

DISCOVERY OF CP VIOLATION IN CHARM DECAYS AT THE LHCb EXPERIMENT AND PROSPECTS FOR RUN 3 AND RUN 4

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CP violation in decays of charm hadrons has been recently observed for the first time. The measured value of asymmetry differed from zero by more than five standard deviations. For further research of the CP asymmetry using the charm baryon decay modes, especially Ξ_c , a new approach using the Kernel Density Estimation may prove useful. Its sensitivity has been tested on Monte Carlo samples with and without CP asymmetries. Further studies will be held to enhance its performance.

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1. Introduction

1.1. CP-violation discovery in decays of charm mesons

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 just recently been observed. The CP asymmetries were measured in $D^0 \rightarrow K^+ K^-$ and $D^0 \rightarrow \pi^+ \pi^-$ decays using a large sample of charmed hadrons collected by the LHCb Collaboration during the LHC Run 1 and Run 2 at a center of energy of 13 TeV corresponding to an integrated luminosity of 6 fb^{-1} [2].

The CP asymmetry A_{CP} between states produced as D^0 or $\bar{D}^0$ mesons decaying to CP eigenstates f is defined as follows:

$$A_{\text{CP}}(f) \equiv \frac{\Gamma(D^0 \rightarrow f) - \Gamma(\bar{D}^0 \rightarrow f)}{\Gamma(D^0 \rightarrow f) + \Gamma(\bar{D}^0 \rightarrow f)}. \quad (1)$$

However, there are many effects that can generate pollution asymmetries, which make it difficult to access physical asymmetry A_{CP} . They can be described as

$$\begin{aligned} A_{\text{raw}}^{\pi\text{-tagged}}(f) &\approx A_{\text{CP}}(f) + A_{\text{D}}(\pi) + A_{\text{P}}(D^*), \\ A_{\text{raw}}^{\mu\text{-tagged}}(f) &\approx A_{\text{CP}}(f) + A_{\text{D}}(\mu) + A_{\text{P}}(B), \end{aligned} \quad (2)$$

where $A_{\text{raw}}^{\pi\text{-tagged}}$ and $A_{\text{raw}}^{\mu\text{-tagged}}$ are raw asymmetries for π -tagged and μ -tagged D^0 decays, respectively. $A_{\text{D}}(\pi)$ and $A_{\text{D}}(\mu)$ are detector asymmetries, whereas $A_{\text{P}}(D^*)$ and $A_{\text{P}}(B)$ are production asymmetries for D^* mesons and B hadrons.

In order to simplify the analysis, one can compose a new observable that represents the difference in the respective CP asymmetries. All nuisance asymmetries cancel out to the first order. Other valuable feature is that both contributing asymmetries are expected to be roughly of the equal magnitude and opposite sign [1]

$$\Delta A_{\text{CP}}(f) \equiv A_{\text{CP}}(K^+K^-) - A_{\text{CP}}(\pi^+\pi^-) = A_{\text{raw}}(K^+K^-) - A_{\text{raw}}(\pi^+\pi^-). \quad (3)$$

The measured difference of CP asymmetries of $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+\pi^-$ combined with the previous LHCb results gave the following value [2]:

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

The significance deviation from zero is equal to 5.3 standard deviation. That is, the first observation in CP violation in the decay of charm hadrons.

1.2. Prospects for Run 3 and Run 4

Discovery of CP violation in the decays of charm hadrons opens the window to the search for new possible sources of CP asymmetries in charm particles. One group of the particularly interesting decays wherein CP symmetry is suspected to be broken are Ξ_c decays. They were analysed with various techniques such as unbinned S_{CP} and binned KNN methods. All of them showed no sign of CP violation. Another advanced technique that has never been tested before to search for differences between matter and anti-matter is the Kernel Density Estimation (KDE). A report on initial studies performed for the binned Dalitz space is presented in the next section.

2. Kernel Density Estimation

The Kernel Density Estimation is a non-parametric way 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 a finite data sample

$$\hat{f}(x) = \frac{1}{n} \sum_{i=1}^n \omega(x - x_i, h), \quad (5)$$

where

$$\omega(t, h) = \frac{1}{h} K\left(\frac{t}{h}\right) \quad (6)$$

is the weighting function. K is the kernel, which determines the shape of the weighting function and h is the smoothing parameter, often called bandwidth. In this analysis, two kernel functions were used: Gaussian and triangle, which can be respectively described as follows:

$$w(t, h) = \frac{1}{\sqrt{2\pi}h} \exp -t^2/2h^2, \quad -\infty < t < \infty, \quad (7)$$

$$w(t, h) = \begin{cases} \frac{1}{h}(1 - |t|/h) & \text{for } |t| < h, \\ 0 & \text{otherwise.} \end{cases} \quad (8)$$

Two simulated data sets, containing events from $\Xi_c^\pm \rightarrow p^\pm K^\pm \pi^\mp$ decays, have been considered. The first one was generated according to a CP-conserving model, and the other with a moderate amount of CP violation (20%) in the vector resonance K^* . The respective Dalitz plots are shown in Figs. 1 and 2.

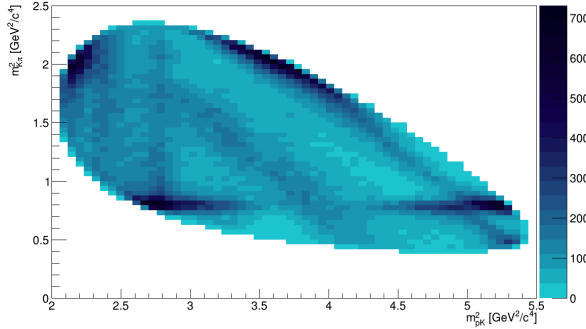


Fig. 1. Dalitz plot for decays with no CP violation.

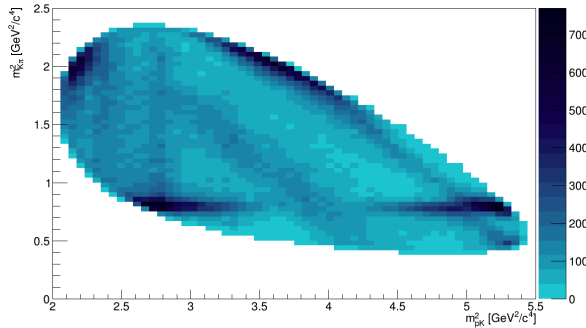


Fig. 2. Dalitz plot for decays with 20% CP violation.

The Dalitz plots were split into four kinematic regions, each of which was subsequently projected onto the horizontal axis. Then, the KDE technique was used with the two mentioned different kernel functions. Preliminary results are presented in Figs. 3–6.

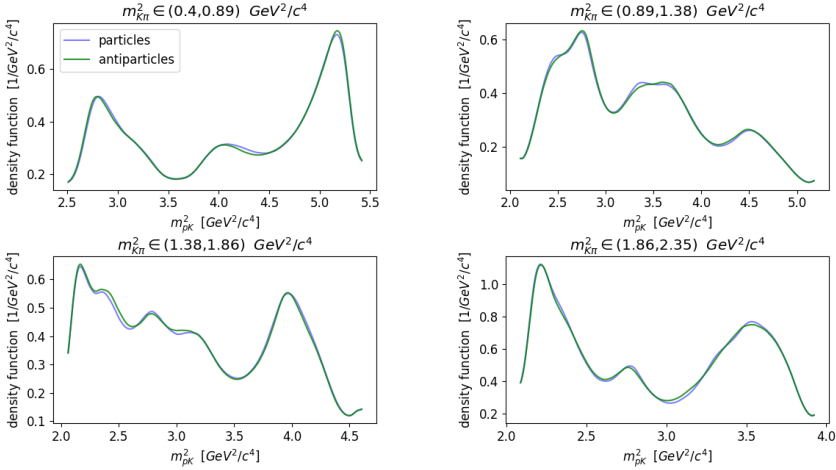


Fig. 3. Density function with triangle kernel for chosen regions for the sample with no CP violation.

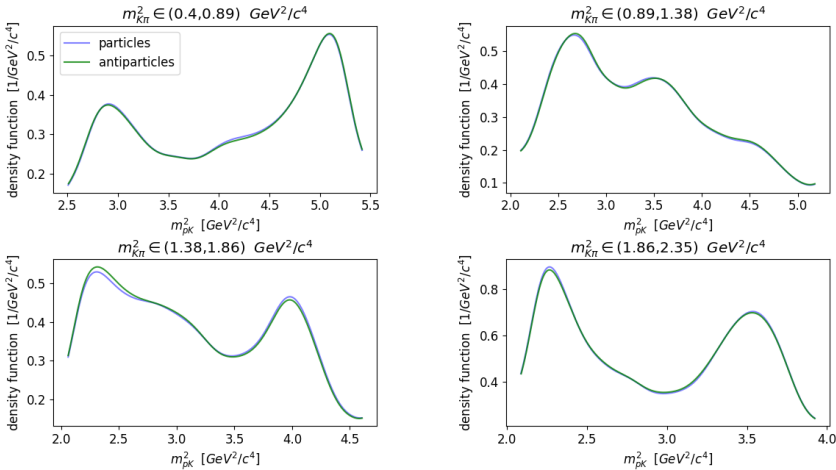


Fig. 4. Density function with Gauss kernel for chosen regions for the sample with no CP violation.

There are no visible differences (as expected) between samples generated with CP-conserving mode in Figs. 3 and 4. The difference between density function for particles and antiparticles can be easily spotted in Figs. 5 and 6.

The preliminary results show that the Kernel Density Estimation technique may potentially be sensitive to CP violation and works properly when there is no asymmetry to be found, which can be checked by using, for instance, the Anderson–Darling test for goodness-of-fit. In this case, one of the distributions can be taken as the true one (since there is no CP violation both samples representing a studied decay and its charge conjugation were drawn from the same parent distribution).

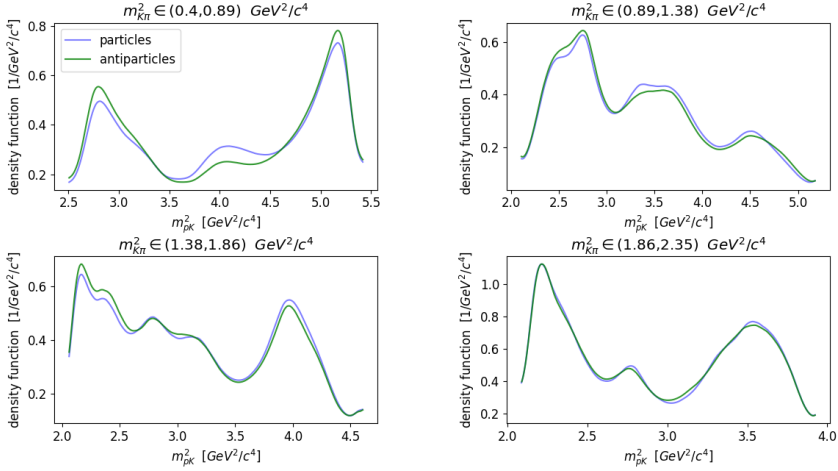


Fig. 5. Density function with triangle kernel for chosen regions for the sample with 20% CP violation.

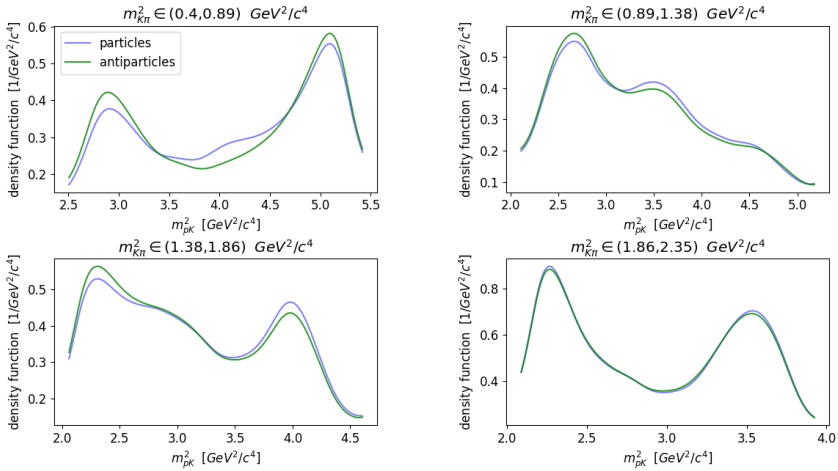


Fig. 6. Density function with Gauss kernel for chosen regions for the sample with 20% CP violation.

A critical issue related to the kernel method is the optimal selection of the bandwidth parameter. It has a significant impact on the estimated results. For invariant functions, one can use a globally determined bandwidth, often called fixed bandwidth, which is described by the formula

$$h^{\text{opt}} = \kappa \hat{S} N^{-\frac{1}{5}}, \quad (9)$$

where $\hat{S}$ is the sample standard deviation, N is its size and κ is a so-called correction parameter. It controls the degree of smoothing of the final estimate. It takes values from 1.06 to 1.44. However, for distribution with more complicated shape, a fixed bandwidth may lead to a large drop in the sensitivity to the estimated distribution. It should depend on the local features of the data. Hence, adaptive bandwidth parameter h_i takes into account properties of the analysed data. For instance, one can use an approach known as square root law [3]

$$h_i = \frac{h^{\text{opt}}}{\sqrt{f(x_i)}}, \quad (10)$$

where the $f(x_i)$ may be taken as the KDE approximation of the true probability density function with the fixed bandwidth h^{opt} .

Distribution of the adaptive bandwidth for the triangle kernel for the sample with no CP violation is presented in the figure below.

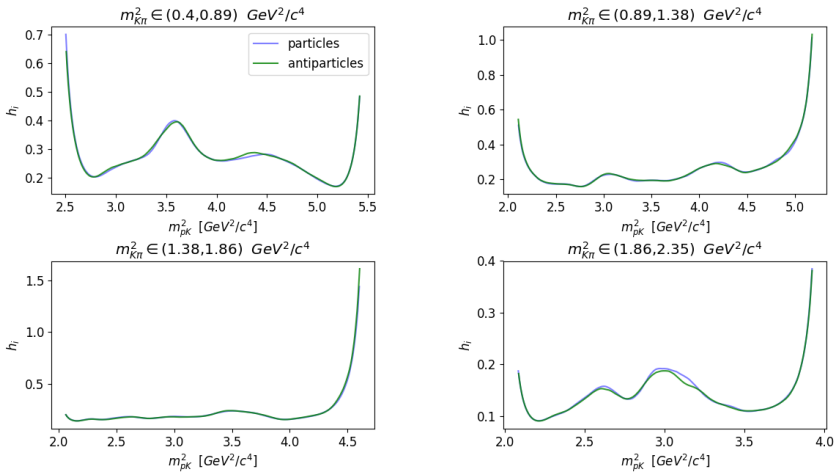


Fig. 7. Adaptive bandwidth distribution.

As it is shown in Fig. 7, for high density regions, where narrow kernel is sufficient to estimate the distribution parameter, h takes small values and for the opposite situation, h is large to smooth out statistical fluctuations.

3. Conclusion

CP violation in charm particles decays has recently been observed for the first time in history. The measured value of asymmetry differed from zero by more than five standard deviations. This discovery opens new opportunities to search for other sources of CP asymmetries in charm particles, which might be found during next Run 3 and Run 4. A new approach called Kernel Density Estimation, for observing this phenomena, has been presented and the preliminary results showed that the proposed method is sensitive to the sign of CP violation. Further studies will be carried out in order to improve its performance. In particular, a full 2D KDE approach will be used and the p -value estimated using the re-sampling techniques.

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