STUDY OF CP VIOLATION IN CHARM MESON DECAYS*

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The basic idea of CP violation and its importance for cosmology, Standard Model, and possible new physics are introduced. Recent (2019) discovery of CP violation in charm in the ΔA_{CP} between $D^0 \to K^-K^+$ and $D^0 \to \pi^+\pi^-$ decay channels and evidence for direct CP violation in $D^0 \to \pi^-\pi^+$ decays in 2023 are discussed. Motivation and a brief outline for the search of CP violation in the $D^0 \to V\gamma$, where $V = \phi, \rho^0, \bar{K}^{*0}$ decays are given.

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1. Introduction

CP (charge-parity conjugation) is the operator that changes a particle X into its anti-particle $\bar{X}$ and reverses spatial coordinates. Non-conservation of CP symmetry (henceforth CP violation) is the second of Sakharov's cosmological conditions [1], necessary to explain the observed prevalence of baryons over anti-baryons in the observable Universe. In the Standard Model (SM), the only measurable source of CP violation is a weak phase in the quark mixing CKM matrix. Since CP violation in SM is small, some new physics (NP) is believed to be necessary in order to explain the predominance of baryons [2].

One can distinguish between three types of CP violation: CP violation in the decay, CP violation in the mixing of neutral mesons (*e.g.* D^0 and $\bar{D}^0$), and CP violation in the interference between mixing and decay. CP violation in decay occurs when partial decay widths for final states f and $\bar{f}$ are different for D^0 and $\bar{D}^0$ flavours

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

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In experimental terms, measuring the CP asymmetry usually means measuring raw asymmetry by counting flavour *tags* (pions for $D^{*+} \to D^0\pi^+$ and muons for $B^+ \to \bar{D}^0\mu^+\nu_\mu$, h.c. implied) and subtracting *nuisance* asymmetries, *e.g.* production and detection asymmetries

$$A_{\mathrm{raw}} = \frac{N_{D^0} - N_{\bar{D}^0}}{N_{D^0} + N_{\bar{D}^0}} \approx A_{\mathrm{CP}} + A_{\mathrm{det}} + A_{\mathrm{prod}} \,. \tag{2}$$

More about those additional sources of observed asymmetry will be said in Section 2.1. These proceedings are focused on the CP violation in decays. CPV in D^0–$\bar{D}^0$ mixing results in a time-dependent correction to the measured direct asymmetry: $A_{\mathrm{CP}}(f) \approx a_f^d + \frac{\langle t \rangle_f}{\tau_D}\Delta Y_f$, where t_f is the mean decay time for D^0 in the experimental data, τ_D is the mean lifetime of D^0, and ΔY_f is one of the parameters quantifying CPV in mixing and in interference between mixing and decay, previously measured at B-factories [3, 4] and LHCb [5].

1.1. CP violation in the decays of charmed mesons

Within the Standard Model, CP violation in the charm decays is expected to be small — $10^{-4} \div 10^{-3}$ (see, for example, [2]), owing to suppressed penguin amplitude compared to the tree level due to small differences between masses of light quarks (s, d) and strong CKM suppression of the V_{ub} coupling. However, the contribution of some NP to the penguin amplitude (Fig. 1 (right)) can alter the A_{CP} compared to SM predictions. Although it was predicted for a long time, the first observation of the CP violation in charm was reported by the LHCb experiment in 2019 [6]. That analysis utilized $\pi^\pm$-tagged charm decays $D^{*+} \to (D^0 \to h^-h^+)\pi^+_{\mathrm{tag}}$, where $h^+ = K^+, \pi^+$ (here and afterwards charge conjugation is implied unless stated otherwise), promptly produced in pp collisions, as well as muon-tagged $D^0 \to h^-h^+$ decays produced in semileptonic $\bar{B} \to D^0\mu^-\bar{\nu}_\mu X$ decays, for 5.9 fb^{-1} of Run 2 data. Combined with the previous LHCb results [7], it gives the first observation of CP violation in decays of charmed mesons

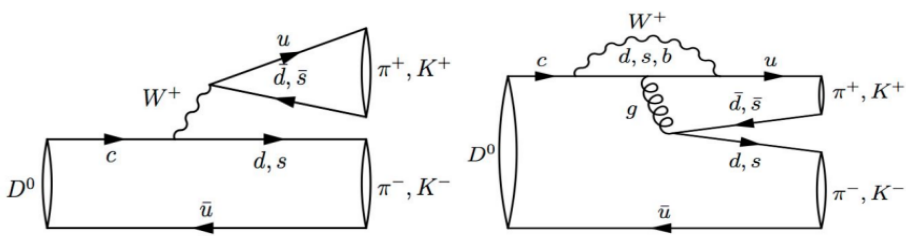


Fig. 1. Example of a tree-level and one-loop (penguin) diagrams of $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays. The weak CKM phase enters through the penguin $c \to u$ transition.

at more than 5σ: $\Delta A_{\rm CP} \equiv A_{\rm CP}(D^0 \to K^-K^+) - A_{\rm CP}(D^0 \to \pi^-\pi^+) = (-15.4 \pm 2.9) \times 10^{-4}$, where error contains both statistical and systematic contributions (but is dominated by statistics).

In order to obtain such extraordinary precision in $A_{\rm CP}$ asymmetries for individual decay channels, it is necessary to control other sources of asymmetry, which will be discussed in the next section. The nuisance asymmetries cancel out within the $\Delta A_{\rm CP}$, but the price to pay for measuring $\Delta A_{\rm CP}$ is the inability to disentangle individual asymmetries.

2. Direct CP violation in $D^0 \to h^+h^-$ decays

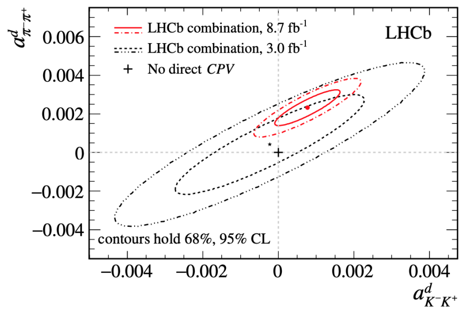
2.1. Nuisance asymmetries

Measured (*raw*) asymmetry can be driven not only by CP violation. The main sources of nuisance asymmetries at the LHCb are production ($\sigma(pp \to D^{*+}) \neq \sigma(pp \to D^{*-})$) and detection asymmetry (Eq. (2)) between positively and negatively charged hadrons — the latter arises due to different detection efficiency. In the busy environment of a hadron collider, it is considered implausible to precisely calculate production and detection asymmetries for any given decay from the theory and/or from simulation, and therefore, a data-driven approach is required. A reference channel is selected, with the final state similar to a studied decay, and asymmetry is measured for that channel.

An important caveat is that $A_{\rm det}$ and $A_{\rm prod}$ are dependent on kinematics, and the asymmetry tends to be larger for smaller momenta. Therefore, it is necessary to use the kinematics matching procedure — usually done by assigning weights on per-event based until distributions of kinematic variables (p, η, ϕ (*azimuthal angle*)) match between corresponding particles in signal and reference data. This usually leads to a significant drop in statistics of weighted dataset compared to unweighted one. Multiple reference channels can be used in order to mitigate that penalty.

2.2. Measurement of $A_{\rm CP}(D^0 \to K^-K^+)$

After discovering the CP violation in the charm sector, the next step is to disentangle individual asymmetries $A_{\rm CP}(D^0 \to K^-K^+)$ and $A_{\rm CP}(D^0 \to \pi^-\pi^+)$ from $\Delta A_{\rm CP}$. Two complementary calibration procedures are introduced: through $D^+ \to K^-\pi^+\pi^+$, $D^+ \to \bar{K}^0\pi^+$, and $D_s^+ \to \phi\pi^+$, $D_s^+ \to \bar{K}^0K^+$ decays, and, with either, $D^0 \to K^-\pi^+$. All those are high-statistics and high-purity channels dominated by Cabbibo-favoured transitions with the expectation of no CP violation in the SM. The explicit formula for each calibration follows and Fig. 2 (right) demonstrates cancellation of nuisance asymmetries



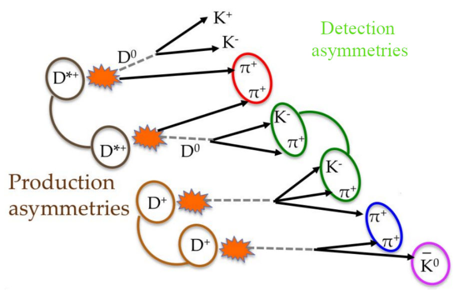


Fig. 2. Left: Recent measurement of $A_{\rm CP}(D^0 \to h^- h^+)$ at the LHCb shows tension with the CP conservation. Right: Illustration of calibration with D^+ decays used to extract $A_{\rm CP}$ from measured $A_{\rm raw}$.

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

The last term arises from combined effects of CP violation and mixing in the neutral kaon system and different interaction rates of K^0 and $\bar{K}^0$ with the detector material. After combining the results from both, the most precise measurement of $A_{\rm CP}(D^0 \to K^-K^+)$ was obtained [8]: $A_{\rm CP}(D^0 \to K^-K^+) = (6.8 \pm 5.4(\text{stat.}) \pm 1.6(\text{sys.})) \times 10^{-4}$. By itself, it is quite consistent with hypothesis of no CP violation. However, after subtracting time-dependent asymmetry due to D^0–$\bar{D}^0$ mixing and combining this result with the $\Delta A_{\rm CP}$ analysis [6], one obtains: $a^d_{\rm CP}(\pi^-\pi^+) = 23.2 \pm 6.1 \times 10^{-4}$ (3.8σ), $a^d_{\rm CP}(K^-K^+) = 7.7 \pm 5.4 \times 10^{-4}$. This is the first evidence of a direct CPV in an individual decay. Figure 2 (left) shows a comparison between results based on Run 1 and Run 1+Run 2 LHCb data.

In the limit of the $\mathrm{SU}(3)_{\rm F}$, symmetry for $m_u = m_d = m_s$, $a^d_{\rm CP}(K^-K^+) = -a^d_{\rm CP}(\pi^-\pi^+)$ [9]. Breaking $\mathrm{SU}(3)_{\rm F}$ leads to the different values, with exact size of the effect being uncertain. The experimental results are in disagreement with those predictions.

3. Radiative charm decays $D^0 \to V\gamma$

Decays $D^0 \to V\gamma$, where $V = \phi, \rho^0, \bar{K}^*(892)^0$, were studied at B-factories [10], and today best results for their branching fractions are: $\mathrm{BF}(D^0 \to \phi\gamma) = 2.81 \pm 0.19 \times 10^{-5}$, $\mathrm{BF}(D^0 \to \rho^0\gamma) = 1.82 \pm 0.32 \times 10^{-5}$, $\mathrm{BF}(D^0 \to \bar{K}^*(892)^0)\gamma) = 4.1 \pm 0.7 \times 10^{-4}$ [11]. $A_{\rm CP}$ is consistent with zero for all three modes with with uncertanties at the level of %. SM predicts CP violation of up to $\sim 10^{-3}$ for ϕ and ρ^0, which can be enhanced further by NP [12]. Studying $D^0 \to V\gamma$ is possible at the LHCb, but there are challenges to overcome. Irreducible peaking background from $D^0 \to V\pi^0$ — decays with branching ratio $\sim 10^{-3}$ — one or two orders of magnitude over the signal, and boosted $\pi^0 \to \gamma\gamma$ are usually reconstructed as a single energy cluster in the LHCb electromagnetic calorimeter.

We aim to measure $A_{\rm CP}(D^0 \to V\gamma)$. To that end, the LHCb analysis employs $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ reference channels to correct for nuisance asymmetries in $D^0 \to (\phi \to K^-K^+)\gamma$ and $D^0 \to (\rho^0 \to \pi^-\pi^+)\gamma$, respectively, whereas $D^0 \to K^-\pi^+\pi^0$ is used for $D^0 \to (\bar{K}^{*0} \to K^-\pi^+)\gamma$. We can measure $\Delta A_{\rm CP}^{\rm rad} = A_{\rm CP}(D^0 \to V\gamma) - A_{\rm CP}(D^0 \to h^-h^+(\pi^0)) \approx A_{\rm raw}(D^0 \to V\gamma) - A_{\rm raw}(D^0 \to h^-h^+(\pi^0))$, after the kinematics matching, as discussed in Section 2.1, then take measured $D^0 \to h^-h^+$ asymmetries [6, 8] as external inputs in order to obtain individual $A_{\rm CP}(D^0 \to V\gamma)$.

A multivariate tool IsPhoton, based on shapes of energy clusters in the calorimeter, is used for γ/π^0 separation. The signal is distinguished from the residual background using three variables: D^0 invariant mass $m(D^0)$, the difference between D^{*+} and D^0 masses $\Delta m = m(D^{*+}) - m(D^0)$, and $\cos\theta$. The helicity angle of the V meson $\cos\theta$ is important, as its expected distribution for $D^0 \to V\pi^0$ is similar to $\cos^2\theta$, whilst for signal channels $D^0 \to V\gamma$, it is $\sin^2\theta$. A three-dimensional maximum likelihood fit is performed to these variables, taking into account correlations between $m(D^0)$ and Δm. Figures 3 and 4 show $m(D^0)$, $\cos\theta$, and Δm distributions for samples of pseudodata based on real $D^0 \to \bar{K}^{*0}\gamma$ decays reconstructed in the Run 1 LHCb data. The number of pseudo-events generated is similar to the number of events observed in real data after selection. These are combined $\pi^+_{\rm tag}$ and $\pi^-_{\rm tag}$ samples, and fit results are superimposed. Figure 3 shows the sample for the $\cos\theta$ region with the negligible signal contribution. It is used for calibration of the π^0 background description. The sample for the signal-enhanced $\cos\theta$ region is presented in Fig. 4.

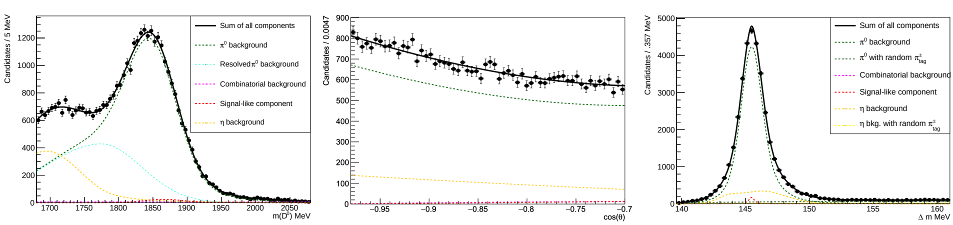


Fig. 3. Distributions of $m(D^0), \cos\theta$, and Δm for $D^0 \to \bar{K}^{*0}\gamma$ pseudodata in the signal-suppressed $\cos\theta$ region. The results of the three-dimensional fit are superimposed. Fit components are specified in the legend. The number of events generated is 40000.

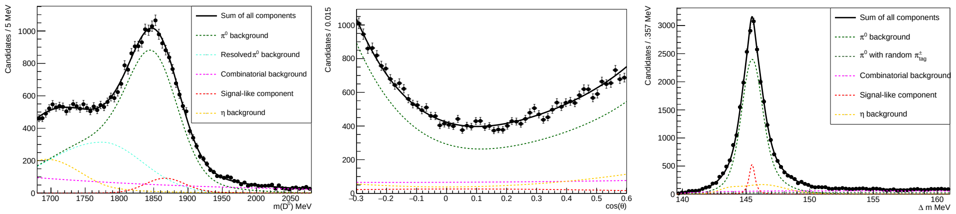


Fig. 4. Distributions of $m(D^0), \cos\theta$, and Δm for $D^0 \to \bar{K}^{*0}\gamma$ pseudodata in the signal-enhanced $\cos\theta$ region. The results of the three-dimensional fit are superimposed. Fit components are specified in the legend. The number of events generated is 33000.

4. Conclusion and outlook

Direct CP violation in the charm sector was observed through ΔA_{CP} in 2019 [6]. A follow-up analysis [8] shows evidence of direct CP violation in the individual decay channel $D^0 \to \pi^-\pi^+$. When combined, these two results demonstrate some tension with theoretical prediction, although the difficulty of precise theoretical calculations in charm [2, 9] makes it hard to judge whether this is a sign of NP. Other decay modes such as radiative charm decays $D^0 \to V\gamma$ can provide more insight into the CP violation in charm.

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