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# CP violation and mixing in charm with LHCb

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Measurements of charge-parity (*CP*) violation and mixing in charm provide a sensitive test of the Standard Model and can potentially probe physics beyond the Standard Model. The LHCb experiment has provided the most precise measurements in this scope to date. This year has brought two milestones in charm physics: the first observation of *CP* violation in charm decays and the first evidence of a non-zero mass difference between the neutral charm eigenstates. These results are both included in this contribution together with searches for direct *CP* violation in quasi two-body decays. Despite the recent discoveries, the theoretical framework is still not clear and more precise measurements, expected with the coming upgrade of detector, are required.

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## 1. Introduction

In the Standard Model (SM) of particle physics, *CP* violation (CPV) is introduced through an irreducible complex phase in the Cabibbo-Kobayashi-Maskawa (CKM) mixing matrix [1]. The smallness of the elements of the CKM matrix involved suppresses the expectations for CPV in charm at a level typically below $10^{-3}$ [2] and makes *CP* violation in charm sensitive to possible contributions of physics beyond the SM. Furthermore, the charm-quark sector offers a unique opportunity to test the CKM formalism, since it provides access to operators that affect only up-type quarks, while leaving the strange and beauty hadrons unaffected. Testing the SM expectations for CPV in charm requires huge data samples, $\mathcal{O}(10^7)$ decays, that have become available only recently thanks to the large $c\bar{c}$ production cross-section at the LHC [3] and the dedicated detector and trigger of the LHCb experiment [4]. This has made the LHCb experiment the main player in this quest. In March 2019, the LHCb collaboration announced the first observation of CPV in the decay of charm hadrons [5]. However, the interpretation of this observation is unclear, since theoretical predictions are difficult to compute reliably due to low-energy quantum-chromodynamics effects [6, 7, 8]. For this reason, further studies of charm decays are needed to clarify the picture. Additional measurements of CPV in decays with the same underlying physics might help in this regard as well as complementary results from mixing and time-dependent CPV studies.

The first observation of *CP* violation in the charm sector [5], some searches for CPV in the decay [9] and the first evidence for the mixing parameter $x$ larger than zero [10] are presented in Sects. 2, 3 and 4, respectively.

Improvements in precision are expected in the next few years. In the long term, the Upgrade I (2021-2029) [11] and the proposed Upgrade II (2031-2038) [12] of the LHCb detector will be essential to explore the SM phenomenology in charm decays.

## 2. Observation of *CP* violation in charm decays

The time-integrated *CP* asymmetry in the decay of a $D$ meson to a final state $f$ is defined as

$$A_{CP}(f) \equiv \frac{\Gamma(D\to f)-\Gamma(\bar{D}\to \bar{f})}{\Gamma(D\to f)+\Gamma(\bar{D}\to \bar{f})} \tag{2.1}$$

where $\Gamma$ is the decay width. Cabibbo-suppressed decays, such as $D^0\to K^-K^+$ and $D^0\to\pi^-\pi^+$, are the most promising channels since CPV can occur in the interference between loop and tree-level processes in $c\to d\bar{d}u$ or $c\to s\bar{s}u$ transitions. In the case of the decay of a neutral $D^0$ meson to a *CP*-even final state $f=K^-K^+$ or $\pi^-\pi^+$, $A_{CP}$ is unaffected by $D^0$-$\bar{D}^0$ mixing and corresponds to the direct *CP* asymmetry, excepting terms of order $10^{-5}$.

This analysis uses data collected during Run 2, corresponding to an integrated luminosity of 5.9 $\text{fb}^{-1}$ [5]. The $D^0$ mesons considered are produced either promptly in $D^{*+}\to D^0\pi^+$ flavor-conserving decays or in inclusive semi-leptonic $B\to\bar{D}^0\mu^+X$ decays. The flavor of the $D^0$ meson is inferred from the charge of the accompanying pion ($\pi$-tagged) or from that of the muon ($\mu$-tagged).

The raw asymmetry between the observed yields of $D^0\to f$ and $\bar{D}^0\to f$ decays can be approximated as

$$A^{\pi\text{-tagged}}(f) \approx A_{CP}(f)+A_D(\pi^+)+A_P(D^{*+}), \tag{2.2}$$

$$A^{\mu\text{-tagged}}(f) \approx A_{CP}(f) + A_D(\mu^-) + A_P(B), \tag{2.3}$$

where $A_D$ and $A_P$ are the detection and production asymmetries, respectively. These asymmetries are independent on the final state, and thus cancel in the difference, giving

$$\Delta A_{CP} \equiv A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+), \tag{2.4}$$
$$= A(K^-K^+) - A(\pi^-\pi^+). \tag{2.5}$$

The raw asymmetries are determined by means of simultaneous fits to the invariant-mass distributions of $D^{*+}$ and $D^{*-}$ ($D^0$ and $\overline{D}^0$) mesons for the $\pi$-tagged ($\mu$-tagged) sample. The projections of the fits to the combined $D^0$ and $\overline{D}^0$ samples are shown in Figure 1.

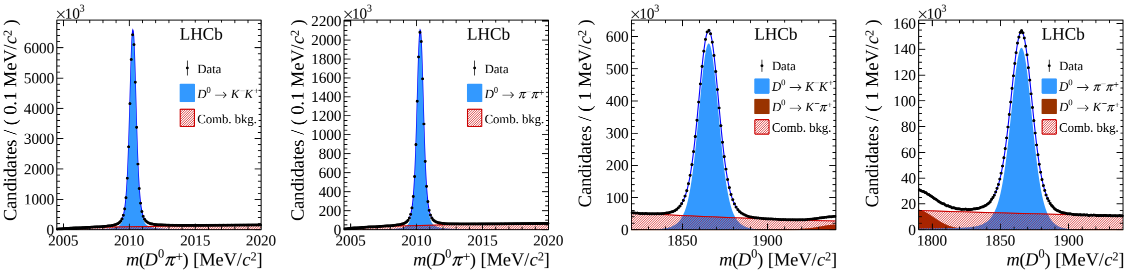


**Figure 1:** Invariant-mass distributions for the $\pi$-tagged (left) $K^-K^+$ and (mid left) $\pi^-\pi^+$, and $\mu$-tagged (mid right) $K^-K^+$ and (right) $\pi^-\pi^+$ final states. The fit projections are overlaid.

Several sources of systematic uncertainties are considered. In the $\pi$-tagged sample, the main systematic uncertainty is related to the inaccuracy of the fit model and to the presence of backgrounds that peak in the $m(D^0\pi^+)$ distribution even if they do not in that of $m(D^0)$. In the case of the $\mu$-tagged sample, the dominant systematic uncertainty is due to the possibility that the flavor of the $D^0$ is not correctly assigned due to the matching with a wrong $\mu$.

The results obtained for the difference of the raw asymmetries of $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays are $\Delta A_{CP}^{\pi-tagged} = [-18.2 \pm 3.2 \pm 0.9] \times 10^{-4}$ and $\Delta A_{CP}^{\mu-tagged} = [-9 \pm 8 \pm 5] \times 10^{-4}$, where the first uncertainties are statistical and the second systematic. The measurements are compatible within their uncertainties. By combining them with previous LHCb results [13, 14], the following value for $\Delta A_{CP}$ is obtained:

$$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}. \tag{2.6}$$

This result deviates from zero with a significance of 5.3 standard deviations and corresponds to the first observation of *CP* violation in the decay of charm hadrons. Measurements of $A_{CP}$ ($K^-K^+$) and $A_{CP}$ ($\pi^-\pi^+$) with comparable precision will only be available in the next decade [11, 12].

## 3. Search for *CP* violation in $D_s^+ \to K_S^0\pi^+$, $D^+ \to K_S^0 K^+$ and $D^+ \to \phi\pi^+$

Further studies in SU(3) related decays may help in finding correlations between *CP* asymmetries and constrain theoretical predictions. A search for *CP* violation in the Cabibbo-suppressed $D_s^+ \to K_S^0\pi^+$, $D^+ \to K_S^0 K^+$ and $D^+ \to \phi\pi^+$ decays was performed with a partial Run 2 dataset corresponding to an integrated luminosity of 3.8 fb$^{-1}$ [9]. The *CP* asymmetries are obtained from the raw ones by correcting them with kinematically weighted samples of Cabibbo-favored $D^+_{(s)}$ decays where CPV can be neglected:

$$A_{CP}(D_s^+ \to K_S^0\pi^+) \approx A(D_s^+ \to K_S^0\pi^+) - A(D_s^+ \to \phi\pi^+), \tag{3.1}$$

$$A_{CP}(D^+ \to K_S^0K^+) \approx A(D^+ \to K_S^0K^+) - A(D^+ \to K_S^0\pi^+) - A(D_s^+ \to K_S^0K^+) + A(D_s^+ \to \phi\pi^+), \tag{3.2}$$

$$A_{CP}(D^+ \to \phi\pi^+) \approx A(D^+ \to \phi\pi^+) - A(D^+ \to K_S^0\pi^+), \tag{3.3}$$

where the contribution from the detection asymmetry of the $\bar{K}^0$ is omitted and should be subtracted from any of the measured asymmetries where it is present.

The raw asymmetries of the decay modes of interest are determined by simultaneous fit to the $D^+_{(s)}$ and $D^-_{(s)}$ invariant-mass distributions. The results, combined with the previous LHCb measurements [15, 16], give

$$A_{CP}(D_s^+ \to K_S^0\pi^+) = (\ \ 1.6\ \pm 1.7\ \pm 0.5\ ) \times 10^{-3}, \tag{3.4}$$

$$A_{CP}(D^+ \to K_S^0K^+) = (-0.04 \pm 0.61 \pm 0.45) \times 10^{-3}, \tag{3.5}$$

$$A_{CP}(D^+ \to \phi\pi^+) = (\ \ 0.03 \pm 0.40 \pm 0.29) \times 10^{-3}, \tag{3.6}$$

where the first uncertainties are statistical and the second systematic. No evidence for *CP* violation in these decays is found. More precise measurements of these asymmetries can be expected when the data already collected by LHCb in 2018 will be included in a future analysis, and when much larger samples will become available with the upgraded LHCb detector [11, 12].

## 4. Measurement of the mass difference between neutral charm-meson eigenstates with $D^0 \to K_S^0\pi^-\pi^+$

The split of the masses ($m_{1,2}$) and of decay widths ($\Gamma_{1,2}$) of the neutral charm-meson eigenstates $|D_{1,2}\rangle \equiv p|D^0\rangle \pm q|\bar{D}^0\rangle$, with $|p|^2 + |q|^2 = 1$, governs the oscillations of $D^0$ mesons and can be conveniently parametrized through the mixing parameters $x \equiv \frac{m_1 - m_2}{\Gamma}$ and $y \equiv \frac{\Gamma_1 - \Gamma_2}{2\Gamma}$, where $\Gamma = (\Gamma_1 + \Gamma_2)/2$. While the measurement of mixing with the two-body decays $D^0 \to K^\pm\pi^\mp$ led to the discovery of mixing in charm and provides the most precise measurement for the parameter $y$ [17], it supplies only limited information on the mixing parameter $x$. On the contrary, the rich resonance structure of $D^0 \to K_S^0\pi^-\pi^+$ decays implies the presence of large strong phases that vary across the Dalitz plane and, consequently, provides good sensitivity to all mixing and *CP*-violating parameters.

However, the decay dynamics of this three body decay and the variations of the detector efficiency across the Dalitz plane as a function of decay time need to be modeled carefully in order to take advantage of this feature. Both these challenges are mitigated by the "Bin-Flip method" proposed in Ref. [18], a model-independent analysis procedure. This consists in dividing the Dalitz plane into two set of regions, symmetrically distributed with respect to its bisector $m_+^2 = m_-^2$ where $m_\pm^2$ is equal to $m^2(K_S^0\pi^\pm)$ for $D^0$ decays and to $m^2(K_S^0\pi^\mp)$ for $\bar{D}^0$ decays, chosen so as to keep the strong-phase difference ($\Delta\delta$) between $D^0$ and $\bar{D}^0$ decays approximately constant within each region, as displayed in Figure 2. The lower part of the Dalitz plane is dominated by unmixed, Cabibbo-favored $D^0$ decays, while in the upper part of the Dalitz plane the contribution of Cabibbo-favored decays following mixing becomes more and more important with respect to the unmixed doubly-Cabibbo-suppressed decays as decay time increases.

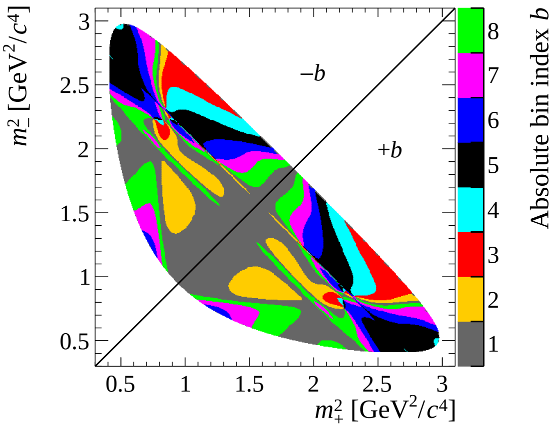


**Figure 2:** Iso-$\Delta\delta$ binning of the $D^0 \to K_S^0\pi^-\pi^+$ Dalitz plot, based on the BaBar 2008 amplitude model [19]. Positive indices refer to bins in the (lower) $m_+^2 > m_-^2$ region; negative indices refer to those in the (upper) $m_+^2 < m_-^2$ region. Colors indicate the absolute value of the bin index $b$.

This method is employed in the recent LHCb measurement of mixing and CPV with $D^0 \to K_S^0\pi^-\pi^+$ decays using the Run 1 data sample, corresponding to an integrated luminosity of 3 fb$^{-1}$ [10]. The flavor at production of the $D^0$ meson is inferred either from the charge of the accompanying pion in $D^{*+} \to D^0\pi^+$ decays or from the charge of the muon in inclusive semi-leptonic $B \to \bar{D}^0\mu^+X$ decays. The mixing and *CP*-violating parameters are measured through a least-squares fit to the time-dependent ratios of the yields in the bins symmetric with respect to the bisector of the Dalitz plane, simultaneously for all Dalitz bins, for the $D^0$ and $\bar{D}^0$ candidates. In the fit, the strong-phase differences are constrained to the values measured by CLEO [19] and the mixing and *CP*-violating parameters are parametrized through two complex parameters defined as $z_{CP} \pm \Delta z \equiv -(q/p)^{\pm 1}(y+ix)$ [18]. The results are

$$x_{CP} \equiv -\mathrm{Im}(z_{CP}) = (\ 2.7 \pm 1.6 \pm 0.4\ ) \times 10^{-3}, \tag{4.1}$$

$$y_{CP} \equiv -\mathrm{Re}(z_{CP}) = (\ 7.4 \pm 3.6 \pm 1.1\ ) \times 10^{-3}, \tag{4.2}$$

$$\Delta x \equiv -\mathrm{Im}(\Delta z) = (-0.53 \pm 0.70 \pm 0.22) \times 10^{-3}, \tag{4.3}$$

$$\Delta y \equiv -\mathrm{Re}(\Delta z) = (\ 0.6 \pm 1.6 \pm 0.3\ ) \times 10^{-3}, \tag{4.4}$$

where the first uncertainties are statistical and the second systematic. This is the most precise measurement of the parameter $x$ from a single experiment. In particular, the new world average gives the first evidence that $x > 0$, *i.e.* the mass of the *CP*-even eigenstate of the neutral charm mesons is heavier than the *CP*-odd one, at the level of 3 standard deviations. In the short period, this measure will benefit from the increased statistics taken during Run 2 and from the new measurements of the strong phase differences from BESIII. Even more precision is expected in the future data taking periods [11, 12].

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