PROCEEDINGS OF SCIENCE

Direct CPV in charm hadrons at LHCb

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LHCb has collected the world's largest sample of charmed hadrons. This sample is used to measure the time-integrated *CP* asymmetry in the Cabibbo-suppressed decay $D^0 \to K^-K^+$, $\mathcal{A}_{CP}(K^-K^+)$. The direct *CP* asymmetries in $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays, $a^d_{K^-K^+}$ and $a^d_{\pi^-\pi^+}$, are derived by combining $\mathcal{A}_{CP}(K^-K^+)$ with the time-integrated *CP* asymmetry difference, $\Delta A_{CP} = \mathcal{A}_{CP}(K^-K^+) - \mathcal{A}_{CP}(\pi^-\pi^+)$, and accounting for time-dependent effects. The result consists in the first evidence for direct *CP* violation in a specific D^0 decay.

41st International Conference on High Energy physics - ICHEP2022
6-13 July, 2022
Bologna, Italy

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1. Introduction

One of the three necessary conditions for baryon asymmetry in the Universe is the noninvariance of the fundamental interactions under the simultaneous transformation of the charge conjugation (C) and parity (P) operators, referred to as *CP* violation [1]. In the Standard Model (SM) of particle physics, the Cabibbo-Kobayashi-Maskawa [2] formalism describes *CP* violation through an irreducible phase in the quark-mixing matrix. The recent observation of *CP* violation in the charm quark sector [3] 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 [4–8]. The discovery measurement of *CP* violation in neutral charm meson decays used the difference between two time-integrated *CP*-violating asymmetries of Cabibbo-suppressed D^0 decays, $\Delta A_{CP} = \mathcal{A}_{CP}(K^-K^+) - \mathcal{A}_{CP}(\pi^-\pi^+)$, found to be $\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$ [3]. The time-integrated *CP* asymmetry for $f = K^-K^+$ and $f = \pi^-\pi^+$ can be written as[1]

$$\mathcal{A}_{CP}(f) \approx a^d_f + \frac{\langle t\rangle_f}{\tau_D} \cdot \Delta Y_f, \tag{1}$$

where a^d_f is the *CP* violation in the decay amplitude, ΔY_f is related to mixing-induced *CP* violation [9], $\langle t\rangle_f$ is the mean decay time of the D^0 mesons in the experimental data sample, and τ_D is the D^0 lifetime.

This document presents a measurement of the time-integrated *CP* asymmetry in $D^0 \to K^-K^+$ decays. Combining the measurements of $\mathcal{A}_{CP}(K^-K^+)$, ΔA_{CP} and ΔY it is possible to quantify the amount of *CP* violation in the decay amplitude for $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays and provide important insight in the breaking of U-spin symmetry.

2. Direct *CP* asymmetries in $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays

The measurement of $\mathcal{A}_{CP}(K^-K^+)$ is performed using proton-proton (pp) collision data collected with the LHCb detector during Run 2 ($\sqrt{s}$ =13 TeV, 5.7 fb^{-1}) [10]. Previous attempts are reported in Refs. [11, 12]. The neutral charm mesons considered are produced in the strong-interaction decays $D^{*+} \to D^0\pi^+$. where the charge of the accompanying "tagging" pion (π^+_{tag}) is used to identify the flavour of the D^0 meson at production[2]. The measured asymmetry, $A(K^-K^+)$, is defined as

$$A(K^-K^+) \equiv \frac{N\left(D^{*+} \to D^0\pi^+\right) - N\left(D^{*-} \to \overline{D}^0\pi^-\right)}{N\left(D^{*+} \to D^0\pi^+\right) + N\left(D^{*-} \to \overline{D}^0\pi^-\right)}, \tag{2}$$

where N denotes the observed signal yield in the data, and the D^0 meson decays into K^-K^+. This asymmetry can be approximated[3] as

$$A(K^-K^+) \approx \mathcal{A}_{CP}(K^-K^+) + A_{\text{P}}(D^{*+}) + A_{\text{D}}(\pi^+_{\text{tag}}), \tag{3}$$

[1]The equation is valid up to first order in the D^0 mixing parameters [9].

[2]Throughout this document, the inclusion of charge conjugation decay modes is implied, except in the definition of the asymmetries, and D^{*+} and ϕ indicate the $D^*(2010)^+$ and $\phi(1020)$ mesons, respectively.

[3]The equation is valid up to corrections of $O(10^{-6})$ assuming individual terms of $O(10^{-2})$ or less [10].

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where $A_{\rm P}(D^{*+})$ is the production asymmetry arising from the different hadronization probabilities between D^{*+} and D^{*-} mesons in pp collisions, and $A_{\rm D}(\pi^+_{\rm tag})$ is the instrumental asymmetry due to different reconstruction efficiencies of positive and negative pions. These nuisance asymmetries are removed exploiting Cabibbo-favoured decays, where *CP* violation is assumed to be negligible. Two calibration procedures, denoted as C_{D^+} and $\mathrm{C}_{D_s^+}$, are used. Namely, the C_{D^+} procedure uses $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$, $D^+ \to K^-\pi^+\pi^+$ and $D^+ \to \overline{K}^0(\to \pi^-\pi^+)\pi^+$ decays; while the $\mathrm{C}_{D_s^+}$ procedure uses $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$, $D_s^+ \to \phi(\to K^-K^+)\pi^+$ and $D_s^+ \to \overline{K}^0(\to \pi^-\pi^+)K^+$ decays. In analogy to Eq. 3, the corresponding measured asymmetries in the calibration decays are decomposed as

$$\begin{aligned}
A(K^-\pi^+) &\approx A_{\rm P}(D^{*+}) - A_{\rm D}(K^+) + A_{\rm D}(\pi^+) + A_{\rm D}(\pi^+_{\rm tag}),\\
A(K^-\pi^+\pi^+) &\approx A_{\rm P}(D^+) - A_{\rm D}(K^+) + A_{\rm D}(\pi^+) + A_{\rm D}(\pi^+),\\
A(\overline{K}^0\pi^+) &\approx A_{\rm P}(D^+) + A(\overline{K}^0) + A_{\rm D}(\pi^+),\\
A(\phi\pi^+) &\approx A_{\rm P}(D_s^+) + A_{\rm D}(\pi^+),\\
A(\overline{K}^0K^+) &\approx A_{\rm P}(D_s^+) + A(\overline{K}^0) + A_{\rm D}(K^+).
\end{aligned} \tag{4}$$

In the equations above, $A(\overline{K}^0)$ is the asymmetry arising from the combined effect of the different interaction rates of $\overline{K}^0$ and K^0 with the detector material and the *CP* violation and mixing in the neutral kaon system. The time-integrated *CP* asymmetry, $\mathcal{A}_{CP}(K^-K^+)$, is obtained for each of the two calibration procedures individually, by combining the measured asymmetries as follows

$$\begin{aligned}
\mathrm{C}_{D^+} : \mathcal{A}_{CP}(K^-K^+) &= A(K^-K^+) - A(K^-\pi^+) + A(K^-\pi^+\pi^+) - A(\overline{K}^0\pi^+) + A(\overline{K}^0),\\
\mathrm{C}_{D_s^+} : \mathcal{A}_{CP}(K^-K^+) &= A(K^-K^+) - A(K^-\pi^+) + A(\phi\pi^+) - A(\overline{K}^0K^+) + A(\overline{K}^0).
\end{aligned} \tag{5}$$

Given that the individual nuisance asymmetries depend on the kinematics of the corresponding particles, 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. This ensures a proper cancellation in Eq. 5.

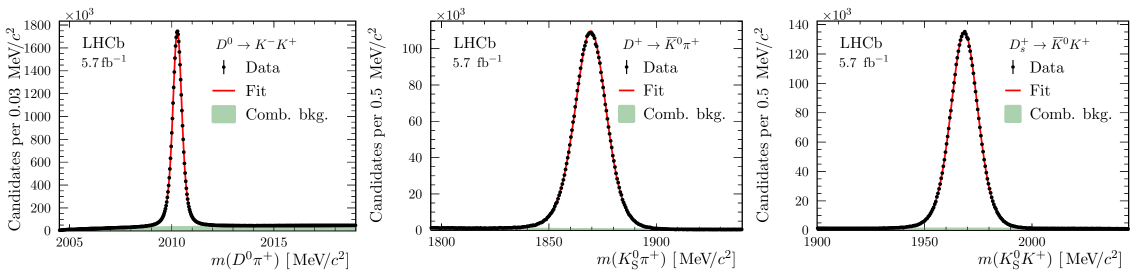

Figure 1: Distributions of the invariant mass for the weighted charm-meson candidates, for the decays $D^{*+} \to D^0\,(\to K^-K^+)\pi^+$, $D^+ \to \overline{K}^0\pi^+$, and $D_s^+ \to \overline{K}^0K^+$ from the (left and center) C_{D^+} and (right) $\mathrm{C}_{D_s^+}$ calibration procedure. The results of the fits to these distributions are also shown.

Figure 1 presents the distribution of the $D^0 \to K^-K^+$, $D^+ \to \overline{K}^0\pi^+$, and $D_s^+ \to \overline{K}^0K^+$ decays invariant masses and the results of the fits for the extraction of the measured asymmetries. The signal yields, together with the statistical reduction factor[4] are reported in Table 1. It is possible

[4]The reduction factor is defined as $(\Sigma_{i=1}^K w_i)^2/(N \cdot \Sigma_{i=1}^K w_i^2)$, where K is the total number of candidates and w_i includes background-subtraction and kinematic weights. These 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.

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Decay mode	Signal yield [10^6]		Red. factor	
	C_{D^+}	$C_{D_s^+}$	C_{D^+}	$C_{D_s^+}$
$D^0 \to K^- K^+$	37	37	0.72	0.76
$D^0 \to K^- \pi^+$	58	56	0.33	0.76
$D^+ \to K^- \pi^+ \pi^+$	188	–	0.23	–
$D^+ \to \overline{K}^0 \pi^+$	6	–	0.25	–
$D_s^+ \to \phi \pi^+$	–	43	–	0.55
$D_s^+ \to \overline{K}^0 K^+$	–	5	–	0.70

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.

to notice that the precision of the measurements is dominated by the modes with a $\overline{K}^0$ in the final state, due to the low reconstruction efficiency of the neutral kaon combined with the impact of the weighting procedure.

The contribution from the neutral kaon asymmetry, $A(\overline{K}^0)$, is estimated by combining the LHCb material map from simulation with measured *CP*-violation and cross-section parameters of the neutral kaon system following the procedure described in Ref. [12]. The correction for the C_{D^+} and $C_{D_s^+}$ calibration procedure corresponds to $(-5.1 \pm 0.6) \times 10^{-4}$ and $(-8.5 \pm 1.3) \times 10^{-4}$, respectively. The uncertainties are evaluated with a model-independent strategy based on data and result to be one of the main contribution to the systematic uncertainty, as shown in Table 2. Additional sources of systematic uncertainties are considered. They account for the inaccuracy of the fit models used to extract the signal yields, the presence of background components peaking in $m(D^0\pi)$ and not in $m(K^-K^+)$ in the $D^0 \to K^-K^+$ samples, the impact of different levels of contamination of D mesons from b-hadron decays among the various decay samples, the effect of residual disagreements between the kinematic distributions leading to an imperfect cancellation of the nuisance asymmetries, and the repercussion of the presence of $D_s^+ \to K^-K^+\pi^+$ decay modes other than $D_s^+ \to \phi\pi^+$ breaking the symmetry between the K^- and K^+ meson kinematic distributions in the $C_{D_s^+}$ procedure. The total systematic uncertainties are given by 1.6×10^{-4} and 2.0×10^{-4} for the C_{D^+} and $C_{D_s^+}$ procedures, respectively.

The resulting values for $\mathcal{A}_{CP}(K^-K^+)$ for both calibration procedures are

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

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

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

consistent with the previous results [11, 12].

A combination of all the time-integrated *CP* asymmetries measured by the LHCb collaboration to date is performed, under the hypothesis that $\Delta Y_{K^-K^+} = \Delta Y_{\pi^-\pi^+} = \Delta Y$, as the final-state dependent

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

Table 2: Systematic uncertainties on $\mathcal{A}_{CP}(K^-K^+)$ 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.

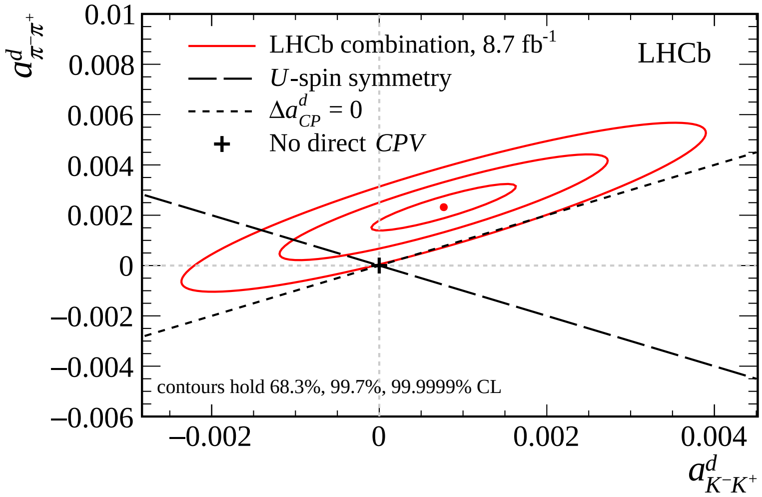

Figure 2: Central values and two-dimensional confidence regions in the $(a^d_{K^-K^+}, a^d_{\pi^-\pi^+})$ plane for the combination of the LHCb currently public results obtained with the dataset taken between 2010 and 2018.

contributions are estimated to be of the order of 10^{-5} [9]. The combination includes the previous LHCb measurements of $\mathcal{A}_{CP}(K^-K^+)$ [11, 12] and ΔA_{CP} [3] as well as the current LHCb average of ΔY [9], the world average of the D^0 lifetime [13] and the values of reconstructed mean decay times for the $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays in the various analysis. The combination leads to

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

where the uncertainties include systematic and statistical contributions with a correlation coefficient of 0.88. Figure 2 shows the central values and the confidence regions in the $(a^d_{K^-K^+}, a^d_{\pi^-\pi^+})$ plane for this combination. The direct *CP* asymmetries deviate from zero by 1.4 and 3.8 standard deviations for $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays, respectively. This is the first evidence for direct *CP* violation in the $D^0 \to \pi^-\pi^+$ decay. *U*-spin symmetry implies $a^d_{K^-K^+} + a^d_{\pi^-\pi^+} = 0$. A value of

$a^d_{K^-K^+} + a^d_{\pi^-\pi^+} = (30.8 \pm 11.4) \times 10^{-4}$ has been found, corresponding to a departure from U-spin symmetry of 2.7 standard deviations.

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