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

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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 $\text{Br}(B^+_s \to D^{(*)}_s D_s^{(*)})$ 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 $\phi_s$, although a four-fold ambiguity remains. This result is combined with other D0 measurements to yield $\Delta\Gamma_s = 0.13 \pm 0.09 \text{ ps}^{-1}$, $\phi_s = -0.70_{-0.39}^{+0.47}$.

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 $B^0_s$ system can be described by the Schrödinger equation:

$$i\frac{d}{dt}\begin{pmatrix} B^0_s \\ B^0_{s\bar{s}} \end{pmatrix} = M \begin{pmatrix} 0 & \frac{i}{\sqrt{2}} \\ \frac{i}{\sqrt{2}} & 0 \end{pmatrix} \begin{pmatrix} B^0_s \\ B^0_{s\bar{s}} \end{pmatrix},$$

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 $|B_L\rangle = p \ |B^0_s\rangle + q \ |B^0_{s\bar{s}}\rangle$, $|B_H\rangle = p \ |B^0_{s\bar{s}}\rangle - q \ |B^0_s\rangle$, 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 $\Delta\Gamma_{s_{CP}} = \Gamma_{\text{even}} - \Gamma_{\text{odd}} \sim 2|\Gamma_{12}|$ 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 ($\approx 0$), but may be enhanced through fourth generation models to $\pm 0.5 - 0.7$.

The D0 detector is a general purpose spectrometer and calorimeter. 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 microstrip 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 $\theta$ 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 $\Delta M_s$

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

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1 Charge-conjugate states are implied throughout.
3 Width difference $\Delta \Gamma_s$

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

The decay of $B_s^0$ mesons to $D_s^+ D_s^-$ produces a CP-even final state \[^4\], and under certain theoretical assumptions, the decay $B_s^0 \rightarrow D_s^{(*)} D_s^{(*)}$ is also predominately CP-even, up to $t^2 < 95\% \[^5\]$. Under these assumptions, the branching fraction of this decay can be related to the CP width difference $\Delta \Gamma_s^{CP} \approx 2 |\Gamma_s| (\Delta \Gamma_s = \Delta \Gamma_s^{CP} \cos \phi_s)$ by:

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

(1)

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

To reduce detector related systematics effects, the above process was normalised to the decay $B_s^0 \rightarrow D_s^{(*)} \mu^+ \nu X$, $D_s^+ \rightarrow \phi K^+ K^-$, 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, $17670 \pm 230$ events were estimated for the normalisation data.

For the signal decay, $13.4^{+6.0}_{-6.2}$ events were estimated in data, from a two-dimensional fit to the invariant mass of $D_s$ mesons from $D_s \rightarrow \phi \pi$, and $\phi$ mesons in the decay $D_s \rightarrow \phi \mu \nu X$. 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 $\text{Br}(B_s^0 \rightarrow D_s^{(*)} D_s^{(*)})$ was measured to be:

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

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

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

(2)

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

The decay $B_s^0 \rightarrow J/\psi \phi$ 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 $\phi_s$ can also be extracted.

\(^2\) It should be noted that some estimates consider a CP-odd fraction up to 30%.

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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 $\phi$ and $D_s$ mesons (dash-dotted).

Fig. 2. Invariant mass distribution of the $\phi$ meson from $D_s \rightarrow \phi \mu \nu X$, 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 $\phi$ and $D_s$ mesons (dash-dotted).

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

The average lifetime extracted from the fit is \( \Gamma \) phase angle through the untagged time-dependent width \( \delta \).

Above, the constraint on \( \phi \) is discussed in detail, due to a sign reversal of \( \sin \phi \).

In this case there exists a four-fold ambiguity on the simultaneous flip of the strong phase angles \( \cos \phi \).

The maximum likelihood fit yields \( \Delta \Gamma \) for multi-body decays of the \( B \)

and in the case \( \cos \phi > 0, \cos \phi < 0 \):

\[
|\Delta \Gamma_s| = 0.17^{+0.09}_{-0.09} \text{ ps}^{-1},
\]

\[
\phi_s = \begin{cases} 
+0.79 \pm 0.56, & \Delta \Gamma_s > 0, \\
-2.35 \pm 0.56, & \Delta \Gamma_s < 0.
\end{cases}
\]

5 Combination results

Using the results from the \( B^0 \rightarrow J/\psi \phi \) analysis with the \( \Delta M_s \) mixing measurement \( \Delta \Gamma_s \) and the world-average flavour specific lifetime, which includes a D0 measurement \( \Delta \Gamma_s \), and an additional constraint described below, an improved estimate of the CP-violating phase value was obtained \( \phi_s \).

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

\[
A_{SL}^{\mu} = \frac{N(bb \rightarrow \mu^+ \mu^+ X) - N(bb \rightarrow \mu^- \mu^- X)}{N(bb \rightarrow \mu^+ \mu^+ X) + N(bb \rightarrow \mu^- \mu^- X)}
\]

was measured, and from this asymmetry value \( A_{SL} \) extracted:

\[
A_{SL} = -0.0064 \pm 0.0101.
\] (3)

In Ref. \[12\] the charge asymmetry value from semileptonic decays from \( B^0 \rightarrow D_s \mu \nu \), \( D_s \rightarrow \phi \pi \) was measured from which the value \( A_{SL} \) extracted:

\[
A_{SL} = +0.0245 \pm 0.0193 \text{ (stat)} \pm 0.0035 \text{ (syst).}
\] (4)

Together, Eqs. \[4\] and \[3\] are almost independent and can be combined to provide the current best limits on \( A_{SL} \):

\[
A_{SL} = 0.0001 \pm 0.0090.
\] (5)

This charge asymmetry value, with the measurement \( \delta \) of \( \Delta M_s \), is used to provide the additional constraint \( \Delta \Gamma_s \cdot \tan \phi_s = A_{SL} \cdot \Delta M_s = 0.02 \text{ ps}^{-1} \):

\[
\Delta \Gamma_s \cdot \tan \phi_s = A_{SL} \cdot \Delta M_s = 0.02 \text{ ps}^{-1}.
\] (6)

The fit to the \( B^0 \rightarrow J/\psi \phi \) data was repeated with this constraint, and the results of which are shown as projections in Fig. \[4\] for the contour of \( \tau_s \) versus \( \phi_s \) and in Fig. \[5\] for \( \Delta \Gamma_s \) versus \( \phi_s \). The contours are for the change in likelihood value \( \Delta \ln(L) = 0.5 \), which corresponds to a 30\% CL. Whilst the four-fold ambiguity on the sign of \( \Delta \Gamma_s \) with \( \phi_s \) remains, the solution closest to the SM prediction yields:

\[
\Delta \Gamma_s = 0.13 \pm 0.09 \text{ ps}^{-1},
\]

\[
\phi_s = -0.70^{+0.47}_{-0.39}.
\]

6 Summary

The \( B_s \) meson now has information regarding all of its observable parameters, both in precision measurements (i.e. \( M_s, \Delta M_s \)), or a constraint, such as in \( \phi_s \).

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. 3. Proper decay-length of the \( B_s \) meson candidates in \( B_s \rightarrow J/\psi \phi \). 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 \( J/\psi \) mesons and additional track from hadronisation; and non-prompt, where \( J/\psi \) mesons are produced from \( B \) mesons decays, but combined with a \( \phi \) 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 (\( \phi_s = 0 \)), the maximum likelihood fit yields

\[
|\Delta \Gamma_s| = 0.12^{+0.08}_{-0.10} \text{ ps}^{-1},
\]

\[
\tau_s = 1.52 \pm 0.08 \text{ ps}.
\]

4 CP-violating phase \( \phi_s \)

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

From the same \( B^0 \rightarrow J/\psi \phi \) analysis described above, the constraint on \( \phi_s \) 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 \( \cos \phi_1 \) and \( \cos \phi_2 \) which appears in the likelihood fitting procedure. The average lifetime extracted from the fit is

\[
\tau_s = 1.49 \pm 0.08 \text{ ps},
\]

and for the case \( \cos \phi_1 < 0, \cos \phi_2 > 0 \):

\[
|\Delta \Gamma_s| = 0.17^{+0.09}_{-0.09} \text{ ps}^{-1},
\]

\[
\phi_s = \begin{cases} 
-0.79 \pm 0.56, & \Delta \Gamma_s > 0, \\
+2.35 \pm 0.56, & \Delta \Gamma_s < 0.
\end{cases}
\]
**Fig. 4.** Contours of $\ln L = 0.5$ (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 $\ln L = 0.5$ (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 $\Delta \Gamma_s = \Delta \Gamma_s^{SM} |\cos \phi_s|$, $\Delta \Gamma_s^{SM} = 0.088 \pm 0.017$ ps$^{-1}$ [14]. The lighter shaded area corresponds to the result of Eq. [14].

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