DØConference note 4557

Measurement of the Lifetime Difference in the B_s System

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We present a study of the untagged decay $B_s^0 \to J/\psi\phi$. From a simultaneous fit to the distributions in the mass, proper decay length, and transversity, we obtain the CP-odd fraction in the final state at time zero, $R_\perp(B_s) = 0.17 \pm 0.10 \pm 0.02$, the average lifetime of the $(B_s^0, \overline{B}_s^0)$ system, $\overline{\tau} = 1.39^{+0.15}_{-0.19}$ ps (stat+syst), and the relative width difference, $\Delta\Gamma/\overline{\Gamma} \equiv (\Gamma_L - \Gamma_H)/\overline{\Gamma} = 0.21^{+0.33}_{-0.45}$ (stat+syst). With the constraint from the world average of the B_s lifetime measurements using semileptonic decays, the one standard deviation range for the average lifetime of the $(B_s^0, \overline{B}_s^0)$ system is narrowed down to $\overline{\tau} = 1.39^{+0.05}_{-0.06}$ ps, and for the relative width difference to $\Delta\Gamma/\overline{\Gamma} = 0.23^{+0.16}_{-0.17}$. For the ratio of the average B_s lifetime to the B_d lifetime, we obtain $\frac{\overline{\tau}(B_s)}{\tau(B_d)} = 0.91 \pm 0.09(stat) + 0.003(syst)$. We also explore the evidence for non-vanishing CP-violating phase. The data sample corresponds to an integrated luminosity of 450 pb^{-1} accumulated with the DØ detector at the Tevatron. All results are preliminary.

Preliminary Results for Winter 2005 Conferences

I. INTRODUCTION

The decay $B_s^0 \to J/\psi\phi$, proceeding through the quark sub-process $b \to c\bar{c}s$, is a B_s counterpart of the decay $B_d \to J/\psi K_s^0$. Because of the presence of final states common to B_s^0 and its charge conjugate $\overline{B}_s^0$, the two meson states are expected to mix in such a way that the two CP eigenstates may have a relatively large lifetime difference. 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, by studying the time evolution of the polarization states of the vector mesons in the final state.

The present work is an extension of a recently published study[1] done under the single-lifetime hypothesis. We perform an unbinned maximum likelihood fit to the data, including the B_s candidate mass, lifetime, and the transversity angle in the decay. (In the following, we use the shorthand "transversity" for the cosine of the transversity angle.) We extract three parameters characterizing the B_s^0 system and its decay $B_s^0 \to J/\psi\phi$: $\overline{\tau} = 1/\overline{\Gamma}$, where $\overline{\Gamma} \equiv (\Gamma_H + \Gamma_L)/2$; $\Delta\Gamma/\overline{\Gamma}$, where $\Delta\Gamma \equiv \Gamma_L - \Gamma_H$; and the relative rate of the decay to the CP-odd states at time zero, $R_\perp$. The subscripts L and H refer to the *Heavy* and *Light* components of the B_s system.

II. DATA

The data were collected between June 2002 and August 2004. The preselected 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 reject runs where the muon or central tracking information was corrupted. We require the events to satisfy a muon trigger that does not include a cut on the impact parameter. The muon system covers the pseudorapidity range to $|\eta| \approx 2$. The sample corresponds to an integrated luminosity of 450 pb^{-1}.

To select the B_s candidate sample, we apply the following kinematic and quality cuts. Transverse momentum, p_T, thresholds for the B_s and ϕ mesons are necessary to control the signal to background ratio and to minimize the statistical uncertainty of the lifetime measurement. In this analysis we set the p_T thresholds at 6.0 GeV for B_s, 1.5 GeV for ϕ, and 0.7 GeV for each ϕ decay product. The B_s candidate sample is selected by requiring a $(J/\psi, \phi)$ pair to be consistent with coming from a common vertex, and to have a mass in the range 5.0 – 5.8 GeV. In case of multiple candidates, we select the one with the highest $\phi(p_T)$. Monte Carlo studies show that the p_T spectrum of the ϕ mesons coming from B_s decays is harder than the p_T of a pair of random tracks from the underlying event. J/ψ candidates are accepted if the unconstraint invariant mass resulting from the vertex fit is in the range 2.9 – 3.25 GeV. For events in the central rapidity region (defined by the requirement on the pseudorapidity of the higher p_T muon $|\eta_{\mu 1}|$), we require the transverse momentum of J/ψ to exceed 4 GeV. ϕ candidates are required to satisfy a fit to a common vertex, and to have the invariant mass in the range 1.01 – 1.03 GeV. We require the B_s proper decay length to be well measured, with the uncertainty $\sigma(c\tau) < 0.006$ cm. Finally, we reject an event if the number of tracks other than muons in a cone ΔR around J/ψ is greater than 25. The selected sample of 9699 events is used in the B_s lifetime measurement. The resulting invariant mass distribution of the $(J/\psi, \phi)$ system is shown in Fig. 1 (left panel). The curve is a projection of the maximum likelihood fit, described later. The fit assigns 483±32 events to the B_s^0 decay.

III. FITTING PROCEDURE

An unbinned maximum likelihood fit is performed to the proper decay length, transversity, and mass. 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=9699 is the total number of events, $\mathcal{F}_{sig}^i$ is the product of the signal mass, proper decay length, and the transversity probability density functions, $\mathcal{F}_{bck}^i$ is the product of the background mass, proper decay length and transversity probability density functions, and f_{sig} is the fraction of signal in the sample.

Signal parametrization

The mass distribution of the signal is parametrized by a Gaussian function with two free parameters, mean and RMS. The lifetime distribution of the signal is parametrized by an exponential convoluted with a Gaussian function. We allow for a different time evolution of the high mass (CP-odd) and low mass (CP-even) B_s states. The width of the Gaussian functions is taken from the event-by-event measurement. To allow for the possibility of the lifetime uncertainty to be systematically underestimated, we introduce a free scale factor ϵ. The transversity distribution of the signal is determined in the following way. The three-angle distribution for the decay of an initially present (i.e. tagged) B_s meson has the form[2] (the corresponding distribution for $\bar{B}_s$ has the signs of of the interferance terms reversed):

$$\frac{d^3\Gamma[B_s(t) \to J/\psi(\to l^+l^-)\phi(\to K^+K^-)]}{d\cos\theta\ d\varphi\ d\cos\psi} \propto \frac{9}{32\pi}\Big[\ 2|A_0(t)|^2\cos^2\psi(1-\sin^2\theta\cos^2\varphi)$$

$$+\sin^2\psi\{|A_\parallel(t)|^2(1-\sin^2\theta\sin^2\varphi)+|A_\perp(t)|^2\sin^2\theta-\ \mathrm{Im}\ (A_\parallel^*(t)A_\perp(t))\sin 2\theta\sin\varphi\}$$

$$+\frac{1}{\sqrt{2}}\sin 2\psi\{\ \mathrm{Re}\ (A_0^*(t)A_\parallel(t))\sin^2\theta\sin 2\varphi+\ \mathrm{Im}\ (A_0^*(t)A_\perp(t))\sin 2\theta\cos\varphi\ \}\ \Big]\ . \quad (2)$$

In the coordinate system in the J/ψ rest frame, where ϕ 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 coordinates (θ,φ) describe the direction of μ^+. The helicity angle ψ is made by $\vec{p}(K^+)$ and the direction opposite to the J/ψ flight in the ϕ rest frame.

We model the nonuniformity of the acceptance in the three angles by polynomials, with parameters determined using MC simulations. To obtain the one-angle (transversity) distribution, we integrate the three-angle distribution over the angles ψ and ϕ. The resulting distribution depends on one free parameter, $R_\perp = |A_\perp(0)|^2$. There is a small correction term due to the nonuniformity of the acceptance in the angle ϕ, which is proportional to $|A_0(0)|^2 - |A_\parallel(0)|^2$. We use the CDF measurement[8] of this difference, 0.355±0.066.

Background parametrization

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 negative $c\tau$ region and two exponentials for the positive $c\tau$ region, with free slopes and normalizations. The mass distribution of background is parametrized by a first-order polynomial. We allow for a separate free slope for the prompt and non-prompt components. The transversity distribution of background is parametrized as $(1 + A_2\cos^2\theta + A_4\cos^4\theta)$. We allow for independent parameters for prompt and non-prompt components of the background.

IV. RESULTS

Results of this analysis are listed in Table I. The proper decay length distribution, and the transversity distribution, with the fit results overlaid are shown in Fig. 2. Figure 3 shows the 1-σ contour for $c\overline{\tau}$ versus $\Delta\Gamma/\overline{\Gamma}$. It provides the best display of the uncertainty range for these correlated parameters. Our best fit returns $\overline{\tau}(B_s^0) = 1.39^{+0.13}_{-0.14}$ ps ($c\overline{\tau}(B_s^0) = 416^{+39}_{-42}\ \mu$m) at $\Delta\Gamma/\overline{\Gamma} = 0.21^{+0.27}_{-0.40}$. For reference, a constraint $\Delta\Gamma/\overline{\Gamma} = 0.12$ (the current theoretical prediction[14]) gives $c\tau(\Delta\Gamma/\overline{\Gamma} = 0.12) = 407 \pm 23\ \mu$m. A constraint $\Delta\Gamma/\overline{\Gamma} = 0$ gives $c\tau(single-lifetime) = 394 \pm 22$ μm (2nd column in Table I). The same result is obtained for a single-lifetime fit that ignores the transversity information (2D fit, 3rd column in Table I.)

We have verified the procedure by performing fits on a sample of ≈50,000 MC events passed through a full chain of the detector simulation, event reconstruction, and maximum likelihood fitting. We see no bias in the event reconstruction or fitting procedure. The fits reproduce the inputs ($c\tau = 439\ \mu$m, $\Delta\Gamma/\overline{\Gamma} = 0$, and a range of $R_\perp$ between 0 and 1) correctly within the statistical precision of 2μm for $c\tau$, 0.01 for $R_\perp$, and 0.025 for $\Delta\Gamma/\overline{\Gamma}$. These and other systematic uncertainties are summarized in Table II. Our results, including the systematic uncertainties, are listed in the Summary.

We have also conducted a test with an ensemble of 1000 pseudo-experiments with similar statistical sensitivity, tossed with the same parameters as obtained in this analysis, i.e. with the parameters listed in the first column of Table I. Both the spread of uncertainties and of the central values of the fit parameters are in good agreement with the collider results reported here (see Fig. 4). About 5% of experiments return $\Delta\Gamma/\overline{\Gamma} > 0.65$, i.e. above the CDF value[8].

Our results are consistent with the published CDF results [8]. The "single-lifetime" result from CDF, $c\tau(single-lifetime) = 395^{+33}_{-30}\ \mu$m), is almost identical to the DØ result. Our central value for $\Delta\Gamma/\overline{\Gamma}$ is lower by one standard deviation. If we constrain $R_\perp$ to 0.125 (CDF value of $|A_\perp|^2$), we obtain $\Delta\Gamma/\overline{\Gamma} = 0.32 \pm 0.23$ and $c\tau = 429 \pm 29\ \mu$m.

TABLE I: Main results of the maximum likelihood fits.

Parameter	3D free $\Delta\Gamma/\overline{\Gamma}$	3D $\Delta\Gamma/\overline{\Gamma} \equiv 0$	2D
f_{sig}	0.050±0.003	0.050±0.003	0.050±0.003
$mass$ (in GeV)	5.331±0.002	5.331±0.002	5.331±0.002
σ (in MeV)	28.3±2.1	28.3±2.1	28.5±2.1
$c\tau$ (in μm)	**416^{+39}_{-42}**	**394±22**	**394±22**
ϵ	1.29±0.02	1.29±0.02	1.29±0.02
$mean-bkg-neg$ (in μm)	51±4	51±4	51±4
$mean-bkg-pos$ (in μm)	89±7	89±7	90±7
$mean-bkg-pos-long$ (in μm)	416±53	416±53	418±53
$norm-bkg-neg$	0.07±0.01	0.07±0.01	0.07±0.01
$norm-bkg-pos$	0.17±0.01	0.17±0.01	0.17±0.01
$norm-bkg-pos-long$	0.03±0.006	0.03±0.006	0.03±0.006
$R_\perp$	**0.17±0.10**	**0.21±0.09**	**not used**
$\Delta\Gamma/\overline{\Gamma}$	**$0.21^{+0.27}_{-0.40}$**	**fixed at 0**	**not used**
A_2 $prompt$	1.0 ±0.2	1.0 ±0.2	not used
A_4 $prompt$	-0.66 ±0.22	-0.66 ±0.22	not used
A_2 $non-prompt$	0.65 ±0.33	0.66 ±0.31	not used
A_4 $non-prompt$	-0.67 ±0.36	-0.67 ±0.33	not used

	Source	$c\tau(B_s)$, μm	$\Delta\Gamma/\overline{\Gamma}$	$R_\perp$	Comment
1	Signal eff. vs transversity	0.6	0.001	0.005	MC
2	Signal eff. vs ϕ, ψ	0.2	0.001	0.02	MC +Ref. [8]
3	Signal mass model	0.4	0.016	0.006	data
4	Procedure bias	2	0.025	0.01	MC
5	Detector alignment	2	–	–	Ref. [1]
6	Background lifetime model	0.5	0.016	0.005	data

TABLE II: Sources of the systematic uncertainty. The above numbers reflect the variation of the fitted central values associated with the 1-σ variation of the corresponding input parameter. The total effect of the systematic uncertainties quoted in the text is obtained by reading out the extrema of the curve encompassing all the alternative 1-σ contours corresponding to the sources listed above.

Constraints from semileptonic B_s decays

B_s lifetime measurements from semileptonic data provide an independent constraint on the average lifetime and lifetime difference in the B_s system. The world average[11] B_s lifetime, including the new, preliminary DØ measurement[12], 426±13±17 μm, is $c\tau_{fs} = c/\Gamma_{fs} = 430 \pm 15$ μm. This result is based on single-exponential fits in the flavor-specific decay channels, which determine the following function (shown in Fig. 3) of $\overline{\Gamma}$ and $\Delta\Gamma/\overline{\Gamma}$: $\Gamma_{fs} = \overline{\Gamma} - (\Delta\overline{\Gamma})^2/2\overline{\Gamma} + O(\Delta\overline{\Gamma})^3/\overline{\Gamma}^2)$. Applying the above constraint to our data, we obtain $\overline{\tau} = 1.39 \pm 0.05$ ps ($c\overline{\tau} = 417 \pm 15$ μm), and $\Delta\Gamma/\overline{\Gamma} = 0.23^{+0.16}_{-0.17}$.

In pursuit of new physics

All the results presented above were obtained under a tacit assumption that the CP-violating phase is negligible, as predicted by the Standard Model ($\phi_{\rm CKM} = -0.03$), and that the mass eigenstates coincide with CP eigenstates. New phenomena may cause the effective phase, $\delta\phi$, to deviate from $\phi_{\rm CKM}$. In this case, the relations between $\Delta\Gamma/\overline{\Gamma}$ as defined in the introduction, the relative decay rate difference for the two CP eigenstates, $\Delta\Gamma/\overline{\Gamma}_{\rm CP}$, and the observable that we measure are [13]: $\Delta\Gamma/\overline{\Gamma} = \Delta\Gamma/\overline{\Gamma}_{\rm CP}\cos(\delta\phi)$, and $\Delta\Gamma/\overline{\Gamma}_{meas} = \Delta\Gamma/\overline{\Gamma}_{\rm CP}\cos^2(\delta\phi)$.

We have performed a modified maximum likelihood fit to our data, applying the constraint from the World Average (WA) semileptonic lifetime, and the theoretical prediction[14] $\Delta\Gamma/\overline{\Gamma}_{\rm CP} = 0.12 \pm 0.05$, allowing for an additional free parameter, $\cos(\delta\phi)$. We used the Gaussian model for the probability distribution functions for both constraints. The result is $|\cos(\delta\phi)| = 1.46^{+0.73}_{-0.69}$. The best value of $\cos(\delta\phi)$ is greater than 1, this is due to the fact that our measured $\Delta\Gamma/\overline{\Gamma}_{meas}$ is greater than the predicted value $\Delta\Gamma/\overline{\Gamma}_{\rm CP}$, and the assumption that new phenomena alter the phase while preserving the value of the nondiagonal term in the decay matrix. This modest constraint means that our measurement of the lifetime difference in the B_s system disfavors the angle $\delta\phi$ near $\pi/2$. It also demonstrates the potential of the analysis of **untagged** $B_s \to J/\psi\phi$ decay, when combined with semileptonic results.

V. SUMMARY

V-A. Results without Outside Constraints

We have measured the CP-odd fraction for the B_s decay and the correlated parameters of the average lifetime of the $(B_s^0, \overline{B}_s^0)$ system, $\tau(B_s^0) = 1/\overline{\Gamma}$, and the relative width difference $\Delta\Gamma/\overline{\Gamma}$, or, equivalently, the mean lifetimes of the light and heavy B_s eigenstates, which in the SM coincide with CP-even and CP-odd states, respectively. For the default fit (free $c\tau(B_s^0)$) we obtain:

$$R_\perp(B_s) = 0.17 \pm 0.10 \pm 0.02$$

$$\Delta\Gamma/\overline{\Gamma} = 0.21^{+0.27}_{-0.40}(stat), \qquad \Delta\Gamma/\overline{\Gamma} = 0.21^{+0.33}_{-0.45}(stat+syst)$$

$$\overline{\tau}(B_s^0) = 1.39^{+0.13}_{-0.14}(stat), \qquad \overline{\tau}(B_s^0) = 1.39^{+0.15}_{-0.19}(stat+syst)$$

$$\tau_L = 1.23^{+0.14}_{-0.11}(stat), \qquad \tau_L = 1.23^{+0.16}_{-0.13}(stat+syst)$$

$$\tau_H = 1.52^{+0.39}_{-0.43}(stat), \qquad \tau_H = 1.52^{+0.41}_{-0.45}(stat+syst)$$

Our results are consistent with previously published results. Comparisons with other measurements are presented in Table III.

Experiment	$R_\perp$	$\Delta\Gamma/\overline{\Gamma}$	$\overline{\tau}(ps)$	τ_L (ps)	τ_H (ps)
Aleph[9]				1.27 $\pm$0.34	
CDF Run II[8]	0.125 ± 0.08	$0.65^{+0.25}_{-0.33} \pm 0.01$	$1.40^{+0.15}_{-0.13}$	$1.05^{+0.16}_{-0.13}$	$2.07^{+0.58}_{-0.46}$
DØ RunII	0.17 ± 0.10	$0.21^{+0.33}_{-0.45}$	$1.39^{+0.15}_{-0.16}$	$1.23^{+0.16}_{-0.13}$	$1.52^{+0.39}_{-0.43}$

TABLE III: Comparison of the existing direct measurements of the CP-odd fraction in the decay to the $J/\psi\phi$ final state, relative decay rate difference between CP-even and CP-odd components, the average lifetime (inverse of the average decay rate), and the lifetime of the light and heavy component of the B_s system.

We have measured the mean lifetime of the B_d meson $c\tau(B_d^0) = 459 \pm 13(stat)$ μm, or $\tau(B_d^0) = 1.530 \pm 0.043(stat)$ ps. With the systematic uncertainty estimated in Ref. [1], the updated measurement is

$$\tau(B_d^0) = 1.530 \pm 0.043(stat) \pm 0.023(syst)ps.$$

For the ratio of the average B_s lifetime to the B_d lifetime, we obtain

$$\frac{\overline{\tau}(B_s)}{\tau(B_d)} = 0.91 \pm 0.09(stat) + 0.003(syst).$$

V-B. Results Constrained by Semileptonic Measurements

Using the default results, and applying a constraint on this pair of parameters from the existing semileptonic (i.e. flavor-specific) measurements [10], we obtain:

$$\overline{\tau} = 1.39^{+0.05}_{-0.06}\ ps \text{ (stat+syst)},$$

$$\Delta\Gamma/\overline{\Gamma} = 0.23^{+0.16}_{-0.17} \text{ (stat+syst)}.$$

V-C. Beyond SM: First Constraints on CP-violating phase in B_s

Comparison of our results with the lifetime measurements from semileptonic decays, and with the theoretical prediction for $\Delta\Gamma_{\rm CP}$ leads to the following best estimate for the cosine of the mixing phase,

$$|\cos(\delta\phi)| = 1.46^{+0.73}_{-0.69}.$$

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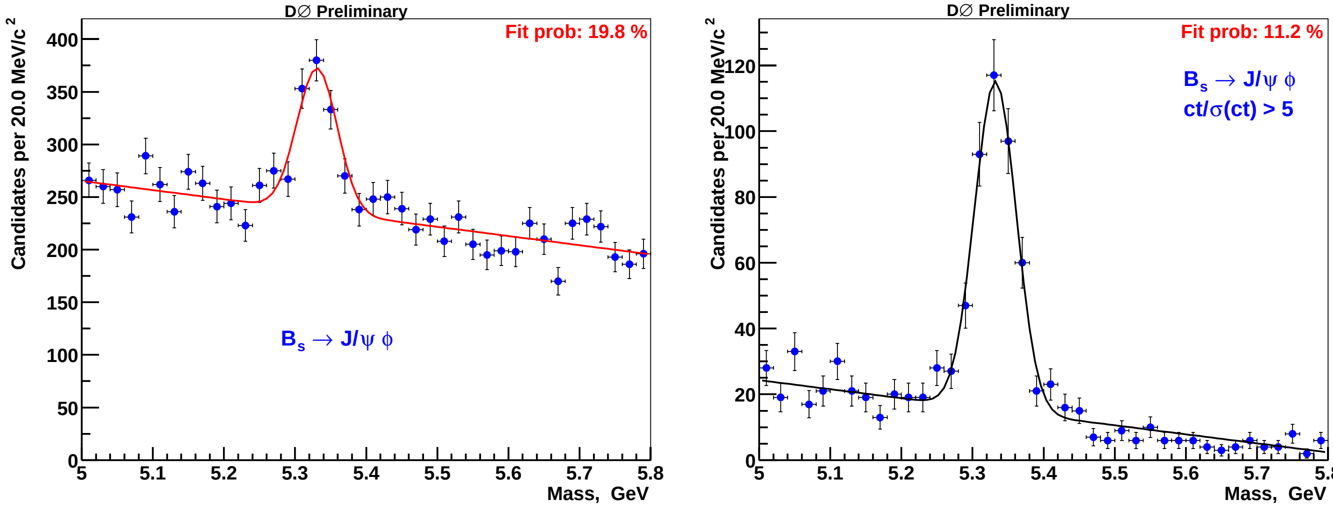

FIG. 1: The invariant mass distribution of the $(J/\psi, \phi)$ system for B_s^0 candidates. Left: All events. The curve is the projection of the maximum likeligood fit. Right: Subsample with the prompt background suppressed. The curve is a fit to a sum of two Gaussian distributions, derived using an MC sample, and a linear background.

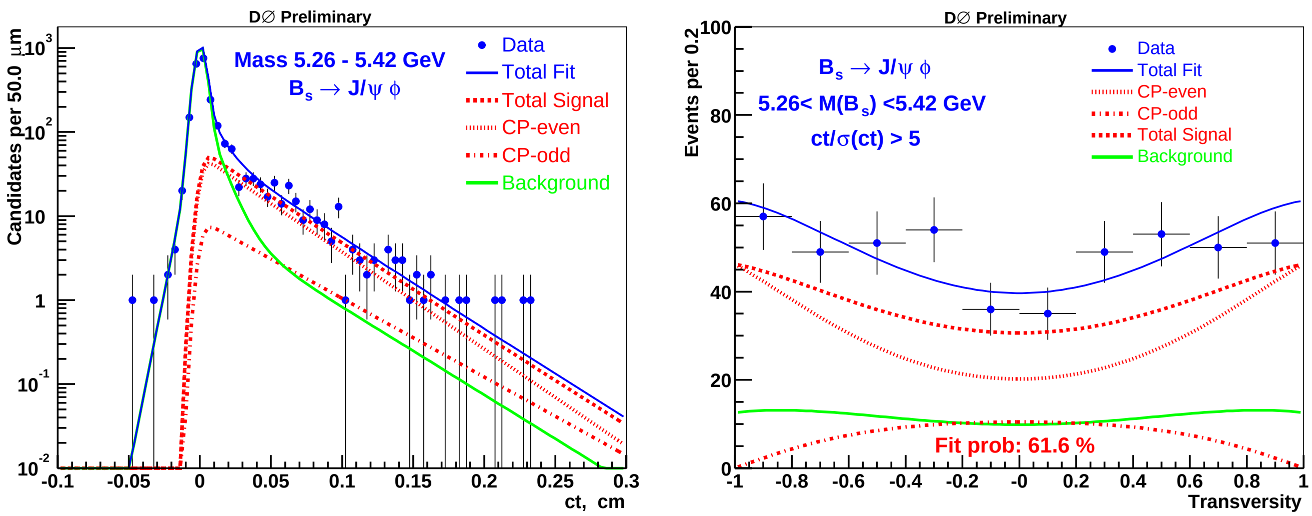

FIG. 2: Left: The proper decay length, $c\tau$, of the B_s^0 candidates in the signal mass region. The curves show: the signal contribution, dotted(red); the background, dashed(green); and total, solid(blue) in the signal mass region. Right: The distribution of cosine of the transversity angle in the signal mass region, for "non-prompt" events, with the results of the maximum likelihood fit overlaid.

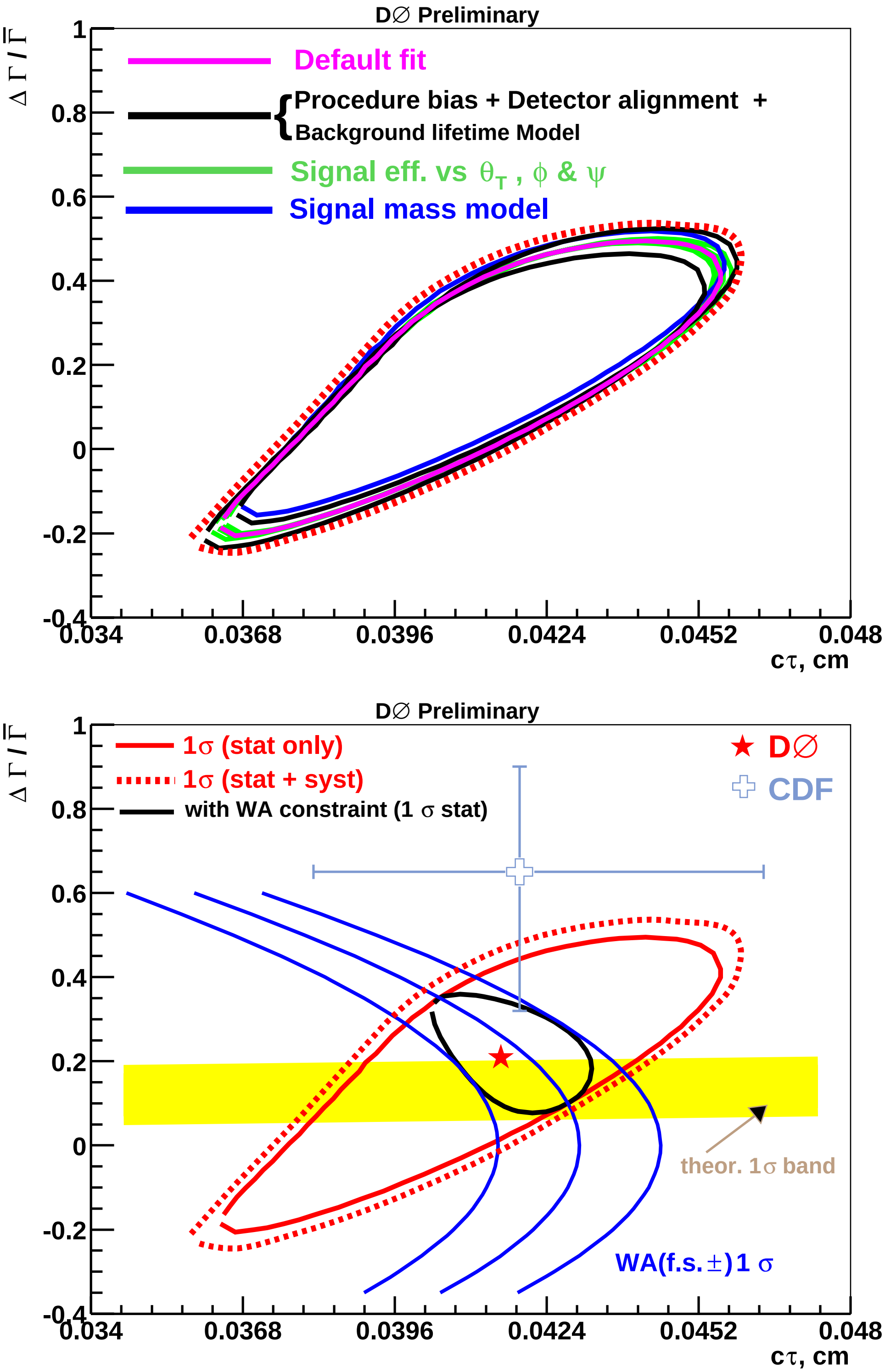

FIG. 3: Top: The 1-σ contour for the fitted parameters $c\tau$ and $\Delta\Gamma/\overline{\Gamma}$. An alternative diagram for all sources of the systematic uncertainty is drawn along with the result of the default fit. Errors due to sources 4, 5, and 6 in TableII were added in quadrature, and the alternative countours were drawn by shifting the default curve by (+3μm,+.03) and (-3μm,-.03). Bottom: The 1-σ contour for our default fit, compared to a 1-σ band for the World Average (WA) measurement based on semileptonic decays, $c\tau_{sl} = 430.0 \pm 15.0$ μm. A simultaneous fit to our data and the WA gives a 1-σ range $c\tau = 418^{+14}_{-15}$ μm and $\Delta\Gamma/\overline{\Gamma} = 0.23^{+0.13}_{-0.14}$ (stat), and $c\tau = 418^{+16}_{-17}$ μm and $\Delta\Gamma/\overline{\Gamma} = 0.23^{+0.16}_{-0.17}$ (stat+syst).

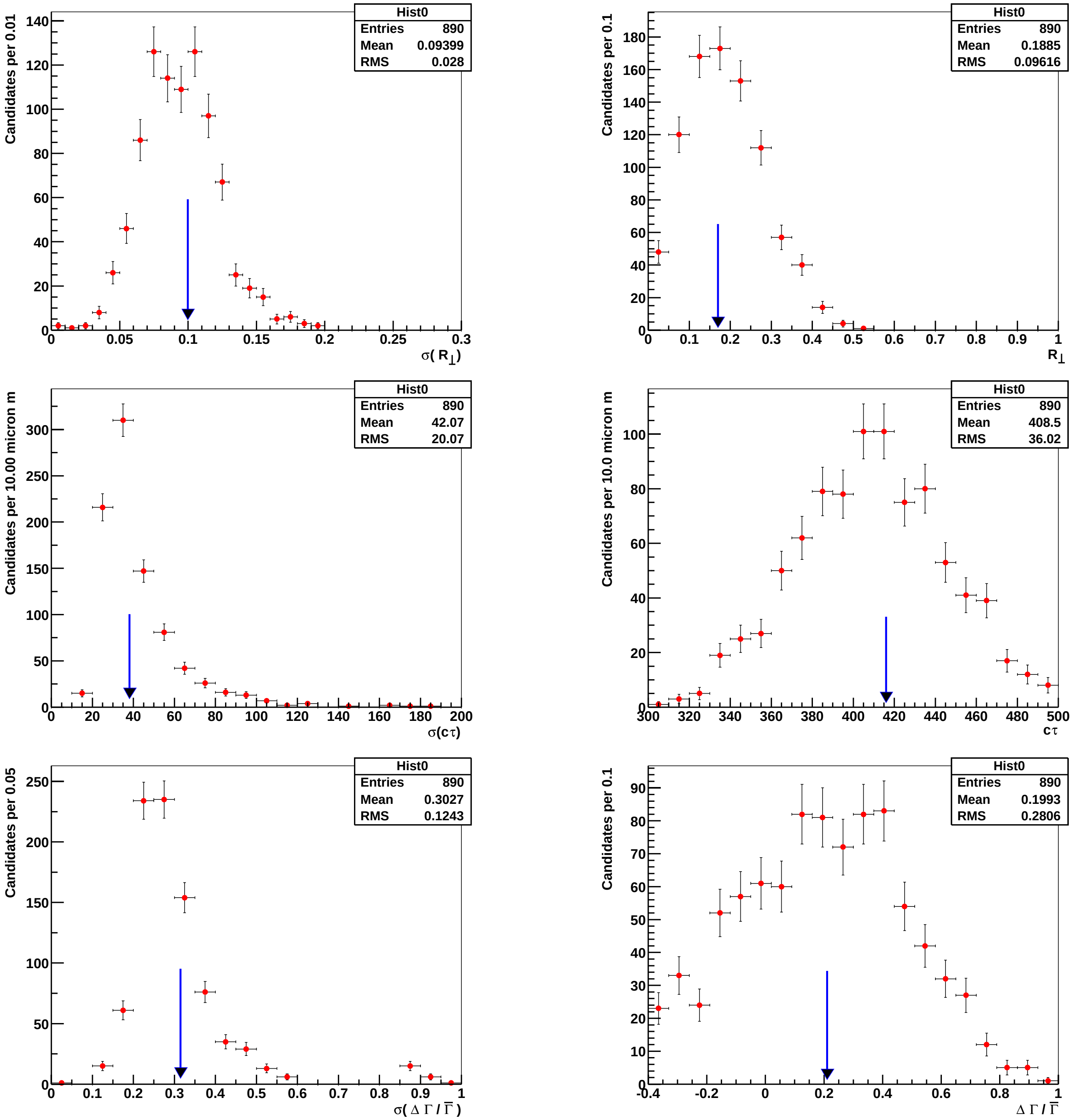

FIG. 4: Top left: Distribution of errors of the fit parameter $R_\perp$ (an average of asymmetric errors) returned by fits to an ensemble of 1000 simulated experiments. The arrow indicates the value 0.1 obtained in the Tevatron collider experiment reported here. Top right: Distribution of the fitted values of $R_\perp$. Middle left: Distribution of errors of the fit parameter $c\tau$ (average over asymmetric errors) for an ensemble of 1000 simulated experiments. The arrow indicates the value 38 μm obtained in this measurement. Middle right: Distribution of the fitted values of $c\tau$. Bottom left: Distribution of errors (average over asymmetric errors) of the fit parameter $\Delta\Gamma/\overline{\Gamma}$ for an ensemble of 1000 simulated experiments. The arrow indicates the value 0.31 obtained in this measurement. Bottom right: Distribution of the fitted values of $\Delta\Gamma/\overline{\Gamma}$.