec{\rho}) + |A_{\parallel}|^2 e^{-\Gamma_L t} \cdot f_2(\vec{\rho}) \\ &\quad + |A_{\perp}|^2 e^{-\Gamma_H t} \cdot f_3(\vec{\rho}) + \text{Re}(A_0^* A_{\parallel}) \cdot f_5(\vec{\rho}) e^{-\Gamma_L t}. \end{aligned}$$

In the  $B_s^0$  analysis, the observed final states have definite  $CP$  which depends on  $L$ . The  $CP$ -even angular decay terms ( $A_{0,\parallel}$ ) evolve in time as  $e^{-\Gamma_L t}$ , while the  $CP$ -odd angular decay terms ( $A_{\perp}$ ) evolve as  $e^{-\Gamma_H t}$ .

For both  $B_d^0$  and  $B_s^0$  decays, the amplitudes are normalized so that  $|A_0|^2 + |A_{\parallel}|^2 + |A_{\perp}|^2 = 1$ , and an unobservable overall phase is removed by setting  $\arg(A_0) = 0$ . The decay amplitudes are assumed to be  $CP$  conserving. The decay amplitudes  $A_{0,\parallel,\perp}$  and decay widths  $\Gamma_H$  and  $\Gamma_L$  are extracted by fitting the observed angular decay distribution as a function of the decay time.

An unbinned likelihood fit is performed to mass,  $ct$ , and  $\vec{\rho}$ . Inclusion of the mass information in the fit is crucial for separation of the signal from the background. The mass distribution is modeled with a Gaussian for the signal peak and a linear shape for the background. The mass-measurement uncertainty is incorporated for each candidate. The probability density function for  $ct$  includes positive exponentials for the signal, a  $\delta$ -function for the prompt background (which is about 85% of the total) and a set of exponentials for positive and negative decay lengths which describe a short-lived background component due to mis-measured vertices and a long-lived contribution due to incorrectly reconstructed heavy-flavor decays. Each contribution is convoluted with a Gaussian resolution function, the width of which is proportional to the uncertainty of the candidate's  $ct$  measurement. To allow for a systematic underestimate of the uncertainties, the mass and the  $ct$  uncertainties are multiplied by scale factors determined in the fit. The (time-dependent)  $\vec{\rho}$  distribution of the signal is parameterized in accordance with the equations above. The background distributions in  $ct$  and  $\vec{\rho}$  are assumed to be uncorrelated. The latter is described by a shape similar to that of the signal, but with an independent set of amplitudes:

$$\begin{aligned} \frac{d^3\mathcal{P}(\vec{\rho})}{d\vec{\rho}} &= |B_0|^2 \cdot f_1(\vec{\rho}) + |B_{\parallel}|^2 \cdot f_2(\vec{\rho}) \\ &\quad + |B_{\perp}|^2 \cdot f_3(\vec{\rho}) + \text{Re}(B_0^* B_{\parallel}) \cdot f_5(\vec{\rho}). \end{aligned}$$

The relationship of mass,  $ct$ , and  $\vec{\rho}$  of the  $B_d^0$  candidates with  $K\pi$  mis-assignment to those of correctly reconstructed candidates is established via Monte Carlo simulation.

Distributions in  $\vec{\rho}$  are distorted by the detector acceptance, the trigger efficiency and, most importantly, the kinematic selection criteria. We use the method developed for the CDF Run I measurement of transversity amplitudes [10, 11] to account for this distortion. With as little as six constants extracted from Monte Carlo decays generated uniformly in  $\vec{\rho}$ , this method allows one to avoid the need for explicit parameterization of the distortion in the likelihood. All aspects of the fitting are extensively verified using Monte Carlo simulations.

Data and fit projections in mass and  $ct$  for the  $B_s^0$  and  $B_d^0$  are shown in Figures 1 and 2. Fits in the transversity sub-space are illustrated by Figure 3.

The single largest source of systematic uncertainty in the measurement of the transversity amplitudes of  $B_d^0$  and  $B_s^0$  is the choice of parameterization of the background distribution in  $\vec{\rho}$ . The  $B_s^0$  transversity amplitudes receive a small contribution to their systematic uncertainty from a 3.5% contamination from  $B_d^0$ . Two other sources contribute to the uncertainty in  $B_d^0$  amplitudes: the way candidates with incorrect  $K\pi$  assignment are handled and the potential contribution of  $\mu^+\mu^-K^+\pi^-$  final states that are not due to  $B_d^0 \rightarrow J/\psi K^{*0}(892)$  decays, which is estimated to be

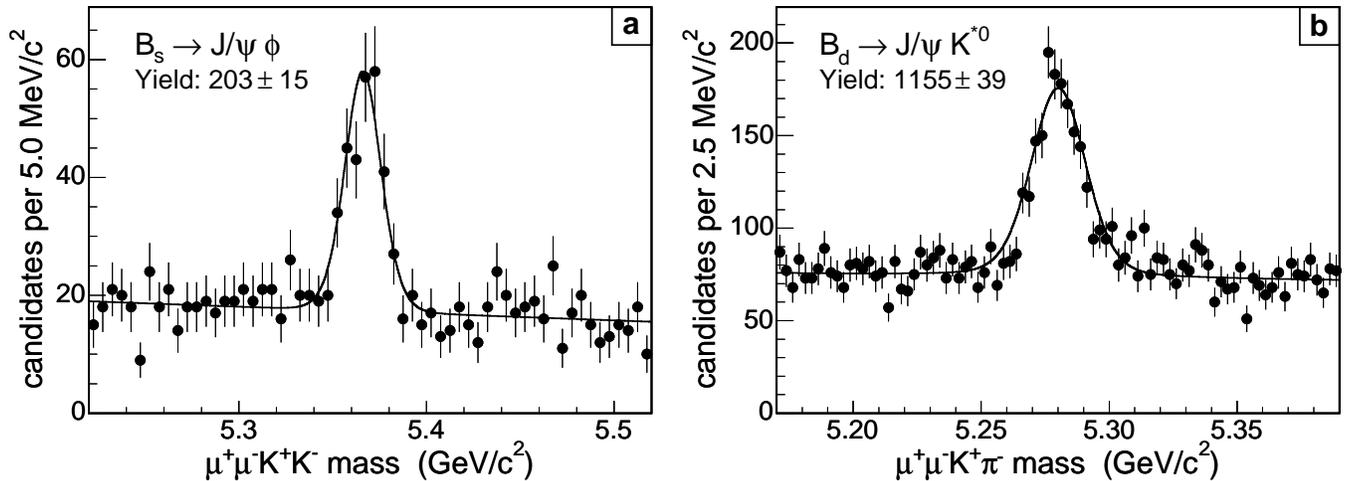


FIG. 1: Mass distribution with the fit projection overlaid: (a)  $B_s^0 \rightarrow J/\psi \phi$ , (b)  $B_d^0 \rightarrow J/\psi K^{*0}$ .

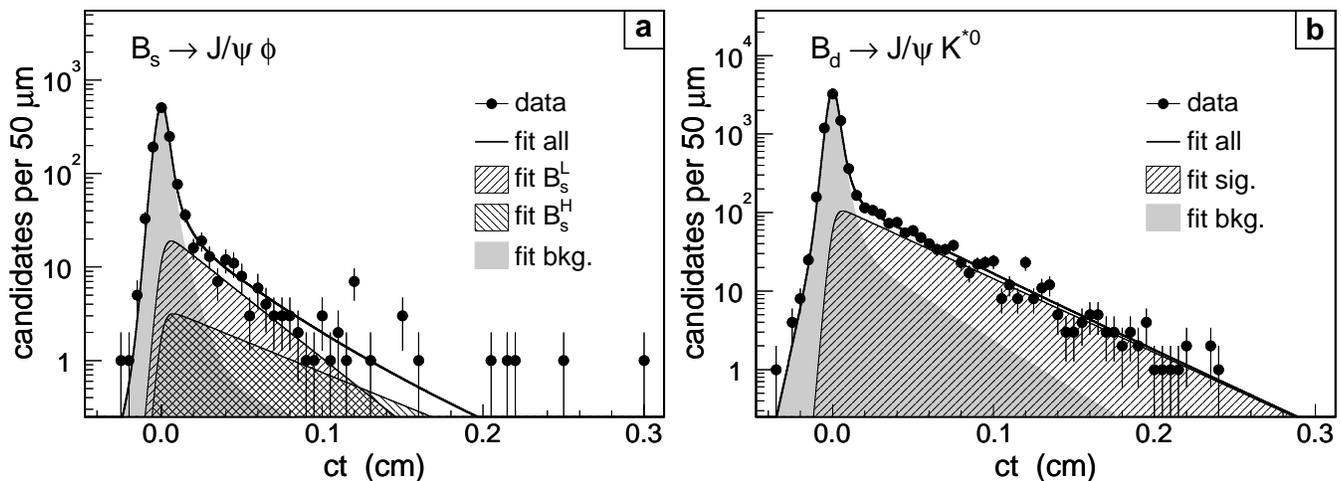


FIG. 2:  $ct$  distribution with the fit projection overlaid: (a)  $B_s^0 \rightarrow J/\psi \phi$ , (b)  $B_d^0 \rightarrow J/\psi K^{*0}$ .

less than 4% of the total signal. The systematic uncertainty in the lifetimes receives contributions from the choice of the  $ct$  model and the SVX alignment. Slightly larger contributions come from the choice of the background parameterization in  $\vec{p}$  and, in the case of  $B_s^0$ , from  $B_d^0$  contamination. For  $\Delta\Gamma_s/\Gamma_s$  the only two sources of systematic uncertainty are from the choice of the background  $\vec{p}$  parameterization and from  $B_d^0$  contamination. Other potential sources of systematic uncertainty, including those from the method of correcting for distortion of the signal distribution in  $\vec{p}$  and potential contribution of  $B_s^0 \rightarrow J/\psi f^0(980)$  decays, were found to be negligible. The precision of all of the results of this analysis is statistically limited.

Results from the time-dependent angular analysis are given in Table I. The  $B_d^0$  decay amplitudes and phases are of comparable precision and in agreement with results from BaBar [12] and Belle [13], and the lifetime is in agreement with the world average value [1]. Previous results [11] for the  $B_s^0$  decay amplitudes, obtained from a time-integrated analysis, are in agreement with the results obtained in this analysis. Within uncertainties, the amplitudes for the  $B_s^0$  and  $B_d^0$  decays are in agreement, as is expected in the limit of  $SU(3)$  flavor symmetry [9]. Explicitly requiring exact  $SU(3)$  symmetry by setting the  $B_s^0$  decay amplitudes to be equal to those of the  $B_d^0$ , gives a consistent result for  $\Delta\Gamma_s/\Gamma_s$  within uncertainties.

It is predicted [4] that the  $B_d^0$  and  $B_s^0$  total decay widths should be equal to within 1%. This expectation can be used as a constraint in the  $B_s^0$  fit by requiring  $1/\Gamma_s \equiv \tau_{B_s^0} \equiv 2\tau_H\tau_L/(\tau_H + \tau_L) = \tau_{B_d^0} \equiv 1/\Gamma_d$ , with  $c\tau_{B_d^0} = 460.8 \pm 4.2 \mu\text{m}$ , the known value for the  $B_d^0$  lifetime [1] with an additional 1% uncertainty added in quadrature. By applying this constraint in the fit, we find  $\Delta\Gamma_s/\Gamma_s = (71^{+24}_{-28} \pm 1)\%$  and  $\Delta\Gamma_s = (0.46^{+0.17}_{-0.18} \pm 0.01) \text{ps}^{-1}$ . Although the uncertainties are still sizable, the fits with and without the  $\Gamma_s = \Gamma_d$  constraint favor a non-zero value for  $\Delta\Gamma_s/\Gamma_s$ .

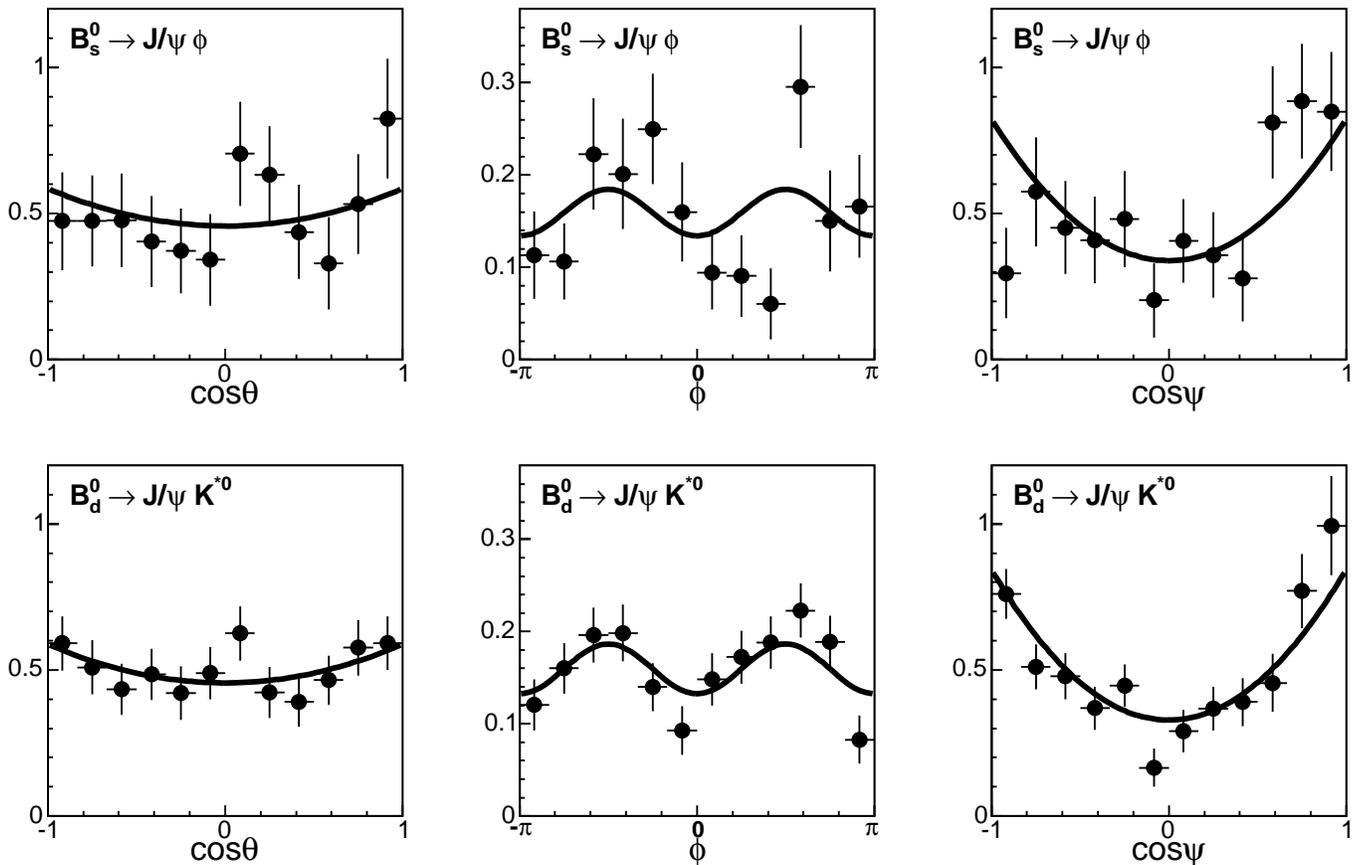


FIG. 3: Projections of the fit onto transversity variables for the mass-sideband-subtracted acceptance-corrected signal:  $B_s^0 \rightarrow J/\psi \phi$  (top row),  $B_d^0 \rightarrow J/\psi K^{*0}$  (bottom row). A  $ct > 0$  cut is applied.

Monte Carlo methods are employed to estimate the probability for an experiment with similar statistical sensitivity to yield  $\Delta\Gamma_s/\Gamma_s$  as large as is observed in this analysis. For the SM expectation,  $\Delta\Gamma_s/\Gamma_s = 12\%$ , one experiment in 84 (204) would give a result larger than that obtained from the unconstrained (constrained) fit. If no lifetime difference were expected,  $\Delta\Gamma_s/\Gamma_s = 0$ , one experiment in 315 (718) would give a result larger than that obtained from the unconstrained (constrained) fit.

A lifetime difference should result in an increase of the fraction of  $CP$ -odd  $B_s^0 \rightarrow J/\psi \phi$  decays obtained in a time-integrated angular fit as a function of a cut on  $ct$ . The time-integrated  $CP$ -odd fraction extracted from fits for four values of the  $ct$  cut are shown in the second column of Table II. Using  $c\tau_L$  and  $c\tau_H$  obtained from the time-dependent fit and the observation that the time integrated  $CP$ -odd fraction is 20% for  $ct > 0$ , one obtains expected fractions for the other  $ct$  cuts, shown in the third column in Table II, which are in agreement with the observations. The  $B_d^0 \rightarrow J/\psi K^{*0}$  decays provide an important cross check of the results obtained for the  $B_s^0 \rightarrow J/\psi \phi$  decays. Fits for the time-integrated fraction of parity-odd  $B_d^0$  decays show, as expected, that the fraction remains unchanged with respect to cuts on  $ct$  (last column of Table II). In addition, a fit of the  $B_d^0$  data can be performed allowing two lifetime components. The results are consistent with no lifetime difference for the full sample ( $\Delta\Gamma/\Gamma = (15 \pm 12)\%$ ), as well as for independent subsamples having a statistical sensitivity similar to the  $B_s^0$  decay sample. This result is not a measurement of a lifetime difference in the  $B_d^0$  system, but rather a cross check of the analysis technique.

In conclusion, we have performed the first time-dependent angular analysis of  $B_d^0 \rightarrow J/\psi K^{*0}$  and  $B_s^0 \rightarrow J/\psi \phi$  decays. The measured  $B_d^0$  polarization amplitudes are of comparable precision to, and in agreement with, previously published results. The measured  $B_s^0$  polarization amplitudes are the most precise available. Analysis of the  $B_s^0 \rightarrow J/\psi \phi$  decays indicates a non-zero lifetime difference between the heavy and light mass eigenstates of the  $B_s^0$  system. The result obtained,  $\Delta\Gamma_s/\Gamma_s = (65^{+25}_{-33} \pm 1)\%$ , has a central value larger than the SM expectation of  $(12 \pm 6)\%$ .

	$B_s^0$	$B_d^0$
$N_{sig}$	$203 \pm 15$	$1155 \pm 39$
$A_0$	$0.784 \pm 0.039 \pm 0.007$	$0.750 \pm 0.017 \pm 0.012$
$ A_{\parallel} $	$0.510 \pm 0.082 \pm 0.013$	$0.473 \pm 0.034 \pm 0.006$
$ A_{\perp} $	$0.354 \pm 0.098 \pm 0.003$	$0.464 \pm 0.035 \pm 0.007$
$\arg(A_{\parallel})$	$1.94 \pm 0.36 \pm 0.03$	$2.86 \pm 0.22 \pm 0.07$
$\arg(A_{\perp})$		$0.15 \pm 0.15 \pm 0.04$
$c\tau_{B_d^0}$		$(462 \pm 15 \pm 6) \mu\text{m}$
$c\tau_{B_s^0}$	$(419 \text{ }^{+45}_{-38} \pm 6) \mu\text{m}$	
$c\tau_L$	$(316 \text{ }^{+48}_{-40} \pm 6) \mu\text{m}$	
$c\tau_H$	$(622 \text{ }^{+175}_{-138} \pm 9) \mu\text{m}$	
$\Delta\Gamma_s/\Gamma_s$	$(65 \text{ }^{+25}_{-33} \pm 1) \%$	
$\Delta\Gamma_s$	$(0.47 \text{ }^{+0.19}_{-0.24} \pm 0.01) \text{ ps}^{-1}$	

TABLE I: Summary of the results of the time-dependent angular analysis of  $B_s^0 \rightarrow J/\psi \phi$  and  $B_d^0 \rightarrow J/\psi K^{*0}$  decays. A measurement of  $\arg(A_{\perp})$  is not possible for the  $B_s^0$  decays because the final state particles do not distinguish the decay of a  $B_s^0$  from that of a  $\bar{B}_s^0$ . For the  $B_s^0$  decays, any pair of quantities describing signal lifetimes ( $\tau_{B_s^0} = 1/\Gamma_s$ ,  $\tau_H$ ,  $\tau_L$ ,  $\Delta\Gamma_s/\Gamma_s$  and  $\Delta\Gamma_s$ ) are allowed to be free parameters in a fit; separate fits using different pairs are performed to obtain directly the results and asymmetric (statistical) uncertainties for each of the quantities.

$ct$ cut	$B_s^0$ fitted	$B_s^0$ expected	$B_d^0$ fitted
$> 0 \mu\text{m}$	$20 \pm 9$	20 (reference)	$22 \pm 4$
$> 150 \mu\text{m}$	$24 \pm 10$	24	$23 \pm 4$
$> 300 \mu\text{m}$	$30 \pm 13$	29	$23 \pm 4$
$> 450 \mu\text{m}$	$39 \pm 12$	34	$24 \pm 5$

TABLE II: Time-integrated  $CP$ -odd  $B_s^0$  and parity-odd  $B_d^0$  fractions (in %) vs. a cut on the proper decay length,  $ct$ .

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