A search for charge-parity (CP) violation in $D^0 \rightarrow K^- K^+$ and $D^0 \rightarrow \pi^- \pi^+$ 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 $D^0$ meson is determined from the charge of the pion in $D^* (2010)^+ \rightarrow D^0 \pi^+$ decays or from the charge of the muon in $B \rightarrow D^0 \mu^- \bar{\nu}_\mu X$ decays. The difference between the CP asymmetries in $D^0 \rightarrow K^- K^+$ and $D^0 \rightarrow \pi^- \pi^+$ decays is measured to be $\Delta A_{\text{CP}} = [\pm 18.2 \pm 3.2 \text{(stat.)} \pm 0.9 \text{(syst.)}] \times 10^{-4}$ for $\pi$-tagged and $\Delta A_{\text{CP}} = [\pm 9 \pm 8 \text{(stat.)} \pm 5 \text{(syst.)}] \times 10^{-4}$ for $\mu$-tagged $D^0$ mesons. The combination with previous LHCb results leads to $\Delta A_{\text{CP}} = (\pm 15.4 \pm 2.9) \times 10^{-4}$, where the uncertainty includes both statistical and systematic contributions. The measured value differs from zero by more than five standard deviations. This is the first observation of CP violation in the decay of charm hadrons.

1 Introduction

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. CP violation is included in the Standard Model (SM) of particle physics through an irreducible complex phase in the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix. Several experiments established the presence of CP violation in weak interactions in the $K$- and $B$-meson systems, and all results are well interpreted within the CKM formalism. However, the size of CP violation in the SM is too small to account for the observed matter-antimatter asymmetry, suggesting the existence of beyond-the-SM sources of CP violation.

Despite decades of experimental searches, the observation of CP violation in the charm sector has not yet been achieved. Because of the presence of low-energy strong-interaction effects, theoretical predictions of the size of CP violation in charm decays are difficult to compute reliably, and the asymmetries are expected to be of the order of $10^{-4}$ to $10^{-3}$ in magnitude. Searches for CP violation in $D^0 \rightarrow K^- K^+$ and $D^0 \rightarrow \pi^- \pi^+$ modes have been performed by the BaBar, Belle, CDF, and LHCb collaborations, which measured values of CP asymmetries consistent with zero within a precision of a few per mille. This document presents a measurement of the difference of the time-integrated CP asymmetries in $D^0 \rightarrow K^- K^+$ and $D^0 \rightarrow \pi^- \pi^+$ decays, performed using $pp$ collision data collected with the LHCb detector between

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*The inclusion of charge-conjugate decay modes is implied throughout except in asymmetry definitions.*
2015 and 2018 at a center-of-mass energy of 13 TeV, 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

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

where $\Gamma$ 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 to CP violation in the decay amplitude and another component associated to CP violation in $D^0-\bar{D}^0$ mixing or in the interference between mixing and decay. The corresponding time-integrated asymmetry, $A_{CP}(f)$, can be written to first order in the $D^0-\bar{D}^0$ mixing parameters as

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

where $\langle t(f) \rangle$ denotes the mean decay time of $D^0 \rightarrow f$ decays in the reconstructed sample, $a_{CP}^{dir}(f)$ is the direct CP asymmetry, $\tau(D^0)$ the $D^0$ lifetime and $A_{\Gamma}(f)$ the asymmetry between the $D^0 \rightarrow f$ and $\bar{D}^0 \rightarrow f$ effective decay widths. Taking $A_{\Gamma}$ to be independent of the final state, the difference between CP asymmetries in $D^0 \rightarrow K^-K^+$ and $D^0 \rightarrow \pi^-\pi^+$ decays is

$$\Delta A_{CP} = A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+) \approx \Delta a_{CP}^{dir} - \frac{\Delta \langle t \rangle}{\tau(D^0)} A_{\Gamma}, \quad (3)$$

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

$$A_{\text{raw}}^{\pi\text{-tagged}}(f) = \frac{N(D^{*+} \rightarrow D^0(f)\pi^+) - N(D^{-} \rightarrow \bar{D}^0(f)\pi^-)}{N(D^{*+} \rightarrow D^0(f)\pi^+) + N(D^{-} \rightarrow \bar{D}^0(f)\pi^-)},$$

$$A_{\text{raw}}^{\mu\text{-tagged}}(f) = \frac{N(\bar{B} \rightarrow D^0(f)\mu^-\bar{\nu}_\mu X) - N(B \rightarrow \bar{D}^0(f)\mu^+\nu_\mu X)}{N(\bar{B} \rightarrow D^0(f)\mu^-\bar{\nu}_\mu X) + N(B \rightarrow \bar{D}^0(f)\mu^+\nu_\mu X)}, \quad (4)$$

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

$$A_{\text{raw}}^{\pi\text{-tagged}}(f) \approx A_{CP}(f) + A_D(\pi) + A_P(D^*),$$

$$A_{\text{raw}}^{\mu\text{-tagged}}(f) \approx A_{CP}(f) + A_D(\mu) + A_P(B), \quad (5)$$

where $A_D(\pi)$ and $A_D(\mu)$ are detection asymmetries due to different reconstruction efficiencies between positive and negative tagging particles, whereas $A_P(D^*)$ and $A_P(B)$ are the production asymmetries of $D^*$ mesons and $b$ hadrons, arising from the hadronization of charm and beauty quarks in $pp$ collisions. The involved terms, averaged over phase space for selected events are $\mathcal{O}(10^{-3})$ or less, hence the approximations in Eqs. 5 are valid up to corrections of $\mathcal{O}(10^{-6})$. The values of the detection and production asymmetries are independent of the final state $f$,
and thus cancel in the difference, if the kinematic distributions of the two channels are equal, resulting in

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

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

## 2 Selection

The LHCb detector is a single-arm forward spectrometer designed for the study of particles containing $b$ or $c$ quarks\(^53,54\). The magnetic-field polarity of the dipole magnet used by the LHCb tracking system is reversed periodically during data taking to mitigate the differences of reconstruction efficiencies of particles with opposite charges, though the analysis presented in this document is expected to be insensitive to such effects.

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. $D^0$ candidates are fully reconstructed in the second software stage using kinematic, topological and particle-identification (PID) criteria. In the $\mu$-tagged sample, $D^0$ candidates are combined with muons to form $B$ candidates, 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\(^b\) are applied in the $\mu$-tagged sample.

In certain kinematic regions very large raw asymmetries, up to 100%, occur because, for a given magnet polarity, low-momentum particles of one charge at small or large polar angles in the horizontal plane may be deflected out of the detector or into the LHC beam pipe, whereas particles with the other charge are more likely to remain within the acceptance. For this reason, in the offline selection, fiducial requirements are imposed to exclude kinematic regions characterized by large detection asymmetries for the tagging particle. About 35% and 10% of the selected candidates are rejected by these fiducial requirements for the $\pi$-tagged and $\mu$-tagged samples, respectively. For $\pi$-tagged $D^0$ mesons, a requirement on the $D^0 \chi^2_{IP}$ is applied\(^c\) to suppress the background of $D^0$ mesons produced in $B$ decays, and PID requirements on the $D^0$ decay products are tightened. The $D^0$ and pion candidates are combined to form $D^{*+}$ candidates by requiring a good fit quality of the $D^{*+}$ vertex, that is constrained to coincide with the nearest PV\(^56\). The invariant mass of $D^0$ candidates is required to lie within a range of about ±3 standard deviations around the known $D^0$ mass. For $\mu$-tagged mesons, in order to suppress the combinatorial background due to random combinations of charged kaon or pion pairs not originating from a $D^0$ decay, the $B$ candidates are further filtered using a dedicated boosted decision tree (BDT) that uses variables related to the topology and the kinematics of the reconstructed decay. A veto in the invariant mass of the $\mu^+\pi^\pm$ ($\mu^\pm K^{\mp}$) pair, where the pion (kaon) is given the muon mass hypothesis, is applied to suppress background from $b$-hadron decays to $c\pi^{\pm}X$ ($c\bar{c}K^{\pm}X$), where the $c\bar{c}$ resonance decays to a pair of muons.

The data sample includes events with multiple $D^{*+}$ and $B$ candidates, that are mostly due to a common reconstructed $D^0$ meson combined with different tagging particles. The fractions of events with multiple candidates are about 10% and 0.4% in the $\pi$-tagged and $\mu$-tagged samples, respectively. When multiple candidates are present in the event, only one is kept randomly.

Since the detection and production asymmetries are expected to depend on the kinematics of the reconstructed particles, the possible difference between the kinematic distributions of reconstructed $D^{*+}$ or $B$ candidates and of the tagging pions or muons in the $K^- K^+$ and $\pi^- \pi^+$ decay modes may induce an incomplete cancellation in the difference in Eq. 6. Hence,

\(^b\)The corrected mass is defined as $m_{corr} \equiv \sqrt{m(D^0\mu)^2 + p_{\perp}(D^0\mu)^2 + p_{\perp}(D^0\mu))^55}$, where $p_{\perp}(D^0\mu)$ is the momentum of the $D^0\mu$ system transverse to the flight direction of the $b$ hadron.

\(^c\)The $\chi^2_{IP}$ is defined as the difference between the $\chi^2$ of the PV reconstructed with and without the considered particle.
a small correction to the $K^-K^+$ sample is applied by means of a weighting procedure: for the \( \pi^\pm \)-tagged sample, the ratio between the three-dimensional background-subtracted distributions of pseudorapidity, transverse momentum and azimuthal angle of the $D^{*+}$ meson in the $K^-K^+$ and $\pi^-\pi^+$ modes is taken and candidate-by-candidate weights are calculated. An analogous procedure is followed for the $\mu^\pm$-tagged sample, where $D^0$ distributions are used in place of those of the $D^{*+}$ meson. It is then checked \textit{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 results in a small variation of $\Delta A_{CP}$, below $10^{-4}$ for both the $\pi^\pm$-tagged and $\mu^\pm$-tagged samples.

### 3 Measurement of the Asymmetries

For each decay mode, simultaneous least-square fits to the binned mass distributions of $D^{*+}$ and $D^{*-}$ candidates for the $\pi^\pm$-tagged sample, or $D^0$ and $\bar{D}^0$ candidates for the $\mu^\pm$-tagged sample, are performed to obtain the raw asymmetries of signal and background components, which are free parameters of the fits.

In the analysis of the $\pi^\pm$-tagged sample the fits are performed to the $m(D^0\pi^\pm)$ and $m(D^0\pi^-)$ distributions, that are defined using the known value of the $D^0$ mass\textsuperscript{37}. The signal mass model consists of the sum of three Gaussian functions and a Johnson $S_U$ function\textsuperscript{57}, whereas the
combining background is described by an empirical function of the form \([m(D^0\pi^+) - m(D^0) - m(\pi^+)]e^{\beta m(D^0\pi^+)}\). All the parameters of the models are free to be adjusted by the fit and are shared among positive and negative tags, except for the mean values of the Gaussian functions, which are different to take into account small shifts in the raw mass measurements between opposite tags.

In the analysis of the \(\mu\)-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 accounting for final-state photon radiation effects, while the combinatorial background is modeled by an exponential function. A small contribution from a misidentified kaon or pion is visible and is modeled as the tail of a Gaussian function. The fit parameters are shared among positive and negative tags, except for the mean values of the Gaussian functions.

Fits are performed to subsamples of data split according to magnet polarities and years of data taking. The final results are obtained by averaging the partial \(\Delta A_{\text{CP}}\) values corresponding to each subsample, which are found to be in good agreement. Performing single fits the overall \(\pi\)-tagged and \(\mu\)-tagged samples gives small differences of the order of a few \(10^{-5}\). Figure 1 displays the \(m(D^0\pi^+)\) and \(m(D^0)\) distributions corresponding to the entire samples. The \(\pi\)-tagged (\(\mu\)-tagged) signal yields are approximately 44 (9) million \(D^0 \rightarrow K^-\pi^+\) decays and 14 (3) million \(D^0 \rightarrow \pi^-\pi^+\) decays.

4 Systematic Uncertainties

Several sources of systematic uncertainties affecting the measurement are considered and studied independently for the \(\pi\)-tagged and \(\mu\)-tagged samples. In the case of \(\pi\)-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 both baseline and alternative models to those data and considering the difference between the resulting values of \(\Delta A_{\text{CP}}\). A value of \(0.6 \times 10^{-4}\), corresponding to the largest observed variation, is assigned as a systematic uncertainty. A similar study with pseudoexperiments is also performed with the \(\mu\)-tagged sample and a value of \(2 \times 10^{-4}\) is found.

In the case of \(\mu\)-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 measured on a large sample of \(\mu\)-tagged \(D^0 \rightarrow K^-\pi^+\) 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, and the corresponding systematic uncertainty is estimated to be \(4 \times 10^{-4}\).

Systematic uncertainties of \(0.2 \times 10^{-4}\) and \(1 \times 10^{-4}\) accounting for the knowledge of the weights used in the kinematic weighting procedure are assessed for \(\pi\)-tagged and \(\mu\)-tagged decays, respectively. A fraction of \(D^0\) mesons from \(B\) decays (secondary decays) is still present in the final \(\pi\)-tagged sample even after the requirement that the \(D^0\) trajectory points back to the PV. Possible different levels of contamination from secondary decays in \(D^0 \rightarrow K^-K^+\) and \(D^0 \rightarrow \pi^-\pi^+\) samples may bias the value of \(\Delta A_{\text{CP}}\) because of an incomplete cancellation of the production asymmetries of \(b\) hadrons. The fractions of secondary 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, and the corresponding systematic uncertainty is estimated to be \(0.3 \times 10^{-4}\). 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 after the removal of the signal window requirement, where these components are modeled using fast simulation. The main sources are the \(D^0 \rightarrow K^-\pi^+\pi^0\) decay for the \(K^+K^-\) mode, and the \(D^0 \rightarrow \pi^-\mu^+\nu_\mu\) and \(D^0 \rightarrow \pi^-e^+\nu_e\) decays for the \(\pi^+\pi^-\) mode. Yields and raw asymmetries of the peaking-background components measured from the fits are then used as inputs to pseudoexperiments.
Table 1: Systematic uncertainties on $\Delta A_{CP}$ for $\pi$- and $\mu$-tagged decays (in $10^{-4}$). The total uncertainties are obtained as the sums in quadrature of the individual contributions.

| Source             | $\pi$-tagged | $\mu$-tagged |
|--------------------|--------------|--------------|
| Fit model          | 0.6          | 2            |
| Mistag             | –            | 4            |
| Weighting          | 0.2          | 1            |
| Secondary decays   | 0.3          | –            |
| Peaking background | 0.5          | –            |
| $B$ fractions      | –            | 1            |
| $B$ reco. efficiency | –          | 2            |
| **Total**          | 0.9          | 5            |

performed to evaluate the corresponding effects on the determination of $\Delta A_{CP}$, resulting in a systematic uncertainty of $0.5 \times 10^{-4}$.

In the case of $\mu$-tagged decays, the fractions of reconstructed $\overline{B}$ decays can be slightly different between the $K^-K^+$ and $\pi^-\pi^+$ decay modes, which could lead to a small bias in $\Delta A_{CP}$. Using the LHCb measurements of the $b$-hadron production asymmetries$^{49}$, the associated systematic uncertainty on $\Delta A_{CP}$ is estimated to be $1 \times 10^{-4}$. The combination of a difference in the $B$ reconstruction efficiency as a function of the decay time between the $D^0 \rightarrow K^-K^+$ and $D^0 \rightarrow \pi^-\pi^+$ modes and the presence of neutral $B$-meson oscillations may also cause an imperfect cancellation of $A_P(B)$ in $\Delta A_{CP}$, and the related systematic uncertainty is estimated to be $2 \times 10^{-4}$.

The total systematic uncertainties on $\Delta A_{CP}$ are given by the sum in quadrature of all individual contributions, and are equal to $0.9 \times 10^{-4}$ and $5 \times 10^{-4}$ for the $\pi$-tagged and $\mu$-tagged samples, respectively. A summary of all systematic uncertainties is reported in Table 1.

Numerous additional robustness checks are carried out. The measured value of $\Delta A_{CP}$ is studied as a function of several geometrical and kinematic variables. 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 $\Delta A_{CP}$ is found in any of these tests. A check using more stringent PID requirements is performed, and all variations of $\Delta A_{CP}$ are found to be compatible within statistical uncertainties. An additional check concerns the measurement of $\Delta A_{bkg}$, which is the difference of the background raw asymmetries in $K^-K^+$ and $\pi^-\pi^+$ final states. The prompt background is mainly composed of genuine $D^0$ candidates paired with unrelated pions originating from the PV, so $\Delta A_{bkg}$ is expected to be compatible with zero. A value of $\Delta A_{bkg} = (-2 \pm 4) \times 10^{-4}$ is obtained.

5 Results

The measured differences of time-integrated $CP$ asymmetries of $D^0 \rightarrow K^-K^+$ and $D^0 \rightarrow \pi^-\pi^+$ decays are$^{58}$

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

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

both in good agreement with world averages$^{59}$ and previous LHCb results$^{41,42}$.

The full combination with previous LHCb measurements$^{41,42}$ gives the following value of $\Delta A_{CP}$

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

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.
As shown in Eq. 3, the interpretation of $\Delta A_{CP}$ in terms of direct $CP$ violation and $A_{\Gamma}$ 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. The values corresponding to the present measurements, using the world average of the $D^0$ lifetime$^{60}$, are $\Delta \langle t \rangle_{\pi^-\pi^+\text{-tagged}} / \tau(D^0) = 0.135 \pm 0.002$ 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. By using the LHCb average$^{45,46}$ $A_{\Gamma} = (-2.8 \pm 2.8) \times 10^{-4}$, from Eq. 3 it is possible to derive $\Delta a_{dir}^{CP} = (-15.7 \pm 2.9) \times 10^{-4}$.

As expected, $\Delta A_{CP}$ is primarily sensitive to direct $CP$ violation.

In summary, this document 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. In the next future, further measurements with charmed particles, along with possible theoretical improvements, will help clarify the present physics picture, to establish whether this result is consistent with the SM or indicates the presence of new physics processes in the up-quark sector.

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