Charm CPV: observation and prospects

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1 Introduction

In physics, the symmetries and their violation always provide deep insights into the Nature. The parity ($P$) symmetry represents the system is unchanged under the space reflection. The violation of parity, firstly proposed by Lee and Yang and subsequently discovered in 1956, plays the key role in the understanding of the weak interaction which is one of the four basic forces of nature. The charge ($C$) symmetry describes a property between particles and their anti-particles. The violation of the combined charge-parity ($CP$) symmetry was unexpectedly observed in kaon meson decays in 1964. The $C$ and $CP$ violation ($CPV$) are required to explore why there are much more matter than anti-matter in the Universe.

The explanation of $CPV$ was proposed by Kobayashi and Maskawa (KM) in 1973 by introducing three generations of quarks, or say six quarks, whereas only three quarks were established at the time. All the six quarks were found in the following twenty years. This theory was finally manifested by the observation of $CPV$ in the bottom-quark meson system in 2001. The measured amount of $CPV$ in the Standard Model (SM) of particle physics is about ten orders of magnitude smaller than required by the matter-antimatter asymmetry in the Universe. Therefore, it is important to search for new sources of $CPV$ beyond the SM (BSM). The KM mechanism also predicts the existence of $CPV$ in the charm-quark system which, however, had never been discovered with a lot of efforts during the past decade. The LHCb collaboration eventually observed the charm $CPV$ in 2019 via measuring the difference of $CP$ asymmetries of $D^0 \to K^+K^−$ and $D^0 \to π^+π^−$ with the result of $(1.54 \pm 0.29) \times 10^{−3}$ [1], with the significance of 5.3σ. After the establishment of $CPV$ in the strange- and bottom-quark systems, the observation of charm $CPV$ is a milestone of particle physics.

2 LHCb and recent measurement

Large Hadron Collider beauty experiment (LHCb) on Large Hadron Collider (LHC) is a dedicated heavy-flavour (particles containing $c$ and $b$ quarks) experiment with a special focus on $CPV$ measurements. Being a single-arm forward spectrometer with excellent vertex, interaction point and momentum resolution in combination with high efficient particle identification systems and large $c\bar{c}$ cross-section, LHCb can study charm physics, especially possible $CP$ violating processes, with higher precision than previous dedicated $B$-factory experiments.

In the time period from 2011 to 2018, LHCb has collected 9 fb$^{−1}$ of data, roughly corresponding to the sample of decays of $10^{10} D^0$ whose components are a charm quark and an anti-up quark. Charmed mesons can be produced as a direct result of proton-proton collisions (prompt production) or via weak decays of $b$-hadrons (semileptonic productions). In the case of studies using $D^0$ mesons, prompt production is in fact a strong decay $D^{*(2010)^+} \to D^0 π^+$ and charge conjugated decay as well. Usage of this decays allows to determine exact charm charge of $D$ meson according to the charge of bachelor pion. Semileptonic process are then defined by the weak decay $\overline{B}^0 \to D^0 μ^+τ_μX$ and charge conju-
gated, where $X$ stands for any allowed additional particles.

Recently reported $CPV$ observation in Charm by the LHCb is utilising around $44 \times 10^6$ and $14 (3) \times 10^6 D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+\pi^-$ prompt (semileptonic) decays, respectively. This data set, corresponding to 6 fb$^{-1}$, was recorded from 2015 to 2018 at collision energy 13 TeV.

Time dependent $CP$ asymmetry of decays into a final state $f$ is given by

$$A_{CP}(f, t) \equiv \frac{\Gamma(D^0(t) \rightarrow f) - \Gamma(\overline{D}^0(t) \rightarrow f)}{\Gamma(D^0(t) \rightarrow f) + \Gamma(\overline{D}^0(t) \rightarrow f)}, \quad (1)$$

where $\overline{D}^0$ is the anti-particle of $D^0$. This asymmetry can be also written as the combination of direct and indirect $CP$ asymmetry effect: $A_{CP}(f) \approx a_{CP}^{dir}(f) - \frac{\langle t(f) \rangle}{\tau(D^0)} A_T(f)$, where $\langle t(f) \rangle$ denotes the mean decay time of $D^0 \rightarrow f$ influenced by the experimental efficiency, $a_{CP}^{dir}(f)$ is the direct $CP$ asymmetry, $\tau(D^0)$ the $D^0$ lifetime and $A_T$ the asymmetry between the $D^0 \rightarrow f$ and $\overline{D}^0 \rightarrow f$ effective decay widths.

However, the $A_{CP}$ values, as defined above are not accessible directly by the experimental methods and must be extracted from the data. Directly measurable value is the difference between raw yields, $A_{raw}$, of $D^0 \rightarrow K^+K^-$ and $\overline{D}^0 \rightarrow K^-K^+$ decays or between $D^0 \rightarrow \pi^+\pi^-$ and $\overline{D}^0 \rightarrow \pi^-\pi^+$, respectively. $A_{raw}$ can be very well approximated, up to the order $O(10^{-6})$, as linear combination of physical $CP$ asymmetry $A_{CP}$, detection asymmetry of $D^0$ which is equal to zero due to charge conjugated final states, mother particle production asymmetry and detection asymmetry of tagging particle. These detection and production asymmetries are cancelled by equalising kinematics between $K^+K^-$ and $\pi^+\pi^-$ decay modes and then taking a difference. This equalisation is done in three dimension of kinematic variables simultaneously after the removal of phase space regions with large intrinsic asymmetries due to the LHCb detector geometry. Final experimental formula is then written as following

$$\Delta A_{CP} \equiv A_{CP}(D^0 \rightarrow K^+K^-) - A_{CP}(D^0 \rightarrow \pi^+\pi^-) = A_{raw}^{equalised}(K^+K^-) - A_{raw}^{equalised}(\pi^+\pi^-). \quad (2)$$

The difference of $CP$ asymmetries in $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+\pi^-$ are finally measured by LHCb as $\Delta A_{CP}^{prompt} = [-18.2 \pm 3.2 (\text{stat.}) \pm 0.9 (\text{syst.})] \times 10^{-4}$, $\Delta A_{CP}^{semileptonic} = [-9 \pm 8 (\text{stat.}) \pm 5 (\text{syst.})] \times 10^{-4}$.

By combing both these results with the previous LHCb measurements with the Run I data of 3 fb$^{-1}$, it can be obtained that

$$\Delta A_{CP}^{combined} = (-15.4 \pm 2.9) \times 10^{-4}, \quad (3)$$

where the uncertainty includes statistical and systematic contributions. This result deviates from zero $CP$ asymmetry hypothesis on 5.3 $\sigma$ level. This is the first observation of $CP$ violation in the charm sector.

With the LHCb average of $A_F$ [2], the direct $CP$ asymmetry can then be obtained as $\Delta a_{CP}^{dir} = (-15.7 \pm 2.9) \times 10^{-4}$, which shows the sensitivity of $\Delta A_{CP}$ to the direct $CPV$. Finally, the combined fit of the direct and indirect $CP$ asymmetries by the Heavy Flavour Averaging Groups (HFLAV) is shown in Fig. 1. The current world average result excludes the no-$CPV$ hypothesis on the level of 5.44 $\sigma$.

### 3 Theoretical explanations and implications

In theory, $CPV$ in $D^0 \rightarrow K^+K^-$ and $\pi^+\pi^-$ results from the interference between the tree and penguin amplitudes of charm decays. It is difficult to calculate in the first-principle QCD methods due to the large non-perturbative contributions at the charm scale. Therefore, the order of magnitude of predictions on the charm $CPV$ is meaningful.

Before 2019, several orders of magnitude of charm $CPV$ have been predicted in literatures, ranging from $10^{-4}$ to $10^{-2}$. If persisting in using the perturbative QCD, $CPV$ in charm decays is naively expected as $A_{CP} \sim \frac{\sin\beta}{1 - \sin\beta} |V_{cs}|^2 |V_{ub}|^2 \approx O(10^{-4})$. On the contrary, If taking the unknown non-perturbative contributions to be arbitrarily large, the charm $CPV$ could be as large as $10^{-2}$, to be consistent with the experimental results in 2011 when $\Delta A_{CP}$ was measured to be $(-0.82 \pm 0.24)\%$ by LHCb [5]. Due to the limit of space of this article,
relevant references can be seen in [6]. The most interesting thing is that only two papers, written by Cheng and Chiang (CC) [7, 8] and Li, Liu and Yu (LLY) [8], quantitatively predicted $\Delta A_{CP}$ at the order of $10^{-3}$ before the observation. They are much smaller than the experimental measurements in 2011 and 2012, but manifested by the recent LHCb result. The comparison between the experimental measurements and the theoretical predictions by CC and LLY are shown in Fig. 2.

To predict the charm $CPV$, it should relyably obtain the tree amplitudes first, to understand the dynamics at the charm scale, and then calculate the penguin amplitudes reasonably. Including all the strong-interaction effects, especially the non-perturbative contributions, the topological diagrammatic approach works well for hadronic charm-meson decays by extracting the tree amplitudes from the data of branching fractions [7, 8]. Under the factorization hypothesis, LLY proposed the factorization-assisted topological-amplitude approach which relate the penguin amplitudes to the tree amplitudes without any additional free parameters. Considering the uncertainties of input parameters, it is predicted that $\Delta A_{CP} = (-0.57 \sim -1.87) \times 10^{-3}$ [8], which is consistent with the latest result by the LHCb measurement. CC assumed that the penguin-exchange diagram is identical to the $W$-exchange diagram, $PE = E$, so that $\Delta A_{CP} = (-1.39 \pm 0.04) \times 10^{-3}$ or $(-1.51 \pm 0.04) \times 10^{-3}$ [7]. To give a reasonable uncertainty of the CC approach, considering the possible difference between $PE$ and $E$, we take $PE$ ranging from $E/2$ to $2E$, and show the result in Fig. 2. Note that both CC and LLY predicted $\Delta A_{CP}$ within the Standard Model.

After the observation of charm $CPV$ by LHCb in 2019, new explanations are explored either in the SM or in the BSM. In the SM picture, the measured result of $\Delta A_{CP}$ can be explained by the non-perturbative final-state-interaction contributions from the rescattering effects [9] or the near-by resonant effects [10]. Alternatively, given that the SM contribution to the charm $CPV$ is very small based on the heavy-quark expansion and the perturbative QCD, the observed $\Delta A_{CP}$ are explored by the BSM explanations, such as the flavour-violating $Z'$ model, the two-Higgs-double model, and vector-like quark models [11-13].

4 Impact and prospect for the future

Although the combination of $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+\pi^-$ was expected to be one of the best probes of $CPV$ in charm, many other studies are possible or even already ongoing, such as $D^0 \rightarrow K^0_S\bar{K}^0_S$ and $D^+ \rightarrow K^+K^-\pi^+$ [6], to test and understand the dynamics of charm decay and to search for new physics beyond the SM. Multibody decays could be potentially more interesting due to richer decay structure, at the same time such studies generally require more complicated analysis methods and higher recorded luminosity. Another interesting measurement is being performed to investigate a novel effect of $CPV$ in charmed meson decaying into $K^0_S$, which comes from mother decay and daughter mixing with predicted values reaching the experimental sensitivity [14].

The LHCb detector is currently going through the substantial upgrade which will allow to record data with 5 times higher luminosity than during the years 2015-2018. This, in combination with the new full software trigger, a crucial point for the charm physics, will allow LHCb to achieve an unprecedented precision in the heavy flavour sector $CPV$ measurements. This opens a door to measure possible $CPV$ effects in rare decays, e.g. radiative and semi-leptonic decays. Another dedicated heavy-flavour experiment is Belle II, which started taking data in 2019, from which contributions to $CPV$ measurements are expected, especially results from the decays with neutral particles in the final states. Another substantial upgrade of the LHCb is planned for the time period after 2030, with additional ten fold increase of luminosity. The LHCb is currently expected to be only dedicated heavy-flavour experiment taking data during that time period. Table 1 summarises future yield prospects and expected sensitivity in $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+\pi^-$ decays.
In summary, the first experimental observation of $CP$ violation in the charm sector was done with an amazing sensitivity obtained by LHCb in 2019. This is a milestone in the high energy physics. The result is consistent with the theoretical predictions by CC and LLY. It is expected that more precise measurements and more theoretical studies in the near future will help us to deeply understand the dynamics at the charm scale and to explore the new physics effects.

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Table 1 Predicted yields for $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+\pi^-$ yields for different data taking periods. Last column shows expected precision of the $\Delta A_{CP}$ measurements with corresponding yields. Taken from Ref. [15].

| Sample (fb$^{-1}$) | $D^0 \rightarrow K^+K^-$ yield | $D^0 \rightarrow \pi^+\pi^-$ yield | $\sigma(\Delta A_{CP})$ [%] |
|------------------|-------------------------------|-------------------------------|-----------------|
| Run 1-2 (9)      | $52 \times 10^6$              | $17 \times 10^6$              | 0.03            |
| Run 1-3 (23)     | $280 \times 10^6$             | $94 \times 10^6$              | 0.013           |
| Run 1-4 (50)     | $1 \times 10^9$               | $305 \times 10^6$             | 0.01            |
| Run 1-5 (300)    | $4.9 \times 10^6$             | $1.6 \times 10^6$             | 0.003           |