



# Observation of $B_s^0 \rightarrow \bar{D}^0 K_S^0$ and evidence for $B_s^0 \rightarrow \bar{D}^{*0} K_S^0$ decays

The LHCb collaboration<sup>†</sup>

## Abstract

The first observation of the  $B_s^0 \rightarrow \bar{D}^0 K_S^0$  decay mode and evidence for the  $B_s^0 \rightarrow \bar{D}^{*0} K_S^0$  decay mode are reported. The data sample corresponds to an integrated luminosity of  $3.0 \text{ fb}^{-1}$  collected in  $pp$  collisions by LHCb at center-of-mass energies of 7 and 8 TeV. The branching fractions are measured to be

$$\begin{aligned} \mathcal{B}(B_s^0 \rightarrow \bar{D}^0 \bar{K}^0) &= (4.3 \pm 0.5 \text{ (stat)} \pm 0.3 \text{ (syst)} \pm 0.3 \text{ (frag)} \pm 0.6 \text{ (norm)}) \times 10^{-4}, \\ \mathcal{B}(B_s^0 \rightarrow \bar{D}^{*0} \bar{K}^0) &= (2.8 \pm 1.0 \text{ (stat)} \pm 0.3 \text{ (syst)} \pm 0.2 \text{ (frag)} \pm 0.4 \text{ (norm)}) \times 10^{-4}, \end{aligned}$$

where the uncertainties are due to contributions coming from statistical precision, systematic effects, and the precision of two external inputs, the ratio  $f_s/f_d$  and the branching fraction of  $B^0 \rightarrow \bar{D}^0 K_S^0$ , which is used as a calibration channel.

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The study of  $CP$  violation is one of the most important topics in flavor physics. In  $B^0$  decays, the phenomenon of  $CP$  violation has been extensively studied at BaBar, Belle and LHCb, which confirmed many predictions of the Standard Model (SM) [1–4]. Nowadays, the focus is on the search for Beyond the Standard Model (BSM) effects by improving the statistical precision of the  $CP$  violation parameters and looking for deviations from the SM predictions.

In the SM, violation of  $CP$  symmetry in  $B$  decays is commonly parameterized by three phase angles ( $\alpha$ ,  $\beta$ ,  $\gamma$ ) derived from the Cabibbo-Kobayashi-Maskawa matrix, which describes the charged-current interactions among quarks [5]. Since the angles sum up to  $180^\circ$ , any deviation found in measurements of the phases would be a sign of BSM physics affecting at least one of the results. Currently the angle  $\gamma$  is only known with an uncertainty of about  $10^\circ$  [6]; experimental efforts are required to improve its precision and thus the sensitivity to BSM effects. Another sensitive observable is the  $B_s^0$  mixing phase,  $\phi_s$ , which in the SM is predicted with good precision to be close to zero [7]. Any significant deviation here would also reveal physics BSM [8,9]. The current uncertainty is  $\mathcal{O}(0.1)$  rad [6].

In this Letter, two decay modes that can improve the knowledge of  $\gamma$  and  $\phi_s$  are studied. The  $B^0 \rightarrow \bar{D}^0 K_s^0$  decay<sup>1</sup> offers a determination of the angle  $\gamma$  with small theoretical uncertainties [10], while  $B_s^0 \rightarrow \bar{D}^{(*)0} K_s^0$ , similar to the  $B_s^0 \rightarrow \bar{D}^{(*)0} \phi$  [11] mode, provides sensitivity to  $\phi_s$  with a theoretical accuracy of  $\mathcal{O}(0.01)$  rad [?].

While the decay  $B^0 \rightarrow \bar{D}^{(*)0} K_s^0$  has been seen at the  $B$  factories [12],  $B_s^0 \rightarrow \bar{D}^{(*)0} K_s^0$  decays have not previously been observed. Theoretical predictions of their branching fractions are of the order of  $5 \times 10^{-4}$  [13–15]. This Letter reports the first observation of  $B_s^0 \rightarrow \bar{D}^0 K_s^0$  and evidence for  $B_s^0 \rightarrow \bar{D}^{*0} K_s^0$  decays, and provides measurements of branching fractions of these channels normalized to  $B^0 \rightarrow \bar{D}^0 K_s^0$  decays.

The analysis is based on data collected in  $pp$  collisions by the LHCb experiment at  $\sqrt{s} = 7$  TeV and 8 TeV corresponding to an integrated luminosity of  $3.0 \text{ fb}^{-1}$ . The LHCb detector [16,17] is a single-arm forward spectrometer covering the pseudorapidity range  $2 < \eta < 5$ , designed for the study of particles containing  $b$  or  $c$  quarks. The detector includes a high-precision tracking system consisting of a silicon-strip vertex detector surrounding the  $pp$  interaction region, a large-area silicon-strip detector located upstream of a dipole magnet with a bending power of about 4 Tm, and three stations of silicon-strip detectors and straw drift tubes placed downstream of the magnet. The tracking system provides a measurement of momentum,  $p$ , of charged particles with a relative uncertainty that varies from 0.5% at low momentum to 1.0% at 200 GeV/ $c$ . Two ring-imaging Cherenkov (RICH) detectors are able to discriminate between different species of charged hadrons. The online event selection is performed by a trigger, which consists of a hardware stage, based on information from the calorimeter and muon systems, followed by a software stage, which applies a full event reconstruction.

In the simulation,  $pp$  collisions are generated using PYTHIA [18] with a specific LHCb configuration [19]. Decays of hadronic particles are described by EVTGEN [20], in which

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<sup>1</sup>Unless otherwise specified, the inclusion of charge conjugate reactions is implied.

final-state radiation is generated using PHOTOS [21]. The interaction of the generated particles with the detector, and its response, are implemented using the GEANT4 toolkit [22] as described in Ref. [23].

At the hardware trigger stage, events are required to have a muon with high  $p_T$  or a hadron, photon or electron with high transverse energy deposited in the calorimeters. The software trigger requires a two-, three- or four-track secondary vertex with a significant displacement from any reconstructed primary vertex (PV). At least one of these tracks must have  $p_T > 1.7 \text{ GeV}/c$  and be inconsistent with originating from a PV. A multivariate algorithm [24] is used to identify secondary vertices consistent with the decay of a  $b$  hadron.

Candidate  $K_s^0 \rightarrow \pi^+\pi^-$  decays are reconstructed in two different categories: the first involving  $K_s^0$  mesons that decay early enough for the daughter pions to be reconstructed in the vertex detector, referred to as *long*; and the second containing  $K_s^0$  that decay later such that track segments of the pions cannot be formed in the vertex detector, referred to as *downstream*. The long category has better mass, momentum and vertex resolution than the downstream category. Long (downstream)  $K_s^0$  candidates are required to have decay lengths larger than 12 (9) times the decay length uncertainty. The invariant mass of the candidate is required to be within  $30 \text{ MeV}/c^2$  of the known  $K_s^0$  mass [25].

The  $\bar{D}^0 \rightarrow K^+\pi^-$  candidates are formed from combinations of kaon and pion candidate tracks identified by the RICH detectors. The pion (kaon) must have  $p > 1$  (5)  $\text{GeV}/c$  and  $p_T > 100$  (500)  $\text{MeV}/c$ , and be inconsistent with originating from a PV. The invariant mass of the candidate is required to be within  $50 \text{ MeV}/c^2$  of the known  $\bar{D}^0$  mass [25].

The  $B$  ( $B^0$  or  $B_s^0$ ) candidate is formed by combining  $\bar{D}^0$  and  $K_s^0$  candidates and requiring an invariant mass in the range  $4500\text{--}7000 \text{ MeV}/c^2$ , a decay time greater than  $0.2 \text{ ps}$  and a momentum vector pointing back to the associated PV. To improve the mass resolution of the  $B$  candidates, a kinematic fit is performed constraining the masses of the  $\bar{D}^0$  and  $K_s^0$  candidates to the known values [25].

The purity of the  $B$  candidate sample is then increased by means of a multivariate classifier [26, 27] that separates signal from combinatorial background. Separate algorithms are trained for candidates with long and downstream  $K_s^0$  candidates. The discriminating variables used in the classifier are the  $\chi^2$  of the kinematic fit, geometric variables related to the finite lifetime of the  $B$ ,  $\bar{D}^0$  and  $K_s^0$ , the decay time,  $p_T$  and  $p$  of the  $K_s^0$  candidate. The multivariate classifier is trained and tested using signal candidates from simulations and background candidates from data in the upper sideband of the  $B$  mass spectrum, corresponding to  $m(\bar{D}^0 K_s^0) > 5500 \text{ MeV}/c^2$ , where no backgrounds are expected from  $B$  decays in which a photon or a  $\pi$  meson is not reconstructed. The selection is optimized to minimize the statistical uncertainty on the ratio of  $B_s^0$  over  $B^0$  signal event yields. The signal efficiency and background rejection factors are 76% and 98%, respectively.  $B$  candidates in the mass range  $5000\text{--}5900 \text{ MeV}/c^2$  are retained. Multiple candidates occur in 0.2% (0.4%) of long (downstream)  $K_s^0$  events in which case one candidate, chosen at random, is kept.

The  $B_s^0$  and  $B^0$  signal yields in the selected sample are obtained from an unbinned extended maximum likelihood fit simultaneously performed on the long and downstream  $K_s^0$  samples. The observables used in the fit are  $m_{K_s^0}$ , the mass of the  $K_s^0 \rightarrow \pi^+\pi^-$

candidates,  $m_{\bar{D}^0}$ , the mass of the  $\bar{D}^0 \rightarrow K^+\pi^-$  candidates, and  $m_B$ , the mass of the  $B$  meson candidates. The probability density function (PDF) contains four terms

$$\mathcal{P}(m_{\bar{D}^0}, m_{K_s^0}, m_B) = \sum_{i=1}^4 N_i \cdot \mathcal{F}_i(m_{\bar{D}^0}, m_{K_s^0}, m_B) = \sum_{i=1}^4 N_i \cdot \mathcal{P}_i(m_B) \cdot \mathcal{S}_i(m_{\bar{D}^0}, m_{K_s^0}) \quad (1)$$

where  $N_i$  represents the respective yield,  $\mathcal{P}_i$  parametrizes the mass distribution of the  $B$  meson candidates and  $\mathcal{S}_i$  is the joint PDF of the candidates for its decay products. The term  $\mathcal{F}_1$  describes correctly reconstructed  $\bar{D}^0$  and  $K_s^0$  candidates,  $\mathcal{F}_2$  a correctly reconstructed  $\bar{D}^0$  meson in association with two random pions,  $\mathcal{F}_3$  a correctly reconstructed  $K_s^0$  meson in association with a random kaon and pion, and  $\mathcal{F}_4$  random combinations of the four final state particles. Johnson SU distributions [28], characterized by asymmetric tails to account for radiative losses and vertex reconstruction uncertainties, are used to parametrize the  $\bar{D}^0$  and  $K_s^0$  signals in  $\mathcal{S}_{1,2,3}$  and exponential functions describe the backgrounds in  $\mathcal{S}_{2,3,4}$ .

The  $B$  mass in candidates with correctly reconstructed  $\bar{D}^0$  and  $K_s^0$  mesons ( $\mathcal{P}_1$ ) is described by three categories of shapes:  $B_{(s)}^0 \rightarrow \bar{D}^0 K_s^0$  signal, peaking structures at lower mass from other  $B$  decays and combinatorial background. Signal shapes for the  $B^0$  and  $B_s^0$  candidates decaying to  $\bar{D}^0 K_s^0$  are described by means of Johnson SU distributions with shape parameters determined from fits to the simulated signal samples, corrected for differences between the simulation and data. The peaking structures at lower mass correspond to decays of  $B^0$  and  $B_s^0$  mesons that include  $\bar{D}^0$  and  $K_s^0$  mesons in the final state where a photon or a  $\pi$  meson is not reconstructed, such as  $B_{(s)}^0 \rightarrow \bar{D}^{*0}(\bar{D}^0\pi^0)K_s^0$ ,  $B_{(s)}^0 \rightarrow \bar{D}^{*0}(\bar{D}^0\gamma)K_s^0$ ,  $B^+ \rightarrow \bar{D}^0 K^{*+}(K_s^0\pi^+)$ , and  $B_{(s)}^0 \rightarrow \bar{D}^0 K^{*0}(K_s^0\pi^0)$ . These shapes are described with kernel estimated PDFs [29] obtained from simulation.

The same exponential function is used for the combinatorial background description of the  $B$  mass distribution in  $\mathcal{P}_{1,2,3,4}$ . Possible contaminations from  $B_{(s)}^0 \rightarrow \bar{D}^0\pi^+\pi^-$  and  $B_{(s)}^0 \rightarrow \bar{D}^{*0}\pi^+\pi^-$  in  $\mathcal{P}_2$ , and  $B_{(s)}^0 \rightarrow K_s^0 K^+\pi^-$  and  $B_{(s)}^0 \rightarrow K^{*0}(K_s^0\pi^0)K^+\pi^-$  in  $\mathcal{P}_3$  are accounted for using the function that describes the  $B_{(s)}^0$  candidates in  $\mathcal{P}_1$ .

The PDFs  $\mathcal{F}_i$  are distinct for the long and downstream samples, but share certain parameters including those of the  $\bar{D}^0$  signal distribution and the yield fractions of the non-combinatorial components of the  $B$  mass spectrum. Gaussian constraints are applied to the branching fraction ratios  $\mathcal{B}(B_s^0 \rightarrow \bar{D}^0 K^{*0})/[\mathcal{B}(B^0 \rightarrow \bar{D}^0 K^{*0}) + \mathcal{B}(B_s^0 \rightarrow \bar{D}^0 K^{*0})]$  and  $\mathcal{B}(B_{(s)}^0 \rightarrow \bar{D}^{*0}(\bar{D}^0\pi^0)K^0)/[\mathcal{B}(B_{(s)}^0 \rightarrow \bar{D}^{*0}(\bar{D}^0\gamma)K^0) + \mathcal{B}(B_{(s)}^0 \rightarrow \bar{D}^{*0}(\bar{D}^0\pi^0)K^0)]$ . These constraints improve the stability of the fit and are determined from measurements of branching fractions reported in Ref. [25], corrected by the efficiencies of the relevant  $B_{(s)}^0$  decays as determined from simulated samples.

Projections of the fit results on the data sample are shown in Fig. 1. The numbers of signal candidates determined from the fit are  $N(B^0 \rightarrow \bar{D}^0 K_s^0) = 219 \pm 21$ ,  $N(B_s^0 \rightarrow \bar{D}^0 K_s^0) = 471 \pm 26$  and  $N(B_s^0 \rightarrow \bar{D}^{*0} K_s^0) = 258 \pm 83$ , where the uncertainties are purely statistical.

The branching fractions,  $\mathcal{B}$ , of the  $B_s^0 \rightarrow \bar{D}^{(*)0} K^0$  decays are calculated from the ratio

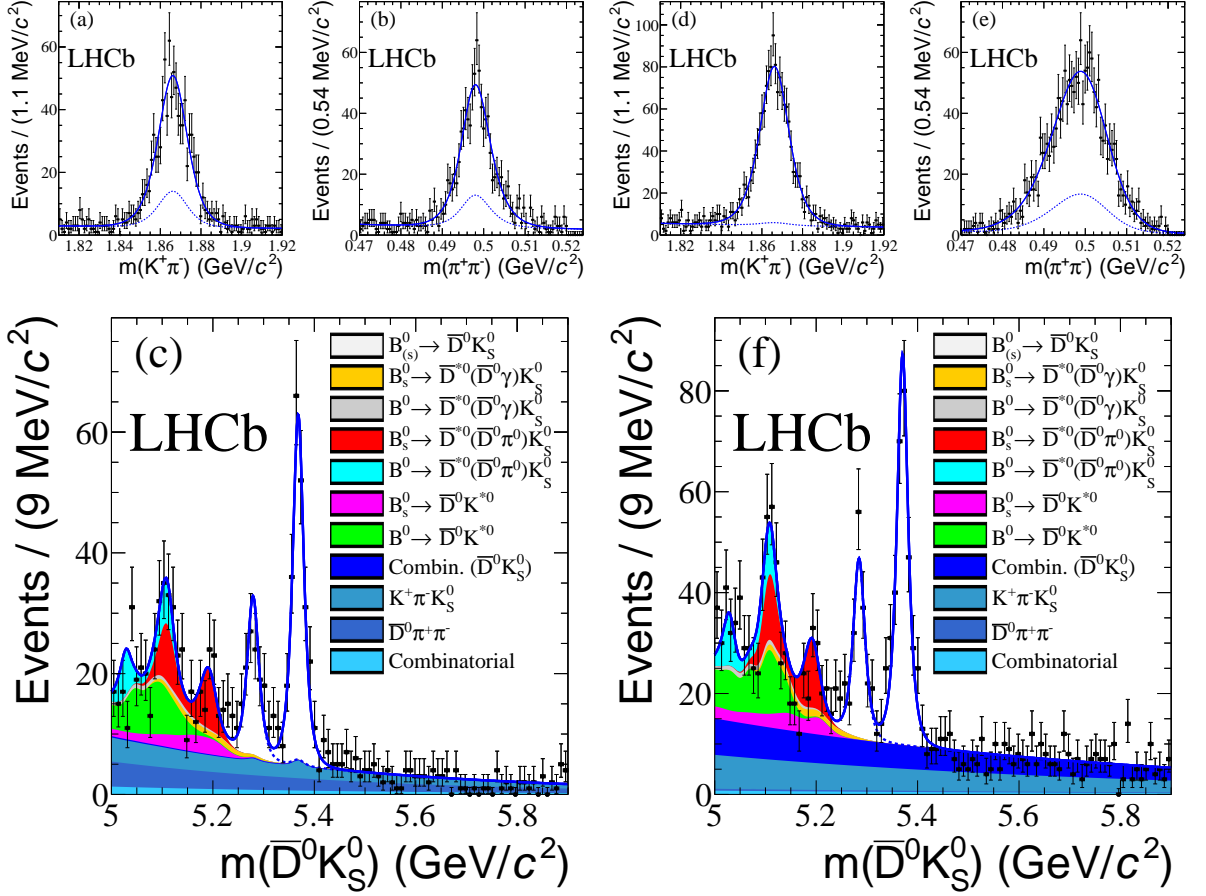


Figure 1: The projection of the fit results (solid line) on the data sample (points) is shown for the  $\bar{D}^0$  candidate (a,d), the  $K_S^0$  candidate (b,e) and  $B$  candidate (c,f) mass spectra. The long  $K_S^0$  sample is shown in (a,b,c), and the downstream sample in (d,e,f). The dashed line in the  $\bar{D}^0$  and  $K_S^0$  candidate mass plots represents events corresponding to background categories  $\mathcal{S}_{2,3,4}$  in the fit, and includes peaks due to, for example, real  $\bar{D}^0$  mesons paired with two random pions. The double-peak behavior of the  $B_{(s)}^0 \rightarrow \bar{D}^{*0}(\bar{D}^0 \pi^0) K_S^0$  shape is due to the missing momentum of the  $\pi^0$  and the helicity amplitude of the  $\bar{D}^{*0} \rightarrow \bar{D}^0 \pi^0$  decay.

of branching fractions between  $B_s^0$  and  $B^0$

$$\mathcal{B}(B_s^0 \rightarrow \bar{D}^{(*)0} \bar{K}^0) = \mathcal{R}^{(*)} \times \mathcal{B}_{\text{sum}} \quad (2)$$

where  $\mathcal{B}_{\text{sum}} = \mathcal{B}(B^0 \rightarrow \bar{D}^0 K^0) + \mathcal{B}(\bar{B}^0 \rightarrow \bar{D}^0 \bar{K}^0)$ , since the analysis does not distinguish between  $K^0$  and  $\bar{K}^0$ . The quantity

$$\mathcal{R}^{(*)} = \frac{f_d}{f_s} \frac{N(B_s^0 \rightarrow \bar{D}^{(*)0} K_S^0)}{N(B^0 \rightarrow \bar{D}^0 K_S^0) + N(\bar{B}^0 \rightarrow \bar{D}^0 K_S^0)} \frac{\epsilon_{B^0}}{\epsilon_{B_s^0}} \quad (3)$$

is the product of the production ratio of  $B^0$  over  $B_s^0$  decays in LHCb ( $f_d/f_s$ ), the ratio of reconstructed  $B_s^0$  and  $B^0$  signal candidates, and the ratio of efficien-

cies of  $B^0$  to  $B_s^0$  candidates decaying to  $\bar{D}^{(*)0}K_s^0$  in the LHCb detector ( $\epsilon_{B^0}/\epsilon_{B_s^0}$ ). The value of  $f_s/f_d = 0.259 \pm 0.015$  is provided by previous LHCb measurements [30, 31]. The ratios of efficiencies  $\epsilon_{B^0 \rightarrow \bar{D}^0 K_s^0}/\epsilon_{B_s^0 \rightarrow \bar{D}^0 K_s^0} = 0.997 \pm 0.024$  and  $\epsilon_{B^0 \rightarrow \bar{D}^0 K_s^0}/\epsilon_{B_s^0 \rightarrow \bar{D}^{*0} K_s^0} = 1.181 \pm 0.029$  are obtained from simulated samples. The ratio of  $B_s^0$  and  $B^0$  signal candidates is a free parameter in the fit and is measured to be  $N(B_s^0 \rightarrow \bar{D}^0 K_s^0)/[N(B^0 \rightarrow \bar{D}^0 K_s^0) + N(\bar{B}^0 \rightarrow \bar{D}^0 K_s^0)] = 2.15 \pm 0.23$ . Similarly, the ratio  $N(B_s^0 \rightarrow \bar{D}^{*0} K_s^0)/[N(B^0 \rightarrow \bar{D}^0 K_s^0) + N(\bar{B}^0 \rightarrow \bar{D}^0 K_s^0)] = 1.17 \pm 0.44$  is measured.

Various sources of systematic uncertainty have been considered. These are summarized in Table 1 and discussed below.

The uncertainty associated to the fit model is assessed by the use of other functions for the PDFs  $\mathcal{P}_i$  and  $\mathcal{S}_i$ . For the mass distribution of the signal events, four alternative models are used. Each pseudoexperiment generated in this way is then fitted with the baseline model and the difference of the signal yields ratio with respect to the generated value is considered. The mean of the distribution that shows the largest deviation from zero is taken as the systematic uncertainty, corresponding to 5.4% (11.9%) for  $B_s^0 \rightarrow \bar{D}^0 K_s^0$  ( $B_s^0 \rightarrow \bar{D}^{*0} K_s^0$ ).

The ratio of efficiencies of the  $B^0$  and  $B_s^0$  decays is determined from simulation and is limited by the finite size of the sample. The statistical uncertainties on the efficiency ratios and the statistical uncertainties of the external inputs,  $f_s/f_d$  and the branching fraction  $\mathcal{B}_{\text{sum}}$ , are propagated to the systematic uncertainty of this measurement.

To test the stability of the result with respect to the offline selection, the measurement is repeated at different selection cuts on the multivariate classifier. The deviations from the nominal result are consistent with statistical fluctuations and no systematic uncertainty is assigned. Possible bias due to the random removal of multiple candidates is tested by removing or keeping all of them, and no significant effect is observed.

Further cross-checks on the stability of the result are made by measuring the branching fractions independently for the long and downstream  $K_s^0$  samples, for the two different polarities of the LHCb magnet and for different running conditions. No significant effect is observed.

Only the fit model is considered when determining the systematic uncertainty on the number of signal candidates. The statistical uncertainty on the efficiencies and on  $f_s/f_d$  are also included in the sum in quadrature to give the systematic uncertainty on the ratio of branching fractions  $\mathcal{R}^{(*)}$ . Finally, the uncertainty on  $\mathcal{B}_{\text{sum}}$  is also included for the measurement of the branching fraction  $\mathcal{B}(B_s^0 \rightarrow \bar{D}^{(*)0} \bar{K}^0)$ .

Table 1: Summary of the systematic uncertainties.

Source	$B_s^0 \rightarrow \bar{D}^0 K_s^0$	$B_s^0 \rightarrow \bar{D}^{*0} K_s^0$
Fit model	5.4%	11.9%
$\epsilon_{B^0}/\epsilon_{B_s^0}$	2.4%	2.5%
$f_s/f_d$		5.8%
$\mathcal{B}_{\text{sum}}$		13.5%

Signal yields of

$$\begin{aligned} N(B^0 \rightarrow \bar{D}^0 K_s^0) &= 219 \pm 21 \text{ (stat)} \pm 11 \text{ (syst)}, \\ N(B_s^0 \rightarrow \bar{D}^0 K_s^0) &= 471 \pm 26 \text{ (stat)} \pm 25 \text{ (syst)}, \\ N(B_s^0 \rightarrow \bar{D}^{*0} K_s^0) &= 258 \pm 83 \text{ (stat)} \pm 30 \text{ (syst)} \end{aligned}$$

are found. Those results correspond to the first observation of the  $B_s^0 \rightarrow \bar{D}^0 K_s^0$  decay with a significance of 13.1 standard deviations and evidence for  $B_s^0 \rightarrow \bar{D}^{*0} K_s^0$  with a significance of 4.4 standard deviations, where the significances are calculated using Wilks' theorem [32].

The ratios of the branching fractions are

$$\begin{aligned} \mathcal{R} &= 8.3 \pm 0.9 \text{ (stat)} \pm 0.5 \text{ (syst)} \pm 0.5 \text{ (frag)}, \\ \mathcal{R}^* &= 5.4 \pm 2.0 \text{ (stat)} \pm 0.7 \text{ (syst)} \pm 0.3 \text{ (frag)}. \end{aligned}$$

Here the correlation coefficient between the two statistical uncertainties is 68% and that between the two systematic uncertainties is 49%. Using the branching fraction  $\mathcal{B}_{\text{sum}} = (5.2 \pm 0.7) \times 10^{-5}$  [25], the values of the branching fractions are

$$\begin{aligned} \mathcal{B}(B_s^0 \rightarrow \bar{D}^0 \bar{K}^0) &= (4.3 \pm 0.5 \text{ (stat)} \pm 0.3 \text{ (syst)} \pm 0.3 \text{ (frag)} \pm 0.6 \text{ (norm)}) \times 10^{-4}, \\ \mathcal{B}(B_s^0 \rightarrow \bar{D}^{*0} \bar{K}^0) &= (2.8 \pm 1.0 \text{ (stat)} \pm 0.3 \text{ (syst)} \pm 0.2 \text{ (frag)} \pm 0.4 \text{ (norm)}) \times 10^{-4}, \end{aligned}$$

where the last uncertainty is due to the uncertainty on  $\mathcal{B}_{\text{sum}}$ . These results are consistent with theoretical predictions from Refs. [13–15], when corrections for the difference in width between the  $B_s^0$  mass eigenstates [33] are taken into account.

This Letter reports the first observation of  $B_s^0 \rightarrow \bar{D}^0 K_s^0$  and first evidence of  $B_s^0 \rightarrow \bar{D}^{*0} K_s^0$ . Since the theoretical predictions for these modes have a small uncertainty, future studies with increased statistics and additional  $\bar{D}^0$  decay modes will give significant improvements in the determination of  $\phi_s$  and  $\gamma$ .

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## References

- [1] BaBar collaboration, B. Aubert *et al.*, *Observation of CP violation in the  $B^0$  meson system*, Phys. Rev. Lett. **87** (2001) 091801, [arXiv:hep-ex/0107013](#).
- [2] Belle collaboration, K. Abe *et al.*, *Observation of large CP violation in the neutral B meson system*, Phys. Rev. Lett. **87** (2001) 091802, [arXiv:hep-ex/0107061](#).
- [3] LHCb collaboration, R. Aaij *et al.*, *A measurement of the CKM angle  $\gamma$  from a combination of  $B^\pm \rightarrow Dh^\pm$  analyses*, Phys. Lett. **B726** (2013) 151, [arXiv:1305.2050](#).
- [4] Belle, BaBar, A. J. Bevan *et al.*, *The Physics of the B Factories*, Eur. Phys. J. **C74** (2014) 3026, [arXiv:1406.6311](#).
- [5] M. Kobayashi and T. Maskawa, *CP Violation in the Renormalizable Theory of Weak Interaction*, Prog. Theor. Phys. **49** (1973) 652.
- [6] Heavy Flavor Averaging Group, Y. Amhis *et al.*, *Averages of b-hadron, c-hadron, and  $\tau$ -lepton properties as of summer 2014*, [arXiv:1412.7515](#), updated results and plots available at <http://www.slac.stanford.edu/xorg/hfag/>.
- [7] J. Charles *et al.*, *Predictions of selected flavour observables within the Standard Model*, Phys. Rev. **D84** (2011) 033005, [arXiv:1106.4041](#).
- [8] A. J. Buras, *Flavour Theory: 2009*, PoS **EPS-HEP2009** (2009) 024, [arXiv:0910.1032](#).
- [9] C.-W. Chiang *et al.*, *New Physics in  $B_{(s)}^0 \rightarrow J/\psi \phi$ : A General Analysis*, JHEP **04** (2010) 031, [arXiv:0910.2929](#).
- [10] M. Gronau *et al.*, *Using untagged  $B^0 \rightarrow DK_S$  to determine  $\gamma$* , Physical Review D **69** (2004) 113003, [arXiv:hep-ph/0402055](#).
- [11] LHCb collaboration, R. Aaij *et al.*, *Observation of the decay  $B_s^0 \rightarrow \bar{D}^0 \phi$* , Phys. Lett. **B727** (2013) 403, [arXiv:1308.4583](#).
- [12] BaBar collaboration, B. Aubert *et al.*, *Measurement of  $\bar{B}^0 \rightarrow D^{(*)0} \bar{K}^{(*)0}$  branching fractions*, Phys. Rev. **D74** (2006) 031101, [arXiv:hep-ex/0604016](#).

- [13] P. Colangelo and R. Ferrandes, *Model independent analysis of a class of  $\bar{B}_s^0$  decay modes*, Phys. Lett. **B627** (2005) 77, [arXiv:hep-ph/0508033](#).
- [14] C.-K. Chua and W.-S. Hou, *Rescattering effects in  $\bar{B}_{u,d,s} \rightarrow DP, \bar{D}P$  decays*, Phys. Rev. **D77** (2008) 116001, [arXiv:0712.1882](#).
- [15] C.-W. Chiang and E. Senaha, *Update analysis of two-body charmed B meson decays*, Phys. Rev. **D75** (2007) 074021, [arXiv:hep-ph/0702007](#).
- [16] LHCb collaboration, A. A. Alves Jr. *et al.*, *The LHCb detector at the LHC*, JINST **3** (2008) S08005.
- [17] LHCb collaboration, R. Aaij *et al.*, *LHCb detector performance*, Int. J. Mod. Phys. **A30** (2015) 1530022, [arXiv:1412.6352](#).
- [18] T. Sjöstrand, S. Mrenna, and P. Skands, *PYTHIA 6.4 physics and manual*, JHEP **05** (2006) 026, [arXiv:0603175](#); T. Sjöstrand, S. Mrenna, and P. Skands, *A brief introduction to PYTHIA 8.1*, Comput. Phys. Commun. **178** (2008) 852, [arXiv:0710.3820](#).
- [19] I. Belyaev *et al.*, *Handling of the generation of primary events in Gauss, the LHCb simulation framework*, J. Phys. Conf. Ser. **331** (2011) 032047.
- [20] D. J. Lange, *The EvtGen particle decay simulation package*, Nucl. Instrum. Meth. **A462** (2001) 152.
- [21] P. Golonka and Z. Was, *PHOTOS Monte Carlo: A precision tool for QED corrections in Z and W decays*, Eur. Phys. J. **C45** (2006) 97, [arXiv:hep-ph/0506026](#).
- [22] Geant4 collaboration, J. Allison *et al.*, *Geant4 developments and applications*, IEEE Trans. Nucl. Sci. **53** (2006) 270; Geant4 collaboration, S. Agostinelli *et al.*, *Geant4: A simulation toolkit*, Nucl. Instrum. Meth. **A506** (2003) 250.
- [23] M. Clemencic *et al.*, *The LHCb simulation application, Gauss: Design, evolution and experience*, J. Phys. Conf. Ser. **331** (2011) 032023.
- [24] V. V. Gligorov and M. Williams, *Efficient, reliable and fast high-level triggering using a bonsai boosted decision tree*, JINST **8** (2013) P02013, [arXiv:1210.6861](#).
- [25] Particle Data Group, K. A. Olive *et al.*, *Review of particle physics*, Chin. Phys. **C38** (2014) 090001.
- [26] L. Breiman, J. H. Friedman, R. A. Olshen, and C. J. Stone, *Classification and regression trees*, Wadsworth international group, Belmont, California, USA, 1984.
- [27] R. E. Schapire and Y. Freund, *A decision-theoretic generalization of on-line learning and an application to boosting*, Jour. Comp. and Syst. Sc. **55** (1997) 119.

- [28] N. L. Johnson, *Systems of Frequency Curves Generated by Methods of Translation*, *Biometrika* **36** (1949), no. 1-2 149.
- [29] K. S. Cranmer, *Kernel estimation in high-energy physics*, *Comput. Phys. Commun.* **136** (2001) 198, [arXiv:hep-ex/0011057](#).
- [30] LHCb collaboration, R. Aaij *et al.*, *Measurement of the fragmentation fraction ratio  $f_s/f_d$  and its dependence on  $B$  meson kinematics*, *JHEP* **04** (2013) 001, [arXiv:1301.5286](#).
- [31] LHCb collaboration, *Updated average  $f_s/f_d$   $b$ -hadron production fraction ratio for 7 TeV  $pp$  collisions*, LHCb-CONF-2013-011.
- [32] S. S. Wilks, *The large-sample distribution of the likelihood ratio for testing composite hypotheses*, *Annals Math. Statist.* **9** (1938) 60.
- [33] K. De Bruyn *et al.*, *Branching Ratio Measurements of  $B_s$  Decays*, *Phys. Rev.* **D86** (2012) 014027, [arXiv:1204.1735](#).

## LHCb collaboration

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