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Measurement of the CP violating phase ϕ_s in $\bar{B}_s^0 \rightarrow J/\psi f_0(980)$

The LHCb Collaboration¹

Abstract

Measurement of mixing-induced CP violation in \bar{B}_s^0 decays is of prime importance in probing new physics. So far only the channel $\bar{B}_s^0 \rightarrow J/\psi\phi$ has been used. Here we report on a measurement using an LHCb data sample of 0.41 fb^{-1} , in the CP odd eigenstate $J/\psi f_0(980)$, where $f_0(980) \rightarrow \pi^+\pi^-$. A time dependent fit of the data with the \bar{B}_s^0 lifetime and the difference in widths of the heavy and light eigenstates constrained to the values obtained from $\bar{B}_s^0 \rightarrow J/\psi\phi$ yields a value of the CP violating phase of $-0.44 \pm 0.44 \pm 0.02$ rad, consistent with the Standard Model expectation.

Keywords: LHC, CP violation, Hadronic B Decays, \bar{B}_s^0 meson

PACS: 13.25.Hw, 14.40.Nd, 11.30.Er

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1 Introduction

An important goal of heavy flavour experiments is to measure the mixing-induced CP violation phase in \bar{B}_s^0 decays, ϕ_s . As this phase is predicted to be small in the Standard Model (SM) [1], new physics can induce large changes [2]. Here we use the decay mode $\bar{B}_s^0 \rightarrow J/\psi f_0(980)$. If only the dominant decay diagrams shown in contribute Fig. 1, then the value of ϕ_s using $\bar{B}_s^0 \rightarrow J/\psi f_0(980)$ is the same as that measured using $\bar{B}_s^0 \rightarrow J/\psi \phi$ decay.

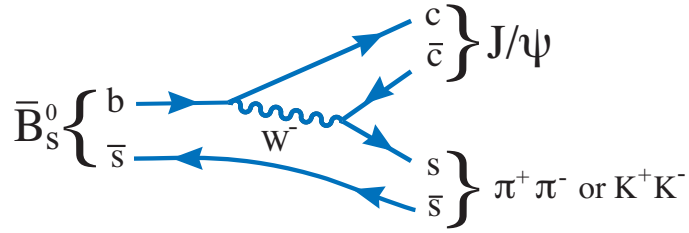


Figure 1: Dominant decay diagrams for $\bar{B}_s^0 \rightarrow J/\psi f_0(980)$ or $J/\psi \phi$ decays.

Motivated by a prediction in Ref. [3], LHCb searched for and made the first observation of $\bar{B}_s^0 \rightarrow J/\psi f_0(980)$ decays [4] that was subsequently confirmed by other experiments [5, 6]. Time dependent CP violation can be measured without an angular analysis, as the final state is a CP eigenstate. From now on f_0 will stand only for $f_0(980)$.

In the Standard Model, in terms of CKM matrix elements, $\phi_s = -2 \arg \left[\frac{V_{ts} V_{tb}^*}{V_{cs} V_{cb}^*} \right]$. The equations below are written assuming that there is only one decay amplitude, ignoring possible small contributions from other diagrams [7]. The decay time evolutions for initial B_s^0 and \bar{B}_s^0 are [8]

$$\Gamma \left(\begin{matrix} (-) \\ B_s^0 \rightarrow J/\psi f_0 \end{matrix} \right) = \mathcal{N} e^{-\Gamma_s t} \left\{ e^{\Delta\Gamma_s t/2} (1 + \cos \phi_s) + e^{-\Delta\Gamma_s t/2} (1 - \cos \phi_s) \pm \sin \phi_s \sin (\Delta m_s t) \right\}, \quad (1)$$

where $\Delta\Gamma_s$ is the decay width difference between light and heavy mass eigenstates, $\Delta\Gamma_s = \Gamma_L - \Gamma_H$. The decay width Γ_s is the average of the widths Γ_L and Γ_H , and \mathcal{N} is a time-independent normalization factor. The plus sign in front of the $\sin \phi_s$ term applies to an initial \bar{B}_s^0 and the minus sign for an initial B_s^0 meson. The time evolution of the untagged rate is then

$$\Gamma (B_s^0 \rightarrow J/\psi f_0) + \Gamma (\bar{B}_s^0 \rightarrow J/\psi f_0) = \mathcal{N} e^{-\Gamma_s t} \left\{ e^{\Delta\Gamma_s t/2} (1 + \cos \phi_s) + e^{-\Delta\Gamma_s t/2} (1 - \cos \phi_s) \right\}. \quad (2)$$

16 Note that there is information in the shape of the lifetime distribution that correlates $\Delta\Gamma_s$
 17 and ϕ_s . In this analysis we will use both samples of flavour tagged and untagged decays.
 18 Both Eqs. 1 and 2 are insensitive to the change $\phi_s \rightarrow \pi - \phi_s$ when $\Delta\Gamma_s \rightarrow -\Delta\Gamma_s$.

19 2 Selection requirements

20 We use a data sample of 0.41 fb^{-1} collected in 2010 and the first half of 2011 at a centre-
 21 of-mass energy of 7 TeV. This analysis is restricted to events accepted by a $J/\psi \rightarrow$
 22 $\mu^+\mu^-$ trigger. The LHCb detector and the track reconstruction are described in Ref. [9].
 23 The detector elements most important for this analysis are the VELO, a silicon strip
 24 device that surrounds the pp interaction region, and other tracking devices. Two Ring
 25 Imaging Cherenkov (RICH) detectors are used to identify charged hadrons, while muons
 26 are identified using their penetration through iron.

27 To be considered 1 a $J/\psi \rightarrow \mu^+\mu^-$ candidate particles of opposite charge are required
 28 to have transverse momentum, p_T , greater than 500 MeV, be identified as muons, and
 29 form a vertex with fit χ^2 per number of degrees of freedom (ndof) less than 11. We work
 30 in units where $c = \hbar = 1$. Only candidates with dimuon invariant mass between -48 MeV
 31 to $+43 \text{ MeV}$ of the J/ψ mass peak are selected. Pion candidates are selected if they are
 32 inconsistent with having been produced at the primary vertex. The impact parameter
 33 (IP) is the minimum distance of approach of the track with respect to the primary vertex.
 34 We require that the χ^2 formed by using the hypothesis that the IP is zero be > 9 for each
 35 track. For further consideration particles forming di-pion candidates must be positively
 36 identified in the RICH system, and must have their scalar sum $p_T > 900 \text{ MeV}$.

37 To select \bar{B}_s^0 candidates we further require that the two pions form a vertex with a
 38 $\chi^2 < 10$, that they form a candidate \bar{B}_s^0 vertex with the J/ψ where the vertex fit χ^2/ndof
 39 < 5 , that this vertex is $> 1.5 \text{ mm}$ from the primary, and points to the primary vertex at
 40 an angle not different from its momentum direction by more than 11.8 mrad.

41 The invariant mass of selected $\mu^+\mu^-\pi\pi$ combinations, where the di-muon pair is con-
 42 strained to have the J/ψ mass, is shown in Fig. 2 for both opposite-sign and like-sign
 43 di-pion combinations, requiring di-pion invariant masses within 90 MeV of 980 MeV. Here
 44 like-sign combinations are defined as the sum of $\pi^+\pi^+$ and $\pi^-\pi^-$ candidates. The signal
 45 shape, the same for both \bar{B}_s^0 and \bar{B}^0 , is a double-Gaussian, where the core Gaussian's mean
 46 and width are allowed to vary, and the fraction and width ratio for the second Gaussian
 47 are fixed to the values obtained in a separate fit to $\bar{B}_s^0 \rightarrow J/\psi\phi$. The mean values of both
 48 Gaussians are required to be the same. The combinatoric background is described by an
 49 exponential function. Other background components are $B^- \rightarrow J/\psi h^-$, where h^- can be
 50 either a K^- or a π^- and an additional π^+ is found, $\bar{B}_s^0 \rightarrow J/\psi\eta'$, $\eta' \rightarrow \rho\gamma$, $\bar{B}_s^0 \rightarrow J/\psi\phi$,
 51 $\phi \rightarrow \pi^+\pi^-\pi^0$, and $\bar{B}^0 \rightarrow J/\psi\bar{K}^{*0}$. The background shapes are taken from Monte Carlo
 52 simulation based on PYTHIA [10] and GEANT-4 [11] with their normalizations allowed
 53 to vary. We performed a simultaneous fit to the opposite-sign and like-sign di-pion event
 54 distributions. There are 1428 ± 47 signal events within $\pm 20 \text{ MeV}$ of the \bar{B}_s^0 mass peak.
 55 The background under the peak in this interval is 467 ± 11 events, giving a signal purity

56 of 75%. Importantly, the like-sign di-pion yield at masses higher than the \bar{B}_s^0 gives an
 57 excellent description of the shape and level of the background. Simulation studies have
 58 demonstrated that it also describes the background under the peak.

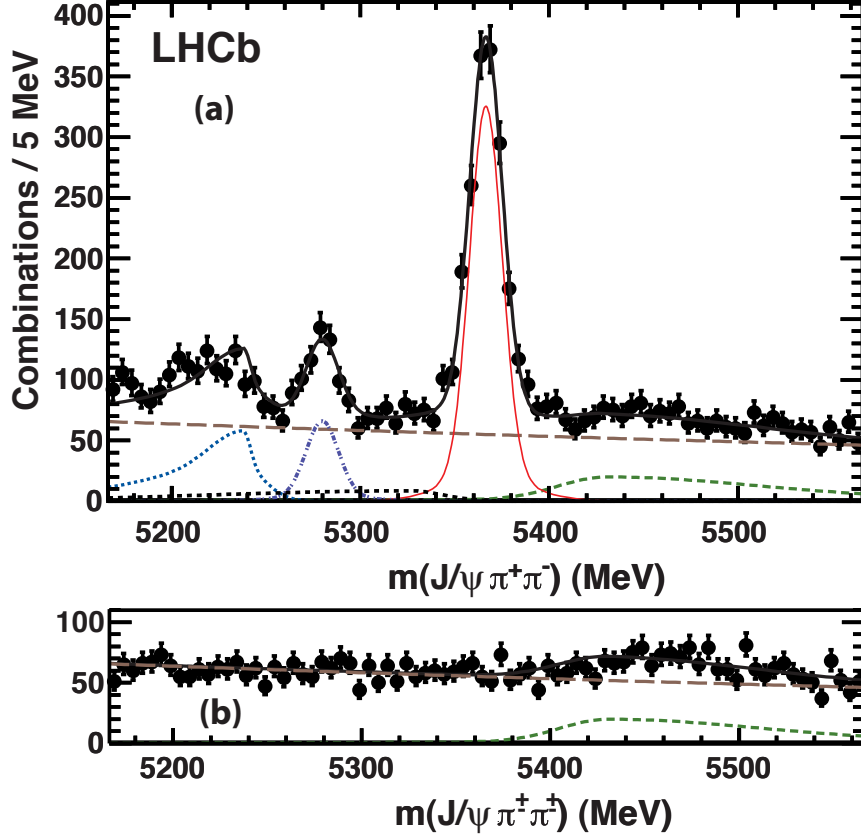


Figure 2: (a) Invariant mass of $J/\psi\pi^+\pi^-$ combinations when the $\pi^+\pi^-$ pair is required to be within ± 90 MeV of the nominal $f_0(980)$ mass. The data have been fitted with a double-Gaussian signal and several background functions. The thin (red) solid line shows the signal, the long-dashed (brown) line the combinatoric background, the dashed (green) line the B^- background (mostly at masses above the signal peak), the dotted (blue) line the $\bar{B}^0 \rightarrow J/\psi\bar{K}^{*0}$ background, the dash-dot line (purple) the $\bar{B}^0 \rightarrow J/\psi\pi^+\pi^-$ background, the dotted line (black) the sum of $\bar{B}_s^0 \rightarrow J/\psi\eta'$ and $J/\psi\phi$ backgrounds (barely visible), and the thick-solid (black) line the total. (b) The mass distribution for like-sign candidates.

59 The invariant mass of di-pion combinations is shown in Fig. 3 for both opposite-sign
 60 and like-sign di-pion combinations within ± 20 MeV of the \bar{B}_s^0 candidate mass peak. In
 61 what follows we only use events in the f_0 signal region from 890 to 1070 MeV. A large
 62 signal is present near the nominal $f_0(980)$ mass. Other $\bar{B}_s^0 \rightarrow J/\psi\pi^+\pi^-$ signal events are
 63 present at higher masses.

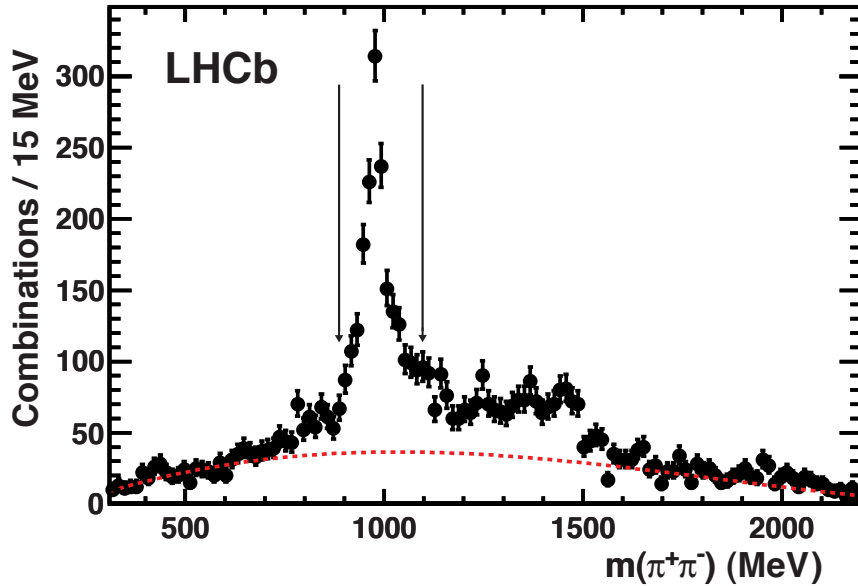


Figure 3: Invariant mass of $\pi^+\pi^-$ combinations (points) and a fit to the $\pi^\pm\pi^\pm$ data (dashed line) for events in the \bar{B}_s^0 signal region. The region between the vertical arrows contains the events selected for further analysis.

3 S-wave content

64

65 Since the initial isospin of the $s\bar{s}$ system that produces the two pions is zero, and since
 66 the G -parity of the two pions is even, only even spin is allowed for the $\pi^+\pi^-$ pair. Since
 67 no spin-4 resonances have been observed below 2 GeV, the angular distributions are
 68 described by the coherent combination of spin-0 and spin-2 resonant decays. We use the
 69 helicity basis and define the decay angles as $\theta_{J/\psi}$, the angle of the μ^+ in the J/ψ rest
 70 frame with respect to the \bar{B}_s^0 direction, and θ_{f_0} , the angle of the π^+ in the $\pi^+\pi^-$ rest
 71 frame with respect to the \bar{B}_s^0 direction. The spin-0 amplitude is labeled as A_{00} , the three
 72 spin-2 amplitudes as A_{2i} , $i = -1, 0, 1$, and δ is the strong phase between the A_{20} and A_{00}
 73 amplitudes.

74 After integrating over the angle between the two decay planes the joint angular dis-
 75 tribution is given by [12]

$$\frac{d\Gamma}{d\cos\theta_{f_0}d\cos\theta_{J/\psi}} = \left| A_{00} + \frac{1}{2}A_{20}e^{i\delta}\sqrt{5}(3\cos^2\theta_{f_0} - 1) \right|^2 \sin^2\theta_{J/\psi} + \frac{1}{4}(|A_{21}|^2 + |A_{2-1}|^2)(15\sin^2\theta_{f_0}\cos^2\theta_{f_0})(1 + \cos^2\theta_{J/\psi}). \quad (3)$$

76 Since the \bar{B}_s^0 is spinless, when it decays into a spin-1 J/ψ and a spin-0 f_0 , $\theta_{J/\psi}$ should be
 77 distributed as $\sin^2\theta_{J/\psi}$ and $\cos\theta_{f_0}$ should be uniformly distributed.

78 The helicity distributions of the opposite-sign data selected with reconstructed
 79 $J/\psi\pi^+\pi^-$ mass within ± 20 MeV of the known \bar{B}_s^0 mass and within ± 90 MeV of the nom-
 80 inal $f_0(980)$ mass, are shown in Fig. 4; the data have been background subtracted, using

81 the like-sign data, and acceptance corrected using Monte Carlo simulation. We perform
 82 a two-dimensional unbinned angular fit. The ratio of rates is found to be

$$\begin{aligned} \frac{|A_{20}|^2}{|A_{00}|^2} &= (0.1^{+2.6}_{-0.1})\%, \\ \frac{|A_{21}|^2 + |A_{2-1}|^2}{|A_{00}|^2} &= (0.0^{+1.7}_{-0.0})\%, \end{aligned} \quad (4)$$

83 where the uncertainties are statistical only. The spin-2 amplitudes are consistent with
 84 zero. Note that the A_{20} amplitude corresponds to CP odd final states, and thus would
 85 exhibit the same CP violating phase as the $J/\psi f_0$ final state, while the $A_{2\pm 1}$ amplitude
 86 can be either CP odd or even. Thus this sample is taken as pure CP odd.

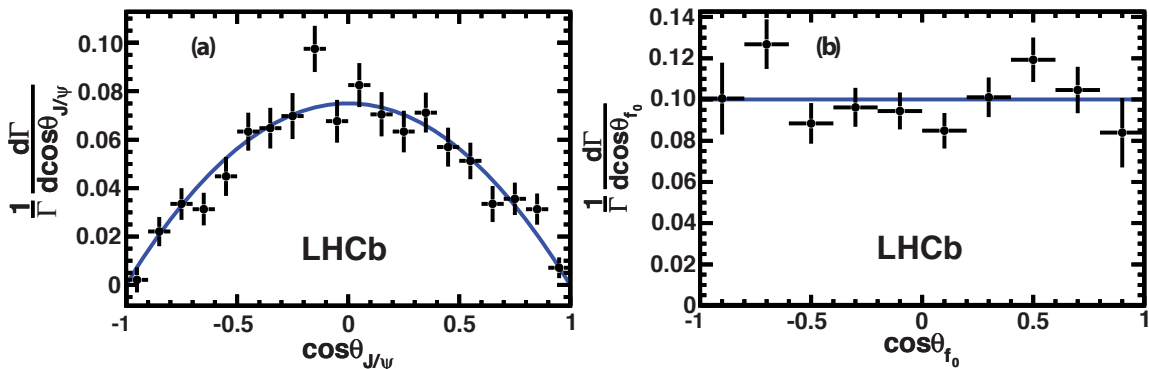


Figure 4: Efficiency corrected, background subtracted angular distributions in the $\pi^+\pi^-$ mass region within ± 90 MeV of 980 MeV and within ± 20 MeV of the \bar{B}_s^0 mass for (a) $\cos^2 \theta_{J/\psi}$, and (b) $\cos \theta_{f_0}$. The solid lines show the expectations for a spin-0 object.

87 4 Time resolution and acceptance

88 The \bar{B}_s^0 decay time is defined here as $t = m \vec{d} \cdot \vec{p} / |\vec{p}|^2$, where m is the reconstructed
 89 invariant mass, \vec{p} the momentum and \vec{d} the flight vector of the candidate \bar{B}_s^0 from the
 90 primary to the secondary vertices. If more than one primary vertex is found, the one that
 91 corresponds to the smallest IP χ^2 of the \bar{B}_s^0 candidate is chosen.

92 The decay time resolution probability distribution function (PDF) is determined from
 93 data using J/ψ detected without any requirement on detachment from the primary vertex
 94 (prompt) plus two oppositely charged particles from the primary vertex with the same
 95 selection criteria as for $J/\psi f_0$ events, except for the IP χ^2 requirement. Monte Carlo
 96 simulation shows that the time resolution PDF is well modelled by these events. Fig. 5
 97 shows the t distribution for our $J/\psi \pi^+ \pi^-$ prompt 2011 data sample. To describe the
 98 background time distribution three components are needed, (i) prompt, (ii) a small long
 99 lived background ($f_{LL1} = 2.64 \pm 0.10$)% modeled by an exponential decay function, and

100 (iii) an even smaller component ($f_{LL2} = 0.46 \pm 0.02$)% from b -hadron decay described by
 101 an additional exponential. Each of these are convolved individually with a triple-Gaussian
 102 resolution function with common means, whose components are listed in Table 1. The
 103 overall equivalent time resolution is $\sigma_t = 38.4$ fs.

104 The functional form for the time dependence is given by

$$N(t) = (1 - f_{LL1} - f_{LL2}) \cdot 3G + f_{LL1} \left[\frac{1}{\tau_1} \exp(-t/\tau_1) \otimes 3G \right] + f_{LL2} \cdot [1/\tau_2 \cdot \exp(-t/\tau_2) \otimes 3G]. \quad (5)$$

105 The fractions f_{LL1} and f_{LL2} , and their respective lifetimes τ_1 and τ_2 , are varied in the
 106 fit. The parameters of the triple-Gaussian time resolution, $3G$, are listed in Table 1. The
 107 symbol \otimes indicates a convolution.

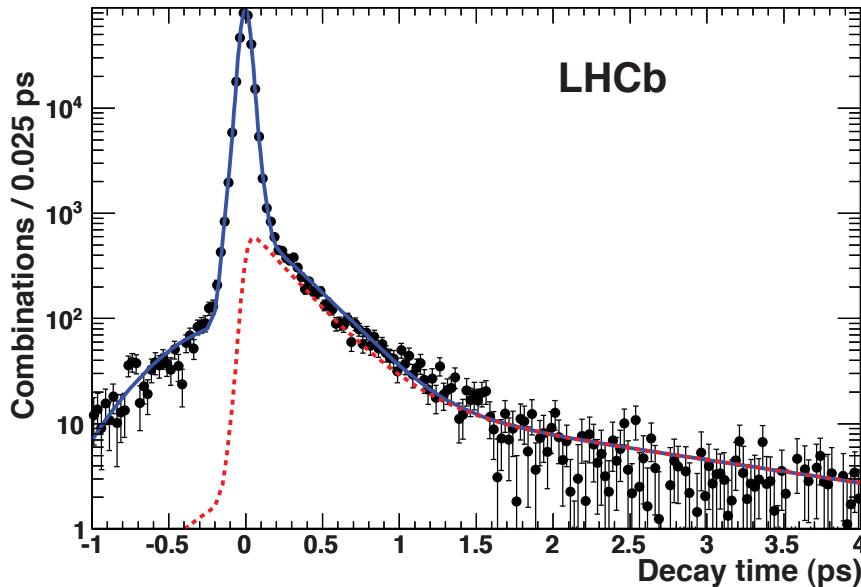


Figure 5: Decay time distribution for prompt $J/\psi\pi^+\pi^-$ events. The dashed line (red) shows the long lived components, while the solid line (blue) shows the total.

A decay time acceptance is introduced by the triggering and event selection requirements. Monte Carlo simulations show that the shape of the decay time acceptance function is well modelled by

$$A(t) = C \frac{[a(t - t_0)]^n}{1 + [a(t - t_0)]^n}, \quad (6)$$

108 where C is a normalization constant. Furthermore, the parameter values are found to be
 109 the same for simulated $\bar{B}^0 \rightarrow J/\psi \bar{K}^{*0}$ events with $\bar{K}^{*0} \rightarrow K^-\pi^+$, as for $\bar{B}_s^0 \rightarrow J/\psi f_0$.

110 Fig. 6(a) shows the $J/\psi \bar{K}^{*0}$ mass distribution in data with an additional requirement
 111 that the kaon candidate be positively identified in the RICH system, and that the $K^-\pi^+$
 112 invariant mass be within ± 100 MeV of 892 MeV. There are 36881 ± 208 signal events.

113 The sideband subtracted decay time distribution is shown in Fig. 6(b) and fit using the
 114 above defined acceptance function gives values of $a = (1.89 \pm 0.07) \text{ ps}^{-1}$, $n = 1.84 \pm 0.12$,
 115 $t_0 = (0.127 \pm 0.015) \text{ ps}$, and also a value of the \bar{B}^0 lifetime of $1.510 \pm 0.016 \text{ ps}$, where the
 116 error is statistical only. This is in good agreement with the PDG average of $1.519 \pm 0.007 \text{ ps}$
 [13].

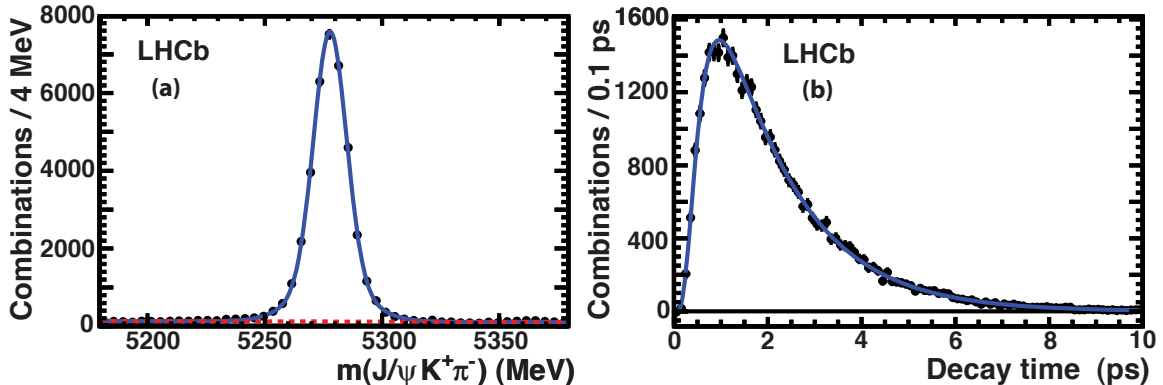


Figure 6: Distributions for $\bar{B}^0 \rightarrow J/\psi \bar{K}^{*0}$ events (a) \bar{B}^0 candidate mass distribution and (b) decay time distribution, where the small background has been subtracted using the \bar{B}^0 candidate mass sidebands.

117 Another check is provided by a recent CDF lifetime measurement of $\bar{B}_s^0 \rightarrow J/\psi f_0$
 118 $1.70_{-0.11}^{+0.12} \pm 0.03 \text{ ps}$ obtained by fitting the data to a single exponential [6]. Such a fit to
 119 our data yields $1.68 \pm 0.05 \text{ ps}$, where the uncertainty is only statistical.
 120

121 5 Fit strategy

122 5.1 Likelihood function characterization

The selected events are used to maximize a likelihood function

$$\mathcal{L} = \prod_i^N P(m_i, t_i, q_i), \quad (7)$$

123 where m_i is the reconstructed candidate \bar{B}_s^0 mass, t_i the decay time, and N the total
 124 number of events. The flavour tag, q_i , takes values of +1, -1 and 0, respectively, if the
 125 signal meson is tagged as B_s^0 , \bar{B}_s^0 , or untagged. The likelihood contains three components:
 126 signal, long-lived (LL) background and short-lived (SL) background.

127 For tagged events we have

$$P(m_i, t_i, q_i) = N_{\text{sig}} \epsilon_{\text{sig}}^{\text{tag}} P_m^{\text{sig}}(m_i) P_t^{\text{sig}}(t_i, q_i) + N_{\text{LL}} \epsilon_{\text{LL}}^{\text{tag}} P_m^{\text{bkg}}(m_i) P_t^{\text{LL}}(t_i) + N_{\text{SL}} \epsilon_{\text{SL}}^{\text{tag}} P_m^{\text{bkg}}(m_i) P_t^{\text{SL}}(t_i), \quad (8)$$

128 where: (i) $P_m^{\text{sig}}(m_i)$ and $P_m^{\text{bkg}}(m_i)$ are the PDFs describing the dependence on recon-
 129 structed mass m_i for signal and background events; (ii) $P_t^{\text{sig}}(t_i, q_i)$ is the PDF used to
 130 describe the signal decay rates for the decay time t_i ; (iii) $P_t^{\text{LL}}(t_i)$ is the PDF describing
 131 the long-lived background decay rates, and $P_t^{\text{SL}}(t_i)$ describes the short-lived background,
 132 both of which do not depend on the tagging; (iv) ϵ^{tag} refers to the respective tagging
 133 efficiencies for signal, long-lived and short-lived backgrounds.

134 For untagged events we have

$$P(m_i, t_i, 0) = N_{\text{sig}}(1 - \epsilon_{\text{sig}}^{\text{tag}})P_m^{\text{sig}}(m_i)P_t^{\text{sig}}(t_i, 0) + N_{\text{LL}}(1 - \epsilon_{\text{LL}}^{\text{tag}})P_m^{\text{bkg}}(m_i)P_t^{\text{LL}}(t_i) + N_{\text{SL}}(1 - \epsilon_{\text{SL}}^{\text{tag}})P_m^{\text{bkg}}(m_i)P_t^{\text{SL}}(t_i). \quad (9)$$

The total yields of the signal and background components are fixed to the number of events determined from the fit to the mass distributions (see Sec. 2). For both, the PDF is a product which models the invariant mass distribution and the time-dependent decay rates. The \bar{B}_s^0 mass spectrum is described by a double-Gaussian for the signal and an exponential function for the background (see Fig. 2). From Eqs. 1 and 2, the decay time function for the signal is

$$R(t, q_i) \propto e^{-\Gamma_s t} \left\{ \cosh \frac{\Delta\Gamma_s t}{2} + \cos \phi_s \sinh \frac{\Delta\Gamma_s t}{2} - q_i D \sin \phi_s \sin(\Delta m_s t) \right\}. \quad (10)$$

135 The probability of a wrong tag, ω , is included in the dilution factor $D \equiv (1 - 2\omega)$ (see
 136 Section 5.2).

137 The signal PDF is taken as a product of the decay time function, $R(t, q_i)$, convolved
 138 with the triple Gaussian time resolution function multiplied with the time acceptance
 139 function found from $J/\psi K^{*0}$ discussed in Section 4. The background decay time PDFs
 140 are determined using the like-sign $\pi^\pm \pi^\pm$ combinations. The time distribution of the like-
 141 sign background agrees in both yield and shape with the opposite-sign events in the upper
 142 \bar{B}_s^0 mass candidate sideband 50–200 MeV above the mass peak.

143 The background functions and parameters are listed in Table 1. The short-lived back-
 144 ground component results from combining prompt J/ψ events with a opposite-sign pion
 145 pair that is not rejected by our selection requirements. The long-lived part constitutes
 146 $\approx 85\%$ of the background.

Table 1: The PDFs for the invariant mass and proper time describing the signal and background. P_t^{sig} refers to the decay time distribution in Eq. 9 and A is given in Eq. 6. Where two numbers are listed, the first refers to the 2011 data and the second to the 2010 data. If only one number is listed they are the same for both years. The symbol \hat{t} refers to the true time.

P_m	P_t
Signal	
Double-Gaussian ($2G$) $2G(m; m_0, \sigma_1, \sigma_2, f_2)$	$P_t^{\text{sig}}(t, q) = R(\hat{t}, q) \otimes 3G(t - \hat{t}; \mu, \sigma_1^t, \sigma_2^t, \sigma_3^t, f_2^t, f_3^t)$ $\cdot A(t; a, n, t_0)$ $\mu = -0.0021(1) \text{ ps}, -0.0011(1) \text{ ps}$ $\sigma_1^t = 0.0300(4) \text{ ps}, 0.0295(5) \text{ ps}$ $\sigma_2^t/\sigma_1^t = 1.92(4), 1.88(3)$ $\sigma_3^t/\sigma_1^t = 14.6(10), 14.0(9)$ $f_2^t = 0.23(2), 0.27(3)$ $f_3^t = 0.0136(6), 0.0121(7)$ $a = 1.89(7) \text{ ps}^{-1}, n = 1.84(12), t_0 = 0.127(15) \text{ ps}$
Long-lived background	
Exponential	$[e^{-\hat{t}/\tau^{\text{bkg}}} \otimes 2G(t - \hat{t}; \mu, \sigma_1^t, \sigma_2^t, f_2^t)] \cdot A(t; a, n, t_0)$ $\mu = 0$ $\sigma_1^t = 0.088 \text{ ps}$ $\sigma_2^t = 5.94 \text{ ps}$ $f_2^t = 0.0137$ $\tau^{\text{bkg}} = 0.96 \text{ ps}$ $a = 4.44 \text{ ps}^{-1}, n = 4.56, t_0 = 0 \text{ ps}$
Short-lived background	
Exponential	$2G(t; \mu, \sigma_1^t, \sigma_2^t, f_2^t) \cdot A(t; a, n, t_0)$ All parameters are the same as for LL background

5.2 Flavour tagging

Flavour tagging uses decays of the other b hadron in the event, exploiting information from several sources including high transverse momentum muons, electrons and kaons, and the charge of inclusively reconstructed secondary vertices. The decisions of the four tagging algorithms are individually calibrated using $B^- \rightarrow J/\psi K^-$ decays and combined [14]. The effective tagging performance is characterized by $\epsilon_{\text{sig}}^{\text{tag}} D^2$, where $\epsilon_{\text{sig}}^{\text{tag}}$ is the efficiency and D the dilution. We use a per-candidate analysis that uses both the information of the tag decision and of the predicted mistag probability to classify and assign a weight to each event. The PDFs of the predicted mistag are taken from the side-bands for the background and side-band subtracted data for the signal.

The calibration procedure uses a linear dependence between the estimated per event mistag probability η and the actual mistag probability ω given by $\omega = p_0 + p_1 \cdot (\eta - \langle \eta \rangle)$, where p_0 and p_1 are calibration parameters and $\langle \eta \rangle$ is the average estimated mistag probability as determined from the calibration sample. In the 2011 data $p_0 = 0.384 \pm 0.003 \pm 0.009$, $p_1 = 1.037 \pm 0.040 \pm 0.070$, and $\langle \eta \rangle = 0.379$, with similar values in the 2010 sample. In this paper whenever two errors are given, the first is statistical and the second systematic. Systematic uncertainties are evaluated by using different channels to perform the calibration including $\bar{B}^0 \rightarrow D^{*+} \mu^- \bar{\nu}$, $B^+ \rightarrow J/\psi K^+$ separately from $B^- \rightarrow J/\psi K^-$, and viewing the dependence on different data taking periods. For our 2011 sample $\epsilon_{\text{sig}}^{\text{tag}}$ is $(25.6 \pm 1.3)\%$ providing us with 365 ± 22 tagged signal events. For signal the mean mistag fraction, $\langle \eta \rangle$, is 0.375 ± 0.005 , while for background the mean is 0.388 ± 0.006 . After subtracting background using like-sign events, we determine $D = 0.289$ leading to an ϵD^2 of 2.1% [14].

6 Results

Several parameters are input as Gaussian constraints in the fit. These include the LHCb measured value of $\Delta m_s = (17.63 \pm 0.11 \pm 0.02) \text{ ps}^{-1}$ [15], the tagging parameters p_0 and p_1 , and both the decay width given by the $J/\psi \phi$ analysis of $\Gamma_s = (0.657 \pm 0.009 \pm 0.008) \text{ ps}^{-1}$ and $\Delta \Gamma_s = (0.123 \pm 0.029 \pm 0.011) \text{ ps}^{-1}$ [16]; we also include the correlation of -0.30 between Γ_s and $\Delta \Gamma_s$. The fit has been validated both samples generated from PDFs and full Monte Carlo simulations.

Fig. 7 shows the difference of log-likelihood value compared to that at the point with the best fit, as a function of ϕ_s . At each ϕ_s value, the likelihood function is maximized with respect to all other parameters. The best fit value is $\phi_s = -0.44 \pm 0.44 \text{ rad}$. The projected decay time distribution is shown in Fig. 8.

7 Systematic uncertainties

The systematic errors are small compared to the statistical errors. No additional uncertainty is needed for errors on Δm_s , Γ_s , $\Delta \Gamma_s$ or flavour tagging, since Gaussian constraints

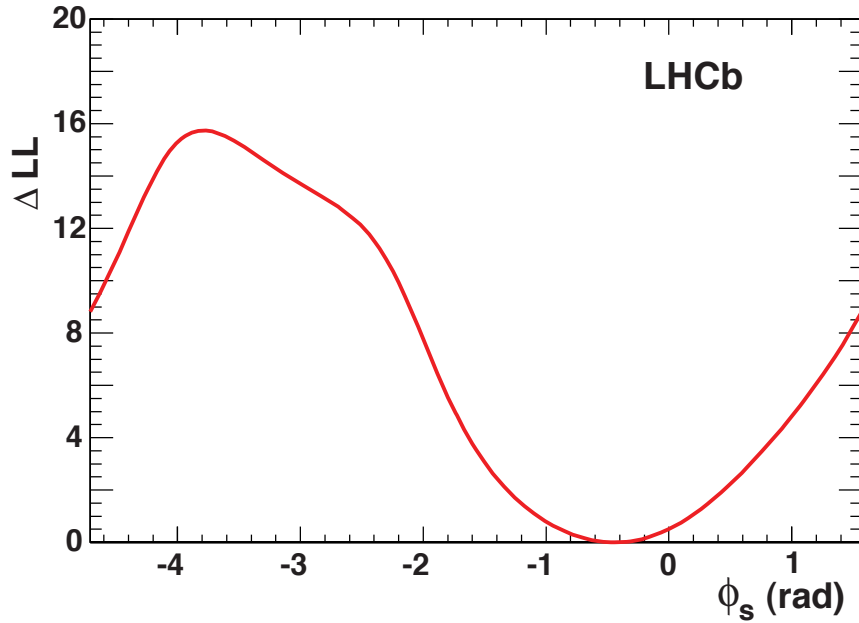


Figure 7: Log-likelihood profile of ϕ_s for $\bar{B}_s^0 \rightarrow J/\psi f_0$ events.

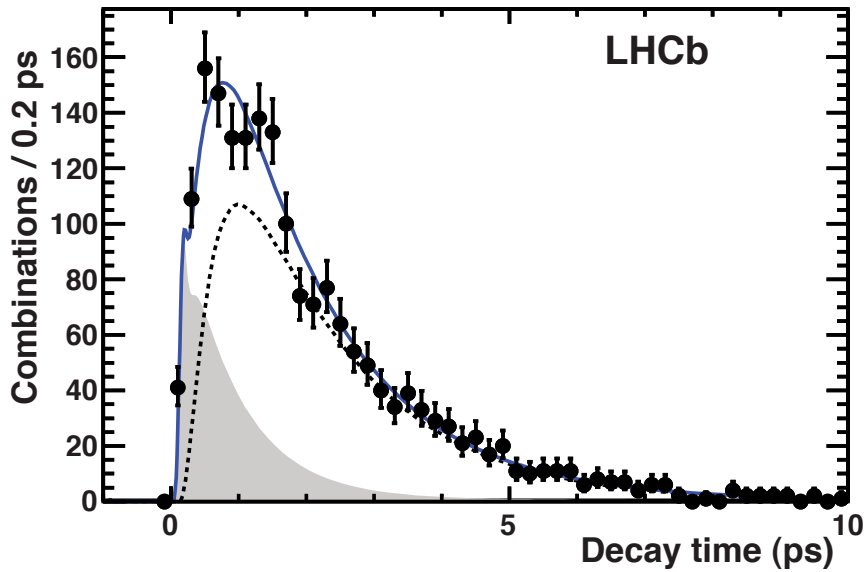


Figure 8: Decay time distribution from the fit for $J/\psi f_0$ candidates. The solid line shows the results of the fit, the dashed line shows the signal, and the shaded region the background.

184 are applied in the fit. Other uncertainties associated parameters fixed in the fit are
 185 evaluated by changing them by ± 1 standard deviation from their nominal values and
 186 determining the change in fit value of ϕ_s . These are listed in Table 2. An additional

187 uncertainty is included due to the possible CP even D-wave. This has been measured at
188 $(0.0_{-0.0}^{+1.7})\%$ of the S-wave and contributes a small error to ϕ_s , $+0.007$ rad, as determined by
189 repeating the fit with the mistag rate increased by 1.7%. The asymmetry in production
190 between B_s^0 and \bar{B}_s^0 is believed to be small, about 1%, and similar to the same asymmetry
191 in B^0 production which has been measured by LHCb to be about 1% [17]. The effect
192 of neglecting a 1% production asymmetry is the same as ignoring a 1% difference in the
mistag rate and causes negligible bias in ϕ_s .

Table 2: Summary of systematic uncertainties. Here N_{bkg} refers to the number of back-
ground events, N_{sig} the number of signal, $N_{\eta'}$ the number of η' , α the exponential back-
ground parameter for the \bar{B}_s^0 candidate mass, $N_{\text{LL}}/N_{\text{bkg}}$ the long-lived background frac-
tion. The Gaussian signal parameters are the mean m_0 , the width $\sigma(m)$; t_0 , a and n are
the three parameters in the acceptance time function. The final uncertainty is found by
adding all the sources in quadrature.

Quantity (Q)	$\pm\Delta Q$	+Change in ϕ_s	-Change in ϕ_s
N_{bkg}	10.1	0.0025	-0.0030
$N_{\eta'}$	3.4	-0.0001	-0.0001
N_{sig}	46.47	-0.0030	0.0028
α	$1.7 \cdot 10^{-4}$	-0.0002	-0.0002
$N_{\text{LL}}/N_{\text{bkg}}$	0.0238	0.0060	-0.0063
m_0 (MeV)	0.32	-0.0003	0.0011
$\sigma(m)$ (MeV)	0.31	-0.0026	0.0020
τ_{bkg} (ps)	0.05	-0.0075	0.0087
$\sigma(t)$ (ps)	5%	-0.0024	0.0022
t_0 (ps)	0.015	0.0060	0.0050
a (ps $^{-1}$)	0.07	-0.0065	-0.0065
n	0.12	-0.0089	-0.0089
CP -even D-wave		0.0070	0
Total Systematic Error		+0.018	-0.017

193

194 8 Conclusions

Using 0.41 fb^{-1} of data collected with the LHCb detector, the decay mode $\bar{B}_s^0 \rightarrow J/\psi f_0$,
 $f_0 \rightarrow \pi^+\pi^-$ is selected and then used to measure the CP violating phase, ϕ_s . We perform
a time dependent fit of the data with the \bar{B}_s^0 lifetime and the difference in widths of the
heavy and light eigenstates constrained. Based on the likelihood curve in Fig. 7 we find

$$\phi_s = -0.44 \pm 0.44 \pm 0.02 \text{ rad},$$

195 consistent with the SM value is $-0.0363_{-0.0015}^{+0.0016}$ rad [1]. Assuming the SM, the probability
196 to observe our measured value is 36%. There is an ambiguous solution with $\phi_s \rightarrow \pi - \phi_s$

197 and $\Delta\Gamma_s \rightarrow -\Delta\Gamma_s$.

LHCb provides an independent measurement of $\phi_s = 0.15 \pm 0.18 \pm 0.06$ [16] using the $\bar{B}_s^0 \rightarrow J/\psi\phi$ decay. Combining these two results, taking into account all correlations, we obtain

$$\phi_s = 0.07 \pm 0.17 \pm 0.06 \text{ rad (combined)}.$$

198 This is the most accurate determination of ϕ_s to date, and is consistent with the SM
199 prediction.

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