DØ Note 6093-CONF

Updated Combined DØ results on $\Delta\Gamma_s$ versus CP-Violating Phase $\phi_s^{J/\psi\phi}$

The DØ Collaboration
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Results from a new DØ preliminary measurement of the B_s^0 width difference, $\Delta\Gamma_s$, and the CP-violating phase, $\phi_s^{J/\psi\phi}$, between the B_s^0 mixing and decay amplitudes determined via the angular analysis of $B_s^0 \to J/\psi\phi$ decays where the flavor (B_s^0 or $\bar{B}_s^0$) at the time of production is tagged in an integrated luminosity of 6.1 fb^{-1} are now available. Comparisons and combinations are presented applying further constraints provided by DØ determinations of the flavor-specific asymmetry of B_s^0 semileptonic decays, from measurements of the dimuon charge asymmetry and single muon charge asymmetry as well as the charge asymmetry of the decay $B_s^0 \to D_s^0\mu\nu$. Constraints from the measurement of the predominantly CP-even branching fraction $Br(B_s^0 \to D_s^{(*)+}D_s^{(*)-})$ are also applied.

Preliminary Results for Summer 2010 Conferences

I. INTRODUCTION

The DØ Collaboration has submitted for publication the description of an analysis demonstrating evidence for an anomalous like-sign dimuon charge asymmetry [1]. The semileptonic charge asymmetry, $A^b_{\rm sl}$ from neutral B^0_d and B^0_s mesons is measured and then used to extract the specific charge asymmetry $a^s_{\rm sl}$ for "wrong-charge" semileptonic B^0_s-meson decay induced by oscillations. The $a^s_{\rm sl}$ asymmetry can be used to provide preferred regions of the mixing and CP-violating parameters $\Delta\Gamma_s$ and ϕ_s (defined below) for the B^0_s system. The measured value of ϕ_s may be anomalously large due to an additional phase caused by new physics. A similar phase angle $\phi_s^{J/\psi\phi}$ can be measured in a study of the angular distribution of decay products as a function of proper time in flavor-tagged $B^0_s \to J/\psi\phi$ decays. This angle $\phi_s^{J/\psi\phi}$ is expected to be sensitive to the same new physics phase. Ref. [1] compares its results on $a^s_{\rm sl}$ to the published results of the DØ [2] from $B^0_s \to J/\psi\phi$ with integrated luminosity of 2.8 fb^{-1} and combines the two results.

This note updates the comparison and combination presented in Ref. [1] with new preliminary results of an analysis of $B^0_s \to J/\psi\phi$ in 6.1 fb^{-1} of integrated luminosity [3]. It also includes a direct DØ measurement [4] of the $a^s_{\rm sl}$ asymmetry from flavor-tagged $B^0_s \to D^0_s\mu\nu$ decays in the combination, and then uses a DØ measurement [5] of the branching fraction $\mathcal{B}(B^0_s \to D_s^{(*)+}D_s^{(*)-})$ as an additional constraint.

This note updates and closely follows the procedures described in Ref. [6].

II. THEORY AND NOMENCLATURE

For the B^0_s system, we have the matrix time evolution equation:

$$i\frac{d}{dt}\begin{pmatrix} |B^0_s\rangle \\ |\bar{B}^0_s\rangle \end{pmatrix} = \begin{pmatrix} M - \frac{i\Gamma}{2} & M_{12} - \frac{i\Gamma_{12}}{2} \\ M^*_{12} - \frac{i\Gamma^*_{12}}{2} & M - \frac{i\Gamma}{2} \end{pmatrix}\begin{pmatrix} |B^0_s\rangle \\ |\bar{B}^0_s\rangle \end{pmatrix}. \quad (1)$$

In the Standard Model, B^0_s-$\bar{B}^0_s$ oscillations are caused by flavor-changing weak interaction box diagrams that induce non-zero off-diagonal elements in the mixing matrix above. The mass eigenstates, defined as the eigenvectors of the above matrix, are different from the flavor eigenstates, with a heavy (H) and light (L) mass eigenstate, respectively:

$$|B_{sH}\rangle = p|B^0_s\rangle - q|\bar{B}^0_s\rangle; \;\; |B_{sL}\rangle = p|B^0_s\rangle + q|\bar{B}^0_s\rangle, \quad (2)$$

with $|p|^2 + |q|^2 = 1$. If CP is conserved in mixing in the B^0_s system, then $q = p$, and

$$|B_{sH}\rangle = |B_s^{CP-{\rm odd}}\rangle; \;\; |B_{sL}\rangle = |B_s^{CP-{\rm even}}\rangle. \quad (3)$$

CPT is assumed to be conserved throughout. Matrix elements can be extracted experimentally by measuring a mass and width difference between mass eigenstates:

$$\begin{aligned} \Delta m_s &= M_H - M_L &\approx 2|M_{12}|; \\ \Delta\Gamma_s &= \Gamma_L - \Gamma_H &\approx 2|\Gamma_{12}|\cos\phi_s, \end{aligned} \quad (4)$$

where ϕ_s is defined below. Note the sign convention for $\Delta\Gamma_s$ compared to Δm_s. In this convention, the Standard Model (SM) prediction for $\Delta\Gamma_s$ is positive. The current theoretical expectation in the SM is $\Delta\Gamma_s^{\rm SM} = 0.096 \pm 0.039$ ps^{-1} [7].

The parameter Γ_{12} is dominated by the decay path $b \to c\bar{c}s$ in decays into final states common to both B^0_s ($\bar{b}s$) and $\bar{B}^0_s$ ($b\bar{s}$). Examples of such decays are $B^0_s \to J/\psi\phi$ and $B^0_s \to D_s^{(*)+}D_s^{(*)-}$, as shown in Fig. 1.

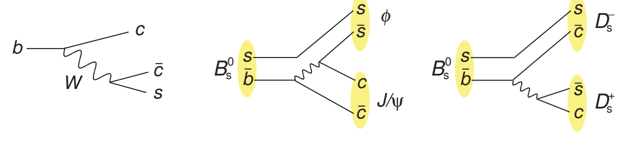

FIG. 1: Example B^0_s decays giving rise to a non-zero Γ_{12}.

The analogous decay diagram for a width difference in the B^0_d system substitutes the s quark for a d quark. This decay is Cabibbo suppressed, hence $\Delta\Gamma_d$ is negligible. In the case of $\Delta\Gamma_s$, decays into CP-even final states increase the value of $\Delta\Gamma_s$, while decays into CP-odd final states decrease it.

An average width is defined as $\Gamma_s = (\Gamma_L + \Gamma_H)/2$. The measured lifetime of the B^0_s will depend on the mix of CP eigenstates involved in its decay. A more fundamental lifetime based on the average width is defined as $\bar{\tau}_s = 1/\Gamma_s$.

A. Weak Phase in B_s^0 Mixing

In general there will be a CP-violating weak phase difference:

$$\phi_s = \arg\left[-M_{12}/\Gamma_{12}\right], \tag{5}$$

between the B_s^0-$\bar{B}_s^0$ amplitude and the amplitudes of the subsequent B_s^0 and $\bar{B}_s^0$ decay to a common final state. In this convention, ϕ_s is defined to fall in the range $[-\pi/2, \pi/2]$. This can affect the observed $\Delta\Gamma_s$ as given above. The SM prediction for this phase is tiny, $\phi_s^{\rm SM} = 0.0042 \pm 0.0014$ [7]; however, new physics in B_s^0 mixing could change this observed phase to

$$\phi_s = \phi_s^{\rm SM} + \phi_s^{\rm NP}. \tag{6}$$

The parameter ϕ_s is the phase *difference* between M_{12} and Γ_{12}, so new physics can arise from a phase added to either or both [8]. Most new physics models contribute to the M_{12} term, and in the following, to allow for the described combinations, we assume only one new physics phase affecting M_{12} in the B_s^0 system. In this case, the new physics would affect the measured width difference via [7]:

$$\Delta\Gamma_s = 2|\Gamma_{12}|\cos\phi_s. \tag{7}$$

In the case of $B_s^0 \to J/\psi\phi$, the decay $\bar{B}_s^0 \to J/\psi\phi$ is also possible, and there is therefore interference between the direct decay and the decay occuring through mixing $B_s^0 \to \bar{B}_s^0$ to the identical final state. The relative phase between the B_s^0 mixing amplitude and that of specific $b \to c\bar{c}s$ quark transitions such as for B_s^0 or $\bar{B}_s^0 \to J/\psi\phi$ in the SM is [7, 9]:

$$2\beta_s^{SM} = 2\arg[-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*] = 0.038 \pm 0.002. \tag{8}$$

This angle is analogous to the β angle in the usual CKM unitarity triangle replacing $d \to s$ aside from the negative sign (resulting in a positive angle in the SM). The same additional contribution $\phi_s^{\rm NP}$ due to new physics would show up in the phase observed in $B_s^0 \to J/\psi\phi$ decays [7], i.e.:

$$\phi_s^{J/\psi\phi} = -2\beta_s^{\rm SM} + \phi_s^{\rm NP}. \tag{9}$$

The current experimental precision does not allow these small CP-violating phases $\phi_s^{\rm SM}$ and $\beta_s^{\rm SM}$ to be resolved, and for a large new physics effect, $\phi_s \approx \phi_s^{J/\psi\phi} \approx \phi_s^{\rm NP}$, i.e., a significantly large observed phase would indicate new physics. However, in all comparisons and combinations that follow, the shift between the two phase angles:

$$\phi_s = \phi_s^{J/\psi\phi} + \phi_s^{\rm SM} + 2\beta_s^{\rm SM} = \phi_s^{J/\psi\phi} + 0.0422 \tag{10}$$

is included.

III. DØ MEASUREMENT, WITH STRONG-PHASE CONSTRAINT

The most direct and precise experimental results on $\Delta\Gamma_s$ and ϕ_s come from the Tevatron where reconstructed decays $B_s^0 \to J/\psi\phi$ are separated into CP-even and CP-odd components from fits to angular distributions of J/ψ and ϕ decay products as a function of proper decay time. Including information on the B_s^0 flavor (i.e., B_s^0 or $\bar{B}_s^0$) at production time via flavor tagging improves precision and also resolves the sign ambiguity on the weak phase angle for a given $\Delta\Gamma_s$. DØ [3] has updated such an analysis based on 6.1 fb^{-1} of integrated luminosity. DØ reports two-dimensional profile likelihoods and hence confidence-level (CL) contours in the $\phi_s^{J/\psi\phi}$ vs. $\Delta\Gamma_s$ plane. Details of the analysis and likelihood fits can be found in the indicated reference.

Note that this updated result constrained the strong phases δ_i, i.e., the angles between polarization amplitudes in the decays, to be equal to those determined in the B_d^0 system [10]. The decay $B_s^0 \to J/\psi\phi$ is related to $B_d^0 \to J/\psi K^*$ by flavor U(3) symmetry so that their strong phases should agree within 10 degrees [11], comparable to the measurement uncertainty on the B_d^0 strong phase angles δ_i used for the constraint. The previous published $B_s^0 \to J/\psi\phi$ result imposed weaker constraints on δ_i and a subsequent analysis also allowed the strong phase angles to float freely to allow a combination with CDF [12]. An updated combination with CDF will require DØ to also supply updated results with the δ_i allowed to float freely in the fit.

TABLE I: $\Delta \log \mathcal{L}$ value incorporating correct statistical coverage and taking into account external systematic uncertainties for a given confidence level, compared to the usual Gaussian values.

Confidence Level	$\Delta \log \mathcal{L}$ Gaussian	$\Delta \log \mathcal{L}$ Coverage and Syst. Unc.
68%	1.150	1.179
90%	2.305	2.380
95%	2.995	3.085
99%	4.605	4.756

A. Correcting for Non-Gaussian Uncertainties and Systematic Uncertainties

There is non-Gaussian behavior of the uncertainties on the fit parameters of the DØ analysis. Many systematic uncertainties are included in the fit by treating them as nuisance parameters, for example, placing a Gaussian constraint on Δm_s equivalent to the the measurement uncertainty on the world average of Δm_s, fitting for the parameterization of backgrounds, etc. Some systematic uncertainties, such as the calibration of the dilution of the flavor tag, are external to the fit. To determine the statistical coverage and to incorporate these external systematic uncertainties in confidence-level contours, an ensemble of Monte Carlo (MC) pseudo-experiments were generated with the same statistics as for the DØ analysis as described in Ref. [3]. From these studies, the difference of the logarithm between the maximum likelihood value and a given likelihood, $\Delta \log \mathcal{L}$, for a given confidence level to obtain the correct statistical coverage taking into account the worst case of the "alternative universes" for external systematic uncertainties are shown in Table I and compared to the usual Gaussian values. As described in Ref. [6], the likelihood values in the $\phi_s^{J/\psi\phi}$ vs. $\Delta\Gamma_s$ scan are adjusted to correspond to those expected for Gaussian errors corresponding to a given CL.

Figure 2 shows the resulting CL contours for the new preliminary DØ result [3], with the preferred region implied by the dimuon asymmetry $a_{\rm sl}^s$ value [1]. The strong phases δ_i were constrained to the B_d^0 values shown.

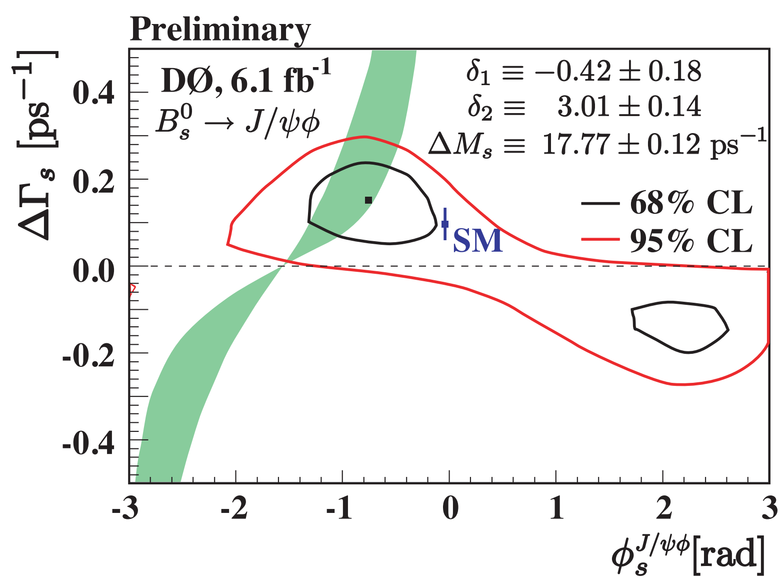

FIG. 2: 68% and 95% CL contours in the $\Delta\Gamma_s$-$\phi_s^{J/\psi\phi}$ plane. Also shown (green shaded region) is the 68% CL contour from $a_{\rm sl}^s$ of the DØ dimuon charge asymmetry analysis [1]. Figure from Ref. [3].

IV. APPLYING ADDITIONAL CONSTRAINTS

Other measurements can be used to supply additional constraints on $\phi_s^{J/\psi\phi}$ and $\Delta\Gamma_s$. Known relations between these additional external parameters measured in the analyses considered and the values of $\phi_s^{J/\psi\phi}$ and $\Delta\Gamma_s$ are used to calculate a predicted value of the parameter, $x_{\rm pred}$, for a given point in the likelihood scan. A constraint is applied using a Gaussian penalty function expressing the agreement between $x_{\rm pred}$ and its average value $x_{\rm meas}$, including its uncertainty. Three constraints are considered as listed below.

A. Flavor-Specific Semileptonic Asymmetry

Complementary measurements of the flavor-specific B_s^0 semileptonic asymmetry:

$$a_{\rm sl}^s = \frac{N(\bar{B}_s^0(t) \to \ell^+ \nu_\ell X) - N(B_s^0(t) \to \ell^- \bar{\nu}_\ell X)}{N(\bar{B}_s^0(t) \to \ell^+ \nu_\ell X) + N(B_s^0(t) \to \ell^- \bar{\nu}_\ell X)} = \frac{|p/q|_s^2 - |q/p|_s^2}{|p/q|_s^2 + |q/p|_s^2}, \tag{11}$$

and the like-sign dimuon charge asymmetry $A_{\rm sl}^b$ for semileptonic decays of b hadrons:

$$A_{\rm sl}^b = \frac{N_b(\mu^+\mu^+) - N_b(\mu^-\mu^-)}{N_b(\mu^+\mu^+) + N_b(\mu^-\mu^-)} = (0.506 \pm 0.043) a_{\rm sl}^d + (0.494 \pm 0.043) a_{\rm sl}^s \tag{12}$$

(see Ref. [1] for the calculation of coefficients) can provide additional information on the CP-violating phase specifically in the B_s^0 system through the relation [13]:

$$a_{\rm sl}^s = \frac{|\Gamma_s^{12}|}{|m_s^{12}|} \sin\phi_s = \frac{\Delta\Gamma_s}{\Delta m_s} \tan\phi_s. \tag{13}$$

This parameter has been measured in both inclusive and exclusive semileptonic decays. As shown in Fig. 3, the Heavy Flavor Averaging Group (HFAG) has determined the world average of this quantity to be [14]:

$$a_{\rm sl}^s({\rm WA}) = -0.0085 \pm 0.0058, \tag{14}$$

to be compared with the SM expectation of $(0.0206 \pm 0.0057) \times 10^{-3}$ [7].

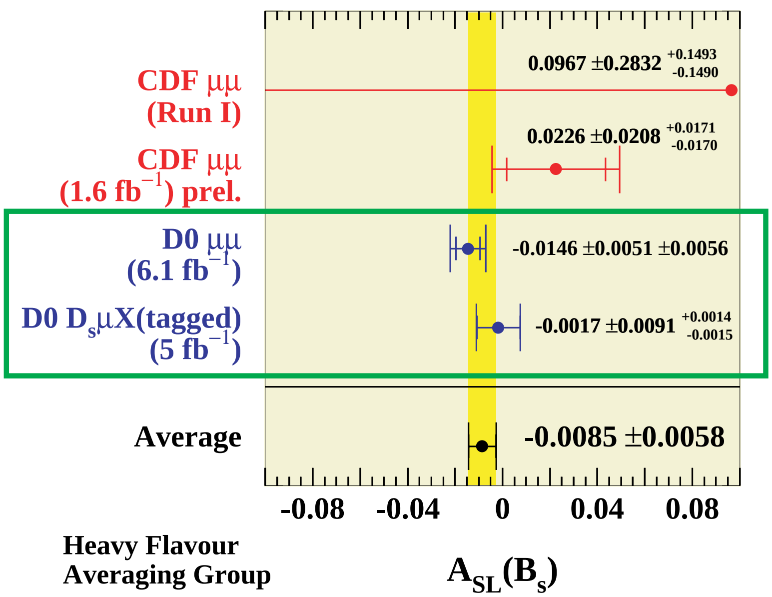

FIG. 3: Measurements [14] contributing to world average of $\mathcal{A}_{\rm SL}^s$ from the Heavy Flavor Averaging Group.

The DØ results dominate the world average, and taking just the two published DØ results [1, 4], the resulting average is:

$$a_{\rm sl}^s({\rm D\O}) = -0.0100 \pm 0.0059, \tag{15}$$

taking into account both the correlations between the two measurements and between the coefficients of Eq. 12. Figure 4 shows the CL contours of this DØ average overlaid on the preliminary $B_s^0 \to J/\psi\phi$ results for comparison.

In the penalty function in the combination, the uncertainty on $\Delta m_s = 17.77 \pm 0.12$ ps^{-1} is taken into account by convoluting a Gaussian PDF with a width of 0.12 ps^{-1}. When this constraint to the DØ average value of $a_{\rm sl}^s$ is imposed, confidence contours as shown in Fig. 5 are obtained. In this combination the p-value at the Standard Model point is 7.5% (not taking into account the uncertainty on $\Delta\Gamma_s^{\rm SM}$).

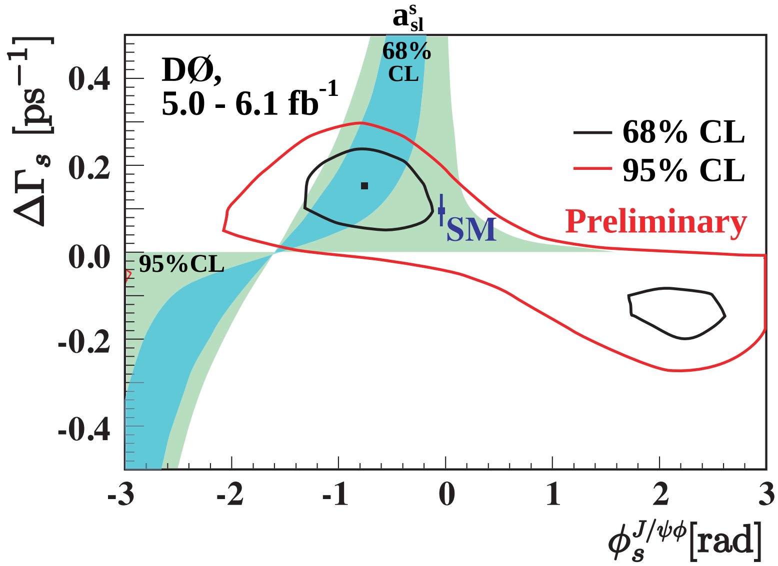

FIG. 4: 68% and 95% CL contours in the $\Delta\Gamma_s$-$\phi_s^{J/\psi\phi}$ plane compared to the 68% and 95% CL preferred regions from the average of the $a_{\rm sl}^s$ of the DØ dimuon charge asymmetry analysis [1] and that obtained from the DØ semileptonic asymmetry of $B_s^0 \to D_s^0 \mu\nu$ measurement [4]. The square is the best-fit value for the $\Delta\Gamma_s$-$\phi_s^{J/\psi\phi}$ analysis. Only one new physics phase affecting M_{12} in the B_s^0 system is assumed.

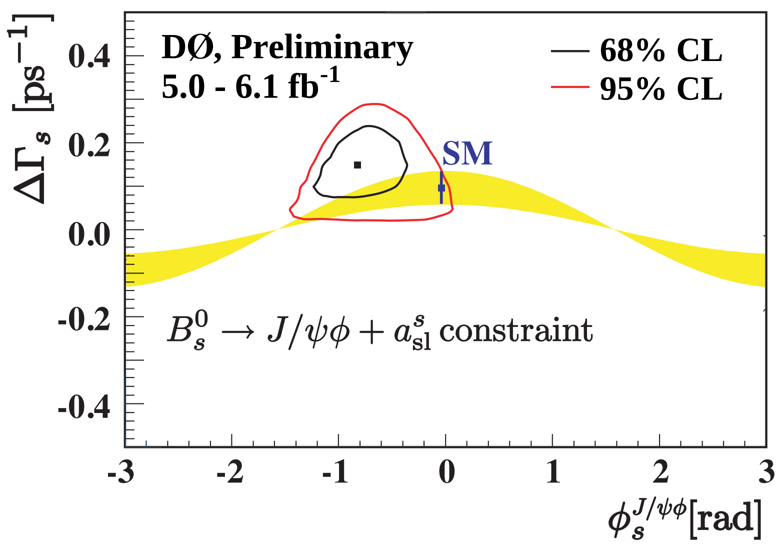

FIG. 5: Confidence-level contours for $\phi_s^{J/\psi\phi}$ and $\Delta\Gamma_s$ for DØ's $B_s^0 \to J/\psi\phi$ preliminary analysis using 6.1 fb^{-1} of data [3] with strong phases constrained after combining with the DØ average value of the CP-violating asymmetry $a_{\rm sl}^s$. The black square is the new best-fit value, and the Standard Model expectation and uncertainty is indicated by the blue point with an error bar. The region allowed in new physics models given by $\Delta\Gamma_s = 2|\Gamma_{12}|\cos\phi_s$ is also shown (yellow band). Only one new physics phase affecting M_{12} in the B_s^0 system is assumed.

B. Branching Fraction $\mathcal{B}(B_s^0 \to D_s^{(*)+} D_s^{(*)-})$

Measurements of the branching fraction $\mathcal{B}(B_s^0 \to D_s^{(*)+} D_s^{(*)-})$ can also be sensitive to the parameters considered. The decay $B_s^0 \to D_s^+ D_s^-$ gives a purely CP-even state. Under various theoretical assumptions [15], the inclusive decay into this final state plus the excited states, i.e., $B_s^0 \to D_s^{(*)+} D_s^{(*)-}$ is also CP even to within 5% (with the latter due to the omission of CKM-suppressed decays through the $b \to u\bar{u}s$ transition that is of order $2|V_{ub}V_{us}/V_{cb}V_{cs}| \simeq 3$ –

5%) and $B_s^0 \to D_s^{(*)+} D_s^{(*)-}$ saturates $\Gamma_s^{CP\,\text{even}}$. If $\Delta\Gamma_s^{CP} = \Gamma_s^{CP\,\text{even}} - \Gamma_s^{CP\,\text{odd}}$, then [16]:

$$2\mathcal{B}(B_s^0 \to D_s^{(*)+} D_s^{(*)-}) \simeq \Delta\Gamma_s^{\text{CP}} \left[\frac{\frac{1}{1-2x_f} + \cos\phi_s}{2\Gamma_L} + \frac{\frac{1}{1-2x_f} - \cos\phi_s}{2\Gamma_H} \right], \tag{16}$$

where x_f is the fraction of the CP-odd component of the decay. However, there are concerns [17] that the assumptions [15] needed for the above are overly restrictive and that the estimate above is good to only 30%.

To apply this as a constraint, expanding to second order,

$$2\mathcal{B}(B_s^0 \to D_s^{(*)+} D_s^{(*)-}) \simeq \frac{\Delta\Gamma_s}{\Gamma_s \cos\phi_s} \left[\frac{1}{1-2x_f} - \frac{\Delta\Gamma_s \cos\phi_s}{2\Gamma_s} \right]. \tag{17}$$

A measurement of this branching fraction from DØ using 2.8 fb^{-1} of data [5] gives

$$\mathcal{B}(B_s^0 \to D_s^{(*)+} D_s^{(*)-}) = 0.035 \pm 0.015. \tag{18}$$

In the absence of CP violation where $\phi_s = 0$, this mostly limits the value of $\Delta\Gamma_s$, i.e.,

$$\frac{\Delta\Gamma_s}{\Gamma_s} = 0.072 \pm 0.030. \tag{19}$$

In the application of the constraint as a Gaussian penalty function, the theoretical uncertainty is dealt with in two ways. The PDF of x_f is taken to be a uniform distribution ranging from 0 to 0.05 and convoluted in the Gaussian function. Alternatively, the fractional uncertainty on the measured value is increased in quadrature by 30%. The more conservative result is taken.

When this additional constraint is applied, confidence contours as shown in Fig. 6 are obtained. For this combination, the p-value at the Standard Model point is 6% (not taking into account the uncertainty on $\Delta\Gamma_s^{\text{SM}}$).

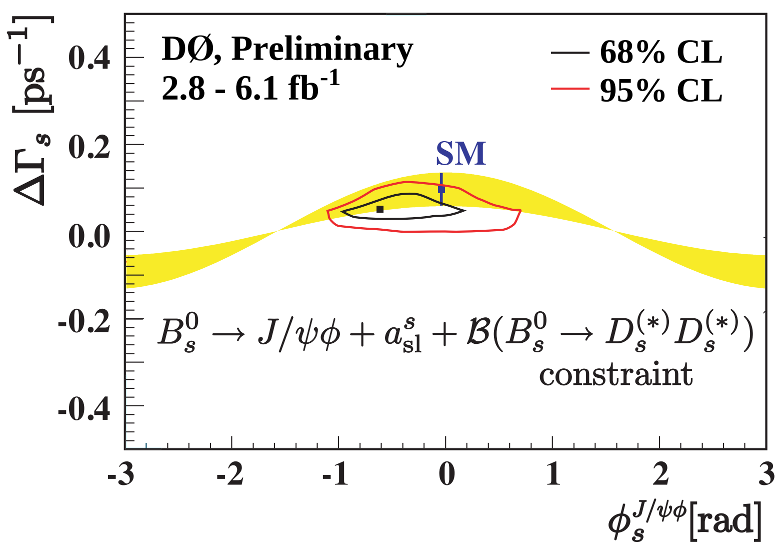

FIG. 6: Confidence-level contours for $\phi_s^{J/\psi\phi}$ and $\Delta\Gamma_s$ for DØ's $B_s^0 \to J/\psi\phi$ preliminary analysis using 6.1 fb^{-1} of data [3] with strong phases constrained after combining with the DØ average value of the CP-violating asymmetry a_{sl}^s, and to the DØ measured value of $\mathcal{B}(B_s^0 \to D_s^{(*)+} D_s^{(*)-})$. The square is the constrained best-fit value. The black square is the new best-fit value, and the Standard Model expectation and uncertainty is indicated by the blue point with an error bar. The region allowed in new physics models given by $\Delta\Gamma_s = 2|\Gamma_{12}| \cos\phi_s$ is also shown (yellow band). Only one new physics phase affecting M_{12} in the B_s^0 system is assumed.

V. SUMMARY

In summary, the method of analyzing an ensemble of "toy" Monte Carlo samples to adjust likelihood values to take into account correct statistical coverage of confidence level regions is described. This is also used to include the effect of external systematic uncertainties into the regions. With a preliminary update [3] of the published analysis [2] of flavor-tagged $B_s^0 \to J/\psi\phi$ decays to 6.1 fb^{-1} of integrated luminosity, new comparisons and combinations with other DØ analyses that are sensitive to the same mixing and CP-violating parameters are made. The DØ average of the B_s^0 semileptonic charge asymmetry, $a_{\rm sl}^s$, extracted from a new dimuon charge asymmetry analysis [1] and published asymmetry of $B_s^0 \to D_s^0\mu\nu$ [4] provides constraints on the parameters $\Delta\Gamma_s$ and $\phi_s^{J/\psi\phi}$ that are consistent with the updated $B_s^0 \to J/\psi\phi$ results. When a combination is made, the p-value at the Standard Model point is found to be 7.5% . When the constraint due to a DØ measurement [5] of $\mathcal{B}(B_s^0 \to D_s^{(*)+}D_s^{(*)-})$ is added, the p-value decreases to 6%.

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