EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2022-163
LHCb-PAPER-2022-024
September 7, 2022

Measurement of the time-integrated *CP* asymmetry in $D^0 \to K^-K^+$ decays

LHCb collaboration

Abstract

The time-integrated *CP* asymmetry in the Cabibbo-suppressed decay $D^0 \to K^-K^+$ is measured using proton-proton collision data, corresponding to an integrated luminosity of $5.7\,\text{fb}^{-1}$ collected at a center-of-mass energy of 13 TeV with the LHCb detector. The D^0 mesons are required to originate from promptly produced $D^{*+} \to D^0\pi^+$ decays and the charge of the companion pion is used to determine the flavor of the charm meson at production. The time-integrated *CP* asymmetry is measured to be

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

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, $\Delta A_{CP} = \mathcal{A}_{CP}(K^-K^+) - \mathcal{A}_{CP}(\pi^-\pi^+)$, giving

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

with a correlation coefficient corresponding to $\rho = 0.88$. The compatibility of these results with *CP* symmetry is 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 a specific D^0 decay.

Submitted to Phys. Rev. Lett.

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]. The Cabibbo-Kobayashi-Maskawa (CKM) formalism describes CP violation in the Standard Model (SM) of particle physics [2,3] through an irreducible phase in the quark-mixing matrix. Over the past sixty years, CP violation has been observed in the K, D, and B-meson systems by several experiments [4–13]. In the charm quark sector, the recent observation of CP violation [13] 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 [14–29]. 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 $\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$ [13]. The time-integrated CP asymmetry for $f = K^-K^+$ and $f = \pi^-\pi^+$ corresponds to

$$\mathcal{A}_{CP}(f) \equiv \frac{\int \mathrm{d}t\, \epsilon(t) \left[\Gamma(D^0 \to f)(t) - \Gamma(\overline{D}^0 \to f)(t)\right]}{\int \mathrm{d}t\, \epsilon(t) \left[\Gamma(D^0 \to f)(t) + \Gamma(\overline{D}^0 \to f)(t)\right]}, \tag{1}$$

where $\epsilon(t)$ is the reconstruction efficiency as a function of the D^0 decay time and Γ denotes the decay rate. This Letter presents measurements of the time-integrated CP asymmetries in $D^0 \to K^-K^+$ decays. Combining the measurements of $\mathcal{A}_{CP}(K^-K^+)$ and ΔA_{CP}, 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. The mixing in the neutral charm system implies that $\mathcal{A}_{CP}(f)$ is the sum of a component related to the CP violation in the decay amplitude, a^d_f, and a component related to D^0–$\overline{D}^0$ mixing and the interference between mixing and decay, ΔY_f. Up to first order in the D^0 mixing parameters [30–37], the time-integrated CP asymmetry can be written as

$$\mathcal{A}_{CP}(f) \approx a^d_f + \frac{\langle t \rangle_f}{\tau_D} \cdot \Delta Y_f, \tag{2}$$

where $\langle t \rangle_f$ is the mean decay time of the D^0 mesons in the experimental data sample and τ_D is the D^0 lifetime [38,39].

The neutral charm mesons considered are produced in the strong-interaction decays $D^{*+} \to D^0\pi^+$ from D^{*+} mesons created in proton-proton (pp) interactions. The charge of the accompanying "tagging" pion (π^+_{tag}) is used to identify the flavor of the D^0 meson at production. Throughout this Letter, 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. The measured asymmetry, $A(K^-K^+)$, is defined as

$$A(K^-K^+) \equiv \frac{N\left(D^{*+} \to D^0\pi^+\right) - N\left(D^{*-} \to \overline{D}^0\pi^-\right)}{N\left(D^{*+} \to D^0\pi^+\right) + N\left(D^{*-} \to \overline{D}^0\pi^-\right)}, \tag{3}$$

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

$$A(K^-K^+) \approx \mathcal{A}_{CP}(K^-K^+) + A_{\mathrm{P}}(D^{*+}) + A_{\mathrm{D}}(\pi^+_{\mathrm{tag}}), \tag{4}$$

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 tagging pions. The contributions from the production and instrumental asymmetries, referred to as nuisance asymmetries, are estimated and removed through two calibration procedures denoted as C_{D^+} and $\mathrm{C}_{D_s^+}$, using a set of promptly produced D^+ and D_s^+ meson decays. Namely, the C_{D^+} procedure uses $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$, $D^+ \to K^-\pi^+\pi^+$ and $D^+ \to \overline{K}^0\pi^+$ 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 $D_s^+ \to \overline{K}^0K^+$ decays. To avoid statistical overlap, the sample of $D^0 \to K^-\pi^+$ decays is randomly split in two, and the two halves are used separately for the C_{D^+} and $\mathrm{C}_{D_s^+}$ calibration procedures. All these decays are Cabibbo favored, therefore their CP asymmetries are assumed to be negligible. In analogy to Eq. 4, the corresponding measured asymmetries in the calibration decays are decomposed as

$$\begin{aligned}
&A(K^-\pi^+) \approx A_{\rm P}(D^{*+}) - A_{\rm D}(K^+) + A_{\rm D}(\pi^+) + A_{\rm D}(\pi^+_{\rm tag}),\\
&A(K^-\pi^+\pi^+) \approx A_{\rm P}(D^+) - A_{\rm D}(K^+) + A_{\rm D}(\pi^+_1) + A_{\rm D}(\pi^+_2),\\
&A(\overline{K}^0\pi^+) \approx A_{\rm P}(D^+) + A(\overline{K}^0) + A_{\rm D}(\pi^+),\\
&A(\phi\pi^+) \approx A_{\rm P}(D_s^+) + A_{\rm D}(\pi^+),\\
&A(\overline{K}^0K^+) \approx A_{\rm P}(D_s^+) + A(\overline{K}^0) + A_{\rm D}(K^+).
\end{aligned} \tag{5}$$

In the equations above, $A_{\rm D}(K^+)$ is the kaon instrumental asymmetry, $A_{\rm P}(D^+_{(s)})$ is the $D^+_{(s)}$ meson production asymmetry and $A(\overline{K}^0)$ is the asymmetry arising from the combined effect of CP violation and mixing in the neutral kaon system and the different interaction rates of $\overline{K}^0$ and K^0 with the detector material. The asymmetries $A_{\rm D}(\pi^+_1)$ and $A_{\rm D}(\pi^+_2)$ are related to the two pions in the $D^+ \to K^-\pi^+\pi^+$ decay, distinguished by the online selection criteria. In $A(\phi\pi^+)$, the asymmetry from the oppositely charged kaons is not included as it is estimated to be negligible. With the individual terms of $\mathcal{O}(10^{-2})$ or less [40–43], the approximations in Eqs. 4 and 5 are valid up to corrections of $\mathcal{O}(10^{-6})$. The individual nuisance asymmetries depend on the kinematics of the corresponding particles. After accounting for this kinematic dependence, 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

$$\begin{aligned}
&\mathrm{C}_{D^+} : \mathcal{A}_{CP}(K^-K^+) = A(K^-K^+) - A(K^-\pi^+) + A(K^-\pi^+\pi^+) - A(\overline{K}^0\pi^+) + A(\overline{K}^0),\\
&\mathrm{C}_{D_s^+} : \mathcal{A}_{CP}(K^-K^+) = A(K^-K^+) - A(K^-\pi^+) + A(\phi\pi^+) - A(\overline{K}^0K^+) + A(\overline{K}^0).
\end{aligned} \tag{6}$$

The asymmetries are measured in pp collision data, collected with the LHCb detector at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of $5.7\,\mathrm{fb}^{-1}$. The LHCb detector is a single-arm forward spectrometer designed for the study of particles containing b or c quarks [44, 45]. A high-precision tracking system with a dipole magnet and vertex detector measures the momentum (p) and impact parameter (IP) of charged particles. The IP is defined as the distance of closest approach between the reconstructed trajectory and any pp interaction. The IP is used to distinguish between particles produced in the primary collisions and those produced in heavy-flavor decays. Different species of charged hadrons are distinguished using particle identification (PID) information from two ring-imaging Cherenkov detectors, an electromagnetic and a hadronic calorimeter, and a muon detector.

The online event selection, the trigger, consists of a hardware stage followed by two software stages within which a near real-time alignment and calibration of the detector are performed [46]. In the hardware stage, events are selected based on calorimeter and muon detector information and are accepted independently of the charm decay of interest, reducing any related asymmetry to a negligible level. In the subsequent first-stage of the software trigger, requirements on the transverse momentum ($p_{\rm T}$), the IP, and the displacement from any primary vertex (PV) of the charm-meson decay products are imposed. To pass the selection, at least one charged particle or two particles forming a high-quality vertex must fulfill these criteria. In the second stage of the software trigger, charm decays are selected using further requirements on PID, kinematics and the decay topology. Moreover, the trajectories of the considered particles are reconstructed using information from all the tracking detectors.

The $D_s^+ \to \phi\pi^+$ decays are selected from $D_s^+ \to K^-K^+\pi^+$ decay candidates requiring that the invariant mass of the kaon pair must be within $\pm 5\,{\rm MeV}/c^2$ of the ϕ mass. Similarly, the $\overline{K}^0$ mesons, produced in $D^+ \to \overline{K}^0\pi^+$ and $D_s^+ \to \overline{K}^0K^+$ decays, are reconstructed using their decay to two pions, which is dominated by the $K^0_{\rm S}$ state. The two pions are required to have an invariant mass within $\pm 10\,{\rm MeV}/c^2$ of the $K^0_{\rm S}$ mass and to form a vertex significantly displaced from that of the $D^+_{(s)}$-meson decay. The D^0 candidates are required to have a reconstructed invariant mass between 1844 and 1887 ${\rm MeV}/c^2$.

An offline selection is applied to reduce background, including combinations of random tracks and tracks from other c-hadron decays, and to ensure a further cancellation of nuisance asymmetries which can depend on the kinematics of the charm mesons, the kaons, and the pions. These kinematics and PID requirements are applied to both the signal and related control modes where applicable. To improve the overall precision, these selections have been optimized independently for each of the two calibration sets C_{D^+} and $\mathrm{C}_{D_s^+}$. For all decay modes, a requirement on the IP of the charm hadron suppresses charm mesons from b-hadron decays. To improve the resolution on the track momenta and the charm meson decay length and invariant mass, a global decay-chain fit [47] is performed, constraining the origin vertex of the charm meson to the position of the nearest primary vertex and the invariant mass of the two pion system to the known $K^0_{\rm S}$ mass [48].

In the construction of the D^{*+} candidate, only one of the combinations of the D^0-meson candidate with different pions in the same event is randomly retained. In addition, requirements are imposed on the tagging pion to exclude kinematic regions which show a large asymmetry in $A_{\rm D}(\pi^+_{\rm tag})$ [49].

The nuisance asymmetries introduced in Eqs. 4 and 5 are expected to depend on the kinematics of the individual particles. To ensure a proper cancellation of those asymmetries, 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. The values of the weights are calculated separately for each calibration procedure using an iterative technique. It is verified that the background-subtracted, weighted distributions of the components of momenta of the relevant particles agree among the different decays. The weighting procedure is repeated for each data-taking year and magnet polarity to account for the dependence of the nuisance asymmetries on data-taking conditions.

The measured asymmetries of signal components for each decay mode are determined through least-square fits to the weighted, binned mass distributions of the charm-meson candidates, simultaneously for both flavors. The invariant of the D^{*+} candidates, $m(D^0\pi^+)$, is calculated using the vector sum of the momenta of the three charged particles and the

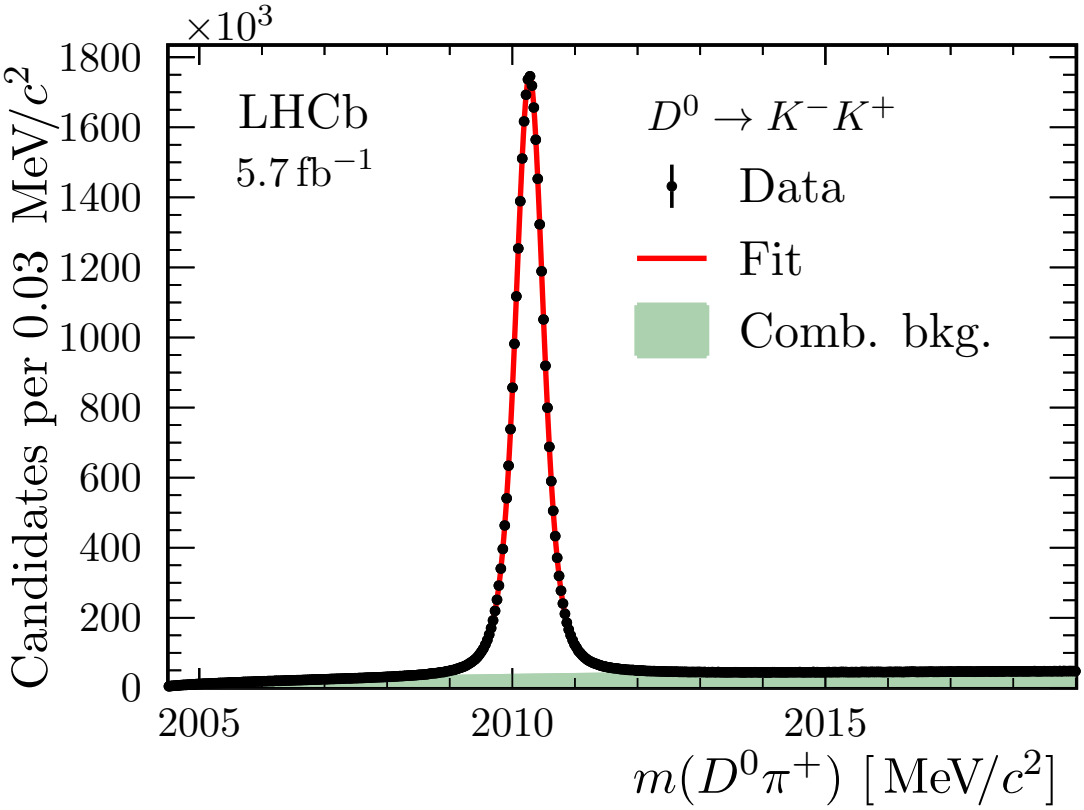

Figure 1: Distribution of the invariant mass for the weighted $D^{*+} \to D^0$ $(\to K^-K^+)\pi^+$ decay candidates, from the C_{D^+} calibration procedure. The result of the fit to this distribution is also shown.

known D^0 and π^+ masses [48]. The signal models consist of a sum of Gaussian and Johnson S_U functions [50], empirically describing the experimental resolution and the energy loss due to final-state radiation. The means of the signal distributions are distinct for the two charm meson flavors, whereas all the other parameters, including the relative fractions among the various functions, are shared. For D^{*+} decays, the combinatorial background is described by an empirical function of the form $[m(D^0\pi^+) - m(D^0) - m(\pi^+)]^\alpha e^{\beta m(D^0\pi^+)}$, where α and β are two parameters shared between the two flavors. In the other cases, an exponential function with a distinct parameter for positive and negative particles is used.

Figure 1 presents the distribution of the $D^0 \to K^-K^+$ invariant mass and the result of the fit. The signal yields, together with the statistical reduction factor, defined as $(\Sigma_{i=1}^{i=K} w_i)^2/(N \cdot \Sigma_{i=1}^{i=K} w_i^2)$, where K is the total number of candidates and w_i includes background subtraction and kinematic weights, are reported in Table 1. These reduction factors are for illustrative purposes only and indicate the hypothetical number of signal events that would provide the same statistical power as the weighted data sample.

Separate fits are performed to subsamples of data collected in different years and with different magnet polarities. After determining the asymmetries in these subsamples, the values of $\mathcal{A}_{CP}(K^-K^+)$ are calculated according to Eq. 6, taking into account the contribution from the neutral kaon asymmetry. This is estimated by combining the LHCb material map from simulation with measured CP-violation and cross-section parameters of the neutral kaon system [51–53], following the procedure described in Ref. [54]. The correction is -5.1×10^{-4} (-8.5×10^{-4}) for the C_{D^+} $(C_{D_s^+})$ calibration procedure. The

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.

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	0.75	0.75
$D^0 \to K^-\pi^+$	58	56	0.35	0.75
$D^+ \to K^-\pi^+\pi^+$	188	–	0.25	–
$D^+ \to \overline{K}^0\pi^+$	6	–	0.25	–
$D_s^+ \to \phi\pi^+$	–	43	–	0.55
$D_s^+ \to \overline{K}^0K^+$	–	5	–	0.70

individual $\mathcal{A}_{CP}(K^-K^+)$ values per subsample are found to be in agreement, with a p-value of 0.85 and 0.22 for the C_{D^+} and $C_{D_s^+}$ methods, respectively. Finally, the measurements in each subsample are averaged to obtain the final result for each procedure.

Several sources of systematic uncertainties are considered. The systematic uncertainty related to the description of signal and background in the invariant-mass distributions is evaluated by generating pseudoexperiments according to the baseline fit models, and fitting alternative models to those samples. A fit-independent approach is also considered, based on a sideband subtraction. Systematic uncertainties of 1.1×10^{-4} and 1.0×10^{-4} are assigned for the C_{D^+} and $C_{D_s^+}$ procedures, with a correlation of 0.05.

A systematic uncertainty associated to the presence of background components peaking in $m(D^0\pi)$ and not in $m(K^-K^+)$ is determined by fitting the latter distribution in the $D^0 \to K^-K^+$ samples. Various backgrounds are modeled using fast simulation [55]. The main sources are $D^0 \to K^-\pi^+\pi^0$ and $D^0 \to K^-e^+\nu_e$ decays. A similar study is performed on the $D^0 \to K^-\pi^+$ decay sample, where the peaking-background contributions are found to be negligible. As a result, the values 0.3×10^{-4} and 0.4×10^{-4} are assigned as systematic uncertainties for the C_{D^+} and $C_{D_s^+}$ calibration procedures, respectively, with a correlation coefficient of 0.74.

Although suppressed by the stringent requirement on the IP, a fraction of D mesons from b-hadron decays is still present in the final sample. As the different decay modes may have different levels of contamination, the value of $\mathcal{A}_{CP}(K^-K^+)$ may be affected by an incomplete cancellation of the production asymmetries of b-hadrons. The contributions from b-hadron decays in data are estimated by fitting the IP distribution of charm mesons using shapes obtained from simulation. The corresponding systematic uncertainties are estimated to be 0.6×10^{-4} and 0.3×10^{-4} for the C_{D^+} and $C_{D_s^+}$ calibration procedures, respectively, with a negligible correlation between them.

Any residual disagreement between the kinematic distributions among the various decay modes leads to an imperfect cancellation of the nuisance asymmetries. The systematic uncertainties related to this effect are estimated to be 0.8×10^{-4} and 0.4×10^{-4} for the C_{D^+} and $C_{D_s^+}$ procedures, respectively, with a negligible correlation.

To test the accuracy of the estimated value for $A(\overline{K}^0)$, a linear term with one free parameter is introduced in the model that describes the dependence of $A(\overline{K}^0)$ on the

Table 2: Systematic uncertainties on $\mathcal{A}_{CP}(K^-K^+)$ for the two calibration procedures C_{D^+} and $\mathrm{C}_{D_s^+}$. 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.

Source	C_{D^+} $[10^{-4}]$	$\mathrm{C}_{D_s^+}$ $[10^{-4}]$	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

neutral-kaon decay time. The parameter is determined by fitting the charge asymmetry in $D^+ \to \overline{K}^0\pi^+$ decays as a function of the $\overline{K}^0$ decay time. This is done using a control sample where the neutral kaon decays outside the vertex detector. The parameter is found to be consistent with zero. Its uncertainty is propagated to the $\overline{K}^0$ lifetimes relevant for $\mathcal{A}_{CP}(K^-K^+)$ and assigned as systematic uncertainty. The resulting, fully correlated, systematic uncertainties are 0.6×10^{-4} and 1.3×10^{-4} for the C_{D^+} and $\mathrm{C}_{D_s^+}$ procedures, respectively.

In the $\mathrm{C}_{D_s^+}$ procedure, $D_s^+ \to K^-K^+\pi^+$ decay modes other than $D_s^+ \to \phi\pi^+$ may break the symmetry between the K^- and K^+ meson kinematic distributions. This leads to a bias in the measured asymmetry due to the momentum-dependent instrumental asymmetry of the kaon. This effect is estimated by combining the two momentum distributions with the expected charged-kaon asymmetry from simulation. The resulting systematic uncertainty is 1.0×10^{-4}.

All individual contributions are summed in quadrature to give the total systematic uncertainties of 1.6×10^{-4} and 2.0×10^{-4} for the C_{D^+} and $\mathrm{C}_{D_s^+}$ procedures, respectively. A summary of all systematic uncertainties is shown in Table 2.

Numerous additional checks are carried out. The measurements of $\mathcal{A}_{CP}(K^-K^+)$ are verified to not depend on the decay time, the transverse momentum and the pseudorapidity of the D^0 meson; the decay time and the pseudorapidity of the $\overline{K}^0$ meson; and the IP significance of the final-state particles with respect to all the PVs in the event of the control modes. The IP significance is defined as the difference between the χ^2 of the PV reconstructed with and without the considered particle. Furthermore, the total sample is split by different data-taking periods, also distinguishing different magnet polarities. Splitting into subsamples based on the trigger configuration is also considered. The p-values under the hypothesis of no dependencies of $\mathcal{A}_{CP}(K^-K^+)$ on the various variables are found to be uniformly distributed. Checks using alternative PID requirements and trigger selections are performed, and all variations of $\mathcal{A}_{CP}(K^-K^+)$ are found to be compatible within statistical uncertainties. The resulting values for $\mathcal{A}_{CP}(K^-K^+)$ for both calibration

procedures are

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

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

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

consistent with the previous LHCb results [54, 56]. Assuming that *CP* is conserved in mixing and in the interference between decay and mixing, the comparison of the result reported here with the current world average [57] gives a compatibility of 1.3 standard deviations.

A combination of all the time-integrated *CP* asymmetries measured by the LHCb collaboration to date is performed, under the hypothesis that the time-dependent *CP* violation term in Eq. 2 is final-state independent, *i.e.* $\Delta Y_{K^-K^+} = \Delta Y_{\pi^-\pi^+} = \Delta Y$. The combination includes the previous LHCb measurements of $\mathcal{A}_{CP}(K^-K^+)$ [54, 56] and ΔA_{CP} [13, 49, 54] as well as the current LHCb average of ΔY [39], the world average of the D^0 lifetime [48] 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, obtained by minimizing a χ^2 function that includes all the measurements and their correlations, leads to

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

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 and the one realized with data collected between 2010 and 2012 [49, 54, 56, 58, 59]. The two combinations are based on an integrated luminosity of 8.7 fb^{-1} and 3.0 fb^{-1}, respectively.

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 $a^d_{K^-K^+} + a^d_{\pi^-\pi^+} = 0$ [60]. 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.

In summary, this Letter reports the most precise measurement of the time-integrated *CP* asymmetry in the $D^0 \to K^-K^+$ decay to date. A combination with the previous LHCb measurements shows the first evidence of direct *CP* asymmetry in an individual charm meson decay. These results will help to clarify the theoretical understanding of whether the observed *CP* violation in neutral charm meson decays is consistent with the SM, or an indication of the existence of new dynamics.

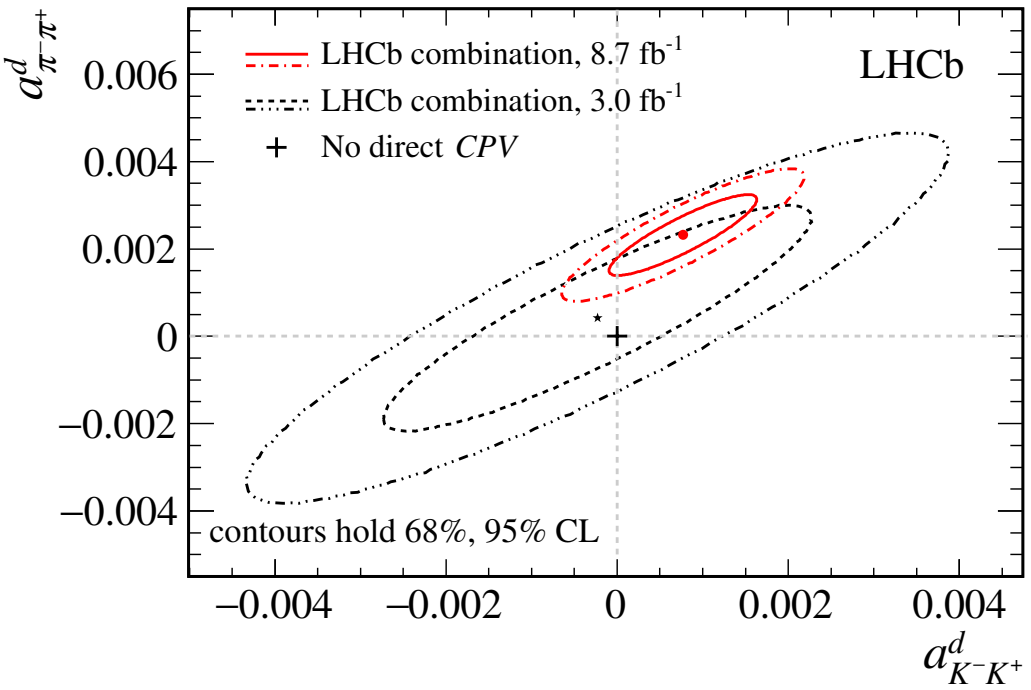

Figure 2: Central values and two-dimensional confidence regions in the $(a^d_{K^-K^+}, a^d_{\pi^-\pi^+})$ plane for the combinations of the LHCb results obtained with the dataset taken between 2010 and 2018 and the one taken between 2010 and 2012, corresponding to an integrated luminosity of $8.7\,\text{fb}^{-1}$ and $3.0\,\text{fb}^{-1}$, respectively.

Supplemental material

Reconstructed mean decay times

The interpretation of $\mathcal{A}_{CP}(K^-K^+)$ in terms of direct CP asymmetries, $a^d_{\pi^-\pi^+}$ and $a^d_{K^-K^+}$ requires the measurement of the reconstructed mean decay time of $D^0 \to K^-K^+$ decay. The values corresponding to the measurements presented in this Letter are $\langle t \rangle_{K^-K^+} = (7.315 \pm 0.020) \times 10^{-13}$ s and $\langle t \rangle_{K^-K^+} = (6.868 \pm 0.014) \times 10^{-13}$ s for the C_{D^+} and $C_{D_s^+}$ methods, respectively. Their correlation corresponds to $\rho = 0.74$. These measurements are also correlated with the difference of reconstructed mean decay times for $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays, $\Delta\langle t \rangle^{\pi-\text{tagged}}$, measured in Ref. [13]. The correlation coefficients between $\langle t \rangle_{K^-K^+}$ and $\Delta\langle t \rangle^{\pi-\text{tagged}}$ are $\rho = 0.23$ and $\rho = 0.25$ for the C_{D^+} and $C_{D_s^+}$ methods, respectively.

Additional plots

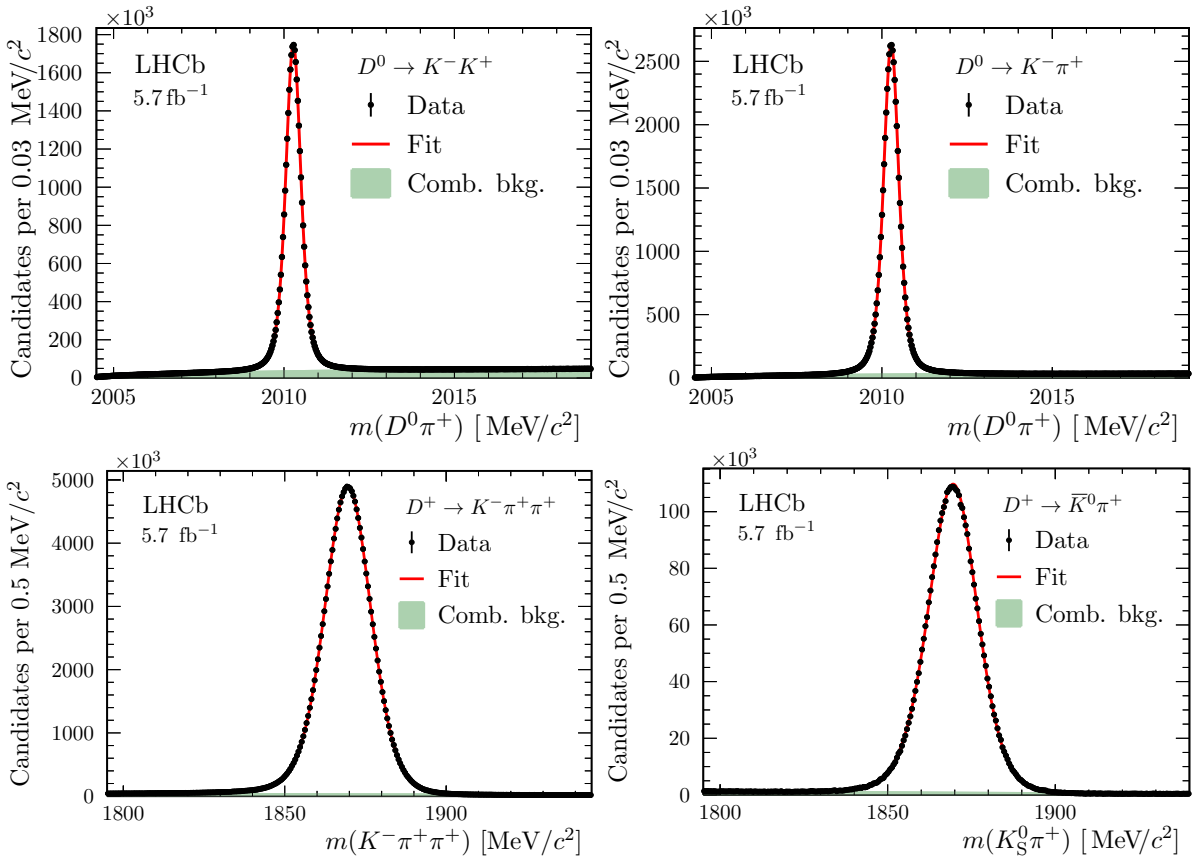

Figure 3: Distributions of the invariant mass for the weighted charm-meson candidates, for the decays (top left) $D^{*+} \to D^0\,(\to K^-K^+)\pi^+$, (top right) $D^{*+} \to D^0\,(\to K^-\pi^+)\pi^+$, (bottom left) $D^+ \to K^-\pi^+\pi^+$, (bottom right) $D^+ \to \overline{K}^0\pi^+$. The data are from the C_{D^+} calibration procedure. The results of the fits to these distributions are also shown. The top left is repeated from the main text.

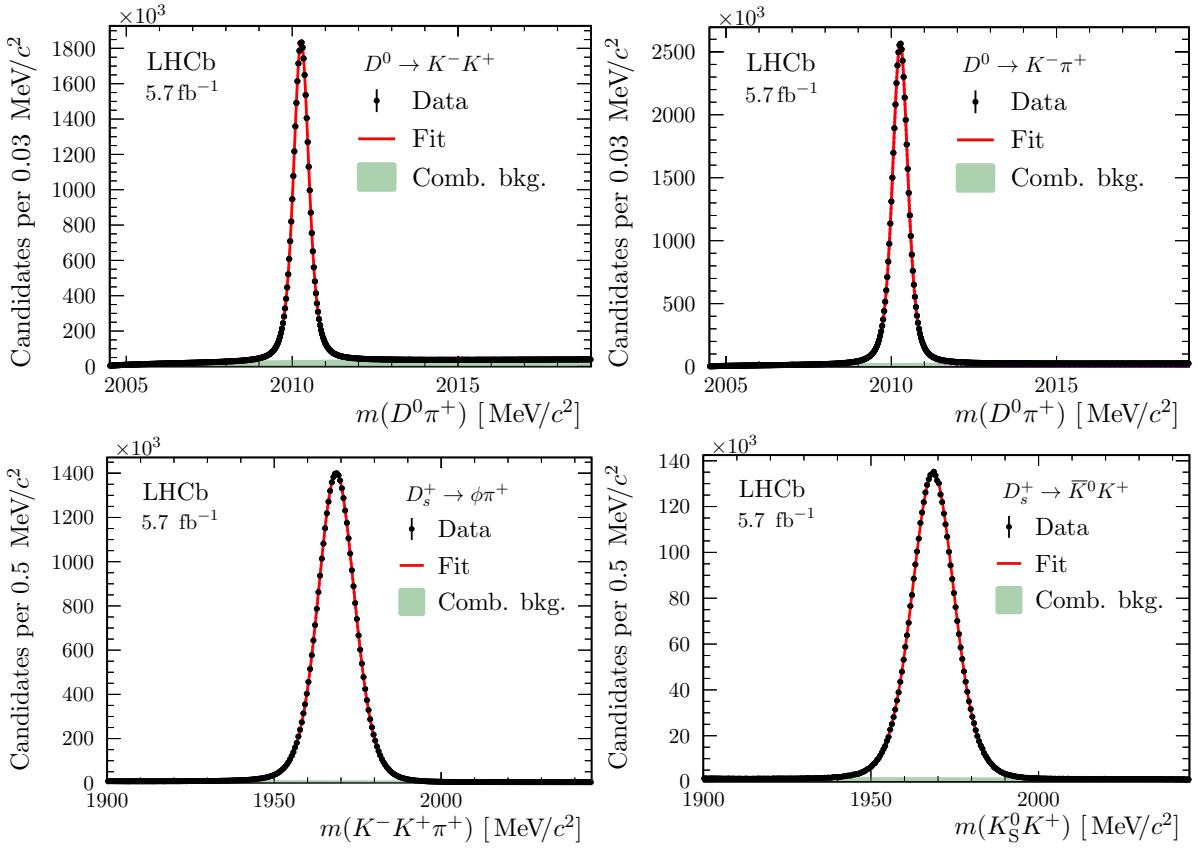

Figure 4: Distributions of the invariant mass for the weighted charm-meson candidates, for the decays (top left) $D^{*+} \to D^0\ (\to K^-K^+)\pi^+$, (top right) $D^{*+} \to D^0\ (\to K^-\pi^+)\pi^+$, (bottom left) $D_s^+ \to K^-K^+\pi^+$, and (bottom right) $D_s^+ \to \overline{K}^0K^+$. The data are from the $\mathrm{C}_{D_s^+}$ calibration procedure. The results of the fits to these distributions are also shown.

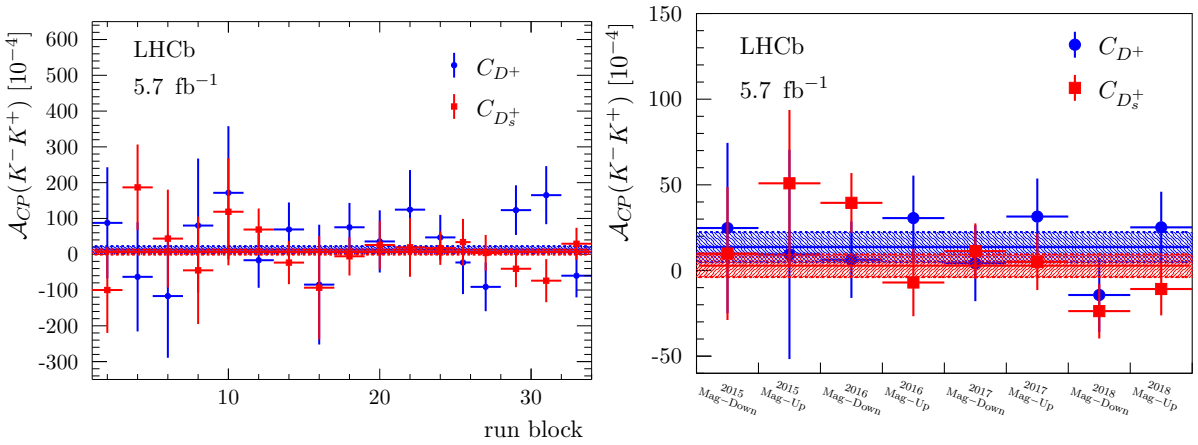

Figure 5: Measurements of $\mathcal{A}_{CP}(K^-K^+)$ in (left) time-ordered data-taking (referred to as run blocks) and (right) year of data-taking and dipole-magnet polarity for the C_{D^+} and $\mathrm{C}_{D_s^+}$ calibration procedures. The uncertainties are statistical only. The horizontal lines are the averaged values for the C_{D^+} and $\mathrm{C}_{D_s^+}$ methods, while the bands represent the one-standard-deviation regions. The labels *Mag-Up* and *Mag-Down* refer to the direction of the magnetic field along the positive and negative directions of y-axis, respectively.

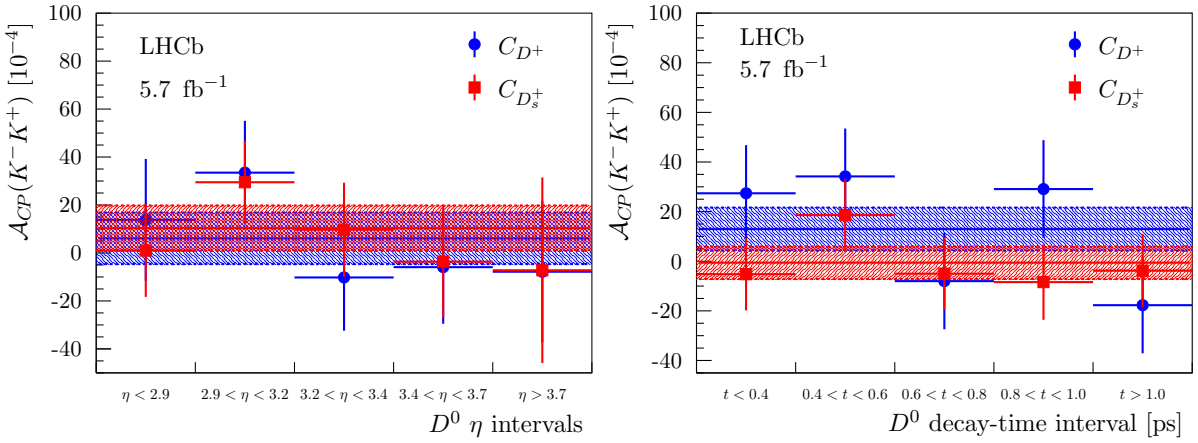

Figure 6: Comparison of the results for $\mathcal{A}_{CP}(K^-K^+)$ per different intervals of D^0 candidates (left) pseudorapidity and (right) decay time for the C_{D^+} and $C_{D_s^+}$ calibration procedures. The horizontal lines are the averaged values for the C_{D^+} and $C_{D_s^+}$ methods, while the bands represent the one-standard-deviation regions.

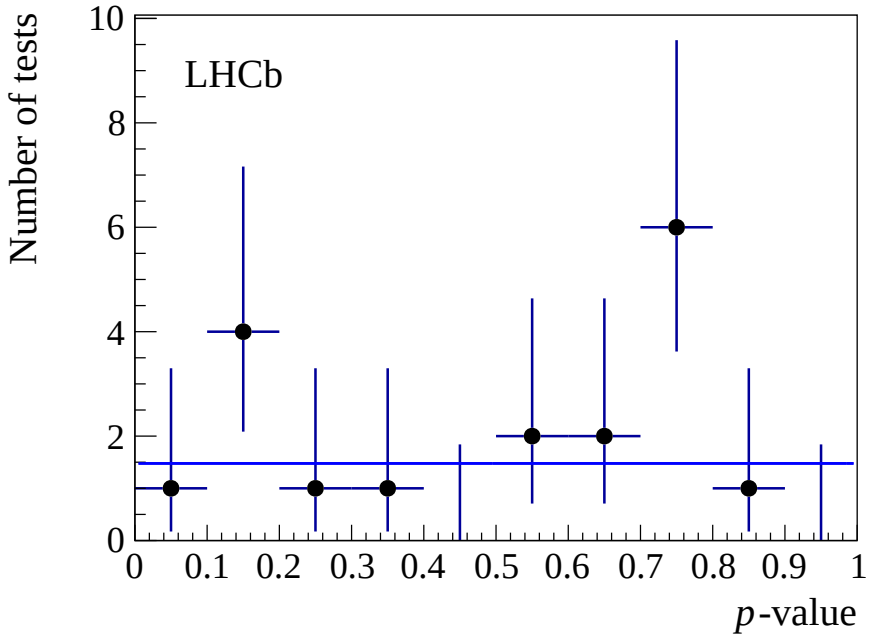

Figure 7: Distribution of the p-values resulting from the consistency checks on $\mathcal{A}_{CP}(K^-K^+)$ measured in different data subsamples. The blue line represents the expected uniform distribution.

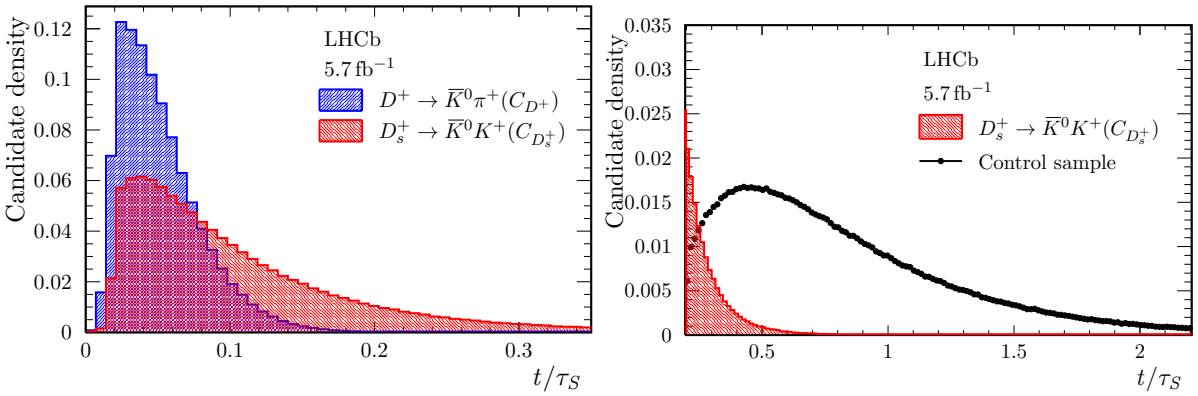

Figure 8: Distributions of the neutral-kaon decay time for background-subtracted and weighted candidates considered in the determination of $\mathcal{A}_{CP}(K^-K^+)$ values. The left panel presents the distributions at low neutral-kaon decay time, and the right panel presents the distributions at higher decay times. The right panel includes the distribution for the $D^+ \to \overline{K}^0\pi^+$ decays where the neutral kaon decays outside of the vertex detector, used as a control sample in the estimation of $A(\overline{K}^0)$.

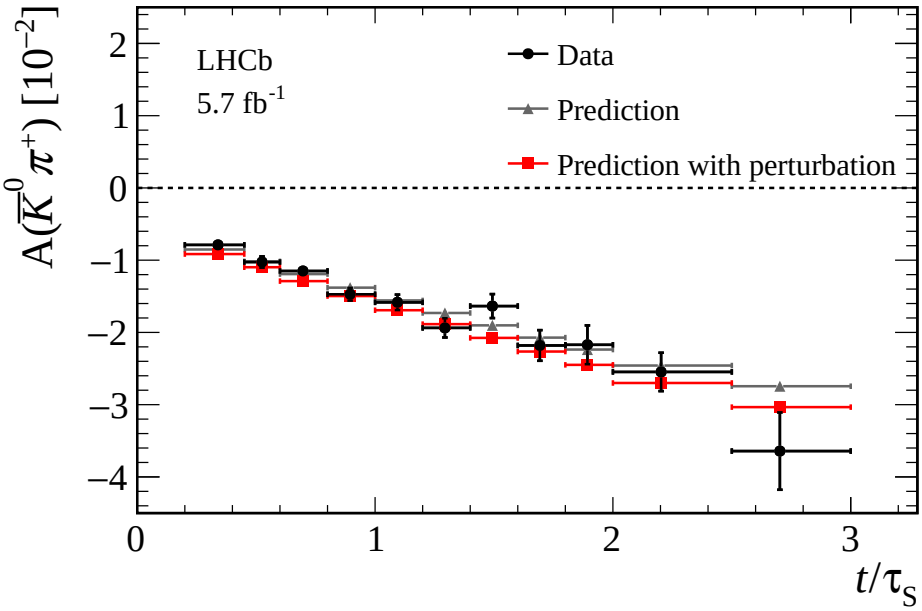

Figure 9: Measured asymmetry in $D^+ \to \overline{K}^0\pi^+$ decays as a function of $\overline{K}^0$ decay time in units of K^0_S-meson decay time, in data where the neutral kaon meson decays outside of the vertex detector. The predictions for the neutral kaon asymmetry, from the model with and without an additional linear degree of freedom, are shown as well. An overall shift is applied to the model's predictions to account for unrelated nuisance asymmetries, *i.e.* $A_P(D^+)$ and $A_D(\pi^+)$.

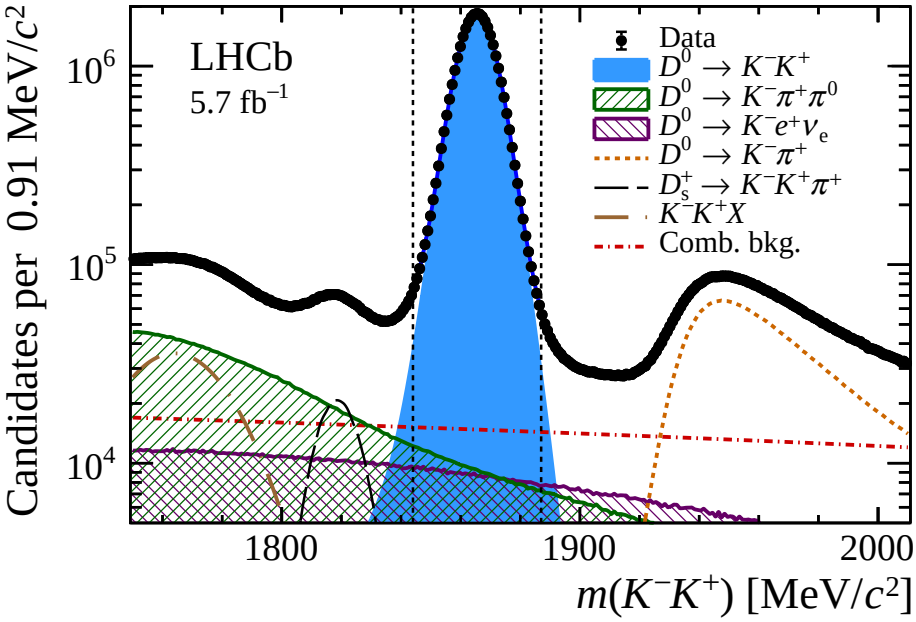

Figure 10: Distribution of the K^-K^+ invariant mass, along with the result of the fit describing the expected background components. The vertical lines indicate the interval applied in the selection of D^0 candidates for the determination of $\mathcal{A}_{CP}(K^-K^+)$. The fit results are used to evaluate the systematic uncertainties related to the peaking background.

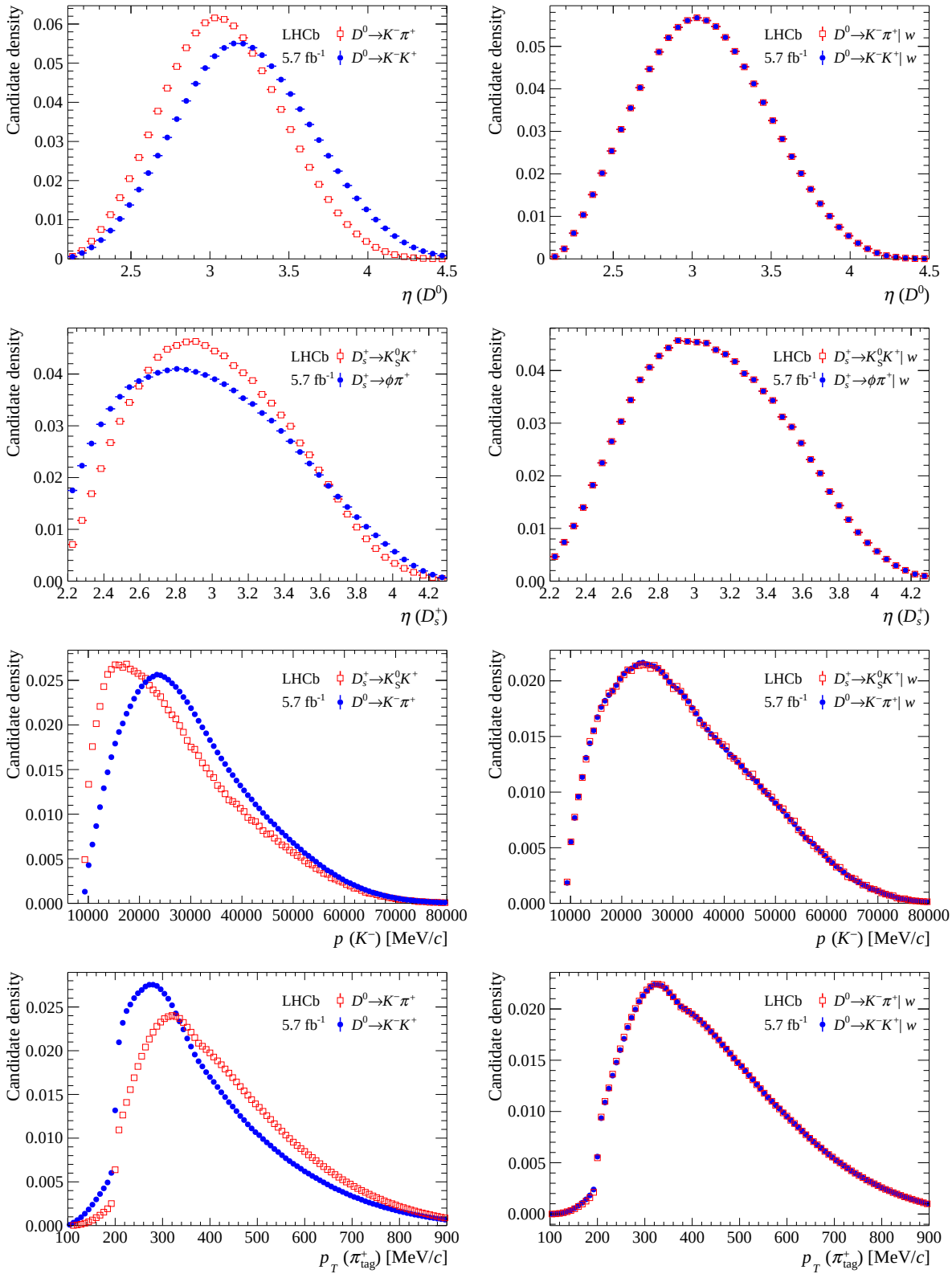

Figure 11: Background-subtracted kinematic distributions for the charm-meson pseudorapidity (η), the kaon momentum (p) and the tagging-pion transverse momentum (p_{T}) (left column) before and (right column) after the per-candidate $\mathrm{C}_{D_s^+}$ weighting procedure. The distributions are normalized to unit area.

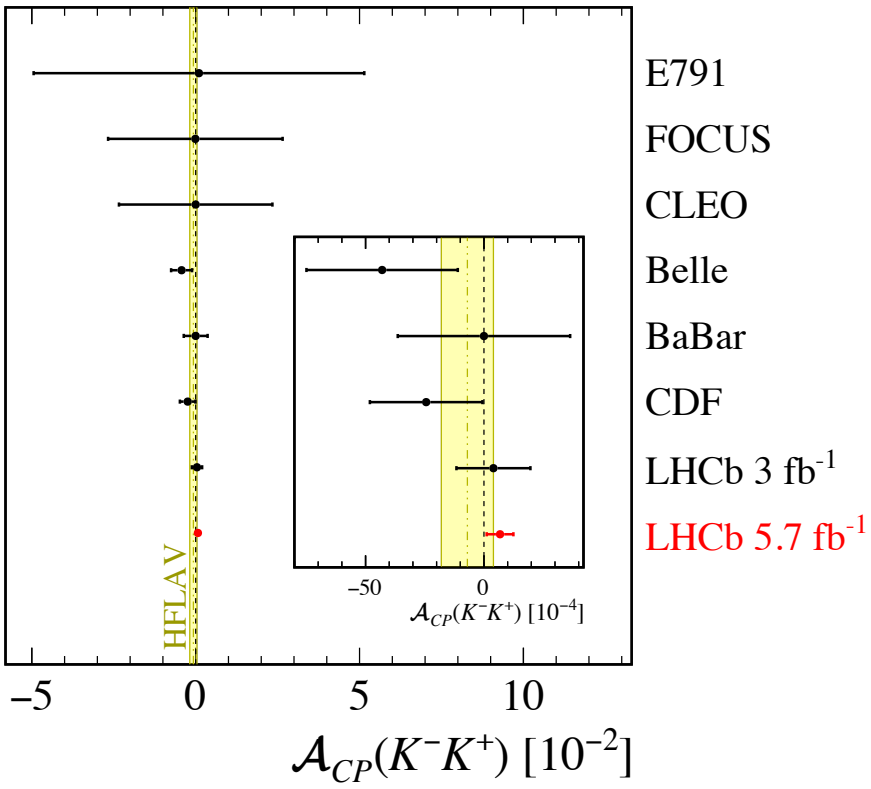

Figure 12: Measurements of $\mathcal{A}_{CP}(K^-K^+)$ from various experiments [56, 61–66]. The presented measurement is highlighted in red. The vertical band corresponds to the average of all measurements previous to the presented, computed by HFLAV [57], where it is assumed that *CP* is conserved in mixing and in the interference between decay and mixing. This assumption is necessary when results from different experiments are compared. The inset plot shows the five most precise measurements in a reduced horizontal range.

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