PROCEEDINGS OF SCIENCE

Mixing and CPV in charm decays at LHCb

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After Run 2, LHCb has collected the world's largest sample of charmed hadrons. This sample is further investigated to understand the *CP* violation observed in charm decays in 2019. The measurement of the time-integrated *CP* asymmetry in $D^0 \to K^-K^+$ decays, $\mathcal{A}_{CP}(K^-K^+)$, and its combination with the observed $\Delta A_{CP} = \mathcal{A}_{CP}(K^-K^+) - \mathcal{A}_{CP}(\pi^-\pi^+)$ are presented in this document, reporting the first evidence of *CP* violation in $D^0 \to \pi^-\pi^+$. Due to the variation of the strong phase across the Dalitz plane, multi-body decays have unique features for *CP* violation searches. The decays $D^+_{(s)} \to K^-K^+K^+$ and $D^0 \to \pi^-\pi^+\pi^0$ have been also investigated with model-independent approaches, reporting no evidence for *CP* violation in these decay modes.

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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 (CPV) [1]. In the Standard Model (SM) of particle physics, the Cabibbo-Kobayashi-Maskawa [2, 3] formalism describes CP violation through an irreducible phase in the quark-mixing matrix. CP violation in charm decays is suppressed by the SM with expected asymmetries on the order of 10^{-3} or below [2–4], making room for new physics enhancements. However, predictions are hard to compute due to the low-energy strong interaction effects [5]. The direct CP asymmetry in a decay $D \to f$ corresponds to

$$\mathcal{A}_{CP} = \frac{|A_f|^2 - |\overline{A}_{\overline{f}}|^2}{|A_f|^2 + |\overline{A}_{\overline{f}}|^2}, \tag{1}$$

where A_f ($\overline{A}_{\overline{f}}$) is the amplitue connecting the initial state D ($\overline{D}$) to the final state f ($\overline{f}$). Most decay processes receive contributions from multiple amplitudes, *i.e.* $A_f = \sum_j |A_j| e^{-i(\delta_j + \phi_j)}$ and $\overline{A}_{\overline{f}} = \sum_j |A_j| e^{-i(\delta_j - \phi_j)}$, where δ_j and ϕ_j are the strong and weak phases, respectively. Thus, $\mathcal{A}_{CP}$ can be written as

$$\mathcal{A}_{CP} = \frac{-2\sum_{i,j} |A_i||A_j| \sin(\delta_i - \delta_j)\sin(\phi_i - \phi_j)}{\sum_i |A_i|^2 + \sum_{i\neq j} |A_i||A_j| \cos(\delta_i - \delta_j)\cos(\phi_i - \phi_j)} \tag{2}$$

revealing that CP violation appears as a result of the interference among at least two processes with both different weak and strong phases. Decays with $c \to u$ transitions are the most interesting channel, as more contributions, such as the so-called tree, penguin, or rescattering amplitudes, can appear.

The recent observation of CP violation in the charm quark sector [6] stimulates a wide discussion to understand its nature. The discovery measurement 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 $\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$. Further precise measurements may resolve the intricate theoretical debate on whether the observed value is consistent with the SM [7–11].

This document presents the measurement of the time-integrated CP asymmetry in $D^0 \to K^-K^+$ decays. Combining the measurement with ΔA_{CP} it is possible to quantify the amount of CP violation in the decay amplitude for $D^0 \to \pi^-\pi^+$ decays and provide important insight in the breaking of U-spin symmetry. Furthermore, the decays $D^+_{(s)} \to K^-K^+K^+$ and $D^0 \to \pi^-\pi^+\pi^0$ have been investigated with model independent approaches.

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}) [12]. Previous attempts are reported in Refs. [13, 14]. 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. 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[1] as

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

where $A_{\mathrm{P}}(D^{*+})$ is the production asymmetry arising from the different hadronization probabilities between D^{*+} and D^{*-} mesons in pp collisions, and $A_{\mathrm{D}}(\pi^+_{\mathrm{tag}})$ 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. 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 in the final state. This ensures a proper cancellation in Eq. 5.

Fits to the invariant mass distributions are used to extract the measured asymmetries in each decay mode. The signal yields, together with the statistical reduction factor[2] are reported in Table 1. It is possible 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 resulting values for $\mathcal{A}_{CP}(K^-K^+)$ for both calibration procedures are found to be 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 results [13, 14].

A combination of all the time-integrated *CP* asymmetries in $D^0 \to K^-K^+$ measured by the LHCb collaboration to date is performed, including ΔA_{CP} [6] and possible effects from time-dependentant

[1] The equation is valid up to corrections of $O(10^{-6})$ assuming individual terms of $O(10^{-2})$ or less [12].

[2] 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.

CP violation [15]. 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 1 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.

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	–
$D^+ \to \bar{K}^0\pi^+$	6	–	0.25	–
$D_s^+ \to \phi\pi^+$	–	43	–	0.55
$D_s^+ \to \bar{K}^0K^+$	–	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.

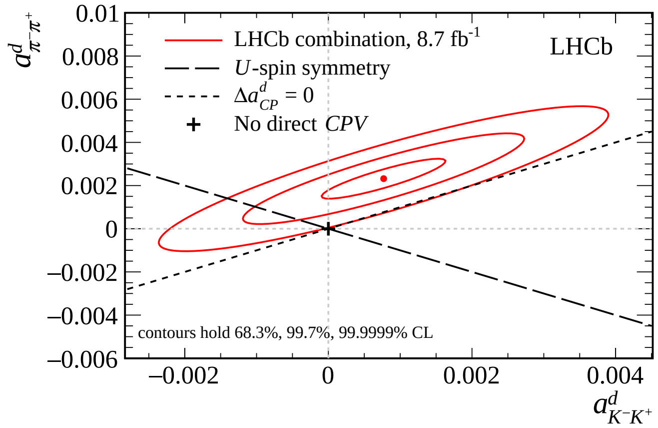

Figure 1: Central values and two-dimensional confidence regions in the $(a^d_{K^-K^+}, a^d_{\pi^-\pi^+})$ plane for the combination. The lines $a^d_{K^-K^+} - a^d_{\pi^-\pi^+} = 0$ for the ΔA_{CP}observable and $a^d_{K^-K^+} + a^d_{\pi^-\pi^+} = 0$ for the *U*-spin symmetry are also shown.

3. Search for *CP* violation in $D^+_{(s)} \to K^-K^+K^+$ and $D^0 \to \pi^-\pi^+\pi^0$ decays

Given the dependance of $\mathcal{A}_{CP}$ on strong phases (Eq. 2), multi-body decays are the perfect tool for search of new physics effects through the interference with the intermediate resonances. As an example, Fig. 2 (top) shows the distribution of a local CPV estimator, $\mathcal{S}^{CP}$, in simulated $D^+ \to K^-K^+\pi^+$ data with and without the injection of a *CP*-violating new physics interfering with the ϕ resonance. Currently, two model-independent approaches are used at LHCb. They are

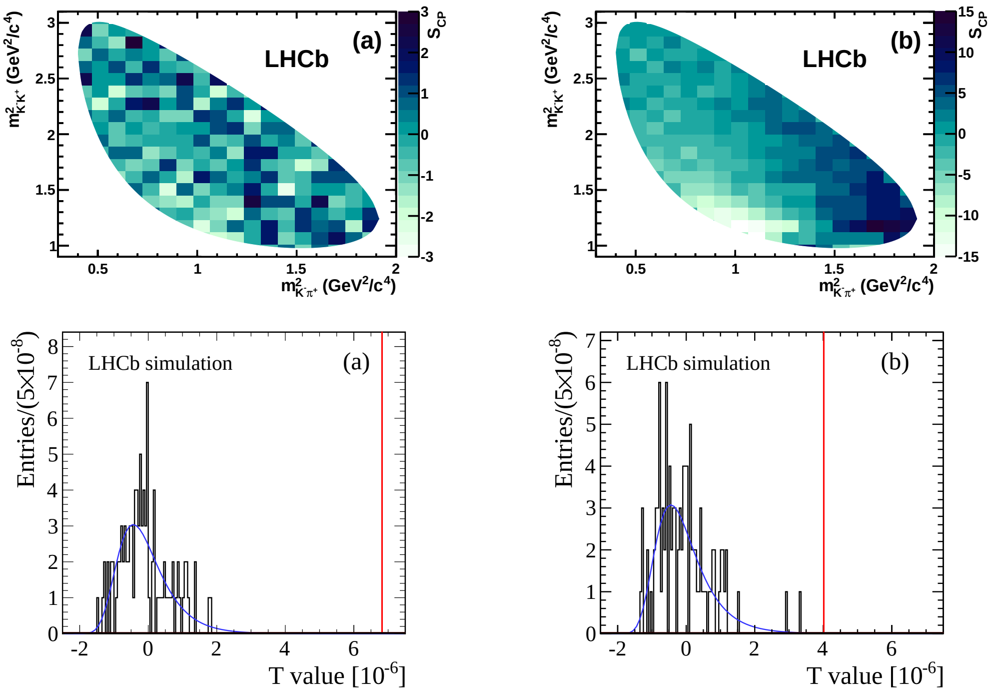

Figure 2: (top) $\mathcal{S}^{CP}$ across the Dalitz plot in a Monte Carlo pseudo-experiment for $D^+ \to K^-K^+\pi^+$ decays with (left) no CPV and (right) a 4° CPV in the $\phi\pi$ phase. Note the difference in colour scale between (left) and (right). Reproduced from Ref. [16]. (bottom) Distribution of permutation T values for the simulated sample for $D^0 \to \pi^-\pi^+\pi^0$ decays and showing the nominal T value as a vertical line for (left) 2% *CP* violation in the amplitude and (right) 1° phase *CP* violation of the ρ^+ resonance. Reproduced from Ref. [17].

the so-called "Miranda method" and the "Energy test" being a binned and unbinned approach, respectively. These strategies are not able to measure a *CP*-violating observable as $\mathcal{A}_{CP}$ but they will report a p-value related to the probability of the observed data being consistent with the *CP*-symmetry conservation hypothesis.

The Miranda method consists in dividing the phase-space in different sub-regions and calculating $\mathcal{S}^i_{CP}$ in each bin i (as described in Fig. 2 (top)). The local CPV estimator can be defined as

$$\mathcal{S}^i_{CP} = \frac{N^i(D) - \alpha N^i(\overline{D})}{\sqrt{\alpha(\delta^2_{N^i(D)} + \delta^2_{N^i(\overline{D})})}} \qquad \text{with } \alpha = \frac{\sum_i^{N_{bins}} N^i(D)}{\sum_i^{N_{bins}} N^i(\overline{D})} \tag{6}$$

where $N^i(D)$ and $N^i(\overline{D})$ are the yields for the $D \to f$ and $\overline{D} \to \overline{f}$ decays candidates for each bin i and N_{bins} is the number of sub-regions. The p-value of the observed data is calculated considering the χ^2 of $\mathcal{S}_{CP}$, *i.e.* $\chi^2 = \sum_i^{N_{bins}} \mathcal{S}^i_{CP}$, with a number of degrees of freedom corresponding to $N_{bins} - 1$.

The Energy test method relies on the test statistic T being sensitive to both local and global asymmetries, as shown in Fig. 2 (bottom). The p-value is obtained by comparing the T value observed in data to the distribution of T, obtained from permutation samples, where the flavour is randomly assigned. The test statistic is defined as

$$T = \sum_{i,j>i}^{n} \frac{\psi_{ij}}{n(n-1)} + \sum_{i,j>i}^{\overline{n}} \frac{\psi_{ij}}{\overline{n}(\overline{n}-1)} - \sum_{i,j}^{n,\overline{n}} \frac{\psi_{ij}}{n\overline{n}}, \tag{7}$$

representing the difference among the average difference of events with the same flavour and the one among events with opposite flavour. In particular, n and $\overline{n}$ are the yields for the $D \to f$ and $\overline{D} \to \overline{f}$ decays candidates. The distance among a pair of events ij in the phase-space is defined as $d_{ij} = |(m^{2,j}_{12} - m^{2,i}_{12}, m^{2,j}_{23} - m^{2,i}_{23}, m^{2,j}_{13} - m^{2,i}_{13})|$, where $m^{2,i}_{lk}$ represents the squared invariant mass of two of the three particles in the final state for each candidate i. The metric function is defined as $\psi_{ij} = e^{-d^2_{ij}/2\sigma^2}$ where σ is related to the sensitivity of the test and its value is optmized with simulated samples.

The two presented approaces have been used in the lastest searches for CPV, investigating $D^+_{(s)} \to K^-K^+K^+$ and $D^0 \to \pi^-\pi^+\pi^0$ decays, using respectively the Miranda method and the Energy test [18, 19]. These analysis are performed using proton-proton (pp) collision data collected with the LHCb detector during Run 2 ($\sqrt{s}$ =13 TeV, 5.7 fb^{-1}). While a search was already carried out in $D^0 \to \pi^-\pi^+\pi^0$ decays with Run 1 data [17], the $D^+_{(s)} \to K^-K^+K^+$ decays are investigated for the first time. In both the analysis, the model-independent approaches are also applied to Cabbibbo-favoured decays with similar kinematic distributions, *i.e.* $D^+_s \to K^-K^+\pi^+$ and $D^0 \to K^-\pi^+\pi^0$ decays, as a cross-check. In the analysis for $D^+_{(s)} \to K^-K^+K^+$ decays the phase-space is divided in 21 physically-motivated bins to increase the sensitivity of $\mathcal{S}_{CP}$. The observed yields are about $0.97 \cdot 10^6$ and $1.27 \cdot 10^6$ candidates for the D^+_s and the D^+ decays, respectively. $\mathcal{S}^i_{CP}$ is measured in each bin and represented in Fig. 3 (top). The p-values results to be 13.3% and 31.6% for D^+_s and D^+ decays, respectively, stating no evidence for *CP* violation in these decays. In the Energy test with $D^0 \to \pi^-\pi^+\pi^0$ decays the best value for σ has been found to be 0.2 (GeV/c^2)^2 thanks to simulated data. The final result is shown in Fig. 3 (bottom), reporing a p-value = 62% and thus no evidence for *CP* violation in this decay.

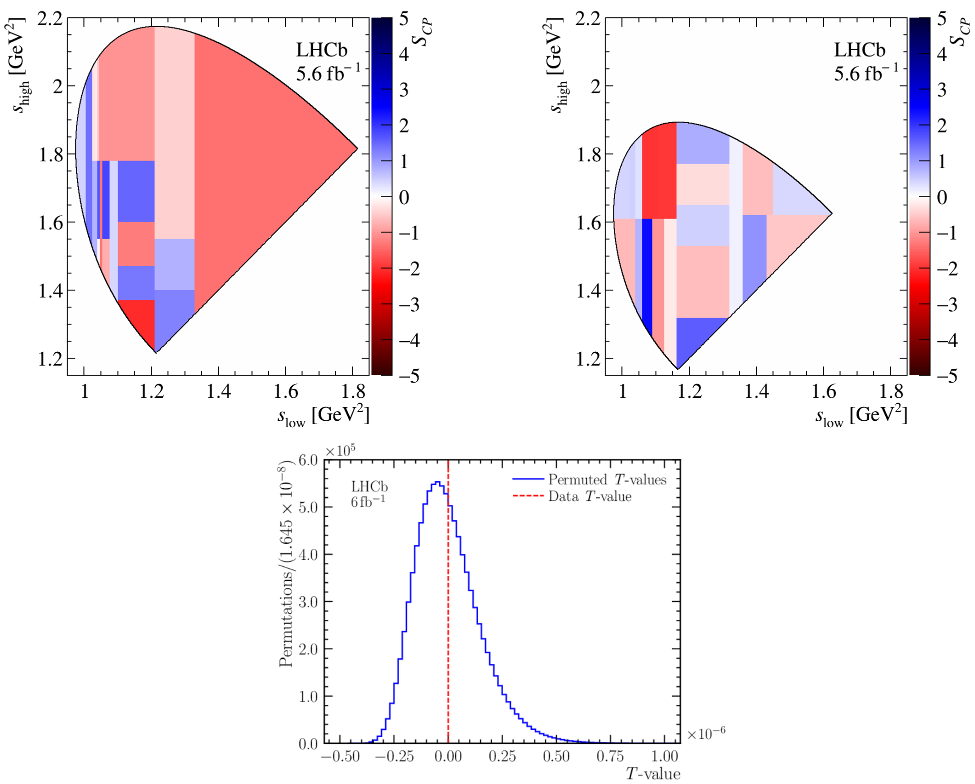

Figure 3: (top) $\mathcal{S}_{CP}$ values across the Dalitz plot for (left) $D_s^+ \to K^-K^+K^+$ and (right) $D^+ \to K^-K^+K^+$ signal candidates using 21 bins [18]. (bottom) Distribution of T-values obtained by running the energy test over the final signal $D^0 \to \pi^-\pi^+\pi^0$ sample (red dashed line) superimposed on the corresponding distribution for the CP-symmetry hypothesis, obtained from flavour-randomised permutations of the same data sample [19].

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