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Time-integrated CP violation in charm decays

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The search for CP violation (CPV) in decays of charmed hadrons is a unique probe of New Physics (NP) beyond the Standard Model (SM), complementary to searches in the down-type quark sector where these effects are relatively large. CPV in charm is expected to be small within the SM. Therefore, the observation of sizeable CPV effects would provide strong indication for NP. Some of the most recent result in the search for CPV effects in the decay of charmed hadrons are presented.

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1. Introduction

The non-invariance of weak interactions with respect to the combined application of charge conjugation (C) and parity (P) transformations is explained within the Standard Model (SM) by the Cabibbo-Kobayashi-Maskawa (CKM) mechanism [1]. According to this mechanism, CP violation (CPV) in the decays of charmed hadrons is expected to be much smaller than 1% [2, 3]. Recent calculation indicate that CPV at the level of few 10^{-3} may be possible within the SM [4, 5, 6]. Consequently, any observation of sizeable CPV could represent a strong indication of New Physics (NP). Only recently the experimental sensitivity approached the level of precision required to probe the CKM mechanism in the charm sector. In this paper we present the most recent experimental results regarding the measurement of direct CPV in the decays of charmed hadrons.

The main experimental observable indicating the presence of direct CPV in the decays of a charmed hadron is the asymmetry between the observed number of $D \to f$ decays (where D represent a generic D hadron and f a generic final state of the decay) and the observed number of the charge conjugate processes. Such observable is often referred to as the raw asymmetry

$$A_{\mathrm{RAW}} = \frac{N(D \to f) - N(\bar{D} \to \bar{f})}{N(D \to f) + N(\bar{D} \to \bar{f})}, \tag{1.1}$$

where N indicates the number of reconstructed events of a given decay after background subtraction. The value of the raw asymmetry is the result of several factors contributing to the imbalance between the observed occurrencies of the $D \to f$ and $\bar{D} \to \bar{f}$ decays: the asymmetry between the production rates of D and $\bar{D}$ hadrons (A_{P}), the asymmetry between the reconstruction efficiencies of the two charge conjugate final states f and $\bar{f}$ (A_{D}), the asymmetry between the efficiencies in the determination of the initial flavour of the D hadron (A_{T}), and, of course, the physical CP asymmetry (A_{CP}) related to the parameters of the CKM matrix. For small values of these asymmetries, the relation among them can be approximated by a linear sum of the various contributions:

$$A_{\mathrm{RAW}} \approx A_{CP} + A_{\mathrm{P}} + A_{\mathrm{D}} + A_{\mathrm{T}}. \tag{1.2}$$

The main challenge in order to determine the relevant quantity A_{CP} is to separate it from the nuisance asymmetries introduced by the experimental conditions. The mostly used strategy is to measure the raw asymmetry for Cabibbo-favoured (CF) decays, where no CPV is expected. Hence, the value of A_{RAW} will represent a measurement of the spurious asymmetries.

2. Search for CP violation in the decay $D^+ \to \pi^-\pi^+\pi^+$

Using the pp collision data, collected during 2011, and corresponding to an integrated luminosity of 1 fb^{-1}, the LHCb experiment investigated the presence of localised CPV across the Dalitz plot of the decay $D^+ \to \pi^-\pi^+\pi^+$[1] [7]. The sample contains about 3.1 million of signal candidates with a purity of 82%. A model-independent technique has been used to search for local CPV, based on a bin-by-bin comparison between the D^+ and D^- Dalitz plots, as described in Reference [8].

[1] Unless stated explicitly, the inclusion of charge conjugate states is implied in the rest of this document.

For each bin of the Dalitz plot, the test statistics $\mathscr{S}^i_{CP}$ is computed as

$$\mathscr{S}^i_{CP} \equiv \frac{N_i^+ - \alpha N_i^-}{\sqrt{\alpha(N_i^+ + N_i^-)}}\,, \qquad \alpha \equiv \frac{N^+}{N^-}, \tag{2.1}$$

where N_i^+ (N_i^-) is the number of D^+ (D^-) candidates in the ith bin and N^+ (N^-) is the sum of N_i^+ (N_i^-) over all bins. The parameter α removes the contribution of global asymmetries which may arise due to production and detection effects. Assuming the absence of localised asymmetries, the values of $\mathscr{S}^i_{CP}$ will be distributed according to a Gaussian function with zero mean and unitary width. Any deviation from this behaviour would imply the presence of *CPV*. The p-value for the no *CPV* hypothesis is calculated from a χ^2 statistic with $N_{bins} - 1$ degree of freedom, constructed by the sum $\chi^2 = \sum_i (\mathscr{S}^i_{CP})^2$. Different grids with 20, 32, 52 and 98 bins of equal size have been used to compute the χ^2 and the corresponding p-value. Moreover the phase space has also been subdivided into 20, 30, 40, 49 and 100 bins containing the same number of events by means of an adaptive binning method. The p-values computed for each binning scheme are always above the 50%, thus consistent with the no *CPV* hypothesis. In Figure 1 the results for the adaptive binning schemes with 100 bins are reported. The CF decay $D_s^+ \to \pi^-\pi^+\pi^+$, where *CPV* is not

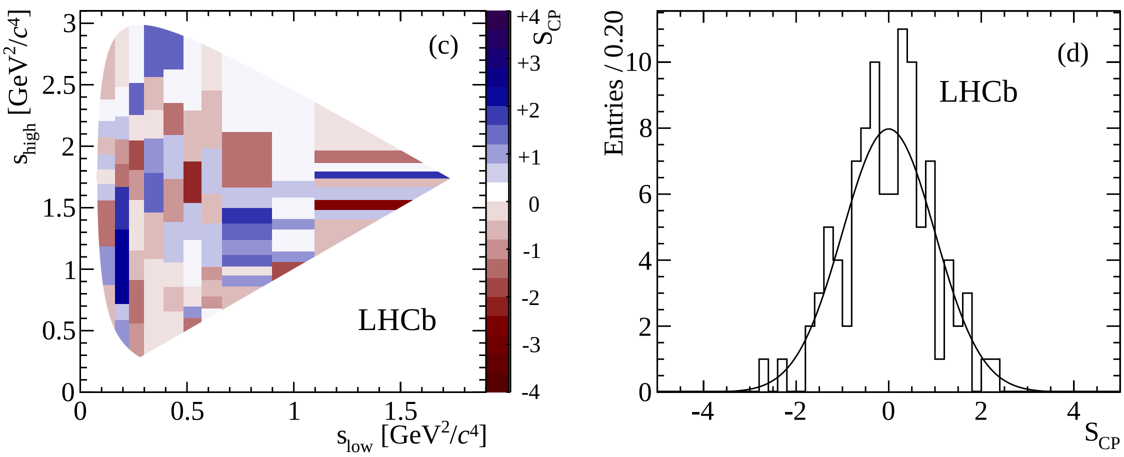

Figure 1: On the left: distributions of $\mathscr{S}^i_{CP}$ across the D^+ Dalitz plane, with the adaptive binning scheme of uniform population for the total $D^+ \to \pi^-\pi^+\pi^+$ data sample with 100 bins. The corresponding one-dimensional $\mathscr{S}^i_{CP}$ distribution is shown on the right with a standard normal Gaussian function superimposed (solid line).

expected at any significant level, has been analyzed with the same technique, in order to verify the absence of localised asymmetries due to instrumental and/or production effects. Inspecting the signal sidebands showed that also the presence of local instrumental asymmetries in the background can be excluded.

3. Search for direct *CP* violation in $D^0 \to \pi^+\pi^-\pi^0$ decays

The LHCb experiment also searches for direct *CPV* effects in $D^0 \to \pi^+\pi^-\pi^0$ decays [9]. The analysis uses the pp collisions collected by LHCb during 2012, corresponding to an integrated luminosity of 2 fb^{-1}. The presence of a π^0 in the final state makes the analysis particularly challenging at a hadronic collider. Neutral pions (and consequently D candidates) at LHCb are reconstruced in two different ways. When the two photons in the decay $\pi^0 \to \gamma\gamma$ generate distinct clusters in the electromagnetic calorimeter, the reconstructed π^0 is referred to as “resolved”. The D^0 candidates that are reconstructed using resolved π^0s have a relatively good invariant mass resolution and lower transverse momentum. When the two photons generate a single cluster the reconstructed π^0 is referred to as “merged”. The corresponding merged D^0 candidates have worse invariant mass resolution, but higher signal purity can be achieved owing to their larger average transverse momentum. A model-independent method, called “the energy test” [10], has been used to investigate the presence of local CPV across the Dalitz plane. The method is based on a test statistic T, defined as

$$T = \sum_{i,j>i}^{n} \frac{\psi_{ij}(d_{ij})}{n(n-1)} + \sum_{i,j>i}^{\bar{n}} \frac{\psi_{ij}(d_{ij})}{\bar{n}(\bar{n}-1)} - \sum_{i,j}^{n,\bar{n}} \frac{\psi_{ij}(d_{ij})}{n\bar{n}}, \tag{3.1}$$

where the n ($\bar{n}$) is the number of candidates tagged as D^0 ($\bar{D}^0$); $\psi_{ij}(d_{ij}) \equiv e^{-d_{ij}^2/2\sigma^2}$ is a Gaussian metric used to weight the distance $d_{ij} = (m_{12}^{2,j} - m_{12}^{2,i}, m_{23}^{2,j} - m_{23}^{2,i}, m_{13}^{2,j} - m_{13}^{2,i})$ between two candidates (i and j) in the Dalitz plane. The initial flavour of the D^0 is determined by the charge of the slow pion in the decay $D^{*+} \to D^0\pi^+$. By definition, T is not sensitive to global asymmetries. Assuming no CPV the T expectation value is zero, while in case of non-zero CPV it is positive. In order to establish the presence of localised CPV, the value of T computed from data has been compared with the distribution of T in the no CPV hypothesis. Such distribution is constructed performing 1000 permutations of the data sample where the initial flavour of the D^0 candidates is randomly assigned. The p-value for the no CPV hypothesis is $(2.6 \pm 0.5) \times 10^{-2}$, obtained from the fraction of premutations with values of T larger than that obtained in data. The result is consistent with CP conservation. Several tests have been performed in order to control the stability of the result. The analysis has been performed on sub-samples, separated by magnet polarity and trigger configurations. Moreover a set of fiducal requirements has been used to remove areas where very large local asymmetries are observed in reconstructing oppositely charged soft pions. All the tests provide consistent results. Further checks have also been performed to ensure the absence of spurious asymmetries coming from background events or related to detector asymmetries. The analysis has the world best sensitivity from a single experiment to local CPV in this decay.

4. Search for direct CPV in $D^+_{(s)} \to K^0_S h^+ decays$

Using the full sample of pp collision collected during Run1, corresponding to an integrated luminosity of 3 fb^{-1}, the LHCb experiment measures the direct CP asymmetries in the Cabibbo-Suppressed (CS) $D_s^+ \to K_S^0\pi^+$ and $D^+ \to K_S^0K^+$ decays [11]. The total sample contains about 4.8×10^6 $D^+ \to K_S^0\pi^+$, 0.12×10^6 $D_s^+ \to K_S^0\pi^+$, 1.0×10^6 $D^+ \to K_S^0K^+$ and 1.5×10^6 $D_s^+ \to K_S^0K^+$ decays. The analysis is performed extracting the raw asymmetries of the decays by means of fits to the invariant mass spectra of the reconstructed candidates. In order to remove the spurious asymmetries coming from production or detection effects, the raw asymmetries of the CF $D_s^+ \to K_S^0K^+$, $D^+ \to K_S^0\pi^+$ and $D_s^+ \to \phi\pi^+$ decays, where CPV is assumed to be negligible, are used. Each raw asymmetry is the sum of the $D^+_{(s)}$ production asymmetry and of the detection asymmetry of the bachelor particle (that can be a pion or a kaon), plus the physical *CP* asymmetry (where assumed non-negligible). Hence the following relations are used to determine the relevant quantities:

$$A_{CP}^{D^+\to K_S^0 K^+} = \left[A_{\rm RAW}^{D^+\to K_S^0 K^+} - A_{\rm RAW}^{D_s^+\to K_S^0 K^+}\right] - \left[A_{\rm RAW}^{D^+\to K_S^0 \pi^+} - A_{\rm RAW}^{D_s^+\to \phi \pi^+}\right] - 2A_{K^0}, \quad (4.1)$$

$$A_{CP}^{D_s^+\to K_S^0 \pi^+} = A_{\rm RAW}^{D_s^+\to K_S^0 \pi^+} - A_{\rm RAW}^{D_s^+\to \phi \pi^+} - A_{K^0}. \quad (4.2)$$

The term A_{K^0} is the asymmetry related to the interaction with the detector material of the neutral kaon, as well as to K^0 *CPV*. Its determination is done by means of simulation. The analysis is performed separately for 2011 and 2012 data, and for both magnet polarities. Additionally, in order to achieve a better cancellation of spurious asymmetries, the samples are weighted in order to equalize the transverse momentum and pseudo-rapidity distributions of $D_{(s)}^+$ mesons. The results are:

$$A_{CP}^{D^+\to K_S^0 K^+} = (+0.03 \pm 0.17({\rm stat.}) \pm 0.14({\rm syst.}))\%, \quad (4.3)$$

$$A_{CP}^{D_s^+\to K_S^0 \pi^+} = (+0.38 \pm 0.46({\rm stat.}) \pm 0.26({\rm syst.}))\%. \quad (4.4)$$

These are the most precise measurements of these quantities to date.

5. Search for *CP* violation in $D^0 \to \pi^0\pi^0$ decays

Using the full sample collected at the KEKB e^+e^- collider, corresponding to an integrated luminosity of 966 fb^{-1}, the Belle experiment measures the *CP* asymmetry of the $D^0 \to \pi^0\pi^0$ and $D^0 \to K_S^0\pi^0$ decays [12]. In this analysis the intial flavour of the D^0 candidates is determined by the charge of the soft pion in the decay $D^{*+} \to D^0\pi_s^+$. A total sample of about 0.35×10^6 $D^0 \to \pi^0\pi^0$ and 0.47×10^6 $D^0 \to K_S^0\pi^0$ "tagged" decays is selected. The detection asymmetry of the soft pion is determined in bins of the trasverse momentum ($p_T^{\pi_s}$) and polar angle (θ^{π_s}) of the π_s^+, by subtracting the raw asymmetries of the CF decays $D^0 \to K^-\pi^+$ ("untagged") and $D^{*+} \to D^0(K^-\pi^+)\pi_s^+$ ("tagged"). A further correction to be applied is the forward-backward asymmetry in the production of D^{*+} mesons ($A_{\rm FB}$), due to the $\gamma - Z^0$ interference in $e^+e^- \to c\bar{c}$ processes. $A_{\rm FB}$ is an odd function of the cosine of the D^{*+} polar angle (θ^*) in the center-of-mass system. Hence $A_{\rm FB}$ can be subtracted from the raw asymmetry using the equation

$$A_{CP} = \frac{A_{\rm RAW}^{\rm corr.}(\cos\theta^*) + A_{\rm RAW}^{\rm corr.}(-\cos\theta^*)}{2}. \quad (5.1)$$

where $A_{\rm RAW}^{\rm corr.}(\cos\theta^*)$ is the raw asymmetry of the signals, determined in bins of $\cos\theta^*$ and corrected for the detection asymmetry of the soft pion. In order to take into account all the corrections and their dependence on kinematic variables, the total data sample is divided into 10 bins of $\cos\theta^*$, 7 bins of $p_T^{\pi_s}$ and 8 bins of θ^{π_s}. A fit to the mass difference $\Delta M = M_{D^*} - M_{D^0}$ is performed in each 3D bin and the obtained raw asymmetry is corrected for the detection asymmetry of the soft pion. Final results are

$$A_{CP}(D^0 \to \pi^0\pi^0) = (-0.03 \pm 0.64({\rm stat.}) \pm 0.10({\rm syst.}))\%, \quad (5.2)$$

$$A_{CP}(D^0 \to K_S^0\pi^0) = (-0.21 \pm 0.16({\rm stat.}) \pm 0.07({\rm syst.}))\%. \quad (5.3)$$

After subtracting *CPV* due to $K^0 - \bar{K}^0$ mixing, $(-0.339 \pm 0.007)\%$ [13], the *CP* asymmetry in $D^0 \to K_S^0\pi^0$ decays is found to be $(+0.12 \pm 0.16({\rm stat.}) \pm 0.07({\rm syst.}))\%$. All the measurements are compatible with the absence of *CPV*.

6. Measurement of *CPV* in charged two-body D^0 decays

Using the full sample of pp collisions collected during Run1, the LHCb experiment updated the measurement of the difference between the CP asymmetries of the $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays, $\Delta A_{CP} = A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)$. Measuring the difference between the two asymmetries nuisance asymmetries coming from production or detection effects cancel out to first order. Moreover, a reweighting of the candidates has been used to equalize the distributions of the kinematical variables, in order to avoid second order effects that may lead to a non-perfect cancellation. The main experimental challenge is to disentangle the two asymmetries, providing a measurement of the two A_{CP} values. In this analysis a technique peculiar to LHCb has been used to determine the initial flavour of the D^0 candidate. A muon compatible to have a common origin vertex with the D^0 candidate is used to inclusively reconstruct the decays $\bar{B} \to D^0\mu^-\bar{\nu}_\mu X$. Hence the charge of the muon defines the flavour of the D^0 coming from B hadron decays. Using this technique about 2.1×10^6 $D^0 \to K^+K^-$ and 0.7×10^6 $D^0 \to \pi^+\pi^-$ "muon-tagged" decays are reconstructed. The spurious asymmetries introduced by this technique are the production asymmetry associated with the b-hadron and the detection asymmetry of the muon. The corrections to the raw asymmetry can be determined using the $\bar{B} \to D^0\mu^-\bar{\nu}_\mu X$ decays where the D^0 decays to the CF $K^-\pi^+$ final state. However, the raw asymmetry of this control channel contains an additional term, that is the detection asymmetry of the $K^-\pi^+$ pair. This detection asymmetry is determined from the difference between the raw asymmetries of the CF $D^+ \to K^-\pi^+\pi^+$ and $D^+ \to K^0_S\pi^+$ decays, where the effect of CPV and detection asymmetry of the neutral kaon is computed from simulation and then subtracted. The candidates of the control channels are also weighted in order to equalize the distributions of the relevant kinematic variables, to avoid second order effects that may introduce a non perfect cancellation of the spurious asymmetries. Combining the raw asymmetries of the $\bar{B} \to D^0(K^-\pi^+)\mu^-\bar{\nu}_\mu X$, $D^+ \to K^-\pi^+\pi^+$ and $D^+ \to K^0_S\pi^+$ candidates it is then possible to determine the production asymmetry associated with the b-hadron and the detection asymmetry of the muon, and consequently the CP asymmetry of the $D^0 \to K^+K^-$ decay. The CP asymmetry of the $D^0 \to \pi^+\pi^-$ decay is obtained from the difference between ΔA_{CP} and $A_{CP}(D^0 \to K^+K^-)$. The results are [14]

$$\Delta A_{CP} = (+0.14 \pm 0.16(\text{stat.}) \pm 0.08(\text{syst.}))\%, \tag{6.1}$$

$$A_{CP}(D^0 \to K^+K^-) = (-0.06 \pm 0.15(\text{stat.}) \pm 0.10(\text{syst.}))\%, \tag{6.2}$$

$$A_{CP}(D^0 \to \pi^+\pi^-) = (-0.20 \pm 0.19(\text{stat.}) \pm 0.10(\text{syst.}))\%. \tag{6.3}$$

The individual A_{CP} values are the most precise measurements of these quantities to date and are compatible with the no CPV hypothesis. The quantity ΔA_{CP} is not a measurement of pure direct CPV since in D^0 decays one should take into account also CPV coming from mixing and interference between mixing and decay. To first order the relation $\Delta A_{CP} = \Delta A_{\text{dir.}} - A_\Gamma \cdot \Delta\langle t\rangle/\tau$ holds, where: $\Delta A_{\text{dir.}}$ measures direct CPV, A_Γ is the asymmetry between the effective lifetime of D^0 mesons decaying to CP eigenstates and measures the indirect CPV component, $\Delta\langle t\rangle$ is the average between the effective lifetimes of the $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays, and τ is the mean lifetime of the D^0 meson. Two recent measurements of A_Γ are available: one from the CDF experiment [15] (using the $D^{*+} \to D^0\pi_s^+$ decays to tag the initial flavour of the D^0) and one from the

LHCb experiment [16] (using the "muon-tagging" technique). The two experiments use the same strategy to determine A_Γ, that consists in measuring the raw asymmetry of the $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays in bins of t/τ (where t is the measured decay time of the D^0) and then fitting the observed behaviour with

$$A_{\mathrm{RAW}}(t) \approx A_0 - A_\Gamma(t/\tau) \tag{6.4}$$

to extract A_Γ. Here A_0 contains the spurious asymmetries plus the direct *CPV* component and does not affect the determination of A_Γ. The main experimental effect is the independence of A_0 from the decay time of the D^0 and can be controlled using the CF $D^0 \to K^-\pi^+$ decays. Numerical results are

$$A_\Gamma(D^0 \to K^+K^-) = (-0.19 \pm 0.15(\mathrm{stat.}) \pm 0.04(\mathrm{syst.}))\%, \tag{6.5}$$
$$A_\Gamma(D^0 \to \pi^+\pi^-) = (-0.01 \pm 0.18(\mathrm{stat.}) \pm 0.03(\mathrm{syst.}))\%, \tag{6.6}$$

for CDF, and

$$A_\Gamma(D^0 \to K^+K^-) = (-0.134 \pm 0.077(\mathrm{stat.})^{+0.026}_{-0.034}(\mathrm{syst.}))\%, \tag{6.7}$$
$$A_\Gamma(D^0 \to \pi^+\pi^-) = (-0.092 \pm 0.145(\mathrm{stat.})^{+0.025}_{-0.033}(\mathrm{syst.}))\%, \tag{6.8}$$

for LHCb. All the available measurements of direct and indirect *CPV* from two-body D^0 decays are reported in Figure 2. The global combination performed by HFAG [17] is consistent with the no *CPV* hypothesis at 1.8% confidence level.

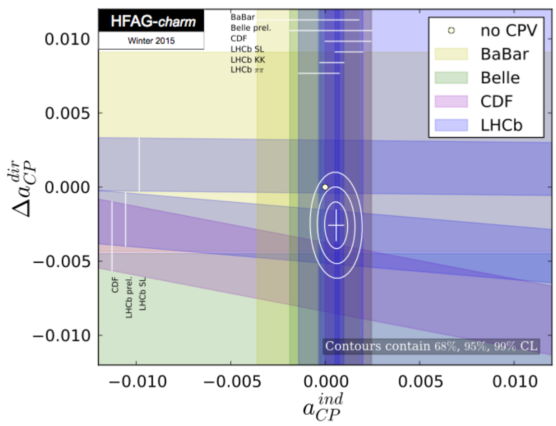

Figure 2: Combination plot of all the available measurements for ΔA_{CP} and A_Γ as performed by HFAG. The bands represent $\pm 1\sigma$ intervals. The point of no *CP* violation $(0,0)$ is shown, and two-dimensional 68% C.L., 95% C.L., and 99.7% C.L. regions are plotted as ellipses with the best fit value as a cross indicating the one-dimensional uncertainties.

7. Summary

In this paper some of the most recent measurements of direct and indirect *CPV* in two- and multi-body decays of D mesons have been presented. The results are compatible with the no *CPV* hypothesis and in agreement with the SM at the current level of precision.

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