Measurements of charge-parity (CP) violation and mixing in charm provide a precise test of the Standard Model and can potentially probe interactions beyond the Standard Model. The LHCb experiment has provided the most precise measurements to date in this scope. We present recent results obtained during the current year, including the first observation of a non-zero mass difference between the neutral charm eigenstates – a new milestone in charm physics.
1. Introduction

In the Standard Model (SM) of particle physics, CP violation (CPV) is introduced through an irreducible complex phase in the Cabibbo-Kobayashi-Maskawa (CKM) mixing matrix [1]. The smallness of the elements of the CKM matrix involves suppresses the expectations for CPV in charm at a level typically below $10^{-3}$ [2] and makes CP violation in charm sensitive to possible contributions of physics beyond the SM. Most importantly, the charm-quark sector offers a unique opportunity to test the CKM formalism, since it provides access to operators that affect only up-type quarks, while leaving the strange and beauty hadrons unaffected. In March 2019, the LHCb collaboration announced the first observation of CPV in the decay of charm hadrons [3]. However, the interpretation of this observation is unclear, since theoretical predictions are difficult to compute reliably due to non-perturbative quantum-chromodynamics effects [4–6]. Further studies of direct CPV as well as mixing and time-dependent CPV in charm decays are needed to clarify the picture.

2. Observation of the mass difference between neutral charm-meson eigenstates with $D^0 \rightarrow K^0_S \pi^- \pi^+$ decays

The splitting of the masses ($m_{1,2}$) and decay widths ($\Gamma_{1,2}$) of the neutral charm-meson eigenstates, where $|D_{1,2}| = p|D^0| + q|\bar{D}^0|$ with $|p|^2 + |q|^2 = 1$, governs the oscillations of $D^0$ mesons and can be conveniently parametrized through the mixing parameters $x \equiv (m_1 - m_2)/(\Gamma)$ and $y \equiv (\Gamma_1 - \Gamma_2)/(2\Gamma)$, where $\Gamma = (\Gamma_1 + \Gamma_2)/2$. The rich resonance structure of $D^0 \rightarrow K^0_S \pi^- \pi^+$ decays implies the presence of large strong phases that vary across the Dalitz plane and, consequently, provides good sensitivity to all mixing and CP violation parameters. However, the decay dynamics of this three-body decay and the variations of the detector efficiency across the Dalitz plane as a function of decay time need to be modeled carefully in order to take advantage of this feature. Both these challenges are mitigated by a model-independent analysis procedure proposed in Ref. [7], the so-called “Bin-Flip method”. This consists in dividing the Dalitz plane into two sets of regions, symmetrically distributed with respect to the bisector $m_x^2 = m_y^2$, where $m_x^2$ is equal to $m^2(K^0_S \pi^- \pi^+)$ for $D^0$ decays and to $m^2(K^0_S \pi^-)$ for $\bar{D}^0$ decays, chosen so as to keep the strong-phase difference ($\Delta \delta$) between $D^0$ and $\bar{D}^0$ decays approximately constant within each region. The binning, together with Dalitz plot distribution, is displayed in Fig. 1. The lower part of the Dalitz plane is dominated by unmixed, Cabibbo-favored $D^0$ decays, while in the upper part of the Dalitz plane the contribution of Cabibbo-favored decays following mixing becomes more and more important with respect to the unmixed doubly Cabibbo-suppressed decays as decay time increases. For each $D^0$ decay time, and each spatial region of constant strong-phase difference, labelled $\pm b$, the ratio of the number of decays in the in the upper Dalitz-plot bin ($-b$) to its lower counterpart ($+b$) is approximately equal to

$$R_b(t)^\pm \approx r_b - \sqrt{r_b} \left[ (1 - r_b) c_b y - (1 + r_b) s_b x \right] t / \tau_{D^0},$$

where $\tau_{D^0}$ is the lifetime of the $D^0$ meson, $R_b^\pm$ corresponds to the yield ratio for initially produced $D^0$ ($\bar{D}^0$) mesons, $r_b$ is the value of $R_b$ at zero decay time, and $c_b$ and $s_b$ are the average cosine and sine of the strong-phase $d$ difference between positive and negative Dalitz-plot bins and are based on external inputs [8]. A previous LHCb measurement [9] using the full LHCb Run 1 dataset

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Each of the 8 Dalitz-plots bins. Right: Differences of integrated luminosity of 5.4 fb$^{-1}$ analysis presented in this document relies on the LHCb Run 2 dataset (2016–2018, corresponding to an integrated luminosity of 5.4 fb$^{-1}$). Positive indices refer to bins in the lower region, $m_2^2 > m_1^2$; negative indices refer to those in the upper region, $m_2^2 < m_1^2$. Colors indicate the absolute value of the bin index $b$. Right: Dalitz plot of the $D^0 \rightarrow K^0_S \pi^+ \pi^-$ decay.

Figure 1: Left: Iso-$\Delta \delta$ binning of the $D^0 \rightarrow K^0_S \pi^+ \pi^-$ Dalitz plot, based on the BaBar 2008 amplitude model [8]. Positive indices refer to bins in the lower region, $m_2^2 > m_1^2$; negative indices refer to those in the upper region, $m_2^2 < m_1^2$. Colors indicate the absolute value of the bin index $b$. Right: Dalitz plot of the $D^0 \rightarrow K^0_S \pi^+ \pi^-$ decay.

Figure 2: Left: Time-dependent $CP$-averaged yield ratios of initially-produced $D^0$ and $\bar{D}^0$ candidates for each of the 8 Dalitz-plots bins. Right: Differences of $D^0$ and $\bar{D}^0$ yield ratios. Fit projections are overlaid.
for the mixing and CP violation parameters $x$, $y$, $|q/p|$ and $\phi \sim \arg (q/p)$ are

$$x = (3.98^{+0.56}_{-0.54}) \cdot 10^{-3},$$

$$y = (4.6^{+1.5}_{-1.0}) \cdot 10^{-3},$$

$$|q/p| = 0.996 \pm 0.052,$$

$$\phi = (-0.056^{+0.047}_{-0.051}) \text{ rad.}$$

The parameter $x$ is found to be inconsistent with zero with a statistical significance of seven standard deviations. This constitutes the world’s first observation of a non-zero mass difference between neutral charm-meson eigenstates.

3. Other searches for CP violation in charm decays

Cabibbo-suppressed $D \to f$ decays provide the most sensitive tests of CP violation, through the measurement of the time-dependent and time-integrated CP asymmetry between the $D$ and $\bar{D}$ meson decay rates,

$$A_{CP}(f,t) = \frac{\Gamma(D \to f,t) - \Gamma(\bar{D} \to \bar{f},t)}{\Gamma(D \to f,t) + \Gamma(\bar{D} \to \bar{f},t)}.$$  

In the case of $D^0 \to f$, where the final state $f = K^- K^+$ or $\pi^- \pi^+$ is common to $D^0$ and $\bar{D}^0$ mesons, the asymmetry can be expanded to linear order in the mixing parameters as

$$A_{CP}(D \to f,t) = a_f^d + \Delta Y_f t/\tau_{D^0},$$

where $a_f^d$ is the CP asymmetry in the decay and $\Delta Y_f$ quantifies time-dependent CP-violating effects.

In the case of charged charm mesons, $A_{CP}(D \to f)$ is constant as a function of the decay time. The latest experimental measurements in this field, performed using the full LHCb Run 2 dataset (2015–2018, corresponding to an integrated luminosity of 5.7 fb$^{-1}$) [11–13], are

$$\Delta Y_{KK} = (-2.3 \pm 1.5 \pm 0.3) \cdot 10^{-4},$$

$$\Delta Y_{\pi\pi} = (-4.0 \pm 2.8 \pm 0.4) \cdot 10^{-4},$$

$$A_{CP}(D^+ \to \pi^+ \pi^0) = (-1.3 \pm 0.9 \pm 0.6)\%,$$

$$A_{CP}(D^+ \to K^+ \pi^0) = (-3.2 \pm 4.7 \pm 2.1)\%,$$

$$A_{CP}(D^+ \to \pi^+ \eta) = (-0.2 \pm 0.8 \pm 0.4)\%,$$

$$A_{CP}(D^+ \to K^+ \eta) = (-6 \pm 10 \pm 4)\%,$$

$$A_{CP}(D_s^+ \to K^+ \pi^0) = (-0.8 \pm 3.9 \pm 1.2)\%,$$

$$A_{CP}(D_s^+ \to \pi^+ \eta) = (0.8 \pm 0.7 \pm 0.5)\%,$$

$$A_{CP}(D_s^+ \to K^+ \eta) = (0.9 \pm 3.7 \pm 1.1)\%,$$

$$A_{CP}(D^0 \to K^0 \bar{K}^0_s) = (-3.1 \pm 1.2 \pm 0.4)\%,$$

where the first uncertainties are statistical and the second are systematic. All results are found to be compatible with the conservation of CP symmetry.

These new measurements constitute the world’s most precise determinations of those quantities with the exception of the CP asymmetries $A_{CP}(D_s^+ \to \pi^+ \eta)$ and $A_{CP}(D_s^+ \to K^+ \eta)$. In the latters, however, an outstanding result is achieved if the hadronic nature of the collider is taken into account.
References


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