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Study of the decay $B_s^0 \rightarrow D_s^{(*)} D_s^{(*)}$

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We report a study of the decay $B_s^0 \to D_s^{(*)} D_s^{(*)}$ using a data sample corresponding to 1.3 fb^{-1} of integrated luminosity collected by the D0 experiment in 2002–2006 during Run II of the Fermilab Tevatron Collider. One $D_s^{(*)}$ meson was partially reconstructed in the decay $D_s \to \phi\mu\nu$, and the other $D_s^{(*)}$ meson was identified using the decay $D_s \to \phi\pi$ where no attempt was made to distinguish D_s and D_s^* states. For the branching fraction $\mathrm{Br}(B_s^0 \to D_s^{(*)}D_s^{(*)})$ we obtain a 90% CL range $[0.002, 0.080]$ and central value $0.039^{+0.019}_{-0.017}(\mathrm{stat})^{+0.016}_{-0.015}(\mathrm{syst})$. This was subsequently used to make the most precise estimate of the width difference $\Delta\Gamma_s^{CP}$ in the B_s^0–$\bar{B}_s^0$ system: $\Delta\Gamma_s^{CP}/\Gamma_s = 0.079^{+0.038}_{-0.035}(\mathrm{stat})^{+0.031}_{-0.030}(\mathrm{syst})$.

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In the standard model (SM), mixing in the B_s^0 system is expected to produce a large decay width difference $\Delta\Gamma_s = \Gamma_L - \Gamma_H$ between the light and heavy mass eigenstates with a small CP-violating phase ϕ_s [1]. New phenomena could produce a significant CP-violating phase leading to a reduction in the observed value of $\Delta\Gamma_s$ compared with the SM prediction of $\Delta\Gamma_s/\Gamma_s = 0.127 \pm 0.024$ [2]. $\Delta\Gamma_s^{CP} = \Gamma_s^{\mathrm{CP-even}} - \Gamma_s^{\mathrm{CP-odd}}$ ($\Delta\Gamma_s = \Delta\Gamma_s^{CP}\cos\phi_s$) can be estimated from the branching fraction $\mathrm{Br}(B_s^0 \to D_s^{(*)}D_s^{(*)})$. This decay is predominantly CP-even and is related to $\Delta\Gamma_s^{CP}$ [1, 3]: $2\mathrm{Br}(B_s^0 \to D_s^{(*)}D_s^{(*)}) \approx \left(\Delta\Gamma_s^{CP}/\Gamma_s\right)[1 + \mathcal{O}(\Delta\Gamma_s/\Gamma_s)]$, where contributions of charmonium final states have been ignored. Only one measurement of $\mathrm{Br}(B_s^0 \to D_s^{(*)}D_s^{(*)})$ has previously been published, by the ALEPH [4] experiment at the CERN LEP collider from the study of correlated production of $\phi\phi$ in Z^0 decays.

In this Letter we present a study of the decay chain $B_s^0 \to D_s^{(*)}D_s^{(*)}$ where one D_s^+ decays to $\phi\pi^+$, the other D_s^- decays to $D_s^- \to \phi\mu^-\nu$, and where each ϕ meson decays to K^+K^-. We denote the final states as $\phi_{(1)}\pi$ and $\phi_{(2)}\mu\nu$ respectively. A semileptonic decay of one D_s meson was required to trigger on selected events. Charge conjugate reactions are implied throughout. No attempt was made to reconstruct the photon or π^0 from the decay $D_s^* \to D_s\,\gamma/\pi^0$ and thus the state $D_s^{(*)}D_s^{(*)}$ contains contributions from D_sD_s, $D_s^*D_s$ and $D_s^*D_s^*$. To reduce systematic effects, $\mathrm{Br}(B_s^0 \to D_s^{(*)}D_s^{(*)})$ was normalized to the decay $B_s^0 \to D_s^{(*)}\mu\nu X$.

We use a sample of events collected by the D0 experiment at Fermilab in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. The D0 detector is described in detail elsewhere [5]. The data used in this analysis correspond to an integrated luminosity of approximately 1.3 fb^{-1}, and were selected without any explicit trigger requirement, although most events satisfied inclusive single-muon triggers.

The analysis began with the reconstruction of the decay chain $D_s \to \phi_{(1)}\pi$, $\phi_{(1)} \to K^+K^-$, from events containing an identified muon. Muons were required to have transverse momentum $p_T > 2$ GeV/c, total momentum $p > 3$ GeV/c, and to have measurements in at least two layers of the muon system. Two oppositely charged particles with $p_T > 0.8$ GeV/c were selected from the remaining particles in the event and were assigned the mass of a kaon. An invariant mass of $1.01 < M(K^+K^-) < 1.03$ GeV/c^2 was required, to be consistent with the mass of a ϕ meson. Each pair of kaons satisfying these criteria was combined with a third particle with $p_T > 1.0$ GeV/c, which was assigned the mass of a pion. The three tracks were required to form a D_s vertex using the algorithm described in Ref. [6]. The cosine of the angle between the D_s momentum and the direction from the $p\bar{p}$ collision point (primary vertex) to the D_s vertex was required to be greater than 0.9. The D_s vertex was required to have a displacement from the primary vertex in the plane perpendicular to the beam with at least 4σ significance. The helicity angle χ is defined as the angle between the momenta of the D_s and a kaon in the (K^+K^-) center of mass system. The decay of $D_s \to \phi\pi$ follows a $\cos^2\chi$ distribution, while for background $\cos\chi$ is expected to be flat. Therefore, to enhance the signal, the criterion $|\cos\chi| > 0.35$ was applied. The muon and pion were required to have opposite charge. The events passing these selections, referred to as the preselection sample, were used to produce the samples of $(\mu\phi_{(2)}D_s)$ and the normalizing sample (μD_s) defined below.

To construct a (μD_s) candidate from the preselection sample, the D_s candidate and the muon were required to originate from a common B_s^0 vertex. The mass of the (μD_s) system was required to be less than 5.2 GeV/c^2. The number of tracks near the B_s^0 meson tends to be small, thus to reduce the background from combinatorics, an isolation criterion was applied. The isolation is defined as the sum of the momenta of the tracks used to reconstruct the signal divided by the total momentum of tracks contained within a cone of radius $\Delta\mathcal{R} = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.5$ centered on the direction of the B_s^0 candidate. We required the isolation to exceed 0.6. To suppress background, the visible proper decay length (VPDL), defined as $M(B_s^0)\cdot(\vec{L}_T\cdot\vec{p}_T)/p_T^2$, was required to exceed 150 μm. Here $\vec{L}_T$ is the displacement from the primary vertex to the B_s^0 decay vertex in the transverse plane, and $M(B_s^0)$ is the mass of the B_s^0 meson [8]. These data are referred to as the (μD_s) sample; the resulting mass spectrum of the $(K^+K^-\pi)$ system is shown in Fig. 1(a), where the D_s and D^+ mass peaks are described by single Gaussians with a second-order polynomial used to parameterize the background. Figure 1(b) shows the mass spectrum of the (K^+K^-) system, where a double Gaussian describes the ϕ mass peak, and a second-order polynomial is used to parameterize the background.

To construct a $(\mu\phi_{(2)}D_s)$ candidate from the preselection sample, a second ϕ meson, from $D_s \to \phi_{(2)}\mu\nu$, was required. The selection criteria to reconstruct the second $\phi_{(2)}$ meson were identical to those of the first $\phi_{(1)}$ me-

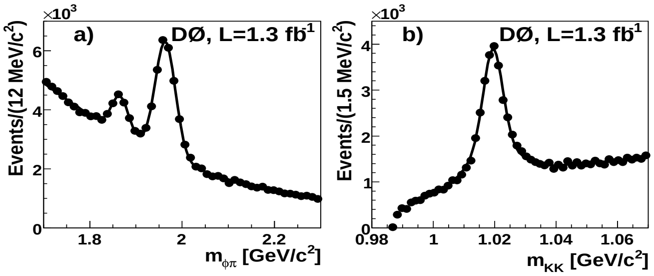

FIG. 1: (a) The $(K^+K^-\pi)$ invariant mass spectrum of the (μD_s) sample in the mass window $1.01 < M(K^+K^-) < 1.03$ GeV/c^2. The D^+ and D_s mass peaks are clearly visible. (b) Mass spectrum of the (K^+K^-) system of the (μD_s) sample in the mass window $1.92 < M(K^+K^-\pi) < 2.00$ GeV/c^2.

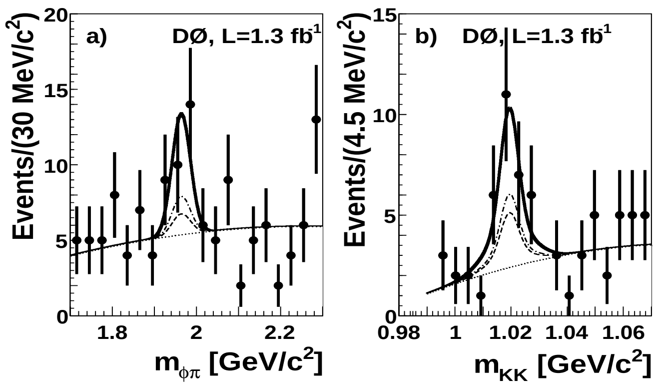

FIG. 2: Invariant mass distributions of (a) $D_s(\phi_{(1)}\pi)$ events in the signal window $1.01 < M_{\phi_{(2)}} < 1.03$ GeV/c^2, and (b) (K^+K^-) events from $D_s(\phi_{(2)}\mu)$ in the invariant mass signal window $1.92 < M_D < 2.00$ GeV/c^2. The solid curve is the projected result of the unbinned log-likelihood fit, the dotted curve shows the polynomial background contribution, the dashed line shows the uncorrelated production of (a) $D_s(\phi_{(1)}\pi)$ and (b) $\phi_{(2)}$ mesons, and the dash-dotted curve is the total background contribution.

son, with the exception that a wider mass range $0.99 < M(K^+K^-) < 1.07$ GeV/c^2 allows the background distribution under the $\phi_{(2)}$ meson to be estimated. This $\phi_{(2)}$ meson and muon were required to form a D_s vertex. To suppress background, the mass of the $(\mu\phi_{(2)})$ system was required to be $1.2 < M(\mu\phi_{(2)}) < 1.85$ GeV/c^2. The $D_s(\phi_{(1)}\pi)$ and $D_s(\phi_{(2)}\mu)$ mesons were required to form a B_s^0 vertex. The mass of the $(\mu\phi_{(2)}D_s)$ system, i.e., the combined mass of $D_s \to \phi_{(2)}\mu\nu$ and $D_s \to \phi_{(1)}\pi$ candidates, was required to be $4.3 < M(\mu\phi_{(2)}D_s) < 5.2$ GeV/c^2. An isolation value exceeding 0.6 and VPDL greater than 150 μm were required for the B_s^0 meson.

To reduce the effect of systematic uncertainties, we calculated the ratio $R = \mathrm{Br}(B_s^0 \to D_s^{(*)}D_s^{(*)}) \cdot \mathrm{Br}(D_s \to \phi\mu\nu)/\mathrm{Br}(B_s^0 \to D_s^{(*)}\mu\nu X)$. We extracted $\mathrm{Br}(B_s^0 \to D_s^{(*)}D_s^{(*)})$ from R using the known values [8] for $\mathrm{Br}(D_s \to \phi\mu\nu)$, $\mathrm{Br}(B_s^0 \to D_s^{(*)}\mu\nu X)$, and $\mathrm{Br}(D_s \to \phi\pi)$. R can be expressed in terms of experimental observables:

$$R = \frac{N_{\mu\phi_{(2)}D_s} - N_{\rm bkg}}{N_{\mu D_s}\ f(B_s^0 \to D_s^{(*)}\mu\nu X)} \times \frac{1}{2\mathrm{Br}(\phi \to K^+K^-)} \frac{\varepsilon(B_s^0 \to D_s^{(*)}\mu\nu X)}{\varepsilon(B_s^0 \to D_s^{(*)}D_s^{(*)})}, \quad (1)$$

where $N_{\mu D_s}$ is the number of (μD_s) events, $N_{\mu\phi_{(2)}D_s}$ is the number of $(\mu\phi_{(2)}D_s)$ events, $N_{\rm bkg}$ is the number of background events in the $(\mu\phi_{(2)}D_s)$ sample that are not produced by $B_s^0 \to D_s^{(*)}D_s^{(*)}$ decays, and $f(B_s^0 \to D_s^{(*)}\mu\nu X)$ is the fraction of events in (μD_s) coming from $B_s^0 \to D_s^{(*)}\mu\nu X$. The ratio of efficiencies $\varepsilon(B_s^0 \to D_s^{(*)}D_s^{(*)})/\varepsilon(B_s^0 \to D_s^{(*)}\mu\nu X)$ to reconstruct the two processes was determined from simulation. All processes involving b hadrons were simulated with EvtGen [9] interfaced to pythia [10], followed by full modeling of the detector response with geant [11] and event reconstruction as in data. The number of (μD_s) events was estimated from a binned fit to the $(K^+K^-\pi)$ mass distribution shown in Fig. 1(a) from the 145,000 candidates passing the selection criteria. The resulting fit is superimposed in Fig. 1(a) as a solid line and gives $N_{\mu D_s} = 17670 \pm 230$ (stat) events.

The number of $(\mu\phi_{(2)}D_s)$ events was extracted using a unbinned log-likelihood fit to the two-dimensional distribution of the invariant masses M_D of the $(\phi_{(1)}\pi)$ system and $M_{\phi_{(2)}}$ of the two additional kaons from the $(\phi_{(2)}\mu)$ system. All candidates from the $(\mu\phi_{(2)}D_s)$ sample with $1.7 < M_D < 2.3$ GeV/c^2 and $0.99 < M_{\phi_{(2)}} < 1.07$ GeV/c^2 were included in the fit. In the fit, the masses and widths for both D_s and ϕ signals were fixed to the values extracted from a fit to the (μD_s) data sample. Extracted from the fit were the numbers of: $N_{\mu\phi_{(2)}D_s}$ events from correlated (joint) signal production of $(\phi_{(1)}\pi)$ and $\phi_{(2)}$, events with a reconstructed $(\phi_{(1)}\pi)$ in the mass peak of $D_s(\phi_{(1)}\pi)$ without joint production of $\phi_{(2)}$ from $(\phi_{(2)}\mu)$ (i.e., uncorrelated), events with a reconstructed $\phi_{(2)}$ from $(\phi_{(2)}\mu)$ without joint production of $(\phi_{(1)}\pi)$ in the mass peak of the $D_s(\phi_{(1)}\pi)$ (i.e., also uncorrelated), and combinatorial background.

The results of the fit are displayed in Fig. 2. The fit gives $N_{\mu\phi_{(2)}D_s} = 13.4^{+6.6}_{-6.0}$ events from the 340 candidates included in the fit, with a statistical significance of 2.2σ.

The fraction $f(B_s^0 \to D_s^{(*)}\mu\nu X)$ was determined similarly to [12], assuming that in addition to the decays $B_s^0 \to D_s^{(*)}\mu\nu X$ and $B_s^0 \to D_s^{(*)}\tau(\to \mu\nu)\nu X$, the following decays contribute to the (μD_s) sample: $B \to D_s D^{(*)} X$, $B_s^0 \to D_s^{(*)}D_s^{(*)}$, and $B_s^0 \to D_s D X$. The branching fractions for $B \to D_s D^{(*)} X$ and $B_s^0 \to D_s^{(*)}D_s^{(*)}$ are taken from Ref. [8]. There is no experimental information for the $\mathrm{Br}(B_s^0 \to D_s D X)$, therefore we used the value 15.4% provided by Ref. [9] with an assigned uncertainty of 100%.

In addition, the (μD_s) sample includes the processes $c\bar{c} \to D_s^{(*)}\mu\nu X$, $b\bar{b} \to D_s^{(*)}\mu\nu X$, and events with a misidentified muon, etc., with a contribution estimated in Ref. [7] as $(10 \pm 5)\%$, without any requirement on the VPDL. When the requirement of VPDL $> 150\,\mu$m is included, we estimate the contribution as $(2 \pm 1)\%$ in the (μD_s) signal. In total, we estimate that the fraction of events in the (μD_s) signal coming from $B_s^0 \to D_s^{(*)}\mu\nu X$ is $f(B_s^0 \to D_s^{(*)}\mu\nu X) = 0.82 \pm 0.05$.

We considered the number of events $N_{\mu\phi_{(2)}D_s}$ from the $(\mu\phi_{(2)}D_s)$ sample to contain contributions from 1) the main signal $B_s^0 \to D_s^{(*)}D_s^{(*)}$, and the following background processes 2) $B \to D_s^{(*)}D_s^{(*)}KX$, 3) $B_s^0 \to D_s^{(*)}D_s^{(*)}X$, 4) $B_s^0 \to D_s^{(*)}\phi\mu\nu$, 5) $c\bar{c} \to D_s\mu\nu X$ and $b\bar{b} \to D_s\mu\nu X$, and 6) $B_s^0 \to D_s^{(*)}\mu\nu$ combined with a ϕ meson from fragmentation. There is no experimental information for most of the processes, therefore their contributions were estimated by counting events in different regions of the $(\mu\phi_{(2)}D_s)$ phase space and comparing the obtained numbers with the expected mass distribution for each background process.

The mass of the $(\mu\phi_{(2)}D_s)$ system for the second and third processes is much less than that for the main decay $B_s^0 \to D_s^{(*)}D_s^{(*)}$ because of the additional particles, and the requirement $M(\mu\phi_{(2)}D_s) > 4.3$ GeV/c^2 strongly suppresses them. The contribution of $B_s^0 \to D_s^{(*)}D_s^{(*)}X$ is much less than $B \to D_s^{(*)}D_s^{(*)}KX$ because of higher production rates of B^+ and B^0 compared to B_s^0. Compared to the $B \to D_s^{(*)}D_s^{(*)}KX$ process, the final state in the decay $B_s^0 \to D_s^{(*)}D_s^{(*)}X$ includes at least two pions due to isospin considerations. At least two gluons are required to produce this state (similar to $\psi(2S) \to J/\psi\pi\pi$); it is therefore additionally suppressed and its contribution was neglected. Simulation shows that for the $B \to D_s^{(*)}D_s^{(*)}KX$ decay, the fraction of events with $M(\mu\phi_{(2)}D_s) > 4.3$ GeV/c^2 is 0.05. Requiring $M(\mu\phi_{(2)}D_s) < 4.3$ GeV/c^2 and keeping all other selections, we observe $2.8^{+11.2}_{-2.8}$ events in data. Assuming that all these events are due to $B \to D_s^{(*)}D_s^{(*)}KX$, we estimate their contribution to the signal $(\mu\phi_{(2)}D_s)$ as $0.14^{+0.56}_{-0.14}$ events.

The fourth process produces a high mass for both the $(\mu\phi_{(2)})$ and $(\mu\phi_{(2)}D_s)$ systems and requiring $M(\mu\phi_{(2)}) < 1.85$ GeV/c^2 strongly suppresses it. Simulation shows that for this process, the fraction of events with $M(\mu\phi_{(2)}) < 1.85$ GeV/c^2 is 0.14. Requiring $M(\mu\phi_{(2)}) > 1.85$ GeV/c^2 and keeping all other selections, we observe 13 ± 11 events. Assuming that all these events are due to the fourth background process, we estimate its contribution to the $(\mu\phi_{(2)}D_s)$ signal as 1.88 ± 1.51 events.

We estimate the total number of background events from the above contributions as $N_{\mathrm{bkg}} = 2.0 \pm 1.6\,(\mathrm{stat})$.

The contribution of the fifth process is strongly suppressed by the event selection, and we estimate an upper limit of 0.4 events. We therefore included this contribution as an additional uncertainty in the number of background events.

The fitting procedure accounts for the possible background contribution of the decay $B_s^0 \to D_s^{(*)}\mu\nu$ together with the uncorrelated production of a ϕ meson from fragmentation. In addition, an attempt was made to reconstruct $(\mu\phi_{(2)}D_s)$ events in the $B_s^0 \to D_s^{(*)}\mu\nu X$ simulation containing approximately 9200 reconstructed (μD_s) events, and no such events were found. Therefore the contribution from this process was neglected.

In determination of efficiencies, the final states in the (μD_s) and $(\mu\phi_{(2)}D_s)$ samples differ only by the two kaons from the additional $\phi_{(2)}$ meson. All other applied selections are the same, so many detector-related systematic uncertainties cancel. The muon p_T spectrum in $B_s^0 \to D_s^{(*)}\mu\nu X$ decay differs between data and simulation due to trigger effects, reconstruction efficiencies, and the uncertainties in B meson production in simulation. To correct for this difference, we normalized the MC to the data by applying weighting functions to all MC events, which were obtained from the ratio of simulated and data events for p_T distributions of the B_s^0 meson and muon. With this correction, the ratio of efficiencies is $\varepsilon(B_s^0 \to D_s^{(*)}D_s^{(*)})/\varepsilon(B_s^0 \to D_s^{(*)}\mu\nu X) = 0.055 \pm 0.001$ (stat). The systematic uncertainty of this ratio is discussed below.

Using all these inputs and taking the value $\mathrm{Br}(\phi \to K^+K^-) = 0.492 \pm 0.006$ [8], we obtain $R = 0.015 \pm 0.007$ (stat). The statistical uncertainty shown includes only the uncertainty in $N_{\mu\phi_{(2)}D_s}$. All other uncertainties are included in the systematics. The experimental extraction of both $\mathrm{Br}(B_s^0 \to D_s^{(*)}\mu\nu X)$ and $\mathrm{Br}(D_s \to \phi\mu\nu)$ depend on $\mathrm{Br}(D_s \to \phi\pi)$. Factorizing the dependence on $\mathrm{Br}(D_s \to \phi\pi)$, we obtain from [8] $\mathrm{Br}(B_s^0 \to D_s^{(*)}\mu\nu X)\mathrm{Br}(D_s \to \phi\pi) = (2.84 \pm 0.49) \times 10^{-3}, \mathrm{Br}(D_s \to \phi\mu\nu) = (0.55 \pm 0.04) \cdot \mathrm{Br}(D_s \to \phi\pi)$. Using these numbers, we finally obtain from (1) $\mathrm{Br}(B_s^0 \to D_s^{(*)}D_s^{(*)}) = 0.039^{+0.019}_{-0.018}(\mathrm{stat})$.

The systematic uncertainties in the measured value of $\mathrm{Br}(B_s^0 \to D_s^{(*)}D_s^{(*)})$ were estimated as follows. All external branching fractions [8] were varied within one standard deviation. A 100% uncertainty in the number of background events N_{bkg} in the $(\mu\phi_{(2)}D_s)$ sample was assumed. The uncertainty on the reconstruction efficiency of two additional kaons from ϕ meson decay was estimated to be 14%, following the results of a previous study [7]. For the ratio of efficiencies, a 15% uncertainty was assigned for the reweighting procedure, which reflects the difference in efficiency between weighted and unweighted estimates and includes all effects of modeling the production and decays of B_s^0 mesons. The dependence of the number of $(\mu\phi_{(2)}D_s)$ events on the fitting procedure was estimated by adding a possible signal contribution from D^+ events which decreased the correlated signal by 3%, which we assigned as a systematic uncertainty.

Using these numbers, we obtain $\text{Br}(B_s^0 \to D_s^{(*)}D_s^{(*)}) = \left[0.039^{+0.019}_{-0.017}(\text{stat}) \pm 0.014(\text{syst})\right] \cdot [0.044/\text{Br}(D_s \to \phi\pi)]^2$. Using $\text{Br}(D_s \to \phi\pi) = 0.044 \pm 0.006$ [8], we find

$$\text{Br}(B_s^0 \to D_s^{(*)}D_s^{(*)}) = 0.039^{+0.019}_{-0.017}(\text{stat})^{+0.016}_{-0.015}(\text{syst}), \quad (2)$$

which yields a 90% CL interval for $\text{Br}(B_s^0 \to D_s^{(*)}D_s^{(*)})$ of $[0.002, 0.080]$. The result is consistent with, and more precise than the ALEPH measurement $\text{Br}(B_s^0 \to D_s^{(*)}D_s^{(*)}) = 0.077 \pm 0.034^{+0.038}_{-0.026}$ [4, 15], where the value has been recalculated using the current value of $\text{Br}(D_s \to \phi\pi)$ [8]. We calculate $\Delta\Gamma_s^{CP}$ [1] assuming that the decay $B_s^0 \to D_s^{(*)}D_s^{(*)}$ is mainly CP-even and gives the primary contribution to the width difference between the CP-even and CP-odd B_s^0 states [3]:

$$\frac{\Delta\Gamma_s^{CP}}{\Gamma_s} = 0.079^{+0.038}_{-0.035}(\text{stat})^{+0.031}_{-0.030}(\text{syst}). \quad (3)$$

Assuming CP-violation in B_s^0 mixing is small [2], this estimate is in good agreement with the SM prediction $\Delta\Gamma_s/\Gamma_s = 0.127 \pm 0.024$ [2] and with the direct measurement of this parameter by the D0 experiment in $B_s^0 \to J/\psi\phi$ decays [13]. The agreement with the CDF measurement of $\Delta\Gamma_s/\Gamma_s$, also performed in $B_s^0 \to J/\psi\phi$ [14], is not as good, although still within two standard deviations.

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