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

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The very large datasets of charm decays collected by the LHCb experiment from 2011 to 2018 allow the measurement of the mixing and charge-parity (*CP*) violation properties of D^0 mesons with unprecedented precision. This document covers two recent analyses studying mixing and time-dependent *CP* violation in charm decays at LHCb. The first analysis presents the world's most precise determination of the *CP* violation parameter ΔY, while the second accounts for the first observation of the mass difference between neutral charm-meson eigenstates.

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1. Introduction

The Standard Model (SM) of particle physics incorporates *CP* violation through a single complex phase in the Cabibbo–Kobayashi–Maskawa (CKM) matrix [1]. *CP* violation has been observed in kaon and beauty meson systems [2–4]. Very recently, it has also been observed in neutral charm meson decays by the LHCb experiment [5]. However, the amount of *CP* violation predicted by the SM is too small to account for the matter–antimatter asymmetry of the Universe [6], implying that new sources of *CP* violation need to be uncovered. The combination of CKM elements responsible for *CP* violation in the charm sector is $\mathrm{Im}(V_{cb}V_{ub}^*/V_{cs}V_{us}^*) \approx -6 \times 10^{-4}$. This corresponds to *CP* asymmetries of the order of 10^{-4} to 10^{-3}, hence leaving room to significant New Physics enhancements [7, 8].

Neutral charm mesons can change their flavour and turn into their antimeson counterpart before decaying. This process is referred to as $D^0 - \overline{D}^0$ mixing. The mass eigenstates of neutral charm mesons can be expressed as a function of their flavour eigenstates as

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle, \tag{1}$$

where p and q are complex parameters satisfying $|p|^2 + |q|^2 = 1$, and the convention that $|D_1\rangle$ ($|D_2\rangle$) is the *CP* even (odd) eigenstate in the limit of *CP* symmetry is adopted. The $D^0 - \overline{D}^0$ oscillations are described by the dimensionless parameters $x = (m_1 - m_2)c^2/\Gamma$ and $y = (\Gamma_1 - \Gamma_2)/(2\Gamma)$, where $m_{1(2)}$ and $\Gamma_{1(2)}$ are the mass and decay width of the $D_{1(2)}$ state, respectively, and Γ is the average decay width [9]. The charm mixing parameters are measured to be small, $x = (3.7 \pm 1.2) \times 10^{-3}$ and $y = (6.8\,^{+0.6}_{-0.7}) \times 10^{-3}$ [10]. A departure of x from zero still needs to be discovered.

CP violation phenomena in the charm sector can be split into three families:

- *CP* violation in the decay occurs when the magnitudes of the decay amplitudes of the D^0 meson to a final state f and of a $\overline{D}^0$ meson to the *CP*-conjugate state $\overline{f}$ differ ($|A_f| \neq |\overline{A}_{\overline{f}}|$). This type of *CP* violation is often referred to as *direct CP* violation;
- *CP* violation in the mixing appears if $|q/p| \neq 1$;
- *CP* violation in the interference between mixing and decay arises if the value of $\phi_{\lambda_f} \equiv \arg\left(\frac{q}{p}\frac{\overline{A}_f}{A_f}\right)$ differs from zero or π.

The last two families are sometimes combined into the term *indirect CP* violation.

The LHCb detector has collected copious samples of charm decays with excellent time, momentum and tracking resolutions, and particle identification performances [11, 12]. Therefore, it provides a unique laboratory to study mixing and indirect *CP* violation properties of charm decays.

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

The time-dependent asymmetry between D^0 and $\overline{D}^0$ decays to a common final state f,

$$A_{CP}(f,t) = \frac{\Gamma(D^0 \to f,t) - \Gamma(\overline{D}^0 \to f,t)}{\Gamma(D^0 \to f,t) + \Gamma(\overline{D}^0 \to f,t)}, \tag{2}$$

is equal to

$$A_{CP}(f,t) \approx A_{CP}^{\text{decay}}(f) + \Delta Y_f \frac{t}{\tau_{D^0}}\,, \tag{3}$$

up to the first order in the mixing parameters, where τ_{D^0} is the lifetime of the D^0 meson and $A_{CP}^{\text{decay}}(f)$ is the *CP* asymmetry in the decay. The slope of $A_{CP}(f,t)$ is approximately equal to

$$\Delta Y_f \approx x\phi_{\lambda_f} - y\left(\left|\frac{q}{p}\right| - 1\right) + yA_{CP}^{\text{decay}}(f)\,. \tag{4}$$

The first two terms are due to *CP* violation in the interference between mixing and decay and to *CP* violation in the mixing, respectively, while the last term arises from *CP* violation in the decay and is estimated to be much smaller than current experimental sensitivities [5, 10, 13]. A departure of ΔY_f from zero would be a signal of *CP* violation. The current SM model expectations for ΔY_f are at the level of 10^{-5} or less [14–17], even though enhancements up to 10^{-4} from non-perturbative strong-interaction effects are not excluded [15, 16]. Furthermore, at the current level of precision, the final-state dependence of ΔY_f is predicted to be negligible, meaning that $\Delta Y_{K^+K^-} \approx \Delta Y_{\pi^+\pi^-}$ [18]. Consequently, the weighted average of $\Delta Y_{K^+K^-}$ and $\Delta Y_{\pi^+\pi^-}$ is denoted as ΔY; its current world average value is $\Delta Y = (3.1 \pm 2.0) \times 10^{-4}$ [10].

The recent measurements of $\Delta Y_{K^+K^-}$ and $\Delta Y_{\pi^+\pi^-}$ have been performed using the full LHCb Run 2 dataset (2015–2018), corresponding to an integrated luminosity of 6 fb^{-1} [19]. The $D^0 \to f$ candidates are obtained from prompt $D^{*+}(2010) \to D^0\pi^+$ decays,[1] where the charge of the pion tags the flavour at production of the D^0 meson. The analysis procedure is validated by measuring the analogue of ΔY_f for $D^0 \to K^-\pi^+$ decays. The parameter $\Delta Y_{K^-\pi^+}$ is known to be smaller than 0.3×10^{-4} at 90% confidence level [18]. This cross-check measurement benefits from the very high yield of the $D^0 \to K^-\pi^+$ sample. The two main background contributions come from the combinatorial background of the proton–proton (pp) collisions and the nuisance contribution of D^{*+} candidates coming from B mesons (called secondary decays). The contribution to the measurement of these two background components is subtracted by means of dedicated data-driven methods. The signal yields of the $D^0 \to K^-\pi^+$, $D^0 \to K^+K^+$, and $D^0 \to \pi^+\pi^-$ samples amount to 519, 58, and 18 million candidates, respectively. The corresponding $m(D^0\pi^+)$ distributions are shown in Fig. 1.

The signal yields allow to reach a precision on ΔY at the level of 10^{-4}. At such precision, it is crucial to control instrumental biases. The polarity of the LHCb dipole magnet is reversed periodically to point upwards (*MagUp*) and downwards (*MagDown*). For a given magnet polarity, the tagging pion induces large $D^0 - \overline{D}^0$ momentum-dependent detection asymmetries along the horizontal plane. The trigger requirements set to remove a large fraction of the combinatorial background from the pp collisions correlate the D^0 kinematics and decay time, and therefore make these tagging pion detection asymmetries time-dependent, thus biasing the measurement. These nuisance asymmetries are removed by equalising the kinematics of D^0 and $\overline{D}^0$ candidates. This correction procedure is developed by studying the sample of $D^0 \to K^-\pi^+$ decays (Fig. 2). It allows to obtain a compatibility of $\Delta Y_{K^-\pi^+}$ with zero within an uncertainty of 0.5×10^{-4}, thus validating the analysis procedure at very high precision.

[1] Hereafter, the $D^{*+}(2010)$ meson is referred to as D^{*+}.

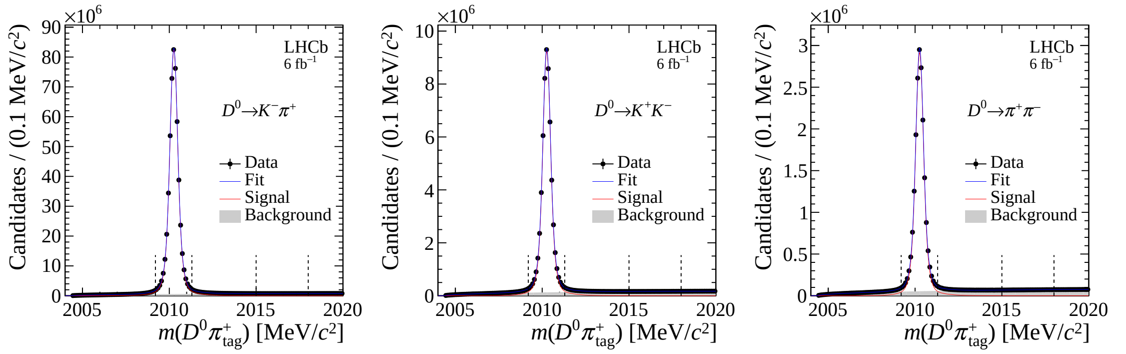

Figure 1: Distribution of $m(D^0\pi^+_{\rm tag})$ for $D^0 \to K^-\pi^+$ (left), $D^0 \to K^+K^-$ (middle) and $D^0 \to \pi^+\pi^-$ (right) candidates. The signal window and the sideband window employed to remove the combinatorial background (grey filled area) through a dedicated sideband subtraction procedure are delimited by the vertical dashed lines. Fit projections are overlaid.

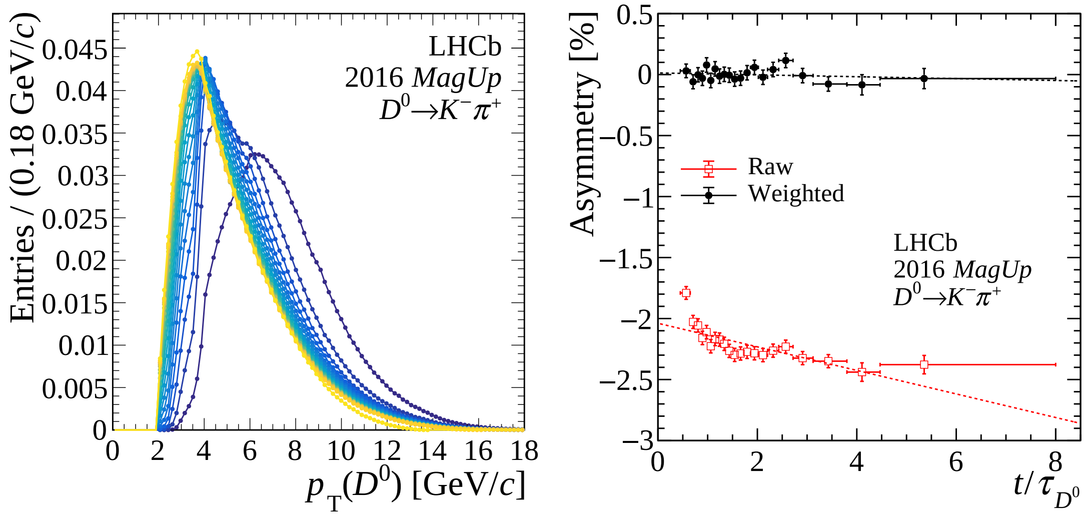

Figure 2: Left: Normalised distributions of D^0 transverse momentum for different bins of D^0 decay time, where decay time increases from blue to yellow colour. Right: Fits to $\Delta Y_{K^-\pi^+}$ for the sample (red) before and (black) after the equalisation of D^0 and $\overline{D}^0$ kinematics, respectively. Both plots are obtained with the 2016 subsample collected with the *MagUp* polarity.

The procedure is then employed to fit for $\Delta Y_{K^+K^-}$ and $\Delta Y_{\pi^+\pi^-}$. The fits to the time-dependent asymmetries are shown in Fig. 3. The parameters $\Delta Y_{K^+K^-}$ and $\Delta Y_{\pi^+\pi^-}$ are measured to be

$$\begin{aligned} \Delta Y_{K^+K^-} &= (-2.3 \pm 1.5 \pm 0.3) \times 10^{-4}\,, \\ \Delta Y_{\pi^+\pi^-} &= (-4.0 \pm 2.8 \pm 0.4) \times 10^{-4}\,. \end{aligned} \tag{5}$$

The final value measured by the LHCb experiment with the Run 1 and 2 data samples, corresponding to 9 fb^{-1} of integrated luminosity, is obtained by combining the two above measurements with those reported in Refs. [20–22], and is equal to

$$\Delta Y = (-1.0 \pm 1.1 \pm 0.3) \times 10^{-4}\,. \tag{6}$$

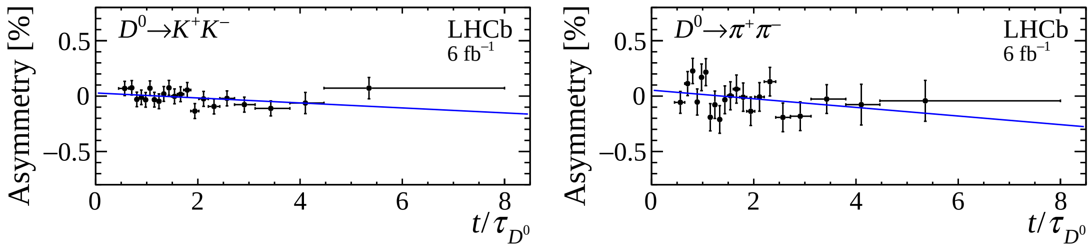

Figure 3: Fits to the time-dependent asymmetry $\Delta Y_{K^+K^-}$ (left) and $\Delta Y_{\pi^+\pi^-}$ (right) using the full LHCb Run 2 dataset.

This value of ΔY is consistent with the *CP* symmetry and constitutes the world's most precise determination of this quantity. The LHCb experiment plans to have additional runs of data taking, starting in 2022. It is expected that by the year 2035, LHCb will collect a data sample of 300 fb^{-1}, allowing the statistical uncertainty of ΔY to reach the level of 10^{-5} [23], similar in precision to the SM expectation.

3. Observation of the mass difference between neutral charm-meson eigenstates

The $D^0 \to K^0_S\pi^+\pi^-$ decay displays a very rich resonant structure and can be used to measure precisely the mixing and *CP* violation parameters x, y, $|q/p|$ and $\phi \equiv \arg(q/p)$, where the last parameter equals ϕ_{λ_f} when neglecting final-state dependent contributions and its definition is based on a convenient choice of the conventions for meson and quark phases [16]. These quantities are determined from a time-dependent fit to the Dalitz plot of this decay. A dedicated method, called the *bin-flip* method [24], was specifically developed for this kind of measurement. The bin-flip method is a model-independent approach avoiding the need of a detailed modelling of the efficiency and resolution effects across the Dalitz plane, and a precise amplitude model of the complex $D^0 \to K^0_S\pi^+\pi^-$ decay. This is achieved by partitioning the Dalitz plot into regions (bins) set to preserve nearly constant strong-phase differences between the D^0 and $\overline{D}^0$ amplitudes within each bin [25]. The method is optimised for the determination of the parameter x and therefore probes with high precision the mass difference between the neutral charm-meson eigenstates D_1 and D_2.

The parametrisation of the phase space of the $D^0 \to K^0_S\pi^+\pi^-$ decay is described in the Dalitz plane with the parameters $m^2_\pm \equiv m^2(K^0_S\pi^\pm)$ for D^0 decays and $m^2_\pm \equiv m^2(K^0_S\pi^\mp)$ for $\overline{D}^0$ decays (left plot of Fig. 4). For each interval of D^0 decay-time, and each spatial region of constant strong-phase difference, depicted in the right plot of Fig. 4 and indexed $\pm b$, the ratio of the number of decays in the negative Dalitz-plot bin $(-b)$ to its positive counterpart $(+b)$ is measured as

$$R^\pm_b(t) \approx r_b - \sqrt{r_b}\,[(1-r_b)\,c_b y - (1+r_b)\,s_b x]\,\frac{t}{\tau_{D^0}}\,, \tag{7}$$

where $R^\pm_b$ is the yield ratio for initially produced $D^0(\overline{D}^0)$ mesons, $r_b \equiv R^\pm_b(t=0)$, and c_b and s_b are the cosine and sine of the strong-phase differences between positive and negative Dalitz-plot bins, averaged over the Dalitz bin, and are measured at charm factories [25, 26].

A previous LHCb measurement using the full LHCb Run 1 dataset (2011–2012, 3 fb^{-1}) reported the first evidence of a non-zero mass difference between neutral charm-meson eigenstates, yielding

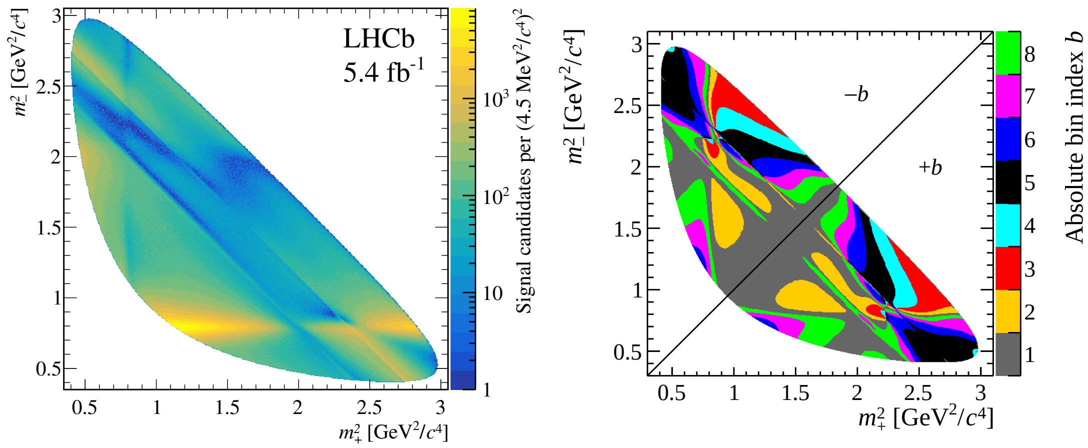

Figure 4: Left: Dalitz plot of the $D^0 \to K_S^0\pi^+\pi^-$ decay. Right: Binning scheme of the 8 regions with constant strong-phase difference denoted as $\pm b$.

$x = (3.9^{+1.1}_{-1.2}) \times 10^{-3}$ [27]. The analysis presented in this document relies on the LHCb Run 2 dataset (2016–2018), corresponding to an integrated luminosity of 5.4 fb^{-1} [28]. As in the measurement presented in Sect. 2, D^0 candidates are obtained from prompt $D^{*+} \to D^0\pi^+$ decays, where the pion tags the flavour of the D^0. The online event selection consists of a hardware and two software stages. At the hardware stage, the selection is performed based on information from the calorimeters and the muon chambers. At the software stage, tracks with high quality, high momenta, good particle identification criteria and found to be significantly displaced from the primary vertex (PV) are selected. Finally, in the offline selection, specific kinematic constraints are constructed, forcing the tracks to form vertices according to the decay topology. There are two categories of reconstructed candidates: in the first category K_S^0 mesons decay early enough for their pion bachelors to be reconstructed in all tracking detectors; while in the second category K_S^0 mesons decay such that pion track segments cannot be formed in the vertex detector that surrounds the pp interaction region. Secondary D^0 decays are suppressed by requiring the D^0 momentum to point back to the PV. The signal yield is determined by fitting the distribution of the mass difference between D^{*+} and D^0 candidates, denoted as Δm, and amounts to 31 million events (Fig. 5).

The fits to the time-dependent yield ratios (Eq. 7) in each region b are shown in Fig. 6. For the *CP*-averaged yield ratios (left plots), deviations from constant values are due to mixing. In particular, the results of the fit (blue line) are incompatible with those where x is fixed to zero (red dashed line). The right plots display the differences of ratios between D^0 and $\overline{D}^0$ decays, where a significant slope would correspond to the presence of *CP* violation.

The results for the mixing and *CP* violation parameters are

$$\begin{aligned} x &= (3.98\,^{+0.56}_{-0.54}) \times 10^{-3}\,, \\ y &= (4.6\,^{+1.5}_{-1.4}) \times 10^{-3}\,, \\ |q/p| &= 0.996 \pm 0.052\,, \\ \phi &= -0.056\,^{+0.047}_{-0.051}\ \text{rad}\,. \end{aligned} \tag{8}$$

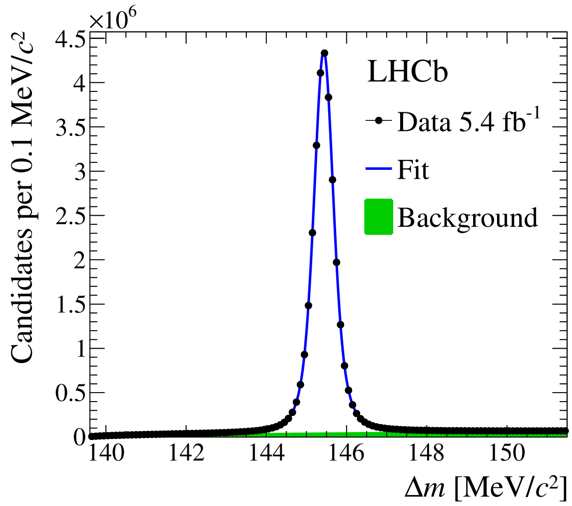

Figure 5: Fit to the Δm distribution.

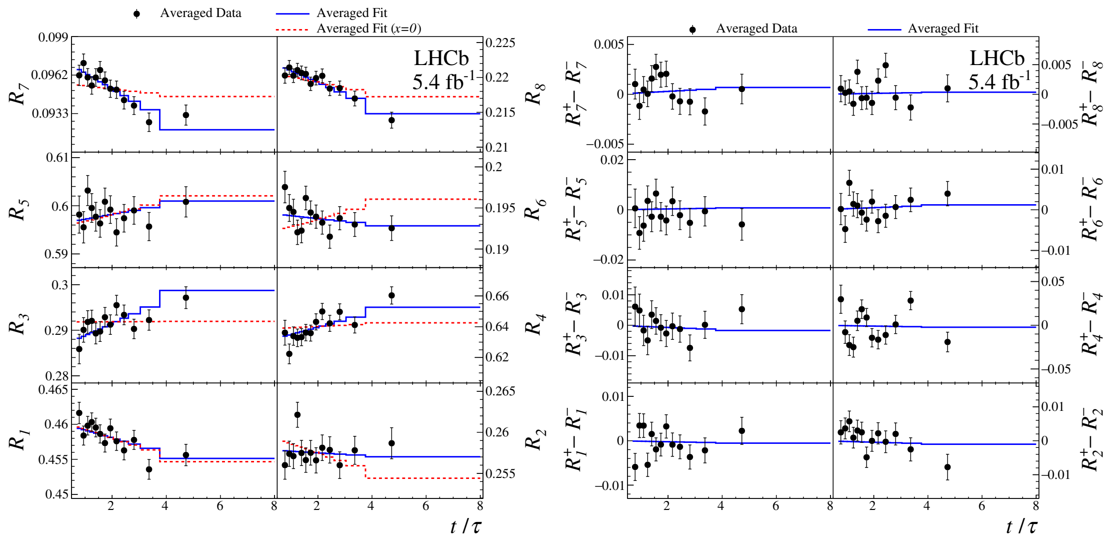

Figure 6: Left: Time-dependent *CP*-averaged yield ratios of initially-produced D^0 and $\overline{D}^0$ candidates for each of the 8 Dalitz-plots bins. Fit projections are overlaid. Right: Differences of D^0 and $\overline{D}^0$ yield ratios.

The parameter x is measured to be inconsistent with zero with a significance of seven standard deviations. This constitutes the first observation of a non-zero mass difference between neutral charm-meson eigenstates. The improvement on the knowledge of the mixing and *CP*-violation parameters is shown in Fig. 7. All results are compatible with *CP* symmetry.

4. Conclusion

The two analysis reported in this document both reach unprecedented precision in probing mixing and *CP* violation effects in charm decays. The new measurement of ΔY constitutes the world's most precise determination of this quantity, with a sensitivity of 10^{-4}. In addition, the

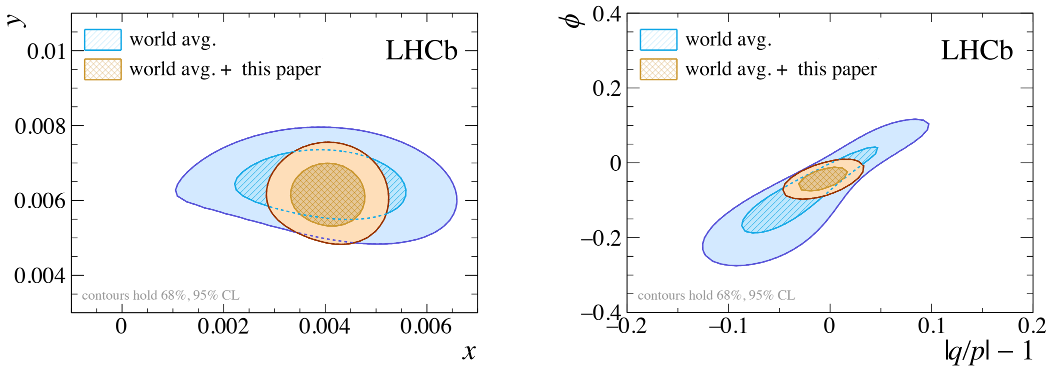

Figure 7: Improvement of the world average values of x and y (left), and $|q/p|$ and ϕ (right). The contours in blue obtained before the results of this measurement do not include the measurement of ΔY presented in Sect. 2.

study of the three-body structure of the $D^0 \to K^0_S\pi^+\pi^-$ decay provides the first observation of a non-zero mass difference between neutral charm-meson eigenstates. The high statistics of these two measurements do not allow yet for an evidence of time-dependent *CP* violation, owing to the smallness of *CP*-violating effects in the charm sector. The next LHCb data-taking periods will decrease the statistical uncertainties on mixing and *CP*-violating parameters by up to one order of magnitude [23], allowing to test the predictions of the SM.

References

[1] M. Kobayashi and T. Maskawa, *CP violation in the renormalizable theory of weak interaction*, Prog. Theor. Phys. **49** (1973) 652.

[2] J. H. Christenson, J. W. Cronin, V. L. Fitch, and R. Turlay, *Evidence for the 2π decay of the K^0_2 meson*, Phys. Rev. Lett. **13** (1964) 138.

[3] Belle collaboration, *Observation of large CP violation in the neutral B meson System*, Physical Review Letters **87** (2001) , `arXiv:hep-ex/0107061`.

[4] BaBar collaboration, *Observation of CP violation in the B^0 meson system*, Physical Review Letters **87** (2001) , `arXiv:hep-ex/0107013`.

[5] LHCb collaboration, R. Aaij *et al.*, *Observation of CP violation in charm decays*, Phys. Rev. Lett. **122** (2019) 211803, `arXiv:1903.08726`.

[6] P. Huet and E. Sather, *Electroweak baryogenesis and standard model CP violation*, Phys. Rev. D **51** (1995) 379.

[7] Y. Grossman, A. L. Kagan, and Y. Nir, *New physics and CP violation in singly Cabibbo suppressed D decays*, Phys. Rev. **D75** (2007) 036008, `arXiv:hep-ph/0609178`.

[8] A. Dery and Y. Nir, *Implications of the LHCb discovery of CP violation in charm decays*, JHEP **12** (2019) 104, `arXiv:1909.11242`.

[9] Particle Data Group, Zyla et al. , *Review of particle physics*, Prog. Theor. Exp. Phys. (2020) .

[10] Heavy Flavor Averaging Group, Y. Amhis *et al.*, *Averages of b-hadron, c-hadron, and τ-lepton properties as of 2018*, arXiv:1909.12524, updated results and plots available at https://hflav.web.cern.ch.

[11] LHCb collaboration, A. A. Alves Jr. *et al.*, *The LHCb detector at the LHC*, JINST **3** (2008) S08005.

[12] LHCb collaboration, R. Aaij *et al.*, *LHCb detector performance*, Int. J. Mod. Phys. **A30** (2015) 1530022, arXiv:1412.6352.

[13] LHCb collaboration, R. Aaij *et al.*, *Measurement of CP asymmetry in $D^0 \to K^+K^-$ decays*, Phys. Lett. **B767** (2017) 177, arXiv:1610.09476.

[14] I. I. Bigi, A. Paul, and S. Recksiegel, *Conclusions from CDF results on CP violation in $D^0 \to \pi^+\pi^-, K^+K^-$ and future tasks*, JHEP **06** (2011) 089, arXiv:1103.5785.

[15] M. Bobrowski, A. Lenz, J. Riedl, and J. Rohrwild, *How large can the SM contribution to CP violation in $D^0 - \bar{D}^0$ mixing be?*, JHEP **03** (2010) 009, arXiv:1002.4794.

[16] A. L. Kagan and L. Silvestrini, *Dispersive and absorptive CP violation in $D^0 - \overline{D^0}$ mixing*, Phys. Rev. **D103** (2021) 053008, arXiv:2001.07207.

[17] H.-N. Li, H. Umeeda, F. Xu, and F.-S. Yu, *D meson mixing as an inverse problem*, Phys. Lett. **B810** (2020) 135802, arXiv:2001.04079.

[18] T. Pajero, *Search for time-dependent CP violation in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays*, , CERN-THESIS-2020-231.

[19] LHCb collaboration, R. Aaij *et al.*, *Search for time-dependent CP violation in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays*, arXiv:2105.09889, Submitted to PRD.

[20] LHCb collaboration, R. Aaij *et al.*, *Measurement of indirect CP asymmetries in $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays using semileptonic B decays*, JHEP **04** (2015) 043, arXiv:1501.06777.

[21] LHCb collaboration, R. Aaij *et al.*, *Measurement of the CP violation parameter A_Γ in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays*, Phys. Rev. Lett. **118** (2017) 261803, arXiv:1702.06490.

[22] LHCb collaboration, R. Aaij *et al.*, *Updated measurement of decay-time-dependent CP asymmetries in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays*, Phys. Rev. **D101** (2020) 012005, arXiv:1911.01114.

[23] LHCb collaboration, *Physics case for an LHCb Upgrade II — Opportunities in flavour physics, and beyond, in the HL-LHC era*, arXiv:1808.08865.

[24] A. Di Canto *et al.*, *Novel method for measuring charm-mixing parameters using multibody decays*, Phys. Rev. D **99** (2019) 012007, arXiv:1811.01032.

[25] CLEO, J. Libby *et al.*, *Model-independent determination of the strong-phase difference between D^0 and $\bar{D}^0 \to K^0_{S,L} h^+ h^-$ $(h = \pi, K)$ and its impact on the measurement of the CKM angle γ/ϕ_3*, Phys. Rev. D **82** (2010) 112006, arXiv:1010.2817.

[26] BESIII, M. Ablikim *et al.*, *Model-independent determination of the relative strong-phase difference between D^0 and $\bar{D}^0 \to K^0_{S,L} \pi^+ \pi^-$ and its impact on the measurement of the CKM angle γ/ϕ_3*, Phys. Rev. D **101** (2020) 112002, arXiv:2003.00091.

[27] LHCb collaboration, R. Aaij *et al.*, *Measurement of the mass difference between neutral charm-meson eigenstates*, Phys. Rev. Lett. **122** (2019) 231802, arXiv:1903.03074.

[28] LHCb collaboration, R. Aaij *et al.*, *Observation of the mass difference between neutral charm-meson eigenstates*, arXiv:2106.03744, Accepted by PRL.