DØ Conference note 5052

Measurement of the Lifetime Difference in the B_s^0 System

(Dated: May 11, 2006)

We present a study of the decay $B_s^0 \to J/\psi\phi$. From a simultaneous fit to the distributions in the candidate mass, proper decay length, and three angles of the decay products, we obtain the average lifetime of the (B_s^0, $\overline{B}_s^0$) system, $\overline{\tau}(B_s^0)$ =1.53 ±0.08 (stat)$^{+0.01}_{-0.04}$ (syst) ps, and the width difference between the light and heavy mass eigenstates, $\Delta\Gamma \equiv (\Gamma_L - \Gamma_H) = 0.15 \pm 0.10$ (stat) $^{+0.03}_{-0.04}$ (syst) ps^{-1}. The data sample corresponds to an integrated luminosity of 0.8 fb^{-1} accumulated with the DØ detector at the Tevatron. All results are preliminary.

Preliminary Results for Winter 2006 Conferences

I. INTRODUCTION

In the standard model (SM), the light (L) and heavy (H) eigenstates of the B_s^0 system are expected to mix in such a way that the mass and decay width differences between them, $\Delta M \equiv M_H - M_L$ and $\Delta\Gamma \equiv \Gamma_L - \Gamma_H$, are sizeable. The mixing phase $\delta\phi$ is predicted to be small, and to a good approximation the two mass eigenstates (B_s^L and B_s^H) are expected to be CP eigenstates (CP-even and CP-odd). New phenomena may alter $\delta\phi$, leading to a reduction of the observed $\Delta\Gamma$ compared to the SM prediction [1]. 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 simultaneous study of the time evolution and angular distributions of the decay products of the J/ψ and ϕ mesons.

In Ref. [2] 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 ≈450 pb^{-1} of data. In that analysis, we performed an unbinned maximum likelihood fit to the data, including the B_s^0 candidate mass, lifetime, and the transversity polar angle. We extracted three parameters characterizing the B_s^0 system and its decay $B_s^0 \to J/\psi\phi$: $\overline{\tau} = 1/\overline{\Gamma}$, 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, improvements in the analysis and in the data handling include: (i) extending the fit from three to five dimensions by including the information on all three angles characterizing the final state, and (ii) the track momentum bias is reduced by applying an improved energy loss correction. For (B_s^0, $\overline{B}_s^0$) system, we measure decay width difference between heavy and light mass eigenstates $\Delta\Gamma$, the average lifetime $\overline{\tau}$, the magnitudes of the decay amplitudes, and the relative phase of the two CP-even amplitudes. We also discuss the sensitivity to the CP violation.

II. DATA

The data used for this analysis have pre-selected events include two reconstructed muons with a transverse momentum greater than 1.5 GeV. Each muon is required to be detected as a track segment in at least one layer 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. We require the events to satisfy a muon trigger that does not include a cut on the impact parameter. For this sample, the estimated luminosity based on triggers we are using is approximately 0.8 fb^{-1}.

To select the B_s^0 candidate sample, we apply kinematic and quality cuts listed in table I. In case of multiple B_s^0 candidates after all final selection cuts, we select the one with the lowest χ^2. 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 world average mass of the B_s^0 meson [3]. 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. There are 21380 events satisfying the above cuts. The resulting invariant mass distribution of the $(J/\psi, \phi)$ system is shown in Fig. 1 (left panel). The fitted curve is a projection of the maximum likelihood fit, described later. The fit assigns 978±45 events to due the B_s^0 decay. The B_s^0 signal for "long-lived" events, i.e. for events with ct/σ(ct) >5, is shown in Fig. 1 (right panel).

III. FITTING PROCEDURE

We perform a simultaneous unbinned maximum likelihood fit to B_s^0 candidates mass, proper decay length, and three decay angles describing the angular distribution of $B_s^0 \to J/\psi\phi$ in transversity basis. The likelihood function $\mathcal{L}$ is given by:

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

where N is the total number of events, and f_{sig} is the fraction of signal in the sample. $\mathcal{F}_{sig}^i$ is product of probability distribution functions (PDFs) of the signal mass, proper decay length, and the decay angles, while $\mathcal{F}_{bck}^i$ is for background. Backgrounds are divided into two categories, based on their origin and lifetime characteristics. "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

Quantity	Cut
B_s^0 candidate mass	$5.0 < M(\psi, \phi) < 5.8$ GeV
ϕ candidate mass	$1.01 < M(K^+, K^-) < 1.03$ GeV
J/ψ candidate mass	$2.9 < M(\mu^+, \mu^-) < 3.3$ GeV
p_T of B_s^0	> 6.0 GeV
p_T of J/ψ	> 4 GeV if $\|\eta\| < 1$
χ^2 of J/ψ	< 10.0
p_T of ϕ	> 1.5 GeV
χ^2 of ϕ	< 15.0
p_T of hadronic track	> 0.7 GeV
SMT hits on track	> 1
CFT hits on track	> 1
CFT + SMT hits on track	> 7
Decay length error of B_s^0 candidate	< 0.006 cm
Absolute decay length difference between B_s^0 candidate and J/ψ	< 0.2 cm

TABLE I: Summary of event selection cuts.

while the tracks forming the ϕ candidate emanate from a multibody decay of the same B hadron or from hadronization. We allow for independent parameters for the two background components in mass, lifetime, and decay angles.

Signal parametrization

For B_s^0 signal mass PDF we use Gaussian with free mean and width. Lifetime and decay angles PDF is described by the time-dependent three-angle distribution for the decay of *untagged* B_s^0 mesons (i.e., summed over B_s^0 and $\overline{B}_s^0$), in transversity basis [4], as given below:

$$\frac{d^3\Gamma(t)}{d\cos\theta\ d\varphi\ d\cos\psi} \propto\ 2|A_0(0)|^2 e^{-\Gamma_L t}\cos^2\psi(1-\sin^2\theta\cos^2\varphi)$$

$$+\sin^2\psi\{|A_\parallel(0)|^2 e^{-\Gamma_L t}(1-\sin^2\theta\sin^2\varphi)+|A_\perp(0)|^2 e^{-\Gamma_H t}\sin^2\theta\}$$

$$+\frac{1}{\sqrt{2}}\sin 2\psi|A_0(0)||A_\parallel(0)|\cos(\delta_2-\delta_1)e^{-\Gamma_L t}\sin^2\theta\sin 2\varphi$$

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

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

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. The quantity $\delta\phi$ is a CP-violating weak phase, due to the interference effects between $B_s^0 - \overline{B}_s^0$ mixing and decay processes. In the standard model, $\delta\phi$ is negligibly small ($\delta\phi = \phi_{\rm CKM} = \mathcal{O}(0.03)$), justifying the small-angle approximation in the above equation. In the following, we set $\delta\phi$ to zero.

Due to limited detector coverage and kinematic thresholds, the detector response to the angles is non-uniform. The acceptance functions are determined using Monte Carlo (MC) simulations, and modeled by polynomials. To generate MC we have used the *SVV_HELAMP* model in the EvtGen generator [5]. Simulated events were reweighted to match the kinematic distributions observed in the data.

Background parametrization

The background mass distributions are parametrized by low-order polynomials: prompt component by linear polynomial, while non-prompt by 2^{nd} order polynomial. The lifetime 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 proper decay length region and two exponentials for the positive ct region, with free slopes and normalization. For the prompt and non-prompt background decay angles distributions, we have used various polynomials: $(1 + X_{2x}\cos^2\theta + X_{4x}\cos^4\theta)$ for θ, $1 + Y_{1x}\cos(2\varphi) + Y_{2x}\cos^2(2\varphi)$ for φ, and $1 + Z_{2x}\cos^2(\psi)$ for ψ. We also allow for a background term analogous to the interference term of the CP-even waves, with a free coefficient Int_x.

There are total 32 free parameters in the fit, listed in table II.

	Parameter notation	description
1	f_{sig} (N_{sig})	fraction of the signal in the total number of candidate events, defined in Eq. 1 ($N_{sig} = f_{sig} \times N_{tot}$).
2	M	The mean value of the Gaussian function in the signal mass PDF.
3	σ	The width of the Gaussian function in the signal mass PDF.
4	$\overline{\tau}$	The inverse of the average decay width i.e. $\overline{\tau} = 1/\overline{\Gamma}$, where $\overline{\Gamma} = (\Gamma_L + \Gamma_H)/2$.
5	$\Delta\Gamma$	Decay width difference between two CP eigenstates of (B_s^0, $\overline{B}_s^0$) system, i.e. $\Delta\Gamma = \Gamma_L - \Gamma_H$.
6	$A_\perp(0)$	The magnitude of the CP-odd linear polarization amplitude at time t=0 in $B_s^0 \to J/\psi\phi$ decay. The fraction of CP-odd component at time t=0 is given by $R_\perp = \|A_\perp(0)\|^2$ and $(1 - R_\perp) = \|A_{\|\|}(0)\|^2 + \|A_0(0)\|^2$.
7	$\|A_0(0)\|^2 - \|A_{\|\|}(0)\|^2$	The difference in square of CP-even linear polarization amplitude at time t=0 in $B_s^0 \to J/\psi\phi$ decay.
8	δ_1	$\equiv Arg(A_{\|\|}(0)^* A_\perp(0))$, $CP-conserving$ strong phase, expected to be mod π.
9	δ_2	$\equiv Arg(A_0(0)^* A_\perp(0))$, $CP-conserving$ strong phase, expected to be 0.
10	$\delta\phi$	$CP-violating$ weak phase. It can be expressed in terms of elements of the CKM matrix as $e^{i\delta\phi} = \frac{V_{ts}V_{tb}^*V_{cs}^*V_{cb}}{V_{ts}^*V_{tb}V_{cs}V_{cb}^*}$, expected to be very small $\mathcal{O}(0.03)$.
11	S	A parameter multiplied to the proper decay length uncertainty ($\sigma(ct)$), if it is under/over estimated.
12	a_{1p}	The coefficient of the mass term in the linear parametrization, describing the mass distribution of prompt background.
13	a_{1l}	The coefficient of the linear term in 2^{nd} order polynomial $1 + a_{1l}m + a_{2l}m^2$, describing the mass distribution of non-prompt background.
14	a_{2l}	same as above but coefficient of the quadratic term.
15	f_-	The normalization constant of the exponential at $ct < 0$ in the background lifetime PDF.
16	f_+	The normalization constant of the first exponential at $ct > 0$ in the background lifetime PDF.
17	f_{++}	The normalization constant of the second exponential at $ct > 0$ in the background lifetime PDF.
18	b_-	The slope of the exponential function at $ct < 0$ in the background lifetime PDF.
19	b_+	The slope of the first exponential function at $ct > 0$ in the background lifetime PDF.
20	b_{++}	The slope of the second exponential function at $ct > 0$ in the background lifetime PDF.
21	X_{2p}	Coefficient of $cos^2\theta$ term in the polynomial $1 + X_{2p}cos^2\theta + X_{4p}cos^4\theta$, describing the transversity-angle distribution of the prompt background.
22	X_{4p}	same as above but of $cos^4\theta$ term.
23	X_{2l}	Coefficient of $cos^2\theta$ term in the polynomial $1+X_{2l}cos^2\theta+X_{4l}cos^4\theta$, describing the transversity-angle distribution of the non-prompt background.
24	X_{4l}	same as above but of $cos^4\theta$ term.
25	Y_{1p}	Coefficient of $cos(2\phi)$ term in the polynomial $1 + Y_{1p}cos(2\phi) + Y_{2p}cos^2(2\phi)$, describing the ϕ-angle distribution of the prompt background.
26	Y_{2p}	same as above but of $cos^2(2\phi)$ term.
27	Y_{1l}	Coefficient of $cos(2\phi)$ term in the polynomial $1 + Y_{1l}cos(2\phi) + X_{2l}cos^2(2\phi)$, describing the ϕ-angle distribution of the non-prompt background.
28	Y_{2l}	same as above but of $cos^2(2\phi)$ term.
29	Z_{2p}	Coefficient of $cos^2\psi$ term in the polynomial $1+Z_{2p}cos^2\psi$, describing the ψ-angle distribution of the prompt background.
30	Z_{2l}	Coefficient of $cos^2\psi$ term in the polynomial $1+Z_{2l}cos^2\psi$, describing the ψ-angle distribution of the non-prompt background.
31	Int_p	Allowing for a term analogous to line 3 of Eq. 2 for the prompt background.
32	Int_l	Allowing for a term analogous to line 3 of Eq. 2 for the non-prompt background.

TABLE II: Definition of the fit parameters used in unbinned maximum likelihood fit.

IV. RESULTS

In the limit $\delta\phi = 0$, the last term in Eq. 2 vanishes, and the strong phases δ_1 and δ_2 enter only as a difference. We set δ_2 to zero and vary δ_1. Our results, and comparisons with previous measurements, are presented in Table III. Figures 2 - 5 show the fit projections on the three decay angles and on the lifetime distribution. Figure 6 shows a the 1-σ contour for $\Delta\Gamma$ versus c$\overline{\tau}$. Note that this measurement of $\overline{\tau}$ should not be directly compared to the earlier measurements of the B_s^0 lifetime that assumed a single lifetime. The one-slope fit to this data, i.e. a fit for the case $\Delta\Gamma \equiv 0$, gives $\overline{\tau} = 1.450 \pm 0.058$ ps.

Sensitivity to CP violation

The decay rate in Eq. 2 includes a dependence on CP - *violating* weak phase, $\delta\phi$ as well as on two CP - *conserving* strong phases, δ_1 and δ_2, through the interference terms between the CP-even and CP-odd waves. With a sizeable lifetime difference, one should in principle be able to detect their presence. We find it impossible for our fit to converge, if we allow all three phases to vary simultaneously. We test the sensitivity to the terms proportional to $\delta\phi$ by setting $\delta_2 = 0$ (to its expected value in SM) and allowing δ_1 to vary. Results of this fit are shown in Table III in the column marked "$D\text{Ø}$ $'06$ free $\delta\phi$". We find the CP-violating phase in the (B_s^0, $\overline{B}_s^0$) system to be consistent with zero. The statistical precision of our estimate of the CP-violating angle is ±0.7 at a fixed value of one strong phase.

TABLE III: Comparison of the existing direct measurements of decay rate difference between B_s^0 mass eigenstates ($\Delta\Gamma$), the average lifetime (i.e. inverse of the average decay rate, $\overline{\tau} = 1/\overline{\Gamma}$), the CP-violating weak phase ($\delta\phi$), and decay amplitudes to the ($J/\psi, \phi$) final state.

Observable	CDF '04 ref. [7]	DØ '05 ref. [2]	**DØ '06** CP conserved	DØ '06 free $\delta\phi$
$\Delta\Gamma$ (ps^{-1})	$0.47^{+0.19}_{-0.24} \pm 0.01$	$0.17^{+0.20}_{-0.27}{}^{+0.02}_{-0.03}$	$0.15^{+0.10}_{-0.10}{}^{+0.03}_{-0.04}$	$0.17^{+0.09}_{-0.09}$
$\overline{\tau}$ (ps)	$1.40^{+0.15}_{-0.13}$	$1.39^{+0.13}_{-0.16}{}^{+0.01}_{-0.02}$	$1.53^{+0.08}_{-0.08}{}^{+0.01}_{-0.04}$	$1.53^{+0.08}_{-0.08}$
$\delta\phi$	$\equiv 0$	–	$\equiv 0$	-0.9±0.7
$R_\perp$	0.13 ± 0.08	0.16 ± 0.10	$0.19 \pm 0.05 \pm 0.01$	0.19 ± 0.05
$\vert A_0(0)\vert^2 - \vert A_\parallel(0)\vert^2$	0.355 ± 0.067	$\equiv 0.355$	0.35±0.07± 0.01	0.34±0.07
δ_1 - δ_2	1.94±0.36	–	2.5±0.4	2.6±0.4

Systematic uncertainties

Systematic uncertainties come from several sources. To test the sensitivity to the detection acceptance, we vary the parameters describing the efficiency by $\pm1\sigma$. We also perform maximum likelihood fits using several alternative approaches to the function needed to match the kinematic distributions of simulated events and data. We use our earlier estimates [2] of the MC verification of the event processing and fitting procedure. The event processing of real data entails additional uncertainties, not fully accounted for by MC simulations. About half of our present data sample was processed twice, with two different versions of the reconstruction program. We use the difference of the fit results for the corresponding samples to set the uncertainty due to the inadequacies of the event processing. We use our earlier estimate of the effect of the imperfect detector alignment.

Our adopted definition of the measured proper decay time uses the world average B_s^0 mass. Alternatively, one could use the measured mass of the candidate (J/ψ,ϕ) pair. The difference for background events near the edges of the allowed mass range is $\pm8\%$. The difference in the decay length value changes the background mass and lifetime parameters, but has little effect on the physics observables. We include the difference in the fit results for the two definitions in the discussion of the systematic uncertainties.

Our sample includes one B_s^0 candidate that has a very low probability to be a well-measured signal or background event. Its proper lifetime, $ct = 0.38$ cm, is more than 0.1 cm above the next highest ct event. The mass value of 5.43 GeV is more than two σ above the average signal mass. Removing this event lowers $\Delta\Gamma$ by 0.03 ps^{-1} and $\overline{\tau}$ by 0.03 ps, and increases $R_\perp$ by 0.01. We assign asymmetric systematic uncertainties to this effect, called "Outlier".

TABLE IV: Sources of systematic uncertainty. The numbers reflect the variation of the fitted central values associated with the 1-σ variation of the corresponding external input parameters.

Source	$c\tau(B_s^0)$ μm	$\Delta\Gamma$ ps^{-1}	$R_\perp$	$\|A_0(0)\|^2 - \|A_\parallel(0)\|^2$	δ_1
Acceptance vs. θ,φ, ψ	±0.5	±0.001	±0.003	±0.01	±0.02
Procedure test	±2.0	±0.025	±0.01	–	–
Event processing	-8.0	0.00	-0.01	–	–
Detector alignment	±2.0	–	–	–	–
ct definition	1.3	0.001	-0.001	-0.002	-0.009
"Outlier"	-7.5	-0.03	0.01	0.0	0.0
Total	-11.3,$+3.2$	-0.04, $+0.03$	±0.01	±0.01	±0.02

V. SUMMARY

We have measured the width difference, $\Delta\Gamma$, between the light and heavy B_s^0 mass eigenstates, which in the limit of no CP violation coincides with CP-even and CP-odd states of the (B_s^0, $\overline{B}_s^0$) system. We have also measured the average lifetime $\overline{\tau}(B_s^0) = 1/\overline{\Gamma}$, the magnitude of the decay amplitudes, and the difference between CP *conserving* strong phases. We obtain:

$$\Delta\Gamma = 0.15 \pm 0.10^{+0.03}_{-0.04}\ \text{ps}^{-1}$$

$$\overline{\tau}(B_s^0) = 1.53 \pm 0.08^{+0.01}_{-0.04}\ \text{ps}$$

$$R_\perp = |A_\perp(0)|^2 = 0.19 \pm 0.05 \pm 0.01$$

$$|A_0(0)|^2 - |A_\parallel(0)|^2 = 0.35 \pm 0.07 \pm 0.01$$

$$\delta_1 - \delta_2 = 2.5 \pm 0.4 \pm 0.02$$

These measurements are consistent with SM predictions within the measurement uncertainties.

We have also explored the CP-violating interference terms, and find our data to be consistent with no CP violation in the (B_s^0, $\overline{B}_s^0$) system. The statistical precision of our estimate of the CP-violating angle ($\delta\phi$) is -0.9±0.7 with one of the strong phases fixed at its expected value of zero, and the other allowed to vary.

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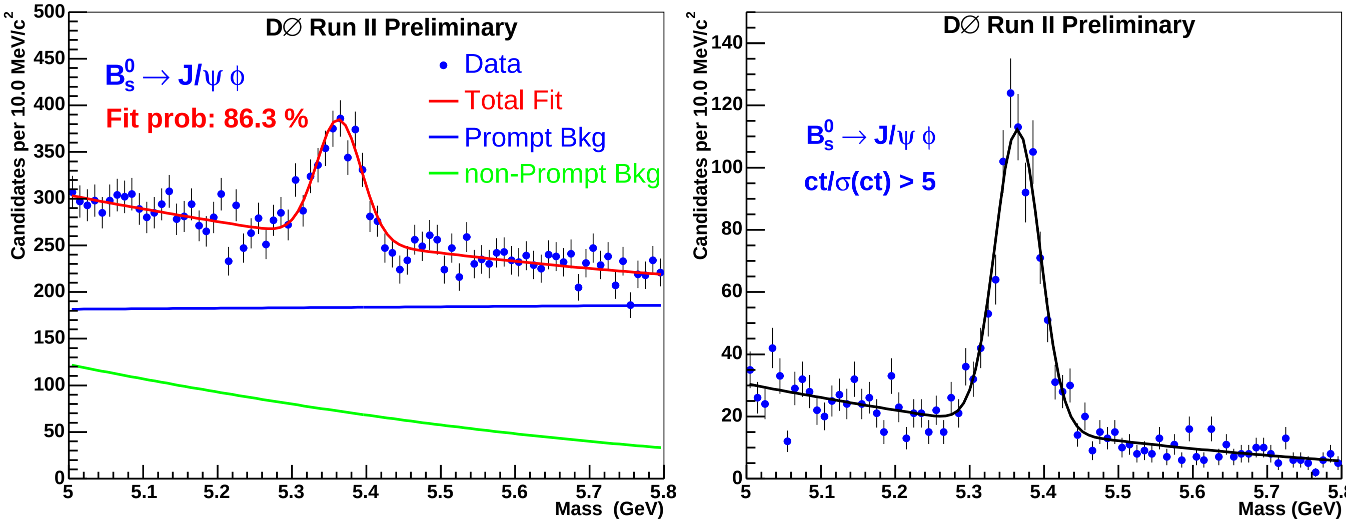

FIG. 1: The invariant mass distribution of the $(J/\psi, \phi)$ system for data B_s^0 candidates. Left: All events. The curves show: the total fit (red solid line), prompt background (blue solid line) and non-prompt background (light-green solid line). Right: Subsample with the prompt background suppressed.

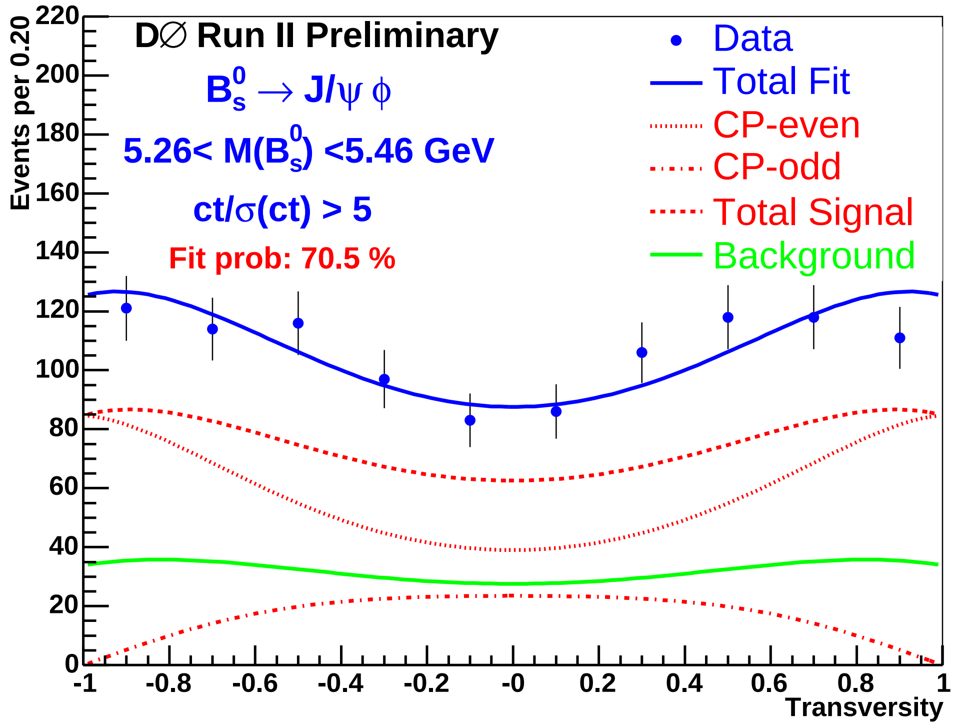

FIG. 2: The transversity distribution for the data signal-enhanced subsample (i.e. "non-prompt" and signal mass range). The curves show: the total fit (blue solid line); CP-even (red dotted line), CP-odd (red dashed-dotted line) and the total signal contribution (red dashed line); the background (light-green solid line).

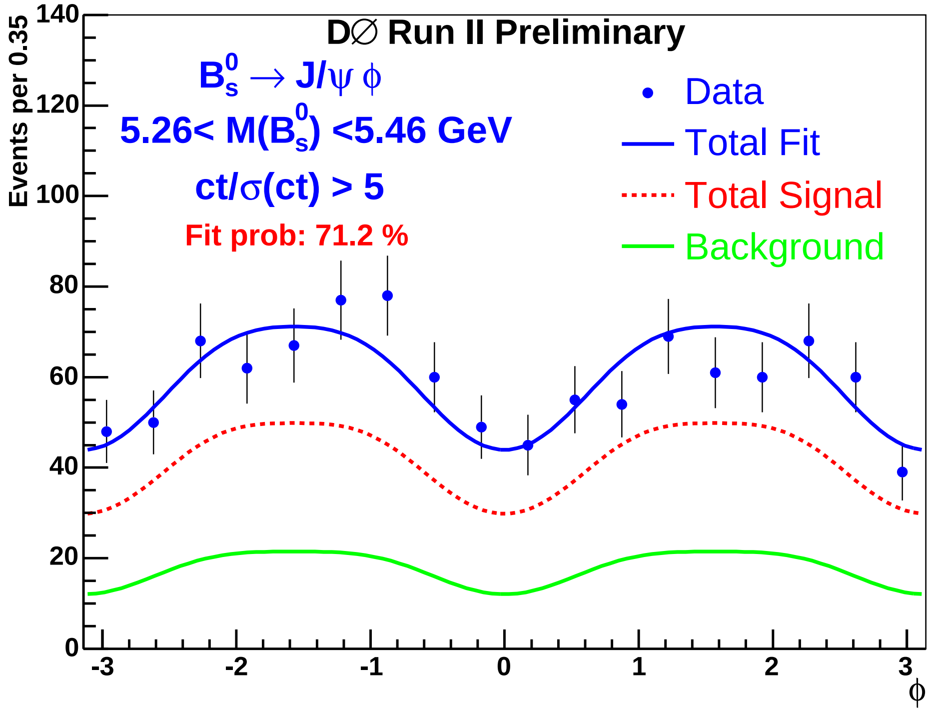

FIG. 3: The distribution in the decay angle φ for the data signal-enhanced subsample (i.e. "non-prompt" and signal mass range). The curves show: the total fit (blue solid line); signal contribution (red dashed line); and the background (light-green solid line).

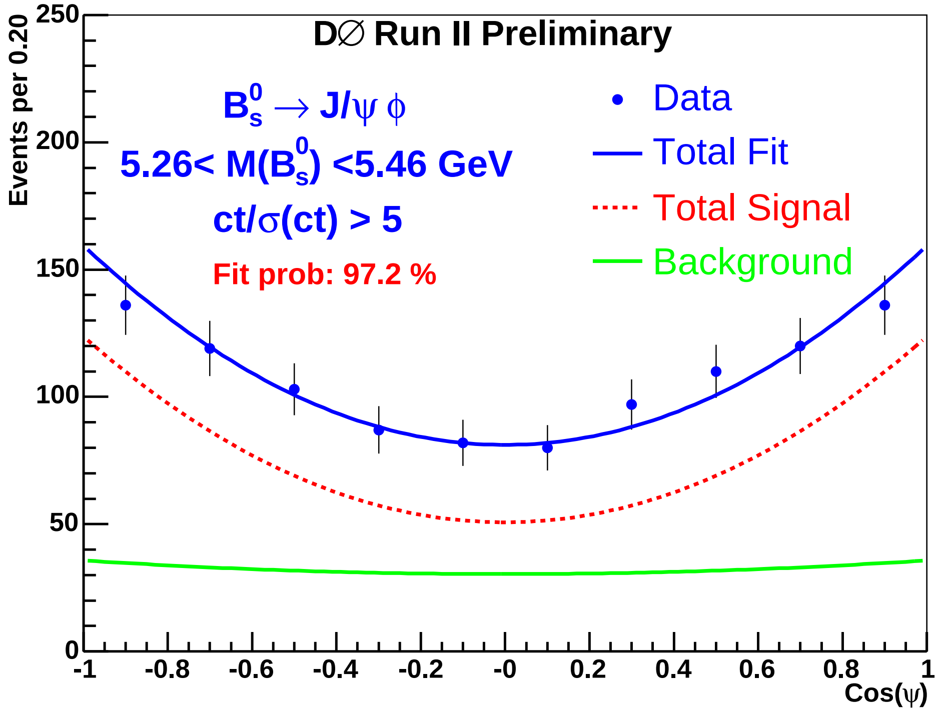

FIG. 4: The distribution in the decay angle ψ for the data signal-enhanced subsample (i.e. "non-prompt" and signal mass range). The curves show: the total fit (blue solid line); signal contribution (red dashed line); and the background (light-green solid line).

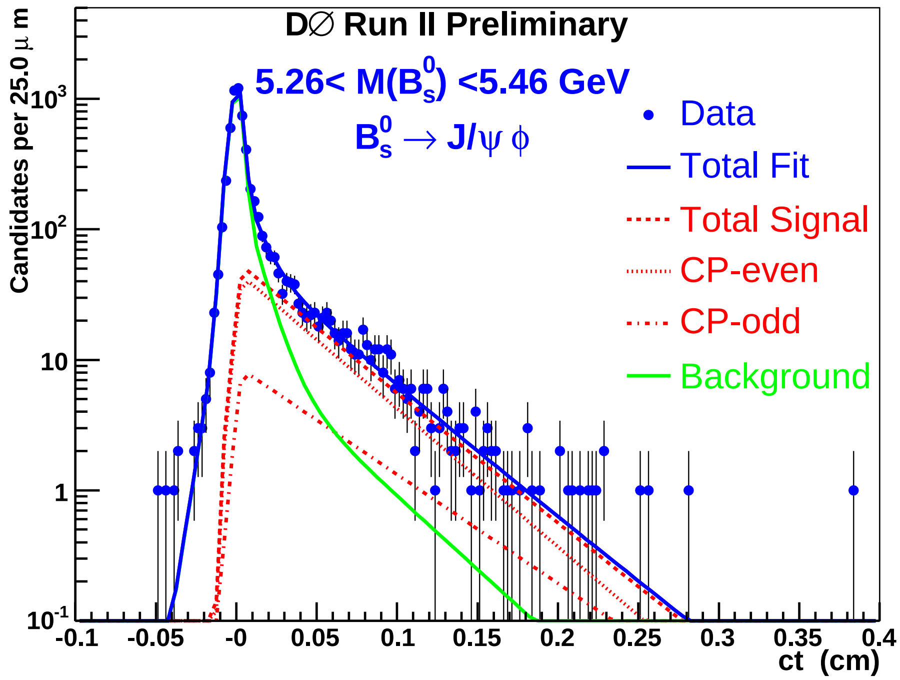

FIG. 5: The proper decay length, ct, of the data B_s^0 candidates in the signal mass region. The curves show: the total fit (blue solid line); the total signal contribution (red dashed line) CP-even (red dotted line), and CP-odd (red dashed-dotted line); the background (light-green solid line).

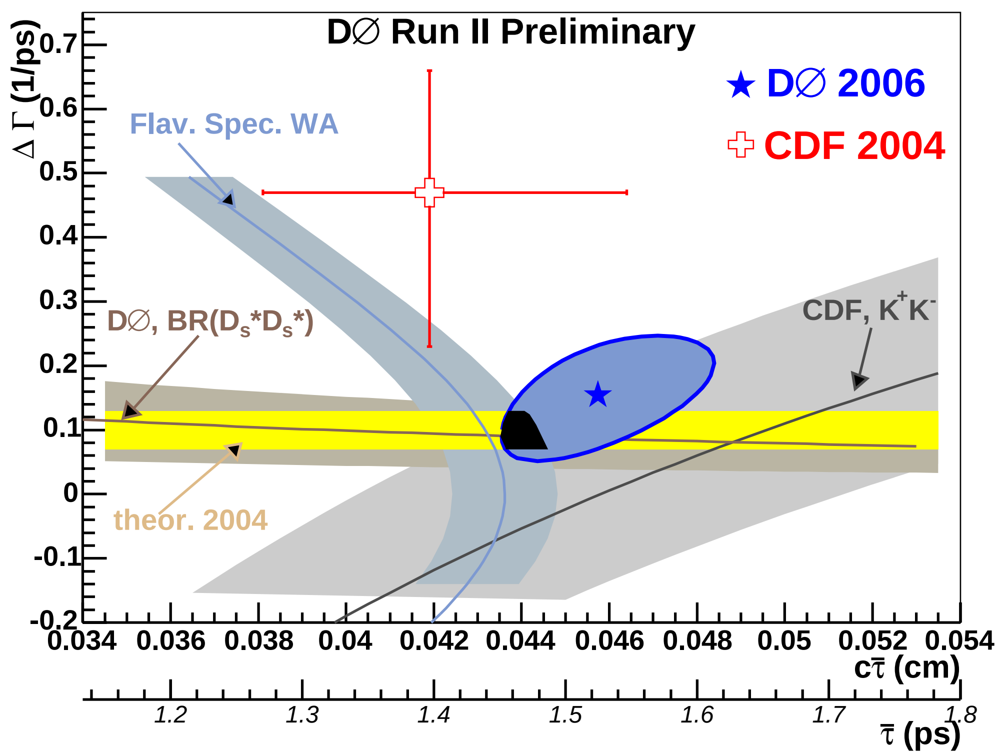

FIG. 6: The DØ default (three-angle fit) 1-σ (stat.) contour in $\Delta\Gamma$ vs $c\overline{\tau}$ plane, compared to a 1-σ band for the world average [3] (WA) measurement based on flavor-specific decays, $\tau_{fs} = 1.442 \pm 0.066$ ps. The SM theoretical prediction [8] is shown as the horizontal band. Also shown is the CDF 2004 result [7], the recent CDF measurement of the B_s^0 lifetime from the $B_s^0 \to K^+K^-$ decay [9], and the implication of the preliminary DØ result [10] of the branching fraction for the decay BR($B_s^0 \to D_s^* D_s^*$).