

**Original citation:**

LHCb Collaboration (Including: Back, John J., Craik, Daniel, Dossett, D., Gershon, Timothy J., Harrison, Paul F., Kreps, Michal, Latham, Thomas, Reid, Matthew M., Silva Coutinho, R., Pilar, T., Poluektov, Anton, Whitehead, M. (Mark), Williams, M. P. and Aaij, R.). (2013) First observation of CP violation in the decays of  $B_s^0$  mesons. Physical Review Letters, Volume 110 (Number 22). Article number 221601.

**Permanent WRAP url:**

<http://wrap.warwick.ac.uk/57232>

**Copyright and reuse:**

The Warwick Research Archive Portal (WRAP) makes this work of researchers of the University of Warwick available open access under the following conditions.

This article is made available under the Creative Commons Attribution- 3.0 Unported (CC BY 3.0) license and may be reused according to the conditions of the license. For more details see <http://creativecommons.org/licenses/by/3.0/>

**A note on versions:**

The version presented in WRAP is the published version, or, version of record, and may be cited as it appears here.

For more information, please contact the WRAP Team at: [publications@warwick.ac.uk](mailto:publications@warwick.ac.uk)

warwick**publications**wrap

highlight your research

<http://wrap.warwick.ac.uk/>



# First Observation of $CP$ Violation in the Decays of $B_s^0$ Mesons

R. Aaij *et al.*\*

(LHCb Collaboration)

(Received 24 April 2013; published 30 May 2013)

Using  $pp$  collision data corresponding to an integrated luminosity of  $1.0 \text{ fb}^{-1}$  and collected by LHCb in 2011 at a center-of-mass energy of 7 TeV, we report the measurement of direct  $CP$  violation in  $B_s^0 \rightarrow K^- \pi^+$  decays,  $A_{CP}(B_s^0 \rightarrow K^- \pi^+) = 0.27 \pm 0.04(\text{stat}) \pm 0.01(\text{syst})$ , with significance exceeding 5 standard deviations. This is the first observation of  $CP$  violation in the decays of  $B_s^0$  mesons. Furthermore, we provide an improved determination of direct  $CP$  violation in  $B^0 \rightarrow K^+ \pi^-$  decays,  $A_{CP}(B^0 \rightarrow K^+ \pi^-) = -0.080 \pm 0.007(\text{stat}) \pm 0.003(\text{syst})$ , which is the most precise measurement of this quantity to date.

DOI: [10.1103/PhysRevLett.110.221601](https://doi.org/10.1103/PhysRevLett.110.221601)

PACS numbers: 11.30.Er, 13.25.Hw

The noninvariance of fundamental interactions under the combined action of the charge conjugation ( $C$ ) and parity ( $P$ ) transformations is experimentally well established in the  $K^0$  and  $B^0$  meson systems [1–4]. The standard model (SM) description of  $CP$  violation, as given by the Cabibbo-Kobayashi-Maskawa theory of quark-flavor mixing [5,6], has been very successful in describing existing data. However, the source of  $CP$  violation in the SM is known to be too small to account for the matter-dominated universe [7–9].

The study of  $CP$  violation in charmless charged two-body decays of neutral  $B$  mesons provides stringent tests of the Cabibbo-Kobayashi-Maskawa picture in the SM, and is a sensitive probe to search for the presence of non-SM physics [10–16]. However, quantitative SM predictions for  $CP$  violation in these decays are challenging because of the presence of hadronic factors in the decay amplitudes, which cannot be accurately calculated from quantum chromodynamics at present. It is crucial to combine several measurements from such two-body decays, exploiting approximate flavor symmetries in order to cancel the unknown parameters. An experimental program for measuring the properties of these decays has been carried out during the last decade at the  $B$  factories [17,18] and at the Tevatron [19], and is now continued by LHCb with increased sensitivity. The discovery of direct  $CP$  violation in the  $B^0 \rightarrow K^+ \pi^-$  decay dates back to 2004 [20,21]. This observation raised the question of whether the effect could be accommodated by the SM or was due to non-SM physics. A simple but powerful model-independent test was proposed in Refs. [11,14], which required the measurement of direct  $CP$  violation in the  $B_s^0 \rightarrow K^- \pi^+$  decay. However,  $CP$  violation has never been observed with

significance exceeding 5 Gaussian standard deviations ( $\sigma$ ) in any  $B_s^0$  meson decay so far.

In this Letter, we report measurements of direct  $CP$ -violating asymmetries in  $B^0 \rightarrow K^+ \pi^-$  and  $B_s^0 \rightarrow K^- \pi^+$  decays using  $pp$  collision data, corresponding to an integrated luminosity of  $1.0 \text{ fb}^{-1}$ , collected with the LHCb detector in 2011 at a center-of-mass energy of 7 TeV. The present results supersede those given in Ref. [22]. The inclusion of charge-conjugate decay modes is implied except in the asymmetry definitions. The direct  $CP$  asymmetry in the  $B_{(s)}^0$  decay rate to the final state  $f_{(s)}$ , with  $f = K^+ \pi^-$  and  $f_s = K^- \pi^+$ , is defined as

$$A_{CP}(B_{(s)}^0 \rightarrow f_{(s)}) = \Phi[\Gamma(\bar{B}_{(s)}^0 \rightarrow \bar{f}_{(s)}), \Gamma(B_{(s)}^0 \rightarrow f_{(s)})], \quad (1)$$

where  $\Phi[X, Y] = (X - Y)/(X + Y)$  and  $\bar{f}_{(s)}$  denotes the charge conjugate of  $f_{(s)}$ .

The LHCb detector [23] 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 trigger [24] consists of a hardware stage, based on information from the calorimeter and muon systems, followed by a software stage that applies a full event reconstruction. The hadronic hardware trigger selects large transverse energy clusters in the hadronic calorimeter. The software trigger requires a two-, three-, or four-track secondary vertex with a large sum of the transverse momenta ( $p_T$ ) of the tracks and a significant displacement from the primary  $pp$  interaction vertices (PVs). At least one track should have  $p_T$  and impact parameter (IP)  $\chi^2$  with respect to all PVs exceeding given thresholds. The IP is defined as the distance between the reconstructed trajectory of a particle and a given  $pp$  collision vertex, and the IP  $\chi^2$  is the difference between the  $\chi^2$  of the PV reconstructed with and without the considered track. A multivariate algorithm is used for the identification of secondary vertices consistent with the decay of a  $b$  hadron. In order to improve the trigger efficiency on hadronic two-body decays, a dedicated two-body software trigger is also used. This trigger imposes requirements on the following

\*Full author list given at the end of the article.

Published by the American Physical Society under the terms of the [Creative Commons Attribution 3.0 License](https://creativecommons.org/licenses/by/3.0/). Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI.

quantities: the quality of the on-line-reconstructed tracks, their  $p_T$  and IP, the distance of the closest approach of the decay products of the  $B$  meson candidate, its  $p_T$ , IP, and the decay time in its rest frame.

More selective requirements are applied off-line. Two sets of criteria have been optimized with the aim of minimizing the expected statistical uncertainty either on  $A_{CP}(B^0 \rightarrow K^+ \pi^-)$  or on  $A_{CP}(B_s^0 \rightarrow K^- \pi^+)$ . In addition to the requirements on the kinematic variables already used in the trigger, requirements on the largest  $p_T$  and IP of the  $B$  daughter particles are applied. In the case of  $B_s^0 \rightarrow K^- \pi^+$  decays, a tighter selection is needed to achieve a stronger rejection of combinatorial background. For example, the decay time is required to exceed 1.5 ps, whereas in the  $B^0 \rightarrow K^+ \pi^-$  selection a lower threshold of 0.9 ps is applied. This is because the probability for a  $b$  quark to form a  $B_s^0$  meson, which subsequently decays to the  $K^- \pi^+$  final state, is 1 order of magnitude smaller than that to form a  $B^0$  meson decaying to  $K^+ \pi^-$  [25]. The two samples are then subdivided according to the various final states using the particle identification (PID) provided by the two ring-imaging Cherenkov (RICH) detectors [26]. Two sets of PID selection criteria are applied: a loose set optimized for the measurement of  $A_{CP}(B^0 \rightarrow K^+ \pi^-)$  and a tight set for that of  $A_{CP}(B_s^0 \rightarrow K^- \pi^+)$ . More details on the event selection can be found in Ref. [22].

To determine the amount of background events from other two-body  $b$ -hadron decays with a misidentified pion or kaon (cross-feed background), the relative efficiencies of the RICH PID selection criteria must be determined. This is achieved by means of a data-driven method that uses  $D^{*+} \rightarrow D^0(K^- \pi^+) \pi^+$  and  $\Lambda \rightarrow p \pi^-$  decays as control samples. The production and decay kinematic properties of the  $D^0 \rightarrow K^- \pi^+$  and  $\Lambda \rightarrow p \pi^-$  channels differ from those of the  $b$ -hadron decays under study. Since the RICH PID information is momentum dependent, a calibration procedure is performed by reweighting the distributions of the PID variables obtained from the calibration samples, in order to match the momentum distributions of signal final-state particles observed in data.

Unbinned maximum likelihood fits to the mass spectra of the selected events are performed. The  $B^0 \rightarrow K^+ \pi^-$  and  $B_s^0 \rightarrow K^- \pi^+$  signal components are described by double Gaussian functions convolved with a function that describes the effect of final-state radiation [27]. The background due to partially reconstructed three-body  $B$  decays is parametrized by means of two ARGUS functions [28] convolved with a Gaussian resolution function. The combinatorial background is modeled by an exponential function and the shapes of the cross-feed backgrounds, mainly due to  $B^0 \rightarrow \pi^+ \pi^-$  and  $B_s^0 \rightarrow K^+ K^-$  decays with one misidentified particle in the final state, are obtained from

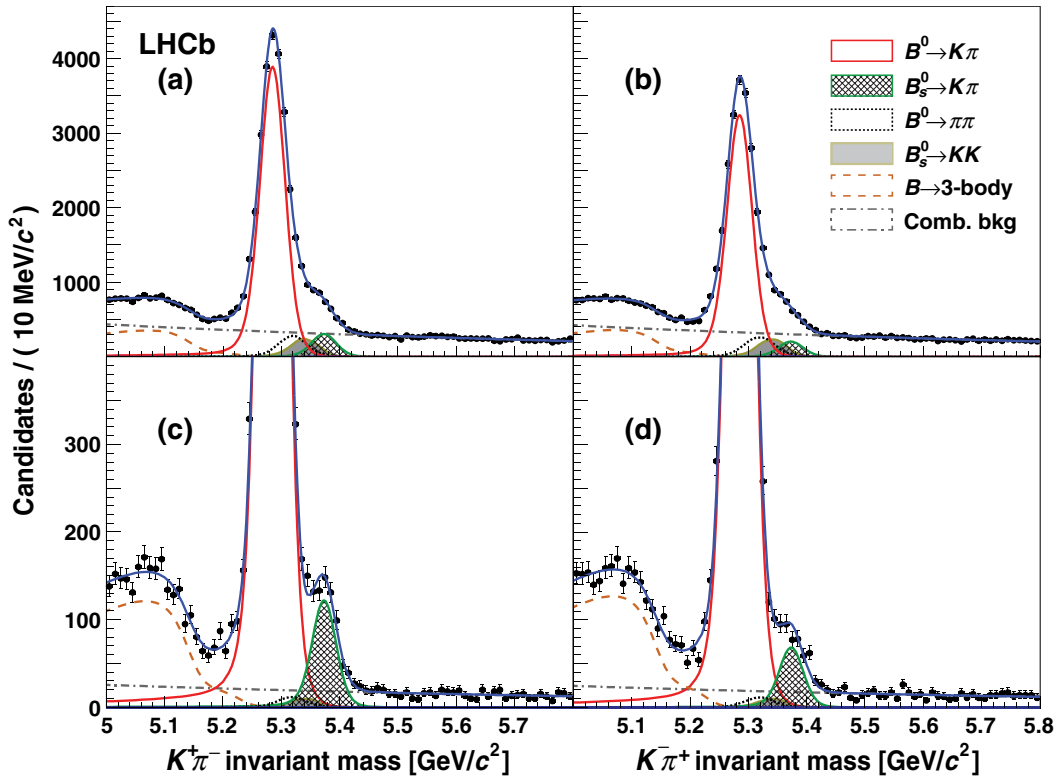


FIG. 1 (color online). Invariant mass spectra obtained using the event selection adopted for the best sensitivity on (a), (b)  $A_{CP}(B^0 \rightarrow K^+ \pi^-)$  and (c), (d)  $A_{CP}(B_s^0 \rightarrow K^- \pi^+)$ . Panels (a) and (c) represent the  $K^+ \pi^-$  invariant mass, whereas panels (b) and (d) represent the  $K^- \pi^+$  invariant mass. The results of the unbinned maximum likelihood fits are overlaid. The main components contributing to the fit model are also shown.

simulation. The cross-feed background yields are determined from the  $\pi^+\pi^-$ ,  $K^+K^-$ ,  $p\pi^-$ , and  $pK^-$  mass spectra, using events passing the same selection as the signal and taking into account the appropriate PID efficiency factors. The  $K^+\pi^-$  and  $K^-\pi^+$  mass spectra for the events passing the two selections are shown in Fig. 1. The average invariant mass resolution is about  $22 \text{ MeV}/c^2$ .

From the two mass fits we determine the signal yields  $N(B^0 \rightarrow K^+\pi^-) = 41420 \pm 300$  and  $N(B_s^0 \rightarrow K^-\pi^+) = 1065 \pm 55$ , as well as the raw asymmetries  $A_{\text{raw}}(B^0 \rightarrow K^+\pi^-) = -0.091 \pm 0.006$  and  $A_{\text{raw}}(B_s^0 \rightarrow K^-\pi^+) = 0.28 \pm 0.04$ , where the uncertainties are statistical only. In order to derive the  $CP$  asymmetries from the observed raw asymmetries, effects induced by the detector acceptance and event reconstruction, as well as due to interactions of final-state particles with the detector material, must be accounted for. Furthermore, the possible presence of a  $B_{(s)}^0 - \bar{B}_{(s)}^0$  production asymmetry must also be considered.

The  $CP$  asymmetry is related to the raw asymmetry by  $A_{CP} = A_{\text{raw}} - A_{\Delta}$ , where the correction  $A_{\Delta}$  is defined as

$$A_{\Delta}(B_{(s)}^0 \rightarrow K\pi) = \zeta_{d(s)}A_D(K\pi) + \kappa_{d(s)}A_P(B_{(s)}^0), \quad (2)$$

with  $\zeta_d = 1$  and  $\zeta_s = -1$ . The instrumental asymmetry  $A_D(K\pi)$  is given in terms of the detection efficiencies  $\varepsilon_D$  of the charge-conjugate final states by  $A_D(K\pi) = \Phi[\varepsilon_D(K^-\pi^+), \varepsilon_D(K^+\pi^-)]$ , and the production asymmetry  $A_P(B_{(s)}^0)$  is defined in terms of the  $\bar{B}_{(s)}^0$  and  $B_{(s)}^0$  production rates,  $R(\bar{B}_{(s)}^0)$  and  $R(B_{(s)}^0)$ , as  $A_P(B_{(s)}^0) = \Phi[R(\bar{B}_{(s)}^0), R(B_{(s)}^0)]$ . The factors  $\kappa_d$  and  $\kappa_s$  take into account dilutions due to  $B^0$  and  $B_s^0$  meson mixing, respectively. Their values also depend on event reconstruction and selection, and are  $\kappa_d = 0.303 \pm 0.005$  and  $\kappa_s = -0.033 \pm 0.003$  [22]. The factor  $\kappa_s$  is 10 times smaller than  $\kappa_d$ , owing to the large  $B_s^0$  oscillation frequency.

The instrumental charge asymmetry  $A_D(K\pi)$  is measured from data using  $D^{*+} \rightarrow D^0(K^-\pi^+)\pi^+$  and  $D^{*+} \rightarrow D^0(K^+K^+)\pi^+$  decays. The combination of the time-integrated raw asymmetries of these two decay modes is used to disentangle the various contributions to each raw asymmetry. The presence of open charm production asymmetries arising from the primary  $pp$  interaction constitutes an additional complication. We write the following equations relating the observed raw asymmetries to the physical  $CP$  asymmetries:

$$A_{\text{raw}}^*(K\pi) = A_D^*(\pi_s) + A_D^*(K\pi) + A_P(D^*), \quad (3)$$

$$A_{\text{raw}}^*(KK) = A_{CP}(KK) + A_D^*(\pi_s) + A_P(D^*), \quad (4)$$

where  $A_{\text{raw}}^*(K\pi)$  and  $A_{\text{raw}}^*(KK)$  are the time-integrated raw asymmetries in  $D^*$ -tagged  $D^0 \rightarrow K^-\pi^+$  and  $D^0 \rightarrow K^+K^+$  decays, respectively,  $A_{CP}(KK)$  is the  $D^0 \rightarrow K^+K^+$   $CP$  asymmetry,  $A_D^*(K\pi)$  is the detection asymmetry in reconstructing  $D^0 \rightarrow K^-\pi^+$  and  $\bar{D}^0 \rightarrow K^+\pi^-$  decays,  $A_D^*(\pi_s)$

is the detection asymmetry in reconstructing positively and negatively charged pions originating from  $D^*$  decays, and  $A_P(D^*)$  is the production asymmetry for prompt charged  $D^*$  mesons. In Eq. (3) any possible  $CP$  asymmetry in the Cabibbo-favored  $D^0 \rightarrow K^-\pi^+$  decay is neglected [29]. By subtracting Eqs. (3) and (4), one obtains

$$A_{\text{raw}}^*(K\pi) - A_{\text{raw}}^*(KK) = A_D^*(K\pi) - A_{CP}(KK). \quad (5)$$

Once the raw asymmetries are measured, this equation determines unambiguously the detection asymmetry  $A_D^*(K\pi)$ , using the world average for the  $CP$  asymmetry of the  $D^0 \rightarrow K^+K^+$  decay. Since the measured value of the time-integrated asymmetry depends on the decay-time acceptance, the existing measurements of  $A_{CP}(KK)$  [30–32] are corrected for the difference in acceptance with respect to LHCb [33]. This leads to the value  $A_{CP}(KK) = (-0.24 \pm 0.18)\%$ . Furthermore,  $B$  meson production and decay kinematic properties differ from those of the  $D$  decays being considered, and different trigger and selection algorithms are applied. In order to correct the raw asymmetries of  $B$  decays, using the detection asymmetry  $A_D^*(K\pi)$  derived from  $D$  decays, a reweighting procedure is needed. We reweight the  $D^0$  momentum, transverse momentum, and azimuthal angle in  $D^0 \rightarrow K^-\pi^+$  and  $D^0 \rightarrow K^+K^+$  decays, to match the respective  $B_{(s)}^0$  distributions in  $B^0 \rightarrow K^+\pi^-$  and  $B_s^0 \rightarrow K^-\pi^+$  decays. The raw asymmetries are determined by means of  $\chi^2$  fits to the reweighted  $\delta m = M_{D^*} - M_{D^0}$  distributions, where  $M_{D^*}$  and  $M_{D^0}$  are the reconstructed  $D^*$  and  $D^0$  candidate invariant masses, respectively.

From the raw asymmetries, values for the quantity  $\Delta A = A_D(K\pi) - A_{CP}(KK)$  are determined. We obtain the values  $\Delta A = (-0.91 \pm 0.15)\%$  and  $\Delta A = (-0.98 \pm 0.11)\%$ , using as target kinematic distributions those of  $B$  candidates passing the event selection optimized for  $A_{CP}(B^0 \rightarrow K^+\pi^-)$  and for  $A_{CP}(B_s^0 \rightarrow K^-\pi^+)$ , respectively. Using these two values of  $\Delta A$  and the value of  $A_{CP}(KK)$ , we obtain the instrumental asymmetries  $A_D(K\pi) = (-1.15 \pm 0.23)\%$  for the  $B^0 \rightarrow K^+\pi^-$  decay and  $A_D(K\pi) = (-1.22 \pm 0.21)\%$  for the  $B_s^0 \rightarrow K^-\pi^+$  decay.

Assuming negligible  $CP$  violation in the mixing, as expected in the SM and confirmed by current experimental determinations [34], the decay rate of a  $B_{(s)}^0$  meson with production asymmetry  $A_P$ , decaying into a flavor-specific final state  $f_{(s)}$  with  $CP$  asymmetry  $A_{CP}$  and detection asymmetry  $A_D$ , can be written as

$$\mathcal{R}(t; p) \propto (1 - pA_{CP})(1 - pA_D)[H_+(t) - pA_P H_-(t)], \quad (6)$$

where  $t$  is the reconstructed decay time of the  $B$  meson and  $p$  assumes the values  $p = +1$  for the final state  $f_{(s)}$  and  $p = -1$  for the final state  $\bar{f}_{(s)}$ . The functions  $H_+(t)$  and  $H_-(t)$  are defined as

$$H_+(t) = \left[ e^{-\Gamma_{d(s)} t'} \cosh\left(\frac{\Delta\Gamma_{d(s)} t'}{2}\right) \otimes R(t, t') \right] \varepsilon_{d(s)}(t), \quad (7)$$

$$H_-(t) = [e^{-\Gamma_{d(s)} t'} \cos(\Delta m_{d(s)} t') \otimes R(t, t')] \varepsilon_{d(s)}(t), \quad (8)$$

where  $\Gamma_{d(s)}$  is the average decay width of the  $B_{(s)}^0$  meson,  $\Delta\Gamma_{d(s)}$  and  $\Delta m_{d(s)}$  are the decay width and mass differences between the two  $B_{(s)}^0$  mass eigenstates, respectively,  $R(t, t')$  is the decay time resolution ( $\sigma \simeq 50$  fs in our case), and the symbol  $\otimes$  stands for convolution. Finally,  $\varepsilon_{d(s)}(t)$  is the acceptance as a function of the  $B_{(s)}^0$  decay time. Using Eq. (6) we obtain the following expression for the time-dependent asymmetry:

$$\begin{aligned} \mathcal{A}(t) &= \Phi[\mathcal{R}(t; -1), \mathcal{R}(t; +1)] \\ &= \frac{(A_{CP} + A_D)H_+(t) + A_P(1 + A_{CP}A_D)H_-(t)}{(1 + A_{CP}A_D)H_+(t) + A_P(A_{CP} + A_D)H_-(t)}. \end{aligned} \quad (9)$$

For illustrative purposes only, we consider the case of perfect decay time resolution and negligible  $\Delta\Gamma$ , retaining only first-order terms in  $A_{CP}$ ,  $A_P$ , and  $A_D$ . In this case, Eq. (9) reduces to the expression

$$\mathcal{A}(t) \approx A_{CP} + A_D + A_P \cos(\Delta m_{d(s)} t); \quad (10)$$

i.e., the time-dependent asymmetry has an oscillatory term with amplitude equal to the production asymmetry  $A_P$ . By studying the full time-dependent decay rate it is then possible to determine  $A_P$  unambiguously.

In order to measure the production asymmetry  $A_P$  for  $B^0$  and  $B_s^0$  mesons, we perform fits to the decay time spectra of the  $B$  candidates, separately for the events passing the two selections. The  $B^0$  production asymmetry is determined from the sample obtained applying the selection optimized for the measurement of  $A_{CP}(B^0 \rightarrow K^+ \pi^-)$ , whereas the  $B_s^0$  production asymmetry is determined from the sample obtained applying the selection optimized for the measurement of  $A_{CP}(B_s^0 \rightarrow K^- \pi^+)$ . We obtain  $A_P(B^0) = (0.1 \pm 1.0)\%$  and  $A_P(B_s^0) = (4 \pm 8)\%$ . Figure 2 shows the raw asymmetries as a function of the decay time, obtained by performing fits to the invariant mass distributions of events restricted to independent intervals of the  $B$  candidate decay times.

By using the values of the detection and production asymmetries, the correction factors to the raw asymmetries  $A_\Delta(B^0 \rightarrow K^+ \pi^-) = (-1.12 \pm 0.23 \pm 0.30)\%$  and  $A_\Delta(B_s^0 \rightarrow K^- \pi^+) = (1.09 \pm 0.21 \pm 0.26)\%$  are obtained, where the first uncertainties are due to the detection asymmetry and the second to the production asymmetry.

Systematic uncertainties on the asymmetries are related to PID calibration, modeling of the signal and background components in the maximum likelihood fits and instrumental charge asymmetries. In order to estimate the impact of imperfect PID calibration, we perform mass fits to determine raw asymmetries using altered numbers of cross-feed background events, according to the systematic

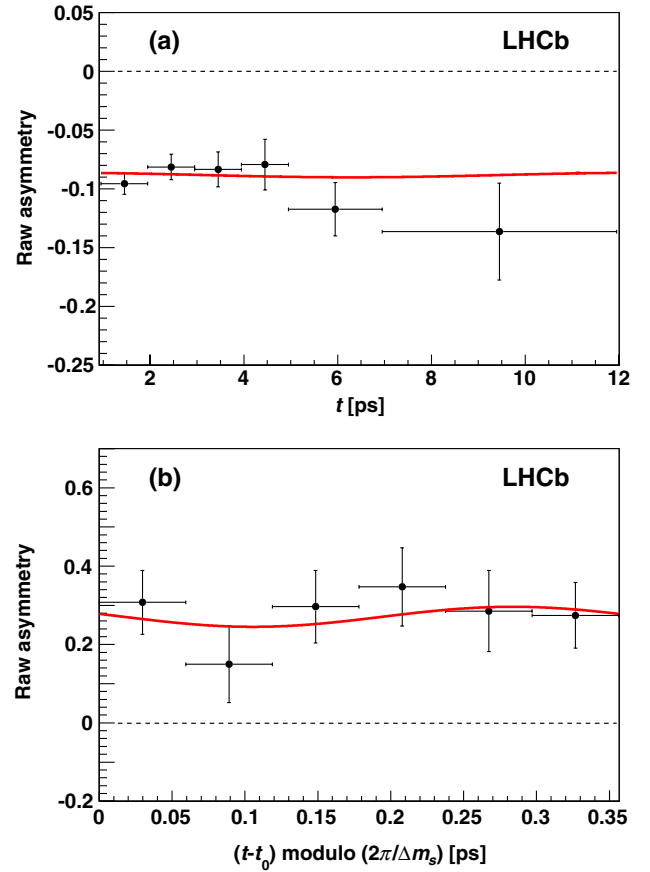


FIG. 2 (color online). Raw asymmetries as a function of the decay time for (a)  $B^0 \rightarrow K^+ \pi^-$  and (b)  $B_s^0 \rightarrow K^- \pi^+$  decays. In (b), the offset  $t_0 = 1.5$  ps corresponds to the minimum value of the decay time required by the  $B_s^0 \rightarrow K^- \pi^+$  event selection. The curves represent the asymmetry projections of fits to the decay time spectra.

uncertainties affecting the PID efficiencies. An estimate of the uncertainty due to possible mismodeling of the final-state radiation is determined by varying the amount of emitted radiation [27] in the signal shape parametrization, according to studies performed on fully simulated events, in which final-state radiation is generated using PHOTOS [35]. The possibility of an incorrect description of the signal mass model is investigated by replacing the double Gaussian function with the sum of three Gaussian functions, where the third component has fixed fraction (5%) and width (50 MeV/ $c^2$ ), and is aimed at describing long tails, as observed in simulation. To assess a systematic uncertainty on the shape of the partially reconstructed backgrounds, we remove the second ARGUS function. For the modeling of the combinatorial background component, the fit is repeated using a straight line. Finally, for the case of the cross-feed backgrounds, two distinct systematic uncertainties are estimated: one due to a relative bias in the mass scale of the simulated distributions with respect to the signal distributions in data, and another accounting for the difference in mass resolution between simulation and

TABLE I. Systematic uncertainties on  $A_{CP}(B^0 \rightarrow K^+ \pi^-)$  and  $A_{CP}(B_s^0 \rightarrow K^- \pi^+)$ . The total systematic uncertainties are obtained by summing the individual contributions in quadrature.

Systematic uncertainty	$A_{CP}(B^0 \rightarrow K^+ \pi^-)$	$A_{CP}(B_s^0 \rightarrow K^- \pi^+)$
PID calibration	0.0006	0.0012
Final-state radiation	0.0008	0.0020
Signal model	0.0001	0.0064
Combinatorial background	0.0004	0.0042
Three-body background	0.0005	0.0027
Cross-feed background	0.0010	0.0033
Detection asymmetry	0.0025	0.0023
Total	0.0029	0.0094

data. All shifts from the relevant baseline values are accounted for as systematic uncertainties. Systematic uncertainties related to the determination of detection asymmetries are calculated by summing in quadrature the respective uncertainties on  $A_\Delta(B^0 \rightarrow K^+ \pi^-)$  and  $A_\Delta(B_s^0 \rightarrow K^- \pi^+)$  with an additional uncertainty of 0.10%, accounting for residual differences in the trigger composition between signal and calibration samples.

The systematic uncertainties for  $A_{CP}(B^0 \rightarrow K^+ \pi^-)$  and  $A_{CP}(B_s^0 \rightarrow K^- \pi^+)$  are summarized in Table I. Since the production asymmetries are obtained from the fitted decay time spectra of  $B^0 \rightarrow K^+ \pi^-$  and  $B_s^0 \rightarrow K^- \pi^+$  decays, their uncertainties are statistical in nature and are then propagated to the statistical uncertainties on  $A_{CP}(B^0 \rightarrow K^+ \pi^-)$  and  $A_{CP}(B_s^0 \rightarrow K^- \pi^+)$ .

In conclusion, the parameters of  $CP$  violation in  $B^0 \rightarrow K^+ \pi^-$  and  $B_s^0 \rightarrow K^- \pi^+$  decays have been measured to be

$$A_{CP}(B^0 \rightarrow K^+ \pi^-) = -0.080 \pm 0.007(\text{stat}) \pm 0.003(\text{syst}),$$

$$A_{CP}(B_s^0 \rightarrow K^- \pi^+) = 0.27 \pm 0.04(\text{stat}) \pm 0.01(\text{syst}).$$

Dividing the central values by the sum in quadrature of statistical and systematic uncertainties, the significances of the measured deviations from zero are  $10.5\sigma$  and  $6.5\sigma$ , respectively. The former is the most precise measurement of  $A_{CP}(B^0 \rightarrow K^+ \pi^-)$  to date, whereas the latter represents the first observation of  $CP$  violation in decays of  $B_s^0$  mesons with significance exceeding  $5\sigma$ . Both measurements are in good agreement with world averages [34] and previous LHCb results [22].

These results allow a stringent test of the validity of the relation between  $A_{CP}(B^0 \rightarrow K^+ \pi^-)$  and  $A_{CP}(B_s^0 \rightarrow K^- \pi^+)$  in the SM given in Ref. [14] as

$$\Delta = \frac{A_{CP}(B^0 \rightarrow K^+ \pi^-)}{A_{CP}(B_s^0 \rightarrow K^- \pi^+)} + \frac{\mathcal{B}(B_s^0 \rightarrow K^- \pi^+) \tau_d}{\mathcal{B}(B^0 \rightarrow K^+ \pi^-) \tau_s} = 0, \quad (11)$$

where  $\mathcal{B}(B^0 \rightarrow K^+ \pi^-)$  and  $\mathcal{B}(B_s^0 \rightarrow K^- \pi^+)$  are  $CP$ -averaged branching fractions, and  $\tau_d$  and  $\tau_s$  are the  $B^0$  and  $B_s^0$  mean lifetimes, respectively. Using additional results for  $\mathcal{B}(B^0 \rightarrow K^+ \pi^-)$  and  $\mathcal{B}(B_s^0 \rightarrow K^- \pi^+)$  [25] and

the world averages for  $\tau_d$  and  $\tau_s$  [34], we obtain  $\Delta = -0.02 \pm 0.05 \pm 0.04$ , where the first uncertainty is from the measurements of the  $CP$  asymmetries and the second is from the input values of the branching fractions and the lifetimes. No evidence for a deviation from zero of  $\Delta$  is observed with the present experimental precision.

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 and Region Auvergne (France); BMBF, DFG, HGF, and MPG (Germany); SFI (Ireland); INFN (Italy); FOM and NWO (The Netherlands); SCSR (Poland); ANCS/IFA (Romania); MinES, Rosatom, RFBR, and NRC “Kurchatov Institute” (Russia); MinECo, XuntaGal, and GENCAT (Spain); SNSF and SER (Switzerland); NAS Ukraine (Ukraine); STFC (U.K.); NSF (U.S.). We also acknowledge the support received from the ERC under FP7. The Tier1 computing centres are supported by IN2P3 (France), KIT, and BMBF (Germany); INFN (Italy); NWO and SURF (The Netherlands); PIC (Spain); and GridPP (U.K.). We are thankful for the computing resources put at our disposal by Yandex LLC (Russia), as well as to the communities behind the multiple open source software packages that we depend on.

- [1] J. H. Christenson, J. W. Cronin, V. L. Fitch, and R. Turlay, *Phys. Rev. Lett.* **13**, 138 (1964).
- [2] B. Aubert *et al.* (BABAR Collaboration), *Phys. Rev. Lett.* **87**, 091801 (2001).
- [3] K. Abe *et al.* (Belle Collaboration), *Phys. Rev. Lett.* **87**, 091802 (2001).
- [4] J. Beringer *et al.* (Particle Data Group), *Phys. Rev. D* **86**, 010001 (2012).
- [5] N. Cabibbo, *Phys. Rev. Lett.* **10**, 531 (1963).
- [6] M. Kobayashi and T. Maskawa, *Prog. Theor. Phys.* **49**, 652 (1973).
- [7] A. G. Cohen, D. Kaplan, and A. Nelson, *Annu. Rev. Nucl. Part. Sci.* **43**, 27 (1993).
- [8] A. Riotto and M. Trodden, *Annu. Rev. Nucl. Part. Sci.* **49**, 35 (1999).
- [9] W.-S. Hou, *Chin. J. Phys. (Taipei)* **47**, 134 (2009).
- [10] N. G. Deshpande and X.-G. He, *Phys. Rev. Lett.* **75**, 1703 (1995).
- [11] X.-G. He, *Eur. Phys. J. C* **9**, 443 (1999).
- [12] R. Fleischer, *Phys. Lett. B* **459**, 306 (1999).
- [13] M. Gronau and J. L. Rosner, *Phys. Lett. B* **482**, 71 (2000).
- [14] H. J. Lipkin, *Phys. Lett. B* **621**, 126 (2005).
- [15] R. Fleischer, *Eur. Phys. J. C* **52**, 267 (2007).
- [16] R. Fleischer and R. Knegjens, *Eur. Phys. J. C* **71**, 1532 (2011).
- [17] J. P. Lees *et al.* (BABAR Collaboration), *Phys. Rev. D* **87**, 052009 (2013).

- [18] Y.-T. Duh *et al.* (Belle Collaboration), *Phys. Rev. D* **87**, 031103 (2013).
- [19] T. Aaltonen *et al.* (CDF Collaboration), *Phys. Rev. Lett.* **106**, 181802 (2011).
- [20] B. Aubert *et al.* (BABAR Collaboration), *Phys. Rev. Lett.* **93**, 131801 (2004).
- [21] Y. Chao *et al.* (Belle Collaboration), *Phys. Rev. D* **71**, 031502 (2005).
- [22] R. Aaij *et al.* (LHCb Collaboration), *Phys. Rev. Lett.* **108**, 201601 (2012).
- [23] A. A. Alves, Jr. *et al.* (LHCb Collaboration), *JINST* **3**, S08005 (2008).
- [24] R. Aaij *et al.*, *JINST* **8**, P04022 (2013).
- [25] R. Aaij *et al.* (LHCb Collaboration), *J. High Energy Phys.* **10** (2012) 037.
- [26] M. Adinolfi *et al.*, *Eur. Phys. J. C* **73**, 2431 (2013).
- [27] E. Baracchini and G. Isidori, *Phys. Lett. B* **633**, 309 (2006).
- [28] H. Albrecht *et al.* (ARGUS Collaboration), *Phys. Lett. B* **229**, 304 (1989).
- [29] S. Bianco, F. L. Fabbri, D. Benson, and I. Bigi, *Riv. Nuovo Cimento* **26N7**, 1 (2003).
- [30] M. Staric *et al.* (Belle Collaboration), *Phys. Lett. B* **670**, 190 (2008).
- [31] B. Aubert *et al.* (BABAR Collaboration), *Phys. Rev. Lett.* **100**, 061803 (2008).
- [32] T. Aaltonen *et al.* (CDF Collaboration), *Phys. Rev. D* **85**, 012009 (2012).
- [33] R. Aaij *et al.* (LHCb Collaboration), *Phys. Rev. Lett.* **108**, 111602 (2012).
- [34] Y. Amhis *et al.* (Heavy Flavor Averaging Group), <http://www.slac.stanford.edu/xorg/hfag>.
- [35] P. Golonka and Z. Was, *Eur. Phys. J. C* **45**, 97 (2006).

R. Aaij,<sup>40</sup> C. Abellan Beteta,<sup>35,n</sup> B. Adeva,<sup>36</sup> M. Adinolfi,<sup>45</sup> C. Adrover,<sup>6</sup> A. Affolder,<sup>51</sup> Z. Ajaltouni,<sup>5</sup> J. Albrecht,<sup>9</sup> F. Alessio,<sup>37</sup> M. Alexander,<sup>50</sup> S. Ali,<sup>40</sup> G. Alkhalaf,<sup>29</sup> P. Alvarez Cartelle,<sup>36</sup> A. A. Alves, Jr.,<sup>24,37</sup> S. Amato,<sup>2</sup> S. Amerio,<sup>21</sup> Y. Amhis,<sup>7</sup> L. Anderlini,<sup>17,f</sup> J. Anderson,<sup>39</sup> R. Andreassen,<sup>56</sup> R. B. Appleby,<sup>53</sup> O. Aquines Gutierrez,<sup>10</sup> F. Archilli,<sup>18</sup> A. Artamonov,<sup>34</sup> M. Artuso,<sup>58</sup> E. Aslanides,<sup>6</sup> G. Auremma,<sup>24,m</sup> S. Bachmann,<sup>11</sup> J. J. Back,<sup>47</sup> C. Baesso,<sup>59</sup> V. Balagura,<sup>30</sup> W. Baldini,<sup>16</sup> R. J. Barlow,<sup>53</sup> C. Barschel,<sup>37</sup> S. Barsuk,<sup>7</sup> W. Barter,<sup>46</sup> Th. Bauer,<sup>40</sup> A. Bay,<sup>38</sup> J. Beddow,<sup>50</sup> F. Bedeschi,<sup>22</sup> I. Bediaga,<sup>1</sup> S. Belogurov,<sup>30</sup> K. Belous,<sup>34</sup> I. Belyaev,<sup>30</sup> E. Ben-Haim,<sup>8</sup> G. Bencivenni,<sup>18</sup> S. Benson,<sup>49</sup> J. Benton,<sup>45</sup> A. Bereznoy,<sup>31</sup> R. Bernet,<sup>39</sup> M.-O. Bettler,<sup>46</sup> M. van Beuzekom,<sup>40</sup> A. Bien,<sup>11</sup> S. Bifani,<sup>44</sup> T. Bird,<sup>53</sup> A. Bizzeti,<sup>17,h</sup> P. M. Bjørnstad,<sup>53</sup> T. Blake,<sup>37</sup> F. Blanc,<sup>38</sup> J. Blouw,<sup>11</sup> S. Blusk,<sup>58</sup> V. Bocci,<sup>24</sup> A. Bondar,<sup>33</sup> N. Bondar,<sup>29</sup> W. Bonivento,<sup>15</sup> S. Borghi,<sup>53</sup> A. Borgia,<sup>58</sup> T. J. V. Bowcock,<sup>51</sup> E. Bowen,<sup>39</sup> C. Bozzi,<sup>16</sup> T. Brambach,<sup>9</sup> J. van den Brand,<sup>41</sup> J. Bressieux,<sup>38</sup> D. Brett,<sup>53</sup> M. Britsch,<sup>10</sup> T. Britton,<sup>58</sup> N. H. Brook,<sup>45</sup> H. Brown,<sup>51</sup> I. Burducea,<sup>28</sup> A. Bursche,<sup>39</sup> G. Busetto,<sup>21,q</sup> J. Buytaert,<sup>37</sup> S. Cadeddu,<sup>15</sup> O. Callot,<sup>7</sup> M. Calvi,<sup>20,j</sup> M. Calvo Gomez,<sup>35,n</sup> A. Camboni,<sup>35</sup> P. Campana,<sup>18,37</sup> D. Campora Perez,<sup>37</sup> A. Carbone,<sup>14,c</sup> G. Carboni,<sup>23,k</sup> R. Cardinale,<sup>19,i</sup> A. Cardini,<sup>15</sup> H. Carranza-Mejia,<sup>49</sup> L. Carson,<sup>52</sup> K. Carvalho Akiba,<sup>2</sup> G. Casse,<sup>51</sup> L. Castillo Garcia,<sup>37</sup> M. Cattaneo,<sup>37</sup> Ch. Cauet,<sup>9</sup> M. Charles,<sup>54</sup> Ph. Charpentier,<sup>37</sup> P. Chen,<sup>3,38</sup> N. Chiapolini,<sup>39</sup> M. Chrzasczcz,<sup>25</sup> K. Ciba,<sup>37</sup> X. Cid Vidal,<sup>37</sup> G. Ciezarek,<sup>52</sup> P. E. L. Clarke,<sup>49</sup> M. Clemencic,<sup>37</sup> H. V. Cliff,<sup>46</sup> J. Closier,<sup>37</sup> C. Coca,<sup>28</sup> V. Coco,<sup>40</sup> J. Cogan,<sup>6</sup> E. Cogneras,<sup>5</sup> P. Collins,<sup>37</sup> A. Comerma-Montells,<sup>35</sup> A. Contu,<sup>15,37</sup> A. Cook,<sup>45</sup> M. Coombes,<sup>45</sup> S. Coquereau,<sup>8</sup> G. Corti,<sup>37</sup> B. Couturier,<sup>37</sup> G. A. Cowan,<sup>49</sup> D. C. Craik,<sup>47</sup> S. Cunliffe,<sup>52</sup> R. Currie,<sup>49</sup> C. D'Amrosio,<sup>37</sup> P. David,<sup>8</sup> P. N. Y. David,<sup>40</sup> A. Davis,<sup>56</sup> I. De Bonis,<sup>4</sup> K. De Bruyn,<sup>40</sup> S. De Capua,<sup>53</sup> M. De Cian,<sup>39</sup> J. M. De Miranda,<sup>1</sup> L. De Paula,<sup>2</sup> W. De Silva,<sup>56</sup> P. De Simone,<sup>18</sup> D. Decamp,<sup>4</sup> M. Deckenhoff,<sup>9</sup> L. Del Buono,<sup>8</sup> N. Déléage,<sup>4</sup> D. Derkach,<sup>14</sup> O. Deschamps,<sup>5</sup> F. Dettori,<sup>41</sup> A. Di Canto,<sup>11</sup> F. Di Ruscio,<sup>23,k</sup> H. Dijkstra,<sup>37</sup> M. Dogaru,<sup>28</sup> S. Donleavy,<sup>51</sup> F. Dordei,<sup>11</sup> A. Dosil Suárez,<sup>36</sup> D. Dosssett,<sup>47</sup> A. Dovbnya,<sup>42</sup> F. Dupertuis,<sup>38</sup> R. Dzhelyadin,<sup>34</sup> A. Dziurda,<sup>25</sup> A. Dzyuba,<sup>29</sup> S. Easo,<sup>48,37</sup> U. Egede,<sup>52</sup> V. Egorychev,<sup>30</sup> S. Eidelman,<sup>33</sup> D. van Eijk,<sup>40</sup> S. Eisenhardt,<sup>49</sup> U. Eitschberger,<sup>9</sup> R. Ekelhof,<sup>9</sup> L. Eklund,<sup>50,37</sup> I. El Rifai,<sup>5</sup> Ch. Elsasser,<sup>39</sup> D. Elsby,<sup>44</sup> A. Falabella,<sup>14,e</sup> C. Färber,<sup>11</sup> G. Fardell,<sup>49</sup> C. Farinelli,<sup>40</sup> S. Farry,<sup>12</sup> V. Fave,<sup>38</sup> D. Ferguson,<sup>49</sup> V. Fernandez Albor,<sup>36</sup> F. Ferreira Rodrigues,<sup>1</sup> M. Ferro-Luzzi,<sup>37</sup> S. Filippov,<sup>32</sup> M. Fiore,<sup>16</sup> C. Fitzpatrick,<sup>37</sup> M. Fontana,<sup>10</sup> F. Fontanelli,<sup>19,i</sup> R. Forty,<sup>37</sup> O. Francisco,<sup>2</sup> M. Frank,<sup>37</sup> C. Frei,<sup>37</sup> M. Frosini,<sup>17,f</sup> S. Furcas,<sup>20</sup> E. Furfaro,<sup>23,k</sup> A. Gallas Torreira,<sup>36</sup> D. Galli,<sup>14,c</sup> M. Gandelman,<sup>2</sup> P. Gandini,<sup>58</sup> Y. Gao,<sup>3</sup> J. Garofoli,<sup>58</sup> P. Garosi,<sup>53</sup> J. Garra Tico,<sup>46</sup> L. Garrido,<sup>35</sup> C. Gaspar,<sup>37</sup> R. Gauld,<sup>54</sup> E. Gersabeck,<sup>11</sup> M. Gersabeck,<sup>53</sup> T. Gershon,<sup>47,37</sup> Ph. Ghez,<sup>4</sup> V. Gibson,<sup>46</sup> V. V. Gligorov,<sup>37</sup> C. Göbel,<sup>59</sup> D. Golubkov,<sup>30</sup> A. Golutvin,<sup>52,30,37</sup> A. Gomes,<sup>2</sup> H. Gordon,<sup>54</sup> M. Grabalosa Gándara,<sup>5</sup> R. Graciani Diaz,<sup>35</sup> L. A. Granado Cardoso,<sup>37</sup> E. Graugés,<sup>35</sup> G. Graziani,<sup>17</sup> A. Grecu,<sup>28</sup> E. Greening,<sup>54</sup> S. Gregson,<sup>46</sup> P. Griffith,<sup>44</sup> O. Grünberg,<sup>60</sup> B. Gui,<sup>58</sup> E. Gushchin,<sup>32</sup> Yu. Guz,<sup>34,37</sup> T. Gys,<sup>37</sup> C. Hadjivasiliou,<sup>58</sup> G. Haefeli,<sup>38</sup> C. Haen,<sup>37</sup> S. C. Haines,<sup>46</sup> S. Hall,<sup>52</sup> T. Hampson,<sup>45</sup> S. Hansmann-Menzemer,<sup>11</sup> N. Harnew,<sup>54</sup> S. T. Harnew,<sup>45</sup> J. Harrison,<sup>53</sup> T. Hartmann,<sup>60</sup> J. He,<sup>37</sup> V. Heijne,<sup>40</sup> K. Hennessy,<sup>51</sup> P. Henrard,<sup>5</sup> J. A. Hernando Morata,<sup>36</sup> E. van Herwijnen,<sup>37</sup> E. Hicks,<sup>51</sup> D. Hill,<sup>54</sup> M. Hoballah,<sup>5</sup> C. Hombach,<sup>53</sup> P. Hopchev,<sup>4</sup> W. Hulsbergen,<sup>40</sup> P. Hunt,<sup>54</sup> T. Huse,<sup>51</sup> N. Hussain,<sup>54</sup> D. Hutchcroft,<sup>51</sup> D. Hynds,<sup>50</sup> V. Iakovenko,<sup>43</sup> M. Idzik,<sup>26</sup> P. Ilten,<sup>12</sup> R. Jacobsson,<sup>37</sup> A. Jaeger,<sup>11</sup> E. Jans,<sup>40</sup> P. Jaton,<sup>38</sup> A. Jawahery,<sup>57</sup> F. Jing,<sup>3</sup> M. John,<sup>54</sup> D. Johnson,<sup>54</sup>

C. R. Jones,<sup>46</sup> C. Joram,<sup>37</sup> B. Jost,<sup>37</sup> M. Kaballo,<sup>9</sup> S. Kandybei,<sup>42</sup> M. Karacson,<sup>37</sup> T. M. Karbach,<sup>37</sup> I. R. Kenyon,<sup>44</sup> U. Kerzel,<sup>37</sup> T. Ketel,<sup>41</sup> A. Keune,<sup>38</sup> B. Khanji,<sup>20</sup> O. Kochebina,<sup>7</sup> I. Komarov,<sup>38</sup> R. F. Koopman,<sup>41</sup> P. Koppenburg,<sup>40</sup> M. Korolev,<sup>31</sup> A. Kozlinskiy,<sup>40</sup> L. Kravchuk,<sup>32</sup> K. Kreplin,<sup>11</sup> M. Kreps,<sup>47</sup> G. Krocker,<sup>11</sup> P. Krokovny,<sup>33</sup> F. Kruse,<sup>9</sup> M. Kucharczyk,<sup>20,25,j</sup> V. Kudryavtsev,<sup>33</sup> T. Kvaratskheliya,<sup>30,37</sup> V. N. La Thi,<sup>38</sup> D. Lacarrere,<sup>37</sup> G. Lafferty,<sup>53</sup> A. Lai,<sup>15</sup> D. Lambert,<sup>49</sup> R. W. Lambert,<sup>41</sup> E. Lanciotti,<sup>37</sup> G. Lanfranchi,<sup>18</sup> C. Langenbruch,<sup>37</sup> T. Latham,<sup>47</sup> C. Lazzeroni,<sup>44</sup> R. Le Gac,<sup>6</sup> J. van Leerdam,<sup>40</sup> J.-P. Lees,<sup>4</sup> R. Lefèvre,<sup>5</sup> A. Leflat,<sup>31</sup> J. Lefrançois,<sup>7</sup> S. Leo,<sup>22</sup> O. Leroy,<sup>6</sup> T. Lesiak,<sup>25</sup> B. Leverington,<sup>11</sup> Y. Li,<sup>3</sup> L. Li Gioi,<sup>5</sup> M. Liles,<sup>51</sup> R. Lindner,<sup>37</sup> C. Linn,<sup>11</sup> B. Liu,<sup>3</sup> G. Liu,<sup>37</sup> S. Lohn,<sup>37</sup> I. Longstaff,<sup>50</sup> J. H. Lopes,<sup>2</sup> E. Lopez Asamar,<sup>35</sup> N. Lopez-March,<sup>38</sup> H. Lu,<sup>3</sup> D. Lucchesi,<sup>21,q</sup> J. Luisier,<sup>38</sup> H. Luo,<sup>49</sup> F. Machefert,<sup>7</sup> I. V. Machikhiliyan,<sup>4,30</sup> F. Maciuc,<sup>28</sup> O. Maev,<sup>29,37</sup> S. Malde,<sup>54</sup> G. Manca,<sup>15,d</sup> G. Mancinelli,<sup>6</sup> U. Marconi,<sup>14</sup> R. Märki,<sup>38</sup> J. Marks,<sup>11</sup> G. Martellotti,<sup>24</sup> A. Martens,<sup>8</sup> L. Martin,<sup>54</sup> A. Martín Sánchez,<sup>7</sup> M. Martinelli,<sup>40</sup> D. Martinez Santos,<sup>41</sup> D. Martins Tostes,<sup>2</sup> A. Massafferri,<sup>1</sup> R. Matev,<sup>37</sup> Z. Mathe,<sup>37</sup> C. Matteuzzi,<sup>20</sup> E. Maurice,<sup>6</sup> A. Mazurov,<sup>16,32,37,e</sup> J. McCarthy,<sup>44</sup> A. McNab,<sup>53</sup> R. McNulty,<sup>12</sup> B. Meadows,<sup>56,54</sup> F. Meier,<sup>9</sup> M. Meissner,<sup>11</sup> M. Merk,<sup>40</sup> D. A. Milanes,<sup>8</sup> M.-N. Minard,<sup>4</sup> J. Molina Rodriguez,<sup>59</sup> S. Monteil,<sup>5</sup> D. Moran,<sup>53</sup> P. Morawski,<sup>25</sup> M. J. Morello,<sup>22,s</sup> R. Mountain,<sup>58</sup> I. Mous,<sup>40</sup> F. Muheim,<sup>49</sup> K. Müller,<sup>39</sup> R. Muresan,<sup>28</sup> B. Muryn,<sup>26</sup> B. Muster,<sup>38</sup> P. Naik,<sup>45</sup> T. Nakada,<sup>38</sup> R. Nandakumar,<sup>48</sup> I. Nasteva,<sup>1</sup> M. Needham,<sup>49</sup> N. Neufeld,<sup>37</sup> A. D. Nguyen,<sup>38</sup> T. D. Nguyen,<sup>38</sup> C. Nguyen-Mau,<sup>38,p</sup> M. Nicol,<sup>7</sup> V. Niess,<sup>5</sup> R. Niet,<sup>9</sup> N. Nikitin,<sup>31</sup> T. Nikodem,<sup>11</sup> A. Nomerotski,<sup>54</sup> A. Novoselov,<sup>34</sup> A. Oblakowska-Mucha,<sup>26</sup> V. Obraztsov,<sup>34</sup> S. Oggero,<sup>40</sup> S. Ogilvy,<sup>50</sup> O. Okhrimenko,<sup>43</sup> R. Oldeman,<sup>15,d</sup> M. Orlandea,<sup>28</sup> J. M. Otorola Goicochea,<sup>2</sup> P. Owen,<sup>52</sup> A. Oyanguren,<sup>35,o</sup> B. K. Pal,<sup>58</sup> A. Palano,<sup>13,b</sup> M. Palutan,<sup>18</sup> J. Panman,<sup>37</sup> A. Papanestis,<sup>48</sup> M. Pappagallo,<sup>50</sup> C. Parkes,<sup>53</sup> C. J. Parkinson,<sup>52</sup> G. Passaleva,<sup>17</sup> G. D. Patel,<sup>51</sup> M. Patel,<sup>52</sup> G. N. Patrick,<sup>48</sup> C. Patrignani,<sup>19,i</sup> C. Pavel-Nicorescu,<sup>28</sup> A. Pazos Alvarez,<sup>36</sup> A. Pellegrino,<sup>40</sup> G. Penso,<sup>24,l</sup> M. Pepe Altarelli,<sup>37</sup> S. Perazzini,<sup>14,c</sup> D. L. Perego,<sup>20,j</sup> E. Perez Trigo,<sup>36</sup> A. Pérez-Calero Yzquierdo,<sup>35</sup> P. Perret,<sup>5</sup> M. Perrin-Terrin,<sup>6</sup> G. Pessina,<sup>20</sup> K. Petridis,<sup>52</sup> A. Petrolini,<sup>19,i</sup> A. Phan,<sup>58</sup> E. Picatoste Olloqui,<sup>35</sup> B. Pietrzyk,<sup>4</sup> T. Pilař,<sup>47</sup> D. Pinci,<sup>24</sup> S. Playfer,<sup>49</sup> M. Plo Casasus,<sup>36</sup> F. Polci,<sup>8</sup> G. Polok,<sup>25</sup> A. Poluektov,<sup>47,33</sup> E. Polcarpo,<sup>2</sup> A. Popov,<sup>34</sup> D. Popov,<sup>10</sup> B. Popovici,<sup>28</sup> C. Potterat,<sup>35</sup> A. Powell,<sup>54</sup> J. Prisciandaro,<sup>38</sup> V. Pugatch,<sup>43</sup> A. Puig Navarro,<sup>38</sup> G. Punzi,<sup>22,f</sup> W. Qian,<sup>4</sup> J. H. Rademacker,<sup>45</sup> B. Rakotomiamanana,<sup>38</sup> M. S. Rangel,<sup>2</sup> I. Raniuk,<sup>42</sup> N. Rauschmayr,<sup>37</sup> G. Raven,<sup>41</sup> S. Redford,<sup>54</sup> M. M. Reid,<sup>47</sup> A. C. dos Reis,<sup>1</sup> S. Ricciardi,<sup>48</sup> A. Richards,<sup>52</sup> K. Rinnert,<sup>51</sup> V. Rives Molina,<sup>35</sup> D. A. Roa Romero,<sup>5</sup> P. Robbe,<sup>7</sup> E. Rodrigues,<sup>53</sup> P. Rodriguez Perez,<sup>36</sup> S. Roiser,<sup>37</sup> V. Romanovsky,<sup>34</sup> A. Romero Vidal,<sup>36</sup> J. Rouvinet,<sup>38</sup> T. Ruf,<sup>37</sup> F. Ruffini,<sup>22</sup> H. Ruiz,<sup>35</sup> P. Ruiz Valls,<sup>35,o</sup> G. Sabatino,<sup>24,k</sup> J. J. Saborido Silva,<sup>36</sup> N. Sagidova,<sup>29</sup> P. Sail,<sup>50</sup> B. Saitta,<sup>15,d</sup> V. Salustino Guimaraes,<sup>2</sup> C. Salzmann,<sup>39</sup> B. Sanmartin Sedes,<sup>36</sup> M. Sannino,<sup>19,i</sup> R. Santacesaria,<sup>24</sup> C. Santamarina Rios,<sup>36</sup> E. Santovetti,<sup>23,k</sup> M. Sapunov,<sup>6</sup> A. Sarti,<sup>18,l</sup> C. Satriano,<sup>24,m</sup> A. Satta,<sup>23</sup> M. Savrie,<sup>16,e</sup> D. Savrina,<sup>30,31</sup> P. Schaack,<sup>52</sup> M. Schiller,<sup>41</sup> H. Schindler,<sup>37</sup> M. Schlupp,<sup>9</sup> M. Schmelling,<sup>10</sup> B. Schmidt,<sup>37</sup> O. Schneider,<sup>38</sup> A. Schopper,<sup>37</sup> M.-H. Schune,<sup>7</sup> R. Schwemmer,<sup>37</sup> B. Sciascia,<sup>18</sup> A. Sciubba,<sup>24</sup> M. Seco,<sup>36</sup> A. Semennikov,<sup>30</sup> K. Senderowska,<sup>26</sup> I. Sepp,<sup>52</sup> N. Serra,<sup>39</sup> J. Serrano,<sup>6</sup> P. Seyfert,<sup>11</sup> M. Shapkin,<sup>34</sup> I. Shapoval,<sup>16,42</sup> P. Shatalov,<sup>30</sup> Y. Shcheglov,<sup>29</sup> T. Shears,<sup>51,37</sup> L. Shekhtman,<sup>33</sup> O. Shevchenko,<sup>42</sup> V. Shevchenko,<sup>30</sup> A. Shires,<sup>52</sup> R. Silva Coutinho,<sup>47</sup> T. Skwarnicki,<sup>58</sup> N. A. Smith,<sup>51</sup> E. Smith,<sup>54,48</sup> M. Smith,<sup>53</sup> M. D. Sokoloff,<sup>56</sup> F. J. P. Soler,<sup>50</sup> F. Soomro,<sup>18</sup> D. Souza,<sup>45</sup> B. Souza De Paula,<sup>2</sup> B. Spaan,<sup>9</sup> A. Sparkes,<sup>49</sup> P. Spradlin,<sup>50</sup> F. Stagni,<sup>37</sup> S. Stahl,<sup>11</sup> O. Steinkamp,<sup>39</sup> S. Stoica,<sup>28</sup> S. Stone,<sup>58</sup> B. Storaci,<sup>39</sup> M. Straticiuc,<sup>28</sup> U. Straumann,<sup>39</sup> V. K. Subbiah,<sup>37</sup> L. Sun,<sup>56</sup> S. Swientek,<sup>9</sup> V. Syropoulos,<sup>41</sup> M. Szczekowski,<sup>27</sup> P. Szczypka,<sup>38,37</sup> T. Szumlak,<sup>26</sup> S. T'Jampens,<sup>4</sup> M. Teklishyn,<sup>7</sup> E. Teodorescu,<sup>28</sup> F. Teubert,<sup>37</sup> C. Thomas,<sup>54</sup> E. Thomas,<sup>37</sup> J. van Tilburg,<sup>11</sup> V. Tisserand,<sup>4</sup> M. Tobin,<sup>38</sup> S. Tolck,<sup>41</sup> D. Tonelli,<sup>37</sup> S. Topp-Joergensen,<sup>54</sup> N. Torr,<sup>54</sup> E. Tournefier,<sup>4,52</sup> S. Tourneur,<sup>38</sup> M. T. Tran,<sup>38</sup> M. Tresch,<sup>39</sup> A. Tsaregorodtsev,<sup>6</sup> P. Tsopelas,<sup>40</sup> N. Tuning,<sup>40</sup> M. Ubeda Garcia,<sup>37</sup> A. Ukleja,<sup>27</sup> D. Urner,<sup>53</sup> U. Uwer,<sup>11</sup> V. Vagnoni,<sup>14</sup> G. Valenti,<sup>14</sup> R. Vazquez Gomez,<sup>35</sup> P. Vazquez Regueiro,<sup>36</sup> S. Vecchi,<sup>16</sup> J. J. Velthuis,<sup>45</sup> M. Veltri,<sup>17,g</sup> G. Veneziano,<sup>38</sup> M. Vesterinen,<sup>37</sup> B. Viaud,<sup>7</sup> D. Vieira,<sup>2</sup> X. Vilasis-Cardona,<sup>35,n</sup> A. Vollhardt,<sup>39</sup> D. Volyanskyy,<sup>10</sup> D. Voong,<sup>45</sup> A. Vorobyev,<sup>29</sup> V. Vorobyev,<sup>33</sup> C. Voß,<sup>60</sup> H. Voss,<sup>10</sup> R. Waldi,<sup>60</sup> R. Wallace,<sup>12</sup> S. Wandernoth,<sup>11</sup> J. Wang,<sup>58</sup> D. R. Ward,<sup>46</sup> N. K. Watson,<sup>44</sup> A. D. Webber,<sup>53</sup> D. Websdale,<sup>52</sup> M. Whitehead,<sup>47</sup> J. Wicht,<sup>37</sup> J. Wiechczynski,<sup>25</sup> D. Wiedner,<sup>11</sup> L. Wiggers,<sup>40</sup> G. Wilkinson,<sup>54</sup> M. P. Williams,<sup>47,48</sup> M. Williams,<sup>55</sup> F. F. Wilson,<sup>48</sup> J. Wishahi,<sup>9</sup> M. Witek,<sup>25</sup> S. A. Wotton,<sup>46</sup> S. Wright,<sup>46</sup> S. Wu,<sup>3</sup> K. Wyllie,<sup>37</sup> Y. Xie,<sup>49,37</sup> F. Xing,<sup>54</sup> Z. Xing,<sup>58</sup> Z. Yang,<sup>3</sup> R. Young,<sup>49</sup> X. Yuan,<sup>3</sup> O. Yushchenko,<sup>34</sup> M. Zangoli,<sup>14</sup> M. Zavertyaev,<sup>10,a</sup> F. Zhang,<sup>3</sup> L. Zhang,<sup>58</sup> W. C. Zhang,<sup>12</sup> Y. Zhang,<sup>3</sup> A. Zhelezov,<sup>11</sup> A. Zhokhov,<sup>30</sup> L. Zhong,<sup>3</sup> and A. Zvyagin<sup>37</sup>



## (LHCb Collaboration)

- <sup>1</sup>Centro Brasileiro de Pesquisas Físicas (CBPF), Rio de Janeiro, Brazil  
<sup>2</sup>Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil  
<sup>3</sup>Center for High Energy Physics, Tsinghua University, Beijing, China  
<sup>4</sup>LAPP, Université de Savoie, CNRS/IN2P3, Annecy-Le-Vieux, France  
<sup>5</sup>Clermont Université, Université Blaise Pascal, CNRS/IN2P3, LPC, Clermont-Ferrand, France  
<sup>6</sup>CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France  
<sup>7</sup>LAL, Université Paris-Sud, CNRS/IN2P3, Orsay, France  
<sup>8</sup>LPNHE, Université Pierre et Marie Curie, Université Paris Diderot, CNRS/IN2P3, Paris, France  
<sup>9</sup>Fakultät Physik, Technische Universität Dortmund, Dortmund, Germany  
<sup>10</sup>Max-Planck-Institut für Kernphysik (MPIK), Heidelberg, Germany  
<sup>11</sup>Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany  
<sup>12</sup>School of Physics, University College Dublin, Dublin, Ireland  
<sup>13</sup>Sezione INFN di Bari, Bari, Italy  
<sup>14</sup>Sezione INFN di Bologna, Bologna, Italy  
<sup>15</sup>Sezione INFN di Cagliari, Cagliari, Italy  
<sup>16</sup>Sezione INFN di Ferrara, Ferrara, Italy  
<sup>17</sup>Sezione INFN di Firenze, Firenze, Italy  
<sup>18</sup>Laboratori Nazionali dell'INFN di Frascati, Frascati, Italy  
<sup>19</sup>Sezione INFN di Genova, Genova, Italy  
<sup>20</sup>Sezione INFN di Milano Bicocca, Milano, Italy  
<sup>21</sup>Sezione INFN di Padova, Padova, Italy  
<sup>22</sup>Sezione INFN di Pisa, Pisa, Italy  
<sup>23</sup>Sezione INFN di Roma Tor Vergata, Roma, Italy  
<sup>24</sup>Sezione INFN di Roma La Sapienza, Roma, Italy  
<sup>25</sup>Henryk Niewodniczanski Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland  
<sup>26</sup>Faculty of Physics and Applied Computer Science, AGH University of Science and Technology, Kraków, Poland  
<sup>27</sup>National Center for Nuclear Research (NCBJ), Warsaw, Poland  
<sup>28</sup>Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest-Magurele, Romania  
<sup>29</sup>Petersburg Nuclear Physics Institute (PNPI), Gatchina, Russia  
<sup>30</sup>Institute of Theoretical and Experimental Physics (ITEP), Moscow, Russia  
<sup>31</sup>Institute of Nuclear Physics, Moscow State University (SINP MSU), Moscow, Russia  
<sup>32</sup>Institute for Nuclear Research of the Russian Academy of Sciences (INR RAN), Moscow, Russia  
<sup>33</sup>Budker Institute of Nuclear Physics (SB RAS) and Novosibirsk State University, Novosibirsk, Russia  
<sup>34</sup>Institute for High Energy Physics (IHEP), Protvino, Russia  
<sup>35</sup>Universitat de Barcelona, Barcelona, Spain  
<sup>36</sup>Universidad de Santiago de Compostela, Santiago de Compostela, Spain  
<sup>37</sup>European Organization for Nuclear Research (CERN), Geneva, Switzerland  
<sup>38</sup>Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland  
<sup>39</sup>Physik-Institut, Universität Zürich, Zürich, Switzerland  
<sup>40</sup>Nikhef National Institute for Subatomic Physics, Amsterdam, The Netherlands  
<sup>41</sup>Nikhef National Institute for Subatomic Physics and VU University Amsterdam, Amsterdam, The Netherlands  
<sup>42</sup>NSC Kharkiv Institute of Physics and Technology (NSC KIPT), Kharkiv, Ukraine  
<sup>43</sup>Institute for Nuclear Research of the National Academy of Sciences (KINR), Kyiv, Ukraine  
<sup>44</sup>University of Birmingham, Birmingham, United Kingdom  
<sup>45</sup>H. H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom  
<sup>46</sup>Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom  
<sup>47</sup>Department of Physics, University of Warwick, Coventry, United Kingdom  
<sup>48</sup>STFC Rutherford Appleton Laboratory, Didcot, United Kingdom  
<sup>49</sup>School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom  
<sup>50</sup>School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom  
<sup>51</sup>Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom  
<sup>52</sup>Imperial College London, London, United Kingdom  
<sup>53</sup>School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom  
<sup>54</sup>Department of Physics, University of Oxford, Oxford, United Kingdom  
<sup>55</sup>Massachusetts Institute of Technology, Cambridge, Massachusetts, USA  
<sup>56</sup>University of Cincinnati, Cincinnati, Ohio, USA  
<sup>57</sup>University of Maryland, College Park, Maryland, USA

<sup>58</sup>*Syracuse University, Syracuse, New York, USA*

<sup>59</sup>*Pontifícia Universidade Católica do Rio de Janeiro (PUC-Rio), Rio de Janeiro, Brazil (associated with Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil)*

<sup>60</sup>*Institut für Physik, Universität Rostock, Rostock, Germany (associated with Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany)*

<sup>a</sup>Also at P.N. Lebedev Physical Institute, Russian Academy of Science (LPI RAS), Moscow, Russia.

<sup>b</sup>Also at Università di Bari, Bari, Italy.

<sup>c</sup>Also at Università di Bologna, Bologna, Italy.

<sup>d</sup>Also at Università di Cagliari, Cagliari, Italy.

<sup>e</sup>Also at Università di Ferrara, Ferrara, Italy.

<sup>f</sup>Also at Università di Firenze, Firenze, Italy.

<sup>g</sup>Also at Università di Urbino, Urbino, Italy.

<sup>h</sup>Also at Università di Modena e Reggio Emilia, Modena, Italy.

<sup>i</sup>Also at Università di Genova, Genova, Italy.

<sup>j</sup>Also at Università di Milano Bicocca, Milano, Italy.

<sup>k</sup>Also at Università di Roma Tor Vergata, Roma, Italy.

<sup>l</sup>Also at Università di Roma La Sapienza, Roma, Italy.

<sup>m</sup>Also at Università della Basilicata, Potenza, Italy.

<sup>n</sup>Also at LIFAELS, La Salle, Universitat Ramon Llull, Barcelona, Spain.

<sup>o</sup>Also at IFIC, Universitat de Valencia-CSIC, Valencia, Spain.

<sup>p</sup>Also at Hanoi University of Science, Hanoi, Vietnam.

<sup>q</sup>Also at Università di Padova, Padova, Italy.

<sup>r</sup>Also at Università di Pisa, Pisa, Italy.

<sup>s</sup>Also at Scuola Normale Superiore, Pisa, Italy.