**Editors' Suggestion**

# Measurement of the Time-Integrated *CP* Asymmetry in $D^0 \to K^- K^+$ Decays

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

(Received 9 September 2022; accepted 17 November 2022; published 29 August 2023)

The time-integrated *CP* asymmetry in the Cabibbo-suppressed decay $D^0 \to K^- K^+$ is measured using proton-proton collision data, corresponding to an integrated luminosity of 5.7 $\mathrm{fb}^{-1}$ collected at a center-of-mass energy of 13 TeV with the LHCb detector. The $D^0$ mesons are required to originate from promptly produced $D^{*+} \to D^0 \pi^+$ decays, and the charge of the companion pion is used to determine the flavor of the charm meson at production. The time-integrated *CP* asymmetry is measured to be $\mathcal{A}_{CP}(K^- K^+) = [6.8 \pm 5.4 \pm 1.6] \times 10^{-4}$ where the first uncertainty is statistical and the second systematic. The direct *CP* asymmetries in $D^0 \to K^- K^+$ and $D^0 \to \pi^- \pi^+$ decays, $a^d_{K^- K^+}$ and $a^d_{\pi^- \pi^+}$, are derived by combining $\mathcal{A}_{CP}(K^- K^+)$ with the time-integrated *CP* asymmetry difference, $\Delta A_{CP} = \mathcal{A}_{CP}(K^- K^+) - \mathcal{A}_{CP}(\pi^- \pi^+)$, and other inputs, giving $a^d_{K^- K^+} = (7.7 \pm 5.7) \times 10^{-4}$, $a^d_{\pi^- \pi^+} = (23.2 \pm 6.1) \times 10^{-4}$, with a correlation coefficient corresponding to $\rho = 0.88$. The compatibility of these results with *CP* symmetry is 1.4 and 3.8 standard deviations for $D^0 \to K^- K^+$ and $D^0 \to \pi^- \pi^+$ decays, respectively. This is the first evidence for direct *CP* violation in a specific $D^0$ decay.

DOI: 10.1103/PhysRevLett.131.091802

One of the three necessary conditions for baryon asymmetry in the Universe is the noninvariance of the fundamental interactions under the simultaneous transformation of the charge conjugation (*C*) and parity (*P*) operators, referred to as *CP* violation [1]. The Cabibbo-Kobayashi-Maskawa formalism describes *CP* violation in the standard model (SM) of particle physics [2,3] through an irreducible phase in the quark-mixing matrix. Over the past sixty years, *CP* violation has been observed in the *K*, *D*, and *B*-meson systems by several experiments [4–13]. In the charm quark sector, the recent observation of *CP* violation [13] stimulates a wide discussion to understand its nature. Further precise measurements may resolve the intricate theoretical debate on whether the observed value is consistent with the SM [14–29]. The discovery measurement of *CP* violation in neutral charm meson decays used the difference between two time-integrated *CP*-violating asymmetries of Cabibbo-suppressed $D^0$ decays, $\Delta A_{CP} = \mathcal{A}_{CP}(K^- K^+) - \mathcal{A}_{CP}(\pi^- \pi^+)$, found to be $\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$ [13]. The time-integrated *CP* asymmetry for $f = K^- K^+$ and $f = \pi^- \pi^+$ corresponds to

$$\mathcal{A}_{CP}(f) \equiv \frac{\int \mathrm{d}t \epsilon(t) [\Gamma(D^0 \to f)(t) - \Gamma(\bar{D}^0 \to f)(t)]}{\int \mathrm{d}t \epsilon(t) [\Gamma(D^0 \to f)(t) + \Gamma(\bar{D}^0 \to f)(t)]}, \quad (1)$$

where $\epsilon(t)$ is the reconstruction efficiency as a function of the $D^0$ decay time and $\Gamma$ denotes the decay rate. This Letter presents measurements of the time-integrated *CP* asymmetries in $D^0 \to K^- K^+$ decays. Combining the measurements of $\mathcal{A}_{CP}(K^- K^+)$ and $\Delta A_{CP}$, it is possible to quantify the amount of *CP* violation in the decay amplitude for $D^0 \to K^- K^+$ and $D^0 \to \pi^- \pi^+$ decays and provide important insight in the breaking of *U*-spin symmetry. The mixing in the neutral charm system implies that $\mathcal{A}_{CP}(f)$ is the sum of a component related to the *CP* violation in the decay amplitude $a^d_f$, and a component related to $D^0$–$\bar{D}^0$ mixing and the interference between mixing and decay, $\Delta Y_f$. Up to first order in the $D^0$ mixing parameters [30–37], the time-integrated *CP* asymmetry can be written as

$$\mathcal{A}_{CP}(f) \approx a^d_f + \frac{\langle t \rangle_f}{\tau_D} \Delta Y_f, \quad (2)$$

where $\langle t \rangle_f$ is the mean decay time of the $D^0$ mesons in the experimental data sample and $\tau_D$ is the $D^0$ lifetime [38,39].

The neutral charm mesons considered are produced in the strong-interaction decays $D^{*+} \to D^0 \pi^+$ from $D^{*+}$ mesons created in proton-proton ($pp$) interactions. The charge of the accompanying "tagging" pion ($\pi^+_{\mathrm{tag}}$) is used to identify the flavor of the $D^0$ meson at production. Throughout this Letter, the inclusion of charge conjugation decay modes is implied, except in the definition of the asymmetries, and $D^{*+}$ and $\phi$ indicate the $D^*(2010)^+$ and $\phi(1020)$ mesons, respectively. The measured asymmetry, $A(K^- K^+)$, is defined as

$$A(K^- K^+) \equiv \frac{N(D^{*+} \to D^0 \pi^+) - N(D^{*-} \to \bar{D}^0 \pi^-)}{N(D^{*+} \to D^0 \pi^+) + N(D^{*-} \to \bar{D}^0 \pi^-)}, \quad (3)$$

---

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

0031-9007/23/131(9)/091802(13)

where $N$ denotes the observed signal yield in the data, and the $D^0$ meson decays into $K^-K^+$. This asymmetry can be approximated as

$$A(K^-K^+) \approx \mathcal{A}_{CP}(K^-K^+) + A_{\mathrm{P}}(D^{*+}) + A_{\mathrm{D}}(\pi^+_{\mathrm{tag}}), \quad (4)$$

where $A_{\mathrm{P}}(D^{*+})$ is the production asymmetry arising from the different hadronization probabilities between $D^{*+}$ and $D^{*-}$ mesons in $pp$ collisions, and $A_{\mathrm{D}}(\pi^+_{\mathrm{tag}})$ is the instrumental asymmetry due to different reconstruction efficiencies of positive and negative tagging pions. The contributions from the production and instrumental asymmetries, referred to as nuisance asymmetries, are estimated and removed through two calibration procedures denoted as $\mathrm{C}_{D^+}$ and $\mathrm{C}_{D_s^+}$, using a set of promptly produced $D^+$ and $D_s^+$ meson decays. Namely, the $\mathrm{C}_{D^+}$ procedure uses $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$, $D^+ \to K^-\pi^+\pi^+$, and $D^+ \to \bar{K}^0\pi^+$ decays, while the $\mathrm{C}_{D_s^+}$ procedure uses $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$, $D_s^+ \to \phi(\to K^-K^+)\pi^+$, and $D_s^+ \to \bar{K}^0K^+$ decays. To avoid statistical overlap, the sample of $D^0 \to K^-\pi^+$ decays is randomly split in two, and the two halves are used separately for the $\mathrm{C}_{D^+}$ and $\mathrm{C}_{D_s^+}$ calibration procedures. All these decays are Cabibbo favored; therefore their $CP$ asymmetries are assumed to be negligible. In analogy to Eq. (4), the corresponding measured asymmetries in the calibration decays are decomposed as

$$\begin{aligned}
A(K^-\pi^+) &\approx A_{\mathrm{P}}(D^{*+}) - A_{\mathrm{D}}(K^+) + A_{\mathrm{D}}(\pi^+) + A_{\mathrm{D}}(\pi^+_{\mathrm{tag}}),\\
A(K^-\pi^+\pi^+) &\approx A_{\mathrm{P}}(D^+) - A_{\mathrm{D}}(K^+) + A_{\mathrm{D}}(\pi^+_1) + A_{\mathrm{D}}(\pi^+_2),\\
A(\bar{K}^0\pi^+) &\approx A_{\mathrm{P}}(D^+) + A(\bar{K}^0) + A_{\mathrm{D}}(\pi^+),\\
A(\phi\pi^+) &\approx A_{\mathrm{P}}(D_s^+) + A_{\mathrm{D}}(\pi^+),\\
A(\bar{K}^0K^+) &\approx A_{\mathrm{P}}(D_s^+) + A(\bar{K}^0) + A_{\mathrm{D}}(K^+). \quad (5)
\end{aligned}$$

In the equations above, $A_{\mathrm{D}}(K^+)$ is the kaon instrumental asymmetry, $A_{\mathrm{P}}(D^+_{(s)})$ is the $D^+_{(s)}$ meson production asymmetry, and $A(\bar{K}^0)$ is the asymmetry arising from the combined effect of $CP$ violation and mixing in the neutral kaon system and the different interaction rates of $\bar{K}^0$ and $K^0$ with the detector material. The asymmetries $A_{\mathrm{D}}(\pi^+_1)$ and $A_{\mathrm{D}}(\pi^+_2)$ are related to the two pions in the $D^+ \to K^-\pi^+\pi^+$ decay, distinguished by the online selection criteria. In $A(\phi\pi^+)$, the asymmetry from the oppositely charged kaons is not included as it is estimated to be negligible. With the individual terms of $\mathcal{O}(10^{-2})$ or less [40–43], the approximations in Eqs. (4) and (5) are valid up to corrections of $\mathcal{O}(10^{-6})$. The individual nuisance asymmetries depend on the kinematics of the corresponding particles. After accounting for this kinematic dependence, the time-integrated $CP$ asymmetry, $\mathcal{A}_{CP}(K^-K^+)$, is obtained for each of the two calibration procedures individually, by combining the measured asymmetries as follows:

$$\begin{aligned}
\mathrm{C}_{D^+}: \mathcal{A}_{CP}(K^-K^+) &= A(K^-K^+) - A(K^-\pi^+)\\
&\quad + A(K^-\pi^+\pi^+) - A(\bar{K}^0\pi^+) + A(\bar{K}^0),\\
\mathrm{C}_{D_s^+}: \mathcal{A}_{CP}(K^-K^+) &= A(K^-K^+) - A(K^-\pi^+)\\
&\quad + A(\phi\pi^+) - A(\bar{K}^0K^+) + A(\bar{K}^0). \quad (6)
\end{aligned}$$

The asymmetries are measured in $pp$ collision data, collected with the LHCb detector at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 5.7 $\mathrm{fb}^{-1}$. The LHCb detector is a single-arm forward spectrometer designed for the study of particles containing $b$ or $c$ quarks [44,45]. A high-precision tracking system with a dipole magnet and vertex detector measures the momentum ($p$) and impact parameter (IP) of charged particles. The IP is defined as the distance of closest approach between the reconstructed trajectory and a $pp$ interaction vertex [46]. The IP is used to distinguish between particles produced in the primary collisions and those produced in heavy-flavor decays. Different species of charged hadrons are distinguished using particle identification (PID) information from two ring-imaging Cherenkov detectors, an electromagnetic and a hadronic calorimeter, and a muon detector.

The online event selection, the trigger, consists of a hardware stage followed by two software stages within which a near real-time alignment and calibration of the detector are performed [47]. In the hardware stage, events are selected based on calorimeter and muon detector information and are accepted independently of the charm decay of interest, reducing any related asymmetry to a negligible level. The subsequent first stage of the software trigger reconstructs the trajectories using information from the full LHCb tracking system and applies requirements on the transverse momentum ($p_T$), the IP, and the displacement from any primary vertex (PV) of the charm-meson decay products. To pass the selection, at least one charged particle or two particles forming a high-quality vertex must fulfill these criteria. The second stage of the software trigger exploits the full information from the tracking subdetectors and performs additional steps of the pattern recognition, including the reconstruction of neutral particles and PID. Further requirements on PID, kinematics, and the decay topology are then applied.

The $D_s^+ \to \phi\pi^+$ decays are selected from $D_s^+ \to K^-K^+\pi^+$ decay candidates requiring that the invariant mass of the kaon pair must be within $\pm 5\ \mathrm{MeV}/c^2$ of the $\phi$ mass. Similarly, the $\bar{K}^0$ mesons, produced in $D^+ \to \bar{K}^0\pi^+$ and $D_s^+ \to \bar{K}^0K^+$ decays, are reconstructed using their decay to two pions, which is dominated by the $K^0_\mathrm{S}$ state. The two pions are required to have an invariant mass within $\pm 10\ \mathrm{MeV}/c^2$ of the $K^0_\mathrm{S}$ mass and to form a vertex displaced more than 20 mm along the beam direction from the $D^+_{(s)}$-meson decay. The $D^0$ candidates are required to have a reconstructed invariant mass between 1844 and 1887 $\mathrm{MeV}/c^2$.

An off-line selection is applied to reduce background, including combinations of random tracks and tracks from other $c$ hadron decays, and to ensure a further cancellation of nuisance asymmetries which can depend on the kinematics of the charm mesons, the kaons, and the pions. These kinematics and PID requirements are applied to both the signal and related control modes where applicable. To improve the overall precision, these selections have been optimized independently for each of the two calibration sets $\mathrm{C}_{D^+}$ and $\mathrm{C}_{D^+_s}$. A requirement on the IP of the charm hadron suppresses charm mesons from $b$ hadron decays to a fraction between 2% and 6% in all decay modes. To improve the resolution on the track momenta and the charm meson decay length and invariant mass, a global decay-chain fit [48] is performed, constraining the origin vertex of the charm meson to the position of the nearest primary vertex and the invariant mass of the two pion system to the known $K^0_\mathrm{S}$ mass [49].

In the construction of the $D^{*+}$ candidate, requirements are imposed on the tagging pion to exclude kinematic regions which show a large asymmetry in $A_\mathrm{D}(\pi^+_\mathrm{tag})$ [50]. The invariant mass of the $D^{*+}$, $m(D^0\pi^+)$, calculated using the vector sum of the momenta of the three charged particles and the known $D^0$ and $\pi^+$ masses [49], is required to be between 2004.5 and 2020 $\mathrm{MeV}/c^2$. For events that contain multiple $D^{*+}$ candidates, one candidate is retained randomly.

The nuisance asymmetries introduced in Eqs. (4) and (5) are expected to depend on the kinematics of the individual particles. To ensure a proper cancellation of those asymmetries, per-candidate weights are applied to all the data samples to equalize the kinematics of $D^{*+}$, $D^+$, and $D^+_s$ mesons and the kaons and pions, as shown in the Supplemental Material [51]. The values of the weights are calculated separately for each calibration procedure using an iterative technique. It is verified that the background-subtracted, weighted distributions of the components of momenta of the relevant particles agree among the different decays. The weighting procedure is repeated for each data-taking year and magnet polarity to account for the dependence of the nuisance asymmetries on data-taking conditions.

The measured asymmetries of signal components for each decay mode are determined through least-square fits to the weighted, binned mass distributions of the charm-meson candidates, simultaneously for both flavors, as shown in the Supplemental Material [51]. The signal models consist of a sum of Gaussian and Johnson $S_U$ functions [59], empirically describing the experimental resolution and the energy loss due to final-state radiation. The means of the signal distributions are distinct for the two charm meson flavors, whereas all the other parameters, including the relative fractions among the various functions, are shared. For $D^{*+}$ decays, the combinatorial background is described by an empirical function of the form $[m(D^0\pi^+) - m(D^0) - m(\pi^+)]^\alpha e^{\beta m(D^0\pi^+)}$, where $\alpha$ and $\beta$ are two parameters shared between the two flavors. In the other cases, an exponential function with a distinct parameter for positive and negative particles is used.

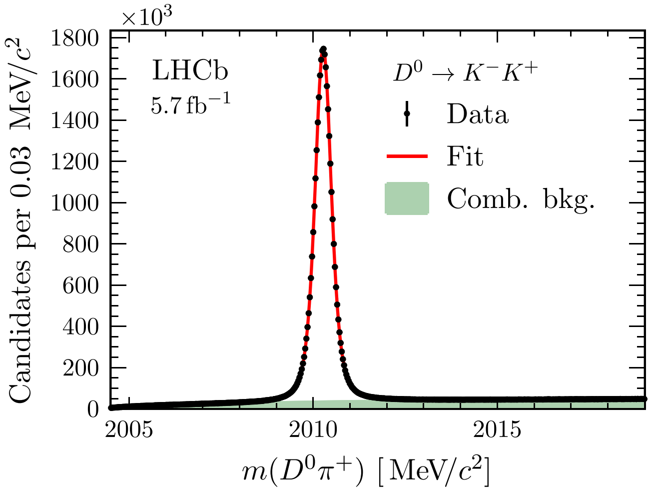

FIG. 1. Distribution of the invariant mass for the weighted $D^{*+} \to D^0(\to K^-K^+)\pi^+$ decay candidates, from the $\mathrm{C}_{D^+}$ calibration procedure. The result of the fit to this distribution is also shown.

Figure 1 presents the distribution of the $D^0 \to K^-K^+$ invariant mass and the result of the fit. The signal yields, together with the statistical reduction factor, defined as $(\Sigma_{i=1}^{i=K} w_i)^2/(N \cdot \Sigma_{i=1}^{i=K} w_i^2)$, where $K$ is the total number of candidates and $w_i$ includes background subtraction and kinematic weights, are reported in Table I. These reduction factors are for illustrative purposes only and indicate the hypothetical fraction of signal events that would provide the same statistical power as the weighted data sample.

Separate fits are performed to subsamples of data collected in different years and with different magnet

TABLE I. Signal yields and statistical reduction factors arising from the kinematic weighting of the sample for the various decay modes and both calibration procedures.

| | Signal yield $[10^6]$ | | Reduction factor | |
|---|---|---|---|---|
| Decay mode | $\mathrm{C}_{D^+}$ | $\mathrm{C}_{D^+_s}$ | $\mathrm{C}_{D^+}$ | $\mathrm{C}_{D^+_s}$ |
| $D^0 \to K^-K^+$ | 37 | 37 | 0.72 | 0.76 |
| $D^0 \to K^-\pi^+$ | 58 | 56 | 0.33 | 0.76 |
| $D^+ \to K^-\pi^+\pi^+$ | 188 | $\cdots$ | 0.23 | $\cdots$ |
| $D^+ \to \bar{K}^0\pi^+$ | 6 | $\cdots$ | 0.25 | $\cdots$ |
| $D^+_s \to \phi\pi^+$ | $\cdots$ | 43 | $\cdots$ | 0.55 |
| $D^+_s \to \bar{K}^0K^+$ | $\cdots$ | 5 | $\cdots$ | 0.70 |

polarities. After determining the asymmetries in these subsamples, the values of $\mathcal{A}_{CP}(K^-K^+)$ are calculated according to Eq. (6), taking into account the contribution from the neutral kaon asymmetry. This is estimated by combining the LHCb material map from simulation with measured $CP$-violation and cross section parameters of the neutral kaon system [60–62], following the procedure described in Ref. [63]. The correction considers different $\bar{K}^0$ momentum spectra for the $\mathrm{C}_{D^+}$ and $\mathrm{C}_{D_s^+}$ calibration procedure and corresponds to $(-5.1 \pm 0.6) \times 10^{-4}$ and $(-8.5 \pm 1.3) \times 10^{-4}$, respectively. The uncertainties are evaluated with a model-independent strategy based on data and discussed later in the Letter. The individual $\mathcal{A}_{CP}(K^-K^+)$ values per subsample are found to be in agreement, with a $p$ value of 0.85 and 0.22 for the $\mathrm{C}_{D^+}$ and $\mathrm{C}_{D_s^+}$ methods, respectively. Finally, the measurements in each subsample are averaged to obtain the final result for each procedure.

Several sources of systematic uncertainties are considered. The systematic uncertainty related to the description of signal and background in the invariant-mass distributions is evaluated by generating pseudoexperiments according to the baseline fit models, and fitting alternative models to those samples. A fit-independent approach is also considered, based on a sideband subtraction. Systematic uncertainties of $1.1 \times 10^{-4}$ and $1.0 \times 10^{-4}$ are assigned for the $\mathrm{C}_{D^+}$ and $\mathrm{C}_{D_s^+}$ procedures, with a correlation of 0.05.

A systematic uncertainty associated to the presence of background components peaking in $m(D^0\pi)$ and not in $m(K^-K^+)$ is determined by fitting the latter distribution in the $D^0 \to K^-K^+$ samples, as shown in the Supplemental Material [51]. Various backgrounds are modeled using fast simulation [64]. The main sources are $D^0 \to K^-\pi^+\pi^0$ and $D^0 \to K^-e^+\nu_e$ decays. A similar study is performed on the $D^0 \to K^-\pi^+$ decay sample, where the peaking-background contributions are found to be negligible. As a result, the values $0.3 \times 10^{-4}$ and $0.4 \times 10^{-4}$ are assigned as systematic uncertainties for the $\mathrm{C}_{D^+}$ and $\mathrm{C}_{D_s^+}$ calibration procedures, respectively, with a correlation coefficient of 0.74.

Although suppressed by the stringent requirement on the IP, a fraction of $D$ mesons from $b$ hadron decays is still present in the final sample. As the different decay modes may have different levels of contamination, the value of $\mathcal{A}_{CP}(K^-K^+)$ may be affected by an incomplete cancellation of the production asymmetries of $b$ hadrons. The contributions from $b$ hadron decays in data are estimated by fitting the IP distribution of charm mesons using shapes obtained from simulation. The corresponding systematic uncertainties are estimated to be $0.6 \times 10^{-4}$ and $0.3 \times 10^{-4}$ for the $\mathrm{C}_{D^+}$ and $\mathrm{C}_{D_s^+}$ calibration procedures, respectively, with a negligible correlation between them.

Any residual disagreement between the kinematic distributions among the various decay modes leads to an imperfect cancellation of the nuisance asymmetries. The systematic uncertainties related to this effect are estimated to be $0.8 \times 10^{-4}$ and $0.4 \times 10^{-4}$ for the $\mathrm{C}_{D^+}$ and $\mathrm{C}_{D_s^+}$ procedures, respectively, with a negligible correlation.

To test the accuracy of the estimated value for $A(\bar{K}^0)$, a linear term with one free parameter is introduced in the model that describes the dependence of $A(\bar{K}^0)$ on the neutral-kaon decay time, as shown in the Supplemental Material [51]. The parameter is determined by fitting the charge asymmetry in $D^+ \to \bar{K}^0\pi^+$ decays as a function of the $\bar{K}^0$ decay time. This is done using a control sample where the neutral kaon decays outside the vertex detector. The parameter is found to be consistent with zero. Its uncertainty is propagated to the $\bar{K}^0$ lifetimes relevant for $\mathcal{A}_{CP}(K^-K^+)$ and assigned as systematic uncertainty. The resulting, fully correlated, systematic uncertainties are $0.6 \times 10^{-4}$ and $1.3 \times 10^{-4}$ for the $\mathrm{C}_{D^+}$ and $\mathrm{C}_{D_s^+}$ procedures, respectively.

In the $\mathrm{C}_{D_s^+}$ procedure, $D_s^+ \to K^-K^+\pi^+$ decay modes other than $D_s^+ \to \phi\pi^+$ may break the symmetry between the $K^-$ and $K^+$ meson kinematic distributions. This leads to a bias in the measured asymmetry due to the momentum-dependent instrumental asymmetry of the kaon. This effect is estimated by combining the two momentum distributions with the expected charged-kaon asymmetry from simulation. The resulting systematic uncertainty is $1.0 \times 10^{-4}$.

All individual contributions are summed in quadrature to give the total systematic uncertainties of $1.6 \times 10^{-4}$ and $2.0 \times 10^{-4}$ for the $\mathrm{C}_{D^+}$ and $\mathrm{C}_{D_s^+}$ procedures, respectively. A summary of all systematic uncertainties is shown in Table II.

Numerous additional checks are carried out, as shown in the Supplemental Material [51]. The measurements of $\mathcal{A}_{CP}(K^-K^+)$ are verified to not depend on the decay time, the transverse momentum, and the pseudorapidity of the $D^0$ meson; the decay time and the pseudorapidity of the $\bar{K}^0$ meson; and the IP significance of the final-state particles with respect to all the PVs in the event of the control modes. The IP significance is defined as the difference between the $\chi^2$ of the PV reconstructed with and without the considered

TABLE II. Systematic uncertainties on $\mathcal{A}_{CP}(K^-K^+)$ for the two calibration procedures $\mathrm{C}_{D^+}$ and $\mathrm{C}_{D_s^+}$. The total uncertainties are obtained as the sums in quadrature of the individual contributions. Correlations (Corr.) between the systematic uncertainties of the two calibration procedures are also reported.

| Source | $\mathrm{C}_{D^+}$ $[10^{-4}]$ | $\mathrm{C}_{D_s^+}$ $[10^{-4}]$ | Corr. |
|---|---|---|---|
| Fit model | 1.1 | 1.0 | 0.05 |
| Peaking backgrounds | 0.3 | 0.4 | 0.74 |
| Secondary decays | 0.6 | 0.3 | ··· |
| Kinematic weighting | 0.8 | 0.4 | ··· |
| Neutral kaon asymmetry | 0.6 | 1.3 | 1.00 |
| Charged kaon asymmetry | ··· | 1.0 | ··· |
| Total | 1.6 | 2.0 | 0.28 |

particle. Furthermore, the total sample is split by different data-taking periods, also distinguishing different magnet polarities. Splitting into subsamples based on the trigger configuration is also considered. The $p$ values under the hypothesis of no dependencies of $\mathcal{A}_{CP}(K^-K^+)$ on the various variables are found to be uniformly distributed. Checks using alternative PID requirements and trigger selections are performed, and all variations of $\mathcal{A}_{CP}(K^-K^+)$ are found to be compatible within statistical uncertainties. The resulting values for $\mathcal{A}_{CP}(K^-K^+)$ for both calibration procedures are

$$\mathrm{C}_{D^+}: \mathcal{A}_{CP}(K^-K^+) = [13.6 \pm 8.8(\mathrm{stat}) \pm 1.6(\mathrm{syst})] \times 10^{-4},$$
$$\mathrm{C}_{D_s^+}: \mathcal{A}_{CP}(K^-K^+) = [2.8 \pm 6.7(\mathrm{stat}) \pm 2.0(\mathrm{syst})] \times 10^{-4},$$

with a statistical and systematic correlation of 0.05 and 0.28, respectively, corresponding to a total correlation of 0.06. The two results are in agreement within 1 standard deviation. Their average is

$$\mathcal{A}_{CP}(K^-K^+) = [6.8 \pm 5.4(\mathrm{stat}) \pm 1.6(\mathrm{syst})] \times 10^{-4},$$

consistent with the previous results [51,52,63]. Assuming that $CP$ is conserved in mixing and in the interference between decay and mixing, the comparison of the result reported here with the current world average [65] gives a compatibility of 1.3 standard deviations.

A combination of all the time-integrated $CP$ asymmetries measured by the LHCb collaboration to date is performed, under the hypothesis that the time-dependent $CP$ violation term in Eq. (2) is final-state independent, i.e., $\Delta Y_{K^-K^+} = \Delta Y_{\pi^-\pi^+} = \Delta Y$, as the final-state dependent contributions are estimated to be of the order of $10^{-5}$ [39]. The combination includes the previous LHCb measurements of $\mathcal{A}_{CP}(K^-K^+)$ [52,63] and $\Delta\mathcal{A}_{CP}$ [13,50,63] as well as the current LHCb average of $\Delta Y$ [39], the world average of the $D^0$ lifetime [49], and the values of reconstructed mean decay times for the $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays in the various analysis. The combination, obtained by minimizing a $\chi^2$ function that includes all the measurements and their correlations, leads to

$$a^d_{K^-K^+} = (7.7 \pm 5.7) \times 10^{-4},$$
$$a^d_{\pi^-\pi^+} = (23.2 \pm 6.1) \times 10^{-4},$$

where the uncertainties include systematic and statistical contributions with a correlation coefficient of 0.88. Figure 2 shows the central values and the confidence regions in the $(a^d_{K^-K^+}, a^d_{\pi^-\pi^+})$ plane for this combination and the one realized with data collected between 2010 and 2012 [50,52,63,66,67]. The two combinations are based on an integrated luminosity of 8.7 fb$^{-1}$ and 3.0 fb$^{-1}$, respectively.

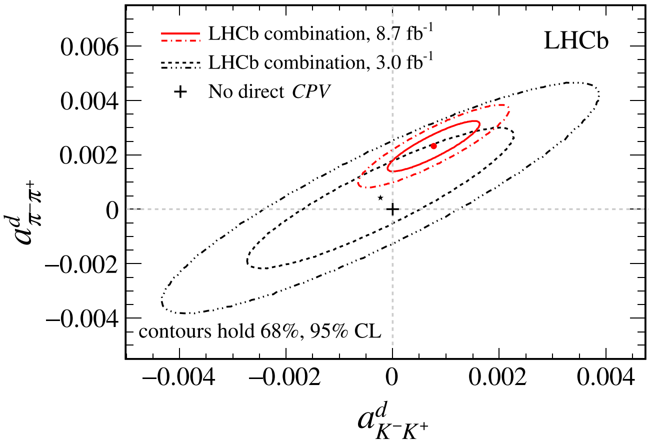

FIG. 2. Central values and two-dimensional confidence regions in the $(a^d_{K^-K^+}, a^d_{\pi^-\pi^+})$ plane for the combinations of the LHCb results obtained with the dataset taken between 2010 and 2018 and the one taken between 2010 and 2012, corresponding to an integrated luminosity of 8.7 fb$^{-1}$ and 3.0 fb$^{-1}$, respectively.

The direct $CP$ asymmetries deviate from zero by 1.4 and 3.8 standard deviations for $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays, respectively. This is the first evidence for direct $CP$ violation in the $D^0 \to \pi^-\pi^+$ decay. $U$-spin symmetry implies $a^d_{K^-K^+} + a^d_{\pi^-\pi^+} = 0$ [68]. A value of $a^d_{K^-K^+} + a^d_{\pi^-\pi^+} = (30.8 \pm 11.4) \times 10^{-4}$ has been found, corresponding to a departure from $U$-spin symmetry of 2.7 standard deviations.

In summary, this Letter reports the most precise measurement of the time-integrated $CP$ asymmetry in the $D^0 \to K^-K^+$ decay to date. A combination with the previous LHCb measurements shows the first evidence of direct $CP$ asymmetry in an individual charm meson decay. These results will help to clarify the theoretical understanding of whether the observed $CP$ violation in neutral charm meson decays is consistent with the SM, or an indication of the existence of new dynamics.

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); MICINN (Spain); SNSF and SER (Switzerland); NASU (Ukraine); STFC (United Kingdom); DOE NP 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), CSCS (Switzerland), IFIN-HH (Romania), CBPF (Brazil), Polish WLCG (Poland), and NERSC (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 ARC and

ARDC (Australia); Minciencias (Colombia); AvH Foundation (Germany); EPLANET, Marie Skłodowska-Curie Actions, and ERC (European Union); A*MIDEX, ANR, IPhU and Labex P2IO, and Région Auvergne-Rhône-Alpes (France); Key Research Program of Frontier Sciences of CAS, CAS PIFI, CAS CCEPP, Fundamental Research Funds for the Central Universities, and Sci. & Tech. Program of Guangzhou (China); GVA, XuntaGal, GENCAT and Prog. Atracción Talento, CM (Spain); SRC (Sweden); the Leverhulme Trust, the Royal Society, and UKRI (United Kingdom).

---

[1] A. D. Sakharov, Violation of $CP$ invariance, C asymmetry, and baryon asymmetry of the universe, Pis'ma Zh. Eksp. Teor. Fiz. **5**, 32 (1967).

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

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

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

[5] A. Alavi-Harati *et al.* (KTeV Collaboration), Observation of Direct $CP$ Violation in $K_{S,L} \to \pi\pi$ Decays, Phys. Rev. Lett. **83**, 22 (1999).

[6] A. Lai *et al.* (NA48 Collaboration), A precise measurement of the direct $CP$ violation parameter $\mathrm{Re}(\varepsilon'/\varepsilon)$, Eur. Phys. J. C **22**, 231 (2001).

[7] B. Aubert *et al.* (*BABAR* Collaboration), Observation of $CP$ Violation in the $B^0$ Meson System, Phys. Rev. Lett. **87**, 091801 (2001).

[8] K. Abe *et al.* (Belle Collaboration), Observation of Large $CP$ Violation in the Neutral $B$ Meson System, Phys. Rev. Lett. **87**, 091802 (2001).

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

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

[11] 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).

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

[13] R. Aaij *et al.* (LHCb Collaboration), Observation of $CP$ Violation in Charm Decays, Phys. Rev. Lett. **122**, 211803 (2019).

[14] 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).

[15] 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).

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

[17] A. Khodjamirian and A. A. Petrov, Direct $CP$ asymmetry in $D \to \pi^-\pi^+$ and $D \to K^-K^+$ in QCD-based approach, Phys. Lett. B **774**, 235 (2017).

[18] M. Chala, A. Lenz, A. V. Rusov, and J. Scholtz, $\Delta A_{CP}$ within the standard model and beyond, J. High Energy Phys. 07 (2019) 161.

[19] Y. Grossman and S. Schacht, The emergence of the $\Delta U = 0$ rule in charm physics, J. High Energy Phys. 07 (2019) 020.

[20] F. Buccella, A. Paul, and P. Santorelli, $SU(3)_F$ breaking through final state interactions and $CP$ asymmetries in $D \to PP$ decays, Phys. Rev. D **99**, 113001 (2019).

[21] H.-N. Li, C.-D. Lü, and F.-S. Yu, Implications on the first observation of charm CPV at LHCb, arXiv:1903.10638.

[22] S. Schacht and A. Soni, Enhancement of charm $CP$ violation due to nearby resonances, Phys. Lett. B **825**, 136855 (2022).

[23] H.-Y. Cheng and C.-W. Chiang, Revisiting $CP$ violation in $D \to PP$ and $VP$ decays, Phys. Rev. D **100**, 093002 (2019).

[24] A. Dery and Y. Nir, Implications of the LHCb discovery of $CP$ violation in charm decays, J. High Energy Phys. 12 (2019) 104.

[25] D. Wang, C.-P. Jia, and F.-S. Yu, A self-consistent framework of topological amplitude and its $SU(N)$ decomposition, J. High Energy Phys. 21 (2020) 126.

[26] R. Bause, H. Gisbert, M. Golz, and G. Hiller, Exploiting $CP$-asymmetries in rare charm decays, Phys. Rev. D **101**, 115006 (2020).

[27] A. Dery, Y. Grossman, S. Schacht, and A. Soffer, Probing the $\Delta U = 0$ rule in three body charm decays, J. High Energy Phys. 05 (2021) 179.

[28] H.-Y. Cheng and C.-W. Chiang, $CP$ violation in quasi-two-body $D \to VP$ decays and three-body $D$ decays mediated by vector resonances, Phys. Rev. D **104**, 073003 (2021).

[29] I. Bediaga, T. Frederico, and P. Magalhaes, Enhanced charm $CP$ asymmetries from final state interactions, arXiv: 2203.04056.

[30] P. del Amo Sanchez *et al.* (*BABAR* Collaboration), Measurement of $D^0 - \bar{D}^0$ Mixing Parameters Using $D^0 \to K_S^0\pi^+\pi^-$ and $D^0 \to K_S^0K^+K^-$ Decays, Phys. Rev. Lett. **105**, 081803 (2010).

[31] J. P. Lees *et al.* (*BABAR* Collaboration), Measurement of $D^0 - \bar{D}^0$ mixing and $CP$ violation in two-body $D^0$ decays, Phys. Rev. D **87**, 012004 (2013).

[32] T. Peng *et al.* (Belle Collaboration), Measurement of $D^0 - \bar{D}^0$ mixing and search for indirect $CP$ violation using $D^0 \to K_S^0\pi^+\pi^-$ decays, Phys. Rev. D **89**, 091103 (2014).

[33] M. Starič *et al.* (Belle Collaboration), Measurement of $D^0 - \bar{D}^0$ mixing and search for $CP$ violation in $D^0 \to K^+K^-, \pi^+\pi^-$ decays with the full Belle data set, Phys. Lett. B **753**, 412 (2016).

[34] R. Aaij *et al.* (LHCb Collaboration), Updated determination of $D^0$–$\bar{D}^0$ mixing and $CP$ violation parameters with $D^0 \to K^+\pi^-$ decays, Phys. Rev. D **97**, 031101 (2018).

[35] R. Aaij *et al.* (LHCb Collaboration), Measurement of the Charm-Mixing Parameter $y_{CP}$, Phys. Rev. Lett. **122**, 011802 (2019).

[36] R. Aaij *et al.* (LHCb Collaboration), Measurement of the Mass Difference Between Neutral Charm-Meson Eigenstates, Phys. Rev. Lett. **122**, 231802 (2019).

[37] R. Aaij *et al.* (LHCb Collaboration), Observation of the Mass Difference Between Neutral Charm-Meson Eigenstates, Phys. Rev. Lett. **127**, 111801 (2021).

[38] A. L. Kagan and L. Silvestrini, Dispersive and absorptive $CP$ violation in $D^0 - \overline{D^0}$ mixing, Phys. Rev. D **103**, 053008 (2021).

[39] R. Aaij *et al.* (LHCb Collaboration), Search for time-dependent $CP$ violation in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays, Phys. Rev. D **104**, 072010 (2021).

[40] R. Aaij *et al.* (LHCb Collaboration), Measurement of $B^0$, $B_s^0$, $B^+$ and $\Lambda_b^0$ production asymmetries in 7 and 8 TeV proton-proton collisions, Phys. Lett. B **774**, 139 (2017).

[41] R. Aaij *et al.* (LHCb Collaboration), Measurement of the flavour-specific $CP$ -violating asymmetry $a_{\mathrm{sl}}^s$ in $B_s^0$ decays, Phys. Lett. B **728**, 607 (2014).

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

[43] R. Aaij *et al.* (LHCb Collaboration), Measurement of the $D_s^+ - D_s^-$ production asymmetry in 7 TeV $p\ p$ collisions, Phys. Lett. B **713**, 186 (2012).

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

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

[46] M. Kucharczyk, P. Morawski, and M. Witek, Primary vertex reconstruction at LHCb, Report No. LHCb-PUB-2014-044, 2014.

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

[48] W. D. Hulsbergen, Decay chain fitting with a Kalman filter, Nucl. Instrum. Methods Phys. Res., Sect. A **552**, 566 (2005).

[49] R. L. Workman *et al.* (Particle Data Group), Review of particle physics, Prog. Theor. Exp. Phys. **2022**, 083C01 (2022).

[50] R. Aaij *et al.* (LHCb Collaboration), Measurement of the Difference of Time-Integrated $CP$ Asymmetries in $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ Decays, Phys. Rev. Lett. **116**, 191601 (2016).

[51] See Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevLett.131.091802 for additional numerical values and plots, which includes Refs. [13,52–58].

[52] R. Aaij *et al.* (LHCb Collaboration), Measurement of $CP$ asymmetry in $D^0 \to K^-K^+$ decays, Phys. Lett. B **767**, 177 (2017).

[53] E. M. Aitala *et al.* (E791 Collaboration), Branching fractions for $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$, and a search for $CP$ violation in $D^0$ decays, Phys. Lett. B **421**, 405 (1998).

[54] J. M. Link *et al.* (FOCUS Collaboration), Search for violation in $D^0$ and $D^+$ decays, Phys. Lett. B **491**, 232 (2000); **495**, 443(E) (2000).

[55] S. E. Csorna *et al.* (CLEO Collaboration), Lifetime differences, direct $CP$ violation and partial widths in $D^0$ meson decays to $K^+K^-$ and $\pi^+\pi^-$, Phys. Rev. D **65**, 092001 (2002).

[56] M. Staric *et al.* (Belle Collaboration), Measurement of $CP$ asymmetry in Cabibbo suppressed $D^0$ decays, Phys. Lett. B **670**, 190 (2008).

[57] B. Aubert *et al.* (*BABAR* Collaboration), Search for $CP$ Violation in the Decays $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$, Phys. Rev. Lett. **100**, 061803 (2008).

[58] T. Aaltonen *et al.* (CDF Collaboration), Measurement of $CP$-violating asymmetries in $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$ decays at CDF, Phys. Rev. D **85**, 012009 (2012).

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

[60] W. Fetscher, P. Kokkas, P. Pavlopoulos, Th. Ruf, and Th. Schietinger, Regeneration of arbitrary coherent neutral kaon states: A new method for measuring the $K^0$ anti-$K^0$ forward scattering amplitude, Z. Phys. C **72**, 543 (1996).

[61] A. Gsponer, J. Hoffnagle, W. R. Molzon, J. Roehrig, V. L. Telegdi, B. Winstein, S. H. Aronson, G. J. Bock, D. Hedin, and G. B. Thomson, Precise Coherent $K_S^0$ Regeneration Amplitudes for C, Al, Cu, Sn and Pb Nuclei from 20 to 140 GeV/$c$ and Their Interpretation, Phys. Rev. Lett. **42**, 13 (1979).

[62] R. A. Briere and B. Winstein, Determining the Phase of a Strong Scattering Amplitude from Its Momentum Dependence to Better Than 1°: The Example of Kaon Regeneration, Phys. Rev. Lett. **75**, 402 (1995).

[63] 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.

[64] G. A. Cowan, D. C. Craik, and M. D. Needham, RapidSim: An application for the fast simulation of heavy-quark hadron decays, Comput. Phys. Commun. **214**, 239 (2017).

[65] Y. Amhis *et al.* (Heavy Flavor Averaging Group), Averages of $b$-hadron, $c$-hadron, and $\tau$-lepton properties as of 2018, Eur. Phys. J. C **81**, 226 (2021).

[66] R. Aaij *et al.* (LHCb Collaboration), Measurement of indirect $CP$ asymmetries in $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays using semileptonic $B$ decays, J. High Energy Phys. 04 (2015) 043.

[67] R. Aaij *et al.* (LHCb Collaboration), Measurement of the $CP$ Violation Parameter $A_\Gamma$ in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ Decays, Phys. Rev. Lett. **118**, 261803 (2017).

[68] M. Gronau, High order U-spin breaking: A precise amplitude relation in $D^0$ decays, Phys. Lett. B **730**, 221 (2014); **735**, 221(A) (2014).

R. Aaij,[32] A. S. W. Abdelmotteleb,[50] C. Abellan Beteta,[44] F. Abudinén,[50] T. Ackernley,[54] B. Adeva,[40]
M. Adinolfi,[48] P. Adlarson,[77] H. Afsharnia,[9] C. Agapopoulou,[13] C. A. Aidala,[78] S. Aiola,[25] Z. Ajaltouni,[9]
S. Akar,[59] K. Akiba,[32] J. Albrecht,[15] F. Alessio,[42] M. Alexander,[53] A. Alfonso Albero,[39] Z. Aliouche,[56]
P. Alvarez Cartelle,[49] R. Amalric,[13] S. Amato,[2] J. L. Amey,[48] Y. Amhis,[11,42] L. An,[42] L. Anderlini,[22]
M. Andersson,[44] A. Andreianov,[38] M. Andreotti,[21] D. Andreou,[62] D. Ao,[6] F. Archilli,[17] A. Artamonov,[38]
M. Artuso,[62] E. Aslanides,[10] M. Atzeni,[44] B. Audurier,[12] S. Bachmann,[17] M. Bachmayer,[43] J. J. Back,[50]
A. Bailly-reyre,[13] P. Baladron Rodriguez,[40] V. Balagura,[12] W. Baldini,[21] J. Baptista de Souza Leite,[1]
M. Barbetti,[22,b] R. J. Barlow,[56] S. Barsuk,[11] W. Barter,[55] M. Bartolini,[49] F. Baryshnikov,[38] J. M. Basels,[14]
G. Bassi,[29,c] B. Batsukh,[4] A. Battig,[15] A. Bay,[43] A. Beck,[50] M. Becker,[15] F. Bedeschi,[29] I. B. Bediaga,[1]
A. Beiter,[62] V. Belavin,[38] S. Belin,[40] V. Bellee,[44] K. Belous,[38] I. Belov,[38] I. Belyaev,[38] G. Benane,[10]
G. Bencivenni,[23] E. Ben-Haim,[13] A. Berezhnoy,[38] R. Bernet,[44] S. Bernet Andres,[76] D. Berninghoff,[17]
H. C. Bernstein,[62] C. Bertella,[56] A. Bertolin,[28] C. Betancourt,[44] F. Betti,[42] Ia. Bezshyiko,[44] S. Bhasin,[48]
J. Bhom,[35] L. Bian,[68] M. S. Bieker,[15] N. V. Biesuz,[21] S. Bifani,[47] P. Billoir,[13] A. Biolchini,[32] M. Birch,[55]
F. C. R. Bishop,[49] A. Bitadze,[56] A. Bizzeti, M. P. Blago,[49] T. Blake,[50] F. Blanc,[43] S. Blusk,[62] D. Bobulska,[53]
J. A. Boelhauve,[15] O. Boente Garcia,[12] T. Boettcher,[59] A. Boldyrev,[38] C. S. Bolognani,[74] R. Bolzonella,[21,d]
N. Bondar,[38,42] F. Borgato,[28] S. Borghi,[56] M. Borsato,[17] J. T. Borsuk,[35] S. A. Bouchiba,[43] T. J. V. Bowcock,[54]
A. Boyer,[42] C. Bozzi,[21] M. J. Bradley,[55] S. Braun,[60] A. Brea Rodriguez,[40] J. Brodzicka,[35] A. Brossa Gonzalo,[40]
J. Brown,[54] D. Brundu,[27] A. Buonaura,[44] L. Buonincontri,[28] A. T. Burke,[56] C. Burr,[42] A. Bursche,[66]
A. Butkevich,[38] J. S. Butter,[32] J. Buytaert,[42] W. Byczynski,[42] S. Cadeddu,[27] H. Cai,[68] R. Calabrese,[21,d]
L. Calefice,[15] S. Cali,[23] R. Calladine,[47] M. Calvi,[26,e] M. Calvo Gomez,[76] P. Campana,[23] D. H. Campora Perez,[74]
A. F. Campoverde Quezada,[6] S. Capelli,[26,e] L. Capriotti,[20] A. Carbone,[20,f] G. Carboni,[31] R. Cardinale,[24,g]
A. Cardini,[27] I. Carli,[4] P. Carniti,[26,e] L. Carus,[14] A. Casais Vidal,[40] R. Caspary,[17] G. Casse,[54] M. Cattaneo,[42]
G. Cavallero,[42] V. Cavallini,[21,d] S. Celani,[43] J. Cerasoli,[10] D. Cervenkov,[57] A. J. Chadwick,[54] M. G. Chapman,[48]
M. Charles,[13] Ph. Charpentier,[42] C. A. Chavez Barajas,[54] M. Chefdeville,[8] C. Chen,[3] S. Chen,[4] A. Chernov,[35]
S. Chernyshenko,[46] V. Chobanova,[40] S. Cholak,[43] M. Chrzaszcz,[35] A. Chubykin,[38] V. Chulikov,[38]
P. Ciambrone,[23] M. F. Cicala,[50] X. Cid Vidal,[40] G. Ciezarek,[42] G. Ciullo,[21,d] P. E. L. Clarke,[52] M. Clemencic,[42]
H. V. Cliff,[49] J. Closier,[42] J. L. Cobbledick,[56] V. Coco,[42] J. A. B. Coelho,[11] J. Cogan,[10] E. Cogneras,[9]
L. Cojocariu,[37] P. Collins,[42] T. Colombo,[42] L. Congedo,[19] A. Contu,[27] N. Cooke,[47] I. Corredoira,[40] G. Corti,[42]
B. Couturier,[42] D. C. Craik,[58] J. Crkovská,[61] M. Cruz Torres,[1,h] R. Currie,[52] C. L. Da Silva,[61] S. Dadabaev,[38]
L. Dai,[65] X. Dai,[5] E. Dall'Occo,[15] J. Dalseno,[40] C. D'Ambrosio,[42] J. Daniel,[9] A. Danilina,[38] P. d'Argent,[15]
J. E. Davies,[56] A. Davis,[56] O. De Aguiar Francisco,[56] J. de Boer,[42] K. De Bruyn,[73] S. De Capua,[56]
M. De Cian,[43] U. De Freitas Carneiro Da Graca,[1] E. De Lucia,[23] J. M. De Miranda,[1] L. De Paula,[2] M. De Serio,[19,i]
D. De Simone,[44] P. De Simone,[23] F. De Vellis,[15] J. A. de Vries,[74] C. T. Dean,[61] F. Debernardis,[19,i] D. Decamp,[8]
V. Dedu,[10] L. Del Buono,[13] B. Delaney,[58] H.-P. Dembinski,[15] V. Denysenko,[44] O. Deschamps,[9] F. Dettori,[27,j]
B. Dey,[71] A. Di Cicco,[23] P. Di Nezza,[23] I. Diachkov,[38] S. Didenko,[38] L. Dieste Maronas,[40] S. Ding,[62]
V. Dobishuk,[46] A. Dolmatov,[38] C. Dong,[3] A. M. Donohoe,[18] F. Dordei,[27] A. C. dos Reis,[1] L. Douglas,[53]
A. G. Downes,[8] P. Duda,[75] M. W. Dudek,[35] L. Dufour,[42] V. Duk,[72] P. Durante,[42] M. M. Duras,[75]
J. M. Durham,[61] D. Dutta,[56] A. Dziurda,[35] A. Dzyuba,[38] S. Easo,[51] U. Egede,[63] V. Egorychev,[38] S. Eidelman,[38,a]
C. Eirea Orro,[40] S. Eisenhardt,[52] E. Ejopu,[56] S. Ek-In,[43] L. Eklund,[77] S. Ely,[62] A. Ene,[37] E. Epple,[59]
S. Escher,[14] J. Eschle,[44] S. Esen,[44] T. Evans,[56] F. Fabiano,[27,j] L. N. Falcao,[1] Y. Fan,[6] B. Fang,[68]
L. Fantini,[72,k] M. Faria,[43] S. Farry,[54] D. Fazzini,[26,e] L. F Felkowski,[75] M. Feo,[42] M. Fernandez Gomez,[40]
A. D. Fernez,[60] F. Ferrari,[20] L. Ferreira Lopes,[43] F. Ferreira Rodrigues,[2] S. Ferreres Sole,[32] M. Ferrillo,[44]
M. Ferro-Luzzi,[42] S. Filippov,[38] R. A. Fini,[19] M. Fiorini,[21,d] M. Firlej,[34] K. M. Fischer,[57] D. S. Fitzgerald,[78]
C. Fitzpatrick,[56] T. Fiutowski,[34] F. Fleuret,[12] M. Fontana,[13] F. Fontanelli,[24,g] R. Forty,[42] D. Foulds-Holt,[49]
V. Franco Lima,[54] M. Franco Sevilla,[60] M. Frank,[42] E. Franzoso,[21,d] G. Frau,[17] C. Frei,[42] D. A. Friday,[53]
J. Fu,[6] Q. Fuehring,[15] T. Fulghesu,[13] E. Gabriel,[32] G. Galati,[19,i] M. D. Galati,[32] A. Gallas Torreira,[40]
D. Galli,[20,f] S. Gambetta,[52,42] Y. Gan,[3] M. Gandelman,[2] P. Gandini,[25] Y. Gao,[5] M. Garau,[27,j]
L. M. Garcia Martin,[50] P. Garcia Moreno,[39] J. García Pardiñas,[26,e] B. Garcia Plana,[40] F. A. Garcia Rosales,[12]
L. Garrido,[39] C. Gaspar,[42] R. E. Geertsema,[32] D. Gerick,[17] L. L. Gerken,[15] E. Gersabeck,[56] M. Gersabeck,[56]

T. Gershon,[50] L. Giambastiani,[28] V. Gibson,[49] H. K. Giemza,[36] A. L. Gilman,[57] M. Giovannetti,[23,l]
A. Gioventù,[40] P. Gironella Gironell,[39] C. Giugliano,[21,d] M. A. Giza,[35] K. Gizdov,[52] E. L. Gkougkousis,[42]
V. V. Gligorov,[13,42] C. Göbel,[64] E. Golobardes,[76] D. Golubkov,[38] A. Golutvin,[55,38] A. Gomes,[1,1,2,a,m,n,m]
S. Gomez Fernandez,[39] F. Goncalves Abrantes,[57] M. Goncerz,[35] G. Gong,[3] I. V. Gorelov,[38] C. Gotti,[26]
J. P. Grabowski,[17] T. Grammatico,[13] L. A. Granado Cardoso,[42] E. Graugés,[39] E. Graverini,[43] G. Graziani,
A. T. Grecu,[37] L. M. Greeven,[32] N. A. Grieser,[4] L. Grillo,[53] S. Gromov,[38] B. R. Gruberg Cazon,[57] C. Gu,[3]
M. Guarise,[21,d] M. Guittiere,[11] P. A. Günther,[17] E. Gushchin,[38] A. Guth,[14] Y. Guz,[38] T. Gys,[42] T. Hadavizadeh,[63]
G. Haefeli,[43] C. Haen,[42] J. Haimberger,[42] S. C. Haines,[49] T. Halewood-leagas,[54] M. M. Halvorsen,[42]
P. M. Hamilton,[60] J. Hammerich,[54] Q. Han,[7] X. Han,[17] E. B. Hansen,[56] S. Hansmann-Menzemer,[17,42] L. Hao,[6]
N. Harnew,[57] T. Harrison,[54] C. Hasse,[42] M. Hatch,[42] J. He,[6,o] K. Heijhoff,[32] K. Heinicke,[15] C. Henderson,[59]
R. D. L. Henderson,[63,50] A. M. Hennequin,[58] K. Hennessy,[54] L. Henry,[42] J. Herd,[55] J. Heuel,[14] A. Hicheur,[2]
D. Hill,[43] M. Hilton,[56] S. E. Hollitt,[15] J. Horswill,[56] R. Hou,[7] Y. Hou,[8] J. Hu,[17] J. Hu,[66] W. Hu,[5] X. Hu,[3]
W. Huang,[6] X. Huang,[68] W. Hulsbergen,[32] R. J. Hunter,[50] M. Hushchyn,[38] D. Hutchcroft,[54] P. Ibis,[15] M. Idzik,[34]
D. Ilin,[38] P. Ilten,[59] A. Inglessi,[38] A. Iniukhin,[38] A. Ishteev,[38] K. Ivshin,[38] R. Jacobsson,[42] H. Jage,[14]
S. J. Jaimes Elles,[41] S. Jakobsen,[42] E. Jans,[32] B. K. Jashal,[41] A. Jawahery,[60] V. Jevtic,[15] E. Jiang,[60] X. Jiang,[4,6]
Y. Jiang,[6] M. John,[57] D. Johnson,[58] C. R. Jones,[49] T. P. Jones,[50] B. Jost,[42] N. Jurik,[42] I. Juszczak,[35]
S. Kandybei,[45] Y. Kang,[3] M. Karacson,[42] D. Karpenkov,[38] M. Karpov,[38] J. W. Kautz,[59] F. Keizer,[42]
D. M. Keller,[62] M. Kenzie,[50] T. Ketel,[32] B. Khanji,[15] A. Kharisova,[38] S. Kholodenko,[38] G. Khreich,[11]
T. Kirn,[14] V. S. Kirsebom,[43] O. Kitouni,[58] S. Klaver,[33] N. Kleijne,[29,c] K. Klimaszewski,[36] M. R. Kmiec,[36]
S. Koliiev,[46] A. Kondybayeva,[38] A. Konoplyannikov,[38] P. Kopciewicz,[34] R. Kopecna,[17] P. Koppenburg,[32]
M. Korolev,[38] I. Kostiuk,[32,46] O. Kot,[46] S. Kotriakhova, A. Kozachuk,[38] P. Kravchenko,[38] L. Kravchuk,[38]
R. D. Krawczyk,[42] M. Kreps,[50] S. Kretzschmar,[14] P. Krokovny,[38] W. Krupa,[34] W. Krzemien,[36] J. Kubat,[17]
S. Kubis,[75] W. Kucewicz,[35,34] M. Kucharczyk,[35] V. Kudryavtsev,[38] G. J. Kunde,[61] A. Kupsc,[77] D. Lacarrere,[42]
G. Lafferty,[56] A. Lai,[27] A. Lampis,[27,j] D. Lancierini,[44] C. Landesa Gomez,[40] J. J. Lane,[56] R. Lane,[48]
G. Lanfranchi,[23] C. Langenbruch,[14] J. Langer,[15] O. Lantwin,[38] T. Latham,[50] F. Lazzari,[29,p] M. Lazzaroni,[25,q]
R. Le Gac,[10] S. H. Lee,[78] R. Lefèvre,[9] A. Leflat,[38] S. Legotin,[38] P. Lenisa,[21,d] O. Leroy,[10] T. Lesiak,[35]
B. Leverington,[17] A. Li,[3] H. Li,[66] K. Li,[7] P. Li,[17] P.-R. Li,[67] S. Li,[7] T. Li,[66] Y. Li,[4] Z. Li,[62] X. Liang,[62]
C. Lin,[6] T. Lin,[51] R. Lindner,[42] V. Lisovskyi,[15] R. Litvinov,[27,j] G. Liu,[66] H. Liu,[6] Q. Liu,[6] S. Liu,[4,6]
A. Lobo Salvia,[39] A. Loi,[27] R. Lollini,[72] J. Lomba Castro,[40] I. Longstaff,[53] J. H. Lopes,[2] A. Lopez Huertas,[39]
S. López Soliño,[40] G. H. Lovell,[49] Y. Lu,[4,r] C. Lucarelli,[22,b] D. Lucchesi,[28,s] S. Luchuk,[38] M. Lucio Martinez,[74]
V. Lukashenko,[32,46] Y. Luo,[3] A. Lupato,[56] E. Luppi,[21,d] A. Lusiani,[29,c] K. Lynch,[18] X.-R. Lyu,[6] L. Ma,[4]
R. Ma,[6] S. Maccolini,[20] F. Machefert,[11] F. Maciuc,[37] I. Mackay,[57] V. Macko,[43] P. Mackowiak,[15]
L. R. Madhan Mohan,[48] A. Maevskiy,[38] D. Maisuzenko,[38] M. W. Majewski,[34] J. J. Malczewski,[35] S. Malde,[57]
B. Malecki,[35,42] A. Malinin,[38] T. Maltsev,[38] G. Manca,[27,j] G. Mancinelli,[10] C. Mancuso,[11,25,q] D. Manuzzi,[20]
C. A. Manzari,[44] D. Marangotto,[25,q] J. F. Marchand,[8] U. Marconi,[20] S. Mariani,[22,b] C. Marin Benito,[39]
J. Marks,[17] A. M. Marshall,[48] P. J. Marshall,[54] G. Martelli,[72,k] G. Martellotti,[30] L. Martinazzoli,[42,e]
M. Martinelli,[26,e] D. Martinez Santos,[40] F. Martinez Vidal,[41] A. Massafferri,[1] M. Materok,[14] R. Matev,[42]
A. Mathad,[44] V. Matiunin,[38] C. Matteuzzi,[26] K. R. Mattioli,[12] A. Mauri,[32] E. Maurice,[12] J. Mauricio,[39]
M. Mazurek,[42] M. McCann,[55] L. Mcconnell,[18] T. H. McGrath,[56] N. T. McHugh,[53] A. McNab,[56] R. McNulty,[18]
J. V. Mead,[54] B. Meadows,[59] G. Meier,[15] D. Melnychuk,[36] S. Meloni,[26,e] M. Merk,[32,74] A. Merli,[25,q]
L. Meyer Garcia,[2] D. Miao,[4,6] M. Mikhasenko,[70,t] D. A. Milanes,[69] E. Millard,[50] M. Milovanovic,[42]
M.-N. Minard,[8,a] A. Minotti,[26,e] T. Miralles,[9] S. E. Mitchell,[52] B. Mitreska,[56] D. S. Mitzel,[15] A. Mödden,[15]
R. A. Mohammed,[57] R. D. Moise,[14] S. Mokhnenko,[38] T. Mombächer,[40] M. Monk,[50,63] I. A. Monroy,[69]
S. Monteil,[9] M. Morandin,[28] G. Morello,[23] M. J. Morello,[29,c] J. Moron,[34] A. B. Morris,[70] A. G. Morris,[50]
R. Mountain,[62] H. Mu,[3] E. Muhammad,[50] F. Muheim,[52] M. Mulder,[73] K. Müller,[44] C. H. Murphy,[57]
D. Murray,[56] R. Murta,[55] P. Muzzetto,[27,j] P. Naik,[48] T. Nakada,[43] R. Nandakumar,[51] T. Nanut,[42] I. Nasteva,[2]
M. Needham,[52] N. Neri,[25,q] S. Neubert,[70] N. Neufeld,[42] P. Neustroev,[38] R. Newcombe,[55] J. Nicolini,[15,11]
E. M. Niel,[43] S. Nieswand,[14] N. Nikitin,[38] N. S. Nolte,[58] C. Normand,[8,27,j] J. Novoa Fernandez,[40] C. Nunez,[78]
A. Oblakowska-Mucha,[34] V. Obraztsov,[38] T. Oeser,[14] D. P. O'Hanlon,[48] S. Okamura,[21,d] R. Oldeman,[27,j]

F. Oliva,[52] C. J. G. Onderwater,[73] R. H. O’Neil,[52] J. M. Otalora Goicochea,[2] T. Ovsiannikova,[38] P. Owen,[44] A. Oyanguren,[41] O. Ozcelik,[52] K. O. Padeken,[70] B. Pagare,[50] P. R. Pais,[42] T. Pajero,[57] A. Palano,[19] M. Palutan,[23] Y. Pan,[56] G. Panshin,[38] L. Paolucci,[50] A. Papanestis,[51] M. Pappagallo,[19,i] L. L. Pappalardo,[21,d] C. Pappenheimer,[59] W. Parker,[60] C. Parkes,[56] B. Passalacqua,[21,d] G. Passaleva,[22] A. Pastore,[19] M. Patel,[55] C. Patrignani,[20,f] C. J. Pawley,[74] A. Pearce,[42] A. Pellegrino,[32] M. Pepe Altarelli,[42] S. Perazzini,[20] D. Pereima,[38] A. Pereiro Castro,[40] P. Perret,[9] M. Petric,[53] K. Petridis,[48] A. Petrolini,[24,g] A. Petrov,[38] S. Petrucci,[52] M. Petruzzo,[25] H. Pham,[62] A. Philippov,[38] R. Piandani,[6] L. Pica,[29,c] M. Piccini,[72] B. Pietrzyk,[8] G. Pietrzyk,[11] M. Pili,[57] D. Pinci,[30] F. Pisani,[42] M. Pizzichemi,[26,42,e] V. Placinta,[37] J. Plews,[47] M. Plo Casasus,[40] F. Polci,[13,42] M. Poli Lener,[23] M. Poliakova,[62] A. Poluektov,[10] N. Polukhina,[38] I. Polyakov,[42] E. Polycarpo,[2] S. Ponce,[42] D. Popov,[6,42] S. Popov,[38] S. Poslavskii,[38] K. Prasanth,[35] L. Promberger,[42] C. Prouve,[40] V. Pugatch,[46] V. Puill,[11] G. Punzi,[29,u] H. R. Qi,[3] W. Qian,[6] N. Qin,[3] S. Qu,[3] R. Quagliani,[43] N. V. Raab,[18] R. I. Rabadan Trejo,[6] B. Rachwal,[34] J. H. Rademacker,[48] R. Rajagopalan,[62] M. Rama,[29] M. Ramos Pernas,[50] M. S. Rangel,[2] F. Ratnikov,[38] G. Raven,[33,42] M. Rebollo De Miguel,[41] F. Redi,[42] J. Reich,[48] F. Reiss,[56] C. Remon Alepuz,[41] Z. Ren,[3] P. K. Resmi,[10] R. Ribatti,[29,c] A. M. Ricci,[27] S. Ricciardi,[51] K. Richardson,[58] M. Richardson-Slipper,[52] K. Rinnert,[54] P. Robbe,[11] G. Robertson,[52] A. B. Rodrigues,[43] E. Rodrigues,[54] E. Rodriguez Fernandez,[40] J. A. Rodriguez Lopez,[69] E. Rodriguez Rodriguez,[40] D. L. Rolf,[42] A. Rollings,[57] P. Roloff,[42] V. Romanovskiy,[38] M. Romero Lamas,[40] A. Romero Vidal,[40] J. D. Roth,[78,a] M. Rotondo,[23] M. S. Rudolph,[62] T. Ruf,[42] R. A. Ruiz Fernandez,[40] J. Ruiz Vidal,[41] A. Ryzhikov,[38] J. Ryzka,[34] J. J. Saborido Silva,[40] N. Sagidova,[38] N. Sahoo,[47] B. Saitta,[27,j] M. Salomoni,[42] C. Sanchez Gras,[32] I. Sanderswood,[41] R. Santacesaria,[30] C. Santamarina Rios,[40] M. Santimaria,[23] E. Santovetti,[31,l] D. Saranin,[38] G. Sarpis,[14] M. Sarpis,[70] A. Sarti,[30] C. Satriano,[30,v] A. Satta,[31] M. Saur,[15] D. Savrina,[38] H. Sazak,[9] L. G. Scantlebury Smead,[57] A. Scarabotto,[13] S. Schael,[14] S. Scherl,[54] M. Schiller,[53] H. Schindler,[42] M. Schmelling,[16] B. Schmidt,[42] S. Schmitt,[14] O. Schneider,[43] A. Schopper,[42] M. Schubiger,[32] S. Schulte,[43] M. H. Schune,[11] R. Schwemmer,[42] B. Sciascia,[23,42] A. Sciuccati,[42] S. Sellam,[40] A. Semennikov,[38] M. Senghi Soares,[33] A. Sergi,[24,g] N. Serra,[44] L. Sestini,[28] A. Seuthe,[15] Y. Shang,[5] D. M. Shangase,[78] M. Shapkin,[38] I. Shchemerov,[38] L. Shchutska,[43] T. Shears,[54] L. Shekhtman,[38] Z. Shen,[5] S. Sheng,[4,6] V. Shevchenko,[38] B. Shi,[6] E. B. Shields,[26,e] Y. Shimizu,[11] E. Shmanin,[38] R. Shorkin,[38] J. D. Shupperd,[62] B. G. Siddi,[21,d] R. Silva Coutinho,[62] G. Simi,[28] S. Simone,[19,i] M. Singla,[63] N. Skidmore,[56] R. Skuza,[17] T. Skwarnicki,[62] M. W. Slater,[47] J. C. Smallwood,[57] J. G. Smeaton,[49] E. Smith,[44] K. Smith,[61] M. Smith,[55] A. Snoch,[32] L. Soares Lavra,[9] M. D. Sokoloff,[59] F. J. P. Soler,[53] A. Solomin,[38,48] A. Solovev,[38] I. Solovyev,[38] R. Song,[63] F. L. Souza De Almeida,[2] B. Souza De Paula,[2] B. Spaan,[15,a] E. Spadaro Norella,[25,q] E. Spedicato,[20] E. Spiridenkov,[38] P. Spradlin,[53] V. Sriskaran,[42] F. Stagni,[42] M. Stahl,[42] S. Stahl,[42] S. Stanislaus,[57] E. N. Stein,[42] O. Steinkamp,[44] O. Stenyakin,[38] H. Stevens,[15] S. Stone,[62,a] D. Strekalina,[38] F. Suljik,[57] J. Sun,[27] L. Sun,[68] Y. Sun,[60] P. Svihra,[56] P. N. Swallow,[47] K. Swientek,[34] A. Szabelski,[36] T. Szumlak,[34] M. Szymanski,[42] Y. Tan,[3] S. Taneja,[56] A. R. Tanner,[48] M. D. Tat,[57] A. Terentev,[38] F. Teubert,[42] E. Thomas,[42] D. J. D. Thompson,[47] K. A. Thomson,[54] H. Tilquin,[55] V. Tisserand,[9] S. T’Jampens,[8] M. Tobin,[4] L. Tomassetti,[21,d] G. Tonani,[25,q] X. Tong,[5] D. Torres Machado,[1] D. Y. Tou,[3] E. Trifonova,[38] S. M. Trilov,[48] C. Trippl,[43] G. Tuci,[6] A. Tully,[43] N. Tuning,[32] A. Ukleja,[36] D. J. Unverzagt,[17] A. Usachov,[32] A. Ustyuzhanin,[38] U. Uwer,[17] A. Vagner,[38] V. Vagnoni,[20] A. Valassi,[42] G. Valenti,[20] N. Valls Canudas,[76] M. van Beuzekom,[32] M. Van Dijk,[43] H. Van Hecke,[61] E. van Herwijnen,[38] C. B. Van Hulse,[40,w] M. van Veghel,[73] R. Vazquez Gomez,[39] P. Vazquez Regueiro,[40] C. Vázquez Sierra,[42] S. Vecchi,[21] J. J. Velthuis,[48] M. Veltri,[22,x] A. Venkateswaran,[43] M. Veronesi,[32] M. Vesterinen,[50] D. Vieira,[59] M. Vieites Diaz,[43] X. Vilasis-Cardona,[76] E. Vilella Figueras,[54] A. Villa,[20] P. Vincent,[13] F. C. Volle,[11] D. vom Bruch,[10] A. Vorobyev,[38] V. Vorobyev,[38] N. Voropaev,[38] K. Vos,[74] C. Vrahas,[52] R. Waldi,[17] J. Walsh,[29] G. Wan,[5] C. Wang,[17] J. Wang,[5] J. Wang,[4] J. Wang,[3] J. Wang,[68] M. Wang,[5] R. Wang,[48] X. Wang,[66] Y. Wang,[7] Z. Wang,[44] Z. Wang,[3] Z. Wang,[6] J. A. Ward,[50,63] N. K. Watson,[47] D. Websdale,[55] Y. Wei,[5] C. Weisser,[58] B. D. C. Westhenry,[48] D. J. White,[56] M. Whitehead,[53] A. R. Wiederhold,[50] D. Wiedner,[15] G. Wilkinson,[57] M. K. Wilkinson,[59] I. Williams,[49] M. Williams,[58] M. R. J. Williams,[52] R. Williams,[49] F. F. Wilson,[51] W. Wislicki,[36] M. Witek,[35] L. Witola,[17] C. P. Wong,[61] G. Wormser,[11] S. A. Wotton,[49] H. Wu,[62] K. Wyllie,[42] Z. Xiang,[6] D. Xiao,[7] Y. Xie,[7] A. Xu,[5] J. Xu,[6] L. Xu,[3]

L. Xu,[3] M. Xu,[50] Q. Xu,[6] Z. Xu,[9] Z. Xu,[6] D. Yang,[3] S. Yang,[6] X. Yang,[5] Y. Yang,[6] Z. Yang,[5] Z. Yang,[60] L. E. Yeomans,[54] V. Yeroshenko,[11] H. Yeung,[56] H. Yin,[7] J. Yu,[65] X. Yuan,[62] E. Zaffaroni,[43] M. Zavertyaev,[16] M. Zdybal,[35] O. Zenaiev,[42] M. Zeng,[3] C. Zhang,[5] D. Zhang,[7] L. Zhang,[3] S. Zhang,[65] S. Zhang,[5] Y. Zhang,[5] Y. Zhang,[57] A. Zharkova,[38] A. Zhelezov,[17] Y. Zheng,[6] T. Zhou,[5] X. Zhou,[6] Y. Zhou,[6] V. Zhovkovska,[11] X. Zhu,[3] X. Zhu,[7] Z. Zhu,[6] V. Zhukov,[14,38] Q. Zou,[4,6] S. Zucchelli,[20,f] D. Zuliani,[28] and G. Zunica[56]

(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]*School of Physics State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China*
[6]*University of Chinese Academy of Sciences, Beijing, China*
[7]*Institute of Particle Physics, Central China Normal University, Wuhan, Hubei, China*
[8]*Université Savoie Mont Blanc, CNRS, IN2P3-LAPP, Annecy, France*
[9]*Université Clermont Auvergne, CNRS/IN2P3, LPC, Clermont-Ferrand, France*
[10]*Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France*
[11]*Université Paris-Saclay, CNRS/IN2P3, IJCLab, Orsay, France*
[12]*Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France*
[13]*LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France*
[14]*I. Physikalisches Institut, RWTH Aachen University, Aachen, Germany*
[15]*Fakultät Physik, Technische Universität Dortmund, Dortmund, Germany*
[16]*Max-Planck-Institut für Kernphysik (MPIK), Heidelberg, Germany*
[17]*Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*
[18]*School of Physics, University College Dublin, Dublin, Ireland*
[19]*INFN Sezione di Bari, Bari, Italy*
[20]*INFN Sezione di Bologna, Bologna, Italy*
[21]*INFN Sezione di Ferrara, Ferrara, Italy*
[22]*INFN Sezione di Firenze, Firenze, Italy*
[23]*INFN Laboratori Nazionali di Frascati, Frascati, Italy*
[24]*INFN Sezione di Genova, Genova, Italy*
[25]*INFN Sezione di Milano, Milano, Italy*
[26]*INFN Sezione di Milano-Bicocca, Milano, Italy*
[27]*INFN Sezione di Cagliari, Monserrato, Italy*
[28]*Università degli Studi di Padova, Università e INFN, Padova, Padova, Italy*
[29]*INFN Sezione di Pisa, Pisa, Italy*
[30]*INFN Sezione di Roma La Sapienza, Roma, Italy*
[31]*INFN Sezione di Roma Tor Vergata, Roma, Italy*
[32]*Nikhef National Institute for Subatomic Physics, Amsterdam, Netherlands*
[33]*Nikhef National Institute for Subatomic Physics and VU University Amsterdam, Amsterdam, Netherlands*
[34]*AGH - University of Science and Technology, Faculty of Physics and Applied Computer Science, Kraków, Poland*
[35]*Henryk Niewodniczanski Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland*
[36]*National Center for Nuclear Research (NCBJ), Warsaw, Poland*
[37]*Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest-Magurele, Romania*
[38]*Affiliated with an institute covered by a cooperation agreement with CERN*
[39]*ICCUB, Universitat de Barcelona, Barcelona, Spain*
[40]*Instituto Galego de Física de Altas Enerxías (IGFAE), Universidade de Santiago de Compostela, Santiago de Compostela, Spain*
[41]*Instituto de Fisica Corpuscular, Centro Mixto Universidad de Valencia - CSIC, Valencia, Spain*
[42]*European Organization for Nuclear Research (CERN), Geneva, Switzerland*
[43]*Institute of Physics, Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland*
[44]*Physik-Institut, Universität Zürich, Zürich, Switzerland*
[45]*NSC Kharkiv Institute of Physics and Technology (NSC KIPT), Kharkiv, Ukraine*
[46]*Institute for Nuclear Research of the National Academy of Sciences (KINR), Kyiv, Ukraine*
[47]*University of Birmingham, Birmingham, United Kingdom*
[48]*H.H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom*
[49]*Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom*

[50]*Department of Physics, University of Warwick, Coventry, United Kingdom*
[51]*STFC Rutherford Appleton Laboratory, Didcot, United Kingdom*
[52]*School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom*
[53]*School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom*
[54]*Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom*
[55]*Imperial College London, London, United Kingdom*
[56]*Department of Physics and Astronomy, University of Manchester, Manchester, United Kingdom*
[57]*Department of Physics, University of Oxford, Oxford, United Kingdom*
[58]*Massachusetts Institute of Technology, Cambridge, Massachusetts, USA*
[59]*University of Cincinnati, Cincinnati, Ohio, USA*
[60]*University of Maryland, College Park, Maryland, USA*
[61]*Los Alamos National Laboratory (LANL), Los Alamos, New Mexico, USA*
[62]*Syracuse University, Syracuse, New York, USA*
[63]*School of Physics and Astronomy, Monash University, Melbourne, Australia*
*(associated with Department of Physics, University of Warwick, Coventry, United Kingdom)*
[64]*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)*
[65]*Physics and Micro Electronic College, Hunan University, Changsha City, China*
*(associated with Institute of Particle Physics, Central China Normal University, Wuhan, Hubei, China)*
[66]*Guangdong Provincial Key Laboratory of Nuclear Science, Guangdong-Hong Kong Joint Laboratory of Quantum Matter, Institute of Quantum Matter, South China Normal University, Guangzhou, China*
*(associated with Center for High Energy Physics, Tsinghua University, Beijing, China)*
[67]*Lanzhou University, Lanzhou, China*
*(associated with Institute Of High Energy Physics (IHEP), Beijing, China)*
[68]*School of Physics and Technology, Wuhan University, Wuhan, China*
*(associated with Center for High Energy Physics, Tsinghua University, Beijing, China)*
[69]*Departamento de Fisica, Universidad Nacional de Colombia, Bogota, Colombia*
*(associated with LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France)*
[70]*Universität Bonn - Helmholtz-Institut für Strahlen und Kernphysik, Bonn, Germany*
*(associated with Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany)*
[71]*Eotvos Lorand University, Budapest, Hungary*
*(associated with European Organization for Nuclear Research (CERN), Geneva, Switzerland)*
[72]*INFN Sezione di Perugia, Perugia, Italy*
*(associated with INFN Sezione di Ferrara, Ferrara, Italy)*
[73]*Van Swinderen Institute, University of Groningen, Groningen, Netherlands*
*(associated with Nikhef National Institute for Subatomic Physics, Amsterdam, Netherlands)*
[74]*Universiteit Maastricht, Maastricht, Netherlands*
*(associated with Nikhef National Institute for Subatomic Physics, Amsterdam, Netherlands)*
[75]*Tadeusz Kosciuszko Cracow University of Technology, Cracow, Poland*
*(associated with Henryk Niewodniczanski Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland)*
[76]*DS4DS, La Salle, Universitat Ramon Llull, Barcelona, Spain*
*(associated with ICCUB, Universitat de Barcelona, Barcelona, Spain)*
[77]*Department of Physics and Astronomy, Uppsala University, Uppsala, Sweden*
*(associated with School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom)*
[78]*University of Michigan, Ann Arbor, Michigan, USA*
*(associated with Syracuse University, Syracuse, New York, USA)*

[a] Deceased.
[b] Also at Università di Firenze, Firenze, Italy.
[c] Also at Scuola Normale Superiore, Pisa, Italy.
[d] Also at Università di Ferrara, Ferrara, Italy.
[e] Also at Università di Milano Bicocca, Milano, Italy.
[f] Also at Università di Bologna, Bologna, Italy.
[g] Also at Università di Genova, Genova, Italy.
[h] Also at Universidad Nacional Autónoma de Honduras, Tegucigalpa, Honduras.
[i] Also at Università di Bari, Bari, Italy.
[j] Also at Università di Cagliari, Cagliari, Italy.
[k] Also at Università di Perugia, Perugia, Italy.
[l] Also at Università di Roma Tor Vergata, Roma, Italy.
[m] Also at Universidade Federal do Triângulo Mineiro (UFTM), Uberaba-MG, Brazil.

[n] Also at Universidade de Brasília, Brasília, Brazil.
[o] Also at Hangzhou Institute for Advanced Study, UCAS, Hangzhou, China.
[p] Also at Università di Siena, Siena, Italy.
[q] Also at Università degli Studi di Milano, Milano, Italy.
[r] Also at Central South U., Changsha, China.
[s] Also at Università di Padova, Padova, Italy.
[t] Also at Excellence Cluster ORIGINS, Munich, Germany.
[u] Also at Università di Pisa, Pisa, Italy.
[v] Also at Università della Basilicata, Potenza, Italy.
[w] Also at Universidad de Alcalá, Alcalá de Henares, Spain.
[x] Also at Università di Urbino, Urbino, Italy.