Measurement of CP asymmetries in $D^0 \to hh$ decays

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The latest measurements of the individual time-integrated CP asymmetry in the Cabibbo-suppressed decays $D^0 \to hh$ decays are presented. The results are based on pp collision data, corresponding to an integrated luminosity of $3\,\text{fb}^{-1}$, collected with the LHCb detector at centre-of-mass energies of 7 and 8 TeV. A combination of the asymmetries using both prompt and secondary charm decays is presented

$$A_{CP}(K^-K^+) = (0.04 \pm 0.12\,(\text{stat}) \pm 0.10\,(\text{syst}))\%,$$
$$A_{CP}(\pi^-\pi^+) = (0.07 \pm 0.14\,(\text{stat}) \pm 0.11\,(\text{syst}))\%.$$

These are the most precise measurements from a single experiment. The result for $A_{CP}(K^-K^+)$ is the most precise determination of a time-integrated CP asymmetry in the charm sector to date, and neither measurement shows evidence of CP asymmetry.

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Charge-parity (*CP*) violation in weak decays is described by the Standard Model (SM) and is governed by a single complex phase in the Cabibbo-Kobayashi-Maskawa (CKM) matrix. The charmed *D* meson system is suitable for probing the *CP* violation in the up-type quark sector. Recent studies of *CP* violation in weak decays of *D* mesons have not found evidence of *CP* violation, while the phenomenon is well established in decays of *K*- and *B*-meson systems [1–5].

To distinguish the two *CP*-conjugate decays, the flavour of the D^0 at production must be known. At LHCb, two different techniques are employed. The flavour of the D^0 can be tagged by the charge of the soft pion, π_s^+, in the strong decay $D^{*+} \to D^0\pi_s^+$ for prompt D^0 decays [6], or by the charge of the muon in the semileptonic decay $\bar{B} \to D^0\mu^-\bar{\nu}_\mu X$ for secondary charm decays [7]. The time-integrated *CP* asymmetry in the decay rates of the singly Cabibbo-supressed process $D^0 \to K^-K^+$

$$A_{CP}(D^0 \to K^-K^+) \equiv \frac{\Gamma(D^0 \to K^-K^+) - \Gamma(\bar{D}^0 \to K^-K^+)}{\Gamma(D^0 \to K^-K^+) + \Gamma(\bar{D}^0 \to K^-K^+)}, \tag{1}$$

was measured recently at LHCb [8]. This observable cannot be accessed directly due to the presence of production asymmetry of the D^0 and $\bar{D}^0$ mesons at *pp* collider, and due to the presence of detection asymmetries. The latter can origin from an asymmetric interaction of the charged particles with the material of the detector. One example for this is the different cross-section for interaction with matter of K^+ and K^-. Any asymmetry in the detector e.g. some inefficient regions, faulty electronics, etc could also contribute to the detection asymmetry. The effect of such asymmetries can cancel to first order with the regular swap of the magnetic field of the dipole magnet at LHCb.

The measured raw asymmetry in the number of background-subtracted number of signal decays

$$A_{\text{raw}} \equiv \frac{N(D^0 \to K^-K^+) - N(\bar{D}^0 \to K^-K^+)}{N(D^0 \to K^-K^+) + N(\bar{D}^0 \to K^-K^+)}, \tag{2}$$

is related to the observable of interest, $A_{CP}(K^-K^+)$, via

$$A_{CP}(D^0 \to K^-K^+) \approx A_{\text{raw}}(D^0 \to K^-K^+) - A_P(D^{*+}) - A_D(\pi_s^+). \tag{3}$$

This approximation is valid only for small asymmetries, this is why a particular care has been taken to exclude regions with large asymmetries, related to detector acceptance effects [6, 8].

To cancel the effect of the nuisance detection and production asymmetry, a set of Cabibbo-favoured decays, $D^0 \to K^-\pi^+, D^+ \to K^-\pi^+\pi^+, D^+ \to \bar{K}^0\pi^+$, in which no *CP* violation is expected, is used. For example, by exploiting the prompt $D^0 \to K^-\pi^+$ channel, one can cancel the D^{*+} production asymmetry, and the soft pion detection asymmetry. However, a new detection asymmetry is present due to the asymmetric final state $K^-\pi^+$. The effect of this asymmetry is mitigated using the other two calibration channels leading to

$$\begin{aligned} A_{CP}(D^0 \to K^-K^+) =\ & A_{\text{raw}}(D^0 \to K^-K^+) - A_{\text{raw}}(D^0 \to K^-\pi^+) \\ & + A_{\text{raw}}(D^+ \to K^-\pi^+\pi^+) - A_{\text{raw}}(D^+ \to \bar{K}^0\pi^+) \\ & + A_D(\bar{K}^0). \end{aligned} \tag{4}$$

$A_{CP}(K^-K^+)$ now only depends on measurable raw asymmetries and the calculable $\bar{K}^0$ detection asymmetry [9]. The method to determine $A_{CP}(K^-K^+)$ has been first used in Ref. [7].

Table 1: Signal yields of the four channels before and after the kinematic weighting. In the case of the weighted samples, effective yields are given.

Channel	Before weighting	After weighting
$D^0 \to K^- K^+$	5.56 M	1.63 M
$D^0 \to K^- \pi^+$	32.4 M	2.61 M
$D^+ \to K^- \pi^+ \pi^+$	37.5 M	13.67 M
$D^+ \to \bar{K}^0 \pi^+$	1.06 M	1.06 M

The results are obtained using a data sample of proton-proton (*pp*) collisions at centre-of-mass energies of 7 and 8 TeV collected by the LHCb detector in 2011 and 2012, corresponding to approximately 3 fb^{-1} of integrated luminosity.

The LHCb detector [10, 11] 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 detector elements that are particularly relevant to this analysis are: a silicon-strip vertex detector surrounding the pp interaction region that allows c- and b-hadrons to be identified from their characteristically long flight distance; a tracking system that provides a measurement of momentum, *p*, of charged particles; and two ring-imaging Cherenkov detectors that are able to discriminate between different species of charged hadrons.

The production and detection asymmetries depend on the kinematics of the particles involved. If the kinematic distributions are very different, this may lead to an imperfect cancellation of the nuisance asymmetries in $A_{CP}(K^- K^+)$. This effect is alleviated by equalising the corresponding kinematical distributions by assigning weights to each candidate [12].

The raw asymmetries and the signal yields are determined from binned likelihood fits to the $\delta m = m(D^{*+}) - m(D^0)$, distributions in the D^0 decay modes, and to the invariant mass distributions $m(D^+)$ in the D^+ channels (see Fig. 1). The yields of the decay modes, before and after the weighting procedure, are listed in Table 1.

The non-adequateness of the fit model, and the presence of peaking background can cause biases in the determination of individual raw asymmetries, and their effects are studied using pseudoexperiments, and simulated events. Possible presence of large local asymmetries can spoil the $A_{CP}(K^- K^+)$ measurement since Eq. 3 is valid only for small asymmetries. This systematic uncertainty is accounted for by excluding additional regions of the detector acceptance, and comparing the result to the nominal one.

The non-cancellation of detection and production asymmetries is accounted for by modifying the configuration of the procedure. Another way to asses this systematic contribution is by modelling the kinematic dependancies of the raw asymmetries, and combining them with per-event weights from data. Presence of secondary charm decays can bias the measurement due to the different asymmetries related to the production of secondary D^0 decays. The uncertainty was calculated by measuring the fraction of secondary decays, and using the measured production asymmetries at LHCb as an input. A systematic uncertainty on the calculation of the neutral kaon detection asymmetry is also taken into account. All other investigated sources are found to be negligible.

A summary of the systematic uncertainties considered can be found in Table 2 and added in

quadrature to obtain the overall systematic uncertainty.

Table 2: Systematic uncertainties from the different categories. The quadratic sum is used to compute the total systematic uncertainty.

Category	Systematic uncertainty[%]
Determination of raw asymmetries:	
Fit model	0.025
Peaking background	0.015
Cancellation of nuisance asymmetries:	
Additional fiducial cuts	0.040
Weighting configuration	0.062
Weighting simulation	0.054
Secondary charm meson	0.039
Neutral kaon asymmetry	0.014
Total	0.10

The time-integrated *CP* asymmetry in $D^0 \to K^- K^+$ decays measured using prompt charm decays is determined to be

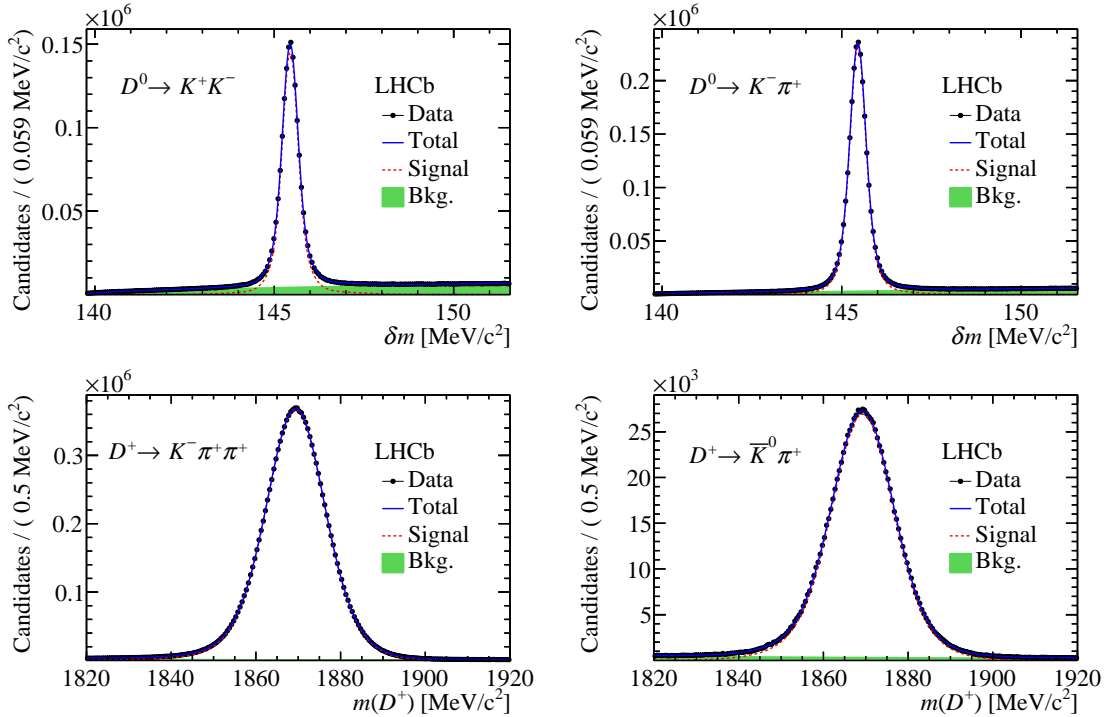$$A_{CP}^{\text{prompt}}(K^- K^+) = (0.14 \pm 0.15\,(\text{stat}) \pm 0.10\,(\text{syst}))\%. \tag{5}$$

Figure 1: Fits to the δm and to the $m(D^+)$ distributions corresponding to the whole data sample and both flavours. Data samples after the kinematic weighting described in the text are used.

This result can be combined with previous LHCb measurements of the same and related observables. A combination with $A_{CP}(K^-K^+)$ measured using secondary charm decays [7] yields

$$A_{CP}^{\text{comb}}(K^-K^+) = (0.04 \pm 0.12\,(\text{stat}) \pm 0.10\,(\text{syst}))\%. \tag{6}$$

Since the same D^+ decay channels are employed for the cancellation of detection asymmetries, the result is partially correlated with $A_{CP}^{\text{prompt}}(K^-K^+)$. The statistical correlation coefficient is $\rho_{\text{stat}} = 0.36$. The difference in CP asymmetries between $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays, ΔA_{CP}^{prompt}, is measured at LHCb using prompt charm decays [6]. A combination of the measurement of $A_{CP}^{\text{prompt}}(K^-K^+)$ with ΔA_{CP} yields a value for

$$A_{CP}^{\text{prompt}}(\pi^+\pi^-) = A_{CP}^{\text{prompt}}(K^+K^-) - \Delta A_{CP}^{prompt} = (0.24 \pm 0.15\,(\text{stat}) \pm 0.11\,(\text{syst}))\%. \tag{7}$$

The statistical correlation coefficient of the two measurements is $\rho_{\text{stat}} = 0.24$.

A combination with the measurement using secondary charm results in

$$A_{CP}^{\text{comb}}(\pi^-\pi^+) = (0.07 \pm 0.14\,(\text{stat}) \pm 0.11\,(\text{syst}))\%.$$

Fig. 2 shows the LHCb measurements of CP asymmetry using both prompt and secondary $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays. Additionally, the latest combined values of the Heavy Flavour Averaging Group [13] for these quantities are presented.

In conclusion, no evidence of CP violation is found in the Cabibbo-suppressed decays $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$. These results are obtained assuming that there is no CP violation in D^0–$\bar{D}^0$ mixing and no direct CP violation in the Cabibbo-favoured $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$ and $D^+ \to \bar{K}^0\pi^+$ decay modes. The combined LHCb results are the most precise measurements of the individual time-integrated CP asymmetries $A_{CP}(K^-K^+)$ and $A_{CP}(\pi^-\pi^+)$ from a single experiment to date.
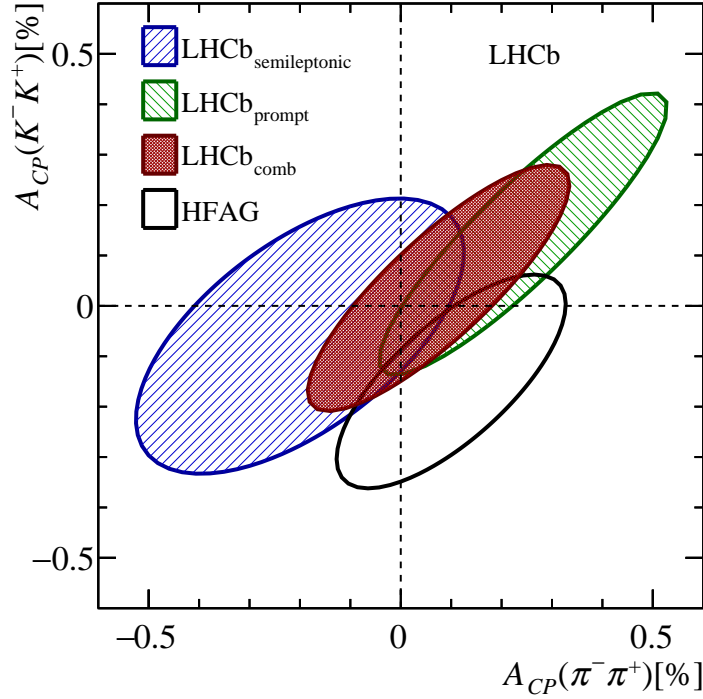
Figure 2: Measurements of *CP* violation asymmetries in $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays. Alongside the two LHCb measurements, presented in this Letter (green ellipse) and in Ref. [7] (blue ellipse), and their combination (red ellipse), the latest value of the Heavy Flavour Averaging Group [13] is shown (black ellipse). The latter already includes the measurement of ΔA_{CP} with muon(pion)-tagged D^0 decays, using 3(1) fb^{-1} pp collision data collected with the LHCb detector [7, 14]. The 68% confidence level contours are displayed where the statistical and systematic uncertainties are added in quadrature.

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