Measurement of the time-integrated $CP$ asymmetry in $D^0 \to K^- K^+$ decays

LHCb collaboration

Abstract
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 $5.7 \text{fb}^{-1}$ 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

$$A_{CP}(K^- K^+) = [6.8 \pm 5.4 \text{ (stat)} \pm 1.6 \text{ (syst)}] \times 10^{-4}.$$  

The direct $CP$ asymmetries in $D^0 \to K^- K^+$ and $D^0 \to \pi^- \pi^+$ decays, $a_{K^- K^+}^d$ and $a_{\pi^- \pi^+}^d$, are derived by combining $A_{CP}(K^- K^+)$ with the time-integrated $CP$ asymmetry difference, $\Delta A_{CP} = A_{CP}(K^- K^+) - A_{CP}(\pi^- \pi^+)$, giving

$$a_{K^- K^+}^d = (7.7 \pm 5.7) \times 10^{-4},$$

$$a_{\pi^- \pi^+}^d = (23.2 \pm 6.1) \times 10^{-4},$$

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.

Published in Phys. Rev. Lett. 131 (2023) 091802

© 2023 CERN for the benefit of the LHCb collaboration, CC BY 4.0 licence
The mixing in the neutral charm system implies that $\epsilon$-violating asymmetries $\Delta A_{\text{CP}} = \mathcal{A}_{\text{CP}}(K^- K^+) - \mathcal{A}_{\text{CP}}(\pi^- \pi^+)$, found to be $\Delta A_{\text{CP}} = (-15.4 \pm 2.9) \times 10^{-4}$ [13]. The time-integrated $\text{CP}$ asymmetry for $f = K^- K^+$ and $f = \pi^- \pi^+$ corresponds to

$$\mathcal{A}_{\text{CP}}(f) \equiv \frac{\int dt \, \epsilon(t) \left[ \Gamma(D^0 \to f)(t) - \Gamma(D^0 \to f)(t) \right]}{\int dt \, \epsilon(t) \left[ \Gamma(D^0 \to f)(t) + \Gamma(D^0 \to f)(t) \right]},$$

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 $\text{CP}$ asymmetries in $D^0 \to K^- K^+$ decays. Combining the measurements of $\mathcal{A}_{\text{CP}}(K^- K^+)$ and $\Delta A_{\text{CP}}$, it is possible to quantify the amount of $\text{CP}$ 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 $\mathcal{A}_{\text{CP}}(f)$ is the sum of a component related to the $\text{CP}$ violation in the decay amplitude, $a^d_f$, and a component related to $D^0 - D^0$ 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 $\text{CP}$ asymmetry can be written as

$$\mathcal{A}_{\text{CP}}(f) \approx a^d_f + \frac{(t)_{\text{f}}}{\tau_D} \cdot \Delta Y_f,$$

where $(t)_{\text{f}}$ 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 ($\pi^+_{\text{tag}}$) 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

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

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

$$A(K^- K^+) \approx \mathcal{A}_{\text{CP}}(K^- K^+) + A_F(D^{*+}) + A_D(\pi^+_{\text{tag}}),$$

One of the three necessary conditions for baryon asymmetry in the Universe is the non-invariance of the fundamental interactions under the simultaneous transformation of the charge conjugation ($C$) and parity ($P$) operators, referred to as $\text{CP}$ violation [1]. The Cabibbo-Kobayashi-Maskawa (CKM) formalism describes $\text{CP}$ 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, $\text{CP}$ 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 $\text{CP}$ 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 $\text{CP}$ violation in neutral charm meson decays used the difference between two time-integrated $\text{CP}$-violating asymmetries of Cabibbo-suppressed $D^0$ decays, $\Delta A_{\text{CP}} = \mathcal{A}_{\text{CP}}(K^- K^+) - \mathcal{A}_{\text{CP}}(\pi^- \pi^+)$, found to be $\Delta A_{\text{CP}} = (-15.4 \pm 2.9) \times 10^{-4}$ [13].
where \( A_p(D^{+}) \) is the production asymmetry arising from the different hadronization probabilities between \( D^{+} \) and \( D^{*+} \) mesons in \( pp \) collisions, and \( A_D(\pi^+_{\text{tag}}) \) 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 \( C_{D^+} \) and \( C_{D^+} \), using a set of promptly produced \( D^+ \) and \( D^{*+} \) meson decays. Namely, the \( C_{D^+} \) 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 \( C_{D^+} \) 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 \( C_{D^+} \) and \( C_{D^+} \) 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

\[
A(K^-\pi^+) \approx A_p(D^{+}) - A_D(K^+) + A_D(\pi^+) + A_D(\pi^+_{\text{tag}}),
\]

\[
A(K^-\pi^+\pi^+) \approx A_p(D^{+}) - A_D(K^+) + A_D(\pi^+) + A_D(\pi^2),
\]

\[
A(^{\overline{0}}K^0\pi^+) \approx A_p(D^{+}) + A(^{\overline{0}}K^0) + A_D(\pi^+),
\]

\[
A(\phi\pi^+) \approx A_p(D^{+}_s) + A(\pi^+),
\]

\[
A(^{\overline{0}}K^0K^+) \approx A_p(D^{+}_s) + A(^{\overline{0}}K^0) + A_D(K^+).
\]

In the equations above, \( A_D(K^+) \) is the kaon instrumental asymmetry, \( A_p(D^{+}_s) \) is the \( D^{+}_s \) meson production asymmetry and \( A(^{\overline{0}}K^0) \) 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 \( A_D(\pi^+) \) and \( A_D(\pi^2) \) 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, \( A^{CP}(K^-K^+) \), is obtained for each of the two calibration procedures individually, by combining the measured asymmetries as follows

\[
C_{D^+} : A^{CP}(K^-K^+) = A(K^-K^+) - A(K^-\pi^+) + A(K^-\pi^+\pi^+) - A(^{\overline{0}}K^0\pi^+) + A(^{\overline{0}}K^0),
\]

\[
C_{D^+} : A^{CP}(K^-K^+) = A(K^-K^+) - A(K^-\pi^+) + A(\phi\pi^+) - A(^{\overline{0}}K^0K^+) + A(^{\overline{0}}K^0).
\]

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 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 sub-detectors 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 $D_s^+ \rightarrow \phi \pi^+$ decays are selected from $D_s^+ \rightarrow K^- K^+ \pi^+$ decay candidates requiring that the invariant mass of the kaon pair must be within $\pm 5 \text{MeV}/c^2$ of the $\phi$ mass. Similarly, the $K^0$ mesons, produced in $D^+ \rightarrow K^0 \pi^+$ and $D_s^+ \rightarrow K^0 K^+$ decays, are reconstructed using their decay to two pions, which is dominated by the $K^0_S$ state. The two pions are required to have an invariant mass within $\pm 10 \text{MeV}/c^2$ of the $K^0_S$ 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 $\text{MeV}/c^2$.

An offline 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 $C_{D^+}$ and $C_{D_s^+}$. 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 $K^0_S$ 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 $A_D(\pi_{\text{tag}})$ [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 $\text{MeV}/c^2$. 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 [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
Figure 1: Distribution of the invariant mass for the weighted $D^{π^+} → D^0 (→ K^- K^+)π^+$ decay candidates, from the $C_{Dπ}$ calibration procedure. The result of the fit to this distribution is also shown.

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 [51]. The signal models consist of a sum of Gaussian and Johnson $S_U$ functions [52], 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 $D^{π^+}_0$ decays, the combinatorial background is described by an empirical function of the form

$$m(D^0π^+) = αe^{βm(D^0π^+)}$$

where $α$ and $β$ 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.

Figure 1 presents the distribution of the $D^0 → K^- K^+$ invariant mass and the result of the fit. The signal yields, together with the statistical reduction factor, defined as

$$\frac{(Σ_{i=1}^K w_i)^2}{(N · Σ_{i=1}^K w_i^2)}$$

where $K$ is the total number of candidates and $w_i$ includes background subtraction and kinematic weights, are reported in Table 1. 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 polarities. After determining the asymmetries in these subsamples, the values of $A^{CP}(K^- K^+)$ are calculated according to Eq. 6, taking into account the
Table 1: Signal yields and statistical reduction factors arising from the kinematic weighting of the sample for the various decay modes and both calibration procedures.

| Decay mode           | Signal yield $[10^6]$ | Red. factor |
|----------------------|-----------------------|-------------|
|                      | $C_{D^+}$             | $C_{D^+_s}$ |
| $D^0 \to K^-K^+$     | 37                    | 37          |
| $D^0 \to K^-\pi^+$   | 58                    | 56          |
| $D^+ \to K^-\pi^+\pi^+$ | 188                  | –           |
| $D^+ \to \bar{K}^0\pi^+$ | 6                    | –           |
| $D^+_s \to \phi\pi^+$ | –                    | 43          |
| $D^+_s \to \bar{K}^0K^+$ | –                    | 5           |

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 [53–55], following the procedure described in Ref. [56]. The correction considers different $K^+$ momentum spectra for the $C_{D^+}$ and $C_{D^+_s}$ calibration procedure and corresponds to $(−5.1 ± 0.6) \times 10^{-4}$ and $(−8.5 ± 1.3) \times 10^{-4}$, 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 $C_{D^+}$ and $C_{D^+_s}$ 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 $C_{D^+}$ and $C_{D^+_s}$ 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 [51]. Various backgrounds are modeled using fast simulation [57]. 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 $C_{D^+}$ and $C_{D^+_s}$ 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 $C_{D^+}$ and $C_{D^+_s}$ calibration procedures,
Table 2: Systematic uncertainties on $A_{CP}(K^-K^+)$ for the two calibration procedures $C_{D+}$ and $C_{D_s^+}$. The total uncertainties are obtained as the sums in quadrature of the individual contributions. Correlations between the systematic uncertainties of the two calibration procedures are also reported.

| Source                      | $C_{D+}$ [$10^{-4}$] | $C_{D_s^+}$ [$10^{-4}$] | 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  |

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 $C_{D+}$ and $C_{D_s^+}$ procedures, respectively, with a negligible correlation.

To test the accuracy of the estimated value for $A(K^0)$, a linear term with one free parameter is introduced in the model that describes the dependence of $A(K^0)$ on the neutral-kaon decay time [51]. The parameter is determined by fitting the charge asymmetry in $D^+ \to K^0\pi^+$ decays as a function of the $K^0$ 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 $K^0$ lifetimes relevant for $A_{CP}(K^-K^+)$ 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 $C_{D+}$ and $C_{D_s^+}$ procedures, respectively.

In the $C_{D_s^+}$ 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 $C_{D+}$ and $C_{D_s^+}$ procedures, respectively. A summary of all systematic uncertainties is shown in Table 2.

Numerous additional checks are carried out [51]. The measurements of $A_{CP}(K^-K^+)$ 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 $K^0$ 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 particle. Furthermore, the total sample
A value of whether the observed CP asymmetry in charm meson decay 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 $A_{CP}^{K^-K^+}$ on the various variables are found to be uniformly distributed. Checks using alternative PID requirements and trigger selections are performed, and all variations of $A_{CP}^{K^-K^+}$ are found to be compatible within statistical uncertainties. The resulting values for $A_{CP}^{K^-K^+}$ for both calibration procedures are

$$C_{D^+}: A_{CP}^{K^-K^+} = [13.6 \pm 8.8 \text{ (stat)} \pm 1.6 \text{ (syst)}] \times 10^{-4},$$
$$C_{D^+}: A_{CP}^{K^-K^+} = [2.8 \pm 6.7 \text{ (stat)} \pm 2.0 \text{ (syst)}] \times 10^{-4},$$

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

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

consistent with the previous results $[51,56,58]$. 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 $[59]$ 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 $A_{CP}^{K^-K^+}$ $[56,58]$ and $\Delta A_{CP}$ $[13,50,56]$ 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 $D^0 \rightarrow K^-K^+$ and $D^0 \rightarrow \pi^-\pi^+$ decays in the various analysis. The combination, obtained by minimizing a $\chi^2$ function that includes all the measurements and their correlations, leads to

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

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 $(a_{K^-K^+}^d, a_{\pi^-\pi^+}^d)$ plane for this combination and the one realized with data collected between 2010 and 2012 $[50,56,58,60,61]$. The two combinations are based on 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 $D^0 \rightarrow K^-K^+$ and $D^0 \rightarrow \pi^-\pi^+$ decays, respectively. This is the first evidence for direct $CP$ violation in the $D^0 \rightarrow \pi^-\pi^+$ decay. $U$-spin symmetry implies $a_{K^-K^+}^d + a_{\pi^-\pi^+}^d = 0$ $[62]$. A value of $a_{K^-K^+}^d + a_{\pi^-\pi^+}^d = (30.8 \pm 11.4) \times 10^{-4}$ 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 $D^0 \rightarrow K^-K^+$ 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.
Figure 2: Central values and two-dimensional confidence regions in the \((a_{K^-K^+}^d, a_{\pi^+\pi^-}^d)\) 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.

Acknowledgements

We express our gratitude to our colleagues in the CERN accelerator departments for the excellent performance of the LHC. We thank the technical and administrative staff at the LHCb institutes. We acknowledge support from CERN and from the national agencies: CAPES, CNPq, FAPERJ and FINEP (Brazil); 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).
Supplemental material

Reconstructed mean decay times

The interpretation of $\mathcal{A}^{\text{CP}}(K^-K^+)$ in terms of direct $CP$ asymmetries, $a_{\pi^-\pi^+}^d$ and $a_{K^-K^+}^d$ requires the measurement of the reconstructed mean decay time of $D^0 \rightarrow K^-K^+$ decay. The values corresponding to the measurements presented in this Letter are $(t)_{K^-K^+} = (7.315 \pm 0.020) \times 10^{-13}$ s and $(t)_{K^-K^+} = (6.868 \pm 0.014) \times 10^{-13}$ s for the $C_{D^+}$ and $C_{D^+_s}$ methods, respectively. Their correlation corresponds to $\rho = 0.74$. These measurements are also correlated with the difference of reconstructed mean decay times for $D^0 \rightarrow K^-K^+$ and $D^0 \rightarrow \pi^-\pi^+$ decays, $\Delta(t)^{\pi^-\text{tagged}}$, measured in Ref. [13]. The correlation coefficients between $(t)_{K^-K^+}$ and $\Delta(t)^{\pi^-\text{tagged}}$ are $\rho = 0.23$ and $\rho = 0.25$ for the $C_{D^+}$ and $C_{D^+_s}$ methods, respectively.

Additional plots

![Diagram](image)

Figure 3: Distributions of the invariant mass for the weighted charm-meson candidates, for the decays (top left) $D^{*+} \rightarrow D^0 \rightarrow K^-K^+$, (top right) $D^{*+} \rightarrow D^0 \rightarrow K^-\pi^+$, (bottom left) $D^+ \rightarrow K^-\pi^+$, (bottom right) $D^+ \rightarrow K^0\pi^+$. The data are from the $C_{D^+}$ calibration procedure. The results of the fits to these distributions are also shown. The top left is repeated from the main text.
Figure 4: Distributions of the invariant mass for the weighted charm-meson candidates, for the decays (top left) $D^{+} \rightarrow D^{0} \rightarrow K^{-}K^{+} \pi^{+}$, (top right) $D^{+} \rightarrow D^{0} \rightarrow K^{-}K^{+} \pi^{+}$, (bottom left) $D_{s}^{+} \rightarrow K^{-}K^{+} \pi^{+}$, and (bottom right) $D_{s}^{+} \rightarrow \bar{K}^{0}K^{+}$. The data are from the $C_{D_{s}^{+}}$ calibration procedure. The results of the fits to these distributions are also shown.

Figure 5: Measurements of $A_{CP}(K^{-}K^{+})$ in (left) time-ordered data-taking (referred to as run blocks) and (right) year of data-taking and dipole-magnet polarity for the $C_{D^{+}}$ and $C_{D_{s}^{+}}$ calibration procedures. The uncertainties are statistical only. The horizontal lines are the averaged values for the $C_{D^{+}}$ and $C_{D_{s}^{+}}$ methods, while the bands represent the one-standard-deviation regions. The labels Mag-Up and Mag-Down refer to the direction of the magnetic field along the positive and negative directions of $y$-axis, respectively.
Figure 6: Comparison of the results for $A_{CP}(K^-K^+)$ per different intervals of $D^0$ candidates (left) pseudorapidity and (right) decay time for the $C_{D^+}$ and $C_{D^+_s}$ calibration procedures. The horizontal lines are the averaged values for the $C_{D^+}$ and $C_{D^+_s}$ methods, while the bands represent the one-standard-deviation regions.

Figure 7: Distribution of the $p$-values resulting from the consistency checks on $A_{CP}(K^-K^+)$ measured in different data subsamples. The blue line represents the expected uniform distribution.
Figure 8: Distributions of the neutral-kaon decay time for background-subtracted and weighted candidates considered in the determination of $A^{CP}(K^-K^+)/A^{CP}(K^+K^-)$ values. The distributions are normalized to have the maximum equal to unity. The control sample is used to estimate $A(K^0)$ and consists of neutral kaons decaying outside of the vertex detector.

Figure 9: Measured asymmetry in $D^+ \rightarrow K^0\pi^+$ decays as a function of $K^0$ decay time in units of $K^0_S$-meson decay time, in data where the neutral kaon meson decays outside of the vertex detector. The predictions for the neutral kaon asymmetry, from the model with and without an additional linear degree of freedom, are shown as well. An overall shift is applied to the model’s predictions to account for unrelated nuisance asymmetries, i.e. $A_p(D^+)$ and $A_D(\pi^+)$.
Figure 10: Distribution of the $K^- K^+$ invariant mass, along with the result of the fit describing the expected background components. The vertical lines indicate the interval applied in the selection of $D^0$ candidates for the determination of $A^{CP}(K^- K^+)$. The fit results are used to evaluate the systematic uncertainties related to the peaking background.
Figure 11: Background-subtracted kinematic distributions for the charm-meson pseudorapidity ($\eta$), the kaon momentum ($p$) and the tagging-pion transverse momentum ($p_T$) (left column) before and (right column) after the per-candidate $C_{D_s^+}$ weighting procedure. The distributions are normalized to unit area.
Figure 12: Background-subtracted kinematic distributions for the kaon and pion transverse momentum ($p_T$) and pseudorapidity ($\eta$) (left column) before and (right column) after the per-candidate $C_D^+$ weighting procedure. The distributions are normalized to unit area.
Figure 13: Measurements of $A^{CP}(K^-K^+)$ from various experiments \[58,63-68\]. The presented measurement is highlighted in red. The vertical band corresponds to the average of all measurements previous to the presented, computed by HFLAV \[59\], where it is assumed that $CP$ is conserved in mixing and in the interference between decay and mixing. This assumption is necessary when results from different experiments are compared. The inset plot shows the five most precise measurements in a reduced horizontal range.
References

[1] A. D. Sakharov, *Violation of CP Invariance, C asymmetry, and baryon asymmetry of the universe*, Pisma Zh. Eksp. Teor. Fiz. 5 (1967) 32.

[2] N. Cabibbo, *Unitary symmetry and leptonic decays*, Phys. Rev. Lett. 10 (1963) 531.

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

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

[5] KTeV collaboration, A. Alavi-Harati et al., *Observation of direct CP violation in K_{S,L} → ππ decays*, Phys. Rev. Lett. 83 (1999) 22, arXiv:hep-ex/9905060.

[6] NA48 collaboration, A. Lai et al., *A precise measurement of the direct CP violation parameter Re(ε'/ε)*, Eur. Phys. J. C22 (2001) 231, arXiv:hep-ex/0110019.

[7] BaBar collaboration, B. Aubert et al., *Observation of CP violation in the B^0 meson system*, Phys. Rev. Lett. 87 (2001) 091801, arXiv:hep-ex/0107013.

[8] Belle collaboration, K. Abe et al., *Observation of large CP violation in the neutral B meson system*, Phys. Rev. Lett. 87 (2001) 091802, arXiv:hep-ex/0107061.

[9] BaBar collaboration, B. Aubert et al., *Direct CP-violating asymmetry in B^0 → K^+π^− decays*, Phys. Rev. Lett. 93 (2004) 131801, arXiv:hep-ex/0407057.

[10] Belle collaboration, Y. Chao et al., *Evidence for direct CP violation in B^0 → K^+π^− decays*, Phys. Rev. Lett. 93 (2004) 191802, arXiv:hep-ex/0408100.

[11] LHCb collaboration, R. Aaij et al., *First observation of CP violation in the decays of B_s^0 mesons*, Phys. Rev. Lett. 110 (2013) 221601, arXiv:1304.6173.

[12] LHCb collaboration, R. Aaij et al., *Observation of CP violation in B^± → DK^± decays*, Phys. Lett. B712 (2012) 203, Erratum ibid. B713 (2012) 351, arXiv:1203.3662.

[13] LHCb collaboration, R. Aaij et al., *Observation of CP violation in charm decays*, Phys. Rev. Lett. 122 (2019) 211803, arXiv:1903.08726.

[14] Y. Grossman, A. L. Kagan, and Y. Nir, *New physics and CP violation in singly Cabibbo suppressed D decays*, Phys. Rev. D75 (2007) 036008, arXiv:hep-ph/0609178.

[15] H.-n. Li, C.-D. Lu, and F.-S. Yu, *Branching ratios and direct CP asymmetries in D → PP decays*, Phys. Rev. D86 (2012) 036012, arXiv:1203.3120.

[16] H.-Y. Cheng and C.-W. Chiang, *Direct CP violation in two-body hadronic charmed meson decays*, Phys. Rev. D85 (2012) 034036, Erratum ibid. D85 (2012) 079903, arXiv:1201.0785.

[17] A. Khodjamirian and A. A. Petrov, *Direct CP asymmetry in D → π^−π^+ and D → K^-K^+ in QCD-based approach*, Phys. Lett. B774 (2017) 235, arXiv:1706.07780.
[18] M. Chala, A. Lenz, A. V. Rusov, and J. Scholtz, ∆A_{CP} within the Standard Model and beyond, JHEP 07 (2019) 161, arXiv:1903.10490.

[19] Y. Grossman and S. Schacht, The emergence of the ΔU = 0 rule in charm physics, JHEP 07 (2019) 020, arXiv:1903.10952.

[20] F. Buccella, A. Paul, and P. Santorelli, SU(3)_F breaking through final state interactions and CP asymmetries in D → PP decays, Phys. Rev. D99 (2019) 113001, arXiv:1902.05564.

[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. B825 (2022) 136855, arXiv:2110.07619.

[23] H.-Y. Cheng and C.-W. Chiang, Revisiting CP violation in D → PP and VP decays, Phys. Rev. D100 (2019) 093002, arXiv:1909.03063.

[24] A. Dery and Y. Nir, Implications of the LHCb discovery of CP violation in charm decays, JHEP 12 (2019) 104, arXiv:1909.11242.

[25] D. Wang, C.-P. Jia, and F.-S. Yu, A self-consistent framework of topological amplitude and its SU(N) decomposition, JHEP 21 (2020) 126, arXiv:2001.09460.

[26] R. Bause, H. Gisbert, M. Golz, and G. Hiller, Exploiting CP-asymmetries in rare charm decays, Phys. Rev. D101 (2020) 115006, arXiv:2004.01206.

[27] A. Dery, Y. Grossman, S. Schacht, and A. Soffer, Probing the ΔU = 0 rule in three body charm decays, JHEP 05 (2021) 179, arXiv:2101.02560.

[28] H.-Y. Cheng and C.-W. Chiang, CP violation in quasi-two-body D → VP decays and three-body D decays mediated by vector resonances, Phys. Rev. D104 (2021) 073003, arXiv:2104.13548.

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

[30] BaBar collaboration, P. del Amo Sanchez et al., Measurement of D⁰ - D̄⁰ mixing parameters using D⁰ → K^0_Sπ^+π^- and D⁰ → K^0_SLK^+K^- decays, Phys. Rev. Lett. 105 (2010) 081803, arXiv:1004.5053.

[31] BaBar collaboration, J. P. Lees et al., Measurement of D⁰ - D̄⁰ Mixing and CP Violation in Two-Body D⁰ Decays, Phys. Rev. D87 (2013) 012004, arXiv:1209.3896.

[32] Belle collaboration, T. Peng et al., Measurement of D⁰ - D̄⁰ mixing and search for indirect CP violation using D⁰ → K^0_SLπ^+π^- decays, Phys. Rev. D89 (2014) 091103, arXiv:1404.2412.

[33] Belle collaboration, M. Starič et al., Measurement of D⁰ - D̄⁰ mixing and search for CP violation in D⁰ → K^+K^-, π^+π^- decays with the full Belle data set, Phys. Lett B753 (2016) 412, arXiv:1509.08266.
[34] LHCb collaboration, R. Aaij et al., Updated determination of $D^0-\overline{D}^0$ mixing and CP violation parameters with $D^0 \rightarrow K^+\pi^-$ decays, Phys. Rev. D97 (2018) 031101, arXiv:1712.03220.

[35] LHCb collaboration, R. Aaij et al., Measurement of the charm-mixing parameter $y_{CP}$, Phys. Rev. Lett. 122 (2019) 011802, arXiv:1810.06874.

[36] LHCb collaboration, R. Aaij et al., Measurement of the mass difference between neutral charm-meson eigenstates, Phys. Rev. Lett. 122 (2019) 231802, arXiv:1903.03074.

[37] LHCb collaboration, R. Aaij et al., Observation of the mass difference between neutral charm-meson eigenstates, Phys. Rev. Lett. 127 (2021) 111801, arXiv:2106.03744.

[38] A. L. Kagan and L. Silvestrini, Dispersive and absorptive CP violation in $D^0-\overline{D}^0$ mixing, Phys. Rev. D103 (2021) 053008, arXiv:2001.07207.

[39] LHCb collaboration, R. Aaij et al., Search for time-dependent CP violation in $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+\pi^-$ decays, Phys. Rev. D104 (2021) 072010, arXiv:2105.09889.

[40] LHCb collaboration, R. Aaij et al., Measurement of $B^0_s, B^0, B^+,$ and $\Lambda^0_b$ production asymmetries in 7 and 8 TeV proton-proton collisions, Phys. Lett. B774 (2017) 139, arXiv:1703.08464.

[41] LHCb collaboration, R. Aaij et al., Measurement of the flavour-specific CP-violating asymmetry $a_{s sl}^*$ in $B_s^0$ decays, Phys. Lett. B728 (2014) 607, arXiv:1308.1048.

[42] LHCb collaboration, R. Aaij et al., Measurement of the $D^\pm$ production asymmetry in 7 TeV pp collisions, Phys. Lett. B718 (2013) 902, arXiv:1210.4112.

[43] LHCb collaboration, R. Aaij et al., Measurement of the $D_s^- - D_s^0$ production asymmetry in 7 TeV pp collisions, Phys. Lett. B713 (2012) 186, arXiv:1205.0897.

[44] LHCb collaboration, A. A. Alves Jr. et al., The LHCb detector at the LHC, JINST 3 (2008) S08005.

[45] LHCb collaboration, R. Aaij et al., LHCb detector performance, Int. J. Mod. Phys. A30 (2015) 1530022, arXiv:1412.6352.

[46] M. Kucharczyk, P. Morawski, and M. Witek, Primary Vertex Reconstruction at LHCb, 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 (2015) 082010.

[48] W. D. Hulsbergen, Decay chain fitting with a Kalman filter, Nucl. Instrum. Meth. A552 (2005) 566, arXiv:physics/0503191.

[49] Particle Data Group, R. L. Workman et al., Review of particle physics, Prog. Theor Exp. Phys. 2022 (2022) 083C01.
LHCb collaboration, R. Aaij et al., *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** (2016) 191601, arXiv:1602.03160.

See supplemental material for additional numerical values and plots.

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

W. Fetscher et al., *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** (1996) 543.

A. Gsponer et al., *Precise coherent K^0_S regeneration amplitudes for C, Al, Cu, Sn and Pb nuclei from 20 to 140 GeV/c and their interpretation*, Phys. Rev. Lett. **42** (1979) 13.

R. A. Briere and B. Winstein, *Determining the phase of a strong scattering amplitude from its momentum dependence to better than 1\(^\circ\): The example of kaon regeneration*, Phys. Rev. Lett. **75** (1995) 402.

LHCb collaboration, R. Aaij et al., *Measurement of CP asymmetry in D^0 \to K^-K^+ and D^0 \to \pi^-\pi^+ decays*, JHEP **07** (2014) 041, arXiv:1405.2797.

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** (2017) 239, arXiv:1612.07489.

LHCb collaboration, R. Aaij et al., *Measurement of CP asymmetry in D^0 \to K^-K^+ decays*, Phys. Lett. B **767** (2017) 177, arXiv:1610.09476.

Heavy Flavor Averaging Group, Y. Amhis et al., *Averages of b-hadron, c-hadron, and \(\tau\)-lepton properties as of 2018*, Eur. Phys. J. C **81** (2021) 226, arXiv:1909.12524, updated results and plots available at https://hflav.web.cern.ch.

LHCb collaboration, R. Aaij et al., *Measurement of indirect CP asymmetries in D^0 \to K^-K^+ and D^0 \to \pi^-\pi^+ decays using semileptonic B decays*, JHEP **04** (2015) 043, arXiv:1501.06777.

LHCb collaboration, R. Aaij et al., *Measurement of the CP violation parameter \(A_F\) in D^0 \to K^+K^- and D^0 \to \pi^+\pi^- decays*, Phys. Rev. Lett. **118** (2017) 261803, arXiv:1702.06490.

M. Gronau, *High order U-spin breaking: A precise amplitude relation in D^0 decays*, Phys. Lett. B **730** (2014) 221, Addendum ibid. B **735** (2014) 221, arXiv:1311.1434.

E791 collaboration, E. M. Aitala et al., *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** (1998) 405, arXiv:hep-ex/9711003.
[64] FOCUS collaboration, J. M. Link et al., Search for violation in $D^0$ and $D^+$ decays, Phys. Lett. B491 (2000) 232, Erratum ibid. B495 (2000) 443, arXiv:hep-ex/0005037.

[65] CLEO collaboration, S. E. Csorna et al., Lifetime differences, direct CP violation and partial widths in $D^0$ meson decays to $K^+K^-$ and $\pi^+\pi^-$, Phys. Rev. D65 (2002) 092001, arXiv:hep-ex/0111024.

[66] Belle collaboration, M. Staric et al., Measurement of CP asymmetry in Cabibbo suppressed $D^0$ decays, Phys. Lett. B670 (2008) 190, arXiv:0807.0148.

[67] BaBar collaboration, B. Aubert et al., Search for CP violation in the decays $D^0 \rightarrow K^-K^+$ and $D^0 \rightarrow \pi^-\pi^+$, Phys. Rev. Lett. 100 (2008) 061803, arXiv:0709.2715.

[68] CDF collaboration, T. Aaltonen et al., Measurement of CP-violating asymmetries in $D^0 \rightarrow \pi^+\pi^-$ and $D^0 \rightarrow K^+K^-$ decays at CDF, Phys. Rev. D85 (2012) 012009, arXiv:1111.5023.
LHCb collaboration

R. Aaij32, A.S.W. Abdelmotteleb54, C. Abellan Beteta44, F. Abudinën54, T. Ackermans41, B. Adeva40, M. Adinolfi48, P. Adlarson73, H. Afsharnia9, C. Agapopoulou12, C.A. Aidala78, S. Aiola24, Z. Ajaltouni9, S. Aka50, K. Akiba32, J. Albrecht13, F. Alessio42, M. Alexander55, A. Alfonso Albero39, Z. Aliouche58, P. Alvarez Cartelle45, R. Amaire11, S. Amato70, J.L. Amey48, Y. Aminis11,42, L. An47, L. Anderlini29, M. Andersson44, A. Andreianov49, M. Andreotti29, D. Andreou62, D. Ao45, F. Archilli17, A. Artamonov48, M. Artuse62, E. Aslanides16, M. Atzeni44, B. Audurie12, S. Bachmann17, M. Bachmayer44, J.J. Back50, A. Bailly-reyre13, P. Baladron Rodriguez40, V. Balagura12, W. Baldini24, J. Baptista de Souza Leite11, M. Barbetti22, R.J. Barlow56, S. Barsuk41, W. Barter54, M. Bartolini49, F. Baryshnikov45, J.M. Basels14, G. Bassi29, A. Batsukh10, A. Battig13, A. Bay44, A. Beck94, M. Becker91, F. Bedeschi29, I.B. Bediako1, A. Beitein38, V. Belavin38, S. Belin40, V. Bellore44, K. Belous38, I. Belov38, I. Belyaev38, G. Benane10, G. Bencivenni23, E. Ben-Haim13, A. Berezhnoy46, R. Bernet44, S. Bernet Andres76, D. Berninghoff17, H.C. Bernstein62, C. Bertella14, A. Bertolin48, C. Betancourt44, F. Betti44, Ia. Bezshykio40, S. Bhasin48, J. Bhom35, L. Bian48, M.S. Bieker13, N.V. Biesius21, S. Bifani47, P. Bilillo13, A. Biocini32, M. Birch50, F.C.R. Bishop47, A. Bitadze46, A. Bizzeti4, M.P. Blago41, T. Blake50, F. Blanc44, S. Blusk52, D. Bobulski52, J.A. Boelhaue15, O. Boente Garcia12, T. Boettcher55, A. Boldyrev38, C.S. Bolognani10, R. Bolzoni21, N. Bondar38,42, F. Bortoletto42, S. Borghi56, M. Borsato17, J.T. Borsuk35, S.A. Bouchiba40, T.J.V. Bowcock43, A. Boyer47, C. Bozzi24, M.J. Bradley55, S. Braun60, A. Brea Rodriguez40, J. Brodzicka32, A. Brossa Gonzalo40, J. Brown54, D. Brundu27, A. Buonaura41, L. Buonincontri25, A.T. Burke56, C. Burr42, A. Bursche66, A. Butkevich38, J.S. Butter42, J. Buytaert43, W. Byczynski45, S. Cadeddu29, H. Cai48, R. Calabrese31, L. Calefie44, S. Cali24, R. Calladine47, M. Calvi26, M. Calvo Gomez70, P. Campana23, D.H. Campana Perez74, A.F. Campoverde Quezada61, S. Capelli26, M. Capriotti20, A. Carbone10, G. Carboni31, R. Cardinale24, A. Cardini27, I. Carli9, P. Carniti26, M. Carus14, A. Casais Vidal40, R. Caspar17, G. Casse54, M. Cattaneo54, G. Cavalleri44, V. Cavallini21, S. Celani45, J. Cerasoli40, D. Cervenkov31, A.J. Chadwick32, M.G. Chapman48, M. Charles15, Ph. Charpentier42, C.A. Chavez Barajas54, M. Chefdeville9, C. Chen10, S. Chen10, A. Chernov30, S. Chernyshevskii46, V. Chobanova44, S. Cholak43, M. Chrzaszczyk35, A. Chubyan31, V. Chulikov38, P. Ciambrone23, M.F. Cicala50, X. Cid Vidal40, G. Ciezarek42, G. Ciunloiu22, P.L. Clarke52, M. Clemente42, H.V. Cliff19, J. Closier42, J.L. Coblentz48, V. Cocchi42, J.A.B. Coelho11, C. J. Cogan41, E. Cognetakis10, L. Cojocaru9, P. Collins42, T. Colomb42, L. Congedo11, A. Contu27, N. Cooke47, I. Correidora46, G. Corti42, B. Couturier42, D.C. Craik8, J. Crkovská60, M. Cruz Torres14, R. Currie54, C.L. Da Silva64, S. Dadabaev35, L. Dai55, X. Dai10, E. Dall’Occo15, J. Dalseno40, C. D’Ambrosio40, J. Daniel4, A. Danilina36, P. d’Argent15, J.E. Davies54, A. Davis41, O. De Aguilar Francisco47, J. de Boer42, K. De Bruyn14, S. De Capua54, M. De Cian43, U. De Freitas Carneiro Da Graca4, E. De Lucía21, J.M. De Miranda4, L. De Paula41, M. De Serio19, D. De Simone44, P. De Simone24, F. De Vellis13, J.A. de Vries44, C.T. Dean61, F. Debernardis19, D. Decamp19, V. Dediu10, L. Del Buono46, B. Delaney48, H.-P. Dembinski44, V. Denysenko14, O. Deschamps49, F. Dettori27, B. Dey77, A. Di Cicco80, P. Di Nezza23, I. Diachkov38.
| Name                  | Affiliation                                                                 |
|----------------------|------------------------------------------------------------------------------|
| D. Wiedner          | 1 Centro Brasileiro de Pesquisas Físicas (CBPF), Rio de Janeiro, Brazil    |
| G. Wilkinson        | 2 Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil     |
| M.K. Wilkinson      | 3 Center for High Energy Physics, Tsinghua University, Beijing, China       |
| I. Williams         | 4 Institute Of High Energy Physics (IHEP), Beijing, China                   |
| M. Williams         | 5 School of Physics State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China |
| R. Williams         | 6 University of Chinese Academy of Sciences, Beijing, China                  |
| F.F. Wilson         | 7 Institute of Particle Physics, Central China Normal University, Wuhan, Hubei, China |
| W. Wislicki         | 8 Université Savoie Mont Blanc, CNRS, IN2P3-LAPP, Annecy, France           |
| M. Witek            | 9 Université Clermont Auvergne, CNRS/IN2P3, LPC, Clermont-Ferrand, France  |
| R. Williams         | 10 Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France                  |
| F. F. Wilson        | 11 Université Paris-Saclay, CNRS/IN2P3, IJCLab, Orsay, France              |
| M. Williams         | 12 Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France |
| R. Williams         | 13 LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France |
| M. Williams         | 14 I. Physikalisches Institut, RWTH Aachen University, Aachen, Germany      |
| R. Williams         | 15 Fakultät Physik, Technische Universität Dortmund, Dortmund, Germany      |
| W. Wislicki         | 16 Max-Planck-Institut für Kernphysik (MPIK), Heidelberg, Germany           |
| M. Witek            | 17 Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany |
| R. Williams         | 18 School of Physics, University College Dublin, Dublin, Ireland            |
| F. F. Wilson        | 19 INFN Sezione di Bari, Bologna, Italy                                     |
| M. Williams         | 20 INFN Sezione di Bologna, Bologna, Italy                                  |
| R. Williams         | 21 INFN Sezione di Ferrara, Ferrara, Italy                                 |
| M. Williams         | 22 INFN Sezione di Firenze, Firenze, Italy                                 |
| R. Williams         | 23 INFN Laboratori Nazionali di Frascati, Frascati, Italy                   |
| M. Williams         | 24 INFN Sezione di Genova, Genova, Italy                                   |
| R. Williams         | 25 INFN Sezione di Milano, Milano, Italy                                   |
| M. Williams         | 26 INFN Sezione di Milano-Bicocca, Milano, Italy                           |
| M. Williams         | 27 INFN Sezione di Cagliari, Monseirato, Italy                             |
| R. Williams         | 28 Università degli Studi di Padova, Università e INFN, Padova, Padova, Italy |
| M. Williams         | 29 INFN Sezione di Pisa, Pisa, Italy                                       |
| R. Williams         | 30 INFN Sezione di Roma La Sapienza, Roma, Italy                           |
| M. Williams         | 31 INFN Sezione di Roma Tor Vergata, Roma, Italy                           |
| M. Williams         | 32 Nikhef National Institute for Subatomic Physics, Amsterdam, Netherlands |
| R. Williams         | 33 Nikhef National Institute for Subatomic Physics and VU University Amsterdam, Amsterdam, Netherlands |
| M. Williams         | 34 AGH - University of Science and Technology, Faculty of Physics and Applied Computer Science, Kraków, Poland |
| R. Williams         | 35 Henryk Niewodniczanski Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland |
| M. Williams         | 36 National Center for Nuclear Research (NCBJ), Warsaw, Poland             |
| R. Williams         | 37 Horia Hubuș National Institute of Physics and Nuclear Engineering, Bucharest-Magurele, Romania |
| M. Williams         | 38 Affiliated with an institute covered by a cooperation agreement with CERN |
| R. Williams         | 39 ICCUB, Universitat de Barcelona, Barcelona, Spain                        |

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, Bologna, 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, Monseirato, 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 Hubuș 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 Física 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, MA, United States
59 University of Cincinnati, Cincinnati, OH, United States
60 University of Maryland, College Park, MD, United States
61 Los Alamos National Laboratory (LANL), Los Alamos, NM, United States
62 Syracuse University, Syracuse, NY, United States
63 School of Physics and Astronomy, Monash University, Melbourne, Australia, associated to 50
64 Pontificia Universidade Católica do Rio de Janeiro (PUC-Rio), Rio de Janeiro, Brazil, associated to 2
65 Physics and Micro Electronic College, Hunan University, Changsha City, China, associated to 7
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 to 3
67 Lanzhou University, Lanzhou, China, associated to 4
68 School of Physics and Technology, Wuhan University, Wuhan, China, associated to 3
69 Departamento de Física, Universidad Nacional de Colombia, Bogota, Colombia, associated to 13
70 Universität Bonn - Helmholtz-Institut für Strahlen und Kernphysik, Bonn, Germany, associated to 17
71 Eotvos Lorand University, Budapest, Hungary, associated to 42
72 INFN Sezione di Perugia, Perugia, Italy, associated to 21
73 Van Swinderen Institute, University of Groningen, Groningen, Netherlands, associated to 32
74 Universiteit Maastricht, Maastricht, Netherlands, associated to 32
75 Adam Mickiewicz University of Lublin, Lublin, Poland, associated to 35
76 STIN, La Salle, Universitat Ramon Llull, Barcelona, Spain, associated to 39
77 Department of Physics and Astronomy, Uppsala University, Uppsala, Sweden, associated to 53
78 University of Michigan, Ann Arbor, MI, United States, associated to 62

a Universidade de Brasília, Brasília, Brazil
b Central South U., Changsha, China
c Hangzhou Institute for Advanced Study, UCAS, Hangzhou, China
d Excellence Cluster ORIGINS, Munich, Germany
e Universidad Nacional Autónoma de Honduras, Tegucigalpa, Honduras
f Università di Bari, Bari, Italy
g Università di Bologna, Bologna, Italy
h Università di Cagliari, Cagliari, Italy
i Università di Ferrara, Ferrara, Italy
j Università di Firenze, Firenze, Italy
k Università di Genova, Genova, Italy
l Università degli Studi di Milano, Milano, Italy
m Università di Milano Bicocca, Milano, Italy
n Università di Modena e Reggio Emilia, Modena, Italy
