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Observation of *CP* Violation in Charm Decays

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A search for charge-parity (CP) violation in $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays is reported, using pp collision data corresponding to an integrated luminosity of 5.9 fb^{-1} collected at a center-of-mass energy of 13 TeV with the LHCb detector. The flavor of the charm meson is inferred from the charge of the pion in $D^*(2010)^+ \to D^0\pi^+$ decays or from the charge of the muon in $\bar{B} \to D^0\mu^-\bar{\nu}_\mu X$ decays. The difference between the CP asymmetries in $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays is measured to be $\Delta A_{CP} = [-18.2 \pm 3.2(\text{stat}) \pm 0.9(\text{syst})] \times 10^{-4}$ for π-tagged and $\Delta A_{CP} = [-9 \pm 8(\text{stat}) \pm 5(\text{syst})] \times 10^{-4}$ for μ-tagged D^0 mesons. Combining these with previous LHCb results leads to $\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$, where the uncertainty includes both statistical and systematic contributions. The measured value differs from zero by more than 5 standard deviations. This is the first observation of CP violation in the decay of charm hadrons.

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The noninvariance of fundamental interactions under the combined action of charge conjugation (C) and parity (P) transformations, so-called CP violation, is a necessary condition for the dynamical generation of the baryon asymmetry of the universe [1]. The standard model (SM) of particle physics includes CP violation through an irreducible complex phase in the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [2,3]. The realization of CP violation in weak interactions has been established in the K- and B-meson systems by several experiments [4–12], and all results are well interpreted within the CKM formalism. However, the size of CP violation in the SM appears to be too small to account for the observed matter-antimatter asymmetry [13–15], suggesting the existence of sources of CP violation beyond the SM.

The observation of CP violation in the charm sector has not been achieved yet, despite decades of experimental searches. Charm hadrons provide a unique opportunity to measure CP violation with particles containing only up-type quarks. The size of CP violation in charm decays is expected to be tiny in the SM, with asymmetries typically of the order of $10^{-4} - 10^{-3}$, but due to the presence of low-energy strong-interaction effects, theoretical predictions are difficult to compute reliably [16–34]. Motivated by the fact that contributions of beyond-the-SM virtual particles may alter the size of CP violation with respect to the SM expectation, a number of theoretical analyses have been performed [19,27,32,35].

Unprecedented experimental precision can be reached at LHCb in the measurement of CP-violating asymmetries in $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays. The inclusion of charge-conjugate decay modes is implied throughout except in asymmetry definitions. Searches for CP violation in these decay modes have been performed by the *BABAR* [36], Belle [37], CDF [38,39], and LHCb [40–44] Collaborations. The corresponding CP asymmetries have been found to be consistent with zero within a precision of a few per mille.

This Letter presents a measurement of the difference of the time-integrated CP asymmetries in $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays, performed using pp collision data collected with the LHCb detector at a center-of-mass energy of 13 TeV, and corresponding to an integrated luminosity of 5.9 fb^{-1}.

The time-dependent CP asymmetry, $A_{CP}(f;t)$, between states produced as D^0 or $\bar{D}^0$ mesons decaying to a CP eigenstate f at time t is defined as

$$A_{CP}(f;t) \equiv \frac{\Gamma(D^0(t) \to f) - \Gamma(\bar{D}^0(t) \to f)}{\Gamma(D^0(t) \to f) + \Gamma(\bar{D}^0(t) \to f)}, \quad (1)$$

where Γ denotes the time-dependent rate of a given decay. For $f = K^-K^+$ or $f = \pi^-\pi^+$, $A_{CP}(f;t)$ can be expressed in terms of a direct component associated with CP violation in the decay amplitude and another component associated with CP violation in D^0-$\bar{D}^0$ mixing or in the interference between mixing and decay.

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A time-integrated asymmetry, $A_{CP}(f)$, can be determined, and its value will exhibit a dependence on the variation of the reconstruction efficiency as a function of the decay time. To first order in the D^0-$\bar{D}^0$ mixing parameters, it can be written as [38,45]

$$A_{CP}(f) \approx a_{CP}^{\rm dir}(f) - \frac{\langle t(f)\rangle}{\tau(D^0)} A_\Gamma(f), \tag{2}$$

where $\langle t(f)\rangle$ denotes the mean decay time of $D^0 \to f$ decays in the reconstructed sample, incorporating the effects of the time-dependent experimental efficiency, $a_{CP}^{\rm dir}(f)$ is the direct CP asymmetry, $\tau(D^0)$ the D^0 lifetime and $A_\Gamma(f)$ the asymmetry between the $D^0 \to f$ and $\bar{D}^0 \to f$ effective decay widths [46,47]. In the limit of U-spin symmetry, the direct CP asymmetry is equal in magnitude and opposite in sign for K^-K^+ and $\pi^-\pi^+$, though the size of U-spin-breaking effects at play is uncertain [19]. Taking A_Γ to be independent of final state [19,48,49], the difference in CP asymmetries between $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays is

$$\begin{aligned}\Delta A_{CP} &\equiv A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+)\\ &\approx \Delta a_{CP}^{\rm dir} - \frac{\Delta\langle t\rangle}{\tau(D^0)} A_\Gamma,\end{aligned} \tag{3}$$

where $\Delta a_{CP}^{\rm dir} \equiv a_{CP}^{\rm dir}(K^-K^+) - a_{CP}^{\rm dir}(\pi^-\pi^+)$ and $\Delta\langle t\rangle$ is the difference of the mean decay times $\langle t(K^-K^+)\rangle$ and $\langle t(\pi^-\pi^+)\rangle$.

The D^0 mesons considered in this analysis are produced either promptly at a pp collision point (primary vertex, PV) in the strong decay of $D^*(2010)^+$ mesons (hereafter referred to as D^{*+}) to a $D^0\pi^+$ pair or at a vertex displaced from any PV in semileptonic $\bar{B} \to D^0\mu^-\bar{\nu}_\mu X$ decays, where $\bar{B}$ denotes a hadron containing a b quark, and X stands for potential additional particles. The flavor at production of D^0 mesons from D^{*+} decays is determined from the charge of the accompanying pion (π tagged), whereas that of D^0 mesons from semileptonic b-hadron decays is obtained from the charge of the accompanying muon (μ tagged). The raw asymmetries measured for π-tagged and μ-tagged D^0 decays are defined as

$$\begin{aligned}A_{\rm raw}^{\pi-{\rm tagged}}(f) &\equiv \frac{N(D^{*+} \to D^0(f)\pi^+) - N(D^{*-} \to \bar{D}^0(f)\pi^-)}{N(D^{*+} \to D^0(f)\pi^+) + N(D^{*-} \to \bar{D}^0(f)\pi^-)},\\ A_{\rm raw}^{\mu-{\rm tagged}}(f) &\equiv \frac{N(\bar{B} \to D^0(f)\mu^-\bar{\nu}_\mu X) - N(B \to \bar{D}^0(f)\mu^+\nu_\mu X)}{N(\bar{B} \to D^0(f)\mu^-\bar{\nu}_\mu X) + N(B \to \bar{D}^0(f)\mu^+\nu_\mu X)},\end{aligned} \tag{4}$$

where N is the measured signal yield for the given decay. These can be approximated as

$$\begin{aligned}A_{\rm raw}^{\pi-{\rm tagged}}(f) &\approx A_{CP}(f) + A_{\rm D}(\pi) + A_{\rm P}(D^*),\\ A_{\rm raw}^{\mu-{\rm tagged}}(f) &\approx A_{CP}(f) + A_{\rm D}(\mu) + A_{\rm P}(B),\end{aligned} \tag{5}$$

where $A_{\rm D}(\pi)$ and $A_{\rm D}(\mu)$ are detection asymmetries due to different reconstruction efficiencies between positive and negative tagging pions and muons, whereas $A_{\rm P}(D^*)$ and $A_{\rm P}(B)$ are the production asymmetries of D^* mesons and b hadrons, arising from the hadronization of charm and beauty quarks in pp collisions [50]. Owing to the smallness of the involved terms, which averaged over phase space for selected events are $O(10^{-2})$ or less [50–53], the approximations in Eq. (5) are valid up to corrections of $O(10^{-6})$. The values of $A_{\rm D}(\pi)$ and $A_{\rm P}(D^*)$, as well as those of $A_{\rm D}(\mu)$ and $A_{\rm P}(B)$, are independent of the final state f and, thus, cancel in the difference, resulting in

$$\Delta A_{CP} = A_{\rm raw}(K^-K^+) - A_{\rm raw}(\pi^-\pi^+). \tag{6}$$

This simple relation between ΔA_{CP} and the measurable raw asymmetries in K^-K^+ and $\pi^-\pi^+$ makes the determination of ΔA_{CP} largely insensitive to systematic uncertainties.

The LHCb detector is a single-arm forward spectrometer designed for the study of particles containing b or c quarks, as described in detail in Refs. [54,55]. The LHCb tracking system exploits a dipole magnet to measure the momentum of charged particles. Although the analysis presented in this Letter is expected to be insensitive to such effects, the magnetic-field polarity is reversed periodically during data taking to mitigate the differences of reconstruction efficiencies of particles with opposite charges. Data sets corresponding to about one half of the total integrated luminosity are recorded with each magnetic-field configuration.

The online event selection is performed by a trigger, which consists of a hardware stage based on information from the calorimeter and muon systems, followed by two software stages. In the first software stage, events used in this analysis are selected if at least one track has large transverse momentum and is incompatible with originating from any PV, or if any two-track combination forming a secondary vertex, consistent with that of a D^0 decay, is found in the event by a multivariate algorithm [56,57]. In between the first and second software stages, detector alignment and calibration are performed, and updated constants are made available to the software trigger [58]. In the second stage, D^0 candidates are fully reconstructed using kinematic, topological and particle-identification

(PID) criteria. Requirements are placed on: the D^0 decay vertex, which must be well separated from all PVs in the event, the quality of reconstructed tracks, the D^0 transverse momentum, the angle between the D^0 momentum and its flight direction, PID information, and the impact-parameter (IP) significances ($\chi^2_{\rm IP}$) of the D^0 decay products with respect to all PVs in the event, where the $\chi^2_{\rm IP}$ is defined as the difference between the χ^2 of the PV reconstructed with and without the considered particle. In the analysis of the μ-tagged sample, B candidates are formed by combining a D^0 candidate with a muon under the requirement that they are consistent with originating from a common vertex. In addition, requirements on the invariant mass of the $D^0\mu$ system, $m(D^0\mu)$, and on the corrected mass ($m_{\rm corr}$) are applied. The corrected mass partially recovers the missing energy of the unreconstructed particles and is defined as $m_{\rm corr} \equiv \sqrt{m(D^0\mu)^2 + p_\perp(D^0\mu)^2} + p_\perp(D^0\mu)$ [59], where $p_\perp(D^0\mu)$ is the momentum of the $D^0\mu$ system transverse to the flight direction of the b hadron, determined from the primary and $D^0\mu$ vertices.

In the off-line selection, trigger signals are associated to reconstructed particles. Selection requirements are applied on the trigger decision, taking into account the information on whether the decision was taken due to the signal decay products or to other particles produced in the event. Fiducial requirements are imposed to exclude kinematic regions characterized by large detection asymmetries for the tagging pion or muon. Very large raw asymmetries, up to 100%, occur in certain kinematic regions because, for a given magnet polarity, low-momentum particles of one charge at large or small polar angles in the horizontal plane may be deflected out of the detector or into the (not instrumented) LHC beam pipe, whereas particles with the other charge are more likely to remain within the acceptance [60]. About 35% and 10% of the selected candidates are rejected by these fiducial requirements for the π-tagged and μ-tagged samples, respectively. In the retained samples, raw asymmetries are typically at the percent level or below. For π-tagged D^0 mesons, a requirement on the D^0 $\chi^2_{\rm IP}$ is applied to suppress the background of D^0 mesons from B decays, and PID requirements on the D^0 decay products are further tightened. Then the D^0 and pion candidates are combined to form D^{*+} candidates by requiring a good fit quality of the D^{*+} vertex and the invariant mass of D^0 candidates to lie within a range of about ± 3 standard deviations around the known D^0 mass. The D^{*+} vertex is determined as a common vertex of D^0 and tagging π^+ candidates, and is constrained to coincide with the nearest PV [61].

For μ-tagged mesons, the B candidates are further filtered using a dedicated boosted decision tree (BDT) to suppress the combinatorial background due to random combinations of charged kaon or pion pairs not originating from a D^0 decay. The variables used in the BDT to discriminate signal from combinatorial background are the fit quality of the D^0 and the B decay vertices, the D^0 flight distance, the D^0 impact parameter, i.e., the minimum distance of its trajectory to the nearest PV, the transverse momenta of the D^0 decay products, the significance of the distance between the D^0 and B decay vertices, the invariant mass $m(D^0\mu)$, and the corrected mass $m_{\rm corr}$. To suppress background from b-hadron decays to $c\bar{c}\pi^\pm X$ ($c\bar{c}K^\pm X$), where the $c\bar{c}$ resonance decays to a pair of muons, D^0 candidates are vetoed if the invariant mass of the $\mu^\mp\pi^\pm$ ($\mu^\mp K^\pm$) pair, where the pion (kaon) is given the muon mass hypothesis, lies within a window of about ± 50 MeV$/c^2$ around the J/ψ or $\psi(2S)$ known masses.

The data sample includes events with multiple D^{*+} and B candidates. The majority of these events contain the same reconstructed D^0 meson combined with different tagging pions or muons. When multiple candidates are present in the event, only one is kept randomly. The fractions of events with multiple candidates are about 10% and 0.4% in the π-tagged and μ-tagged samples, respectively. A small fraction of events, of the order of per mille, belong to both the selected π-tagged and μ-tagged samples.

As the detection and production asymmetries are expected to depend on the kinematics of the reconstructed particles, the cancellation in the difference between the raw asymmetries in Eq. (6) may be incomplete if the kinematic distributions of reconstructed D^{*+} or B candidates and of the tagging pions or muons differ between the K^-K^+ and $\pi^-\pi^+$ decay modes. For this reason, a small correction to the K^-K^+ sample is applied by means of a weighting procedure [60]. For the π-tagged sample, candidate-by-candidate weights are calculated by taking the ratio between the three-dimensional background-subtracted distributions of transverse momentum, azimuthal angle, and pseudorapidity of the D^{*+} meson in the K^-K^+ and $\pi^-\pi^+$ modes. An analogous procedure is followed for the μ-tagged sample, where D^0 distributions are used instead of those of the D^{*+} meson. It is then checked *a posteriori* that the distributions of the same variables for tagging pions and muons are also equalized by the weighting. The application of the weights leads to a small variation of ΔA_{CP}, below 10^{-4} for both the π-tagged and μ-tagged samples.

The raw asymmetries of signal and background components for each decay mode are free parameters determined by means of simultaneous least-square fits to the binned mass distributions of D^{*+} and D^{*-} candidates for the π-tagged sample, or D^0 and $\bar{D}^0$ candidates for the μ-tagged sample. In particular, in the analysis of the π-tagged sample, the fits are performed to the $m(D^0\pi^+)$ and $m(\bar{D}^0\pi^-)$ distributions. As outlined in Ref. [38], using these distributions has the advantage that they are the same for both $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decay modes.

The signal mass model, which is obtained from simulation, consists of the sum of three Gaussian functions and a Johnson S_U function [62], whose parameters are free to be adjusted by the fit to the data. The mean values of the

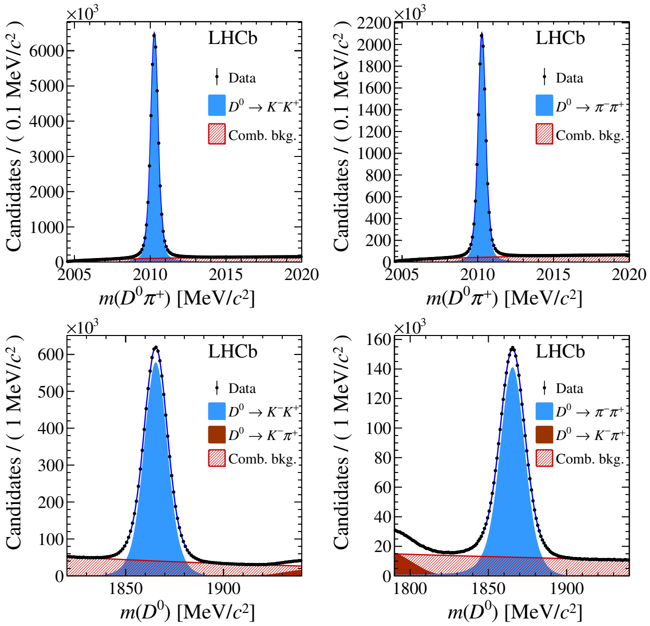

FIG. 1. Mass distributions of selected (top) $\pi^{\pm}$-tagged and (bottom) $\mu^{\pm}$-tagged candidates for (left) K^-K^+ and (right) $\pi^-\pi^+$ final states of the D^0-meson decays, with fit projections overlaid.

Gaussian functions are distinct for positive and negative tags, whereas widths and fractions are shared. The parameters of the Johnson S_U function, which accounts for the slight asymmetric shape of the signal distribution due to the proximity of the $m(D^0) + m(\pi^+)$ threshold, are also shared. 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 α and β are two free parameters which are shared among positive and negative tags. In the analysis of the μ-tagged sample, the fits are performed to the $m(D^0)$ distributions. The signal is described by the sum of two Gaussian functions convolved with a truncated power-law function that accounts for final-state photon radiation effects, whereas the combinatorial background is described by an exponential function. A small contribution from $D^0 \to K^-\pi^+$ decays with a misidentified kaon or pion is also visible, which is modeled as the tail of a Gaussian function. Separate fits are performed to subsamples of data collected with different magnet polarities and in different years. All partial ΔA_{CP} values corresponding to each subsample are found to be in good agreement and then averaged to obtain the final results. If single fits are performed to the overall π-tagged and μ-tagged samples, small differences of the order of a few 10^{-5} are found. The $m(D^0\pi^+)$ and $m(D^0)$ distributions corresponding to the entire samples are displayed in Fig. 1 (see also Ref. [60] for the corresponding asymmetries as a function of mass). The π-tagged (μ-tagged) signal yields are approximately 44 (9) million $D^0 \to K^-K^+$ decays and 14 (3) million $D^0 \to \pi^-\pi^+$ decays. In the case of π-tagged decays, the fits to the $m(D^0\pi^+)$ distributions do not distinguish between background that produces peaks in $m(D^0\pi^+)$, which can arise from D^{*+} decays where the correct tagging pion is found but the D^0 meson is misreconstructed, and signal. The effect on ΔA_{CP} of residual peaking backgrounds, suppressed by selection requirements to less than 1% of the number of signal candidates, is evaluated as a systematic uncertainty.

Studies of systematic uncertainties on ΔA_{CP} are carried out independently for the π-tagged and μ-tagged samples. Several sources affecting the measurement are considered. In the case of π-tagged decays, the dominant systematic uncertainty is related to the knowledge of the signal and background mass models. It is evaluated by generating pseudoexperiments according to the baseline fit model, then fitting alternative models to those data. A value of 0.6×10^{-4} is assigned as a systematic uncertainty, corresponding to the largest variation observed using the alternative functions. Possible differences between $D^0\pi^+$ and $\bar{D}^0\pi^-$ invariant-mass shapes are investigated by studying a sample of 232 million $D^{*+} \to \bar{D}^0(K^-\pi^+)\pi^+$ and $D^{*-} \to \bar{D}^0(K^+\pi^-)\pi^-$ decays. The effect on ΔA_{CP} is estimated to be on the order of 10^{-5} at most, hence, negligible. A similar study with pseudoexperiments is also performed with the μ-tagged sample and a value of 2×10^{-4} is found.

In the case of μ-tagged decays, the main systematic uncertainty is due to the possibility that the D^0 flavor is not tagged correctly by the muon charge because of misreconstruction. The probability of wrongly assigning the D^0 flavor (mistag) is studied with a large sample of μ-tagged $D^0 \to K^-\pi^+$ decays by comparing the charges of kaon and muon candidates. Mistag rates are found to be at the percent level and compatible for positively and negatively tagged decays. The corresponding systematic uncertainty is estimated to be 4×10^{-4}, also taking into account the fact that wrongly tagged decays include a fraction of doubly Cabibbo-suppressed $D^0 \to K^+\pi^-$ and mixed $D^0 \to \bar{D}^0 \to K^+\pi^-$ decays, calculated to be 0.39% with negligible uncertainty for both the $K^+\ \pi^-$ and $K^-\ \pi^+$ final states using input from Ref. [63].

Systematic uncertainties of 0.2×10^{-4} and 1×10^{-4} accounting for the knowledge of the weights used in the kinematic weighting procedure are assessed for π-tagged and μ-tagged decays, respectively. Although suppressed by the requirement that the D^0 trajectory points back to the PV, a fraction of D^0 mesons from B decays is still present in the final π-tagged sample. As $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays may have different levels of contamination, the value of ΔA_{CP} may be biased because of an incomplete cancellation of the production asymmetries of b hadrons. The fractions of D^0 mesons from B decays are estimated by performing a fit to the distribution of the D^0-candidate impact parameter in the plane transverse to the beam direction [60]. The corresponding systematic uncertainty is estimated to be 0.3×10^{-4}. A systematic uncertainty associated to the presence of background components peaking in $m(D^0\pi)$ and not in $m(D^0)$ is determined by fits to the $m(D^0)$ distributions [60], where these components are modeled using fast simulation [64]. The main sources are the $D^0 \to K^-\pi^+\pi^0$ decay for the K^+K^- final state, and the $D^0 \to \pi^-\mu^+\nu_\mu$ and $D^0 \to \pi^-e^+\nu_e$ decays for the $\pi^+\pi^-$ final state. Yields and raw asymmetries of the peaking-background components measured from the fits are then used as inputs to pseudoexperiments designed to evaluate the corresponding effects on the determination of ΔA_{CP}. A value of 0.5×10^{-4} is assigned as a systematic uncertainty.

In the case of μ-tagged decays, the fractions of reconstructed $\bar{B}$ decays can be slightly different between the K^-K^+ and $\pi^-\pi^+$ decay modes, which could lead to a small bias in ΔA_{CP}. Using the LHCb measurements of the b-hadron production asymmetries [50], the systematic uncertainty on ΔA_{CP} is estimated to be 1×10^{-4}. The combination of a difference in the B reconstruction efficiency as a function of the decay time between the $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ modes and the presence of neutral B-meson oscillations may also cause an imperfect cancellation of $A_{\mathrm{P}}(B)$ in ΔA_{CP}. The associated systematic uncertainty is estimated to be 2×10^{-4}.

All individual contributions are summed in quadrature to give total systematic uncertainties on ΔA_{CP} of 0.9×10^{-4} and 5×10^{-4} for the π-tagged and μ-tagged samples, respectively. A summary of all systematic uncertainties is reported in Table I. Other possible systematic uncertainties are investigated and found to be negligible.

Numerous additional robustness checks are carried out [60]. The measured value of ΔA_{CP} is studied as a function of several variables, notably including the azimuthal angle, χ^2_{IP}, transverse momentum, and pseudorapidity of π-tagged and μ-tagged D^0 mesons as well as of the tagging pions or muons; the χ^2 of the D^{*+} and B vertex fits; the track quality of the tagging pion; and the charged-particle multiplicity in the event. Furthermore, the total sample is split into subsamples taken in different run periods within the years of data taking, also distinguishing different magnet polarities. No evidence for unexpected dependences of ΔA_{CP} is found in any of these tests. A check using more stringent PID requirements is performed, and all variations of ΔA_{CP} are found to be compatible within statistical uncertainties. An additional check concerns the measurement of ΔA_{bkg}, that is the difference of the background raw asymmetries in K^-K^+ and $\pi^-\pi^+$ final states. As the prompt background is mainly composed of genuine D^0 candidates paired with unrelated pions originating from the PV, ΔA_{bkg} is expected to be compatible with zero. A value of $\Delta A_{\mathrm{bkg}} = (-2 \pm 4) \times 10^{-4}$ is obtained.

TABLE I. Systematic uncertainties on ΔA_{CP} for π- and μ-tagged decays (in 10^{-4}). The total uncertainties are obtained as the sums in quadrature of the individual contributions.

Source	π tagged	μ tagged
Fit model	0.6	2
Mistag	$\cdots$	4
Weighting	0.2	1
Secondary decays	0.3	$\cdots$
Peaking background	0.5	$\cdots$
B fractions	$\cdots$	1
B reco. efficiency	$\cdots$	2
Total	0.9	5

The difference of time-integrated CP asymmetries of $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays is measured using 13 TeV pp collision data collected with the LHCb detector and corresponding to an integrated luminosity of 5.9 fb^{-1}. The results are

$$\Delta A_{CP}^{\pi\text{-tagged}} = [-18.2 \pm 3.2(\mathrm{stat}) \pm 0.9(\mathrm{syst})] \times 10^{-4},$$
$$\Delta A_{CP}^{\mu\text{-tagged}} = [-9 \pm 8(\mathrm{stat}) \pm 5(\mathrm{syst})] \times 10^{-4}.$$

Both measurements are in good agreement with world averages [65] and previous LHCb results [42,43].

By making a full combination with previous LHCb measurements [42,43], the following value of ΔA_{CP} is obtained

$$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4},$$

where the uncertainty includes statistical and systematic contributions. The significance of the deviation from zero corresponds to 5.3 standard deviations. This is the first observation of CP violation in the decay of charm hadrons.

The interpretation of ΔA_{CP} in terms of direct CP violation and A_Γ requires knowledge of the difference of reconstructed mean decay times for $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays normalized to the D^0 lifetime, as shown in Eq. (3). The values corresponding to the present measurements are $\Delta\langle t\rangle^{\pi\text{-tagged}}/\tau(D^0) = 0.135 \pm 0.002$ and $\Delta\langle t\rangle^{\mu\text{-tagged}}/\tau(D^0) = -0.003 \pm 0.001$, whereas that corresponding to the full combination is $\Delta\langle t\rangle/\tau(D^0) = 0.115 \pm 0.002$. The uncertainties include statistical and systematic contributions, and the world average of the D^0 lifetime is used [66].

By using in addition the LHCb average $A_\Gamma = (-2.8 \pm 2.8) \times 10^{-4}$ [46,47], from Eq. (3), it is possible to derive

$$\Delta a_{CP}^{\mathrm{dir}} = (-15.7 \pm 2.9) \times 10^{-4},$$

which shows that, as expected, ΔA_{CP} is primarily sensitive to direct CP violation. The overall improvement in precision brought by the present analysis to the knowledge of $\Delta a_{CP}^{\mathrm{dir}}$ is apparent when comparing with the value obtained from previous measurements, $\Delta a_{CP}^{\mathrm{dir}} = (-13.4 \pm 7.0) \times 10^{-4}$ [65].

In summary, this Letter reports the first observation of a nonzero CP asymmetry in charm decays, using large samples of $D^0 \to K^- K^+$ and $D^0 \to \pi^- \pi^+$ decays collected with the LHCb detector. The result is consistent with, although in magnitude at the upper end of, SM expectations, which lie in the range $10^{-4} - 10^{-3}$ [16–34]. In particular, the result challenges predictions based on first-principle QCD dynamics [19,33]. It complies with predictions based on flavor-SU(3) symmetry, if one assumes a dynamical enhancement of the penguin amplitude [16,26–30,32]. In the next decade, further measurements with charmed particles, along with possible theoretical improvements, will help clarify the physics picture and establish whether this result is consistent with the SM or indicates the presence of new dynamics in the up-quark sector.

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