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Measurement of CP Violation in D^0 Meson Decays at the CMS Experiment

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Abstract—The paper describes the search results for CP violation in the $D^0 \to K_S^0 K_S^0$ decay. The analysis was performed using the proton–proton collision data with centre-of-mass energy of $\sqrt{s} = 13$ TeV, recorded by the CMS experiment at the Large Hadron Collider. The analyzed data sample contains about 10^{10} events associated with production of charm hadrons, which allows performing precise measurements. The measured CP violation parameter is $A_{\mathrm{CP}}\,(D^0 \to K_S^0 K_S^0) = (6.2 \pm 3.1\text{ (stat.)} \pm 0.2\text{ (syst.)} \pm 0.8\ (A_{\mathrm{CP}}\,(D^0 \to K_S^0 \pi^+\pi^-))\%$, where the last uncertainty is due to the uncertainty in the reference channel asymmetry $A_{\mathrm{CP}}\,(D^0 \to K_S^0 \pi^+\pi^-)$. The obtained results are consistent with no CP violation in the studied decay. This analysis is the first measurement of CP violation in charm sector at the CMS experiment.

Keywords: CP violation, heavy quark physics, flavor physics, heavy hadron physics, charm physics, electroweak interactions, CMS experiment

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INTRODUCTION

Noninvariance of the fundamental interactions under the combined charge and parity transformation (CP) is one of the necessary conditions for generation of the observed baryon asymmetry of the universe [1]. In the standard model, CP violation (CPV) in particle decays originates from complex phase of the CKM quark mixing matrix [2]. Violation of CP symmetry is well-measured in decays of particles containing down-type quarks (b and s), and all the existing measurements are found to be in agreement with the predictions based on the current fundamental interaction theory [3–5]. However, the existing CPV effects within the standard model cannot explain the observed baryonic asymmetry of the universe [6], therefore, there must be processes responsible for these effects beyond the standard model (“New physics”).

According to the standard model, CP violation effects are strongly suppressed in D mesons, as opposed to K and B mesons. Therefore, observation of a significant CPV in the processes involving D mesons would indicate a possible contribution from New physics.

The first observation of CP violation in charm meson sector was made by the LHCb collaboration in 2019: the measured difference in CP-violating parameters between the two decay channels of D^0 mesons, $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$, was significantly different from zero [7]. This measurement proves that there is CP violating effect in at least one of these two decays. According to the theoretical calculations [8], among different D^0 meson decay modes, the $D^0 \to K_S^0 K_S^0$ decay is one of the most promising to search for CPV in. This decay can be described as an interference of W exchange between quarks diagram and penguin annihilation (PA) diagram, as shown in Fig. 1. The two processes may have amplitudes close in the absolute value, but different in phase, thus increasing the CPV effects of interest to the level of about a percent, which is much larger than the expected CPV values in all other D^0 decay modes.

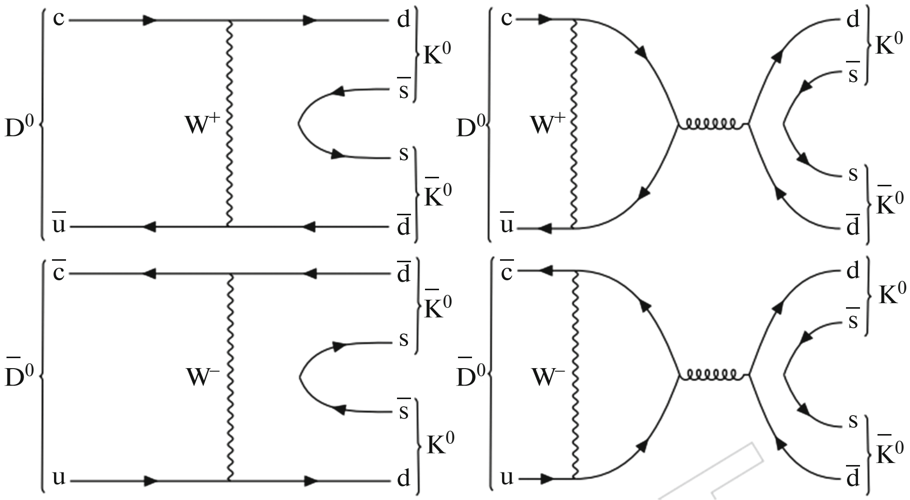

Fig. 1. Feynman diagrams for the decays of neutral charm meson D^0 (up) and $\bar{D}^0$ (bottom) into two neutral K mesons: through W-exchange (left) and through PA (right).

THE MEASURED OBSERVABLE A_{CP}

We study the observable A_{CP} ($D^0 \to K_S^0 K_S^0$), defined as

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

where Γ is the D^0 meson decay width. In order to differentiate between D^0 and $\bar{D}^0$ events, an additional requirement is applied: the D^0 mesons must be produced in the decays $D^*(2010)^+ \to D^0\pi^+$ ($D^*(2010)^- \to \bar{D}^0\pi^-$). Using this approach, the pion charge will identify whether there was a D^0 meson $\bar{D}^0$ meson. Performing a direct measurement of A_{CP} is quite challenging, as there are difficulties in precisely evaluating asymmetries in reconstruction efficiencies of $D^*(2010)^\pm$ and production asymmetries of $D^*(2010)^\pm$. In order to avoid them, one can measure the difference in asymmetries A_{CP} between two similar decay channels. In this paper, using this approach, we measure the A_{CP} ($D^0 \to K_S^0 K_S^0$) through the difference ΔA_{CP} between the $D^0 \to K_S^0 K_S^0$ and $D^0 \to K_S^0\pi^+\pi^-$: their kinematics and topology are close, which makes production and detection asymmetries in these two channels identical, therefore they cancel each other out when evaluating the difference of asymmetries—a value that is insensitive to the production and reconstruction asymmetries:

$$\Delta A_{\mathrm{CP}} = A_{\mathrm{CP}}^{\mathrm{raw}}(D^0 \to K_S^0 K_S^0) - A_{\mathrm{CP}}^{\mathrm{raw}}(D^0 \to K_S^0\pi^+\pi^-), \tag{2}$$

$$A_{\mathrm{CP}}^{\mathrm{raw}}(D^0 \to K_S^0 K_S^0) = \frac{N(D^*(2010)^+ \to D^0\pi^+ \to K_S^0 K_S^0\pi^+) - N(D^*(2010)^- \to \bar{D}^0\pi^- \to K_S^0 K_S^0\pi^-)}{N(D^*(2010)^+ \to D^0\pi^+ \to K_S^0 K_S^0\pi^+) + N(D^*(2010)^- \to \bar{D}^0\pi^- \to K_S^0 K_S^0\pi^-)}, \tag{3}$$

$$A_{\mathrm{CP}}^{\mathrm{raw}}(D^0 \to K_S^0\pi^+\pi^-) = \frac{N(D^*(2010)^+ \to D^0\pi^+ \to K_S^0\pi^+\pi^-\pi^+) - N(D^*(2010)^- \to \bar{D}^0\pi^- \to K_S^0\pi^+\pi^-\pi^-)}{N(D^*(2010)^+ \to D^0\pi^+ \to K_S^0\pi^+\pi^-\pi^+) + N(D^*(2010)^- \to \bar{D}^0\pi^- \to K_S^0\pi^+\pi^-\pi^-)} \tag{4}$$

In addition, the reference decay $D^0 \to K_S^0\pi^+\pi^-$ is not Cabibbo-suppressed, as opposed to the $D^0 \to K_S^0 K_S^0$ decay. Therefore, CPV in the reference channel is strongly suppressed (which is also confirmed by experimental measurements [9]), consequently, the signal channel asymmetry is almost equal to the mea-

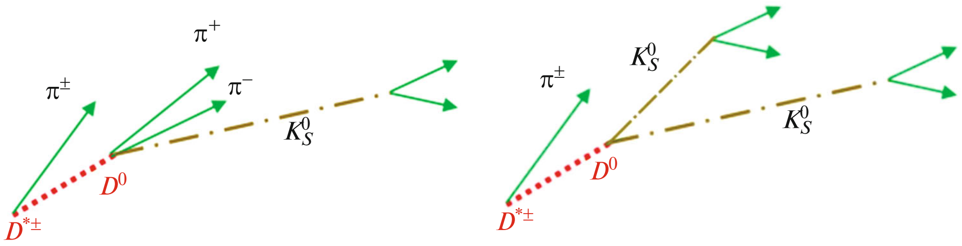

Fig. 2. Decay topology of the studied decays: the signal channel (left), reference channel (right).

sured ΔA_{CP}, after accounting for the uncertainty in A_{CP} ($D^0 \to K_S^0\pi^+\pi^-$) measured in the previous experiments.

CMS DETECTOR

The presented analysis uses the data collected by one of the Large Hadron Collider experiments, the CMS experiment. The main purpose of this experiment is the searches for New physics using precise identification of muons and electrons in a broad energy range [10]. The main feature of the CMS detector is a superconducting solenoid 15 m in diameter, which produces a strong magnetic field of 3.8 T. Inside the solenoid are the electromagnetic and hadronic calorimeters, as well as silicon tracking detectors. Outside of the solenoid, and interlaced with its return yoke, are the muon detectors that are used to identify muons, measure their momenta and trajectories. The superconducting solenoid produces strong magnetic field that bends charged particle tracks at relatively large distance from the collision region (up to 7 m), which allows identifying the outgoing muons with great accuracy.

EVENT SELECTION

One of the major production mechanisms of charm quark production in pp collisions is the decays of a heavier b quark. Therefore, for this analysis, charm hadrons produced mostly in b hadron decays are used. In 2018, the CMS experiment adopted a new strategy for muon triggers: the event was saved for analysis only in case there was a displaced muon with high transverse momentum: p_T should be larger than some value between 5 and 12 GeV depending on a particular trigger. This approach allowed record a sample containing events associated with $b \to \mu X$ decays. This dedicated sample was called "B-parking," it contains about 12 billion events and is described in detail in [11, 12]. It is known that semileptonic b hadron decays almost always result in a charm quark [9]. Thus, B-parking sample contains $O(10^{10})$ events with charm hadrons, which also have high momentum (due to high trigger threshold on the associated muon momentum), which allows concluding that this sample is well-suited for precision measurements in the charm sector, including the CPV measurements.

Reconstruction of the decay of interest is performed by selecting five tracks, assumed to be pions, and applying additional requirements to suppress backgrounds. The CMS detector lacks a dedicated hadron identification system, therefore pion candidate can be any track with pion mass assigned to it. The decay topology schemes are presented in Fig. 2 for $K_S^0K_S^0$ (signal channels) and $K_S^0\pi^+\pi^-$ (reference channel). The two pions are required to form a good-quality vertex consistent K_S^0 decay vertex, with a mass within 3 standard deviations from the known K_S^0 meson mass and vertex fit probability exceeding 1%. For the signal channel, the same requirements are applied to another pair of pions to form the second K_S^0. After this, the virtual K_S^0 meson track and two other pions (or two virtual K_S^0 meson tracks, for the signal channel) are required to be consistent with the $D^0 \to K_S^0\pi^+\pi^-$ ($D^0 \to K_S^0K_S^0$) decay with the corresponding vertex fit probability exceeding 5% (1%). Finally, the reconstructed D^0 candidate is fitted with the fifth track to reconstruct the $D^*(2010)^\pm$ decay vertex. In the following, we study the signal yields of $D^*(2010)^-$ and $D^*(2010)^+$.

To suppress background, additional selection requirements are applied [14]. They are obtained using cross-validation in such a way that the expected statistical uncertainty in the $A_{\text{CP}}^{\text{raw}}(D^0 \to K_S^0K_S^0)$ was the

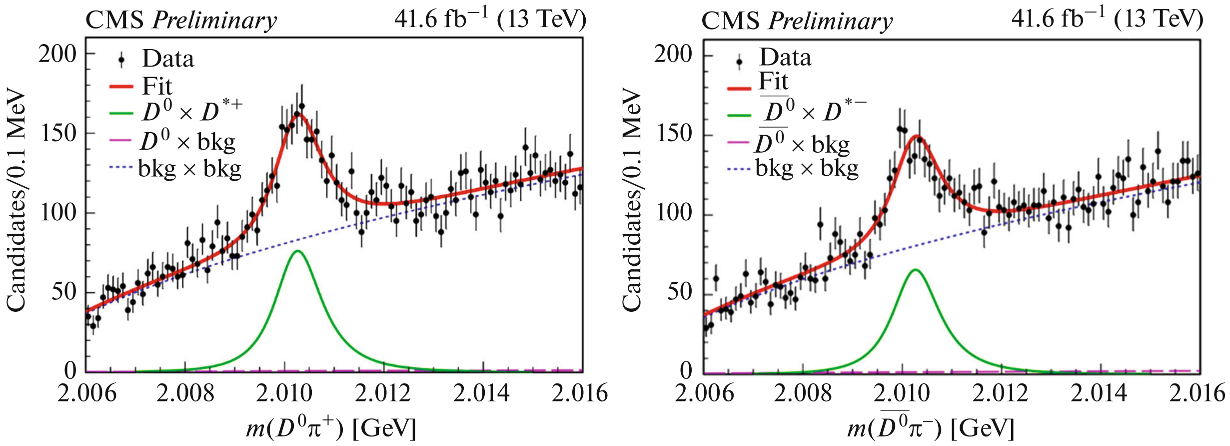

Fig. 3. Projections of the two-dimensional fit: on the $m(D^0\pi^+)$ axis for the $D^*(2010)^+ \to D^0\pi^+ \to K_S^0K_S^0\pi^+$ decays (left) and on the $m(\bar{D}^0\pi^-)$ axis for the $D^*(2010)^- \to \bar{D}^0\pi^- \to K_S^0K_S^0\pi^-$ decays (right) [14].

lowest (as mentioned earlier, the reference channel is not Cabibbo-suppressed, therefore its statistical uncertainty is very small and will almost not affect the uncertainty in the final measurement; it is enough to apply similar requirements in the reference channel to those in the signal channel).

A_{CP} MEASUREMENT

After selecting the events of interest, the fits are performed: reference channel is fitted with a binned maximum-likelihood approach to the distribution of $m(D^0\pi)$ (after reweighting events to remove small difference between signal and reference channel kinematic properties) [14]. Johnson function [13] is used to describe the signal, while the background is described with a threshold function multiplied by a first-degree polynomial. $D^*(2010)^-$ and $D^*(2010)^+$ events are treated as two independent event samples that are used in the simultaneous fit: the signal functions are identical in the two samples, with the exception of the signal yield. This approach allows extracting the most correct value of $A_{\mathrm{CP}}^{\mathrm{raw}}$. Using Eq. (4), the reference channel asymmetry is obtained to be $A_{\mathrm{CP}}^{\mathrm{raw}}(D^0 \to K_S^0\pi^+\pi^-) = (0.8 \pm 0.1)\%$.

The signal channel is fitted using an unbinned maximum-likelihood approach, and two-dimensional distribution of $m(D^0\pi)$ vs $m(D^0)$ is fitted. The products of the corresponding one-dimensional shapes in $m(D^0\pi)$ and $m(D^0)$ are used to fit the two-dimensional distributions. $m(D^0\pi)$ distribution is fit with the same function as in the reference channel, while the $m(D^0)$ distribution is fit with a sum of two Johnson functions for the signal and an exponential function for the background. Similarly to the reference channel, the simultaneous fit procedure is applied. Projections of the resulting fits onto the $m(D^0\pi)$ axis are shown in Fig. 3.

Using these fits and Eq. (3), the value $A_{\mathrm{CP}}^{\mathrm{raw}}(D^0 \to K_S^0K_S^0) = (7.1 \pm 3.0)\%$ is measured. Combining it with the $A_{\mathrm{CP}}^{\mathrm{raw}}(D^0 \to K_S^0\pi^+\pi^-)$, the $\Delta A_{\mathrm{CP}} = (6.3 \pm 3.0)\%$ is calculated.

SYSTEMATIC UNCERTAINTIES

The measured difference between asymmetries is highly insensitive to various systematic uncertainties that are relevant for the A_{CP} measurement in a single channel, such as hardly measurable production and detection asymmetries, which would need a dedicated calibration procedure to evaluate. The uncertainties due to the choice of the fit model are evaluated independently for the signal model and the background model variations. Each of them is estimated by changing the default fit function by a few alternatives, and the largest observed deviation of ΔA_{CP} from the nominal value is taken as a systematic uncertainty. In order to assess the uncertainty due to reweighting of the reference channel sample, several alternative reweighting procedures were considered, and the deviations in ΔA_{CP} are used as systematic uncertainty. The last systematic uncertainty is the central value of ΔA_{CP} in the simulated events, which is not exactly zero due to fluctuations, and its value is used as a systematic uncertainty. All the described above systematic uncertainties are summed in quadrature to evaluate the final systematic uncertainty in the $\Delta A_{\rm CP}$ measurement: 0.2% – which is 10 times smaller than the statistical uncertainty, as expected.

CONCLUSIONS

This analysis resulted in the measurement of CP violation parameters [14] in the $D^0 \to K_S^0 K_S^0$ and $D^0 \to K_S^0 \pi^+ \pi^-$ decays:

$$\Delta A_{\rm CP} = (6.3 \pm 3.0\,({\rm stat.}) \pm 0.2\,({\rm syst.}))\%.$$

Using the known value for $A_{\rm CP}$ ($D^0 \to K_S^0 \pi^+ \pi^-$) [9], we obtain the $A_{\rm CP}$ ($D^0 \to K_S^0 K_S^0$):

$$A_{\rm CP}(D^0 \to K_S^0 \pi^+ \pi^-) = (6.2 \pm 3.0\,({\rm stat.}) \pm 0.2\,({\rm syst.}) \pm 0.8(A_{\rm CP}(D^0 \to K_S^0 \pi^+ \pi^-)))\%.$$

This measurement [14] is consistent with no CP violation in the $D^0 \to K_S^0 K_S^0$ decay within two standard deviations. This is the first CP violation measurement in charm mesons at the CMS experiment, opening the way for a new area of research at this experiment.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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