DIRECT CP VIOLATION IN CHARM MESONS AT THE LHCb*

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The LHCb experiment collected the world's largest data samples with charmed hadrons during the first two runs of the LHC operations. These samples allow us to measure CP-violating observables in D-meson decays with precision not available till now. New measurements of CP violation in different charged and neutral-charm decays based on these data sets are reported.

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1. Introduction

The phenomenon of CP violation (CPV) is one of the least-known part of the Standard Model (SM). The existence of CPV means that the laws of physics change if a particle is replaced by its antiparticle and the directions of all coordinates are changed. The CPV phenomenon is related to basic problems of particle physics. Perhaps here, there is the answer why there are three generations of quarks and leptons. So far, it has been known only that this is the smallest number that allows for the introduction of a non-zero weak phase describing CPV in the Cabibbo–Kobayashi–Maskawa (CKM) matrix. In addition, the known value of CPV in the SM is significantly too small to explain the fact of matter domination over antimatter in our universe. This leads to the conclusion that the SM is not the final theory. Therefore, the main goal of High Energy Physics (HEP) research is a search for physics beyond the SM (called new physics). Such searches are performed in the LHCb experiment [1, 2], for example in particle decays of hadrons containing charm quarks (mesons and baryons). The expected values of CPV in the SM are about a few per milles or less in charm particle decays [3–7]. The first observation of CPV in two-body neutral charm decays [8] is crucial to shed light on CPV phenomenology and motivates further

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searches for similar effects in charged D-meson decays. Such searches could involve dynamics beyond the SM. Recently, the first evidence for CPV in a specific D^0 decay is noticed [9].

In these proceedings, the measurements of CPV in different multi-body charm meson decays are presented. They are based on data samples corresponding to 6 fb^{-1} (Run 2) or 9 fb^{-1} (Run 1 and 2) of integrated luminosity collected in the LHCb experiment in proton–proton collisions at the LHC.

2. Time integrated CPV in $D^0 \to K^0_{\mathrm{S}} K^0_{\mathrm{S}}$ decays

Among many charm decays, in the $D^0 \to K^0_{\mathrm{S}} K^0_{\mathrm{S}}$ decay, the expected size of CPV in the SM can be larger than in the other channels, up to the percent level [3, 7, 10]. Only amplitudes proceeding via loop-suppressed and tree-level diagrams contribute to this decay, and they are similar in size. A different mix of these amplitudes can result in a non-zero CP asymmetry which can be defined as

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

where Γ is the decay width of the D^0 or $\bar{D}^0$ meson decaying to a final state f, and $f = K^0_{\mathrm{S}} K^0_{\mathrm{S}}$.

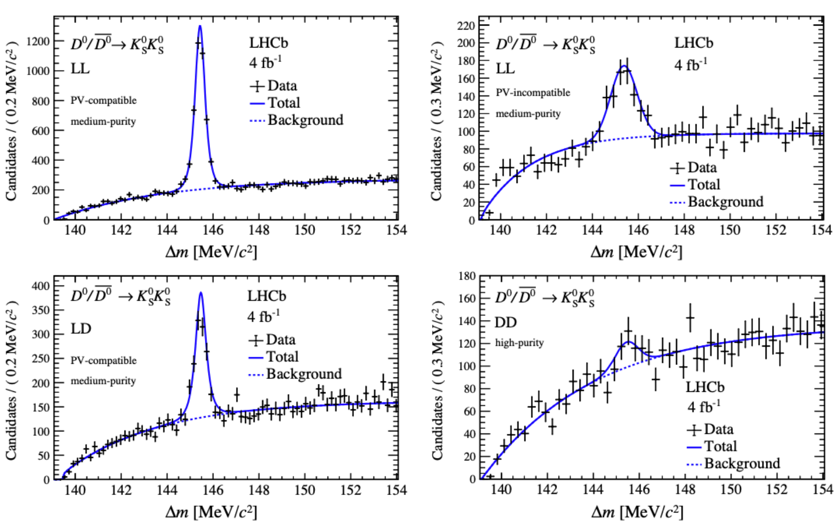

Fig. 1. Fit projections of the Δm observable for representative candidate categories: LL, LD or DD, according to the decay place of the K^0_{S} mesons associated to the D^0 meson. The label "L" is used for the K^0_{S} decay that occurred early enough for the two pions to be reconstructed in the vertex detector and the label "D" for those decaying later.

The measurement of $A_{\rm CP}(K^0_{\rm S}K^0_{\rm S})$ is based on a data sample from Run 2, corresponding to an integrated luminosity of 6 fb^{-1} [11]. The D^0 mesons originate from the $D^{*\pm}$ decays ($D^{*+} \to D^0\pi^+$). The charge of accompanying pion identifies the flavour of the produced D^0 meson, whilst the $K^0_{\rm S}$ mesons are reconstructed as $\pi^+\pi^-$ pairs. Some representative distributions of the reconstructed $D^0 \to K^0_{\rm S}K^0_{\rm S}$ decay candidates are presented in Fig. 1, where the $\Delta m = m(D^{*+}) - m(D^0)$ is the difference of masses between the $D^{*+} \to D^0\pi^+$ ($m(D^{*+})$) and the $D^0 \to K^0_{\rm S}K^0_{\rm S}$ ($m(D^0)$).

The $A_{\rm CP}(K^0_{\rm S}K^0_{\rm S})$ is measured to be $(-3.1 \pm 1.2 \pm 0.4 \pm 0.2)\%$, where the first uncertainty is statistical, the second is systematic, and the third comes from the uncertainty on the $A_{\rm CP}(K^+K^-)$ since the $D^0 \to K^+K^-$ is used as a calibration sample. This measurement is the most precise to date, and is compatible with CP symmetry at the level of 2.4 standard deviations.

3. Time integrated CPV in $D^+_{(s)} \to h^+\pi^0$ and $D^+_{(s)} \to h^+\eta$ decays

The measurements of CPV are also performed in the seven $D^+_{(s)} \to h^+\pi^0$ and $D^+_{(s)} \to h^+\eta$ decays, where h^+ denotes a π^+ or K^+ meson [12]. The π^0 and η are reconstructed using the $e^+e^-\gamma$ final state, which can proceed as three-body decays $\pi^0 \to e^+e^-\gamma$ and $\eta \to e^+e^-\gamma$, or via the two-body decays $\pi^0 \to \gamma\gamma$ and $\eta \to \gamma\gamma$ followed by a photon conversion. The $D^+ \to \pi^+\pi^0$ decay is of particular interest, since no CPV is expected in this channel within the SM as a result of isospin constraints [3]. In this case, the measurement of non-zero value of $A_{\rm CP}(D^+ \to \pi^+\pi^0)$ would be an indication of physics beyond the SM, where $A_{\rm CP}(D^+ \to \pi^+\pi^0)$ is defined in analogous way to Eq. (1). In total, 28×10^3 of $D^+ \to \pi^+\pi^0$, 2.5×10^3 of $D^+ \to K^+\pi^0$, 2.7×10^3 of $D^+_s \to K^+\pi^0$, 33×10^3 of $D^+ \to \pi^+\eta$, 38×10^3 of $D^+_s \to \pi^+\eta$, 900 of $D^+ \to K^+\eta$, and 2.5×10^3 of $D^+_s \to K^+\eta$ candidates are reconstructed in Run 1 and 2 data samples. The production and detection asymmetries are controlled using a large sample of the $D^+_{(s)} \to K^0_{\rm S}h^+$ decays, which is weighted to match the kinematics of the seven analysed decays. The CP asymmetries are measured to be:

$$\begin{aligned}
A_{\rm CP}\left(D^+ \to \pi^+\pi^0\right) &= (-1.3 \pm 0.9 \pm 0.6)\%\,, \\
A_{\rm CP}\left(D^+ \to K^+\pi^0\right) &= (-3.2 \pm 4.7 \pm 2.1)\%\,, \\
A_{\rm CP}\left(D^+ \to \pi^+\eta\right) &= (-0.2 \pm 0.8 \pm 0.4)\%\,, \\
A_{\rm CP}\left(D^+ \to K^+\eta\right) &= (-6 \pm 10 \pm 4)\%\,, \\
A_{\rm CP}\left(D^+_s \to K^+\pi^0\right) &= (-0.8 \pm 3.9 \pm 1.2)\%\,, \\
A_{\rm CP}\left(D^+_s \to \pi^+\eta\right) &= (0.8 \pm 0.7 \pm 0.5)\%\,, \\
A_{\rm CP}\left(D^+_s \to K^+\eta\right) &= (0.9 \pm 3.7 \pm 1.1)\%\,, \qquad (2)
\end{aligned}$$

where the first uncertainty is statistical and the second systematic. All seven above measurements are consistent with no observation of CP asymmetry.

4. Studies in $D^{\pm}_{(s)} \to \eta^{(\prime)}\pi^{\pm}$ decays

The other complementary CPV measurements are done in two-body $D^+ \to \eta^{(\prime)}\pi^+$ and $D_s^+ \to \eta^{(\prime)}\pi^+$ decays [13]. This time, the studies are performed in data recorded only in Run 2, corresponding to an integrated luminosity of 6 fb^{-1}. The η and η' mesons are both reconstructed using the $\pi^+\pi^-\gamma$ final state. The total charge-integrated candidates for the $D_s^+ \to \eta'\pi^+$ decays are $(1\,085.7 \pm 1.2) \times 10^3$, for the $D^+ \to \eta'\pi^+$ are $(555.4 \pm 0.9) \times 10^3$, for the $D_s^+ \to \eta\pi^+$ are $(135.8 \pm 0.7) \times 10^3$, and for the $D^+ \to \eta\pi^+$ are $(110.8 \pm 0.7) \times 10^3$. Using these statistics, the values of A_{CP} are determined to be:

$$\begin{aligned}
A_{\mathrm{CP}}\left(D^+ \to \eta\pi^+\right) &= (0.34 \pm 0.66 \pm 0.16 \pm 0.05)\%\,,\\
A_{\mathrm{CP}}\left(D_s^+ \to \eta\pi^+\right) &= (0.32 \pm 0.51 \pm 0.12)\%\,,\\
A_{\mathrm{CP}}\left(D^+ \to \eta'\pi^+\right) &= (0.49 \pm 0.18 \pm 0.06 \pm 0.05)\%\,,\\
A_{\mathrm{CP}}\left(D_s^+ \to \eta'\pi^+\right) &= (0.01 \pm 0.12 \pm 0.08)\%\,,
\end{aligned} \tag{3}$$

where the first uncertainty is statistical, the second is systematic, and the third, if applicable, is due to the uncertainty on $A_{\mathrm{CP}}(D^+ \to \phi\pi^+)$ which is used as a control channel to remove instrumental asymmetries. These measurements are consistent with the absence of CPV.

5. Very rare $D^0 \to h^+h^-\mu^+\mu^-$ decays

The rare charm decays with two oppositely-charged muons in the final state can be sensitive also to contributions from physics beyond the SM; they represent a unique probe of the SM. These studies are complementary to the ones in rare beauty decays. The difference is that the loop-induced SM processes are more suppressed in charm than in the beauty system. The CP asymmetry measurements in the semileptonic $D^0 \to h^+h^-\mu^+\mu^-$ decays are performed using the combined Run 1 and 2 data statistics, corresponding to an integrated luminosity of 9 fb^{-1} [14]. The distributions of measured masses of four particles (K^+K^- pair and $\mu^+\mu^-$ pair) in the final state are presented in Fig. 2. From the unbinned maximum-likelihood fits to these distributions, the yields of the $D^0 \to K^+K^-\mu^+\mu^-$ and $D^0 \to \pi^+\pi^-\mu^+\mu^-$ candidates are obtained to be 319 ± 19 and 3579 ± 71, respectively.

The CP asymmetries are defined in a similar way to Eq. (1) and their measured values are presented in Fig. 3 in the intervals of dimuon mass ($m(\mu^+\mu^-)$). The results are consistent with no CP asymmetry, but help to constrain the parameter space of physics models extending the SM.

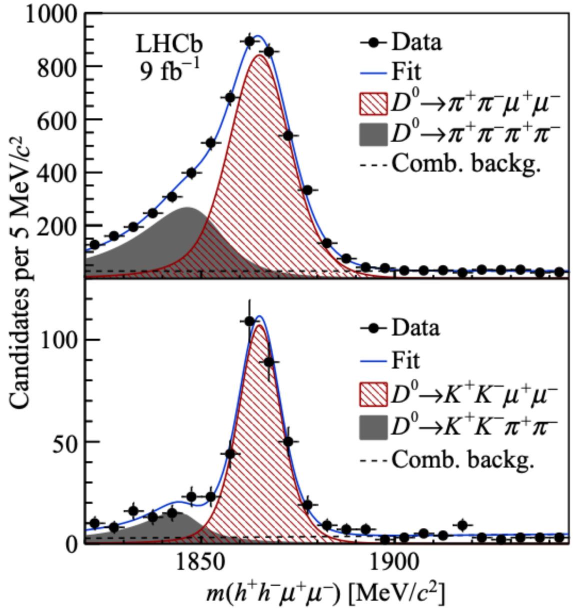

Fig. 2. Fit projections in mass distributions of (top) $D^0 \to \pi^+\pi^-\mu^+\mu^-$ and (bottom) $D^0 \to K^+K^-\mu^+\mu^-$ candidates.

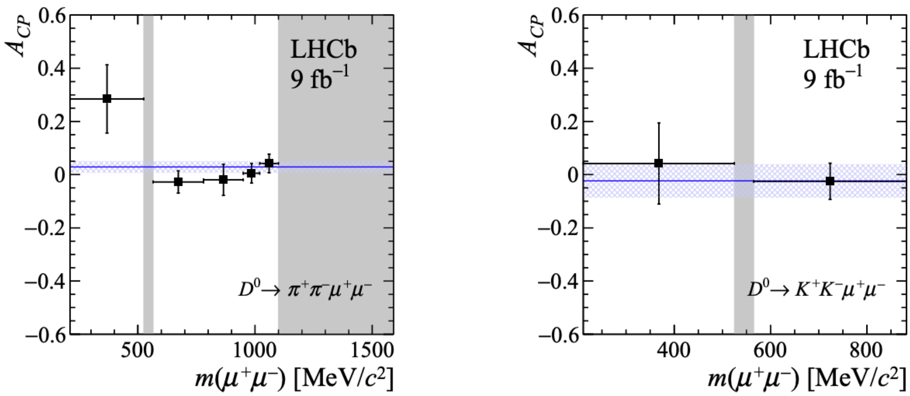

Fig. 3. Measurement of $A_{\rm CP}$ in regions of dimuon mass for (left) $D^0 \to \pi^+\pi^-\mu^+\mu^-$ and (right) $D^0 \to K^+K^-\mu^+\mu^-$ candidates. No measurements were performed in the regions marked via the vertical gray bands. The horizontal bands correspond to the integrated measurements in all regions. The uncertainties are statistical and systematic summed in quadrature.

6. Summary

The searches for CP violation in two- and four-body charm decays were performed using data collected in the LHCb experiment, corresponding to 9 fb^{-1} of the integrated luminosity. These measurements test the Standard Model predictions, and are all consistent with zero CP asymmetry within the uncertainties of a few per mille. So far, the CP violation phenomenon in the charm sector is confirmed only in two-body neutral D-meson decays, such as the $D^0 \to K^+K^-$ and the $D^0 \to \pi^+\pi^-$.

REFERENCES

[1] LHCb Collaboration (R. Aaij *et al.*), *Int. J. Mod. Phys. A* **30**, 1530022 (2015).

[2] LHCb Collaboration (A.A. Alves, Jr. *et al.*), *J. Instrum.* **3**, S08005 (2008).

[3] F. Buccella, A. Paul, P. Santorelli, *Phys. Rev. D* **99**, 113001 (2019).

[4] M. Chala, A. Lenz, A.V. Rusov, J. Scholtz, *J. High Energy Phys.* **2019**, 161 (2019).

[5] S. Bianco, F.L. Fabbri, D. Benson, I. Bigi, *Riv. Nuovo Cim.* **26**, 1 (2003).

[6] A. Khodjamirian, A.A. Petrov, *Phys. Lett. B* **774**, 235 (2017).

[7] H.-Y. Cheng, C.-W. Chiang, *Phys. Rev. D* **100**, 093002 (2019).

[8] LHCb Collaboration (R. Aaij *et al.*), *Phys. Rev. Lett.* **122**, 211803 (2019).

[9] LHCb Collaboration (R. Aaij *et al.*), `arXiv:2209.03179 [hep-ex]`.

[10] U. Nierste, S. Schacht, *Phys. Rev. D* **92**, 054036 (2015).

[11] LHCb Collaboration (R. Aaij *et al.*), *Phys. Rev. D* **104**, L031102 (2021).

[12] LHCb Collaboration (R. Aaij *et al.*), *J. High Energy Phys.* **2021**, 019 (2021).

[13] LHCb Collaboration (R. Aaij *et al.*), `arXiv:2204.12228 [hep-ex]`.

[14] LHCb Collaboration (R. Aaij *et al.*), *Phys. Rev. Lett.* **128**, 221801 (2022).