

# CP violation in charm

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**Abstract.** The existence of  $CP$  violation in the decays of strange and beauty mesons is very well established experimentally. On the contrary,  $CP$  violation in the decays of charmed particles has been elusive for a long time and has been observed for the first time in 2019 by the LHCb experiment. Since then several studies have been performed in the charm sector. During the LHC Run 1 and Run 2, the LHCb collaboration has collected large samples containing charm hadron decays, on a scale never seen before. Collected data enabled physicists to obtain several new results, most of which surpassed previous results and became new world's best measurements. Presently the LHCb spectrometer is being upgraded to enhance readout system, improve subdetector components and increase integrated luminosity to  $50 \text{ fb}^{-1}$  by the end of Run 4.

## 1 Introduction

$CP$  symmetry (charge conjugation parity symmetry) states that laws of physics should be the same if a particle is interchanged with its antiparticle (charge conjugation symmetry) and its spatial coordinates are inversed (parity symmetry). However, in case of weak interactions, the matter-antimatter symmetry can be violated under  $CP$  transformation. The weak interactions of the quarks are described by Cabibbo-Kobayashi-Masakawa (CKM) matrix [1, 2].  $CP$  violation in the Standard Model (SM) of particle physics is included through a complex phase in the CKM quark-mixing matrix. There are three ways to violate  $CP$  symmetry. The first one is induced by neutral mesons mixing and is related to the difference in the time-dependent transition probability of mesons and antimesons. Secondly,  $CP$  symmetry can be broken by the difference in the decay amplitude of a particle in comparison to that of its own antiparticle. Third way is related to the interference between decay and mixing [3] to the same final state. The existence of  $CP$  violation in the decays of strange and beauty mesons is very well established experimentally. Nonetheless, the level of  $CP$  violation in the standard model is not sufficient to fully explain the disparity of matter and antimatter in the observable universe, implying the necessity of the presence of additional sources of  $CP$  violation beyond those known in the SM.

## 2 LHCb detector

The LHCb detector [4, 5], is a forward spectrometer covering the pseudorapidity range  $2 < \eta < 5$ . It operates at Large Hadron Collider (LHC) at the European Organization for Nuclear Research (CERN). The LHCb detector was built to perform precise measurement of matter -

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anti-matter asymmetry in the heavy flavour sector (beauty and charm quarks) and search for New Physics beyond the SM.

### 3 Selected LHCb results

During last few years LHCb experiment has provided several new results in beauty and charm sectors, some of which represent new world's best measurements. The latest selected charm results are presented below.

#### 3.1 First observation of $CPV$ in charm

After decades of experimental searches, the  $CP$  violation in the charm sector has been observed in the  $D^0 \rightarrow K^+K^-$  and  $D^0 \rightarrow \pi^+\pi^-$  decays, using the large samples of charmed hadrons collected in Run 1 and Run 2.

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

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

where  $\Gamma$  stands for the time-dependent rate of a given decay. The result of this analysis has been reported as the difference in  $CP$  asymmetries ( $\Delta A_{CP}$ ) of the decays, which is defined as:

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

By combining the Run 2 results with the earlier LHCb measurements [6, 7], value of  $\Delta A_{CP}$  is obtained as:

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

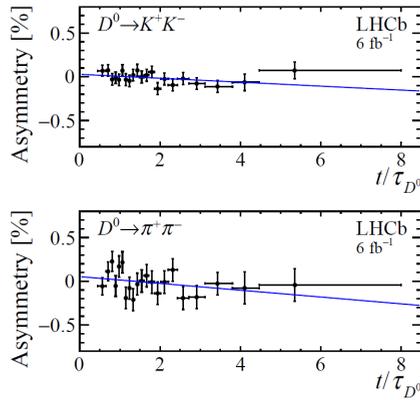
Both statistical and systematic uncertainties are incorporated in one value. The significance of the deviation from zero corresponds to 5.3 standard deviations. This is the first observation of  $CP$  violation in the charm meson decays [8].

#### 3.2 Time-dependent $D^0 - \bar{D}^0$ asymmetry

The Cabibbo-suppressed  $D^0 \rightarrow f$  decays, where typical  $D^0$  and  $\bar{D}^0$  final states consist of either a pair of charged kaons or pions, provide one of the most sensitive tests of time-dependent  $CP$  violation between  $D^0$  and  $\bar{D}^0$  decay rates as defined in eq. (1). The  $D^0$  meson is required to originate from the  $D^*(2010)^+ \rightarrow D^0\pi_{tag}^+$  decay and its flavour is determined by the charge of the accompanying pion. The decay rate can be affected by meson oscillations. The mixing parameters are smaller than 1%, which allows the asymmetry formula to be expanded and approximated by its linear term only:

$$A_{CP}(f, t) \approx a_f^d + \Delta Y_f \frac{t}{\tau_D^0}, \quad (4)$$

where  $a_f^d$  is the  $CP$  asymmetry in the analysed decay,  $\tau_D^0$  is the  $D^0$  meson lifetime, and the  $\Delta Y_f$  is a parameter which approximately equals to the negative of the asymmetry of the effective decay widths of  $D^0$  and  $\bar{D}^0$  mesons into the final state ( $A_f^f$ ). In the Standard Model, the value of  $\Delta Y_f$  is estimated to be of the order of  $10^{-5}$  or less [9].



**Figure 1.** The measured asymmetry ( $A_{CP}$  defined in 4) as a function of decay time for  $D^0 \rightarrow K^+ K^-$  decays (top) and  $D^0 \rightarrow \pi^+ \pi^-$  decays (bottom). A linear fit to data is superimposed.

Nuisance asymmetries are removed by agreeing the kinematics of  $D^0$  and  $\bar{D}^0$  decays and  $\pi_{tag}^+$  and  $\pi_{tag}^-$  candidates. Secondary contributions originated from  $B^0$  or  $B^\pm$  mesons were subtracted with additional cut applied for  $D^0$  impact parameter.

The measured time-dependent asymmetries of the  $D^0 \rightarrow K^+ K^-$  and  $D^0 \rightarrow \pi^+ \pi^-$  decays are presented in Fig. 1. The linear fits to data are overlapped and their slopes are [10]:

$$\begin{aligned} \Delta Y_{K^+ K^-} &= (-2.3 \pm 1.5 \pm 0.3) \times 10^{-4}, \\ \Delta Y_{\pi^+ \pi^-} &= (-4.0 \pm 2.8 \pm 0.4) \times 10^{-4}. \end{aligned} \quad (5)$$

These results are compatible with the conservation of the  $CP$  symmetry within two standard deviations. Moreover, systematic and statistical uncertainties are improved with respect to previous measurements by approximately a factor of two.

The difference of  $\Delta Y_f$  between the two final states, combined with previous LHCb measurements is calculated to be [10]:

$$\Delta Y_f = (-1.0 \pm 1.1 \pm 0.3) \times 10^{-4}. \quad (6)$$

This result is consistent with  $CP$  conservation hypothesis and improves by a factor 2 the uncertainty on the world average.

### 3.3 Measurement of $CP$ asymmetry in $D^0 \rightarrow K_s^0 K_s^0$ decays

Similarly to eq. (1)  $CP$  violation is also measured in the  $D^0 \rightarrow K_s^0 K_s^0$  decays. Its  $CP$  asymmetry is defined as:

$$A^{CP}(K_s^0 K_s^0) \equiv \frac{\Gamma(D^0 \rightarrow K_s^0 K_s^0) - \Gamma(\bar{D}^0 \rightarrow K_s^0 K_s^0)}{\Gamma(D^0 \rightarrow K_s^0 K_s^0) + \Gamma(\bar{D}^0 \rightarrow K_s^0 K_s^0)}. \quad (7)$$

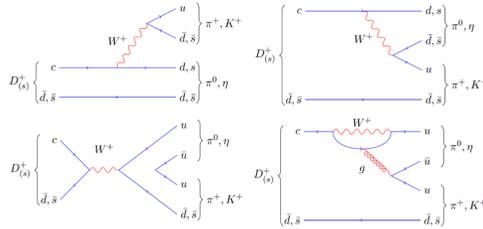
The analysed  $D^0$  mesons come from  $D^{*+} \rightarrow D^0 \pi^+$  decays. The charge of the accompanying so-called tagging pion allows the flavour of the  $D^0$  meson to be determined. Nuisance production and detection asymmetries are removed using the  $D^0 \rightarrow K^+ K^-$  calibration channel, for which  $CP$  asymmetry is known with high precision. The final result after taking into account previous results from whole Run 2 data sample is:

$$A^{CP}(K_s^0 K_s^0) = (-3.1 \pm 1.2 \pm 0.4 \pm 0.2). \quad (8)$$

The current value provides improvement over earlier LHCb result [12]. It is currently the most accurate measurement of this quantity and remains in agreement with  $CP$  conservation hypothesis at the level of 2.4 standard deviations.

### 3.4 $CP$ violation in $D_{(s)}^+ \rightarrow h^+ \pi^0$ and $D_{(s)}^+ \rightarrow h^+ \eta$ decays

The two-body decays  $D_{(s)}^+ \rightarrow h^+ \pi^0$  and  $D_{(s)}^+ \rightarrow h^+ \eta$ , where  $h^+$  denotes either  $\pi^+$  or  $K^+$  are proceed through by Cabibbo favoured (CF), singly-Cabibbo suppressed (SCS) or doubly Cabibbo suppressed (DCS) processes, which are presented in Fig. 2. The SCS  $D^+ \rightarrow \pi^+ \pi^0$  is especially interesting since their  $CP$  asymmetry is expected to be zero in the SM. The definition of this asymmetry is analogous to eq. (7).



**Figure 2.** Feynmann diagrams of  $D_{(s)}^+ \rightarrow h^+ \pi^0/\eta$  decays: tree-level: colour-favored (top left), colour suppressed (top right), annihilation (bottom left) and penguin decay (bottom right).

The  $CP$  asymmetries of seven  $D_{(s)}^+ \rightarrow h^+ \pi^0$  and  $D_{(s)}^+ \rightarrow h^+ \eta$  modes have been measured using samples corresponding respectively to  $9 fb^{-1}$  or  $6 fb^{-1}$ . The raw asymmetries are measured using the following formula:

$$A_{raw}(D_{(s)}^+ \rightarrow h^+ h^0) \equiv \frac{N(D_{(s)}^+ \rightarrow h^+ h^0) - N(D_{(s)}^- \rightarrow h^- h^0)}{N(D_{(s)}^+ \rightarrow h^+ h^0) + N(D_{(s)}^- \rightarrow h^- h^0)}, \quad (9)$$

where  $N$  is the signal yield of the given decay mode. This asymmetry can be approximated by:

$$A_{raw}(D_{(s)}^+ \rightarrow h^+ h^0) \approx A_{CP}(D_{(s)}^+ \rightarrow h^+ h^0) + A_{prod}(D_{(s)}^+) + A_{det}(h^+), \quad (10)$$

where  $A_{prod}(D_{(s)}^+)$  and  $A_{det}(h^+)$  stand for nuisance asymmetries (production and detection), which are eliminated by subtracting the raw asymmetry obtained in the control decay  $D_s^+ \rightarrow K_s^0 h^+$  after kinematically weighted to match the signal modes.

The final  $CP$  asymmetries are resolved to be:

$$\begin{aligned} A_{CP}(D^+ \rightarrow \pi^+ \pi^0) &= (-1.3 \pm 0.9 \pm 0.6)\%, \\ A_{CP}(D^+ \rightarrow K^+ \pi^0) &= (-3.2 \pm 4.7 \pm 2.1)\%, \\ A_{CP}(D^+ \rightarrow \pi^+ \eta) &= (-0.2 \pm 0.8 \pm 0.4)\%, \\ A_{CP}(D^+ \rightarrow K^+ \eta) &= (-6 \pm 10 \pm 4)\%, \\ A_{CP}(D_s^+ \rightarrow K^+ \pi^0) &= (-0.8 \pm 3.9 \pm 1.2)\%, \\ A_{CP}(D_s^+ \rightarrow \pi^+ \eta) &= (0.8 \pm 0.7 \pm 0.5)\%, \\ A_{CP}(D_s^+ \rightarrow K^+ \eta) &= (0.9 \pm 3.7 \pm 1.1)\% \end{aligned} \quad (11)$$

All of the above results are consistent with no  $CP$  violation. The first five values are the world best measurements.

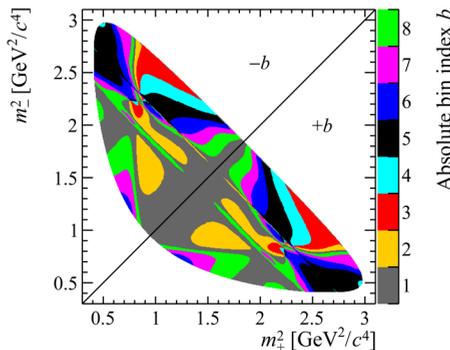
### 3.5 Mass difference between neutral charm meson eigenstates

A neutral meson can oscillate into their own antiparticle. Their mass eigenstates can be expressed as linear combinations of the flavour eigenstates:

$$|M_{1,2}\rangle = p|M^0\rangle \pm q|\bar{M}^0\rangle, \tag{12}$$

where  $p$  and  $q$  are complex parameters satisfying  $|p|^2 + |q|^2 = 1$ . In case of no  $CP$  violation in mixing  $|p/q| = 1$ .  $|M_1\rangle$  and  $|M_2\rangle$  are defined as  $CP$  even and odd eigenstates respectively. There are two mixing parameters:  $x \equiv (m_1 - m_2)c^2/\Gamma$  and  $y \equiv (\Gamma_1 - \Gamma_2)/2\Gamma$ , where  $m_{1,2}$  and  $\Gamma_{1,2}$  are the mass and decay width of the  $M_{1,2}$  states, respectively, and the average decay width is denoted as  $\Gamma$ . Mixing and  $CP$  violation can be described using  $z_{CP}$  and  $\Delta z$  observable, where:  $z_{CP} \pm \Delta z \equiv -(q/p)^{\pm 1}(y + ix)$ . The results are expressed with the  $CP$ -even mixing parameters  $x_{CP} \equiv -Im(z_{CP})$  and  $y_{CP} \equiv -Re(z_{CP})$ , and of the  $CP$ -violating differences  $\Delta x \equiv -Im(\Delta z)$  and  $\Delta y \equiv -Re(\Delta z)$ . Conservation of  $CP$  symmetry indicates that  $x_{CP} = x$  and  $y_{CP} = y$ . In such scenario both  $\Delta x$  and  $\Delta y$  are equal to 0.

The last results on mixing parameters are based on 30.6 million  $D^0 \rightarrow K_s^0\pi^+\pi^-$  decays collected in the LHCb experiment from 2016 to 2018 and analysed using the "bin-flip" method [14]. This technique is based on dividing data into disjoint regions (bins) in the Dalitz space. Within each bin strong-phase differences  $\Delta\delta(m_+^2, m_-^2)$  between the  $D^0$  and  $\bar{D}^0$  amplitudes is almost constant [15]. Two groups of eight bins are assembled symmetrically about the  $m_+^2 = m_-^2$  bisector, where the squared invariant mass  $m^2(K_s^0\pi^\pm)$  is denoted as  $m_\pm^2$  for  $D^0$  decays and  $m_\mp^2$  for  $\bar{D}^0$  decays, and presented in Fig. 3. The region satisfying  $m_+^2 > m_-^2$  is given a positive index  $+b$ , while the opposite region is given a negative index  $-b$ . For each decay-time interval, the ratio of the number of decays in each negative Dalitz plot bin ( $-b$ ) to its positive counterpart ( $+b$ ) is calculated. The benefit from using ratios is that they reduce the need for precise modeling of the efficiency variation across the phase space and the decay time.



**Figure 3.** The Dalitz plot binning scheme for the  $D^0 \rightarrow K_s^0\pi^+\pi^-$  decay.

The mixing and  $CP$ -violating parameters are measured to be [16]:

$$\begin{aligned}
x_{CP} &= (3.97 \pm 0.46 \pm 0.29) \times 10^{-3}, \\
y_{CP} &= (4.59 \pm 1.20 \pm 0.85) \times 10^{-3}, \\
\Delta x &= (-0.27 \pm 0.18 \pm 0.01) \times 10^{-3}, \\
\Delta y &= (0.20 \pm 0.36 \pm 0.13) \times 10^{-3}.
\end{aligned} \tag{13}$$

The first uncertainty is statistical and second is systematic. The nonzero mass difference  $x = 3.98^{+0.56}_{-0.54} \times 10^{-3}$  in the  $D^0$  decays is measured for the first time with a significance of this observation exceeding 7 standard deviations. The results are in agreement with  $CP$  symmetry and provide improvement for limits on the mixing-induced  $CP$  violation in the charm sector.

### 3.6 Searches for direct $CP$ violation in $\Xi_c$ decays

So far, the  $CP$  violation in baryon decays has not been observed. The particularly interesting decays wherein  $CP$  symmetry is suspected to be broken are  $\Xi_c^+ \rightarrow pK^-\pi^+$  decays. The searches [17] are done in model-independent ways with the: binned  $S_{CP}$  [18] method and the unbinned k-nearest neighbour method (kNN) [19–21].

The  $S_{CP}$  method is based on dividing the Dalitz plot into  $n$  bins. For every  $i^{\text{th}}$  bin the significance of the difference between number of particles ( $N_i^+$ ) and antiparticles ( $N_i^-$ ) is calculated using the following formula:

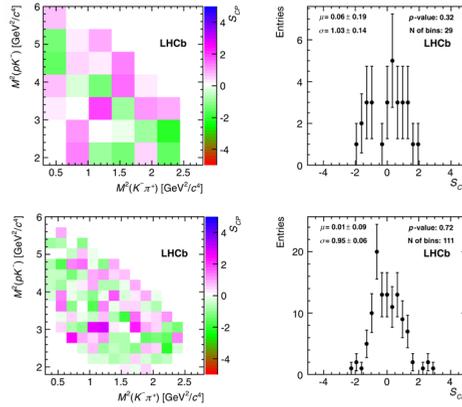
$$S_{CP}^i = \frac{N_i^+ - \alpha N_i^-}{\sqrt{\alpha(N_i^+ + N_i^-)}}, \tag{14}$$

where  $\alpha = N^+/N^-$  parameter accounts for the global nuisance asymmetries such as production asymmetries. The  $N^+$  and  $N^-$  are total number of particles and antiparticles, respectively. The purpose of the  $S_{CP}$  method is to detect local asymmetries. If there are no local  $CP$  asymmetries the  $S_{CP}$  distribution follows a Gaussian distribution with  $\mu = 0$  and  $\sigma = 1$ . Finally, a  $\chi^2$  test is performed in order to measure  $p$ -value. In case of  $CP$  violation  $p$ -value is smaller than  $10^{-5}$  (corresponding to 5 standard deviations). The obtained results are presented in Fig. 4. The measured  $p$ -values are equal to 32% and 72%. The calculated mean and sigma are in agreement with values 0 and 1. The results are consistent with  $CP$  symmetry conservation.

The second method, the kNN, is based on the concept of accounting nearest neighbour events ( $n_k$ ) in the mixed sample of baryons and antibaryons to determine whether they share the same parent distribution function. The test statistic  $T$  is defined as follows:

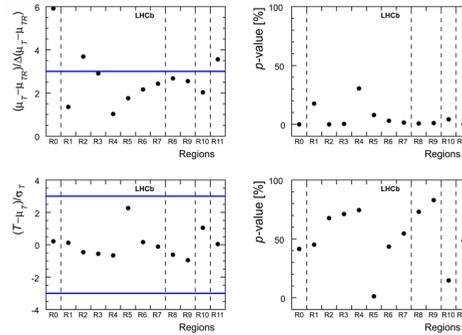
$$T = \frac{1}{n_k(n_+ + n_-)} \sum_{i=1}^{n_+ + n_-} \sum_{k=1}^{n_k} I(i, k), \tag{15}$$

where  $I(i, k) = 1$  if the  $i^{\text{th}}$  event and its  $k^{\text{th}}$  nearest neighbour are from the same set of particles or antiparticles and  $I(i, k) = 0$  if otherwise,  $n_+$  and  $n_-$  are the numbers of particles and antiparticles. Under the hypothesis of no  $CP$  violation the distribution of  $T$  follows a normal distribution with a mean  $\mu_T$  and a variance  $\sigma_T$  computed from known parameters of the distributions. There are two options in which the kNN method is employed to search for  $CP$  asymmetries in a given region of the Dalitz plot: first is looking for "normalization" asymmetry ( $n_+ \neq n_-$ ) using pull  $(\mu_T - \mu_{TR})/\Delta(\mu_T - \mu_{TR})$ , where  $\mu_{TR}$  is reference value and second is searching for "shape" asymmetry using another pull  $(T - \mu_T)/\sigma_T$  from the measured pulls. Their corresponding  $p$ -values are shown in Fig. 5. The values of pulls describing the shape (pdf) asymmetry lay within the range  $-3$  and  $+3$  standard deviations and  $(\mu_T - \mu_{TR})$  pulls are different from zero in all regions. The results are in agreement with



**Figure 4.** Distributions of  $S_{CP}^i$  and matching one-dimensional distributions for  $\Xi_c^+ \rightarrow pK^- \pi^+$  decays for the united samples collected 2011 and 2012: (top row) 29 uniform bins and (bottom row) 111 uniform bins of the Dalitz plot.

no observation of  $CP$  violation. An update of the measurement by using data collected in Run 2 is currently ongoing.



**Figure 5.** (Top row)  $(\mu_T - \mu_{TR})/\Delta(\mu_T - \mu_{TR})$  pulls and their corresponding  $p$ -values and (bottom row)  $(T - \mu_T)/\sigma_T$  pulls and matching  $p$ -values obtained using the kNN method with  $n_k = 50$  for the combined data collected in 2011 and 2012. The horizontal lines in the left plots display  $-3$  and  $+3$  pull values.

### 3.7 Prospects of the LHCb upgrade

The LHCb proved itself to be a general purpose forward physics detector with a rich physics program extending significantly beyond its primary goals. Presently, the LHCb spectrometer is being upgraded and the main goal is focused to increase luminosity to at least  $50 \text{ fb}^{-1}$  by the end of Run 4. To achieve that plan many enhancements will be implemented such as VELO and tracking detectors will be improved, completely new readout system is meant to be installed and other spectrometer components would be updated as well.

## 4 Summary

Recently, the number of charm particle decay studies has increased significantly. The essential part in the conducted analyses was played in the LHCb experiment. The collected data allowed for the first observation of  $CP$  violation in charm and led to update the measurements: the time-dependent  $D^0 - \bar{D}^0$  asymmetry, the  $CP$  asymmetry in  $D^0 \rightarrow K_s^0 K_s^0$  decays,  $CP$  violation in  $D_{(s)}^+ \rightarrow h^+ \pi^0$  and  $D_{(s)}^+ \rightarrow h^+ \eta$  and mass difference between neutral charm-meson eigenstates. Most of them exceeded previous outcomes and became new world's best measurements. So far,  $CP$  asymmetry has not been observed in any baryon decays, but the  $\Xi_c^+ \rightarrow p K^- \pi^+$  decays are being investigated using a new technique based on kernel density estimator.

Run 2 phase of data taking has ended and currently the LHCb spectrometer is undergoing deep modernisation. The most significant changes are the new flexible fully software trigger system, new readout electronics able to process the full detector information at the LHC clock (40 MHz) and brand new tracking detectors. The experiment aims at collecting the data sample corresponding to the integrated luminosity of at least  $50 \text{ fb}^{-1}$  by the end of LHC Run 4 and  $CPV$  observables in charm will be measured with improved precision with Run 3 – 4.

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