DØ Note 5933-CONF

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

The DØ Collaboration
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A procedure is described for the determination of statistical coverage of the DØ measurements 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 flavor-tagged $B_s^0 \to J/\psi\phi$ decays. Results are presented with strong phases, δ_i, allowed to vary in the fit and systematic uncertainties on the two-dimensional confidence-level contours included for the first time. Further results are presented under the constraints provided by current world averages of the flavor-specific asymmetry of B_s^0 semileptonic decays and the measurement of the predominantly CP-even branching fraction $Br(B_s^0 \to D_s^{(*)+} D_s^{(*)-})$.

Preliminary Results for Summer 2009 Conferences

I. THEORY AND NOMENCLATURE

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

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

In the Standard Model, B_s^0-$\bar{B}_s^0$ oscillations are caused by flavor-changing weak interaction box diagrams that induce non-zero off-diagonal elements in the 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:

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

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

$$|B_{sH}\rangle = |B_s^{CP-\mathrm{odd}}\rangle;\;\; |B_{sL}\rangle = |B_s^{CP-\mathrm{even}}\rangle. \tag{3}$$

Matrix elements can be extracted experimentally by measuring a mass and width difference between mass eigenstates:

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

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 $\Delta\Gamma_s^{\mathrm{SM}} = 0.096 \pm 0.039$ ps^{-1} [1].

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_s^0 ($\bar{b}s$) and $\bar{B}_s^0$ ($b\bar{s}$). Examples of such decays are $B_s^0 \to J/\psi\phi$ and $B_s^0 \to D_s^{(*)+}D_s^{(*)-}$, as shown in Fig. 1.

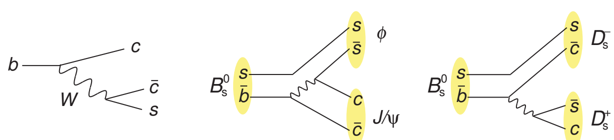

FIG. 1: Example B_s^0 decays giving rise to a non-zero Γ_{12}.

The analogous decay diagram for a width difference in the B_d^0 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_s^0 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, $\phi_s^{\mathrm{SM}} = 0.004$ [1]; however, new physics in B_s^0 mixing could change this observed phase to

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

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 [1, 2]:

$$2\beta_s^{SM} = 2\arg[-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*] \approx 0.04. \tag{7}$$

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 this observed phase [1], i.e.:

$$2\beta_s = 2\beta_s^{\rm SM} - \phi_s^{\rm NP}. \tag{8}$$

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 large new physics effect, we can approximate $\phi_s \approx -2\beta_s \approx \phi_s^{\rm NP}$, i.e., a significantly large observed phase would indicate new physics.

II. DØ MEASUREMENT, NO 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 published such an analysis based on 2.8 fb^{-1} of data. 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.

The DØ published result [3] imposed weak constraints on the strong phases δ_i, i.e., the angles between polarization amplitudes in the decays; however, the CDF analysis [4] allowed these δ_i to float freely in the fit making a straightforward comparison and combination of the CDF and DØ results problematic. The DØ likelihood fit was redone to also allow the strong phases to float freely. Tables collating the two-dimensional likelihood profile for this case can be found in Ref. [5].

A. Correcting for Non-Gaussian Uncertainties

There is non-Gaussian behavior of the uncertainties on the fit parameters of the DØ analysis. In $\phi_s^{J/\psi\phi}$ vs. $\Delta\Gamma_s$ space, the likelihood value at each point is adjusted, i.e., that a particular likelihood ratio in each case represents the same confidence level.

To determine the statistical coverage, 2,000 Monte Carlo (MC) pseudo-experiments generated with the same statistics as for the DØ analysis at the Standard Model point of $\phi_s^{J/\psi\phi} = -0.04$ and $\Delta\Gamma_s = 0.096$ ps^{-1}. The distribution of likelihood ratios, i.e., the ratio of the value of the likelihood in which $\phi_s^{J/\psi\phi}$ and $\Delta\Gamma_s$ are fixed in the fit to particular values of in the scan over this space relative to the single best fit value of $\phi_s^{J/\psi\phi}$ and $\Delta\Gamma_s$ when they are allowed to float freely in the fit is formed. The CL value that corresponds to a given likelihood ratio value in the two-dimensional likelihood scans is found as shown in Fig. 2.

B. Including Systematic Uncertainties

Some systematic uncertainties for the DØ analysis are included as nuisance parameters in the fit. The largest effect is the inclusion of the uncertainty on $\Delta m_s = 17.77 \pm 0.12$ ps^{-1}, which is allowed to vary within a Gaussian constraint of 0.12 ps^{-1}. Parameters in the signal and background models and their systematic uncertainties are also treated as nuisance parameters in the fit. Explicit variations to take into account other dominant systematic uncertainties are also used to generate curves of $(1 - CL)$ versus likelihood ratio in "alternative universes". The most conservative value is taken, i.e., the largest value of $(1 - CL)$ for a given likelihood ratio. 2,000 pseudo-experiments are generated for each of four different acceptance parameterizations, and for an alternative parameterization of the function used to estimate dilution of the flavor tag. Fig. 2 shows the resulting adjustment curve including systematic uncertainties.

C. Adjusted Two-Dimensional Profile Likelihood

Using the curves above, 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. An example is shown in Fig. 3 where ensemble coverage tests for CDF indicate that a value of $2\Delta\log L = 8.13$ corresponds to 95% CL. In the two-dimensional likelihood scans, a value

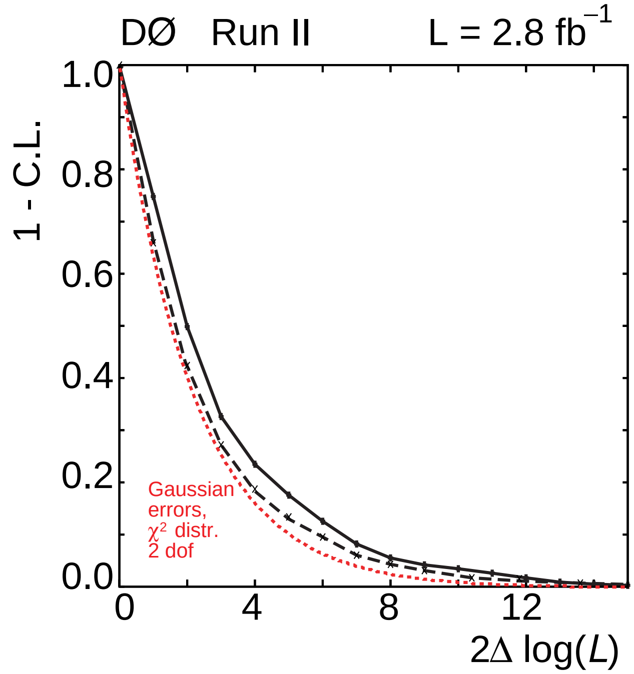

FIG. 2: For the DØ analysis [3], default/nominal correspondence (dashed line) between (1−confidence level) to likelihood ratio for the two-dimensional profile likelihood of $\phi_s^{J/\psi\phi}$ and $\Delta\Gamma_s$ compared to that expected for Gaussian uncertainties (red dotted line). Analogous relation for all of the and the conservative choice of the "alternate universes" (see text) for a given $\Delta \log L$ including systematics (solid line).

of 8.13 is then replaced with 5.99, the value of $2\Delta \log L$ expected for Gaussian errors (i.e., χ^2 with two degrees of freedom).

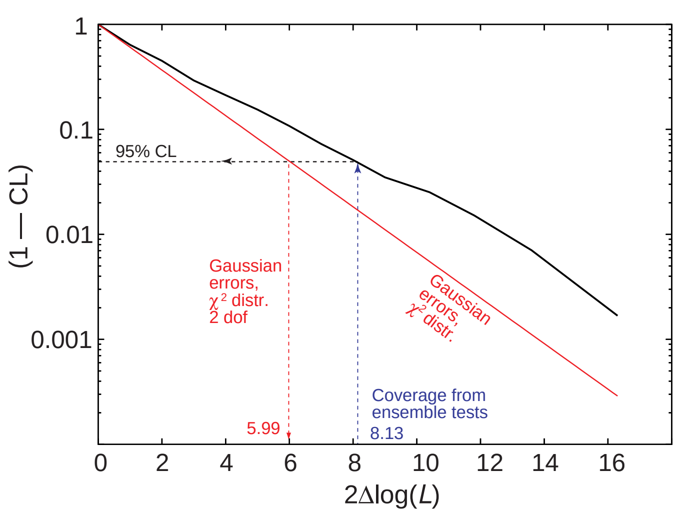

FIG. 3: An example of adjusting the likelihood ratio value at each scan point to correspond to expected Gaussian uncertainties according to relevant coverage.

Figure 4 shows the adjusted CL contours for DØ, both with and without systematic uncertainties included, as described above. Note that these results allow the strong phases, δ_i to float, and are hence different from those reported in the DØ publication [3] where weak constraints were imposed on δ_i.

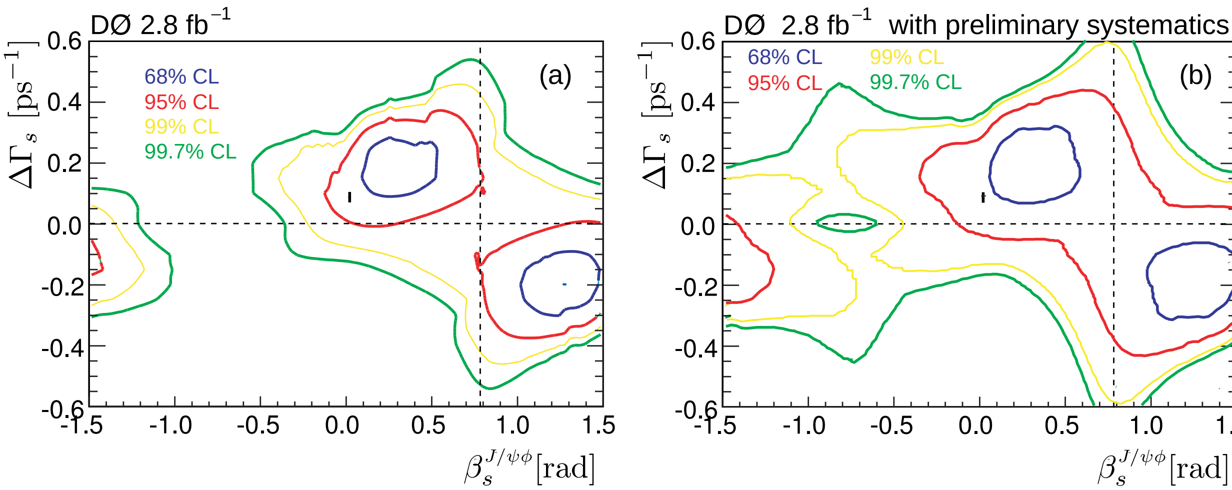

FIG. 4: Adjusted two-dimensional profile likelihood as confidence contours of $\phi_s^{J/\psi\phi}$ and $\Delta\Gamma_s$ for DØ's published analysis using 2.8 fb^{-1} of data [3], but allowing strong phases, δ_i to float when systematic uncertainties are (a) not included, and (b) included. (should these be labeled "preliminary"?) The Standard Model expectation is indicated by the black line.

III. 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 $2\beta_s^{J/\psi\phi} = -\phi_s^{J/\psi\phi}$ 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:

$$\mathcal{A}_{\rm SL}^s = \frac{N(\bar{B}_s^0(t) \to \ell^+\nu_\ell X) - N(B_s^0(t) \to \ell^-\bar{\nu}_\ell X)}{N(\bar{B}_s^0(t) \to \ell^+\nu_\ell X) + N(B_s^0(t) \to \ell^-\bar{\nu}_\ell X)} = \frac{|p/q|_s^2 - |q/p|_s^2}{|p/q|_s^2 + |q/p|_s^2} \tag{9}$$

can provide additional information on the CP-violating phase through the relation [6]:

$$\mathcal{A}_{\rm SL}^s = \frac{\Delta\Gamma_s}{\Delta m_s} \tan\phi_s. \tag{10}$$

This parameter has been measured in both inclusive and exclusive semileptonic decays. As shown in Fig. 5, the Heavy Flavor Averaging Group (HFAG) has determined the world average of this quantity to be [7]:

$$\mathcal{A}_{\rm SL}^s = -0.0027 \pm 0.0066, \tag{11}$$

to be compared with the SM expectation of $(0.0206 \pm 0.0057) \times 10^3$ [1]. In the penalty function, 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 world average value of $\mathcal{A}_{\rm SL}^s$ is imposed, confidence contours as shown in Fig. 6 In this combination the p-value at the Standard Model point is 24% (not taking into account the uncertainty on $\Delta\Gamma_s^{\rm SM}$). the CP-violating asymmetry $\mathcal{A}_{\rm SL}^s$

B. Flavor-Specific B_s^0 Lifetime

Flavor-specific decays are those that have decay products that can be used to determine whether the meson decayed as a B_s^0 or $\bar{B}_s^0$), and will have equal fractions of $B_{\rm L}$ and $B_{\rm H}$ at time zero. Examples are the semileptonic $B_s^0 \to D_s\ell\nu$ or

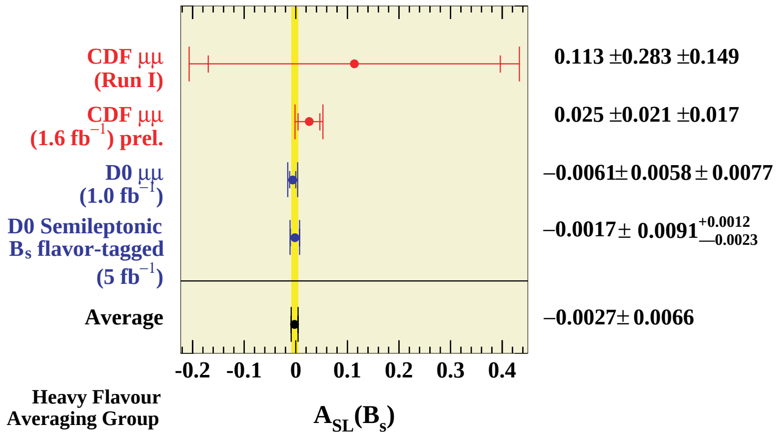

FIG. 5: Measurements [7] contributing to world average of $\mathcal{A}_{\rm SL}^s$ from the Heavy Flavor Averaging Group.

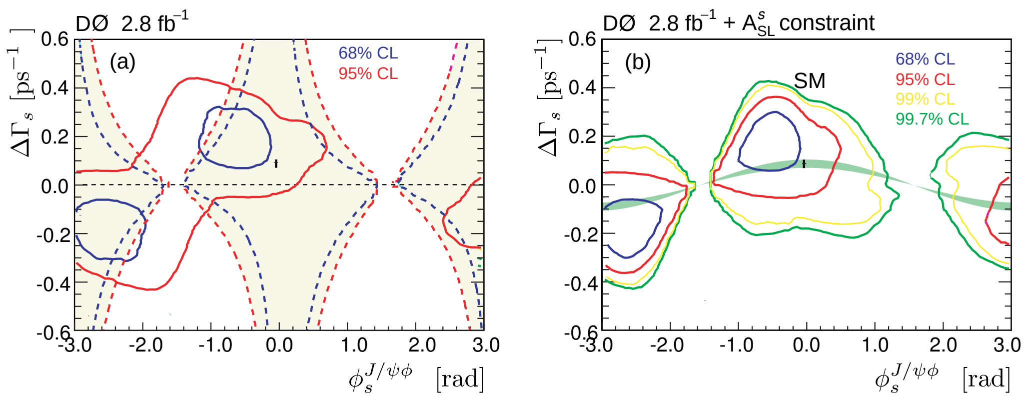

FIG. 6: (a) Confidence-level contours for $\phi_s^{J/\psi\phi}$ and $\Delta\Gamma_s$ for DØ's published analysis (solid lines) using 2.8 fb^{-1} of data [3] and allowing strong phases δ_i to float. The constraint due to the world average of measured values of the CP-violating asymmetry $\mathcal{A}_{\rm SL}^s$ is overlaid (dashed lines). (b) Confidence-level contours after imposing constraints due to $\mathcal{A}_{\rm SL}^s$. The Standard Model expectation and uncertainty is indicated by the black line. The region allowed in new physics models given by $\Delta\Gamma_s = 2|\Gamma_{12}|\cos\phi_s$ is also shown (light green band).

hadronic $B_s^0 \to D_s\pi$ decays. Here $\tau_{\rm L} = 1/\Gamma_{\rm L}$ is the mean lifetime of the light component and is expected to be shorter lifetime, and $\tau_{\rm H} = 1/\Gamma_{\rm H}$ is the mean lifetime of the heavy component, expected to be the longer-lived component. A superposition of two exponentials thus results with decay widths $\Gamma_s \pm \Delta\Gamma_s/2$. Fitting to a single exponential one obtains a measure of the flavor-specific lifetime [8]:

$$\tau(B_s^0)_{\rm fs} = \frac{1}{\Gamma_s}\frac{1+\left(\frac{\Delta\Gamma_s}{2\Gamma_s}\right)^2}{1-\left(\frac{\Delta\Gamma_s}{2\Gamma_s}\right)^2}. \tag{12}$$

From the Heavy Flavor Averaging Group (HFAG) [7], the world average of the flavor-specific B_s^0 lifetime is $\tau(B_s^0)_{\rm fs} = 1.456 \pm 0.030$ ps. The constraint is applied using the best fit value of $\Delta\Gamma_s$ and $1/\Gamma_s$ at each scan point. Results with this constraint added are shown in Fig. 7. In this combination the p-value at the Standard Model point is 12% (not taking into account the uncertainty on $\Delta\Gamma_s^{\rm SM}$).

C. 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 [9], 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

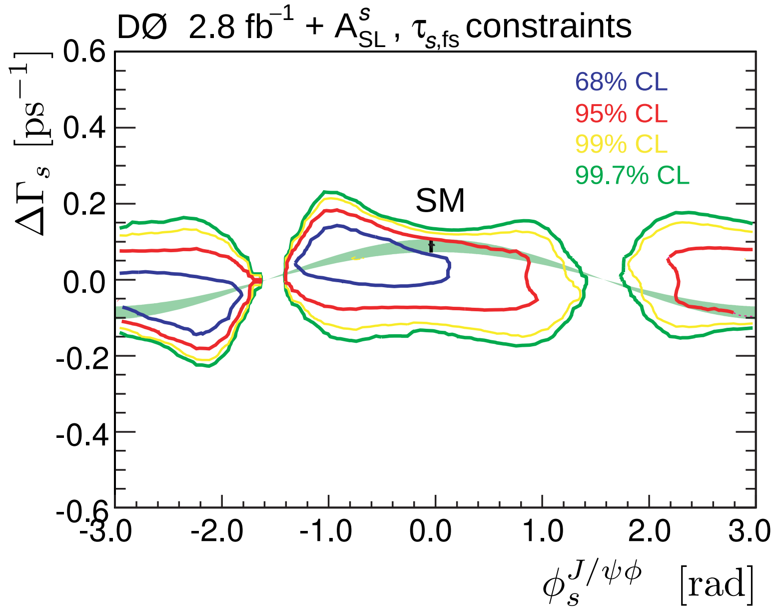

FIG. 7: Confidence-level contours for $\phi_s^{J/\psi\phi}$ and $\Delta\Gamma_s$ for DØ's published analysis (solid lines) using 2.8 fb^{-1} of data [3] and allowing strong phases δ_i to float after imposing the constraint due to the world average of measured values of the CP-violating asymmetry $\mathcal{A}^s_{\rm SL}$ and the world average of measured values of the flavor-specific lifetime $\tau(B^0_s)_{\rm fs}$. The Standard Model expectation and uncertainty is indicated by the black line. The region allowed in new physics models given by $\Delta\Gamma_s = 2|\Gamma_{12}|\cos\phi_s$ is also shown (light green band).

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 $B^0_s \to D_s^{(*)+}D_s^{(*)-}$ saturates $\Gamma_s^{CP\,{\rm even}}$. If $\Delta\Gamma_s^{CP} = \Gamma_s^{CP\,{\rm even}} - \Gamma_s^{CP\,{\rm odd}}$, then [10]:

$$2\mathcal{B}(B^0_s \to D_s^{(*)+}D_s^{(*)-}) \simeq \Delta\Gamma_s^{\rm CP}\left[\frac{\frac{1}{1-2x_f}+\cos\phi_s}{2\Gamma_L} + \frac{\frac{1}{1-2x_f}-\cos\phi_s}{2\Gamma_H}\right], \tag{13}$$

where x_f is the fraction of the CP-odd component of the decay. However, there are concerns [11] that the assumptions 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,

$$2\mathcal{B}(B^0_s \to D_s^{(*)+}D_s^{(*)-}) \simeq \frac{\Delta\Gamma_s}{\Gamma_s\cos\phi_s}\left[\frac{1}{1-2x_f} - \frac{\Delta\Gamma_s\cos\phi_s}{2\Gamma_s}\right]. \tag{14}$$

An update to a measurement of this branching fraction from DØ using 2.8 fb^{-1} of data [12] gives

$$\mathcal{B}(B^0_s \to D_s^{(*)+}D_s^{(*)-}) = 0.035 \pm 0.015. \tag{15}$$

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. 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. 8 are obtained. For this combination, the p-value at the Standard Model point is 10% (not taking into account the uncertainty on $\Delta\Gamma_s^{\rm SM}$).

Acknowledgments

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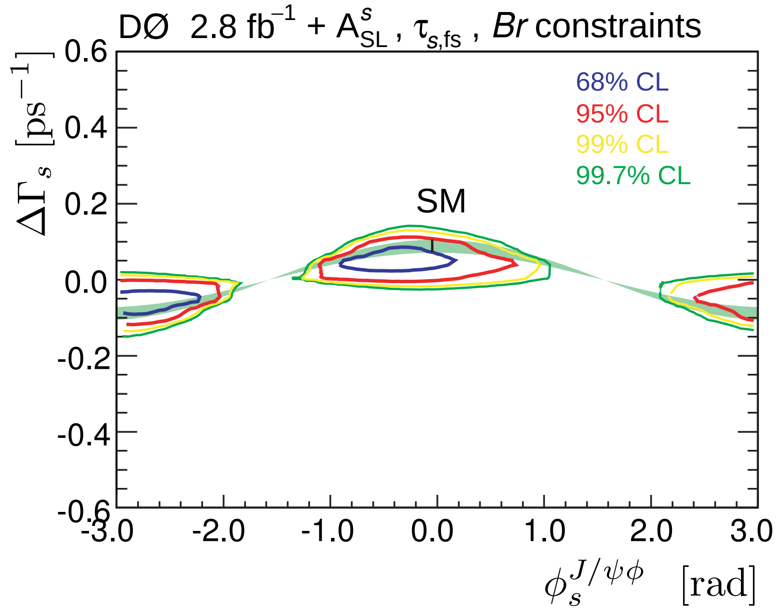

FIG. 8: Confidence-level contours of $\phi_s^{J/\psi\phi}$ and $\Delta\Gamma_s$ for DØ's published analysis using 2.8 fb^{-1} of data [3] but allowing strong phases δ_i to float, after imposing constraints due to world average measured values of the CP-violating asymmetry $\mathcal{A}^s_{\rm SL}$, the flavor-specific B^0_s lifetime, and $\mathcal{B}(B^0_s \to D_s^{(*)+} D_s^{(*)-})$ The Standard Model expectation and uncertainty is indicated by the black line. The region allowed in new physics models given by $\Delta\Gamma_s = 2|\Gamma_{12}|\cos\phi_s$ is also shown (light green band).

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