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CP violation in charm (LHCb)

Guillaume Pietrzyk*
École Polytechnique Fédérale de Lausanne (EPFL), Switzerland
On behalf of the LHCb collaboration
E-mail: guillaume.pietrzyk@cern.ch

Charge-parity (*CP*) violation is well established in the kaon and beauty sectors and was observed in charm decays for the first time in 2019 by the LHCb experiment at the level of 5.3σ. The LHCb detector has collected billions of D^0 decays, making it an ideal laboratory to study charm decays. This document covers four recent analyses that explore various sources of *CP* violation in the charm sector.

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*Speaker

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1. Introduction

In the Standard Model (SM) of particle physics, *CP* violation originates from the presence of a single complex phase in the Cabibbo-Kobayashi-Maskawa (CKM) matrix [1]. However, the amount of *CP* violation in the SM is orders of magnitude too small to describe the observed matter-antimatter asymmetry of the Universe [2] and new sources need to be uncovered. *CP* violation has been observed in the kaon [3] and beauty [4, 5] systems and in 2019 in the decays of neutral charm mesons by the LHCb collaboration [6]. SM theoretical calculations predict *CP* violation effects to be small in the charm sector (at the level of $10^{-3} - 10^{-4}$) [7]), giving room to possible New Physics enhancements. Nonetheless, these SM predictions are difficult to assess with high confidence due to long-distance contributions. Experimental measurements are therefore crucial to improve theoretical inputs. The LHCb detector [8] has collected very large samples of charm decays [9] with excellent time, momentum and tracking resolution coped with a reliable particle identification system [10]. LHCb is therefore an ideal experimental laboratory to study *CP* violation in charm decays.

2. *CP* violation

Charm mixing arises from the distinctness between the neutral meson mass eigenstates $|D_{1,2}\rangle$ and the flavour eigenstates $|D^0\rangle$ and $|\overline{D}^0\rangle$:

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle, \tag{1}$$

where p and q are two non-zero complex numbers. *CP* violation can be split into three families:

- *CP* violation in the decay occurs when $\Gamma(D^0 \to f) \neq \Gamma(\overline{D}^0 \to \overline{f})$.
- *CP* violation in the mixing appears if $|q/p| \neq 1$.
- *CP* violation in the interference between mixing and decay is materialised by a non-zero value of $\phi = \arg\left(\frac{q}{p}\frac{\Gamma(\overline{D}^0 \to f)}{\Gamma(D^0 \to f)}\right)$.

3. Observation of *CP* violation in charm decays

The measurement of $\Delta A_{CP} = A_{CP}(KK) - A_{CP}(\pi\pi)$ has been performed using the full LHCb Run 2 dataset ($6\,\mathrm{fb}^{-1}$) [6] by studying the two Cabibbo-suppressed (CS) decays $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$. The D^0 candidates are required to originate from prompt $D^{*+} \to D^0\pi^+$ decays or from semileptonic $\overline{B} \to D^0 X \overline{\nu}_\mu \mu^-$ decays, where the charge of the accompanying pion of muon tags the flavour of the D^0. The time-integrated *CP* asymmetry $A_{CP}(f)$, in the decay of neutral D mesons to a final state f, is given by:

$$A_{CP}(f) = \frac{\Gamma(D^0 \to f) - \Gamma(\overline{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\overline{D}^0 \to f)}. \tag{2}$$

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The raw asymmetry $A_{\text{raw}}(f)$, obtained by counting the observed number of D^0 and $\overline{D}^0$ mesons, differs from $A_{CP}(f)$ because of the presence of experimental asymmetries:

$$A_{\text{raw}}(f) = \frac{\text{N}(D^0 \to f) - \text{N}(\overline{D}^0 \to f)}{\text{N}(D^0 \to f) + \text{N}(\overline{D}^0 \to f)} = A_{CP}(f) + A_D(\text{tag}) + A_P + O(A^3), \tag{3}$$

where $A_D(\text{tag})$ is the detection asymmetry of the tagging particles and A_P is the asymmetry between the production rates of D^0 and $\overline{D}^0$. After a set of fiducial cuts and a kinematic weighting procedure, $A_D(\text{tag})$ and A_P become independent of the D^0 decay. The difference between the raw asymmetries is therefore equal to the observable

$$\Delta A_{CP} = A_{\text{raw}}(KK) - A_{\text{raw}}(\pi\pi) = A_{CP}(KK) - A_{CP}(\pi\pi). \tag{4}$$

The Run 2 results are

$$\Delta A_{CP}(\text{prompt}) = (-18.2 \pm 3.2 \pm 0.9) \times 10^{-4}, \qquad \Delta A_{CP}(\text{semileptonic}) = (-9 \pm 8 \pm 5) \times 10^{-4}, \tag{5}$$

where the first uncertainties are statistical and the second systematic. By combining these results with the ones obtained using Run 1 data (3fb^{-1}), it yields

$$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}, \tag{6}$$

which corresponds to the first observation of *CP* violation in charm decays at a significance of 5.3σ.

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

CP-violation in the charm sector is also probed in charged decays such as the three CS decay modes $D_s^+ \to K_S^0\pi^+$, $D^+ \to K_S^0K^+$ and $D^+ \to \phi\pi^+$. Detection and production asymmetries are cancelled using the raw asymmetries of the three Cabibbo-favoured control channels $D^+ \to K_S^0\pi^+$, $D_s^+ \to K_S^0K^+$ and $D_s^+ \to \phi\pi^+$ where *CP* asymmetries are known to be negligible. Using data collected from 2015 to 2017 (3.8 fb^{-1}), the measured *CP* asymmetries are:

$$A_{CP}(D_s^+ \to K_S^0\pi^+) = (1.3 \pm 1.9 \pm 0.5) \times 10^{-3} \tag{7}$$

$$A_{CP}(D^+ \to K_S^0K^+) = (-0.09 \pm 0.65 \pm 0.48) \times 10^{-3}, \tag{8}$$

$$A_{CP}(D^+ \to \phi\pi^+) = (0.05 \pm 0.42 \pm 0.29) \times 10^{-3}, \tag{9}$$

which are all compatible with the *CP* conservation hypothesis.

5. Measurement of the mass difference in $D^0 \to K_S^0\pi^+\pi^-$

The bin-flip method [13] is a model-independent approach to probe local *CP* violation effects in a three-body decay such as $D^0 \to K_S^0\pi^+\pi^-$. A binning scheme of Dalitz coordinates is chosen to have nearly constant strong-phase differences, giving access to *CP* parameters through a simultaneous fit of the number of events in various Dalitz bins as a function of D^0 decay time. The corresponding analysis was performed using prompt D^{*+} decays collected in 2012 (2fb^{-1}) and semileptonic B

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decay collected in 2011 and 2012 (3fb^{-1}) [12]. The *CP* parameters as well as the derived mixing parameters are measured to be:

$$x_{CP} = (2.7 \pm 1.6 \pm 0.4) \times 10^{-3} \qquad x = 0.27^{+0.17}_{-0.15} \times 10^{-2}, \tag{10}$$

$$y_{CP} = (7.4 \pm 3.6 \pm 1.1) \times 10^{-3} \qquad y = (0.74 \pm 0.37) \times 10^{-2}, \tag{11}$$

$$\Delta x = (0.53 \pm 0.70 \pm 0.22) \times 10^{-}-3 \qquad |q/p| = 1.05^{+0.22}_{-0.17}, \tag{12}$$

$$\Delta y = (0.6 \pm 1.6 \pm 0.3) \times 10^{-3} \qquad \phi = -0.09^{+0.11}_{-0.16}. \tag{13}$$

The combination of x with the world average value yields

$$x = 3.9^{+1.1}_{-1.2} \times 10^{-3}, \tag{14}$$

being the first evidence of mass difference between neutral charm-meson eigenstates.

6. Search for time-dependent *CP* violation in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays

CP-violation in the mixing and in the interference between mixing and decay can be probed through a study of the raw time-dependent asymmetry

$$A_{\text{raw}}(f,t) = \frac{\text{N}(D^0 \to f,t) - \text{N}(\overline{D}^0 \to f,t)}{\text{N}(D^0 \to f,t) + \text{N}(\overline{D}^0 \to f,t)} = A^{\text{decay}}_{CP}(f) - A_\Gamma \frac{t}{\tau_{D^0}} + A^{\text{tag}}_{D}(f,t) + A_P(f,t), \tag{15}$$

where $A^{\text{tag}}_D(f,t)$ and $A_P(f,t)$ are time-dependent experimental asymmetries. The parameter of interest A_Γ in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays is determined through a linear fit to their respective time-dependent asymmetries. This has been performed using prompt decays collected in 2015 and 2016 (1.9fb^{-1}) [14] and semileptonic B decays collected from 2016 to 2018 (5.4fb^{-1}) [15]. Combinations of $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ results yield:

$$A_\Gamma(\text{prompt}) = (3.4 \pm 3.1 \pm 0.6) \times 10^{-4}, \qquad A_\Gamma(\text{semileptonic}) = (-2.9 \pm 2.0 \pm 0.6) \times 10^{-4}. \tag{16}$$

Combined with previous measurements from LHCb [16, 17] and other experiments [18–20], it leads to the unofficial world average value

$$A_\Gamma = (-1.9 \pm 1.6 \pm 0.5) \times 10^{-4}, \tag{17}$$

which is compatible with the *CP* conservation hypothesis.

7. Conclusion

CP-violation has been observed for the first time in charm decays through a departure from zero of ΔA_{CP} at the level of 5.3σ. Additional signatures of *CP* violation are being investigated and LHCb is dedicated to finalising multiple measurements using the full Run-1 and Run-2 dataset. However, most results are currently limited by statistics, owing to the smallness of *CP* violation in the charm sector. The next data-taking periods will lead to a decrease of the statistical uncertainties by up to one order of magnitude [21] and help to clarify the picture of *CP* violation in the charm sector.

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