# Measurement of $\Delta A_{CP}$ in $D^0 \to h^+h^-$ mesons decay at LHCb

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**Summary.** — A search for CP violation with the observable $\Delta A_{CP}$ in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ singly-Cabibbo-suppressed decays is reported, using data collected by LHCb during 2024 for a total integrated luminosity of 7 fb$^{-1}$. The flavour of the charm meson is inferred from the charge of the pion in $D^{*+}(2010) \to D^0\pi^+$ decays where the $D^{*+}(2010)$ is directly produced in proton-proton interactions. This analysis will improve the uncertainty of $\Delta A_{CP}$ of a factor 2 with respect to the previous measurement performed by LHCb with data collected during Run 1 (2011-2012) and Run 2 (2015-2018).

## 1. – Introduction

One of the three essential conditions required to explain the baryon asymmetry of the Universe is the violation of the combined charge conjugation (C) and parity (P) symmetries—known as CP violation. In the Standard Model (SM) CP violation arises from an irreducible complex phase in the quark mixing matrix, the Cabibbo-Kobayashi-Masakawa (CKM) matrix. Although CP violation has been observed over the past decades in both B and K mesons, only recently has been measured in $D^0$ mesons decay at LHCb [1] with data collected during Run 1 and 2 of LHCb. The analysis focused on measuring the observable $\Delta A_{CP}$ defined as $\Delta A_{CP} = A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)$ where $A_{CP}(D^0 \to f)$ is the CP asymmetry defined as

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

with $\Gamma(D^0 \to f)$ the width of the $D^0$ meson.

During Long Shutdown 2 (LS2), LHCb has completed Upgrade 1 [2], a major upgrade of the detector to be able to record data at an higher instantaneous luminosity. Thanks to this upgrade the efficiency on hadronic final states has greatly improved and in 2024 a total recorded luminosity of $\mathcal{L} = 7$ fb$^{-1}$ in proton-proton collision at a centre-of-mass energy of $\sqrt{s} = 13.6$ TeV has been collected by LHCb. This analysis goal is to measure the observable $\Delta A_{CP}$ with data collected during 2024.

To this aim, decays of $D^0$ mesons into the charge conjugate final states $K^+K^-$ or $\pi^+\pi^-$ have been analysed. The flavour of the $D^0$ meson is inferred from the charge of the *slow* pion $\pi_s$ in the $D^{*+}(2010) \to D^0\pi_s^+$ decay. The $D^{*+}(2010)$ meson will be referred throughout the document as $D^{*+}$. The $D^{*+}$ mesons are produced directly in proton-proton collisions and are referred to as *prompt tag*. For each of the final states, the raw asymmetry $A_{\text{raw}}$ is extracted from fit to data. $A_{\text{raw}}$ is defined as

$$A_{\text{raw}}(f) = \frac{N_{D^{*+}}(f) - N_{D^{*-}}(f)}{N_{D^{*+}}(f) + N_{D^{*-}}(f)}, \tag{2}$$

where $N_{D^{*\pm}}$ is the number of $D^{*\pm}$ mesons obtained from the fit to data. The raw asymmetry can be expanded as

$$A_{\text{raw}}(f) \simeq A_{CP}(D^0 \to f) + A_D(\pi_s) + A_P(D^{*+}), \tag{3}$$

where $A_D(\pi_s)$ is the detection asymmetry of the soft pion and $A_P(D^{*+})$ is the production asymmetry of the $D^{*+}$ meson. The difference in raw asymmetries between the two decay channel allows to cancel these nuisance asymmetries. This difference can be written as

$$A_{\text{raw}}(K^+K^-) - A_{\text{raw}}(\pi^+\pi^-) \simeq A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-) = \Delta A_{CP}. \tag{4}$$

Since the nuisance asymmetries only depends on the kinematics of the $D^{*+}$ and $\pi_s^+$, kinematic weights are applied to the $D^0 \to K^+K^-$ sample to ensure that the kinematic distributions match between the two decay channels before extracting the raw asymmetries from fits to data. The data are first selected from the LHCb trigger and then further filtered offline with a cut based approach. The analysis has been performed independently in sub-samples to cross-check if effects due to magnet polarity or imperfections in the alignment or data taking bias the measurement. Furthermore raw asymmetries have been shifted by a random value, differently for $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$, to blind the analysis.

## 2. – Weighting procedure

Kinematic weights are computed with ratio of three dimensional histograms between the $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$ and applied to the $D^0 \to K^+K^-$ sample. The histograms are normalized background-subtracted distributions of $|\vec{p}|$, $p_T$, $\phi$ of the $D^0$ mesons, where $\phi$ is the azimuthal angle in the reference system of LHCb. The signal weights have been obtained with the sPlot technique [3] from fits to the integrated invariant mass with the model that will be discussed in the next section. The resulting distributions after applying the kinematic weights are shown in fig. 1, showing perfect agreement between the two decay channels. Computing weights from the $D^0$ distributions allows to also match the distributions of $D^{*+}$ and of $\pi_s^+$.

## 3. – Measurement of raw asymmetries

To extract the $A_{\text{raw}}$ a simultaneous extended binned $\chi^2$ fit is performed to $m(D^0\pi)$ for both charges of the $D^{*+}$. The observable $m(D^0\pi)$ is defined as

$$m(D^0\pi) \equiv \left( m_{D^0}^2 + m_\pi^2 + 2\sqrt{m_{D^0}^2 + |\vec{p}_{D^0}|^2} \cdot \sqrt{m_\pi^2 + |\vec{p}_\pi|^2} - 2\vec{p}_{D^0} \cdot \vec{p}_\pi \right)^{\frac{1}{2}}, \tag{5}$$

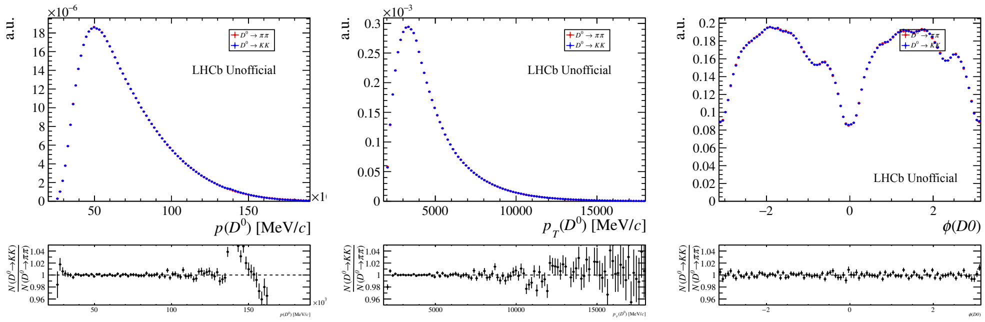


Fig. 1. – Comparison of distributions of $|\vec{p}|(D^0)$ (left), $p_T(D^0)$ (middle) and $\phi(D^0)$ (right) for $D^0 \to K^+K^-$ decays (blue) and $D^0 \to \pi^+\pi^-$ (red) for a sub-sample of the full analysis. The distributions present perfect agreement between the two channels.

where $m_{D^0}$ and $m_\pi$ have been fixed to the PDG values [4], i.e. $m_{D^0} = 1864.84$ MeV/$c^2$ and $m_\pi = 139.57$ MeV/$c^2$. This combination does not rely on any hypothesis on the mass of the daughter particles of $D^0$.

The signal component is parametrised for $D^{*+}$ $(+)$ and $D^{*-}$ $(-)$ decays for $D^0 \to K^+K^-$ sample with

$$(6)\quad \begin{aligned} \mathcal{S}^{\pm}(m) = \Theta(m - m_{\text{trsh.}}) \cdot \Big[ & f_1 \cdot (m - m_{\text{trsh.}})^{1+\rho} \cdot \mathcal{J}(m; \mu^{\pm}_{J1}, \sigma^{\pm}_{J1}, \delta_{J1}, \gamma_{J1}) \\ & + f_2 \cdot (m - m_{\text{trsh.}})^{1+\rho} \cdot \mathcal{J}(m; \mu^{\pm}_{J2}, \sigma^{\pm}_{J2}, \delta_{J2}, \gamma_{J2}) \\ & + f_3 \cdot G(m; \mu^{\pm}_2, \sigma^{\pm}_2) \\ & + (1 - f_1 - f_2 - f_3) \cdot G(m; \mu^{\pm}_3, \sigma^{\pm}_3) \Big], \end{aligned}$$

where $\Theta$ represents the Heaviside function, $m_{\text{trsh.}} = 2004.41$ Mev/$c^2$ is fixed and is the minimum possible value of $m(D^0\pi)$, $G$ is a Gaussian function and $\mathcal{J}$ is a Johnson function [5] defined as

$$(7)\quad \mathcal{J}(m; \mu_J, \sigma_J, \delta_J, \gamma_J) = \frac{e^{-\frac{1}{2}\left[\gamma_J + \delta_J \sinh^{-1}\left(\frac{m-\mu_J}{\sigma_J}\right)\right]^2}}{\sqrt{1 + \left(\frac{m-\mu_J}{\sigma_J}\right)^2}}.$$

The model for $D^0 \to \pi^+\pi^-$, and a sub-sample of $D^0 \to K^+K^-$ with smaller statistics, is similar but with a Gaussian component less. Parameters with superscript $\pm$ are independent between the two charges. In particular, $\sigma^-_i$ are defined as $\sigma^-_i = \sigma^+_i \cdot (1 + a_\sigma)$, where $a_\sigma$ is a parameter shared between all component of the signal, i.e. the Johnson functions and the Gaussian functions. On the parameters of the shape of the tails of the Johnson functions, $\delta_{Ji}, \gamma_{Ji}$, a Guassian constraint is imposed with central value and resolution obtained from the simulation.

To parametrise the background the following empirical function is used

$$(8)\quad \begin{aligned} \mathcal{B}^{\pm}(m) = \Theta(m - m_{\text{trsh.}}) \cdot \Big[ & (m - m_{\text{trsh.}})^{b^{\pm}_1} e^{-c^{\pm}_1 (m - m_{\text{trsh.}})} \\ & + (m - m_{\text{trsh.}})^{b^{\pm}_2} e^{-c^{\pm}_2 (m - m_{\text{trsh.}})} \Big], \end{aligned}$$

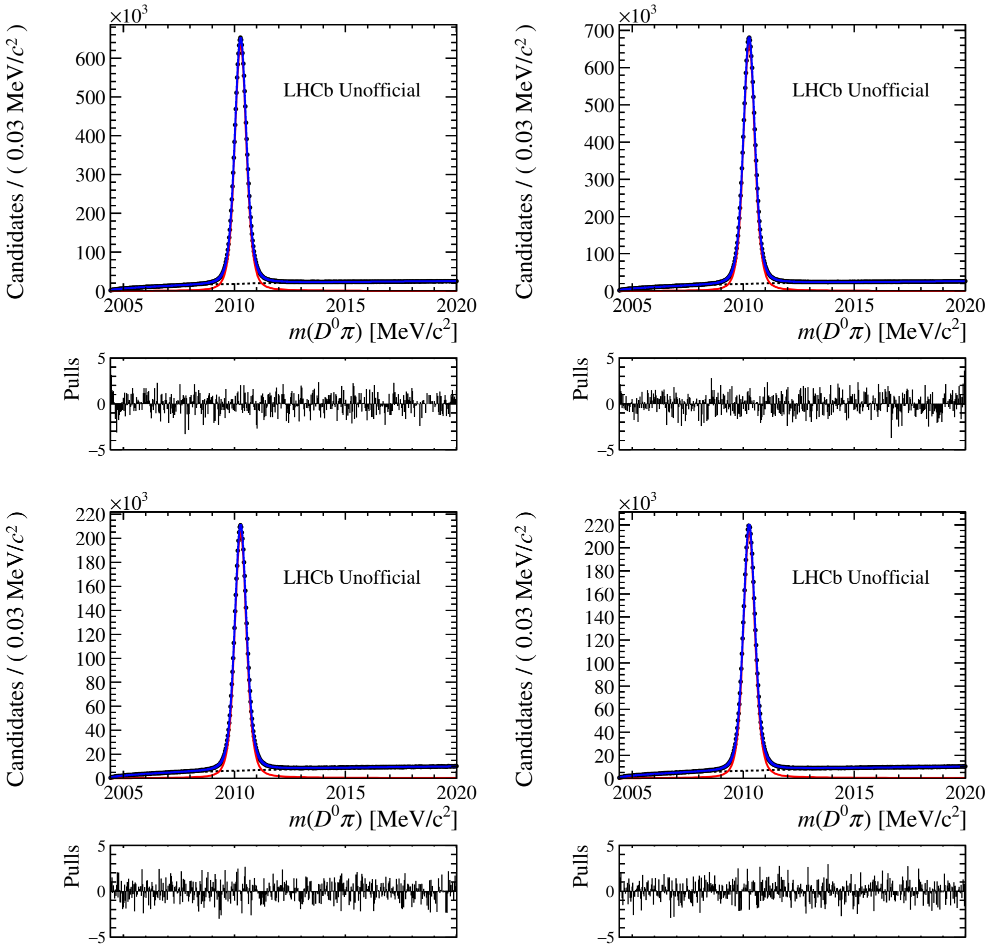


Fig. 2. – Examples of fit to $D^0 \to K^+K^-$ (top) and $D^0 \to \pi^+\pi^-$ (bottom) sub-samples, for $D^{*+}$ (left) and $D^{*-}$ (right). On the plot are represented data points (black dots), the signal model (red), the background model (black dashed line) and the total model (blue).

where $b_i^{\pm}$ and $c_i^{\pm}$ are free parameters in the fit. In fig. 2 examples of fit to sub-samples are reported.

## 4. – Results

From the simultaneous fit to the data raw asymmetries are extracted and the $\Delta A_{CP}$ observable has been measured independently in each sub-sample. A graphical representation of the results is reported in fig 3. To check whether the results are independent from data taking period a $\chi^2$ test is performed before and after the weighting procedure and their p-values are 26.0% for the former and 31.8% for the latter. These results are compatible with the hypothesis of no dependence on the data-taking period. Since sub-samples are statistically independent from each other, they are combined with a weighted

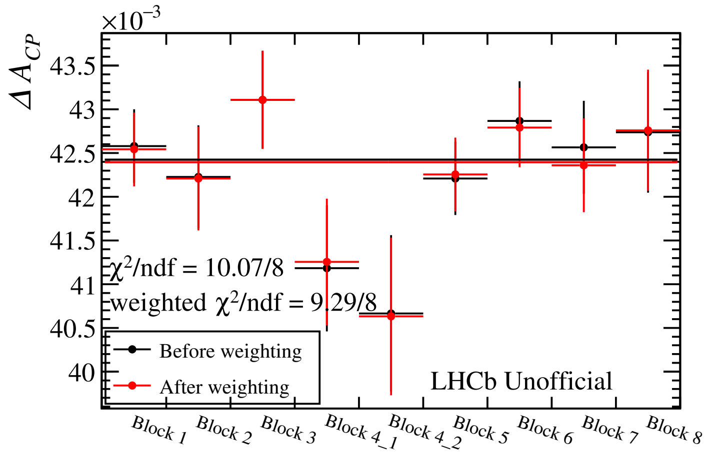


Fig. 3. – Comparison of the analysis results divided in sub-samples corresponding to different data taking periods, before (black) and after (red) applying kinematic weights. Fits (lines) have been performed to check whether the results depend on the data-taking period.

mean resulting in

$$\Delta A_{CP} = (4.240 \pm 0.018)\%, \quad (9)$$

where the quoted uncertainty is only statistical and the central value has been shifted by a random value.

## 5. – Cross-checks

To ensure that $\Delta A_{CP}$ does not depend on any kinematic or topological quantity, a differential measure is performed as function of these variables. For each differential measure, a $\chi^2$ test for the hypothesis of no dependence on such variable is done, and the corresponding p-value is computed. These p-values, from each sub-sample and from each variable are collected together and presented in fig. 4. A $\chi^2$ is performed on this distribution with the hypothesis of a uniform distribution, and its associated p-value is 53% confirming that no dependence of $\Delta A_{CP}$ on these variables have been observed.

## 6. – Preliminary systematic studies

A preliminary estimation of the systematic uncertainty due to the weighting procedure has been performed. To do so, 500 pseudo-experiment are performed for each subsample, where pseudo-data have been generated with weights extracted from a Gaussian, where the central value is the value of the real data weight and the standard deviation is the error associated to the weight. For each pseudo-experiment the fits are performed with the same model of real data, and $\Delta A_{CP}$ is measured. The average $\mu_i$ and the standard deviation $\sigma_i$ of $\Delta A_{CP}$ distributions computed in such way are combined as

$$\sigma_i^{\text{syst}} = \sqrt{\mu_i^2 + \sigma_i^2} \quad (10)$$

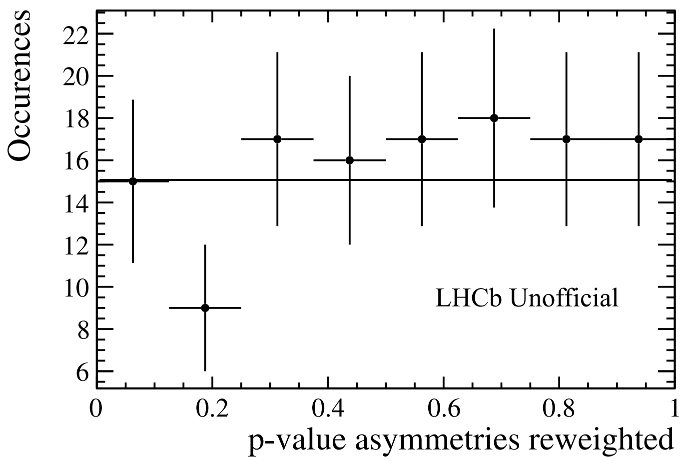


Fig. 4. – Distribution of p-values collected from $\chi^2$ tests on the hypothesis of no dependence of $\Delta A_{CP}$ on various kinematic and topological variables.

and are associated as systematic uncertainty for each sub-sample. These are then combined across each sub-sample and the systematic uncertainty results to be

$$\sigma^{w}_{\text{syst}} = 0.29 \times 10^{-4}, \tag{11}$$

which is a order of magnitude smaller with respect to the statistical uncertainty. Further sources of systematic uncertainty will be considered in the future such as uncertainty due to the fit model, due to the contamination of $B$ produced $D^{*+}$ and due to mis-identified final states.

## 7. – Conclusions

$\Delta A_{CP}$ has been measured with data collected at LHCb during 2024 with prompt $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays. The resulting value is $\Delta A_{CP} = (4.240 \pm 0.018)\%$, where the quoted uncertainty is statistical. The statistical uncertainty has been reduced by a factor 2 with respect to the previous measurement [1] of LHCb even if the integrated luminosity is comparable. This highlights the improved efficiency of the LHCb detector after Upgrade 1. A preliminary estimation of systematic uncertainties has reported that such uncertainties are an order of magnitude smaller with respect to statical ones but further studies on systematic uncertainties will be performed in the next future.

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