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CP Violation and Mixing in Charm at LHCb

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The LHCb experiment has collected the world's largest sample of charmed hadron decays. This, combined with the precision of the LHCb detector designed for studies of charm and beauty physics, enabled the first measurement of CP violation in the charm sector in 2019. These proceedings include a discussion of recent results regarding mixing and CP violation obtained using LHCb Run 1 (2011-2012) and Run 2 (2015-2018) data in $D^0 \to K^+\pi^-$, $D^0 \to \pi^+\pi^-\pi^0$, and $D^0 \to K_S^0 K^\pm \pi^\mp$ decay channels. The presented analyses employed time-dependent and energy-test-based approaches.

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1. Introduction

The Lagrangian of the Standard Model (SM) has two key features relevant for precision searches for beyond-the-Standard Model (BSM) effects in flavour physics. Firstly, flavor-changing neutral currents (FCNCs) are highly suppressed by the Glashow–Iliopoulos–Maiani (GIM) mechanism. Secondly, the only meaningful source of CP-symmetry violation (CPV) in the SM is attributed to a single irreducible complex phase in the Cabibbo–Kobayashi–Maskawa (CKM) matrix. The GIM suppression is particularly strong in the case of hadrons containing a c quark (charmed hadrons) [21]. Moreover, the combination of the CKM matrix elements relevant for charmed hadron weak interactions results in a very small complex phase [1], leading to highly suppressed CPV at the level of $10^{-4} - 10^{-3}$. An interesting effect involving FCNCs enabling studies of CPV in the charm sector is the phenomenon of quantum oscillations, or mixing, between neutral D^0 ($c\bar{u}$) mesons and their anti-particles [12]. These are the only neutral mesons that allow studies involving the decay of up-type quarks. Therefore, they are sensitive to a different class of interactions than studies with neutral B and K mesons.

The precision studies involving D^0 mixing and decays pose two challenges. The first one is the long time required to detect a single oscillation of D^0 resulting from the slowness of mixing in the charm sector, which implies large samples of D^0 decays. Another challenge can be encountered in the interpretation of measurements involving charmed hadrons, which is complicated due to the presence of low-energy strong interactions. Given this, the assessment of the agreement between experimental results and the SM would benefit from advancements in theoretical tools and additional experimental input [12, 21].

We distinguish two main types of CPV applicable to neutral-flavoured mesons: direct CPV, characterised by differences in decay amplitudes, and indirect CPV including a mixing contribution arising from the difference in transition rates between matter and antimatter. In the SM, direct CPV can occur only in singly Cabibbo-suppressed (SCS) decays due to the presence of contributions from both tree and penguin diagrams. In contrast, Cabibbo-favored (CF) and doubly-Cabibbo-suppressed (DCS) decays involve only one type of diagram, making direct CPV impossible [22].

The only place where CPV was discovered in charm was SCS decays of D^0 mesons. In 2019 the LHCb experiment reported a non-zero difference between the time-integrated asymmetries of $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ at 5.3σ level [7]. In 2023 the first 3.8σ evidence of direct CPV in a single decay channel $D^0 \to \pi^+\pi^-$ was reported [8]. Both measurements are at the upper end of the SM predictions. As a result both the SM-based and BSM interpretations of these measurements are considered.

2. LHCb data

The LHCb experiment has collected the world's largest sample of charmed hadron decays [10]. The measurements discussed here are based on the LHCb data collected in two periods: from 2011 to 2012 (Run 1) at the center of mass energy $\sqrt{s} = 7 - 8$ TeV, and from 2015 to 2018 (Run 2) at $\sqrt{s} = 13$ TeV, corresponding to total integrated luminosities of 3 fb^{-1} and 6 fb^{-1} respectively. All measurements presented in these proceedings involve D^0 mesons produced in the

[1] $\text{Im}(V_{cb}V^*_{ub}/V_{cb}V^*_{ub}) \approx -6 \cdot 10^{-4}$ [12]

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strong $D^{*+}(2010) \to D^0\pi_s^+$ decays[2] where the D^{*+} mesons are selected to originate directly in the proton-proton collision vertex (prompt decays). This choice ensures high resolution of the D^0 and D^{*+} invariant masses, and the D^0 decay time [9, 17].

3. Search for CPV in three body decays of D^0

In three-body D^0 and $\overline{D}^0$ decays, CPV can result in asymmetry in the phase-space distributions of daughter particles. This asymmetry arises from the change in the sign of the weak phase under charge conjugation, provided that amplitudes with nonzero strong phase differences are present alongside the weak phase [14]. The presence of local resonances in the three-body decay ensures variations in the strong phase across the phase space. This combined with the large weak phases predicted by many extensions of the SM can lead to localised CPV effects [14].

The LHCb experiment searched for this type of CPV in SCS $D^0 \to \pi^0\pi^-\pi^+$ and $D^0 \to K_S^0K^\pm\pi^\mp$ decays [1–3]. These searches employed the energy-test method, which allows to compare phase-space distributions of the D^0 daughter particles in an unbinned and model-independent way. The test quantifies localised sample differences by calculating a single test statistic T [14]:

$$T \equiv \frac{1}{2n(n-1)}\sum_{i,j\neq i}^{n}\psi_{i,j} + \frac{1}{2\bar{n}(\bar{n}-1)}\sum_{i,j\neq i}^{n}\psi_{i,j} - \frac{1}{n\bar{n}}\sum_{i,j}^{n\bar{n}}\psi_{i,j}, \tag{1}$$

where $\psi_{ij} = e^{-d_{ij}^2/2\delta^2}$ is the weight associated with the distance d_{ij} between pairs of candidates, while n and $\bar{n}$ are the total numbers of D^0 and $\overline{D}^0$ mesons. The tunable parameter δ constrains the radius in the phase space where the local asymmetry can be probed. The phase space is parametrised with the squared invariant masses of the three D^0 daughter particles. The calculated T-value is converted to a p-value by comparing it with the null hypothesis of CP-symmetry conservation. The null-hypothesis distribution is obtained by computing the test statistic for samples with randomly assigned D^0 flavours. The p-value is the fraction of null hypothesis samples where the T-value exceeds that of the original data.

The recent LHCb study in $D^0 \to \pi^0\pi^-\pi^+$ decay channel, described in Ref. [2], used Run 2 data with approximately 4 times greater signal yield compared to the previous analysis of this type [3]. The analysed data was divided into two samples based on the opening angle between photons in the $\pi^0 \to \gamma\gamma$ decays from which the final-state neutral pions were reconstructed. The event selection was optimised separately for the two categories to reflect their different characteristics. The two datasets were combined before applying the final energy test. The $D^0 \to K^-\pi^+\pi^-$ decays were used for cross-checks of the detection asymmetries for the different pions in the final state. As a result of the analysis, a p-value of 62% was reported, indicating no evidence of localised CPV. This result does not confirm the small p-value of 2% obtained in the previous measurement using Run 1 data [3]. The data samples used in analysis from Ref. [2] and Ref. [3] are statistically independent and therefore the p-values are expected to follow the uniform distribution provided the null hypothesis is true.

In the analysis with $D^0 \to K_S^0K^\pm\pi^\mp$ decays, see Ref. [1], a subset of the LHCb Run 2 data collected between 2016-2018, corresponding to 5.4 fb^{-1} of total integrated luminosity, was used.

[2]Throughout this paper charge conjugation is implied. The π_s symbol denotes the slowly moving pion.

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The sample was divided into two separate sets depending on the final state. The decays with the final state $K_s^0 K^+ \pi^-$ are called SS (same sign) whereas the decays with final state $K_s^0 K^- \pi^+$ are referred to as OS (opposite sign). The K_s^0 mesons present in both OS and SS final states are reconstructed via their decay to $\pi^+\pi^-$. The analysis used two control channels. The first one, $D^0 \to K^-\pi^+\pi^-\pi^+$, included the same particles as the final states and was used to verify that no $K-\pi$ detection asymmetries mimicking CPV are present. The second one, $D^0 \to K_s^0 \pi^-\pi^+$, was used to confirm negligible asymmetry effects from K_s^0 decays. Tests on background-enhanced samples were performed to assess detection and local background asymmetries. The analysis yielded p-values of 66% (OS) and 70% (SS), indicating agreement with the null hypothesis.

4. CPV in $D^0 \to \pi^0\pi^-\pi^+$ decays (time-dependent)

The asymmetry of the D^0 meson decaying into a CP eigenstate, f_{CP}, can be expanded to first order in the ratio of decay time t to the average lifetime of the D^0 meson τ_{D^0} [4]:

$$A_{CP}(f_{CP}, t) = \frac{\Gamma_{D^0 \to f_{CP}}(t) - \Gamma_{\overline{D}^0 \to f_{CP}}(t)}{\Gamma_{D^0 \to f_{CP}}(t) + \Gamma_{\overline{D}^0 \to f_{CP}}(t)} \approx a^{\text{dir}}_{f_{CP}} + \Delta Y_{f_{CP}} \frac{t}{\tau_{D^0}} \tag{2}$$

In this approximation, $\Delta Y_{f_{CP}}$ is universal across decay modes and can be related to the CPV and mixing parameter $\Delta Y = \eta_{f_{CP}} \cdot \Delta Y_{f_{CP}}$, where $\eta_{f_{CP}}$ is the CP eigenvalue of the final state. The ΔY parameter has been measured in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ by BaBar, CDF, Belle and LHCb collaborations [9, 18–20]. For a generic final state f sensitivity to ΔY is diluted by CP-odd contribution from intermediate states. This dilution is accounted for by parameter F_+^f related to the effective gradient by $\Delta Y_f^{\text{eff}} = (2F_+^f - 1) \cdot \Delta Y$. The value of this dilution factor for the signal decay mode, $f = \pi^0\pi^-\pi^+$, $F_+^{\pi\pi\pi} = 0.973 \pm 0.017$ was measured by CLEO collaboration [16]. The closeness of $F_+^{\pi\pi\pi}$ to unity implies that the sample is almost entirely CP-even. Similarly, to the energy-test analysis from Ref. [3] the reconstruction is optimised separately for the two categories of pions reconstructed via $\pi^0 \to \gamma\gamma$. However, a joined sample is used in the final fit. The CF decay $D^0 \to K^-\pi^+\pi^0$ is used to validate the analysis procedure. The asymmetry observable is constructed by populating 21 bins in decay time with signal yields in distributions of the difference between D^{*+} and D^0 invariant masses. The ΔY parameter is extracted from the fit. The obtained value $\Delta Y = (-1.3 \pm 6.3 \pm 2.4) \cdot 10^{-4}$ is in agreement with the current world average though not competitive, c.f. Ref. [15]. The total uncertainty is dominated by statistical effects.

5. Mixing and CPV in $D^0 \to K^+\pi^-$ (time-dependent)

In the study from Ref. [5], bounds on the target parameters are determined from the fit of the model with CPV and mixing parameters to the measured time-dependent ratio of WS-to-RS decays [3]. The measurement uses LHCb Run 2 candidates from $D^{*+} \to D^0 (\to K^\pm\pi^\mp)\, \pi_s^+$ decay chain. There are two possible WS-to-RS ratios corresponding to the two possible charges final states ($K^-\pi^+$, $K^+\pi^-$):

[3]RS (right-sign decay) corresponds to the situation when the charge of the $\pi^\pm$ in the final state is the same as that of the slowly moving pion (π_s) in the $D^{*+} \to D^0 \left(\to K^\mp\pi^\pm\right) \pi_s^+$ decay chain. In the opposite case, we refer to the decay as WS (wrong-sign decay).

$$R^{+}_{K\pi}(t) = \frac{\Gamma(D^0(t) \to K^+\pi^-)}{\Gamma(\overline{D}^0(t) \to K^+\pi^-)}, \quad R^{-}_{K\pi}(t) = \frac{\Gamma(\overline{D}^0(t) \to K^-\pi^+)}{\Gamma(D^0(t) \to K^-\pi^+)}. \tag{3}$$

Due to the smallness of mixing in charm, these ratios can be expanded up to the quadratic term in the decay-time:

$$R^{\pm}_{K\pi}(t) \approx R_{K\pi}(1 \pm A_{K\pi}) + \sqrt{R_{K\pi}(1 \pm A_{K\pi})}\,(c_{K\pi} \pm \Delta c_{K\pi})\left(\frac{t}{\tau_{D^0}}\right) + (c'_{K\pi} \pm \Delta c'_{K\pi})\left(\frac{t}{\tau_{D^0}}\right)^2. \tag{4}$$

The expression in Eq.(4) contains three CP-even ($R_{K\pi}$, $c_{K\pi}$, $c'_{K\pi}$) and three CP-odd ($A_{K\pi}$, $\Delta c_{K\pi}$, $\Delta c'_{K\pi}$) observables. The CP asymmetry $A_{K\pi}$ serves as a null test of the SM, with its value required to be less than 10^{-5} [5]. The parameters $c_{K\pi}$ and $c'_{K\pi}$ constrain the values of the mixing parameters x_{12}, y_{12}, as well as the strong phase $\Delta_{K\pi}$, for definitions see Ref. [5].

The $R_{K\pi}$ denotes the ratio of the decay rate of the DCS decay to that of the CF decay, which is equal to $\tan^4\theta_c \lll 1$ [4]in the $SU(3)_F$ limit. Consequently, the measurements of $R_{K\pi}$ contribute to research on $SU(3)_F$ symmetry breaking. The CP-odd parameters refer to all three types of CP violations. The parameter $A_{K\pi}$ quantifies direct CPV in decays, $\Delta c_{K\pi}$ quantifies CPV in interference between mixing and decay, and $\Delta c'_{K\pi}$ quantifies CPV in mixing.

The mixing and CPV parameters are determined based on the fit of the model from Eq.(4) to WS-to-RS ratio time-dependence. The data is divided into 108 bins[5]. The signal in each bin is separated from the background based on the simultaneous χ^2 fit of an empirical model to the D^{*+} invariant mass. The model is fitted simultaneously to three candidate types: RS, WS, and a control sample targeting misreconstructed decays. In each fit, most signal and background shape parameters are shared. The raw measurements of WS-to-RS ratios and the average D^0 decay time are adjusted to account for the systematic effects that influence their values. The D^0 decay time is biased due to contamination from mesons produced in long-lived b-hadron decays (secondary decays). The measured WS-to-RS ratios are biased by instrumental differences in reconstruction efficiency between WS and RS decays. Another major source of bias is related to the contamination of the sample with doubly misidentified D^0 decays and the ghost background resulting from the mis-association of correctly identified hits in VELO with hits in T-stations for different particles.

Before the final determination of the target parameter values, the results for the Run 2 sample are averaged with the results obtained using Run 1 data. The averaging procedure involves simultaneous minimisation of χ^2 for both samples ($\chi^2_{\text{Run1}}, \chi^2_{\text{Run2}}$). For the determination of χ^2_{Run1} the information included in the internal LHCb documentation of the analysis from Ref. [6] is used[6]. The new results of the measured CPV and mixing parameters are gathered in Table 1. The results have 1.6× smaller total uncertainties compared to the previous measurement and are still dominated by statistical uncertainties. The most significant source of bias of the previous measurement, see Ref. [6], is reduced by more than one order of magnitude. In the presented analysis no evidence of CPV is

[4] $\theta_c \approx 0.23$ is the Cabibbo angle [22].

[5] Corresponding to 18 different time intervals, 3 data-taking periods, and the two final states of D^0 decay.

[6] The analysis in Ref. [6] does not provide separate results for the two data-taking periods making direct use of the results impossible. However, the internal LHCb documentation related to Ref. [6] contains all the necessary raw data to compute χ^2_{Run1}.

Table 1: Results derived from measurements with Run 1 and Run 2 data, accounting for both statistical and systematic contributions to uncertainties and correlations. Mixing and CPV parameters are weakly correlated.

Parameters		Correlations [%]					
		$R_{K\pi}$	$c_{K\pi}$	$c'_{K\pi}$	$A_{K\pi}$	$\Delta c_{K\pi}$	$\Delta c'_{K\pi}$
$R_{K\pi}$	$(342.7 \pm 1.9) \times 10^{-5}$	100.0	-92.7	80.3	0.9	-0.7	0.2
$c_{K\pi}$	$(52.8 \pm 3.3) \times 10^{-4}$		100.0	-94.2	-1.3	1.2	-0.7
$c'_{K\pi}$	$(12.0 \pm 3.5) \times 10^{-6}$			100.0	0.7	-0.7	0.2
$A_{K\pi}$	$(-6.6 \pm 5.7) \times 10^{-3}$				100.0	-91.9	79.7
$\Delta c_{K\pi}$	$(2.0 \pm 3.4) \times 10^{-4}$					100.0	-94.1
$\Delta c'_{K\pi}$	$(-0.7 \pm 3.6) \times 10^{-6}$						100.0

found. In particular, the parameter $A_{K\pi}$ is in agreement with CP conservation within just over 1σ. However, this is the first measurement to report evidence of 3.4σ divergence from the hypothesis of $c'_{K\pi} = 0$. Once the new results are combined with the other relevant measurements from the charm and beauty sectors, as described in Ref. [11], the departure of the strong phase $\Delta_{K\pi}$ from the value of zero expected in the $SU_F(3)$ symmetry limit is observed. Finally, the new measurement of parameter $\Delta c_{K\pi}$ provides a clean test of CPV in interference leading to the 16% improvement in the determination of the dispersive mixing phase ϕ_{12}^{M} [5].

6. Summary and future prospects

Between 2011 and 2018, LHCb collected the largest sample of charm decays, leading to world-leading measurements, including the 2019 discovery of CPV in the charm sector. The measurement is at the upper end of the SM predictions [13]. Comprehensive CPV studies continue, with recent LHCb results showing no signs of BSM. The uncertainties in the measured CPV parameters are statistically dominated. With the ongoing Run 3 data-taking program expected to collect data corresponding to total-integrated luminosity of ~ 23 fb^{-1} at $\sqrt{s} = 13$ TeV by the end of 2025, as well as, the upgraded detector and trigger system, we expect significant improvements in measurement precision.

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