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Mixing and indirect *CP* violation in charm mesons at LHCb

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The LHCb experiment has collected the world's largest sample of charmed hadrons. This sample is used to measure D^0–$\overline{D}^0$ mixing and to search for *CP* violation. New measurements of the mixing and *CP*-violation parameters x_{CP}, y_{CP}, Δx and Δy are presented.

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1. Introduction

Neutral meson oscillation is the transition between a neutral-flavoured meson and its antiparticle. In neutral charm mesons (D^0), it is known as D^0–$\overline{D}^0$ mixing. This phenomenon involves flavour changing neutral currents through down-type quarks. The study of D^0 mesons is thus complementary to that of mesons containing down-type quark only, K^0 and $B^0_{(s)}$, in searches for interactions beyond the Standard Model of particle physics (SM). Because mixing and charge-parity (*CP*) violation in the charm sector are much more suppressed than in the other decays of down-type mesons, large and clean samples of D^0 decays are required. Such large samples can be obtained at the LHCb experiment [1] which has collected the world's largest sample of charm hadrons during the Run 2 operation of the Large Hadron Collider between 2015 and 2018 [2]. In the following sections, two measurements of D^0–$\overline{D}^0$ mixing and a search for *CP* violation performed at the LHCb experiment are presented.

2. Model-independent measurement of the charm mixing parameters in $\overline{B} \to D^0(\to K^0_S\pi^+\pi^-)\mu^-\overline{\nu}_\mu X$ decays

In the SM, the transition between a neutral flavoured meson and its antiparticle is mediated by charged weak interactions involving the exchange of two W bosons. The oscillation occurs because the mass eigenstates are not eigenstates of the weak interaction. They can be written as a linear combination of flavour eigenstates as $|D_{1,2}\rangle \equiv p|D^0\rangle \pm q|\overline{D}^0\rangle$, where p and q are complex parameters satisfying $|p|^2 + |q|^2 = 1$. The states $|D_{1,2}\rangle$ conventionally denote as the nearly *CP* even (D_1) and odd (D_2) mass eigenstates, with eigenvalues $\omega_{1,2} = m_{1,2} - \frac{i}{2}\Gamma_{1,2}$, where $m_{1(2)}$ and $\Gamma_{1(2)}$ are the mass and decay width of the $D_{1(2)}$ state. The oscillation can simply be described by the dimensionless mass-splitting parameter $x = (m_1 - m_2)/\Gamma$ and decay-width splitting parameter $y = (\Gamma_1 - \Gamma_2)/(2\Gamma)$, where Γ is the average decay width [3].

A recent measurement of these mixing parameters is based on the LHCb dataset of $D^0 \to K^0_S\pi^+\pi^-$ decays collected from 2016 to 2018 [4]. The candidates are exclusively selected with the topology of a b hadron decaying to $D^0\mu^-\overline{\nu}X$, where X stands for any combination of unreconstructed particles. The D^0 flavour is determined from the charge of muon. The decay $D^0 \to K^0_S\pi^+\pi^-$ has a rich resonant structure which can be used to measure the mixing and CP violation parameters x, y, $|q/p|$ and $\phi \sim \arg(q/p)$ [11]. These are expressed in terms of the *CP*-even mixing parameters

$$x_{CP} = \frac{1}{2}\left[x\cos\phi\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) + y\sin\phi\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right)\right], \tag{1}$$

$$y_{CP} = \frac{1}{2}\left[y\cos\phi\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) - x\sin\phi\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right)\right], \tag{2}$$

and the *CP*-violating differences

$$\Delta x = \frac{1}{2}\left[x\cos\phi\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) + y\sin\phi\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right)\right], \tag{3}$$

$$\Delta y = \frac{1}{2}\left[y\cos\phi\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) - x\sin\phi\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right)\right]. \tag{4}$$

Absence of *CP* violation ($|q/p| = 1$, $\phi = 0$) implies $x_{CP} = x$, $y_{CP} = y$, and $\Delta x = \Delta y = 0$.

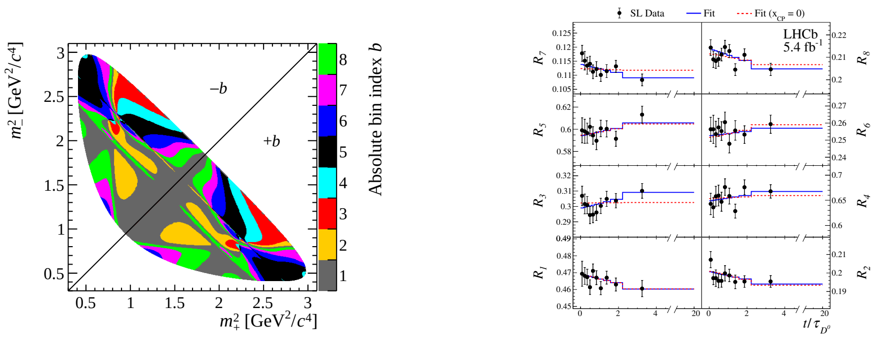

Figure 1: (Left) Iso-$\Delta\delta$ binning scheme of the Dalitz plot of the $D^0 \to K^0_S\pi^+\pi^-$ decay; $m^2_\pm$ represents $m^2(K^0_S\pi^\pm)$ for D^0. (Right) Fit projection of the time-dependent *CP*-even yield ratios for D^0 and $\overline{D}^0$ decays in each Dalitz-plot region.

The bin-flip method [5] measures the time-dependent ratio $R^\pm_{bj}$ between positive (upper-half, $+b$) and negative (lower-half, $-b$) Dalitz bins of constant strong phase difference partitioned according to CLEO iso-$\Delta\delta$ binning scheme [6] as shown in Figure 1 (left). The method suppresses most of the biases induced by non-uniform event reconstruction efficiencies. The fit to this time-dependent ratio is shown in Figure 1 (right), yielding

$$
\begin{aligned}
x_{CP} &= [\ \ 4.29 \pm 1.48 \pm 0.26] \times 10^{-3}\,, & \Delta x &= [-0.77 \pm 0.93 \pm 0.28] \times 10^{-3}\,,\\
y_{CP} &= [\ 12.61 \pm 3.12 \pm 0.83] \times 10^{-3}\,, & \Delta y &= [\ \ 3.01 \pm 1.92 \pm 0.26] \times 10^{-3}\,,
\end{aligned}
$$

where the first uncertainties are statistical and the second are systematic. The results are compatible with those measured in the analysis of $D^{*+} \to D^0(\to K^0_S\pi^+\pi^-)\pi^+$ decays [7]. A combination of the two samples is performed, giving

$$
x = (4.01 \pm 0.49) \times 10^{-3}\,,\ y = (5.5 \pm 1.3) \times 10^{-3}\,,\ |q/p| = 1.012\,^{+0.050}_{-0.048}\,,\ \phi = -0.061\,^{+0.037}_{-0.044}\ \text{rad.}
$$

Figure 2 shows the measured mixing and *CP*-violating parameters of the two samples and their combination. The value of x is incompatible with zero with a significance over 8 standard deviations, constituting the most precise measurement from a single experiment. The results are compatible with *CP* symmetry.

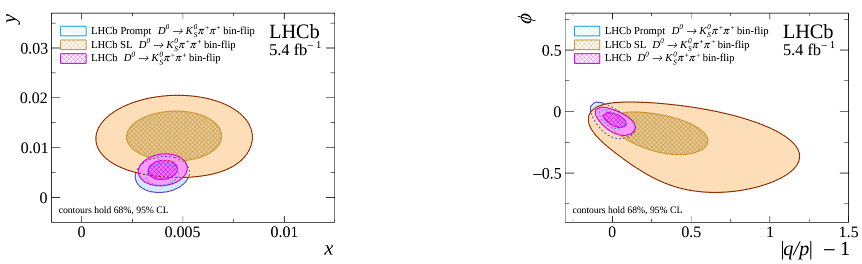

Figure 2: Two-dimensional 68% and 95% confidence-level contours for (left) $(x,\ y)$ and (right) $(|q/p| - 1,\ \phi)$ for the Run 2 $D^{*+} \to D^0(\to K^0_S\pi^+\pi^-)\pi^+$ (Prompt) [7] and $\overline{B} \to D^0(\to K^0_S\pi^+\pi^-)\mu^-\overline{\nu}_\mu X$ (SL) [4] measurements, and for their combination.

3. Measurement of the charm mixing parameter $y_{CP} - y_{CP}^{K\pi}$ using two-body D^0 meson decays

The parameter y_{CP}, related to decay width as defined in Equation 2, is measured by analysing the time-dependent distribution of Cabibbo-suppressed $D^0 \to f$ decays with $f = K^-K^+, \pi^-\pi^+$ final states. The time-dependent ratios, $R^f(t)$, of their yields relative to the $D^0 \to K^-\pi^+$ final state can be approximated with an exponential distribution as

$$R^f(t) = \frac{N(D^0 \to f, t)}{N(D^0 \to K^-\pi^+, t)} \propto e^{-(y_{CP}^f - y_{CP}^{K\pi})\, t/\tau_{D^0}} \frac{\varepsilon(f,t)}{\varepsilon(K^-\pi^+, t)}, \tag{5}$$

where y_{CP}^f is the y_{CP} parameter measured in the final state f, and $\varepsilon(f,t)$ is the time-dependent efficiency for the considered final state. The $y_{CP}^{K\pi}$ and $\varepsilon(K^-\pi^+, t)$ are y_{CP} and efficiency measured in the $K\pi$ final state. The measurement of y_{CP} is performed using the full Run 2 dataset collected by the LHCb experiment, corresponding to an integrated luminosity of $6\,\mathrm{fb}^{-1}$ [8]. D^0 candidates are obtained from $D^{*+} \to D^0\pi^+$ decays. The analysis measures y_{CP}^f relative to the one in $K^-\pi^+$ final state, $y_{CP}^f - y_{CP}^{K\pi}$. Figure 3 presents a fit to the ratios. This yields

$$y_{CP}^{\pi\pi} - y_{CP}^{K\pi} = (6.57 \pm 0.53 \pm 0.16) \times 10^{-3},$$
$$y_{CP}^{KK} - y_{CP}^{K\pi} = (7.08 \pm 0.30 \pm 0.14) \times 10^{-3},$$

where the first uncertainties are statistical and the second systematic. The results show good compatibility between K^-K^+ and $\pi^-\pi^+$. A combination of the two measurements is performed, yielding

$$y_{CP} - y_{CP}^{K\pi} = (6.96 \pm 0.26 \pm 0.13) \times 10^{-3}.$$

This result is compatible with the world average before this measurement [9] and more precise by a factor of four. The world average is dominated by this measurement and provides the most precise constraint on y_{CP}.

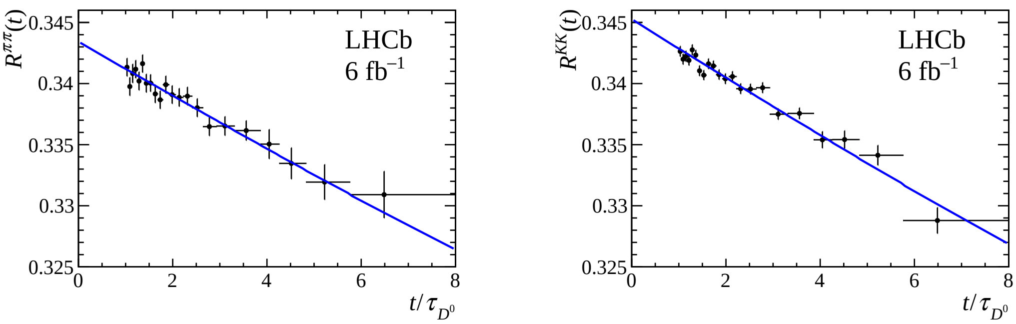

Figure 3: Fit projection of time-dependent ratios $R^f(t)$ for (left) $f = \pi^-\pi^+$ and (right) $f = K^-K^+$.

4. Search for time-dependent *CP* violation in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays

A measurement of the time-dependent asymmetry between D^0 and $\overline{D}^0$ decays into a common final state f, where $f = K^-K^+, \pi^-\pi^+$, is presented. Since D^0 mixing is very slow, the decay rate asymmetry can be smaller than 1%. This allows their decay rate asymmetry to be approximated up to the first order in the mixing parameters as

$$A_{CP}(f,t) \approx A_{CP}^{\text{decay}}(f) + \Delta Y_f \frac{t}{\tau_{D^0}}, \tag{6}$$

where τ_{D^0} is the lifetime of the D^0 meson and $A_{CP}^{\text{decay}}(f)$ is the final state dependent CP asymmetry in the decay. A significant deviation of ΔY_f from zero would indicate the presence of CP violation. The SM estimation of ΔY_f is of the order of 10^{-5}, but could be enhanced by non-perturbative strong interaction effects to 10^{-4} [10, 11].

The most recent measurement from the LHCb collaboration is performed on the full LHCb Run 2 dataset, corresponding to an integrated luminosity of $6\,\text{fb}^{-1}$ [12]. The $D^0 \to h^+h^-$ ($h = K, \pi$) candidates are obtained from $D^{*+} \to D^0\pi^+$ decays. The analysis procedure is validated in the $D^0 \to K^-\pi^+$ channel, where $\Delta Y_{K^-\pi^+}$ is expected to be compatible with zero at the current level of sensitivity. The fits to the time-dependent asymmetries are shown in Figure 4, and yield $\Delta Y_{K^+K^-} = (-2.3 \pm 1.5 \pm 0.3) \times 10^{-4}$ and $\Delta Y_{\pi^+\pi^-} = (-4.0 \pm 2.8 \pm 0.4) \times 10^{-4}$. These values are compatible within uncertainties. A weighted average, denoted as ΔY, between the results for the two final states, and including also previous LHCb measurements [13–15], yields

$$\Delta Y = (-1.0 \pm 1.1 \pm 0.3) \times 10^{-4}, \tag{7}$$

where the first uncertainty is statistical and the second systematic. This value is consistent with CP symmetry and constitutes the world most precise determination of this quantity.

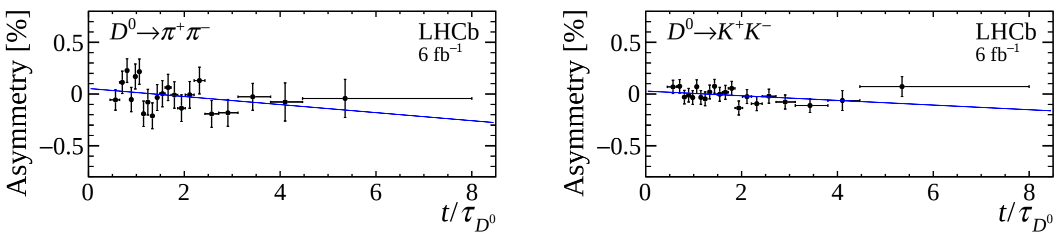

Figure 4: Fits to the time-dependent asymmetry $\Delta Y_{\pi^-\pi^+}$ (left) and $\Delta Y_{K^-K^+}$ (right) using the full LHCb Run 2 dataset.

5. Conclusion and outlook

LHCb has produced the largest dataset of charm hadrons. This leads to new interesting results and often provides world-best measurements. However, the measurements are statistically limited. This is expected to be improved in Run 3, which is starting this year and will collect up to 50 fb^{-1} of integrated luminosity by 2030 with an upgraded detector software-only trigger [16, 17].

Acknowledgments

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