Studies of CP-conserving and CP-violating B_s mixing parameters with the D0 experiment

James Walder (for the D0 Collaboration)

Department of Physics,
Lancaster University,
Lancaster,
LA1 4YB, UK.

Abstract. This paper summarises the recent results of the Run IIa D0 experiment at the Tevatron Collider at Fermilab on the observable parameters of the B_s meson. A measurement of the branching fraction $\mathrm{Br}(B_s^0 \to D_s^{(*)} D_s^{(*)})$ is reported, which provides an estimate of the width difference $\Delta\Gamma_s^{CP}/\Delta\Gamma_s$. Through the decay $B_s \to J/\psi\phi$ the width difference $\Delta\Gamma_s$ is extracted, and for the first time a constraint is set on the CP-violating phase ϕ_s, although a four-fold ambiguity remains. This result is combined with other D0 measurements to yield $\Delta\Gamma_s = 0.13 \pm 0.09\,\mathrm{ps}^{-1}$, $\phi_s = -0.70^{+0.47}_{-0.39}$.

PACS. 13.25.Hw Decays of bottom mesons – 11.30.Er Charge conjugation, parity, time reversal, and other discrete symmetries – 14.40.Nd Bottom mesons

1 Introduction

The standard model (SM) of particle physics, with three families of quarks contains the CKM matrix which contains one complex phase that governs CP-violation. The B_s^0 system can be described by the Schrödinger equation:

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

where from CPT invariance: $M_{11} = M_{22} \equiv M$, and $\Gamma_{11} = \Gamma_{22} \equiv \Gamma$. The light and heavy mass eigenstates are defined as $|B_L\rangle$ and $|B_H\rangle$ respectively, and relate to the flavour eigenstates through $|B_L\rangle = p\left|B_s^0\right\rangle + q\left|\bar{B}_s^0\right\rangle$, $|B_H\rangle = p\left|B_s^0\right\rangle - q\left|\bar{B}_s^0\right\rangle$, where $|p|^2 + |q|^2 = 1$.

Under the assumption of no CP-violation, the light and heavy mass eigenstates correspond to the CP-even and CP-odd eigenstates respectively.

The mass difference, $\Delta M_s = M_H - M_L \sim 2|M_{12}|$ is sensitive to the effects of new physics, whereas the CP width difference $\Delta\Gamma_s^{CP} = \Gamma_{\mathrm{even}} - \Gamma_{\mathrm{odd}} \sim 2|\Gamma_{12}|$ does not provide sensitivity to new physics, as $|\Gamma_{12}|$ is dominated by tree-level processes. However, the width difference $\Delta\Gamma_s = \Gamma_L - \Gamma_H = \Delta\Gamma_s^{CP}\cos\phi_s$ is highly sensitive to possible effects of new physics through the CP-violating phase angle $\phi_s = \arg\left(-\frac{M_{12}}{\Gamma_{12}}\right)$, which in the SM is expected to be small (≈ 0), but may be enhanced through fourth generation models to $-\phi_s \sim$ 0.5–0.7 [1].

The D0 detector is a general purpose spectrometer and calorimeter [2]. The significant components for these measurements are the muon chambers, calorimeters and central tracking region. Enclosed within a 2 T superconducting solenoid is a silicon micostrip tracker (SMT) and central fiber tracker (CFT) for vertexing and tracking of charged particles that extends out to a pseudorapidity of $|\eta| = 2.0$, where $\eta = -\ln[\tan(\theta/2)]$, and θ is the polar angle. The three liquid-argon/uranium calorimeters provide coverage up to $|\eta| \approx 4.0$. The muon system consists of one tracking layer and scintillation trigger counters in front of 1.8 T iron toroids with two layers after the toroids. Coverage extends to $|\eta| = 2.0$.

Results given here correspond to data samples recorded by the D0 detector of integrated luminosities 1.0–1.3 fb^{-1}.

2 Mass difference ΔM_s

In 2006 the D0 experiment made the first direct double-sided constraint [3] on the oscillation frequency ΔM_s of the B_s meson in the semileptonic decays[1] of $B_s^0 \to D_s\mu\nu X$, $D_s \to \phi\pi$, $\phi \to K^+K^-$. A limit of $17 < \Delta M_s < 21\,\mathrm{ps}^{-1}$ at 90% CL was measured. A more recent measurement [4], which includes hadronic modes of B_s meson decay, gives the precision value $\Delta M_s = 17.77 \pm 0.10\,(\mathrm{stat}) \pm 0.07(\mathrm{syst})\,\mathrm{ps}^{-1}$.

[1] Charge-conjugate states are implied throughout.

3 Width difference $\Delta\Gamma_s$

3.1 Br($B_s^0 \to D_s^{(*)} D_s^{(*)}$)

The decay of B_s^0 mesons to $D_s^+ D_s^-$ produces a CP-even final state [5], and under certain theoretical assumptions, the decay $B_s^0 \to D_s^{(*)} D_s^{(*)}$ is also predominately CP-even, up to[2] $\sim 95\%$ [6]. Under these assumptions, the branching fraction of this decay can be related to the CP width difference $\Delta\Gamma_s^{CP} \approx 2|\Gamma_{12}|$ ($\Delta\Gamma_s = \Delta\Gamma_s^{CP} \cos\phi_s$) by:

$$2\mathrm{Br}(B_s^0 \to D_s^{(*)} D_s^{(*)}) = \frac{\Delta\Gamma_s^{CP}}{\Gamma_s}\left[1 + \mathcal{O}\left(\frac{\Delta\Gamma_s^{CP}}{\Gamma_s}\right)\right] \quad (1)$$

The D0 experiment performed a measurement [7] using the decay chain $B_s^0 \to D_s^{(*)\pm} D_s^{(*)\mp}$, $D_s^\pm \to \phi\pi^\pm$, $D_s^\mp \to \phi\mu^\mp\nu X$, $\phi \to K^+K^-$ to extract the branching fraction $\mathrm{Br}(B_s^0 \to D_s^{(*)} D_s^{(*)})$ and the width difference $\Delta\Gamma_s^{CP}/\Gamma_s$.

To reduce detector related systematics effects, the above process was normalised to to the decay $B_s^0 \to D_s^{(*)\pm}\mu^\mp\nu X$, $D_s^\pm \to \phi\pi^\pm$, $\phi \to K^+K^-$, which has a similar final-state to the main process. From a fit to the invariant mass of the $D_s(\phi\pi)$ mass peak, 17670 ± 230 events were estimated for the normalisation data.

For the signal decay, $13.4^{+6.6}_{-6.0}$ events were estimated in data, from a two-dimensional fit to the invariant mass of D_s mesons from $D_s \to \phi\pi$, and ϕ mesons in the decay $D_s \to \phi\mu\nu X$. Figures 1 and 2 shows the result of the fitting procedure projected onto the signal regions of the mass variable not plotted.

Using data and Monte Carlo (MC) simulations, 2.0 background events were estimated to contribute to the signal number. The difference between the efficiencies to reconstruct the signal and normalisation processes is determined in MC, and corrections applied to the in determination of the result.

The branching fraction $\mathrm{Br}(B_s^0 \to D_s^{(*)} D_s^{(*)})$ was measured to be:

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

Under the assumptions leading to Eq. 1, the width difference is estimated to be:

$$\frac{\Delta\Gamma_s^{CP}}{\Gamma_s} = 0.079^{+0.038}_{-0.035}\,(\mathrm{stat})^{+0.031}_{-0.030}\,(\mathrm{syst}). \quad (2)$$

3.2 $B_s^0 \to J/\psi\phi$

The decay $B_s^0 \to J/\psi\phi$ contains final states with both CP-even and CP-odd components, which may be separated using a lifetime-dependent angular analysis, leading to a measurement of the lifetime difference. If the lifetime difference is sufficiently large, the CP-violating phase ϕ_s can also be extracted.

[2] It should be noted that some estimates consider a CP-odd fraction up to 30%.

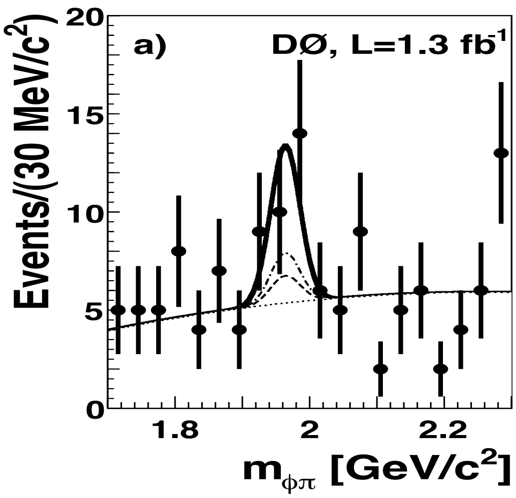

Fig. 1. Invariant mass distribution of the $D_s(\phi\pi)$ meson projected onto the signal region of the fitting procedure. The curves are the projected fit results for the: total fit (solid); polynomial background contribution (dotted); non-peaking background component (dashed); background peaking in the mass region of both the ϕ and D_s mesons (dash-dotted).

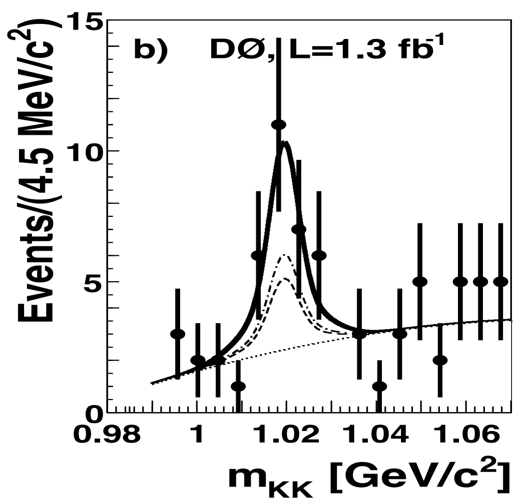

Fig. 2. Invariant mass distribution of the ϕ meson from $D_s \to \phi\mu\nu X$, projected onto the signal region of the fitting procedure. The curves are the projected fit results for the: total fit (solid); polynomial background contribution (dotted); non-peaking background component (dashed); background peaking in the mass region of both the ϕ and D_s mesons (dash-dotted).

The measurement [8] was performed in the decay of untagged B_s mesons: $B_s^0 \to J/\psi\phi$, $J/\psi \to \mu^+\mu^-$, $\phi \to K^+K^-$ with a set of data corresponding to an integrated luminosity of $1.1\,\mathrm{fb}^{-1}$. From 23300 events in the final selection 1039 ± 45 were estimated from the fitting procedure to originate from the B_s decay. The likelihood fitting procedure uses the angle between the kaon and J/ψ in the ϕ meson rest frame, and the tranversity polar and azimuthal angles of the muon in the J/ψ rest frame to separate out the CP-eigenstates. The

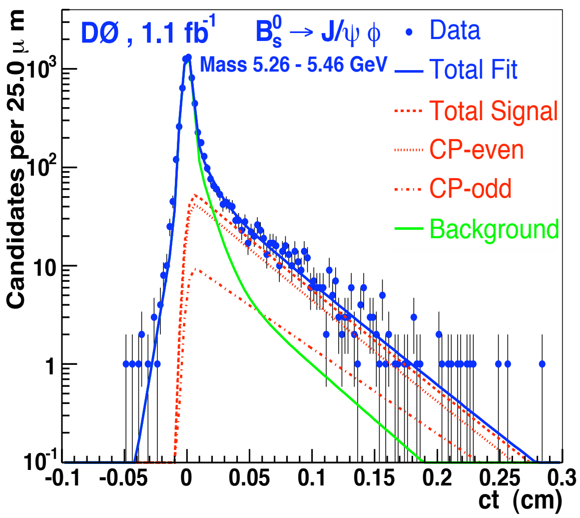

Fig. 3. Proper decay-length of the B_s meson candidates in $B_s \to J\psi\phi$. The curves describe: the total fit in blue (solid); the total signal contribution in red (dashed) with the CP-even (dotted) and CP-odd (dash-dotted) separated; and the background in green (lower solid).

background is separated into contributions of: prompt, from directly produced J/ψ mesons and additional track from hadronisation; and non-prompt, where J/ψ mesons are produced from B mesons decays, but combined with a ϕ meson from track from hadronisation or multi-body decays of the B meson.

In Fig. 3 the contributions of the two CP-eigenstates and backgrounds are shown for the proper decay-lengths of B_s meson candidates.

Under the assumption of no CP-violation ($\phi_s \equiv 0$), the maximum likelihood fit yields

$$|\Delta\Gamma_s| = 0.12^{+0.08}_{-0.10}\,\mathrm{ps}^{-1},$$
$$\tau_s = 1.52 \pm 0.08\,\mathrm{ps}.$$

4 CP-violating phase ϕ_s

If there exists a sizeable width difference in the B_s^0 meson system, there is sensitivity to the CP-violating phase angle through the untagged time-dependent width $\Gamma_s(t) \sim (e^{-\Gamma_s t} - e^{\Gamma_H t})\sin\phi_s$.

From the same $B_s^0 \to J/\psi\phi$ analysis described above, the constraint on ϕ_s was removed and this parameter allowed to float, and the fitting procedure was repeated. In this case there exists a four-fold ambiguity in the results, due to a sign reversal of $\sin\phi_s$ with the simultaneous flip of the strong phase angles $\cos\delta_1$ and $\cos\delta_2$ which appears in the likelihood fitting procedure. The average lifetime extracted from the fit is

$$\tau_s = 1.49 \pm 0.08\,\mathrm{ps},$$

and for the case $\cos\delta_1 < 0$, $\cos\delta_2 > 0$:

$$|\Delta\Gamma_s| = 0.17^{+0.09}_{-0.09}\,\mathrm{ps}^{-1},$$
$$\phi_s = \begin{cases} -0.79 \pm 0.56, & \Delta\Gamma_s > 0, \\ +2.35 \pm 0.56, & \Delta\Gamma_s < 0, \end{cases}$$

and in the case $\cos\delta_1 > 0$, $\cos\delta_2 < 0$:

$$|\Delta\Gamma_s| = 0.17^{+0.09}_{-0.09}\,\mathrm{ps}^{-1},$$
$$\phi_s = \begin{cases} +0.79 \pm 0.56, & \Delta\Gamma_s > 0, \\ -2.35 \pm 0.56, & \Delta\Gamma_s < 0. \end{cases}$$

5 Combination results

Using the results from the $B_s^0 \to J/\psi\phi$ analysis with the ΔM_s mixing measurement [4] and the world-average flavour specific lifetime, which includes a D0 measurment [9], and an additional constraint described below, an improved estimate of the CP-violating phase value was obtained [10].

Two charge asymmetry measurements by the D0 experiment are used in forming the additional constraint. In Ref. [11], the same-sign di-muon charge asymmetry, defined as

$$A^{\mu\mu}_{SL} = \frac{N(b\bar{b} \to \mu^+\mu^+X) - N(b\bar{b} \to \mu^-\mu^-X)}{N(b\bar{b} \to \mu^+\mu^+X) + N(b\bar{b} \to \mu^-\mu^-X)}$$

was measured, and from this asymmetry value A^s_{SL} extracted:

$$A^s_{SL} = -0.0064 \pm 0.0101. \tag{3}$$

In Ref. [12] the charge asymmetry value from semileptonic decays from $B_s^0 \to D_s\mu\nu$, $D_s \to \phi\pi$ was measured from which the value A^s_{SL} extracted:

$$A^s_{SL} = +0.0245 \pm 0.0193\,(\mathrm{stat}) \pm 0.0035\,(\mathrm{syst}). \tag{4}$$

Together, Eqs. 4 and 3 are almost independent and can be combined to provide the current best limits on A^s_{SL}:

$$A^s_{SL} = 0.0001 \pm 0.0090. \tag{5}$$

This charge asymmetry value, with the measurement [4] of ΔM_s, is used to provide the additional constraint [13]:

$$\Delta\Gamma_s \cdot \tan\phi_s = A^s_{SL} \cdot \Delta M_s = 0.02\,\mathrm{ps}^{-1}. \tag{6}$$

The fit to the $B_s^0 \to J/\psi\phi$ data was repeated with this constraint, and the results of which are shown as projections in Fig. 4 for the contour of τ_s versus ϕ_s and in Fig. 5 for $\Delta\Gamma_s$ versus ϕ_s. The contours are for the change in likelihood value $\Delta\ln(\mathcal{L}) = 0.5$, which corresponds to a 39% CL. Whilst the four-fold ambiguity on the sign of $\Delta\Gamma_s$ with ϕ_s remains, the solution closest to the SM prediction yields:

$$\Delta\Gamma_s = 0.13 \pm 0.09\,\mathrm{ps}^{-1},$$
$$\phi_s = -0.70^{+0.47}_{-0.39}.$$

6 Summary

The B_s meson now has information regarding all its observable parameters, be that in precision measurements (i.e. M_s, ΔM_s), or a constraint, such as in ϕ_s.

Whilst no evidence for beyond standard model effects are present, with increased luminosity and improvements in analysis techniques, the available parameter space in which it may manifest is certainly diminishing.

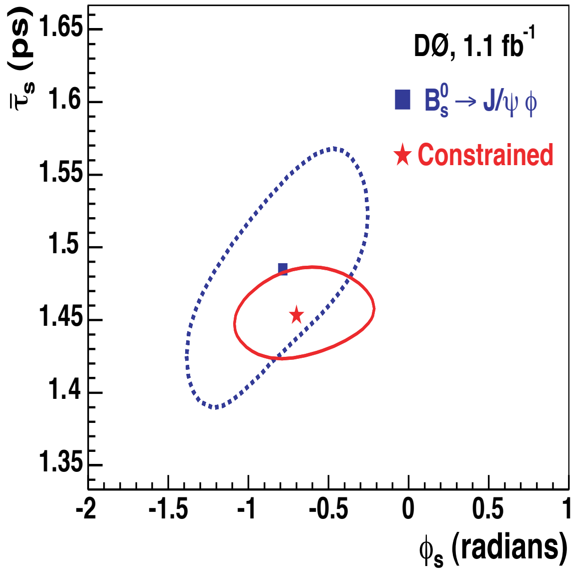

Fig. 4. Contours of $\ln \mathcal{L} = 0.5$ (39% CL) in the plane of lifetime vs. CP-violating phase angle. In blue (dotted) the result from the $B_s^0 \rightarrow J/\psi\phi$ analysis, and in red (solid) the combination analysis results, both shown for the sign combination whose result is closest to the SM prediction.

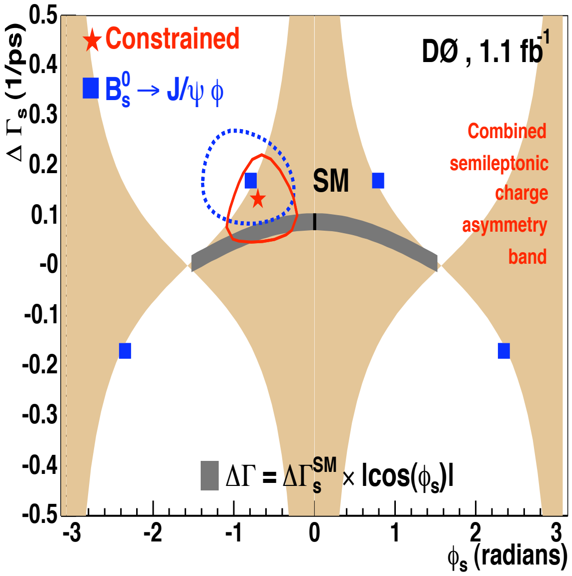

Fig. 5. Contours of $\ln \mathcal{L} = 0.5$ (39% CL) in the plane of width difference vs. CP-violating phase angle for solutions with sign combination closest to the SM prediction of the $B_s^0 \rightarrow J/\psi\phi$ analysis (blue, dotted), and the results of the combination analysis (red, solid). The four solid (blue) squares represents the central values from the $B_s^0 \rightarrow J/\psi\phi$ showing the four-fold ambiguity. The SM prediction is shown as the black vertical bar, and the dark band is the result of $\Delta\Gamma_s = \Delta\Gamma_s^{SM}|\cos\phi_s|$, $\Delta\Gamma_s^{SM} = 0.088\pm0.017\ \mathrm{ps}^{-1}$ [14]. The lighter shaded area corresponds to the result of Eq. 6.

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