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Combined D0 Measurements Constraining the CP-violating Phase and Width Difference in the B_s^0 System

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We combine the D0 measurement of the width difference between the light and heavy B_s^0 mass eigenstates and of the CP-violating mixing phase determined from the time-dependent angular distributions in the $B_s^0 \to J/\psi\phi$ decays along with the charge asymmetry in semileptonic decays also measured with the D0 detector. With the additional constraint from the world average of the flavor-specific B_s^0 lifetime, we obtain $\Delta\Gamma_s \equiv (\Gamma_L - \Gamma_H) = 0.13 \pm 0.09$ ps^{-1} and $\phi_s = -0.70^{+0.47}_{-0.39}$. The data sample corresponds to an integrated luminosity of 1.1 fb^{-1} accumulated with the D0 detector at the Fermilab Tevatron Collider.

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One of the great challenges for elementary particle physics is to trace all possible sources of the violation of CP symmetry. In the standard model (SM) of particle physics, CP symmetry is violated through the CKM mechanism [1]. Although the SM picture of CP violation has so far been confirmed by all laboratory measurements, it has an unsolved problem: the level of CP violation in the SM is too small to produce the observed baryon number density in the universe [2]. Sources of CP violation beyond the CKM mechanism must, therefore, exist to account for the deficit. One source of CP violation arises in the mixing of doublets of neutral mesons. CP violation in K^0 mesons, composed of a down quark and a strange quark, was discovered 40 years ago [3]. The B_s^0 mesons are similar quark-antiquark bound states, with the down quark replaced by a bottom quark.

In the SM, the light (L) and heavy (H) mass eigenstates of the mixed B_s^0 system are expected to have sizeable mass and decay width differences: $\Delta M_s \equiv M_H - M_L$ and $\Delta\Gamma_s \equiv \Gamma_L - \Gamma_H$. The two mass eigenstates are expected to be almost pure CP eigenstates. The CP-violating mixing phase is predicted [4] to be $\phi_s = (4.2 \pm 1.4) \times 10^{-3}$. New phenomena may alter ϕ_s leading to a reduction of the observed $\Delta\Gamma_s$ compared to the SM prediction [4] $\Delta\Gamma_s^{SM}$: $\Delta\Gamma_s = \Delta\Gamma_s^{SM} \times |\cos\phi_s|$. While $B_s^0 - \bar{B}_s^0$ oscillations have been detected [5] and the mass difference has recently been measured to high precision [6], the CP-violating phase remains unknown. The D0 experiment [7] at the Fermilab Tevatron Collider has conducted a series of studies [8–11] of B_s^0 mesons produced in proton-antiproton ($p\bar{p}$) interactions. This Letter utilises these results to obtain the best estimate of the CP-violating phase in the B_s^0 system.

In Ref. [8], we studied the decay sequence $B_s^0 \rightarrow J/\psi\phi$, $J/\psi \rightarrow \mu^+\mu^-$, $\phi \rightarrow K^+K^-$. From a fit to the time-dependent angular distribution of the decay products, we obtained the mean lifetime, $\overline{\tau}_s = 1/\overline{\Gamma}_s$ (where $\overline{\Gamma}_s \equiv (\Gamma_H + \Gamma_L)/2$), $\Delta\Gamma_s$, and the first direct constraint on ϕ_s. As discussed in Ref. [8], there is a 4-fold ambiguity in the result for ϕ_s: $\pm\phi_s$ and $\pm(\pi - \phi_s)$. The sign of $\sin\phi_s$ is reversed with the simultaneous reversal of the signs of the cosines of the CP-conserving strong phases δ_1 and δ_2. (We adopted the amplitude definition and sign convention of Ref. [12]). The possible solutions are

$$\begin{aligned} |\phi_s| &= 0.79 \pm 0.56\ (\text{stat})^{+0.01}_{-0.14}\ (\text{syst}), \\ \Delta\Gamma_s &= 0.17 \pm 0.08\ (\text{stat}) \pm 0.02\ (\text{syst})\ \text{ps}^{-1}; \\ \\ |\phi_s| &= 2.35 \pm 0.56\ (\text{stat})^{+0.14}_{-0.01}\ (\text{syst}), \\ \Delta\Gamma_s &= -0.17 \pm 0.08\ (\text{stat}) \pm 0.02\ (\text{syst})\ \text{ps}^{-1}; \end{aligned} \tag{1}$$

The first two solutions are consistent with the SM prediction [4].

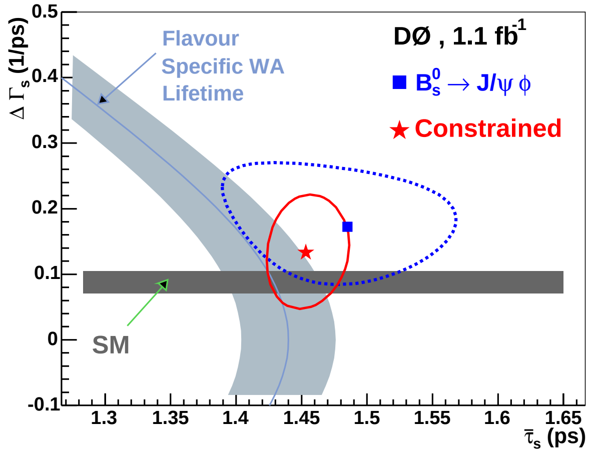

FIG. 1: The error ellipse ($\Delta\ln(\mathcal{L}) = 0.5$) in the plane $\Delta\Gamma_s$ versus $\overline{\tau}_s$ for the fit to the $B_s^0 \rightarrow J/\psi\phi$ data (dashed blue line) and for the fit with the constraint from the two D0 measurements of the charge asymmetry in semileptonic B_s^0 decay, and from the world average flavor-specific lifetime (solid red line). Also shown is a one-σ band representing the world average result [14] for τ_{fs} and a one-σ band representing the theoretical prediction $\Delta\Gamma_s^{SM} = 0.088 \pm 0.017$ ps^{-1} [4]. [color online]

Flavor-specific decays of B_s^0 mesons provide independent constraints on the parameters of the system. An effective mean lifetime, resulting from a single-exponential fit to the decay time distribution, $\tau_{\text{fs}} = 1/\Gamma_{\text{fs}}$, is related to the physics parameters $\overline{\Gamma}_s$ and $\Delta\Gamma_s$ through the equation $\Gamma_{\text{fs}} = \overline{\Gamma}_s - (\Delta\Gamma_s)^2/2\overline{\Gamma}_s + \mathcal{O}(\Delta\Gamma_s)^3/\overline{\Gamma}_s^2$ [13]. We use the world-average value, $\tau_{\text{fs}} = 1/\Gamma_{\text{fs}} = 1.440 \pm 0.036$ ps [14], from a fit including the recent D0 measurement, $\tau_{\text{fs}} = 1/\Gamma_{\text{fs}} = 1.398 \pm 0.044\ (\text{stat})\ ^{+0.028}_{-0.025}\ (\text{syst})$ ps [9].

Independently, we obtained another constraint on the parameters of the B_s^0 system from the measurements of the semileptonic charge asymmetry induced by B_s^0 mixing. In general, the semileptonic charge asymmetry is defined as [15]:

$$A_{SL}^q = \frac{N(\bar{B}_q^0 \rightarrow \ell^+ X) - N(B_q^0 \rightarrow \ell^- X)}{N(\bar{B}_q^0 \rightarrow \ell^+ X) + N(B_q^0 \rightarrow \ell^- X)}. \tag{2}$$

It is related to the CP phase ϕ_q by [16]:

$$A_{SL}^q = \frac{\Delta\Gamma_q}{\Delta M_q} \tan\phi_q. \tag{3}$$

In Ref. [10], we measured the same-sign dimuon charge asymmetry defined as:

$$A_{SL}^{\mu\mu} = \frac{N(b\bar{b} \to \mu^+\mu^+X) - N(b\bar{b} \to \mu^-\mu^-X)}{N(b\bar{b} \to \mu^+\mu^+X) + N(b\bar{b} \to \mu^-\mu^-X)}. \qquad (4)$$

Both B_d^0 and B_s^0 contribute to this quantity [17], and the result of Ref. [10] is given as:

$$\begin{aligned} A_{SL}^d &+ \frac{f_s Z_s}{f_d Z_d} A_{SL}^s = \\ &= -0.0092 \pm 0.0044 \text{ (stat)} \pm 0.0032 \text{ (syst)}; \quad (5) \\ Z_q &= \frac{1}{1-y_q^2} - \frac{1}{1+x_q^2}; \\ x_q &= \Delta M_q/\Gamma_q; \qquad y_q = \Delta\Gamma_q/(2\Gamma_q); \end{aligned}$$

where A_{SL}^d and A_{SL}^s are the charge asymmetries of the B_d^0 and B_s^0 semileptonic decays, and f_d and f_s are the production rates of B_d^0 and B_s^0 mesons in the hadronization of the b quark, respectively. In deriving relation (5), it is assumed that there is no direct CP violation in semileptonic B decays and that the semileptonic width of all B mesons is the same. Using the world-average values [15] $f_d = 0.398 \pm 0.012$, $f_s = 0.103 \pm 0.014$, $x_d = 0.776 \pm 0.008$, and $Z_d = 0.376 \pm 0.006$ we obtain:

$$\frac{f_s Z_s}{f_d Z_d} = 0.70 \pm 0.07 \text{ (syst)} \pm 0.10 \text{ (PDG)}. \qquad (6)$$

The value of Z_s was computed using the measured values of $\Delta\Gamma_s$ [8], $\overline{\tau}_s$ [8], and ΔM_s [6]: $Z_s = 1.015^{+0.018}_{-0.010}$. We have tested that propagating the Z_s dependence on $\Delta\Gamma_s$ has negligible effect on the final results. The systematic uncertainty arises mainly from a conservative estimate of a possible variation in the reconstruction efficiency of muons from semileptonic decays of different B mesons [18].

The asymmetry A_{SL}^d has been measured at B factories where only B_d^0 and $B^\pm$ mesons are produced. The average value of A_{SL}^d is [14]: $A_{SL}^d = -0.0047 \pm 0.0046$. Combining this value and (5,6), and adding statistical and systematic uncertainties in quadrature, we obtain:

$$A_{SL}^s = -0.0064 \pm 0.0101. \qquad (7)$$

In Ref. [11], we measured A_{SL}^s directly by using all events with at least one muon that were consistent with the sequential decay $B_s^0 \to \mu\nu D_s$ with $D_s \to \phi\pi$. The result of this measurement is:

$$A_{SL}^s = +0.0245 \pm 0.0193 \text{ (stat)} \pm 0.0035 \text{ (syst)}. \qquad (8)$$

The measurements (7) and (8) are nearly independent since the fraction of dimuon final states in the sample of semileptonic B_s^0 decays used in Ref. [11] is only about 10% [19], and the fraction of semileptonic decays $B_s^0 \to \mu\nu D_s$ with $D_s \to \phi\pi$ in the dimuon sample used in Ref. [10] is less than 1%. Also, the systematic uncertainties of the two measurements are uncorrelated. The main source of systematic uncertainty in (7) is the correction due to $K^\pm$ decays, while in the case of the measurement (8) it is the fitting procedure.

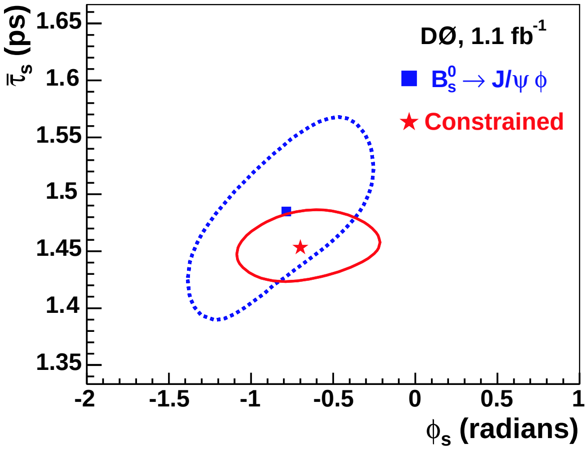

FIG. 2: The error ellipse ($\Delta \ln(\mathcal{L}) = 0.5$) in the plane ($\overline{\tau}_s$, ϕ_s) for the fit to the $B_s^0 \to J/\psi\phi$ data (dashed blue line) and for the fit with the constraint from the two D0 measurements of the charge asymmetry in semileptonic B_s^0 decay, and from the world average flavor-specific lifetime (solid red line).[color online]

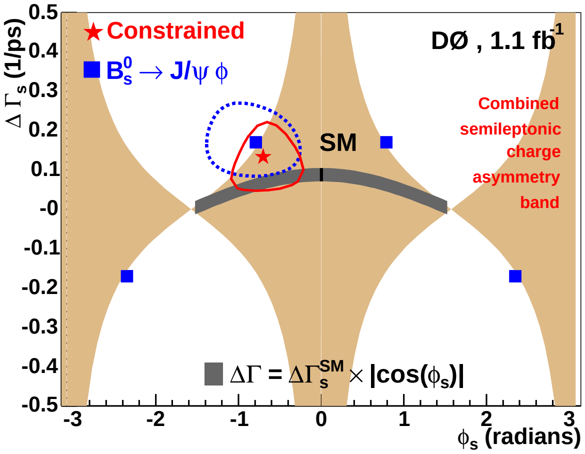

FIG. 3: The error ellipse ($\Delta \ln(\mathcal{L}) = 0.5$) in the plane ($\Delta\Gamma_s$, ϕ_s) for the fit to the $B_s^0 \to J/\psi\phi$ data (dashed blue line) and for the fit with the constraint from the two D0 measurements of the charge asymmetry in semileptonic B_s^0 decay, and from the world average flavor-specific lifetime (solid red line). The central values for all four solutions of the unconstrained fit are indicated by blue squares. Also shown is the band representing the relation $\Delta\Gamma_s = \Delta\Gamma_s^{SM} \times |\cos\phi_s|$, with $\Delta\Gamma_s^{SM} = 0.088 \pm 0.017$ ps^{-1} [4] (dark shade), and the area corresponding to Eq. 10 (light shade) . [color online]

Their combination gives the best estimate of the charge asymmetry in semileptonic B_s^0 decays:

$$A_{SL}^s = 0.0001 \pm 0.0090. \qquad (9)$$

Using relation (3) and the result $\Delta M_s = 17.8 \pm 0.1$ ps^{-1}

from the CDF experiment [6], we obtain:

$$\Delta\Gamma_s \cdot \tan\phi_s = A^s_{SL} \cdot \Delta M_s = 0.02 \pm 0.16 \text{ ps}^{-1}. \qquad (10)$$

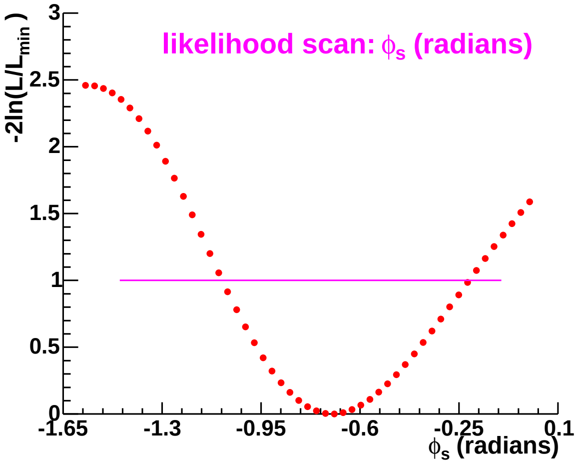

FIG. 4: The likelihood scan versus ϕ_s for the constrained fit (see text).

We have repeated the fit to the $B^0_s \to J/\psi\phi$ data, including the constraints from Eq. 10, and from the world-average measurement of $\tau_{\rm fs}$ discussed earlier. To illustrate the fit results and the impact of the constraints, in Figs. 1 – 3 we present likelihood contours in three planes, $\Delta\Gamma_s$ versus $\overline{\tau}_s$, $\overline{\tau}_s$ versus ϕ_s, and $\Delta\Gamma_s$ versus ϕ_s, respectively. The contours indicate error ellipses, $\Delta\ln(\mathcal{L}) = 0.5$, corresponding to the confidence level of 39%. The 4-fold ambiguity remains unresolved. The likelihood profile as a function of ϕ_s for the first solution listed in Eq. 1 is shown in Fig. 4. The extracted value of ϕ_s deviates from zero by 1.2 standard deviations.

In summary, for the solution with $\phi_s < 0$, $\cos\delta_1 > 0$ and $\cos\delta_2 < 0$, we find the decay width difference and the CP-violating phase in the B^0_s system to be:

$$\begin{aligned} \Delta\Gamma_s &= 0.13 \pm 0.09 \text{ ps}^{-1}, \\ \phi_s &= -0.70^{+0.47}_{-0.39}. \end{aligned} \qquad (11)$$

The measurement uncertainty is dominated by the limited statistics. The systematic uncertainties include a variation of the background model in the analysis of the decay $B^0_s \to J/\psi\phi$, detector acceptance, and sensitivity to the details of the track and vertex reconstruction. The results are consistent with the SM predictions [4].

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