MEASUREMENT OF THE CHARM-MIXING AND CP VIOLATION PARAMETER y_{CP} AT LHCb*

Alessia Anelli

on behalf of the LHCb Collaboration

Università degli Studi di Milano-Bicocca e INFN, Italy
alessia.anelli@cern.ch

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The recent discovery of CP violation in D^0 mesons by the LHCb experiment raised theoretical and experimental interest. It is still unclear whether this result is compatible with the Standard-Model predictions and there is a consensus on the need for further measurements to clarify the picture. The LHCb experiment is therefore conducting a wide range of searches for CP violation in the charm sector using multiple observables. Among those, y_{CP} is sensitive to CP violation in the mixing of D^0 mesons and is sensitive to physics beyond the Standard Model. By measuring the difference between the effective-decay widths of the D^0 meson and its anti-particle to CP eigenstates, the CP violation in the D^0 meson time evolution can be probed. This communication reports the latest measurements of y_{CP} from LHCb as well as prospects for the LHCb Upgrade, which will take data during Runs 3 and 4 of the LHC.

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1. Introduction

The neutral meson mixing is a quantum-mechanical phenomenon in which neutral mesons oscillate between their particle and anti-particle state. The mass eigenstates are related to the flavour eigenstates through the complex parameters p and q: $|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$ with $|p|^2 + |q|^2 = 1$ [1].

In the limit of CP symmetry, $q = p$ and the oscillations are characterized by two dimensionless parameters

$$x \equiv \frac{m_1 - m_2}{\Gamma} = \frac{2(m_1 - m_2)}{\Gamma_1 + \Gamma_2}\,, \tag{1.1a}$$

$$y \equiv \frac{\Gamma_1 - \Gamma_2}{2\Gamma} = \frac{\Gamma_1 - \Gamma_2}{\Gamma_1 + \Gamma_2}\,, \tag{1.1b}$$

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where $m_{1,2}$ and $\Gamma_{1,2}$ are the mass and decay width of the CP-even/odd eigenstate $D_{1,2}$, and $\Gamma = \frac{\Gamma_1+\Gamma_2}{2}$ is the average decay width.

CP violation (CPV) could occur in mixing, in decay, and in the interference between mixing and decay. For CPV in mixing (Fig. 1 (a)), the probabilities of an initially produced D^0 evolving into a given state at the time t are

$$P\left(D^0 \to D^0, t\right) = \left|\left\langle D^0 \middle| D^0(t)\right\rangle\right|^2 = \frac{\mathrm{e}^{-\Gamma t}}{2}\left[\cosh\left(y\Gamma t\right) + \cos\left(x\Gamma t\right)\right] , \quad (1.2)$$

$$P\left(D^0 \to \bar{D}^0, t\right) = \left|\left\langle \bar{D}^0 \middle| D^0(t)\right\rangle\right|^2 = \left|\frac{q}{p}\right|^2 \frac{\mathrm{e}^{-\Gamma t}}{2}\left[\cosh\left(y\Gamma t\right) - \cos\left(x\Gamma t\right)\right] . \quad (1.3)$$

In the case of CPV, $\left|\frac{q}{p}\right|^2 \neq 1$ so the $D^0 \to \bar{D}^0$ and the $\bar{D}^0 \to D^0$ processes do not have the same probability [2].

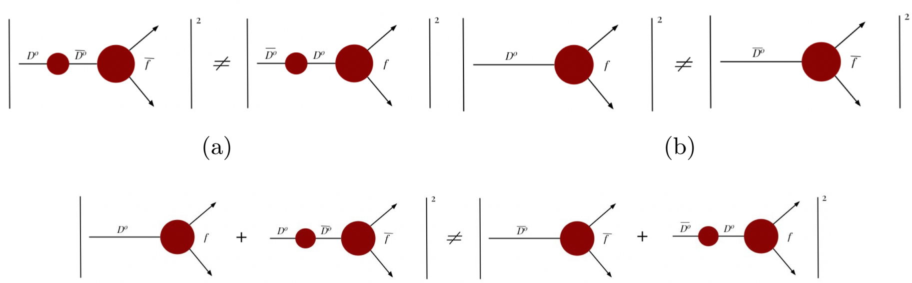
CPV could occur through decay (Fig. 1 (b)) when the total size of the decay amplitudes of a D^0 or $\bar{D}^0$ meson to a final state f or $\bar{f}$, defined in Eq. (1.4), are not equal: $|A_f| \neq |\bar{A}_f|$ [3]

$$A_f = \left\langle f|\mathcal{H}|D^0\right\rangle , \quad \bar{A}_f = \left\langle f|\mathcal{H}|\bar{D}^0\right\rangle , \quad A_{\bar{f}} = \left\langle \bar{f}|\mathcal{H}|D^0\right\rangle , \quad \bar{A}_{\bar{f}} = \left\langle \bar{f}|\mathcal{H}|\bar{D}^0\right\rangle . \quad (1.4)$$

In this case, CPV is measured by the following asymmetry:

$$A_{\mathrm{CP}}(f) = \frac{\Gamma\left(D^0 \to f\right) - \Gamma\left(\bar{D}^0 \to \bar{f}\right)}{\Gamma\left(D^0 \to f\right) + \Gamma\left(\bar{D}^0 \to \bar{f}\right)} = \frac{|A_f|^2 - \left|\bar{A}_{\bar{f}}\right|^2}{|A_f|^2 + \left|\bar{A}_{\bar{f}}\right|^2} . \quad (1.5)$$

For charm decays, it was observed by the LHCb Collaboration in 2019: $\Delta A_{\mathrm{CP}} = A_{\mathrm{CP}}(D^0 \to K^+K^-) - A_{\mathrm{CP}}(D^0 \to \pi^+\pi^-) = (-15.4 \pm 2.9) \times 10^{-4}$, corresponding to violation of CP symmetry with a significance of 5.3σ.



(a) (b) (c)

Fig. 1. Representation of CPV in (a) mixing, (b) in decay, and (c) in the interference between mixing and decay.

Finally, CPV may appear in the interference between the D^0 and $\bar{D}^0$ mesons when they share the same final state ($f = \bar{f}$). This occurs when the decay amplitude for the $D^0 \to f$ process interferes with the decay amplitude for the $D^0 \to \bar{D}^0 \to f$ process (Fig. 1 (c)). Mathematically, this is expressed as a phase, $\phi_{\lambda_f} = \arg\left(\frac{q}{p}\frac{\bar{A}_f}{A_f}\right) = \arg(\lambda_f)$, which is zero in the case of CP symmetry. Due to the D^0–$\bar{D}^0$ mixing, the effective decay width $\hat{\Gamma}_{\mathrm{CP}}$ of decays to CP-even final states differs from the average width Γ. Thus, the parameter used to measure CPV through mixing and the interference between mixing and decay is y_{CP}, defined as in Eq. (1.6). In the case of no CPV, the phase $\phi_{\lambda_f} = 0$ so $y = y^f_{\mathrm{CP}}$ for all decays $D^0 \to f$, where $f = K^+K^0, \pi^+\pi^-$. In the previous measurements of y_{CP}, the average decay widths of $D^0 \to K^\pm\pi^\pm$ were used as a proxy to Γ, but this does not give direct access to y_{CP} but corresponds to $y^f_{\mathrm{CP}} - y^{K\pi}_{\mathrm{CP}}$

$$y^f_{\mathrm{CP}} = \frac{\hat{\Gamma}\left(D^0 \to f\right) + \hat{\Gamma}\left(\bar{D}^0 \to f\right)}{2\Gamma} - 1 \sim |y|\ \cos\phi_{\lambda_f}\,. \tag{1.6}$$

In Section 3, the latest LHCb measurement is described, where the obtained value $y^f_{\mathrm{CP}} - y^{K\pi}_{\mathrm{CP}} = (6.96 \pm 0.26 \pm 0.13) \times 10^{-3}$ is four times more precise than the previous world average.

2. LHCb detector

The LHCb detector [4, 5] is a single-arm forward spectrometer and covers the pseudo-rapidity range of $2 < \eta < 5$. The LHCb's physics programme is focused on the study of heavy-flavour physics and has excellent capabilities in electroweak and QCD physics. Its goal is to search for evidence of new physics, CP violation, and rare decays of beauty and charm hadrons.

LHCb has an excellent primary and secondary vertex reconstruction thanks to the Vertex Locator (VELO), which is the detector closest to the interaction point and provides measurements of the track coordinates used to identify the vertices. A very good momentum resolution is obtained from the tracking detectors placed before and after a 4 Tm dipole magnet, which reconstructs the momentum of the particle with a relative uncertainty of about 0.5% for low-momentum tracks and 1.0% for high-momentum tracks (> 200 GeV/c). A highly efficient particle identification (PID) is achieved with the RICH detectors, together with the hadron and electron calorimeters, muons are identified in the muon chambers located at the end of the LHCb spectrometer.

Despite large data samples and signal purity, measurements are limited by the statistical precision that, for y_{CP}, has not yet reached the depth to correctly probe physics beyond the Standard Model. For this reason, LHCb plans to take pp data at $\sqrt{s} = 13.6$ TeV, collecting a data sample corresponding to an integrated luminosity of 50 fb^{-1}. To cope with these conditions, LHCb upgraded the DAQ system and installed a purely software-based trigger which gave greater flexibility in the design of the selections.

3. Measurement of the charm-mixing and CP violation parameter $y_{\rm CP}$ at LHCb

The measurement of $y_{\rm CP}$ is performed using $D^0 \to K^+K^-$, $D^0 \to \pi^+\pi^-$, and $D^0 \to K^-\pi^+$ decays, where the D^0 mesons are required to originate from $D^*(2010)^+ \to D^0\pi^+$ decays. They are reconstructed from pp collisions at $\sqrt{s} = 13$ TeV recorded by LHCb in the Run 2 data-taking period, corresponding to an integrated luminosity of 6 fb^{-1}.

The parameters $y_{\rm CP} - y_{\rm CP}^{K\pi}$ are measured from ratios of $D^0 \to f$ (with $f = K^+K^-, \pi^+\pi^-$) over $D^0 \to K^-\pi^+$ signal yields as a function of the reconstructed D^0 decay time t

$$R^f(t) = \frac{N\left(D^0 \to f, t\right)}{N\left(D^0 \to K^-\pi^+, t\right)} = \mathrm{e}^{-\left(y_{\rm CP}^f - y_{\rm CP}^{K\pi}\right)\frac{t}{\tau_{D^0}}}\, \frac{\epsilon(f,t)}{\epsilon\left(K^-\pi^+, t\right)} \tag{3.1}$$

with $\tau_{D^0} = (410.1 \pm 1.5)$ fs and $\epsilon(K^\pm\pi^\pm, t)$ being the time-dependent experimental efficiency for the considered final state.

The $D^0 \to f$ and $D^0 \to K^-\pi^+$ decays have different masses of their final-state particles and so different selection efficiencies. Due to this, there are also distinct kinematic distributions of the final-state particles of the D^0 candidate in the laboratory frame (Fig. 2).

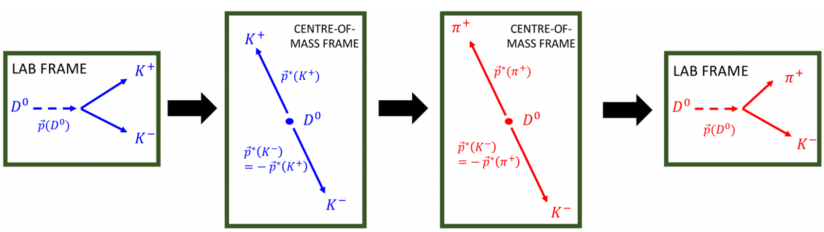


Fig. 2. Schematic view of the laboratory and centre-of-mass frame [6].

To mitigate the experimental differences in the consideration of the different D^0 decays, a kinematic matching procedure is performed, so for both decays, each D^0 candidate selected in one final state would also pass the selection requirements for the other final state with the same D^0 kinematic properties. It is an event-by-event analytical transformation that matches the final-state kinematic variables of one decay to the other. In the rest frame of the charm meson in Eq. (3.2), the mass of one of the kaons in the

$D^0 \to K^-K^+$ decay is exchanged by that of a pion, representing the situation of the $D^0 \to K^-\pi^+$ decays used in the control channel. This ensures that both the D^0 decays selected occupy the same parts of the phase space

$$|\vec{p}^*| = \frac{\sqrt{\left(m_{D^0}^2 - (m_{K^+} - m_{K^-})^2\right)\left(m_{D^0}^2 - (m_{K^+} + m_{K^-})^2\right)}}{2m_{D^0}}. \qquad (3.2)$$

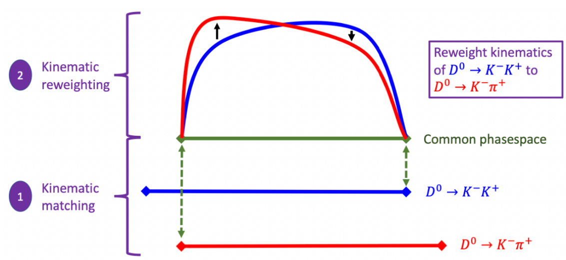


Fig. 3. Schematic view of the kinematic matching and reweighting [6].

A kinematic weighting procedure is then performed to correct the difference in detection efficiencies. The resulting mass distributions, shown in Fig. 4, are fitted with a Johnson S_U and three Gaussian functions for the signal and an empirical model for the combinatorial background. This fitting is performed independently for each D^0 flavour, year, magnet polarity, and in each of the 22 intervals of t_{D^0}.

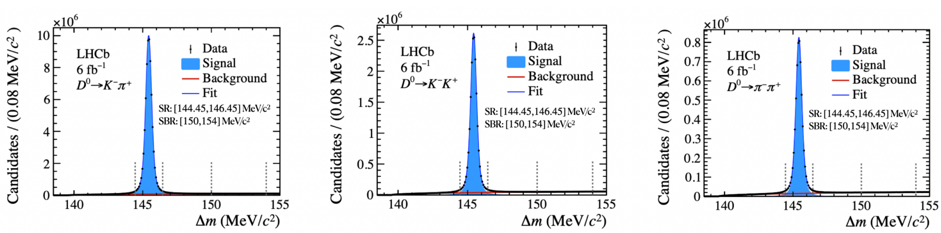


Fig. 4. $\Delta m = m(D^0\pi^+) - m(D^0)$ distributions. Time integrated signal yields are: 70 M for $K^-\pi^+$ decays, 18 M for K^-K^+ and 6 M for $\pi^-\pi^+$ [6].

Finally, the parameters are determined through a χ^2 fit to the corresponding time-dependent $R^f(t)$ ratios (Fig. 5).

The combination of the two measurements gives a result of $y_{\mathrm{CP}} - y_{\mathrm{CP}}^{K\pi} = (6.96 \pm 0.26 \pm 0.13) \times 10^{-3}$ which is four times more precise than the previous world average of $y_{\mathrm{CP}} = (0.57 \pm 0.13 \pm 0.09)\%$ from the HFLAV [7].

The goal for Runs 3 and 4 of the LHC, planned for 2022–2025 and 2029–2032, respectively, is to collect an additional 50 fb^{-1} of data at 13.6 TeV.

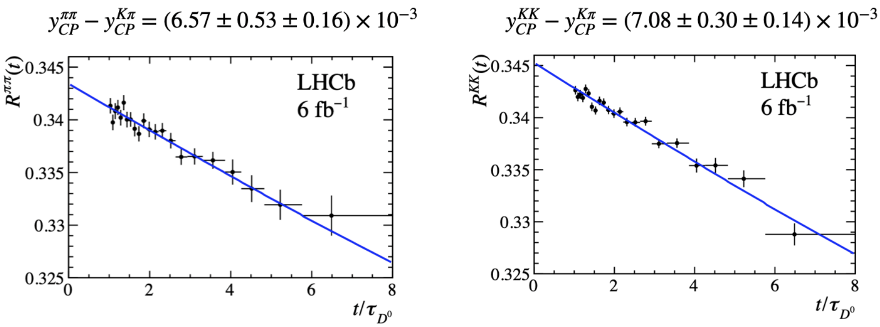


Fig. 5. Time-dependent ratio $R^f(t)$ for the decay of D^0 to (left) $\pi^-\pi^+$ and (right) K^-K^+ [6].

With the removal of the hardware trigger, instrumental biases can be better controlled, and the event selections provide additional flexibility. A specific selection will be introduced to reduce time-momentum correlations and associated systematic uncertainties. These data should provide more precise measurements of mixing and significantly greater sensitivity to direct and indirect CP violation in the charm sector.

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