Measurement of the CP-violating phase $\phi_s$ in $B^{0}s \rightarrow D^+sD^−s$ decays

LHCb Collaboration; Bernet, R; Müller, K; Steinkamp, O; Straumann, U; Vollhardt, A; et al

Abstract: We present a measurement of the CP-violating weak mixing phase $\phi_s$ using the decay $B^{0}s \rightarrow D^+sD^−s$ in a data sample corresponding to 3.0 fb$^{-1}$ of integrated luminosity collected with the LHCb detector in pp collisions at centre-of-mass energies of 7 and 8 TeV. An analysis of the time evolution of the system, which does not constrain $|\phi_s|=1$ to allow for the presence of CP violation in decay, yields $\phi_s=0.02\pm0.17$ (stat) $\pm0.02$ (syst) rad, $|\phi_s|=0.91\pm0.18−0.15$ (stat) $\pm0.02$ (syst). This result is consistent with the Standard Model expectation.

DOI: https://doi.org/10.1103/PhysRevLett.113.211801

Posted at the Zurich Open Repository and Archive, University of Zurich
ZORA URL: https://doi.org/10.5167/uzh-108169
Accepted Version

Originally published at:
LHCb Collaboration; Bernet, R; Müller, K; Steinkamp, O; Straumann, U; Vollhardt, A; et al (2014). Measurement of the CP-violating phase $\phi_s$ in $B^{0}s \rightarrow D^+sD^−s$ decays. Physical Review Letters, 113(211801):online.
DOI: https://doi.org/10.1103/PhysRevLett.113.211801
Measurement of the $CP$-violating phase $\phi_s$ in $\bar{B}_s^0 \rightarrow D_s^+ D_s^-$ decays

The LHCb collaboration

Abstract

We present a measurement of the $CP$-violating weak mixing phase $\phi_s$ using the decay $\bar{B}_s^0 \rightarrow D_s^+ D_s^-$ in a data sample corresponding to 3.0 fb$^{-1}$ of integrated luminosity collected with the LHCb detector in $pp$ collisions at centre-of-mass energies of 7 and 8 TeV. An analysis of the time evolution of the system, which does not use the constraint $|\lambda| = 1$ to allow for the presence of $CP$ violation in decay, yields $\phi_s = 0.02 \pm 0.17$ (stat) $\pm 0.02$ (syst) rad, $|\lambda| = 0.91 \pm 0.18$ (stat) $\pm 0.02$ (syst). This result is consistent with the Standard Model expectation.
The $CP$-violating weak mixing phase $\phi_s$ can be measured in the interference between mixing and decay of $B^0_s$ mesons to $CP$ eigenstates that proceeds via the $b \to c\bar{c}s$ transition, and is predicted to be small in the Standard Model (SM): $\phi_s^{\text{SM}} \approx -2\beta_s = -2 \arg \left( \frac{V_{cs}V_{cb}^*}{V_{cs}V_{cb}} \right) \approx -36.3^{+1.6}_{-1.5} \text{ mrad}$ [1]. Measurements of $\phi_s$ are sensitive to the effects of potential non-SM particles contributing to the $B^0_s\bar{B}^0_s$ mixing amplitude. Several measurements of $\phi_s$ have been made with the decay mode $B^0_s \to J/\psi \phi$, with the first results showing tension with the SM expectation [2,3]. Since then, more recent measurements of $\phi_s$ have found values consistent with the SM prediction in $B^0_s \to J/\psi K^+ K^-$ and $B^0_s \to J/\psi \pi^+ \pi^-$ decays [4-8]. The world average value determined prior to the publication of Ref. [5] is $\phi_s = 0 \pm 70 \text{ mrad}$ [9].

Precise measurements of $\phi_s$ are complicated by the presence of loop (penguin) diagrams, which could have an appreciable effect [10]. It is therefore important to measure $\phi_s$ in additional decay modes where penguin amplitudes may differ [11]. Additionally, in the $B^0_s \to J/\psi \phi$ channel, where a spin-0 meson decays to two spin-1 mesons, an angular analysis is required to disentangle statistically the $CP$-even and $CP$-odd components. The decay $B^0_s \to D^+_sD^-_s$ is also a $b \to c\bar{c}s$ transition with which $\phi_s$ can be measured [12], with the advantage that the $D^+_sD^-_s$ final state is $CP$-even, and does not require angular analysis.

In this Letter, we present the first measurement of $\phi_s$ in $B^0_s \to D^+_sD^-_s$ decays using an integrated luminosity of 3.0 fb$^{-1}$, obtained from $pp$ collisions collected by the LHCb detector. One third of the data were collected at a centre-of-mass energy of 7 TeV, and the remainder at 8 TeV. We perform a fit to the time evolution of the $B^0_s\bar{B}^0_s$ system in order to extract $\phi_s$.

LHCb is a single-arm forward spectrometer at the LHC designed for the study of particles containing $b$ or $c$ quarks in the pseudorapidity range 2 to 5 [13]. Events are selected by a trigger consisting of a hardware stage that identifies high transverse energy particles, followed by a software stage, which applies a full event reconstruction [14]. A multivariate algorithm [15] is used to select candidates with secondary vertices consistent with the decay of a $b$ hadron.

Signal $B^0_s \to D^+_sD^-_s$ candidates are reconstructed in four final states: (i) $D^+_s \to K^+K^0\pi^+$, $D^-_s \to K^-K^0\pi^-$; (ii) $D^+_s \to K^+K^-\pi^+$, $D^-_s \to \pi^-\pi^+\pi^-$; (iii) $D^+_s \to K^+K^-\bar{\pi}^+$, $D^-_s \to K^-\pi^+\pi^-$; and (iv) $D^+_s \to \pi^+\pi^-\pi^+$, $D^-_s \to \pi^-\pi^+\pi^-$. Inclusion of charge-conjugate processes, unless otherwise specified, is implicit. The $B^0 \to D^-D^+_s$ decay mode, where $D^- \to K^-\pi^-\pi^-$, and $D^+_s \to K^+K^-\bar{\pi}^+$, is used as a control channel. The selection requirements follow Ref. [16], apart from minor differences in the particle identification requirements and $B_s$ candidate mass regions. $D_s$ meson candidates are required to have masses within 25 MeV/$c^2$ of their known values [17] and to have a significant separation from the $B_s$ vertex. As the signatures of $b$-hadron decays to double-charm final states are all similar, vetoes are employed to suppress the cross-feed resulting from particle misidentification, following Ref. [18]. All $B_s$ candidates are refitted, taking both $D_s$ mass and vertex constraints into account [19]. A boosted decision tree (BDT) [20,21] is used to improve the signal to background ratio. The BDT is trained with simulated decays to emulate the signal, and same-charge $D^+_sD^+_s$ and $D^+_sD^-_s$ from candidates with masses on the range
The negative log likelihood to be minimised is

\[- \ln \mathcal{L} = -\alpha \sum_{i} W_i \ln \mathcal{P}(t_i, \delta_i, \theta_i^{\text{tag}}|\theta_i^{\text{tag}}),\]  

(1)

Figure 1: Invariant mass distributions of (a) \( \bar{B}^0 \rightarrow D_s^+ D_s^- \) and (b) \( B^0 \rightarrow D^- D_s^+ \) candidates. The points show the data; the individual fit components are indicated in the legend; the black curve shows the overall fit.

5200 < \( M(D_s^+ D_s^-) \) < 5650 MeV/c\(^2\) and 5200 < \( M(D^+ D_s^-) \) < 5600 MeV/c\(^2\), respectively. The selection requirement on the BDT output, which retains about 98% of the signal events, is chosen to minimise the expected relative uncertainty in the \( \bar{B}^0 \rightarrow D_s^+ D_s^- \) yield. The \( B_s(s) \) candidates are required to lie in the mass regions 5300 < \( M(D^+_s D^-) \) < 5450 MeV/c\(^2\) for the signal and 5200 < \( M(D^- D_s^+) \) < 5450 MeV/c\(^2\) for the control channel, where the lower bound is chosen to suppress background contributions from \( B_s(s) \) decays with excited charm mesons in the final state. The decay time distribution is fitted in the range 0.2 < \( t < 12.0 \) ps where the lower bound is chosen to reduce backgrounds from particles originating from the primary vertex.

The mass distributions for the signal, summed over the four final states, and the control channel are shown in Fig. 1 with results of unbinned maximum likelihood fits overlaid. The signal shapes are parameterised by the sum of two asymmetric Gaussian functions with a common mean. The background shapes are obtained from simulation [22–25]. Background rates from misidentified particles are obtained from \( D^{\ast+} \rightarrow D^0 \pi^+ \), \( D^0 \rightarrow K^- \pi^+ \) calibration data. Signal and background components are described in Ref. [16]. All yields in the fits to the full data sample are allowed to vary, except that corresponding to \( \bar{B}_s(s) \rightarrow D_s^+ K^- K^+ \pi^- \) decays, which is fixed to be 1% of the signal yield as determined from a fit to the \( D_s \) mass sidebands. We observe 3345 ± 62 \( \bar{B}_s(s) \rightarrow D_s^+ D_s^- \) signal and 21320 ± 148 \( B^0 \rightarrow D^- D_s^+ \) control channel decays. In the \( D^- D_s^+ \) channel, we also observe a contribution from \( \bar{B}_s(s) \rightarrow D_s^+ D^- \) as reported previously [18]. We use the sPlot technique [26] to obtain the decay time distribution of \( \bar{B}_s(s) \rightarrow D_s^+ D_s^- \) signal decays where the \( D_s^+ D_s^- \) invariant mass is the discriminating variable. A fit to the background-subtracted distribution of the decay time, \( t \), is performed using the signal-only decay time probability density function (PDF).
where $N$ denotes the total number of signal and background candidates in the fit region, $W_i$ is the signal component weight and $\alpha = \sum_i^N W_i/\sum_i^N W_i^2$ [27]. The invariant mass is not correlated with the reconstructed decay time or its uncertainty, nor with flavour tagging output, for signal and background. The signal PDF, $P$, includes detector resolution and acceptance effects and requires knowledge of the $B^0_s(\bar{B}^0_s)$ flavour at production,

$$P(t, \delta; q^{\text{tag}}|\eta^{\text{tag}}) = R(\hat{t}, q^{\text{tag}}|\eta^{\text{tag}}) \otimes G(t - \hat{t}|\delta) \times e^{D^+_{\text{data}}D^-}(t),$$

where $\hat{t}$ is the decay time in the absence of resolution effects, $R(\hat{t}, q^{\text{tag}}|\eta^{\text{tag}})$ describes the rate including imperfect knowledge of the initial $\bar{B}^0_s$ flavour through the flavour tag, $q^{\text{tag}}$, and the wrong-tag probability estimate $\eta^{\text{tag}}$. The flavour tag, $q^{\text{tag}}$, is $-1$ for $\bar{B}^0_s$, $+1$ for $B^0_s$ and zero for untagged candidates. The calibrated decay time resolution is $G(t - \hat{t}|\delta)$ where $\delta$ is the decay time error estimate, and $D^+_{\text{data}}(t)$ is the decay time acceptance.

Allowing for $CP$ violation in decay, the decay rates of $\bar{B}^0_s$ mesons ignoring detector effects can be written as

$$\Gamma(\hat{t}) = \mathcal{N}e^{-\Gamma\hat{t}}\left[\cosh\left(\frac{\Delta \Gamma_s^L}{2}\hat{t}\right) - \frac{2|\lambda|\cos \phi_s}{1 + |\lambda|^2}\sinh\left(\frac{\Delta \Gamma_s^L}{2}\hat{t}\right)
 + \frac{1 - |\lambda|^2}{1 + |\lambda|^2}\cos(\Delta m_s\hat{t}) - \frac{2|\lambda|\sin \phi_s}{1 + |\lambda|^2}\sin(\Delta m_s\hat{t})\right],$$

$$\bar{\Gamma}(\hat{t}) = \left|\frac{p}{q}\right|^2\mathcal{N}e^{-\bar{\Gamma}\hat{t}}\left[\cosh\left(\frac{\Delta \Gamma_s^L}{2}\hat{t}\right) - \frac{2|\lambda|\cos \phi_s}{1 + |\lambda|^2}\sinh\left(\frac{\Delta \Gamma_s^L}{2}\hat{t}\right)
 - \frac{1 - |\lambda|^2}{1 + |\lambda|^2}\cos(\Delta m_s\hat{t}) + \frac{2|\lambda|\sin \phi_s}{1 + |\lambda|^2}\sin(\Delta m_s\hat{t})\right],$$

where $\Gamma_s \equiv (\Gamma_L + \Gamma_H)/2$ is the average decay width of the light and heavy mass eigenstates, $\Delta \Gamma_s \equiv \Gamma_L - \Gamma_H$ is their decay width difference and $\Delta m_s \equiv m_H - m_L$ is their mass difference. As $\Delta m_s$ is large [28] and the production asymmetry is negligible and so the constant $\mathcal{N}$ is the same for both $B^0_s$ and $\bar{B}^0_s$ mesons. Similarly we do not consider a tagging asymmetry in the fit as this is known to be consistent with zero. $CP$ violation in mixing and decay is parameterised by the factor $\lambda \equiv \frac{A_f}{A_s}$, with $\phi_s \equiv -\arg(\lambda)$. The terms $A_f$ ($\bar{A}_s$) are the amplitudes for the $B^0_s(\bar{B}^0_s)$ decay to the final state $f$, which in this case is $f = D^+_sD^-_s$, and the complex parameters $p = \langle B^0_s|B_L \rangle$ and $q = \langle \bar{B}^0_s|\bar{B}_L \rangle$ relate the mass and flavour eigenstates. The factor $|p/q|^2$ in Eq. (4) is related to the flavour-specific $CP$ asymmetry, $a^s_{\text{sl}}$, by

$$a^s_{\text{sl}} = \frac{|p/q|^2 - |q/p|^2}{|p/q|^2 + |q/p|^2} = |p/q|^2 - 1.$$ 

LHCb has measured $a^s_{\text{sl}} = (-0.06 \pm 0.50 \text{(stat)} \pm 0.36 \text{(syst)})\%$ [30], implying $|p/q|^2 = 0.9994 \pm 0.0062$. We assume that it is unity in this analysis and that any observed deviation of $|\lambda|$ from 1 is due to $CP$ violation in the decay, i.e. $|\bar{A}_f/A_f| \neq 1$.

The initial flavor of the signal b hadron is determined using two methods. In hadron collisions, b hadrons are mostly produced as pairs: the opposite-side (OS) tagger [31].
determines the flavour of the other $b$ hadron in the event by identifying the charges of the leptons and kaons into which it decays, or the net charge of particles forming a detached vertex consistent with that of a $b$ hadron. The neural network same-side (SS) kaon tagger [4] exploits the hadronisation process in which the fragmentation of a $\bar{b}(b)$ into a $B_0^s(B_0^s)$ meson leads to an extra $\bar{s}(s)$ quark, which often forms a $K^+(K^-)$ meson, the charge of which identifies the initial $B_0^s$ flavour. The SS kaon tagger uses an improved algorithm with respect to Ref. [4] that enhances the fraction of correctly tagged mesons by 40%. In both tagging algorithms a per-event wrong-tag probability estimate, $\eta_{\text{tag}}$, is determined, based on the output of a neural network trained on either simulated $B_s^0 \to D_s^+\pi^-\pi^+$ events for the SS tagger, or, in the case of the OS algorithm, using a data sample of $B^- \to J/\psi K^-$ decays. The taggers are then calibrated in data using flavour-specific decay modes in order to provide a per-event wrong-tag probability, $\bar{\omega}(\eta_{\text{tag}})$, for an initial flavour $B_0^s$ meson. The calibration is performed separately for the two tagging algorithms, which are then combined in the fit. The effective tagging power is parameterised by $\varepsilon_{\text{tag}}D^2$ where $D \equiv (1 - 2\omega)$ and $\varepsilon_{\text{tag}}$ is the fraction events tagged by the algorithm.

The combined effective tagging power is $\varepsilon_{\text{tag}}D^2 = (5.33 \pm 0.18 \text{ (stat)} \pm 0.17 \text{ (syst)})\%$, comparable to that of other recent analyses [32]. The rate expression including flavour tagging is

$$R(\hat{t}, q^{\text{OS}}|\eta^{\text{OS}}, q^{\text{SS}}|\eta^{\text{SS}}) = (1 + q^{\text{OS}}[1 - 2\omega^{\text{OS}}])(1 + q^{\text{SS}}[1 - 2\omega^{\text{SS}}])\Gamma(\hat{t}) + (1 - q^{\text{OS}}[1 - 2\omega^{\text{OS}}])(1 - q^{\text{SS}}[1 - 2\omega^{\text{SS}}])\bar{\Gamma}(\hat{t}). \quad (6)$$

The track reconstruction, trigger and selection efficiencies vary as a function of decay time, requiring that an acceptance function is included in the fit. The $B_s^0 \to D_s^+D_s^-$
Two fits to the data are performed, one assuming no CP violation in decay, \( |\lambda| = 1 \), and a second where this assumption is removed. The fit is validated using pseudoexperiments and simulated LHCb events.
Figure 3: Distribution of the decay time for $B^0_s \rightarrow D_s^+ D_s^-$ signal decays with background subtracted using the sPlot method, along with the fit as described in the text. Discontinuities in the fit line shape are a result of the binned acceptance.

Table 1: Summary of systematic uncertainties not already accounted for in the fit, where $\sigma$ denotes the statistical uncertainty.

| Systematic uncertainty            | $\phi_s$ (|$\lambda$| = 1) | $\phi_s$ | $\lambda$ |
|-----------------------------------|----------------|----------|-----------|
| Resolution                        | $\pm 0.098 \sigma$ | $\pm 0.094 \sigma$ | $\pm 0.100 \sigma$ |
| Mass                              | $\pm 0.044 \sigma$ | $\pm 0.043 \sigma$ | $\pm 0.010 \sigma$ |
| Acceptance (model)                | $\pm 0.022 \sigma$ | $\pm 0.027 \sigma$ | $\pm 0.027 \sigma$ |
| Acceptance (stat.)                | $\pm 0.013 \sigma$ | $\pm 0.013 \sigma$ | $\pm 0.014 \sigma$ |
| Background subtraction            | $\pm 0.009 \sigma$ | $\pm 0.008 \sigma$ | $\pm 0.046 \sigma$ |
| Total                             | $\pm 0.11 \sigma$ | $\pm 0.11 \sigma$ | $\pm 0.11 \sigma$ |

The systematic uncertainties on $\phi_s$ and $|\lambda|$ that are not accounted for by the use of Gaussian constraints are summarised in Table 1. The systematic uncertainty associated with the resolution calibration in simulated events is studied by generating pseudoexperiments with an alternative resolution parameterisation ($q_0 = 0$, $q_1 \in [1.25, 1.45]$) obtained in $B^0_s$ decays in data. The effect of mismodelling of the mass PDF is studied by fitting using a larger mass window and including an additional background component from $B^0_s \rightarrow D_s^+ D_s^-$. The effect of mismodelling the acceptance distribution is studied by fitting the $B^0_s \rightarrow D_s^+ D_s^-$ derived acceptance in pseudoexperiments generated with the acceptance distribution determined entirely from $B^0_s \rightarrow D_s^+ D_s^-$ simulation. The uncertainty due to the finite size of the simulated data samples used to determine the acceptance correction is evaluated by fitting to the data 500 times with Gaussian fluctuations around the bin values with a width equal to the statistical uncertainties. We evaluate the uncertainty due
to the use of the sPlot method for background subtraction by fitting to simulated events, once with only signal candidates, and again to the sPlot determined from a mass fit to a sample containing the signal and background in proportions determined from data.

Assuming no CP violation in decay, we find

$$\phi_s = 0.02 \pm 0.17 \text{ (stat)} \pm 0.02 \text{ (syst) \ rad},$$

where the first uncertainty is statistical and the second is systematic. In a fit to the same data in which we allow for the presence of CP violation in decay we find

$$\phi_s = 0.02 \pm 0.17 \text{ (stat)} \pm 0.02 \text{ (syst) \ rad}, \quad |\lambda| = 0.91^{+0.18}_{-0.15} \text{ (stat)} \pm 0.02 \text{ (syst)},$$

where $\phi_s$ and $|\lambda|$ have a correlation coefficient of 3%. This measurement is consistent with no CP violation. The decay time distribution and the corresponding fit projection for the case where CP violation in decay is allowed are shown in Fig. 3.

In conclusion, we present the first analysis of the time evolution of flavour-tagged $B_s^0 \to D_s^+D_s^-$ decays. We measure the CP-violating weak phase $\phi_s$, allowing for the presence of CP violation in decay, and find that it is consistent with the Standard Model expectation and with measurements of $\phi_s$ in other decay modes.

**Acknowledgements**

We express our gratitude to our colleagues in the CERN accelerator departments for the excellent performance of the LHC. We thank the technical and administrative staff at the LHCb institutes. We acknowledge support from CERN and from the national agencies: CAPES, CNPq, FAPERJ and FINEP (Brazil); NSFC (China); CNRS/IN2P3 (France); BMBF, DFG, HGF and MPG (Germany); SFI (Ireland); INFN (Italy); FOM and NWO (The Netherlands); MNiSW and NCN (Poland); MEN/IFA (Romania); MinES and FANO (Russia); MinECo (Spain); SNSF and SER (Switzerland); NASU (Ukraine); STFC (United Kingdom); NSF (USA). The Tier1 computing centres are supported by IN2P3 (France), KIT and BMBF (Germany), INFN (Italy), NWO and SURF (The Netherlands), PIC (Spain), GridPP (United Kingdom). We are indebted to the communities behind the multiple open source software packages on which we depend. We are also thankful for the computing resources and the access to software R&D tools provided by Yandex LLC (Russia). Individual groups or members have received support from EPLANET, Marie Skłodowska-Curie Actions and ERC (European Union), Conseil général de Haute-Savoie, Labex ENIGMASS and OCEVU, Région Auvergne (France), RFBR (Russia), XuntaGal and GENCAT (Spain), Royal Society and Royal Commission for the Exhibition of 1851 (United Kingdom).
References


[6] D0 Collaboration, V. M. Abazov et al., Measurement of the $CP$-violating phase $\phi_{J/\psi \phi}^{B_0}$ using the flavor-tagged decay $B_0 \to J/\psi \phi$ in 8 fb$^{-1}$ of $p\bar{p}$ collisions, Phys. Rev. D85 (2012) 032006, arXiv:1109.3166.


[16] LHCb collaboration, R. Aaij et al., Measurement of the $\bar{B}_s^0 \to D^-D^+$ and $\bar{B}_s^0 \to D^+D^-$ effective lifetimes, Phys. Rev. Lett. 112 (2014) 111802, arXiv:1312.1217.


[18] LHCb collaboration, R. Aaij et al., First observations of $\bar{B}_s^0 \to D^+D^-$, $D^+D^-$ and $D^0\bar{D}^0$ decays, Phys. Rev. D87 (2013) 092007, arXiv:1302.5854.


[29] LHCb collaboration, R. Aaij et al., Measurement of the $\bar{B}^0 - B^0$ and $\bar{B}_s^0 - B_s^0$ production asymmetries in pp collisions at $\sqrt{s} = 7$ TeV, arXiv:1408.0275, submitted to Phys. Lett. B.


[32] LHCb collaboration, R. Aaij et al., Measurement of CP asymmetry in $B_s^0 \rightarrow D_s^\mp K^\pm$ decays, arXiv:1407.6127, submitted to JHEP.
LHCb collaboration

Università di Cagliari, Cagliari, Italy
Università di Ferrara, Ferrara, Italy
Università di Firenze, Firenze, Italy
Università di Urbino, Urbino, Italy
Università di Modena e Reggio Emilia, Modena, Italy
Università di Genova, Genova, Italy
Università di Milano Bicocca, Milano, Italy
Università di Roma Tor Vergata, Roma, Italy
Università di Roma La Sapienza, Roma, Italy
Università della Basilicata, Potenza, Italy
AGH - University of Science and Technology, Faculty of Computer Science, Electronics and Telecommunications, Kraków, Poland
LIFAELS, La Salle, Universitat Ramon Llull, Barcelona, Spain
Hanoi University of Science, Hanoi, Viet Nam
Università di Padova, Padova, Italy
Università di Pisa, Pisa, Italy
Scuola Normale Superiore, Pisa, Italy
Università degli Studi di Milano, Milano, Italy
Politecnico di Milano, Milano, Italy