Measurement of the Difference of Time-Integrated CP Asymmetries in $D^0 \to K^- K^+$ and $D^0 \to \pi^- \pi^+$ Decays

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A search for CP violation in $D^0 \to K^- K^+$ and $D^0 \to \pi^- \pi^+$ decays is performed using pp collision data, corresponding to an integrated luminosity of 3 fb^{-1}, collected using the LHCb detector at center-of-mass energies of 7 and 8 TeV. The flavor of the charm meson is inferred from the charge of the pion in $D^{*+} \to D^0 \pi^+$ and $D^{*-} \to \overline{D}^0 \pi^-$ decays. The difference between the CP asymmetries in $D^0 \to K^- K^+$ and $D^0 \to \pi^- \pi^+$ decays, $\Delta A_{CP} \equiv A_{CP}(K^- K^+) - A_{CP}(\pi^- \pi^+)$, is measured to be $[-0.10 \pm 0.08(\mathrm{stat}) \pm 0.03(\mathrm{syst})]\%$. This is the most precise measurement of a time-integrated CP asymmetry in the charm sector from a single experiment.

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Violation of charge-parity (CP) symmetry in weak decays of hadrons is described in the Standard Model (SM) by the Cabibbo-Kobayashi-Maskawa (CKM) matrix and has been observed in K- and B-meson systems [1–5]. However, no CP violation has been observed in the charm sector, despite the experimental progress seen in charm physics in the last decade. Examples are the unambiguous observation of D^0–$\overline{D}^0$ meson mixing [6–11], and measurements of CP asymmetry observables in D meson decays, reaching an experimental precision of $\mathcal{O}(10^{-3})$ [12]. The amount of CP violation is expected to be below the percent level [13–20], but large theoretical uncertainties due to long distance interactions prevent precise SM calculations. Charm hadrons provide a unique opportunity to search for CP violation with particles containing only up-type quarks.

This Letter presents a measurement of the difference between the time-integrated CP asymmetries of $D^0 \to K^- K^+$ and $D^0 \to \pi^- \pi^+$ decays, performed with pp collision data corresponding to an integrated luminosity of 3 fb^{-1} collected using the LHCb detector at center-of-mass energies of 7 and 8 TeV. The inclusion of charge-conjugate decay modes is implied throughout except in the definition of asymmetries. This result is an update of the previous LHCb measurement with 0.6 fb^{-1} of data, in which a value of $\Delta A_{CP} = (-0.82 \pm 0.21)\%$ was obtained [21].

The time-dependent CP asymmetry, $A_{CP}(f;t)$, for D^0 mesons decaying to a CP eigenstate f is defined as

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

where Γ denotes the decay rate. For $f = K^- K^+$ and $f = \pi^- \pi^+$, $A_{CP}(f;t)$ can be expressed in terms of a direct component associated with CP violation in the decay amplitudes, and an indirect component associated with CP violation in the mixing or in the interference between mixing and decay. In the limit of exact symmetry under a transformation interchanging d and s quarks (U-spin symmetry), the direct component is expected to be equal in magnitude and opposite in sign for $K^- K^+$ and $\pi^- \pi^+$ decays [22]. However, large U-spin breaking effects could be present [13,16,23,24].

The measured time-integrated asymmetry, $A_{CP}(f)$, depends upon the reconstruction efficiency as a function of the decay time. It can be written as [25,26]

$$A_{CP}(f) \approx a_{CP}^{\mathrm{dir}}(f)\left(1 + \frac{\langle t(f)\rangle}{\tau} y_{CP}\right) + \frac{\langle t(f)\rangle}{\tau} a_{CP}^{\mathrm{ind}}, \quad (2)$$

where $\langle t(f)\rangle$ denotes the mean decay time of $D^0 \to f$ decays in the reconstructed sample, $a_{CP}^{\mathrm{dir}}(f)$ as the direct CP asymmetry, τ the D^0 lifetime, a_{CP}^{ind} the indirect CP asymmetry, and y_{CP} is the deviation from unity of the ratio of the effective lifetimes of decays to flavor specific and CP-even final states. To a good approximation, a_{CP}^{ind} is independent of the decay mode [22,27].

Neglecting terms of the order $\mathcal{O}(10^{-6})$, the difference in CP asymmetries between $D^0 \to K^- K^+$ and $D^0 \to \pi^- \pi^+$ is

$$\Delta A_{CP} \equiv A_{CP}(K^- K^+) - A_{CP}(\pi^- \pi^+)$$
$$\approx \Delta a_{CP}^{\mathrm{dir}}\left(1 + \frac{\overline{\langle t\rangle}}{\tau} y_{CP}\right) + \frac{\Delta\langle t\rangle}{\tau} a_{CP}^{\mathrm{ind}}, \quad (3)$$

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where $\overline{\langle t \rangle}$ is the arithmetic average of $\langle t(K^-K^+)\rangle$ and $\langle t(\pi^-\pi^+)\rangle$.

The most precise measurements of the time-integrated CP asymmetries in $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays to date have been performed by the LHCb [21,28], CDF [29], *BABAR* [30] and Belle [31,32] collaborations. The measurement in Ref. [28] uses D^0 mesons produced in semileptonic b-hadron decays, where the charge of the muon is used to identify the flavor of the D^0 meson at production, while the other measurements use D^0 mesons produced in the decay of the $D^*(2010)^+$ meson, hereafter referred to as D^{*+}.

The raw asymmetry, $A_{\rm raw}(f)$, measured for D^0 decays to a final state f is defined as

$$A_{\rm raw}(f) \equiv \frac{N(D^{*+} \to D^0(f)\pi_s^+) - N(D^{*-} \to \overline{D}^0(f)\pi_s^-)}{N(D^{*+} \to D^0(f)\pi_s^+) + N(D^{*-} \to \overline{D}^0(f)\pi_s^-)}, \quad (4)$$

where N is the number of reconstructed signal candidates of the given decay and the flavor of the D^0 meson is identified using the charge of the soft pion (π_s^+) in the strong decay $D^{*+} \to D^0\pi_s^+$. The raw asymmetry can be written, up to $\mathcal{O}(10^{-6})$, as

$$A_{\rm raw}(f) \approx A_{CP}(f) + A_{\rm D}(f) + A_{\rm D}(\pi_s^+) + A_{\rm P}(D^{*+}), \quad (5)$$

where $A_{\rm D}(f)$ and $A_{\rm D}(\pi_s^+)$ are the asymmetries in the reconstruction efficiencies of the D^0 final state and of the soft pion, and $A_{\rm P}(D^{*+})$ is the production asymmetry for D^{*+} mesons, arising from the hadronization of charm quarks in pp collisions. The magnitudes of $A_{\rm P}(D^{*+})$ [33] and $A_{\rm D}(\pi_s^+)$ [34] are both about 1%. Equation (5) is only valid when reconstruction efficiencies of the final state f and of the soft pion are independent. Since both K^-K^+ and $\pi^-\pi^+$ final states are self-conjugate, $A_{\rm D}(K^-K^+)$ and $A_{\rm D}(\pi^-\pi^+)$ are identically zero. To a good approximation $A_{\rm D}(\pi_s^+)$ and $A_{\rm P}(D^{*+})$ are independent of the final state f in any given kinematic region, and thus cancel in the difference, giving

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

However, to take into account an imperfect cancellation of detection and production asymmetries due to the difference in the kinematic properties of the two decay modes, the kinematic distributions of D^{*+} mesons decaying to the K^-K^+ final state are reweighted to match those of D^{*+} mesons decaying to the $\pi^-\pi^+$ final state. The weights are calculated for each event using the ratios of the background-subtracted distributions of the D^{*+} momentum, transverse momentum, and azimuthal angle for both final states after the final selection.

The LHCb detector [35,36] is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, designed for the study of particles containing b or c quarks. The two ring-imaging Cherenkov detectors [37] provide particle identification (PID) to distinguish kaons from pions for momenta ranging from a few GeV/c to about 100 GeV/c. The direction of the field polarity (up or down) of the LHCb dipole magnet is reversed periodically, giving data samples of comparable size for both magnet polarities.

To select D^{*+} candidates, events must satisfy hardware and software trigger requirements and a subsequent offline selection. The trigger consists of a hardware stage, based on high transverse momentum signatures in the calorimeter and muon systems, followed by a software stage, which applies a full event reconstruction. When the hardware trigger decision is initiated by calorimeter deposits from D^0 decay products, the event is categorized as "triggered on signal" (TOS). Events that are not TOS, but in which the hardware trigger decision is due to particles in the event other than the D^{*+} decay products, are also accepted; these are referred to as "not triggered on signal" (nTOS). The events associated with these trigger categories present different kinematic properties. To have cancellation of production and detection asymmetries the data are split into TOS and nTOS samples and ΔA_{CP} is measured separately in each sample.

Both the software trigger and subsequent event selection use kinematic variables and decay time to isolate the signal decays from the background. Candidate D^0 mesons must have a decay vertex that is well separated from all primary pp interaction vertices (PVs). They are combined with pion candidates to form D^{*+} candidates. Requirements are placed on the track fit quality, the D^{*+} vertex fit quality, where the vertex formed by D^0 and π_s^+ candidates is constrained to coincide with the associated PV [38], the D^0 transverse momentum and its decay distance, the angle between the D^0 momentum in the laboratory frame and the momentum of the kaon or the pion in the D^0 rest frame, and the smallest impact parameter chi-squared (IP χ^2) of both the D^0 candidate and its decay products with respect to all PVs in the event. The IP χ^2 is defined as the difference between the χ^2 of the PV reconstructed with and without the considered particle. Cross-feed backgrounds from D meson decays with a kaon misidentified as a pion, and vice versa, are reduced using PID requirements. After these selection criteria, the dominant background consists of genuine D^0 candidates paired with unrelated pions originating from the interaction vertex.

Fiducial requirements are imposed to exclude kinematic regions having a large asymmetry in the soft pion reconstruction efficiency (see Figs. 1 and 2 in Ref. [39]). These regions occur because low momentum particles of one charge at large (small) angles in the horizontal plane may be deflected out of the detector acceptance (into the noninstrumented beam pipe region) whereas particles with the other charge are more likely to remain within the

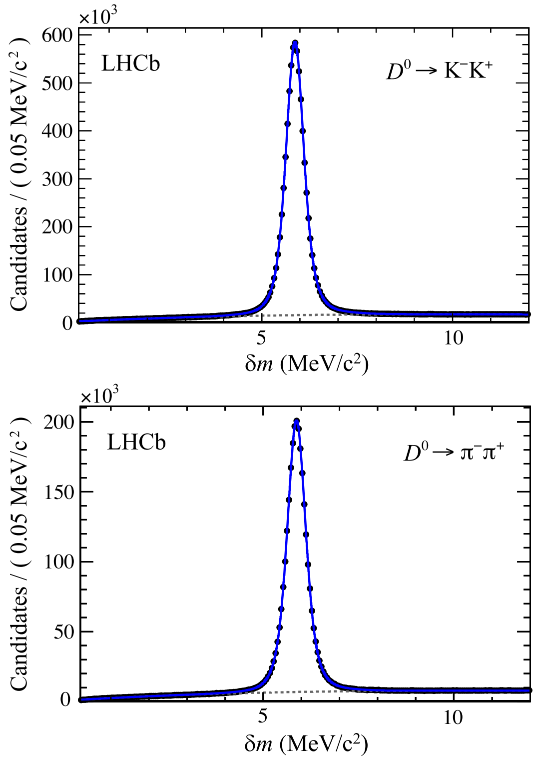

FIG. 1. Fit to the δm spectra, where the D^0 is reconstructed in the final state (left) K^-K^+ and (right) $\pi^-\pi^+$. The dashed line corresponds to the background component in the fit.

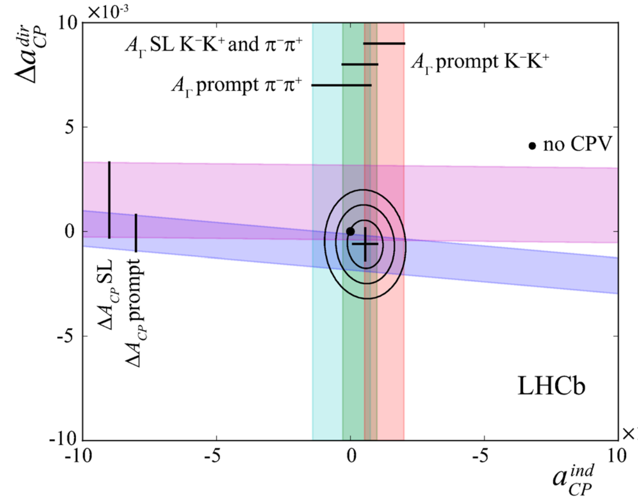

FIG. 2. Contour plot of $\Delta a_{CP}^{\mathrm{dir}}$ versus a_{CP}^{ind}. The point at (0,0) denotes the hypothesis of no CP violation. The solid bands represent the measurements in Refs. [28,45,46] and the one reported in this Letter. The value of y_{CP} is taken from Ref. [47]. The contour lines shows the 68%, 95%, and 99% confidence-level intervals from the combination.

acceptance. About 70% of the selected candidates are retained by these fiducial requirements.

The candidates satisfying the selection criteria are accepted for further analysis if the mass difference $\delta m \equiv m(h^+h^-\pi_s^+) - m(h^+h^-) - m(\pi^+)$ for $h = K$, π is in the range $0.2 - 12.0\ \mathrm{MeV}/c^2$ and the invariant mass of the D^0 candidate is within 2 standard deviations from the central value of the mass resolution model. The standard deviation corresponds to about $8\ \mathrm{MeV}/c^2$ and $10\ \mathrm{MeV}/c^2$ for $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays, respectively.

The data sample includes events with multiple D^{*+} candidates. The majority of these events contain the same reconstructed D^0 meson combined with different soft pion candidates. The fraction of events with multiple candidates in a range of δm corresponding to 4.0–7.5 MeV/c^2 is about 1.2% for TOS events and 2.4% for nTOS events; these fractions are the same for the K^-K^+ and $\pi^-\pi^+$ final states, and for both magnet polarities. The events with multiple candidates are retained and a systematic uncertainty is assessed.

Signal yields and $A_{\mathrm{raw}}(K^-K^+)$ and $A_{\mathrm{raw}}(\pi^-\pi^+)$ are obtained from minimum χ^2 fits to the binned δm distributions of the $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ samples. The data samples are split into eight mutually exclusive subsamples separated by center-of-mass energy, magnet polarity, and trigger category. The signal shape is studied using simulated data and described by the sum of two Gaussian functions with a common mean, and a Johnson S_U function [40]. The background is described by an empirical function of the form $1 - \exp[(\delta m - \delta m_0)/\alpha] + \beta(\delta m/\delta m_0 - 1)$, where δm_0 controls the threshold of the function, and α and β describe its shape. The fits to the eight subsamples and between the K^- K^+ and π^- π^+ final states are independent. Fits to the δm distributions corresponding to the whole data sample are shown in Fig. 1.

The D^{*+} signal yield is 7.7×10^6 for $D^0 \to K^-K^+$ decays, and 2.5×10^6 for $D^0 \to \pi^-\pi^+$ decays. The signal purity is $(88.7 \pm 0.1)\%$ for $D^0 \to K^-K^+$ candidates, and $(87.9 \pm 0.1)\%$ for $D^0 \to \pi^-\pi^+$ candidates, in a range of δm corresponding to $4.0 - 7.5\ \mathrm{MeV}/c^2$. The fits do not distinguish between the signal and the backgrounds that peak in δm. Such backgrounds, which can arise from D^{*+} decays where the correct soft pion is found but the D^0 meson is misreconstructed, are suppressed by the PID requirements to less than 4% of the number of signal events in the case of $D^0 \to K^-K^+$ decays and to a negligible level in the case of $D^0 \to \pi^-\pi^+$ decays. Examples of such backgrounds are $D^{*+} \to D^0(K^-\pi^+\pi^0)\pi_s^+$ and $D^{*+} \to D^0(\pi^-e^+\nu_e)\pi_s^+$ decays. The effect on ΔA_{CP} of residual peaking backgrounds is evaluated as a systematic uncertainty.

The value of ΔA_{CP} is determined in each subsample (see Table 1 in Ref. [39]). Testing the eight independent measurements for mutual consistency gives $\chi^2/\mathrm{ndf} = 6.2/7$, corresponding to a p-value of 0.52. The weighted average of the values corresponding to all subsamples is calculated as $\Delta A_{CP} = (-0.10 \pm 0.08)\%$, where the uncertainty is statistical.

The central value is considerably closer to zero than $\Delta A_{CP} = (-0.82 \pm 0.21)\%$, obtained in our previous analysis where a data sample corresponding to an integrated luminosity of 0.6 fb^{-1} was considered [21]. Several factors contribute to the change, including the increased size of the data sample and changes in the detector calibration and reconstruction software. To estimate the impact of processing data using different reconstruction software, the data used in Ref. [21] are divided into three samples. The first (second) sample contains events that are selected when using the old (new) version of the reconstruction software and are discarded by the new (old) one, while the third sample consists of those events that are selected by both versions. The measured values are $\Delta A_{CP} = (-1.10 \pm 0.46)\%$, $\Delta A_{CP} = (0.13 \pm 0.37)\%$, and $\Delta A_{CP} = (-0.71 \pm 0.26)\%$, respectively. The measurement obtained using the additional data based on an integrated luminosity of 2.4 fb^{-1} corresponds to a value of $\Delta A_{CP} = (-0.06 \pm 0.09)\%$. A comparison of the four independent measurements gives $\chi^2/\mathrm{ndf} = 10.5/3$, equivalent to a p-value of 0.015. Although this value is small, no evidence of incompatibility among the various subsamples has been found. Only statistical uncertainties are considered in this study.

Many sources of systematic uncertainty that may affect the determination of ΔA_{CP} are considered. The possibility of an incorrect description of the signal mass model is investigated by replacing the function in the baseline fit with alternative models that provide equally good descriptions of the data. A value of 0.016% is assigned as systematic uncertainty, corresponding to the largest variation observed using the alternative functions.

To evaluate the systematic uncertainty related to the presence of multiple candidates in an event, ΔA_{CP} is measured in samples where one candidate per event is randomly selected. This procedure is repeated 100 times with a different random selection. The difference of the mean value of these measurements from the nominal result, 0.015%, is taken as systematic uncertainty.

A systematic uncertainty associated with the presence of background peaking in the δm signal distribution and not in the D^0 invariant mass distribution is determined by measuring ΔA_{CP} from fits to the D^0 invariant mass spectra instead of δm. Fits are made for $D^0 \to K^- K^+$ and $D^0 \to \pi^- \pi^+$ candidates within a δm window 4.0–7.5 MeV/c^2. The background due to genuine D^0 mesons paired with unrelated pions originating from the interaction vertex is subtracted by means of analogous fits to the candidates in the δm window 8.0–12.0 MeV/c^2, where the signal is not present. The difference in the ΔA_{CP} value from the baseline, 0.011%, is assigned as a systematic uncertainty. A systematic uncertainty of 0.004% is assigned for uncertainties associated with the weights calculated for the kinematic reweighting procedure.

A systematic uncertainty is associated with the choice of fiducial requirements on the soft pion applied to exclude regions with large raw asymmetries. To evaluate this uncertainty, the baseline results are compared to results obtained when looser fiducial requirements are applied. The resulting samples include events closer to the regions with large raw asymmetries, at the edges of the detector acceptance and around the beam pipe (see Fig. 1 in Ref. [39]). The difference in the ΔA_{CP} values, 0.017%, is taken as the systematic uncertainty.

Although suppressed by the requirement that the D^0 trajectory points back to the primary vertex, D^{*+} mesons produced in the decays of beauty hadrons (secondary charm decays) are still present in the final sample. As the $D^0 \to K^- K^+$ and $D^0 \to \pi^- \pi^+$ decays may have different amounts of this contamination, the value of ΔA_{CP} may be biased because of an incomplete cancellation of the production asymmetries of beauty and charm hadrons. The fractions of secondary charm decays are estimated by performing a fit to the distribution of IP χ^2 of the D^0 with respect to all PVs in the event, and are found to be $(2.8 \pm 0.1)\%$ and $(3.4 \pm 0.1)\%$ for the $D^0 \to K^- K^+$ and $D^0 \to \pi^- \pi^+$ samples, respectively. Using the LHCb measurements of production asymmetries [33,41–43], the corresponding systematic uncertainty is estimated to be 0.004%.

To investigate other sources of systematic uncertainty, numerous robustness checks have been made. The value of ΔA_{CP} is studied as a function of data taking periods and no evidence of any dependence is found. A measurement of ΔA_{CP} using more restrictive PID requirements is performed, and all variations of ΔA_{CP} are found to be compatible within statistical uncertainties. To check for possible reconstruction biases, the stability of ΔA_{CP} is also investigated as a function of many reconstructed quantities, including the number of reconstructed PVs, the D^0 invariant mass, the D^0 transverse momentum, the D^0 flight distance, the D^0 azimuthal angle, the smallest IP χ^2 impact parameter of the D^0 and of the soft pion with respect to all the PVs in the events, the quality of D^{*+} vertex, the transverse momentum of the soft pion, and the quantity $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$, where $\Delta\phi$ and $\Delta\eta$ are the differences between D^0 and soft pion azimuthal angles and pseudorapidities. No evidence of dependence of ΔA_{CP} on any of these variables is found. An additional cross-check concerns the measured value of ΔA_{bkg}, defined as the difference between the background raw asymmetries $A_{\mathrm{bkg}}(K^- K^+)$ and $A_{\mathrm{bkg}}(\pi^- \pi^+)$. A value of $\Delta A_{\mathrm{bkg}} = (-0.46 \pm 0.13)\%$ is obtained from the fits. In the absence of misidentified or misreconstructed backgrounds, one would expect a value consistent with zero. Decays of $D^0 \to K^- K^+$ and $D^0 \to \pi^- \pi^+$ have different sources of backgrounds that do not peak in δm. These include three-body decays of charmed hadrons with misidentified particles in the final state, as well as four-body decays where one particle is not reconstructed. More restrictive PID requirements have been applied to suppress such backgrounds, and the region of the fits has been extended up to 16 MeV/c^2 to improve the precision. A value of $\Delta A_{\mathrm{bkg}} = (-0.22 \pm 0.13)\%$ is found. The corresponding ΔA_{CP} value is $(-0.12 \pm 0.09)\%$, consistent with the baseline result when the overlap of the two samples is taken into account. Hence, the measurement of ΔA_{CP} is robust and is not influenced by the background asymmetry. All contributions are summed in quadrature to give a total systematic uncertainty of 0.03%.

To interpret the ΔA_{CP} result in terms of direct and indirect CP violation, the reconstructed decay time averages, for $D^0 \to K^- K^+$ and $D^0 \to \pi^- \pi^+$ samples, are measured. The difference and the average of the mean decay times relative to the D^0 lifetime are computed, giving $\Delta\langle t\rangle/\tau(D^0) = 0.1153 \pm 0.0007(\mathrm{stat}) \pm 0.0018(\mathrm{syst})$ and $\overline{\langle t\rangle}/\tau(D^0) = 2.0949 \pm 0.0004(\mathrm{stat}) \pm 0.0159(\mathrm{syst})$. The systematic uncertainties are due to the uncertainty on the world average of the D^0 lifetime [44], decay-time resolution model, and the presence of secondary D^0 mesons from b -hadron decays. Given the dependence of ΔA_{CP} on the direct and indirect CP asymmetries [Eq. (3)] and the measured value of $\Delta\langle t\rangle/\tau$, the contribution from indirect CP violation is suppressed and ΔA_{CP} is primarily sensitive to direct CP violation. Assuming that indirect CP violation is independent of the D^0 final state, and combining the measurement reported in this Letter with those reported in Ref. [28] and with the LHCb measurements of indirect CP asymmetries ($A_\Gamma \simeq -a_{CP}^{\mathrm{ind}}$) [45,46] and y_{CP} [47], the values of the direct and indirect CP asymmetries are found to be $a_{CP}^{\mathrm{ind}} = (0.058 \pm 0.044)\%$ and $\Delta a_{CP}^{\mathrm{dir}} = (-0.061 \pm 0.076)\%$. Results are summarized in the ($\Delta a_{CP}^{\mathrm{dir}}$, a_{CP}^{ind}) plane shown in Fig. 2. The result is consistent with the hypothesis of CP symmetry with a p-value of 0.32.

In summary, the difference of time-integrated CP asymmetries between $D^0 \to K^- K^+$ and $D^0 \to \pi^- \pi^+$ decays is measured using pp collision data corresponding to an integrated luminosity of 3.0 fb^{-1}. The final result is

$$\Delta A_{CP} = [-0.10 \pm 0.08(\mathrm{stat}) \pm 0.03(\mathrm{syst})]\%,$$

which supersedes the previous result obtained using the same decay channels based on an integrated luminosity of 0.6 fb^{-1} [21]. This is the most precise measurement of a time-integrated CP asymmetry in the charm sector from a single experiment.

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