Search for *CP* Violation in $D_s^+ \to K_S^0\pi^+$, $D^+ \to K_S^0K^+$, and $D^+ \to \phi\pi^+$ Decays

R. Aaij *et al.*[*]
(LHCb Collaboration)

(Received 5 March 2019; published 17 May 2019)

A search for charge-parity (CP) violation in Cabibbo-suppressed $D_s^+ \to K_S^0\pi^+$, $D^+ \to K_S^0K^+$, and $D^+ \to \phi\pi^+$ decays is reported using proton-proton collision data, corresponding to an integrated luminosity of 3.8 fb^{-1}, collected at a center-of-mass energy of 13 TeV with the LHCb detector. High-yield samples of kinematically and topologically similar Cabibbo-favored $D_{(s)}^+$ decays are analyzed to subtract nuisance asymmetries due to production and detection effects, including those induced by CP violation in the neutral kaon system. The results are

$$\mathcal{A}_{CP}(D_s^+ \to K_S^0\pi^+) = (1.3 \pm 1.9 \pm 0.5) \times 10^{-3},$$
$$\mathcal{A}_{CP}(D^+ \to K_S^0K^+) = (-0.09 \pm 0.65 \pm 0.48) \times 10^{-3},$$
$$\mathcal{A}_{CP}(D^+ \to \phi\pi^+) = (0.05 \pm 0.42 \pm 0.29) \times 10^{-3},$$

where the first uncertainties are statistical and the second systematic. They are the most precise measurements of these quantities to date, and are consistent with CP symmetry. A combination with previous LHCb measurements, based on data collected at 7 and 8 TeV, is also reported.

DOI: 10.1103/PhysRevLett.122.191803

Violation of charge-parity (CP) symmetry arises in the standard model (SM) of particle physics through the complex phase of the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [1,2]. CP violation is well established in K- and B-meson systems [3–7], and has been observed only recently in charm decays [8]. CP violation in charm decays can arise from the interference between tree- and loop-level diagrams through Cabibbo-suppressed $c \to d\bar{d}u$ and $c \to s\bar{s}u$ transition amplitudes. In the loop-level processes, contributions from physics beyond the SM may arise that can lead to additional sources of CP violation [9]. However, the expected SM contribution is difficult to compute due to the presence of low-energy strong-interaction effects, with current predictions spanning several orders of magnitude [9–13]. A promising handle to determine the origin of possible CP-violation signals are correlations between CP asymmetries in flavor-$SU(3)$ related decays [14–22]. Particularly interesting in this respect are D_s^+ and D^+ decays to two-body (or quasi-two-body) final states, such as $D_s^+ \to K_S^0\pi^+$, $D^+ \to K_S^0K^+$, and $D^+ \to \phi\pi^+$. (The inclusion of charge-conjugate processes is implied throughout this Letter, unless stated otherwise.) Searches for CP violation in these modes have been performed by the CLEO [23], *BABAR* [24,25], Belle [26–28], and LHCb [29,30] collaborations. No evidence for CP violation has been found within a precision of a few per mille.

This Letter presents measurements of CP asymmetries in $D_s^+ \to K_S^0\pi^+$, $D^+ \to K_S^0K^+$, and $D^+ \to \phi\pi^+$ decays performed using proton-proton collision data collected with the LHCb detector between 2015 and 2017 at a center-of-mass energy of 13 TeV, and corresponding to an integrated luminosity of 3.8 fb^{-1}. In the presence of a K_S^0 meson in the final state, a CP asymmetry is expected to be induced by K^0–$\overline{K}^0$ mixing [31]. This effect is well known and predictable, allowing for a precise measurement of CP violation in the charm-quark transition. The $D^+ \to \phi\pi^+$ decay is reconstructed with the $\phi \to K^+K^-$ mode. Several intermediate states contribute to the $D^+ \to K^+K^-\pi^+$ decay amplitude [32]. In this Letter, no attempt is made to separate them through an amplitude analysis, and the measurement is performed by simply restricting the K^+K^- pair to the mass region around the $\phi(1020)$ resonance.

The CP asymmetry of a $D_{(s)}^+$ meson decaying to the final state f^+ is defined as

$$\mathcal{A}_{CP}(D_{(s)}^+ \to f^+) \equiv \frac{\Gamma(D_{(s)}^+ \to f^+) - \Gamma(D_{(s)}^- \to f^-)}{\Gamma(D_{(s)}^+ \to f^+) + \Gamma(D_{(s)}^- \to f^-)}, \quad (1)$$

where Γ is the partial decay rate. If CP symmetry is violated in the decay, $\mathcal{A}_{CP} \neq 0$. An experimentally

---

[*] Full author list given at the end of the article.

convenient quantity to measure is the "raw" asymmetry of the observed yields N,

$$A(D^+_{(s)} \to f^+) \equiv \frac{N(D^+_{(s)} \to f^+) - N(D^-_{(s)} \to f^-)}{N(D^+_{(s)} \to f^+) + N(D^-_{(s)} \to f^-)}. \quad (2)$$

The raw asymmetry can be approximated as

$$A(D^+_{(s)} \to f^+) \approx \mathcal{A}_{CP}(D^+_{(s)} \to f^+) + A_P(D^+_{(s)}) + A_D(f^+), \quad (3)$$

where $A_P(D^+_{(s)})$ is the asymmetry of the $D^+_{(s)}$-meson production cross section [33,34] and $A_D(f^+)$ is the asymmetry of the reconstruction efficiency for the final state f^+. When $f^+ = K^0_S h^+$ (with $h = K, \pi$), the detection asymmetry receives contributions from the h^+ hadron (indicated as companion hadron in the following), $A_D(h^+)$, and from the neutral kaon, $A_D(\overline{K}^0)$. Relevant instrumental effects contributing to $A_D(h^+)$ may include differences in interaction cross sections with matter between positive and negative hadrons and the slightly charge-asymmetric performance of the reconstruction algorithms. The contribution to $A_D(\overline{K}^0)$ arises from K^0 and $\bar{K}^0$ mesons having different interaction cross sections with matter and from their propagation in the detector being affected by the presence of CP violation in the K^0–$\overline{K}^0$ system. When $f^+ = \phi(\to K^+K^-)\pi^+$, the detection asymmetry is mostly due to the charged pion, as the contributions from the oppositely charged kaons cancel to a good precision.

The detection and production asymmetries are canceled by using the decays $D^+ \to K^0_S\pi^+$, $D^+_s \to K^0_S K^+$, and $D^+_s \to \phi\pi^+$, which proceed through the Cabibbo-favored $c \to s\bar{d}u$ transition. In the SM, these decays are expected to have CP asymmetries that are negligibly small compared to the Cabibbo-suppressed modes, when effects induced by the neutral kaons are excluded [31,35]. Hence, their raw asymmetries can be approximated as in Eq. (3), but with $\mathcal{A}_{CP} = 0$. The CP asymmetries of the decay modes of interest are determined by combining the raw asymmetries as follows:

$$\mathcal{A}_{CP}(D^+_s \to K^0_S\pi^+) \approx A(D^+_s \to K^0_S\pi^+) - A(D^+_s \to \phi\pi^+), \quad (4)$$

$$\mathcal{A}_{CP}(D^+ \to K^0_S K^+) \approx A(D^+ \to K^0_S K^+) - A(D^+ \to K^0_S\pi^+) - A(D^+_s \to K^0_S K^+) + A(D^+_s \to \phi\pi^+), \quad (5)$$

$$\mathcal{A}_{CP}(D^+ \to \phi\pi^+) \approx A(D^+ \to \phi\pi^+) - A(D^+ \to K^0_S\pi^+), \quad (6)$$

where the contribution from $A_D(\overline{K}^0)$ is omitted and should be subtracted from any of the measured asymmetries where it is present.

The LHCb detector [36,37] is a single-arm forward spectrometer designed for the study of particles containing b or c quarks. The detector elements that are particularly relevant to this analysis are a silicon-strip vertex detector that allows for a precise measurement of the impact parameter, i.e., the minimum distance of a charged-particle trajectory to a pp interaction point (primary vertex), a tracking system that provides a measurement of the momentum of charged particles, two ring-imaging Cherenkov detectors that are able to discriminate between different species of charged hadrons, and a calorimeter system that is used for the identification of photons, electrons and hadrons. The polarity of the magnetic field is periodically reversed during data-taking to mitigate the differences between reconstruction efficiencies of oppositely charged particles.

The online event selection is performed by a trigger, which consists of a hardware stage followed by a two-level software stage. In between the two software stages, an alignment and calibration of the detector is performed in near real-time and their results are used in the trigger [38]. Events with candidate $D^+_{(s)}$ decays are selected by the hardware trigger by imposing either that one or more $D^+_{(s)}$ decay products are associated with large transverse energy deposits in the calorimeter or that the accept decision is independent of the $D^+_{(s)}$ decay products (i.e., it is caused by other particles in the event). In the first level of the software trigger, one or more $D^+_{(s)}$ decay products must have large transverse momentum and be inconsistent with originating from any primary vertex. In the second level, the candidate decays are fully reconstructed using kinematic, topological and particle-identification criteria. The $D^+_{(s)} \to K^0_S h^+$ candidates are made by combining charged hadrons with $K^0_S \to \pi^+\pi^-$ candidates that decay early enough for the final-state pions to be reconstructed in the vertex detector. This requirement suppresses to a negligible level possible CP-violation effects due to interference between Cabibbo-favored and doubly Cabibbo-suppressed amplitudes with neutral-kaon mixing in the control-sample decays $D^+ \to K^0_S\pi^+$ and $D^+_s \to K^0_S K^+$ [35].

The $D^+_{(s)}$ candidates reconstructed in the trigger are used directly in the offline analysis [39,40]. The candidates with a K^0_S meson in the final state are further selected offline using an artificial neural network (NN), based on the multilayer perceptron algorithm [41], to suppress background due to random combinations of K^0_S mesons and hadrons not originating from a $D^+_{(s)} \to K^0_S h^+$ decay. The quantities used in the NN to discriminate signal from combinatorial background are the K^0_S candidate momentum, the transverse momenta of the $D^+_{(s)}$ candidate and of the companion hadron, the angle between the $D^+_{(s)}$ candidate momentum and the vector connecting the primary and secondary vertices, the quality of the secondary vertex, and the track quality of the companion hadron. The NN is trained using signal and background data samples, obtained with the *sPlot* method [42], from a $\mathcal{O}(1\%)$ fraction of candidates randomly sampled. In the $D_s^+ \to K_S^0\pi^+$ case, thanks to similar kinematics, background-subtracted $D^+ \to K_S^0\pi^+$ decays are exploited as a signal proxy to profit from larger yields. The thresholds on the NN response are optimized for the $D_s^+ \to K_S^0\pi^+$ and $D^+ \to K_S^0K^+$ decays by maximizing the value of $S/\sqrt{S+B}$, where S and B stands for the signal and background yield observed in the mass ranges $1.93 < m(K_S^0\pi^+) < 2.01\ \mathrm{GeV}/c^2$ and $1.83 < m(K_S^0K^+) < 1.91\ \mathrm{GeV}/c^2$, respectively. Candidate $D_{(s)}^+ \to \phi(\to K^+K^-)\pi^+$ decays are selected offline with requirements on the transverse momenta of the $D_{(s)}^+$ candidate and of the companion hadron, on the quality of the secondary vertex, and on the K^+K^- mass to be within $10\ \mathrm{MeV}/c^2$ of the nominal $\phi(1020)$-meson mass [32]. The mass window is chosen considering that the observed width is dominated by the $\phi(1020)$-meson natural width of $4.2\ \mathrm{MeV}/c^2$ [32] and is only marginally affected by the experimental resolution of $1.3\ \mathrm{MeV}/c^2$.

The contribution of $D_{(s)}^+$ mesons produced through decays of b hadrons, referred to as secondaries throughout, is suppressed by requiring that the $D_{(s)}^+$ impact parameter in the plane transverse to the beam (TIP) is smaller than 40 μm. The remaining percent-level contribution is evaluated by means of a fit to the TIP distribution when such requirement is released, as shown in Fig. 1 for the $D_s^+ \to K_S^0\pi^+$ decay. The impact of the secondary background on the results is accounted for in the systematic uncertainties.

Typical sources of background from $D_{(s)}^+$ meson and Λ_c^+ baryon decays are the $D_s^+ \to K_S^0K^+$ and $\Lambda_c^+ \to K_S^0p$ decays, where the kaon and the proton are misidentified as a pion, when the signal is the $D_s^+ \to K_S^0\pi^+$ decay, the $D^+ \to K_S^0\pi^+$ and $\Lambda_c^+ \to K_S^0p$ decays, where the pion and the proton are misidentified as a kaon, in the $D^+ \to K_S^0K^+$ case, and the $\Lambda_c^+ \to \phi p$ decay, where the proton is misidentified as a pion, when the signal is the $D^+ \to \phi\pi^+$ decay. These are all reduced to a negligible level using particle-identification requirements and kinematic vetos.

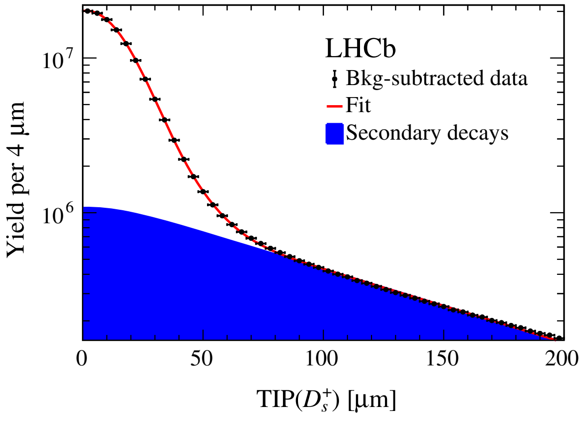

FIG. 1. Distribution of the transverse impact parameter (TIP) for background-subtracted $D_s^+ \to K_S^0\pi^+$ candidates with fit projections overlaid.

Fiducial requirements are imposed to exclude kinematic regions that induce a large asymmetry in the companion-hadron reconstruction efficiency. These regions occur because low momentum particles of one charge at large (small) angles in the bending plane may be deflected out of the detector acceptance (into the noninstrumented beam pipe region), whereas particles with the other charge are more likely to remain within the acceptance. About 78%, 93%, and 94% of the selected candidates are retained by these fiducial requirements for $D_{(s)}^+ \to K_S^0\pi^+$, $D_{(s)}^+ \to K_S^0K^+$, and $D_{(s)}^+ \to \phi\pi^+$ decays, respectively.

Detection and production asymmetries may depend on the kinematics of the involved particles. Therefore, the cancellation provided by the control decays is accurate only if the kinematic distributions agree between any pair of signal and control modes, or pair of control modes entering Eqs. (4)–(6). Differences are observed, and the ratio between background-subtracted [42] signal and control sample distributions of transverse momentum, azimuthal angle and pseudorapidity are used to define candidate-by-candidate weights. The background-subtracted candidates of the control decays are weighted such that their distributions agree with those of the signal using an iterative procedure. The process consists of calculating the weights in each one-dimensional distribution of the weighting variables and repeating the procedure until good agreement is achieved among all the distributions. For the measurements of the $D_s^+ \to K_S^0\pi^+$ and $D^+ \to \phi\pi^+$ CP asymmetries, the $D_s^+ \to \phi\pi^+$ and $D^+ \to K_S^0\pi^+$ control samples are weighted so that the $D_{(s)}^+$ meson and companion-pion kinematic distributions agree with their respective signal samples to cancel the $D_{(s)}^+$ production and companion-pion detection asymmetries. In the case of the $\mathcal{A}_{CP}(D^+ \to K_S^0K^+)$ measurement, the D^+ kinematic distributions of the $D^+ \to K_S^0\pi^+$ sample are weighted to those of the $D^+ \to K_S^0K^+$ signal to cancel the D^+ production asymmetry, and the K^+ distributions of the $D_s^+ \to K_S^0K^+$ decays are weighted to those of the $D^+ \to K_S^0K^+$ signal to cancel the kaon detection asymmetry. The $D^+ \to K_S^0\pi^+$ and $D_s^+ \to K_S^0K^+$ control decays then introduce their own additional nuisance asymmetries, which need to be corrected for using the $D_s^+ \to \phi\pi^+$ control decay. Hence, the D_s^+ and companion-pion kinematic distributions of the $D_s^+ \to \phi\pi^+$ sample are made to agree with those of the $D_s^+ \to K_S^0K^+$ and $D^+ \to K_S^0\pi^+$ samples, respectively, to cancel the D_s^+ production and companion-pion detection asymmetries.

Simultaneous least-squares fits to the mass distributions of weighted $D^+_{(s)}$ and $D^-_{(s)}$ candidates determine the raw asymmetries for each decay mode considered. To avoid experimenter bias, the raw asymmetries of the Cabibbo-suppressed signals were shifted by unknown offsets sampled uniformly between -1% and 1%, such that the results remained blind until the analysis procedure was finalized. In the fits, the signal and control decays are modeled as the sum of a Gaussian function to describe the core of the peaks, and a Johnson S_U distribution [43], which accounts for the asymmetric tails. The combinatorial background is described by the sum of two exponential functions. All shape parameters are determined from the data. In each fit, signal and control decays share the same shape parameters apart from a mass shift, which accounts for the known difference between the D^+_s and D^+ masses [32], and a relative scale factor between the peak widths, which is also determined from the data. The means and widths of the peaks, as well as all background shape parameters, are allowed to differ between $D^+_{(s)}$ and $D^-_{(s)}$ decays. The projections of the fits to the combined $D^+_{(s)}$ and $D^-_{(s)}$ data are shown in Fig. 2. The samples contain approximately 600 thousand $D^+_s \to K^0_S\pi^+$, 5.1 million $D^+ \to K^0_S K^+$, and 53.3 million $D^+ \to \phi\pi^+$ signal candidates, together with approximately 30.5 million $D^+ \to K^0_S\pi^+$, 6.5 million $D^+_s \to K^0_S K^+$, and 107 million $D^+_s \to \phi\pi^+$ control decays.

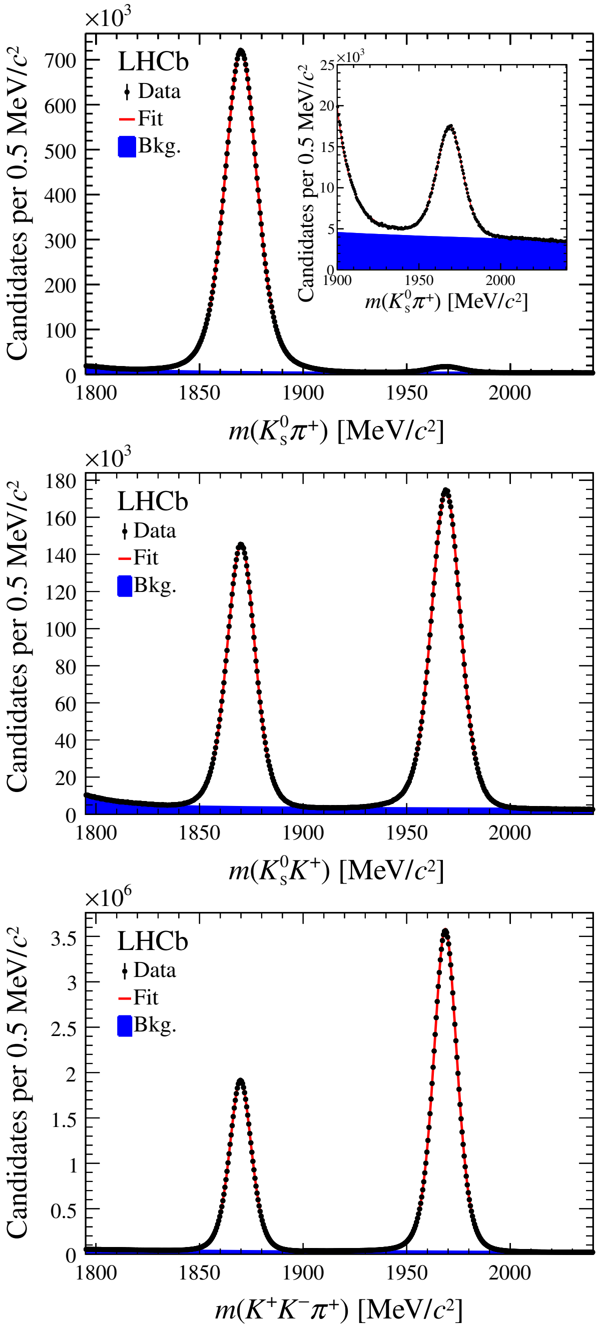

FIG. 2. Mass distributions of the selected (top) $D^+_{(s)} \to K^0_S\pi^+$, (middle) $D^+_{(s)} \to K^0_S K^+$, and (bottom) $D^+_{(s)} \to \phi\pi^+$ candidates with fit projections overlaid. The inset in the top plot shows the mass distribution around the $D^+_s \to K^0_S\pi^+$ signal region.

The raw asymmetries are, where relevant, corrected for the neutral-kaon detection asymmetry. The net correction is estimated following Ref. [44] to be $(+0.084 \pm 0.005)\%$ for $\mathcal{A}_{CP}(D^+_s \to K^0_S\pi^+)$, $(-0.086 \pm 0.005)\%$ for $\mathcal{A}_{CP}(D^+ \to K^0_S K^+)$, and $(-0.068 \pm 0.004)\%$ for $\mathcal{A}_{CP}(D^+ \to \phi\pi^+)$, where the uncertainty is dominated by the accuracy of the detector modeling in the simulation. The asymmetries are combined following Eqs. (4)–(6) to obtain $\mathcal{A}_{CP}(D^+_s \to K^0_S\pi^+) = (1.3 \pm 1.9) \times 10^{-3}$, $\mathcal{A}_{CP}(D^+ \to K^0_S K^+) = (-0.09 \pm 0.65) \times 10^{-3}$, $\mathcal{A}_{CP}(D^+ \to \phi\pi^+) = (0.05 \pm 0.42) \times 10^{-3}$, where the uncertainties are only statistical.

Several sources of systematic uncertainty affecting the measurement are considered as reported in Table I. The dominant contribution is due to the assumed shapes in the mass fits. This is evaluated by fitting with the default model large sets of pseudoexperiments where alternative models that describe data equally well are used in generation. For $\mathcal{A}_{CP}(D^+_s \to K^0_S\pi^+)$ and $\mathcal{A}_{CP}(D^+ \to K^0_S K^+)$, the second leading contribution is due to the residual

TABLE I. Summary of the systematic uncertainties (in units of 10^{-3}) on the measured quantities. The total is the sum in quadrature of the different contributions.

Source	$\mathcal{A}_{CP}$ $(D^+_s \to K^0_S\pi^+)$	$\mathcal{A}_{CP}$ $(D^+ \to K^0_S K^+)$	$\mathcal{A}_{CP}$ $(D^+ \to \phi\pi^+)$
Fit model	0.39	0.44	0.24
Secondary decays	0.30	0.12	0.03
Kinematic differences	0.09	0.09	0.04
Neutral kaon asymmetry	0.05	0.05	0.04
Charged kaon asymmetry	0.08	0.09	0.15
Total	0.51	0.48	0.29

contamination from secondary $D^+_{(s)}$ decays, which introduces a small difference between the asymmetry of $D^+_{(s)}$-meson production cross sections of the signal and control modes. For $\mathcal{A}_{CP}(D^+ \to \phi\pi^+)$, instead, the second leading systematic uncertainty arises from neglected kinematic differences between the ϕ-meson decay products. These differences, mainly caused by the interference between the S wave and $\phi\pi^+$ decay amplitudes in the K^+K^--mass region under study, result in an imperfect cancelation of the charged-kaon detection asymmetry. Other subleading contributions are due to the inaccuracy in the equalization of the kinematic distributions between signal and control samples, and to the uncertainty in the neutral-kaon detection asymmetry.

In addition, several consistency checks are performed to investigate possible unexpected biases by comparing results obtained in subsamples of the data defined according to the data-taking year and magnetic-field polarity, the per-event track multiplicity, the configurations of the hardware- and software-level triggers, and the $D^+_{(s)}$ momentum. A χ^2 test has been performed for each cross-check and the corresponding p values are consistent with being uniformly distributed; the lowest (largest) p value is 4% (86%). Therefore, the observed variations in results are consistent with statistical fluctuations and no additional sources of systematic uncertainties are considered.

In summary, using proton-proton collision data collected with the LHCb detector at a center-of-mass energy of 13 TeV, and corresponding to 3.8 fb^{-1} of integrated luminosity, the following CP asymmetries are measured:

$$\mathcal{A}_{CP}(D_s^+ \to K_S^0\pi^+) = (1.3 \pm 1.9 \pm 0.5) \times 10^{-3},$$
$$\mathcal{A}_{CP}(D^+ \to K_S^0K^+) = (-0.09 \pm 0.65 \pm 0.48) \times 10^{-3},$$
$$\mathcal{A}_{CP}(D^+ \to \phi\pi^+) = (0.05 \pm 0.42 \pm 0.29) \times 10^{-3},$$

where the first uncertainties are statistical and the second systematic. Effects induced by CP violation in the neutral kaon system are subtracted from the measured asymmetries. The results represent the most precise determination of these quantities to date and are consistent with CP symmetry. They are in agreement with previous LHCb determinations based on independent data samples collected at center-of-mass energies of 7 and 8 TeV [29,30], as well as with measurements from other experiments [23–28]. The results are combined with previous LHCb measurements using the BLUE method [45]. The systematic uncertainties are considered uncorrelated, apart from those due to the neutral- and charged-kaon detection asymmetries that are fully correlated. The combination yields

$$\mathcal{A}_{CP}(D_s^+ \to K_S^0\pi^+) = (1.6 \pm 1.7 \pm 0.5) \times 10^{-3},$$
$$\mathcal{A}_{CP}(D^+ \to K_S^0K^+) = (-0.04 \pm 0.61 \pm 0.45) \times 10^{-3},$$
$$\mathcal{A}_{CP}(D^+ \to \phi\pi^+) = (0.03 \pm 0.40 \pm 0.29) \times 10^{-3},$$

where the first uncertainties are statistical and the second systematic. No evidence for CP violation in these decays is found. More precise measurements of these asymmetries can be expected when the data already collected by LHCb in 2018 are included in a future analysis, and when much larger samples will become available at the upgraded LHCb detector [46].

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); MOST and NSFC (China); CNRS/IN2P3 (France); BMBF, DFG, and MPG (Germany); INFN (Italy); NWO (Netherlands); MNiSW and NCN (Poland); MEN/IFA (Romania); MSHE (Russia); MinECo (Spain); SNSF and SER (Switzerland); NASU (Ukraine); STFC (United Kingdom); and NSF (USA). We acknowledge the computing resources that are provided by CERN, IN2P3 (France), KIT and DESY (Germany), INFN (Italy), SURF (Netherlands), PIC (Spain), GridPP (United Kingdom), RRCKI and Yandex LLC (Russia), CSCS (Switzerland), IFIN-HH (Romania), CBPF (Brazil), PL-GRID (Poland), and OSC (USA). We are indebted to the communities behind the multiple open-source software packages on which we depend. Individual groups or members have received support from AvH Foundation (Germany); EPLANET, Marie Skłodowska-Curie Actions, and ERC (European Union); ANR, Labex P2IO and OCEVU, and Région Auvergne-Rhône-Alpes (France); Key Research Program of Frontier Sciences of CAS, CAS PIFI, and the Thousand Talents Program (China); RFBR, RSF, and Yandex LLC (Russia); GVA, XuntaGal, and GENCAT (Spain); the Royal Society and the Leverhulme Trust (United Kingdom); Laboratory Directed Research and Development program of LANL (USA).

---

[1] N. Cabibbo, Unitary Symmetry and Leptonic Decays, Phys. Rev. Lett. **10**, 531 (1963).

[2] M. Kobayashi and T. Maskawa, CP-violation in the renormalizable theory of weak interaction, Prog. Theor. Phys. **49**, 652 (1973).

[3] J. H. Christenson, J. W. Cronin, V. L. Fitch, and R. Turlay, Evidence for the 2π Decay of the K_2^0 Meson, Phys. Rev. Lett. **13**, 138 (1964).

[4] B. Aubert *et al.* (*BABAR* Collaboration), Direct CP Violating Asymmetry in $B^0 \to K^+\pi^-$ Decays, Phys. Rev. Lett. **93**, 131801 (2004).

[5] Y. Chao *et al.* (Belle Collaboration), Evidence for Direct CP Violation in $B^0 \to K^+\pi^-$ Decays, Phys. Rev. Lett. **93**, 191802 (2004).

[6] R. Aaij *et al.* (LHCb Collaboration), First Observation of CP Violation in the Decays of B_s^0 Mesons, Phys. Rev. Lett. **110**, 221601 (2013).

[7] R. Aaij *et al.* (LHCb Collaboration), Observation of CP violation in $B^{\pm} \to DK^{\pm}$ decays, Phys. Lett. B **712**, 203 (2012); Erratum, Phys. Lett. B **713**, 351(E) (2012).

[8] R. Aaij *et al.* (LHCb Collaboration), Observation of CP Violation in Charm Decays, arXiv:1903.08726 [Phys. Rev. Lett. (to be published)].

[9] Y. Grossman, A. L. Kagan, and Y. Nir, New physics and CP violation in singly Cabibbo suppressed D decays, Phys. Rev. D **75**, 036008 (2007).

[10] M. Golden and B. Grinstein, Enhanced CP violations in hadronic charm decays, Phys. Lett. B **222**, 501 (1989).

[11] F. Buccella, M. Lusignoli, G. Miele, A. Pugliese, and P. Santorelli, Nonleptonic weak decays of charmed mesons, Phys. Rev. D **51**, 3478 (1995).

[12] S. Bianco, F. L. Fabbri, D. Benson, and I. Bigi, A Cicerone for the physics of charm, Riv. Nuovo Cimento **26–7**, 1 (2003).

[13] M. Artuso, B. Meadows, and A. A. Petrov, Charm meson decays, Annu. Rev. Nucl. Part. Sci. **58**, 249 (2008).

[14] D. Pirtskhalava and P. Uttayarat, CP violation and flavor $SU(3)$ breaking in D-meson decays, Phys. Lett. B **712**, 81 (2012).

[15] H.-Y. Cheng and C.-W. Chiang, Direct CP violation in two-body hadronic charmed meson decays, Phys. Rev. D **85**, 034036 (2012); Erratum, Phys. Rev. D **85**, 079903(E) (2012).

[16] T. Feldmann, S. Nandi, and A. Soni, Repercussions of flavour symmetry breaking on CP violation in D-meson decays, J. High Energy Phys. 06 (2012) 007.

[17] H.-n. Li, C.-D. Lu, and F.-S. Yu, Branching ratios and direct CP asymmetries in $D \to PP$ decays, Phys. Rev. D **86**, 036012 (2012).

[18] E. Franco, S. Mishima, and L. Silvestrini, The Standard Model confronts CP violation in $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$, J. High Energy Phys. 05 (2012) 140.

[19] J. Brod, Y. Grossman, A. L. Kagan, and J. Zupan, A consistent picture for large penguins in $D^0 \to \pi^-\pi^+, K^-K^+$, J. High Energy Phys. 10 (2012) 161.

[20] D. Atwood and A. Soni, Searching for the origin of CP violation in Cabibbo suppressed D-meson decays, Prog. Theor. Exp. Phys. **2013**, 903B05 (2013).

[21] G. Hiller, M. Jung, and S. Schacht, $SU(3)$-flavor anatomy of nonleptonic charm decays, Phys. Rev. D **87**, 014024 (2013).

[22] S. Müller, U. Nierste, and S. Schacht, Sum Rules of Charm CP Asymmetries beyond the $SU(3)_F$ Limit, Phys. Rev. Lett. **115**, 251802 (2015).

[23] H. Mendez *et al.* (CLEO Collaboration), Measurements of D meson decays to two pseudoscalar mesons, Phys. Rev. D **81**, 052013 (2010).

[24] J. P. Lees *et al.* (*BABAR* Collaboration), Search for CP violation in the decays $D^{\pm} \to K^0_S K^{\pm}$, $D^{\pm}_s \to K^0_S K^{\pm}$, and $D^{\pm}_s \to K^0_S \pi^{\pm}$, Phys. Rev. D **87**, 052012 (2013).

[25] J. P. Lees *et al.* (*BABAR* Collaboration), Search for direct CP violation in singly Cabibbo-suppressed $D^{\pm} \to K^+K^-\pi^{\pm}$ decays, Phys. Rev. D **87**, 052010 (2013).

[26] B. R. Ko *et al.* (Belle Collaboration), Search for CP Violation in the Decays $D^+_{(s)} \to K^0_S \pi^+$ and $D^+_{(s)} \to K^0_S K^+$, Phys. Rev. Lett. **104**, 181602 (2010).

[27] B. R. Ko *et al.* (Belle Collaboration), Search for CP violation in the decay $D^+ \to K^0_S K^+$, J. High Energy Phys. 02 (2013) 098.

[28] M. Starič *et al.* (Belle Collaboration), Search for CP Violation in $D^{\pm}$ Meson Decays to $\phi\pi^{\pm}$, Phys. Rev. Lett. **108**, 071801 (2012).

[29] R. Aaij *et al.* (LHCb Collaboration), Search for CP violation in $D^+ \to \phi\pi^+$ and $D^+_s \to K^0_S \pi^+$ decays, J. High Energy Phys. 06 (2013) 112.

[30] R. Aaij *et al.* (LHCb Collaboration), Search for CP violation in $D^{\pm} \to K^0_S K^{\pm}$ and $D^{\pm}_s \to K^0_S \pi^{\pm}$ decays, J. High Energy Phys. 10 (2014) 025.

[31] H. J. Lipkin and Z.-z. Xing, Flavor symmetry, K^0–$\bar{K}^0$ mixing and new physics effects on CP violation in $D^{\pm}$ and $D^{\pm}_s$ decays, Phys. Lett. B **450**, 405 (1999).

[32] M. Tanabashi *et al.* (Particle Data Group), Review of particle physics, Phys. Rev. D **98**, 030001 (2018).

[33] R. Aaij *et al.* (LHCb Collaboration), Measurement of the $D^{\pm}$ production asymmetry in 7 TeV pp collisions, Phys. Lett. B **718**, 902 (2013).

[34] R. Aaij *et al.* (LHCb Collaboration), Measurement of $D^{\pm}_s$ production asymmetry in pp collisions at $\sqrt{s} = 7$ and 8 TeV, J. High Energy Phys. 08 (2018) 008.

[35] D. Wang, F.-S. Yu, and H.-n. Li, CP Asymmetries in Charm Decays into Neutral Kaons, Phys. Rev. Lett. **119**, 181802 (2017).

[36] A. A. Alves, Jr. *et al.* (LHCb Collaboration), The LHCb detector at the LHC, J. Instrum. **3**, S08005 (2008).

[37] R. Aaij *et al.* (LHCb Collaboration), LHCb detector performance, Int. J. Mod. Phys. A **30**, 1530022 (2015).

[38] G. Dujany and B. Storaci, Real-time alignment and calibration of the LHCb Detector in Run II, J. Phys. Conf. Ser. **664**, 082010 (2015).

[39] R. Aaij *et al.*, The LHCb trigger and its performance in 2011, J. Instrum. **8**, P04022 (2013).

[40] R. Aaij *et al.*, Tesla: An application for real-time data analysis in high energy physics, Comput. Phys. Commun. **208**, 35 (2016).

[41] H. Voss, A. Höcker, J. Stelzer, and F. Tegenfeldt, TMVA, the toolkit for multivariate data analysis with ROOT, Proc. Sci., ACAT2007 (**2007**) 040.

[42] M. Pivk and F. R. Le Diberder, sPlot: A statistical tool to unfold data distributions, Nucl. Instrum. Methods Phys. Res., Sect. A **555**, 356 (2005).

[43] N. L. Johnson, Systems of frequency curves generated by methods of translation, Biometrika **36**, 149 (1949).

[44] R. Aaij *et al.* (LHCb Collaboration), Measurement of CP asymmetry in $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays, J. High Energy Phys. 07 (2014) 041.

[45] L. Lyons, D. Gibaut, and P. Clifford, How to combine correlated estimates of a single physical quantity, Nucl. Instrum. Methods Phys. Res., Sect. A **270**, 110 (1988).

[46] LHCb Collaboration, Physics case for an LHCb Upgrade II—Opportunities in flavour physics, and beyond, in the HL-LHC era, arXiv:1808.08865.

R. Aaij,[28] C. Abellán Beteta,[46] B. Adeva,[43] M. Adinolfi,[50] C. A. Aidala,[77] Z. Ajaltouni,[6] S. Akar,[61] P. Albicocco,[19]
J. Albrecht,[11] F. Alessio,[44] M. Alexander,[55] A. Alfonso Albero,[42] G. Alkhazov,[41] P. Alvarez Cartelle,[57] A. A. Alves Jr.,[43]
S. Amato,[2] Y. Amhis,[8] L. An,[18] L. Anderlini,[18] G. Andreassi,[45] M. Andreotti,[17] J. E. Andrews,[62] F. Archilli,[28] P. d'Argent,[13]
J. Arnau Romeu,[7] A. Artamonov,[40] M. Artuso,[63] K. Arzymatov,[37] E. Aslanides,[7] M. Atzeni,[46] B. Audurier,[23]
S. Bachmann,[13] J. J. Back,[52] S. Baker,[57] V. Balagura,[8,a] W. Baldini,[17,44] A. Baranov,[37] R. J. Barlow,[58] G. C. Barrand,[8]
S. Barsuk,[8] W. Barter,[57] M. Bartolini,[20] F. Baryshnikov,[74] V. Batozskaya,[32] B. Batsukh,[63] A. Battig,[11] V. Battista,[45] A. Bay,[45]
F. Bedeschi,[25] I. Bediaga,[1] A. Beiter,[63] L. J. Bel,[28] S. Belin,[23] N. Beliy,[66] V. Bellee,[45] N. Belloli,[21,b] K. Belous,[40] I. Belyaev,[34]
E. Ben-Haim,[9] G. Bencivenni,[19] S. Benson,[28] S. Beranek,[10] A. Berezhnoy,[35] R. Bernet,[46] D. Berninghoff,[13] E. Bertholet,[9]
A. Bertolin,[24] C. Betancourt,[46] F. Betti,[16,c] M. O. Bettler,[51] M. van Beuzekom,[28] Ia. Bezshyiko,[46] S. Bhasin,[50] J. Bhom,[30]
M. S. Bieker,[11] S. Bifani,[49] P. Billoir,[9] A. Birnkraut,[11] A. Bizzeti,[18,d] M. Bjørn,[59] M. P. Blago,[44] T. Blake,[52] F. Blanc,[45]
S. Blusk,[63] D. Bobulska,[55] V. Bocci,[27] O. Boente Garcia,[43] T. Boettcher,[60] A. Bondar,[39,e] N. Bondar,[41] S. Borghi,[58,44]
M. Borisyak,[37] M. Borsato,[13] M. Boubdir,[10] T. J. V. Bowcock,[56] C. Bozzi,[17,44] S. Braun,[13] M. Brodski,[44] J. Brodzicka,[30]
A. Brossa Gonzalo,[52] D. Brundu,[23,44] E. Buchanan,[50] A. Buonaura,[46] C. Burr,[58] A. Bursche,[23] J. Buytaert,[44] W. Byczynski,[44]
S. Cadeddu,[23] H. Cai,[68] R. Calabrese,[17,f] R. Calladine,[49] M. Calvi,[21,b] M. Calvo Gomez,[42,g] A. Camboni,[42,g] P. Campana,[19]
D. H. Campora Perez,[44] L. Capriotti,[16,c] A. Carbone,[16,c] G. Carboni,[26] R. Cardinale,[20] A. Cardini,[23] P. Carniti,[21,b]
K. Carvalho Akiba,[2] G. Casse,[56] M. Cattaneo,[44] G. Cavallero,[20] R. Cenci,[25,h] D. Chamont,[8] M. G. Chapman,[50]
M. Charles,[9,44] Ph. Charpentier,[44] G. Chatzikonstantinidis,[49] M. Chefdeville,[5] V. Chekalina,[37] C. Chen,[3] S. Chen,[23]
S.-G. Chitic,[44] V. Chobanova,[43] M. Chrzaszcz,[44] A. Chubykin,[41] P. Ciambrone,[19] X. Cid Vidal,[43] G. Ciezarek,[44]
F. Cindolo,[16] P. E. L. Clarke,[54] M. Clemencic,[44] H. V. Cliff,[51] J. Closier,[44] V. Coco,[44] J. A. B. Coelho,[8] J. Cogan,[7]
E. Cogneras,[6] L. Cojocariu,[33] P. Collins,[44] T. Colombo,[44] A. Comerma-Montells,[13] A. Contu,[23] G. Coombs,[44]
S. Coquereau,[42] G. Corti,[44] C. M. Costa Sobral,[52] B. Couturier,[44] G. A. Cowan,[54] D. C. Craik,[60] A. Crocombe,[52]
M. Cruz Torres,[1] R. Currie,[54] C. D'Ambrosio,[44] C. L. Da Silva,[78] E. Dall'Occo,[28] J. Dalseno,[43,i] A. Danilina,[34] A. Davis,[58]
O. De Aguiar Francisco,[44] K. De Bruyn,[44] S. De Capua,[58] M. De Cian,[45] J. M. De Miranda,[1] L. De Paula,[2] M. De Serio,[15,j]
P. De Simone,[19] C. T. Dean,[55] W. Dean,[77] D. Decamp,[5] L. Del Buono,[9] B. Delaney,[51] H.-P. Dembinski,[12] M. Demmer,[11]
A. Dendek,[31] D. Derkach,[38] O. Deschamps,[6] F. Desse,[8] F. Dettori,[23] B. Dey,[69] A. Di Canto,[44] P. Di Nezza,[19] S. Didenko,[74]
H. Dijkstra,[44] F. Dordei,[23] M. Dorigo,[44,k] A. Dosil Suárez,[43] L. Douglas,[55] A. Dovbnya,[47] K. Dreimanis,[56] L. Dufour,[44]
G. Dujany,[9] P. Durante,[44] J. M. Durham,[78] D. Dutta,[58] R. Dzhelyadin,[40,†] M. Dziewiecki,[13] A. Dziurda,[30] A. Dzyuba,[41]
S. Easo,[53] U. Egede,[57] V. Egorychev,[34] S. Eidelman,[39,e] S. Eisenhardt,[54] U. Eitschberger,[11] R. Ekelhof,[11] L. Eklund,[55]
S. Ely,[63] A. Ene,[33] S. Escher,[10] S. Esen,[28] T. Evans,[61] A. Falabella,[16] N. Farley,[49] S. Farry,[56] D. Fazzini,[21,b]
P. Fernandez Declara,[44] A. Fernandez Prieto,[43] F. Ferrari,[16,c] L. Ferreira Lopes,[45] F. Ferreira Rodrigues,[2] S. Ferreres Sole,[28]
M. Ferro-Luzzi,[44] S. Filippov,[36] R. A. Fini,[15] M. Fiorini,[17,f] M. Firlej,[31] C. Fitzpatrick,[45] T. Fiutowski,[31] F. Fleuret,[8,a]
M. Fontana,[44] F. Fontanelli,[20,l] R. Forty,[44] V. Franco Lima,[56] M. Frank,[44] C. Frei,[44] J. Fu,[22,m] W. Funk,[44] C. Färber,[44]
M. Féo,[44] E. Gabriel,[54] A. Gallas Torreira,[43] D. Galli,[16,c] S. Gallorini,[24] S. Gambetta,[54] Y. Gan,[3] M. Gandelman,[2]
P. Gandini,[22] Y. Gao,[3] L. M. Garcia Martin,[76] B. Garcia Plana,[43] J. García Pardiñas,[46] J. Garra Tico,[51] L. Garrido,[42]
D. Gascon,[42] C. Gaspar,[44] G. Gazzoni,[6] D. Gerick,[13] E. Gersabeck,[58] M. Gersabeck,[58] T. Gershon,[52] D. Gerstel,[7] Ph. Ghez,[5]
V. Gibson,[51] O. G. Girard,[45] P. Gironella Gironell,[42] L. Giubega,[33] K. Gizdov,[54] V. V. Gligorov,[9] D. Golubkov,[34]
A. Golutvin,[57,74] A. Gomes,[1,n] I. V. Gorelov,[35] C. Gotti,[21,b] E. Govorkova,[28] J. P. Grabowski,[13] R. Graciani Diaz,[42]
L. A. Granado Cardoso,[44] E. Graugés,[42] E. Graverini,[46] G. Graziani,[18] A. Grecu,[33] R. Greim,[28] P. Griffith,[23] L. Grillo,[58]
L. Gruber,[44] B. R. Gruberg Cazon,[59] C. Gu,[3] X. Guo,[67] E. Gushchin,[36] A. Guth,[10] Yu. Guz,[40,44] T. Gys,[44] C. Göbel,[65]
T. Hadavizadeh,[59] C. Hadjivasiliou,[6] G. Haefeli,[45] C. Haen,[44] S. C. Haines,[51] B. Hamilton,[62] X. Han,[13] T. H. Hancock,[59]
S. Hansmann-Menzemer,[13] N. Harnew,[59] T. Harrison,[56] C. Hasse,[44] M. Hatch,[44] J. He,[66] M. Hecker,[57] K. Heinicke,[11]
A. Heister,[11] K. Hennessy,[56] L. Henry,[76] E. van Herwijnen,[44] J. Heuel,[10] M. Heß,[71] A. Hicheur,[64] R. Hidalgo Charman,[58]
D. Hill,[59] M. Hilton,[58] P. H. Hopchev,[45] J. Hu,[13] W. Hu,[69] W. Huang,[66] Z. C. Huard,[61] W. Hulsbergen,[28] T. Humair,[57]
M. Hushchyn,[38] D. Hutchcroft,[56] D. Hynds,[28] P. Ibis,[11] M. Idzik,[31] P. Ilten,[49] A. Inglessi,[41] A. Inyakin,[40] K. Ivshin,[41]
R. Jacobsson,[44] S. Jakobsen,[44] J. Jalocha,[59] E. Jans,[28] B. K. Jashal,[76] A. Jawahery,[62] F. Jiang,[3] M. John,[59] D. Johnson,[44]
C. R. Jones,[51] C. Joram,[44] B. Jost,[44] N. Jurik,[59] S. Kandybei,[47] M. Karacson,[44] J. M. Kariuki,[50] S. Karodia,[55] N. Kazeev,[38]
M. Kecke,[13] F. Keizer,[51] M. Kelsey,[63] M. Kenzie,[51] T. Ketel,[29] B. Khanji,[44] A. Kharisova,[75] C. Khurewathanakul,[45]
K. E. Kim,[63] T. Kirn,[10] V. S. Kirsebom,[45] S. Klaver,[19] K. Klimaszewski,[32] S. Koliiev,[48] M. Kolpin,[13] R. Kopecna,[13]
P. Koppenburg,[28] I. Kostiuk,[28,48] S. Kotriakhova,[41] M. Kozeiha,[6] L. Kravchuk,[36] M. Kreps,[52] F. Kress,[57] S. Kretzschmar,[10]

P. Krokovny,[39,e] W. Krupa,[31] W. Krzemien,[32] W. Kucewicz,[30,o] M. Kucharczyk,[30] V. Kudryavtsev,[39,e] G. J. Kunde,[78]
A. K. Kuonen,[45] T. Kvaratskheliya,[34] D. Lacarrere,[44] G. Lafferty,[58] A. Lai,[23] D. Lancierini,[46] G. Lanfranchi,[19]
C. Langenbruch,[10] T. Latham,[52] C. Lazzeroni,[49] R. Le Gac,[7] A. Leflat,[35] R. Lefèvre,[6] F. Lemaitre,[44] O. Leroy,[7] T. Lesiak,[30]
B. Leverington,[13] H. Li,[67] P.-R. Li,[66,p] Y. Li,[4] Z. Li,[63] X. Liang,[63] T. Likhomanenko,[73] R. Lindner,[44] P. Ling,[67] F. Lionetto,[46]
V. Lisovskyi,[8] G. Liu,[67] X. Liu,[3] D. Loh,[52] A. Loi,[23] I. Longstaff,[55] J. H. Lopes,[2] G. Loustau,[46] G. H. Lovell,[51]
D. Lucchesi,[24,q] M. Lucio Martinez,[43] Y. Luo,[3] A. Lupato,[24] E. Luppi,[17,f] O. Lupton,[52] A. Lusiani,[25] X. Lyu,[66] R. Ma,[67]
S. Maccolini,[16,c] F. Machefert,[8] F. Maciuc,[33] V. Macko,[45] P. Mackowiak,[11] S. Maddrell-Mander,[50] O. Maev,[41,44]
K. Maguire,[58] D. Maisuzenko,[41] M. W. Majewski,[31] S. Malde,[59] B. Malecki,[44] A. Malinin,[73] T. Maltsev,[39,e] H. Malygina,[13]
G. Manca,[23,r] G. Mancinelli,[7] D. Marangotto,[22,m] J. Maratas,[6,s] J. F. Marchand,[5] U. Marconi,[16] C. Marin Benito,[8]
M. Marinangeli,[45] P. Marino,[45] J. Marks,[13] P. J. Marshall,[56] G. Martellotti,[27] M. Martinelli,[44,21] D. Martinez Santos,[43]
F. Martinez Vidal,[76] A. Massafferri,[1] M. Materok,[10] R. Matev,[44] A. Mathad,[46] Z. Mathe,[44] V. Matiunin,[34] C. Matteuzzi,[21]
K. R. Mattioli,[77] A. Mauri,[46] E. Maurice,[8,a] B. Maurin,[45] M. McCann,[57,44] A. McNab,[58] R. McNulty,[14] J. V. Mead,[56]
B. Meadows,[61] C. Meaux,[7] N. Meinert,[71] D. Melnychuk,[32] M. Merk,[28] A. Merli,[22,m] E. Michielin,[24] D. A. Milanes,[70]
E. Millard,[52] M.-N. Minard,[5] L. Minzoni,[17,f] D. S. Mitzel,[13] A. Mogini,[9] R. D. Moise,[57] T. Mombächer,[11] I. A. Monroy,[70]
S. Monteil,[6] M. Morandin,[24] G. Morello,[19] M. J. Morello,[25,t] J. Moron,[31] A. B. Morris,[7] R. Mountain,[63] F. Muheim,[54]
M. Mukherjee,[69] M. Mulder,[28] C. H. Murphy,[59] D. Murray,[58] A. Mödden,[11] D. Müller,[44] J. Müller,[11] K. Müller,[46]
V. Müller,[11] P. Naik,[50] T. Nakada,[45] R. Nandakumar,[53] A. Nandi,[59] T. Nanut,[45] I. Nasteva,[2] M. Needham,[54] N. Neri,[22,m]
S. Neubert,[13] N. Neufeld,[44] R. Newcombe,[57] T. D. Nguyen,[45] C. Nguyen-Mau,[45,u] S. Nieswand,[10] R. Niet,[11] N. Nikitin,[35]
N. S. Nolte,[44] D. P. O'Hanlon,[16] A. Oblakowska-Mucha,[31] V. Obraztsov,[40] S. Ogilvy,[55] R. Oldeman,[23,r]
C. J. G. Onderwater,[72] J. D. Osborn,[77] A. Ossowska,[30] J. M. Otalora Goicochea,[2] T. Ovsiannikova,[34] P. Owen,[46]
A. Oyanguren,[76] P. R. Pais,[45] T. Pajero,[25,t] A. Palano,[15] M. Palutan,[19] G. Panshin,[75] A. Papanestis,[53] M. Pappagallo,[54]
L. L. Pappalardo,[17,f] W. Parker,[62] C. Parkes,[58,44] G. Passaleva,[18,44] A. Pastore,[15] M. Patel,[57] C. Patrignani,[16,c] A. Pearce,[44]
A. Pellegrino,[28] G. Penso,[27] M. Pepe Altarelli,[44] S. Perazzini,[44] D. Pereima,[34] P. Perret,[6] L. Pescatore,[45] K. Petridis,[50]
A. Petrolini,[20,l] A. Petrov,[73] S. Petrucci,[54] M. Petruzzo,[22,m] B. Pietrzyk,[5] G. Pietrzyk,[45] M. Pikies,[30] M. Pili,[59] D. Pinci,[27]
J. Pinzino,[44] F. Pisani,[44] A. Piucci,[13] V. Placinta,[33] S. Playfer,[54] J. Plews,[49] M. Plo Casasus,[43] F. Polci,[9] M. Poli Lener,[19]
M. Poliakova,[63] A. Poluektov,[7] N. Polukhina,[74,v] I. Polyakov,[63] E. Polycarpo,[2] G. J. Pomery,[50] S. Ponce,[44] A. Popov,[40]
D. Popov,[49,12] S. Poslavskii,[40] E. Price,[50] C. Prouve,[43] V. Pugatch,[48] A. Puig Navarro,[46] H. Pullen,[59] G. Punzi,[25,h] W. Qian,[66]
J. Qin,[66] R. Quagliani,[9] B. Quintana,[6] N. V. Raab,[14] B. Rachwal,[31] J. H. Rademacker,[50] M. Rama,[25] M. Ramos Pernas,[43]
M. S. Rangel,[2] F. Ratnikov,[37,38] G. Raven,[29] M. Ravonel Salzgeber,[44] M. Reboud,[5] F. Redi,[45] S. Reichert,[11] A. C. dos Reis,[1]
F. Reiss,[9] C. Remon Alepuz,[76] Z. Ren,[3] V. Renaudin,[59] S. Ricciardi,[53] S. Richards,[50] K. Rinnert,[56] P. Robbe,[8] A. Robert,[9]
A. B. Rodrigues,[45] E. Rodrigues,[61] J. A. Rodriguez Lopez,[70] M. Roehrken,[44] S. Roiser,[44] A. Rollings,[59] V. Romanovskiy,[40]
A. Romero Vidal,[43] J. D. Roth,[77] M. Rotondo,[19] M. S. Rudolph,[63] T. Ruf,[44] J. Ruiz Vidal,[76] J. J. Saborido Silva,[43]
N. Sagidova,[41] B. Saitta,[23,r] V. Salustino Guimaraes,[65] C. Sanchez Gras,[28] C. Sanchez Mayordomo,[76] B. Sanmartin Sedes,[43]
R. Santacesaria,[27] C. Santamarina Rios,[43] M. Santimaria,[19,44] E. Santovetti,[26,w] G. Sarpis,[58] A. Sarti,[19,x] C. Satriano,[27,y]
A. Satta,[26] M. Saur,[66] D. Savrina,[34,35] S. Schael,[10] M. Schellenberg,[11] M. Schiller,[55] H. Schindler,[44] M. Schmelling,[12]
T. Schmelzer,[11] B. Schmidt,[44] O. Schneider,[45] A. Schopper,[44] H. F. Schreiner,[61] M. Schubiger,[45] S. Schulte,[45]
M. H. Schune,[8] R. Schwemmer,[44] B. Sciascia,[19] A. Sciubba,[27,x] A. Semennikov,[34] E. S. Sepulveda,[9] A. Sergi,[49,44] N. Serra,[46]
J. Serrano,[7] L. Sestini,[24] A. Seuthe,[11] P. Seyfert,[44] M. Shapkin,[40] T. Shears,[56] L. Shekhtman,[39,e] V. Shevchenko,[73]
E. Shmanin,[74] B. G. Siddi,[17] R. Silva Coutinho,[46] L. Silva de Oliveira,[2] G. Simi,[24,q] S. Simone,[15,j] I. Skiba,[17] N. Skidmore,[13]
T. Skwarnicki,[63] M. W. Slater,[49] J. G. Smeaton,[51] E. Smith,[10] I. T. Smith,[54] M. Smith,[57] M. Soares,[16] l. Soares Lavra,[1]
M. D. Sokoloff,[61] F. J. P. Soler,[55] B. Souza De Paula,[2] B. Spaan,[11] E. Spadaro Norella,[22,m] P. Spradlin,[55] F. Stagni,[44]
M. Stahl,[13] S. Stahl,[44] P. Stefko,[45] S. Stefkova,[57] O. Steinkamp,[46] S. Stemmle,[13] O. Stenyakin,[40] M. Stepanova,[41]
H. Stevens,[11] A. Stocchi,[8] S. Stone,[63] S. Stracka,[25] M. E. Stramaglia,[45] M. Straticiuc,[33] U. Straumann,[46] S. Strokov,[75]
J. Sun,[3] L. Sun,[68] Y. Sun,[62] K. Swientek,[31] A. Szabelski,[32] T. Szumlak,[31] M. Szymanski,[66] S. T'Jampens,[5] Z. Tang,[3]
T. Tekampe,[11] G. Tellarini,[17] F. Teubert,[44] E. Thomas,[44] J. van Tilburg,[28] M. J. Tilley,[57] V. Tisserand,[6] M. Tobin,[4] S. Tolk,[44]
L. Tomassetti,[17,f] D. Tonelli,[25] D. Y. Tou,[9] R. Tourinho Jadallah Aoude,[1] E. Tournefier,[5] M. Traill,[55] M. T. Tran,[45]
A. Trisovic,[51] A. Tsaregorodtsev,[7] G. Tuci,[25,44,h] A. Tully,[51] N. Tuning,[28] A. Ukleja,[32] A. Usachov,[8] A. Ustyuzhanin,[37,38]
U. Uwer,[13] A. Vagner,[75] V. Vagnoni,[16] A. Valassi,[44] S. Valat,[44] G. Valenti,[16] H. Van Hecke,[78] C. B. Van Hulse,[14]
R. Vazquez Gomez,[44] P. Vazquez Regueiro,[43] S. Vecchi,[17] M. van Veghel,[28] J. J. Velthuis,[50] M. Veltri,[18,z]

A. Venkateswaran,[63] M. Vernet,[6] M. Veronesi,[28] M. Vesterinen,[52] J. V. Viana Barbosa,[44] D. Vieira,[66] M. Vieites Diaz,[43] H. Viemann,[71] X. Vilasis-Cardona,[42,g] A. Vitkovskiy,[28] M. Vitti,[51] V. Volkov,[35] A. Vollhardt,[46] D. Vom Bruch,[9] B. Voneki,[44] A. Vorobyev,[41] V. Vorobyev,[39,e] N. Voropaev,[41] J. A. de Vries,[28] C. Vázquez Sierra,[28] R. Waldi,[71] J. Walsh,[25] J. Wang,[4] M. Wang,[3] Y. Wang,[69] Z. Wang,[46] D. R. Ward,[51] H. M. Wark,[56] N. K. Watson,[49] D. Websdale,[57] A. Weiden,[46] C. Weisser,[60] M. Whitehead,[10] G. Wilkinson,[59] M. Wilkinson,[63] I. Williams,[51] M. R. J. Williams,[58] M. Williams,[60] T. Williams,[49] F. F. Wilson,[53] M. Winn,[8] W. Wislicki,[32] M. Witek,[30] G. Wormser,[8] S. A. Wotton,[51] K. Wyllie,[44] D. Xiao,[69] Y. Xie,[69] H. Xing,[67] A. Xu,[3] M. Xu,[69] Q. Xu,[66] Z. Xu,[3] Z. Xu,[5] Z. Yang,[3] Z. Yang,[62] Y. Yao,[63] L. E. Yeomans,[56] H. Yin,[69] J. Yu,[69,aa] X. Yuan,[63] O. Yushchenko,[40] K. A. Zarebski,[49] M. Zavertyaev,[12,v] M. Zeng,[3] D. Zhang,[69] L. Zhang,[3] W. C. Zhang,[3,bb] Y. Zhang,[44] A. Zhelezov,[13] Y. Zheng,[66] X. Zhu,[3] V. Zhukov,[10,35] J. B. Zonneveld,[54] and S. Zucchelli[16,c]

(LHCb Collaboration)

[1]*Centro Brasileiro de Pesquisas Físicas (CBPF), Rio de Janeiro, Brazil*
[2]*Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil*
[3]*Center for High Energy Physics, Tsinghua University, Beijing, China*
[4]*Institute Of High Energy Physics (ihep), Beijing, China*
[5]*Univ. Grenoble Alpes, Univ. Savoie Mont Blanc, CNRS, IN2P3-LAPP, Annecy, France*
[6]*Université Clermont Auvergne, CNRS/IN2P3, LPC, Clermont-Ferrand, France*
[7]*Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France*
[8]*LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France*
[9]*LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France*
[10]*I. Physikalisches Institut, RWTH Aachen University, Aachen, Germany*
[11]*Fakultät Physik, Technische Universität Dortmund, Dortmund, Germany*
[12]*Max-Planck-Institut für Kernphysik (MPIK), Heidelberg, Germany*
[13]*Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*
[14]*School of Physics, University College Dublin, Dublin, Ireland*
[15]*INFN Sezione di Bari, Bari, Italy*
[16]*INFN Sezione di Bologna, Bologna, Italy*
[17]*INFN Sezione di Ferrara, Ferrara, Italy*
[18]*INFN Sezione di Firenze, Firenze, Italy*
[19]*INFN Laboratori Nazionali di Frascati, Frascati, Italy*
[20]*INFN Sezione di Genova, Genova, Italy*
[21]*INFN Sezione di Milano-Bicocca, Milano, Italy*
[22]*INFN Sezione di Milano, Milano, Italy*
[23]*INFN Sezione di Cagliari, Monserrato, Italy*
[24]*INFN Sezione di Padova, Padova, Italy*
[25]*INFN Sezione di Pisa, Pisa, Italy*
[26]*INFN Sezione di Roma Tor Vergata, Roma, Italy*
[27]*INFN Sezione di Roma La Sapienza, Roma, Italy*
[28]*Nikhef National Institute for Subatomic Physics, Amsterdam, Netherlands*
[29]*Nikhef National Institute for Subatomic Physics and VU University Amsterdam, Amsterdam, Netherlands*
[30]*Henryk Niewodniczanski Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland*
[31]*AGH—University of Science and Technology, Faculty of Physics and Applied Computer Science, Kraków, Poland*
[32]*National Center for Nuclear Research (NCBJ), Warsaw, Poland*
[33]*Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest-Magurele, Romania*
[34]*Institute of Theoretical and Experimental Physics (ITEP), Moscow, Russia*
[35]*Institute of Nuclear Physics, Moscow State University (SINP MSU), Moscow, Russia*
[36]*Institute for Nuclear Research of the Russian Academy of Sciences (INR RAS), Moscow, Russia*
[37]*Yandex School of Data Analysis, Moscow, Russia*
[38]*National Research University Higher School of Economics, Moscow, Russia*
[39]*Budker Institute of Nuclear Physics (SB RAS), Novosibirsk, Russia*
[40]*Institute for High Energy Physics (IHEP), Protvino, Russia*
[41]*Konstantinov Nuclear Physics Institute of National Research Centre "Kurchatov Institute", PNPI, St.Petersburg, Russia*
[42]*ICCUB, Universitat de Barcelona, Barcelona, Spain*
[43]*Instituto Galego de Física de Altas Enerxías (IGFAE), Universidade de Santiago de Compostela, Santiago de Compostela, Spain*
[44]*European Organization for Nuclear Research (CERN), Geneva, Switzerland*

[45]*Institute of Physics, Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland*
[46]*Physik-Institut, Universität Zürich, Zürich, Switzerland*
[47]*NSC Kharkiv Institute of Physics and Technology (NSC KIPT), Kharkiv, Ukraine*
[48]*Institute for Nuclear Research of the National Academy of Sciences (KINR), Kyiv, Ukraine*
[49]*University of Birmingham, Birmingham, United Kingdom*
[50]*H.H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom*
[51]*Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom*
[52]*Department of Physics, University of Warwick, Coventry, United Kingdom*
[53]*STFC Rutherford Appleton Laboratory, Didcot, United Kingdom*
[54]*School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom*
[55]*School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom*
[56]*Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom*
[57]*Imperial College London, London, United Kingdom*
[58]*School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom*
[59]*Department of Physics, University of Oxford, Oxford, United Kingdom*
[60]*Massachusetts Institute of Technology, Cambridge, Massachusetts, USA*
[61]*University of Cincinnati, Cincinnati, Ohio, USA*
[62]*University of Maryland, College Park, Maryland, USA*
[63]*Syracuse University, Syracuse, New York, USA*
[64]*Laboratory of Mathematical and Subatomic Physics, Constantine, Algeria [associated with Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil]*
[65]*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]*
[66]*University of Chinese Academy of Sciences, Beijing, China (associated with Center for High Energy Physics, Tsinghua University, Beijing, China)*
[67]*South China Normal University, Guangzhou, China (associated with Center for High Energy Physics, Tsinghua University, Beijing, China)*
[68]*School of Physics and Technology, Wuhan University, Wuhan, China (associated with Center for High Energy Physics, Tsinghua University, Beijing, China)*
[69]*Institute of Particle Physics, Central China Normal University, Wuhan, Hubei, China (associated with Center for High Energy Physics, Tsinghua University, Beijing, China)*
[70]*Departamento de Fisica, Universidad Nacional de Colombia, Bogota, Colombia (associated with LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France)*
[71]*Institut für Physik, Universität Rostock, Rostock, Germany (associated with Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany)*
[72]*Van Swinderen Institute, University of Groningen, Groningen, Netherlands (associated with Nikhef National Institute for Subatomic Physics, Amsterdam, Netherlands)*
[73]*National Research Centre Kurchatov Institute, Moscow, Russia [associated with Institute of Theoretical and Experimental Physics (ITEP), Moscow, Russia]*
[74]*National University of Science and Technology "MISIS", Moscow, Russia [associated with Institute of Theoretical and Experimental Physics (ITEP), Moscow, Russia]*
[75]*National Research Tomsk Polytechnic University, Tomsk, Russia [associated with Institute of Theoretical and Experimental Physics (ITEP), Moscow, Russia]*
[76]*Instituto de Fisica Corpuscular, Centro Mixto Universidad de Valencia—CSIC, Valencia, Spain (associated with ICCUB, Universitat de Barcelona, Barcelona, Spain)*
[77]*University of Michigan, Ann Arbor, USA (associated with Syracuse University, Syracuse, New York, USA)*
[78]*Los Alamos National Laboratory (LANL), Los Alamos, USA (associated with Syracuse University, Syracuse, New York, USA)*

[†] Deceased.
[a] Also at Laboratoire Leprince-Ringuet, Palaiseau, France.
[b] Also at Università di Milano Bicocca, Milano, Italy.
[c] Also at Università di Bologna, Bologna, Italy.
[d] Also at Università di Modena e Reggio Emilia, Modena, Italy.
[e] Also at Novosibirsk State University, Novosibirsk, Russia.
[f] Also at Università di Ferrara, Ferrara, Italy.
[g] Also at LIFAELS, La Salle, Universitat Ramon Llull, Barcelona, Spain.
[h] Also at Università di Pisa, Pisa, Italy.
[i] Also at H.H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom.
[j] Also at Università di Bari, Bari, Italy.
[k] Also at Sezione INFN di Trieste, Trieste, Italy.

[l] Also at Università di Genova, Genova, Italy.
[m] Also at Università degli Studi di Milano, Milano, Italy.
[n] Also at Universidade Federal do Triângulo Mineiro (UFTM), Uberaba-MG, Brazil.
[o] Also at AGH—University of Science and Technology, Faculty of Computer Science, Electronics and Telecommunications, Kraków, Poland.
[p] Also at Lanzhou University, Lanzhou, China.
[q] Also at Università di Padova, Padova, Italy.
[r] Also at Università di Cagliari, Cagliari, Italy.
[s] Also at MSU—Iligan Institute of Technology (MSU-IIT), Iligan, Philippines.
[t] Also at Scuola Normale Superiore, Pisa, Italy.
[u] Also at Hanoi University of Science, Hanoi, Vietnam.
[v] Also at P.N. Lebedev Physical Institute, Russian Academy of Science (LPI RAS), Moscow, Russia.
[w] Also at Università di Roma Tor Vergata, Roma, Italy.
[x] Also at Università di Roma La Sapienza, Roma, Italy.
[y] Also at Università della Basilicata, Potenza, Italy.
[z] Also at Università di Urbino, Urbino, Italy.
[aa] Also at Physics and Micro Electronic College, Hunan University, Changsha City, China.
[bb] Also at School of Physics and Information Technology, Shaanxi Normal University (SNNU), Xi’an, China.