THE CHARM OF CHARM*

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The existence of CP violation in charm-particle decays has been elusive for a long time in experiments. It was observed in 2019 in the LHCb experiment for the first time. During the LHC Run 1 and 2, the LHCb Collaboration collected a huge data sample on a scale never seen before. These data enable the most sensitive searches for CP violation ever performed. Such measurements are interpreted as precise tests of the Standard Model. The latest results achieved in charm decays are reviewed in this article. Discussion about two innovative model-independent techniques (Kernel Density Estimation and Energy Test) for searching for CP violation in charm baryons is also done.

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1. Introduction

The elementary particles and their interactions are described using the Standard Model (SM). However, SM does not explain all observed processes. On the one hand, not fully understood issue is matter dominance over antimatter. On the other hand, a known value of CP violation (CPV) is not sufficient to justify the disparity of particles and antiparticles in the universe, implying the necessity of the presence of other sources of CP violation beyond those acknowledged in the SM. Hence, one can interpret CPV searches as looking for a sign of the new physics. These searches are conducted in two ways: in the ATLAS and the CMS experiments, physicists look for new processes and new particles directly produced in proton–proton (pp) interactions, and in the LHCb experiment, physicists test the SM in very precise measurements of well-known processes. Any disagreement with the SM predictions will indirectly indicate the existence of new phenomena. The charm sector is a promising place to find new physics effects.

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The CPV in the charm sector has been observed for the first time in 2019 in the LHCb experiment [1]. The value of CP violation in the charm sector is expected to be less than 10^{-3} [2], which means that the background from the SM is small enough to make searches for new physics easier. However, it should be pointed out that the CP asymmetry ($A_{\rm CP}$) in the SM can only be observed in so-called Singly Cabibbo-suppressed (SCS) decays, for which at least two decay amplitudes interfere with different weak (ϕ) and strong (δ) phases: $A_{\rm CP} \sim |A_1||A_2|sin(\phi_1 - \phi_2)\sin(\delta_1 - \delta_2)$. In the case of baryons of any flavour, CPV is not observed so far.

2. The first evidence of CP violation in charm sector

The CPV was observed in the charm sector for the first time in 2019 after plenty of experimental searches. In these studies, the $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays were analysed using a huge sample of charm hadrons collected by the LHCb experiment during two data-taking cycles of Run 1 and Run 2 at the centre-of-mass energy of 13 TeV corresponding to an integrated luminosity of 5.9 fb^{-1} [1]. The total yields of those decays are about 44 M and 14 M, respectively. The invariant mass distributions corresponding to $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays are presented in Fig 1.

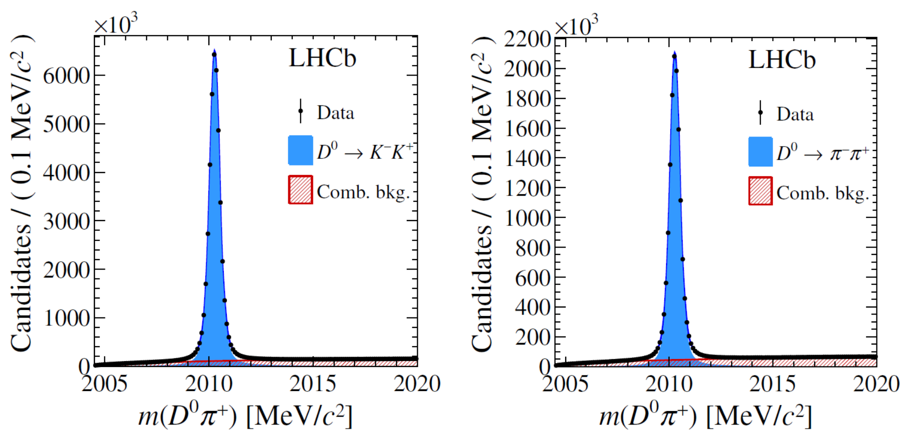

Fig. 1. The invariant mass distribution for the (left) $D^0 \to K^-K^+$ and (right) $D^0 \to \pi^-\pi^+$ decays.

The time-dependent CP asymmetry $A_{\rm CP}(f;t)$ between states produced as D^0 or $\bar{D}^0$ mesons decaying to a CP eigenstate f at time t is defined as

$$A_{\rm CP} = \frac{\Gamma\left(D^0(t) \to f\right) - \Gamma\left(\bar{D}^0(t) \to f\right)}{\Gamma\left(D^0(t) \to f\right) + \Gamma\left(\bar{D}^0(t) \to f\right)}\,, \tag{1}$$

where Γ stands for the time-dependent rate of a given decay. The observable difference in CP asymmetries between two decays is measured

$$\Delta A_{\mathrm{CP}} \equiv A_{\mathrm{CP}}(K^-K^+) - A_{\mathrm{CP}}\left(\pi^-\pi^+\right) = A_{\mathrm{raw}}(K^-K^+) - A_{\mathrm{raw}}\left(\pi^-\pi^+\right) , \quad (2)$$

where A_{raw} is so-called raw (total) asymmetry which is the sum of all existing asymmetries, including A_{CP}: $A_{\mathrm{raw}} = A_{\mathrm{CP}}(f) + A_{\mathrm{D}}(f) + A_{\mathrm{P}}(D)$, where A_{D} is detector and A_{P} is production asymmetries. Both the asymmetries A_{D} and A_{P} could be of the order of 2%. The detector asymmetries cancel in the first order since the final states are charge symmetric. The production asymmetries cancel in the subtraction of two CP asymmetries. Hence, ΔA_{CP} is measured. Another advantage of this approach is that these observables and raw asymmetries are more accessible to obtain than single CP asymmetries.

The ΔA_{CP} is measured [1] as $\Delta A_{\mathrm{CP}} = (-15.4 \pm 2.9) \times 10^{-4}$. Both statistical and systematic contributions are included in one uncertainty. The significance of the deviation from zero corresponds to 5.3 standard deviations. This is the first observation of CPV in the decay of charm hadrons.

The ΔA_{CP} is a combination of direct and indirect CP asymmetries [2]. The contribution from the latter is smaller than 10%.

$$\Delta A_{\mathrm{CP}} = \left[a_{\mathrm{CP}}^{\mathrm{dir}}(K^-K^+) - a_{\mathrm{CP}}^{\mathrm{dir}}(\pi^-\pi^+)\right] + \frac{\Delta\langle t\rangle}{\tau} a_{\mathrm{CP}}^{\mathrm{ind}} . \quad (3)$$

Nevertheless, to properly determine and investigate the source of potential CP violation, one has to examine the single asymmetry.

3. Single charm meson decay

Recently, the LHCb experiment has investigated $D^0 \to K^-K^+$ decays again to measure single CP asymmetry [3]. Data were collected at the centre of mass energy of 13 TeV corresponding to an integrated luminosity of 5.9fb^{-1}. The strategy is similar to that described in Sec. 2, however, instead of calculating ΔA_{CP}, several control channels with negligible CP asymmetries are taken into account to remove nuisance asymmetries and obtain the single CP asymmetry in $D^0 \to K^-K^+$ decay. The raw asymmetries of considered decays can be written as

$$\begin{aligned}
A\left(K^-\pi^+\right) &\approx A_{\mathrm{prod}}\left(D^{*+}\right) - A_{\mathrm{det}}\left(K^+\right) + A_{\mathrm{det}}\left(\pi^+\right) + A_{\mathrm{det}}\left(\pi^+_{\mathrm{tag}}\right) , \\
A\left(K^-\pi^+\pi^+\right) &\approx A_{\mathrm{prod}}\left(D^+\right) - A_{\mathrm{det}}\left(K^+\right) + A_{\mathrm{det}}\left(\pi^+_1\right) + A_{\mathrm{det}}\left(\pi^+_2\right) , \\
A\left(\bar{K}^0\pi^+\right) &\approx A_{\mathrm{prod}}\left(D^+\right) - A_{\mathrm{det}}\left(K^0\right) + A_{\mathrm{det}}\left(\pi^+\right) , \\
A\left(\phi\pi^+\right) &\approx A_{\mathrm{prod}}\left(D^+_s\right) + A_{\mathrm{det}}\left(\pi^+\right) , \\
A\left(\bar{K}^0K^+\right) &\approx A_{\mathrm{prod}}\left(D^+_s\right) - A_{\mathrm{det}}\left(K^0\right) + A_{\mathrm{det}}\left(K^+\right) . \quad (4)
\end{aligned}$$

Ultimately, measurement of a single $A_{\rm CP}$ is performed by two methods:

$$\begin{aligned} A_{\rm CP} &= A\left(K^-K^+\right) - A\left(K^-\pi^+\right) + A\left(K^-\pi^+\pi^+\right) - A\left(\bar{K}^0\pi^+\right) - A\left(K^0\right) , \\ A_{\rm CP} &= A\left(K^-K^+\right) - A\left(K^-\pi^+\right) + A\left(\phi\pi^+\right) - A\left(\bar{K}^0K^+\right) - A\left(K^0\right) . \end{aligned} \tag{5}$$

The resulting values for both methods are: $A_{\rm CP}(K^+K^-) = (13.6 \pm 8.8 \pm 1.6) \times 10^{-4}$ and $A_{\rm CP}(K^+K^-) = (2.8 \pm 6.7 \pm 2.0) \times 10^{-4}$, with a correlation corresponding to 0.06. The central values are consistent with zero. The same conclusion can be made for averaged time-integrated CP asymmetry: $A_{\rm CP}(K^+K^-) = (6.8 \pm 5.4 \pm 1.6) \times 10^{-4}$. Nonetheless, as stated before, $A_{\rm CP}$ is a sum of direct and indirect components: $A_{\rm CP}(f) \approx a^{\rm dir}_{\rm CP} + (\langle t\rangle/\tau_{\rm D})\Delta Y$, where ΔY consists of mixing parameters combined with a contribution from direct CP asymmetry. Therefore, by including previous results from Sec. 2 and subtracting $\Delta A_{\rm CP}$, one can determine direct asymmetries in the $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays: $a^{\rm dir}_{K^-K^+} = (7.7 \pm 5.7) \times 10^{-4}$ and $a^{\rm dir}_{\pi^-\pi^+} = (23.2 \pm 6.1) \times 10^{-4}$. The $a^{\rm dir}_{K^-K^+}$ is consistent with CP symmetry, but $a^{\rm dir}_{\pi^-\pi^+}$ deviates from zero at $3.8\,\sigma$ level. This is the first evidence of direct CPV in a single charm decay.

4. CP violation searches in charm baryons

So far, CP violation has not been observed in any baryon decays. In the charm sector particularly promising is $\Xi_c^+ \to pK^-\pi^+$ channel. First searches were conducted using data collected during Run 1 at the centre-of-mass energy of 7 and 8 TeV corresponding to $3\,{\rm fb}^{-1}$. Analysis was performed with two model independent tests: the binned $S_{\rm CP}$ [4] method and unbinned k-nearest neighbours (kNN) [5] technique. Results were consistent with CP symmetry. Next study of Ξ_c^+ decays is already underway. Data taken in Run 2 is being used and two other approaches were introduced: Energy Test (ET) and Kernel Density Estimation (KDE) technique.

4.1. The Energy Test

The Energy Test (ET) [6–9] was developed in 2004 as an analogue of the potential energy in the field of charges characterised by density functions and represents a test based on an invariant statistic, T, that is evaluated using the notion of potential energy of continuously distributed electric charge. Former studies showed that it vastly outperforms the χ^2 test under conditions typical for this kind of analyses [10]. It calculates a single test statistics T, which correlates the difference between two p.d.f.s in the multivariate space

$$T = \frac{1}{2}\iint \left[f\left(\vec{x}\right) f\left(\vec{x}\,'\right) + \bar{f}\left(\vec{x}\right)\bar{f}\left(\vec{x}\,'\right) - 2f\left(\vec{x}\right)\bar{f}\left(\vec{x}\,'\right)\right]\psi\left(\left|\vec{x}-\vec{x}\,'\right|\right)\,{\rm d}\vec{x}{\rm d}\vec{x}\,' , \tag{6}$$

where $\psi(|\vec{x} - \vec{x}\,'|)$ is a weighting function usually taken as a Gaussian of Euclidean squared distance d^2 between two points in phase space $\psi(\Delta\vec{x}_{ij}) = \mathrm{e}^{-\Delta\vec{x}\,_{ij}^2/2\sigma^2}$.

We assume that the T statistics probes the difference between f and $\bar{f}$ distributions. If we follow the potential energy analogy, we can assume that f represents the distribution of positive and $\bar{f}$ of negative charge respectively. Thus, the potential energy will be minimal if both distributions are identical (charges compensate perfectly). So, T-statistic should tend to zero for similar distributions.

T can be estimated and calculated without knowledge about either f or $\bar{f}$ distributions by using the following approximated formula:

$$T = \frac{1}{n(n-1)} \sum_{i,j>1}^{n} \psi(\Delta\vec{x}_{ij}) + \frac{1}{\bar{n}(\bar{n}-1)} \sum_{i,j>1}^{\bar{n}} \psi(\Delta\vec{x}_{ij}) - \frac{1}{n\bar{n}} \sum_{i,j}^{n,\bar{n}} \psi(\Delta\vec{x}_{ij})\,. \quad (7)$$

The ET was used several times for CP violation studies in LHCb experiment, but only in the mesons decays [11–13].

4.2. Kernel Density Estimation

Kernel Density Estimation is a non-parametric technique to estimate the probability density function $\hat{f}$ of a random variable. KDE is a fundamental data smoothing technique where inferences about population are made, based on the finite data sample

$$\hat{f}(x) = \frac{1}{n} \sum_{i=1}^{n} \omega(x - x_i, h), \quad \omega(t,h) = \frac{1}{h} K\left(\frac{t}{h}\right), \quad (8)$$

where ω is the weighting function. K is the kernel, which regulates the shape of the weighting function and h is a smoothing parameter, often called the bandwidth.

For our analysis, the Triangle kernel is used, which is defined as follows: $w(t,h) = \frac{1}{h}(1 - |t|/h)$ for $|t| < h$ and 0 for $|t| \geq h$.

A huge influence on the performance of the method is given by the choice of the parameter h. For the invariant function, the globally fixed bandwidth can be employed: $h = \kappa\hat{S}N^{-0.2}$, where $\hat{S}$ is the sample standard deviation, N is its size, and κ is the so-called correction parameter. It governs the degree of smoothing of the final estimate and usually takes a value from 1.06 to 1.44. In the case of distribution with a more complicated shape, one has to use the bandwidth parameter, which depends on the local feature of the data, to avoid a significant drop in the sensitivity to the estimation results. Hence, the adaptive bandwidth parameter is introduced [14]: $h_i^{\mathrm{opt}} = h/\sqrt{f(x_i)}$. It is calculated for each point x_i individually. For the first iteration, one uses globally defined h to determine the p.d.f. $f(x_i)$ and then the bandwidth parameter is optimised. This procedure can be repeated several times till the best value of the smoothing parameter is reached.

As stated at the beginning of this section, the KDE technique aims to find the probability density function of a given random variable, *i.e.*, to estimate p.d.f. for particles and antiparticles. To compare those functions and correctly measure differences between them, the p-value has to be obtained. Therefore, the second method, along with KDE, is needed. That method could be Energy Test. Two techniques can be combined to acquire final results. Additionally, the two approaches complement each other as knowledge of density functions allows using the complete formula for test statistics in ET and reach its full potential. It is worth pointing out that the KDE method was never applied in CP violation searches.

5. Conclusions

The searches for CPV in the charm sector have been intensified. Large data samples collected by the LHCb Collaboration allowed for new measurements of CP asymmetry for charm mesons. First observations of CPV in the decays of charm hadrons opened the window to the search for other sources of CP asymmetry in the charm sector. One of the results of this study is a recent measurement of CPV. The obtained CP asymmetry deviates from zero at $3.8\,\sigma$ level, and it is the first evidence of the direct CP asymmetry in the single charm decay. As for CPV in charm baryons, the searches are continuing, and CP asymmetry is yet to be observed.

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