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Search for CP violation in $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays

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Summary. — The existence of CP violation has been recently proved by the LHCb experiment in neutral charm meson decays measuring the CP-violating difference $\Delta A_{CP} = \mathcal{A}^{CP}(K^-K^+) - \mathcal{A}^{CP}(\pi^-\pi^+)$. A measurement of the single $\mathcal{A}^{CP}(K^-K^+)$ and $\mathcal{A}^{CP}(\pi^-\pi^+)$ is presented making use of $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays promptly produced in proton-proton collisions and reconstructed in data recorded by the LHCb experiment at a centre-of-mass energy of 13 TeV, corresponding to 6/fb of integrated luminosity. The flavour of the meson is determined by the charge of the pion in $D^{*+} \to D^0\pi^+$ decays. High-yield samples of Cabibbo-favoured D^{*+}, D^+ and D_s^+ decays are used to subtract nuisance asymmetries due to production and detection effects.

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 with the measurement [5]

$$\Delta A_{CP} = \mathcal{A}^{CP}(K^-K^+) - \mathcal{A}^{CP}(\pi^-\pi^+) = (-15.4 \pm 2.9) \times 10^{-4}. \quad (1)$$

However, the interpretation of this observation is unclear, since theoretical predictions are difficult to compute reliably due to low-energy quantum-chromodynamics effects [6-8]. For this reason, further studies on charm decays are needed to clarify the picture. In particular, the measurement of the individual *CP* asymmetries $\mathcal{A}^{CP}(K^-K^+)$ and $\mathcal{A}^{CP}(\pi^-\pi^+)$ is essential to understand the nature of the observed violation and to provide important insight in the breaking of the U-spin symmetry relation $\mathcal{A}^{CP}(K^-K^+) = -\mathcal{A}^{CP}(\pi^-\pi^+)$. Preliminary results of the measurement of these individual *CP* asymmetries are presented in the next section.

2. – Search for *CP* violation in $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays

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

$$\mathcal{A}^{CP}(f) \equiv \frac{\Gamma(D \to f) - \Gamma(\overline{D} \to \bar{f})}{\Gamma(D \to f) + \Gamma(\overline{D} \to \bar{f})}, \tag{2}$$

where Γ 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 $\pi^-\pi^+$, $\mathcal{A}^{CP}$ is unaffected by D^0-$\overline{D}^0$ mixing and corresponds to the direct *CP* asymmetry, excepting terms of order 10^{-5}.

The analysis currently ongoing within the LHCb Collaboration uses data collected during Run 2, corresponding to an integrated luminosity of $5.7\,\text{fb}^{-1}$. The D^0 mesons considered are promptly produced in $D^{*+} \to D^0\pi^+$ flavor-conserving decays and their flavour is inferred from the charge of the accompanying pion. The strategy consists in measuring $\mathcal{A}^{CP}(K^-K^+)$ and then retrieving $\mathcal{A}^{CP}(\pi^-\pi^+)$ from the combination with ΔA_{CP}.

The raw asymmetry between the observed yields of $D^0 \to K^-K^+$ and $\overline{D}^0 \to K^-K^+$ decays can be approximated as

$$A(K^-K^+) \approx \mathcal{A}^{CP}(K^-K^+) + A_P(D^{*+}) + A_D(\pi^+), \tag{3}$$

where A_P and A_D are the production asymmetry of the D^{*+} meson and the detection asymmetry of the accompanying pion, respectively. Two methods are considered to cancel out these nuisance asymmetries and extract the *CP* asymmetry. This can be obtained by correcting the raw asymmetry with kinematically weighted samples of Cabibbo-favoured D^{*+} and D^+ or D_s^+ decays where CPV can be neglected,

$$\begin{aligned}\mathcal{A}^{CP}(K^-K^+)|D^+ = {} & A(D^0 \to K^-K^+) - A(D^0 \to K^-\pi^+) \\ & + A(D^+ \to K^-\pi^+\pi^+) - A(D^+ \to K^0_{\rm S}\pi^+),\end{aligned} \tag{4}$$

$$\begin{aligned}\mathcal{A}^{CP}(K^-K^+)|D_s^+ = {} & A(D^0 \to K^-K^+) - A(D^0 \to K^-\pi^+) \\ & + A(D_s^+ \to \phi\pi^+) - A(D_s^+ \to K^0_{\rm S}K^+),\end{aligned} \tag{5}$$

TABLE I. – *Summary of the uncertainties in units of* 10^{-4} *on the measured quantities.*

Source	$\mathcal{A}^{CP}(K^-K^+)\|D^+$	$\mathcal{A}^{CP}(K^-K^+)\|D_s^+$	ρ
Secondary decays	0.6	0.3	–
Peaking backgrounds	0.3	0.4	0.74
Fit model	1.1	1.0	0.05
Kinematic diff.	0.8	0.4	–
Neutral kaon asym.	0.6	1.3	1.00
Charged kaon asym.	–	1.0	–
Total systematic	1.6	2.0	0.28
Statistical	8.8	6.7	0.05

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

The kinematic weighting procedure is the core of the analysis. This technique consists in applying weights, appropriately calculated, to the events of the various control channels so that the three-dimensional kinematic distributions of the particles are in agreement between the pairs of samples considered and thus the contributions of induced nuisance asymmetries are canceled. The developed algorithm is based on an iterative method and allows for an excellent agreement between the kinematic distributions of the various channels considered.

The raw asymmetries of the decay modes of interest are determined by simultaneous fit to the D^{*+} and D^{*-} (or $D^+_{(s)}$ and $D^-_{(s)}$) invariant-mass distributions. Several sources of systematic uncertainties are considered. They are due to possible contributions arising from the presence of D^{*+}, D^+ or D_s^+ mesons from b-hadron decays, the presence of peaking backgrounds, the mismodeling in the shapes used to fit the raw asymmetries, the inaccuracy in the kinematic weighting, the uncertainty in the neutral kaon asymmetry, and the neglected contribution from charged kaon detection asymmetries in the $D_s^+ \to \phi\pi^+$ decays. Table I reports a summary of all the systematic uncertainties together with the statistical uncertainties and the correlation coefficients between the two methods.

The preliminary result, obtained by the combination of the two methods, gives an uncertainty of about 6×10^{-4} and 7×10^{-4} for $\mathcal{A}^{CP}(K^-K^+)$ and $\mathcal{A}^{CP}(\pi^-\pi^+)$, respectively. This represents a huge accomplishment due to an improvement of a factor 40% with respect to extrapolation from previous measurements [9]. In fact, the work here presented introduces the use of additional control channels (the D_s^+ decay modes) for the first time. Moreover, thanks to the novel kinematic weighting strategy, the systematic error is kept under control and the uncertainty on the measurement is statistically dominated. This will allow to easily reproduce the measurement on the future data samples that are being collected by the LHCb experiment.

The central values are blinded until the end of the internal review of the LHCb Collaboration. Given the achieved precision and the current predictions, an observation of CP violation is unlikely to be obtained with the individual $\mathcal{A}^{CP}$ measurements, however an evidence is still possible in the case of broken U-spin symmetry.

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