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Particle-antiparticle asymmetries in hadronic charm decays at LHCb

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The Charm sector offers a unique environment to study processes such as neutral meson mixing and *CP* violation, and the LHCb experiment plays a pivotal role in these investigations. Due to the smallness of the parameters describing these phenomena, the high precision measurements LHCb provides allow to perform rigorous null tests of the Standard Model. This proceeding presents some of the latest results from the LHCb collaboration, focusing on measurements of mixing and *CP* violation observables in the Charm sector.

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1. Introduction

The Charm sector is the only environment where phenomena such as charge-parity (*CP*) violation and neutral mesons mixing can be studied for up-type quarks. The characteristics of mixing and *CP* violation involving charm decays make the observables related to both particularly sensitive to New Physics contributions. Specifically, the similarity between the down and strange quarks masses leads to a strong suppression of neutral charm mesons mixing, as explained by the Glashow-Iliopoulous-Maiani mechanism [1]. Furthermore, by considering the CKM matrix [2, 3] elements involved in tree and penguin charm decays, a naive estimate for the amount of *CP* violation appearing in these decays lies between 10^{-4} and 10^{-3}. Given the smallness of the observables describing these phenomena, it clearly appears how very precise measurements and theoretical predictions are required to fully understand them. Furthermore, any deviation between measurements and predictions would directly point toward shortcomings of the Standard Model.

The discovery of *CP* violation in the Charm sector is fairly recent [4] and was only measured as the difference (ΔA^{CP}) between the *CP* asymmetries of the $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays. This observable provides a built-in way to correctly cancel nuisance asymmetries, such as production and detection asymmetries, which originate from differences in the production and detection of charge-conjugated particles and are not of interest for *CP* asymmetry measurements. To date there is no observation of *CP* violation in an individual decay channel, the only evidence for it comes from the combination of the ΔA^{CP} measurement with a precise determination of the direct *CP* asymmetry of the $D^0 \to K^+K^-$ decay [5], which shows a 3.8 sigmas deviation from zero of the $D^0 \to \pi^+\pi^-$ decay's direct *CP* asymmetry.

Recent measurements of *CP* and mixing observables by the LHCb collaboration are shown in the following sections. These are measured using data collected by the LHCb detector [6] operating at a centre of mass energy of 13 TeV. Throughout this document, the inclusion of charge-conjugate processes is implied unless otherwise specified.

2. Measurement of *CP* violation observables in $D^+ \to K^+K^-\pi^+$ decays

Three-body decays offer the possibility to study *CP* violation in regions of the Dalitz plot [7] where it can be locally enhanced [8]. Using data collected between 2016 and 2018, for an integrated luminosity of 5.4 fb^{-1}, the LHCb collaboration measured *CP* violation observables for the Cabibbo-suppressed $D^+ \to K^+K^-\pi^+$ decay in bins of the Dalitz plot [9]. To correctly cancel undesired nuisance contributions, the Cabibbo-favoured $D_s^+ \to K^+K^-\pi^+$ decay is used as control channel. Being Cabibbo-favoured, its *CP* asymmetry is expected to be negligible. After event selection the yields for signal and control channels are approximately 135 and 181 millions, respectively. The Dalitz plots for both decay channels are shown in Fig. 1 with the binning scheme overlaid. Two pronounced resonances can be observed in the Dalitz plots, these belong to $\overline{K}^{*0}(892)$ and $\phi(1020)$, occurring in the decays $D^+_{(s)} \to K^+\overline{K}^{*0}(892)(\to K^-\pi^+)$ and $D^+_{(s)} \to \phi(1020)(\to K^+K^-)\pi^+$, respectively. In each bin of the Dalitz plot (i), the raw asymmetry (A_{raw}) between the positively and negatively charged charmed mesons yields ($N_\pm$) is measured as

$$A^{i,X}_{\text{raw}} = \frac{N^{i,X}_+ - N^{i,X}_-}{N^{i,X}_+ + N^{i,X}_-}\,, \tag{1}$$

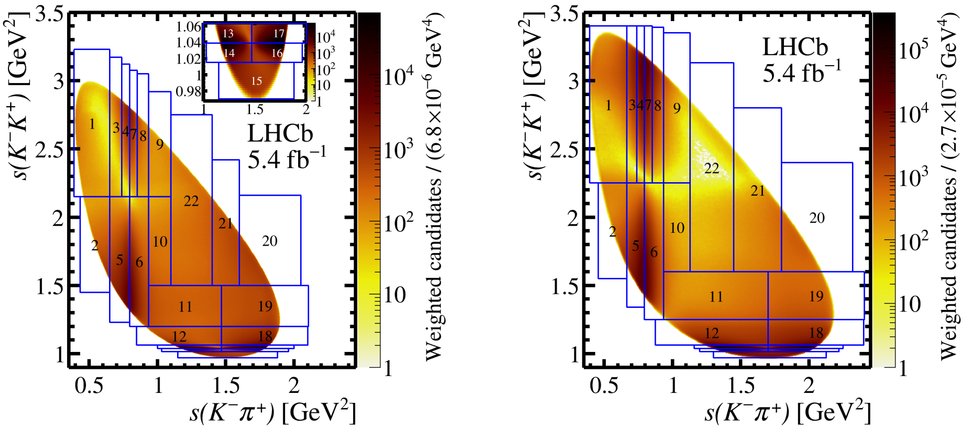

Figure 1: Dalitz plots for (left) $D^+ \to K^+K^-\pi^+$ and (right) $D_s^+ \to K^+K^-\pi^+$ decays with the binning scheme overlaid. The enlarged inset shows the bins around the $\phi\pi^+$ region, where the same numbering scheme is followed for both channels [9].

where $X = S,\ C$ refers to the signal (S) $D^+ \to K^+K^-\pi^+$ and control (C) $D_s^+ \to K^+K^-\pi^+$ channels, respectively. As for the ΔA^{CP} measurement, taking the difference between $A_{\text{raw}}^{i,S}$ and $A_{\text{raw}}^{i,C}$, allows to cancel detection asymmetries arising from the different detection efficiencies oppositely charged final state particles have. Furthermore, under the assumption that the correlation between the final state particles' kinematic and the asymmetries in the production of positively and negatively charged charmed mesons is negligible, the production asymmetries of the D^+ and D_s^+ mesons can be corrected for with a bin independent factor. In particular, subtracting from each bin

$$\Delta A_{\text{raw}}^{\text{global}} = \sum_i^{N_{\text{bins}}} \frac{A_{\text{raw}}^{i,S} - A_{\text{raw}}^{i,C}}{\sigma^2_{A_{\text{raw}}^{i,S}} + \sigma^2_{A_{\text{raw}}^{i,C}}} \Bigg/ \sum_i^{N_{\text{bins}}} \frac{1}{\sigma^2_{A_{\text{raw}}^{i,S}} + \sigma^2_{A_{\text{raw}}^{i,C}}}, \tag{2}$$

where $\sigma^2_{A_{\text{raw}}^{i,X}}$ are the uncertainties of $A_{\text{raw}}^{i,X}$, any global asymmetry difference can be cancelled. The per bin shift with respect to the global *CP* asymmetry can then be defined as

$$\Delta A_{CP}^{i} = A_{\text{raw}}^{i,S} - A_{\text{raw}}^{i,C} - \Delta A_{\text{raw}}^{\text{global}}. \tag{3}$$

The significance of this deviation, in each Dalitz plot bin i, can be obtained as $\mathcal{S}^i_{\Delta CP} = \Delta A^i_{CP}/\sigma_{\Delta A^i_{CP}}$ and it is graphically represented in Fig. 2. From the significance in each Dalitz plot bin, a test for global *CP* violation can be built as $\chi^2(\mathcal{S}_{\Delta CP}) = \sum_i^{N_{\text{bins}}}(\mathcal{S}^i_{\Delta CP})^2$, giving a p-value for the *CP* conservation hypothesis of 8.1%. Therefore there is no evidence for global *CP* violation in $D^+ \to K^+K^-\pi^+$ decays.

Given that the strong phase of the decay varies rapidly across the resonance regions [10], it may happen that a constant *CP* asymmetry is cancelled out when the different regions of the resonance are combined. To exploit this feature, a new observable can be defined as

$$A_{CP|S} = \frac{1}{2}\left[\left(\Delta A_{\text{raw}}^{\text{top-left}} + \Delta A_{\text{raw}}^{\text{bottom-right}}\right) - \left(\Delta A_{\text{raw}}^{\text{top-right}} + \Delta A_{\text{raw}}^{\text{bottom-left}}\right)\right], \tag{4}$$

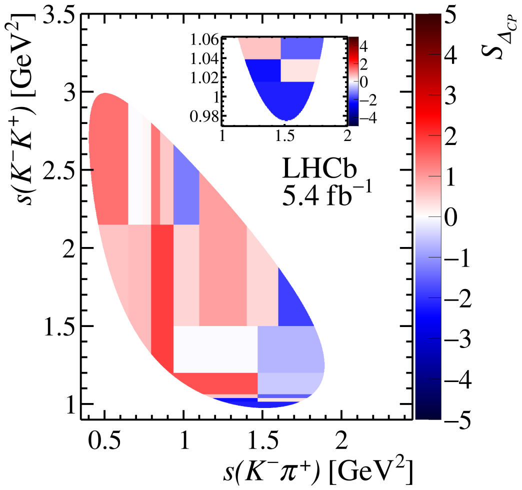

Figure 2: The significance $\mathcal{S}^i_{\Delta_{CP}}$ across the Dalitz plot, which accounts only for the statistical uncertainty. The inset shows an enlargement of the Dalitz plot around the $\phi\pi^+$ region [9].

where $\Delta A_{\text{raw}} = A^S_{\text{raw}} - A^C_{\text{raw}}$ and the Dalitz plot bins top-left, top-right, bottom-left, and bottom-right are the ones numbered in Fig. 1 as bins 13, 17, 14 and 16 (3+4, 7+8, 5 and 6),[1] respectively, for the $\phi\pi^+$ ($\overline{K}^{*0}K^+$) resonant amplitude. The results for the two resonant regions are

$$A^{\phi\pi^+}_{CP|S} = (0.95 \pm 0.43 \pm 0.26) \times 10^{-3} \text{ and}$$
$$A^{\overline{K}^{*0}K^+}_{CP|S} = (-0.26 \pm 0.56 \pm 0.18) \times 10^{-3},$$

which, despite the per mille level precision, do not show any evidence of *CP* violation.

3. Measurement of $D^0 - \overline{D}^0$ mixing and search for *CP* violation in $D^0 \to K^+\pi^-$ decays

The decay $D^0(t) \to K^+\pi^-$, where $D^0(t)$ indicates a particle produced (at $t = 0$) as a D^0 flavour eigenstate, is an ideal candidate to study mixing and *CP* violation. In fact, the contributions the $D^0 \to K^+\pi^-$ decay receives from the doubly Cabibbo-suppressed decay amplitude and from the amplitude of the Cabibbo-favoured $\overline{D}^0 \to K^+\pi^-$ decay, following a $D^0 - \overline{D}^0$ oscillation, are comparable. The time evolution of the decays is described by the 2×2 effective hamiltonian $\boldsymbol{H} \equiv \boldsymbol{M} - \frac{i}{2}\boldsymbol{\Gamma}$, where $\boldsymbol{\Gamma}$ is the decay matrix. The oscillation parameters are defined from the elements of the $\boldsymbol{M}$ and $\boldsymbol{\Gamma}$ matrices as $x_{12} \equiv 2|M_{12}|/\Gamma$ and $y_{12} \equiv |\Gamma_{12}|/\Gamma$, where Γ is the D^0 decay width.

The ratios between the decay rates of the doubly Cabibbo-suppressed and the Cabibbo-favoured decays can be defined as

$$R^+_{K\pi}(t) \equiv \frac{\Gamma(D^0(t) \to K^+\pi^-)}{\Gamma(\overline{D}^0(t) \to K^+\pi^-)} \quad \text{and} \quad R^-_{K\pi}(t) \equiv \frac{\Gamma(\overline{D}^0(t) \to K^-\pi^+)}{\Gamma(D^0(t) \to K^-\pi^+)}, \tag{5}$$

[1] The plus sign indicates that candidates from two bins are combined before computing $A_{CP|S}$.

where the final states within each ratio are the same for favoured and suppressed decay channels. Having the same final state for both decay channels in the ratio allows to avoid corrections due to different efficiencies for oppositely charged particles. Furthermore, thanks to the smallness of the x_{12} and y_{12} mixing parameters, the ratios $R^{\pm}_{K\pi}(t)$ can be approximated by

$$R^{\pm}_{K\pi}(t) \approx R_{K\pi}(1 \pm A_{K\pi}) + \sqrt{R_{K\pi}(1 \pm A_{K\pi})}(c_{K\pi} \pm \Delta c_{K\pi})\, t + (c'_{K\pi} \pm \Delta c'_{K\pi})\, t^2 \,, \tag{6}$$

where the decay time t is expressed in units of the D^0 lifetime (τ_{D^0}) and all other parameters follow the conventions dictated in Ref. [11]. From Eq. 6 it is evident how *CP*-even and *CP*-odd observables, respectively sensitive to mixing and *CP* violation, come into play in the determination of the ratio of doubly Cabibbo-suppressed and Cabibbo-favoured decays. Among the observables of Eq. 6, $A_{K\pi}$ provides a rigorous null test of the SM, as the $c \to ud\bar{s}$ transition does not receive contributions from penguin or chromomagnetic-dipole operators [12]. Thus, any signs of *CP* asymmetry in the decay larger than 10^{-5} would provide unambiguous evidence of new interactions [13].

The LHCb collaboration measured the ratios $R^{\pm}_{K\pi}(t)$ using prompt $D^0 \to K^-\pi^+$ and $D^0 \to K^+\pi^-$ decays collected between 2015 and 2018, for a total integrated luminosity of 6 fb^{-1} [14]. The values of $R^{\pm}_{K\pi}(t)$ are obtained from simultaneous fits, performed in each D^0 decay time bin, on both $K^-\pi^+$ and $K^+\pi^-$ final states, allowing for a direct determination of mixing and *CP* violation observables. The data are fitted with two alternative models, one allowing for *CP* violation and the other not, their results are compared in Fig. 3 and are compatible with each other. This analysis provides

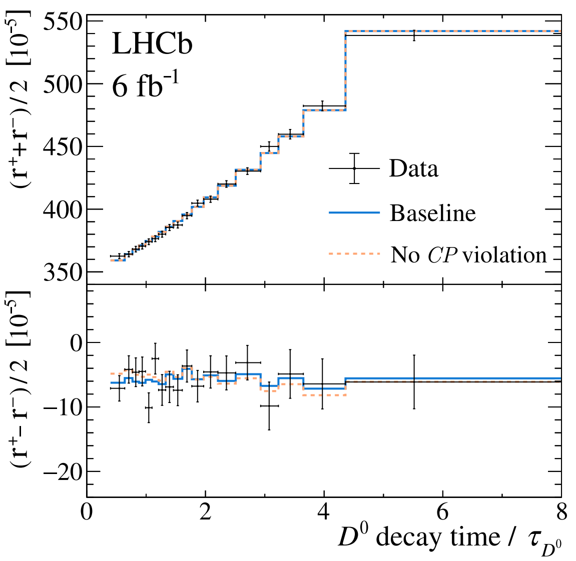

Figure 3: Half sum and half difference of measured doubly Cabibbo-suppressed to Cabibbo-favoured yields ratio for the $K^+\pi^-$ and $K^-\pi^+$ final states as a function of decay time. Projections of fits where *CP* violation effects are allowed (solid line) or forbidden (dotted line) are overlaid. The abscissa of each data point corresponds to the average decay time over the bin, the horizontal error bars delimit the bin, and the vertical error bars indicate the statistical uncertainties [14].

the most precise determination of the mixing and *CP* violation observables up to date and, thanks to the increase in statistical power and a better control over systematic uncertainties, for the first time an evidence of the coefficient of the second order expansion in time ($c'_{K\pi}$) being different from

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

Table 1: Mixing and *CP* violation observables obtained from the combination of this [14] and previous [15] LHCb measurements. Uncertainties and correlations include both statistical and systematic contributions.

zero. These results are compatible with previous results from LHCb using data collected between 2011 and 2016 [15]. Combining all the results obtained with LHCb data, the latest determination of the mixing and *CP* violation observables, along with their correlation, is reported in Tab. 1. All observables describing *CP* violation are compatible with zero, pointing to no significant deviation from the Standard Model predictions.

4. Search for *CP* violation in semileptonically tagged $D^0 \to K^+\pi^-$ decays

Complementarily to the prompt analysis outlined in the previous section [14], mixing and *CP* violation observables can also be measured using doubly-tagged $D^0 \to K^+\pi^-$ decays. These are characterised by the charm meson being produced by the semileptonic decay of a promptly produced beauty meson ($\overline{B} \to D^*(2010)^+\mu^- X$), which usually decays $O(1\,\text{cm})$ away from the primary vertex. Being significantly displaced from the primary vertex, this decay channel offers a

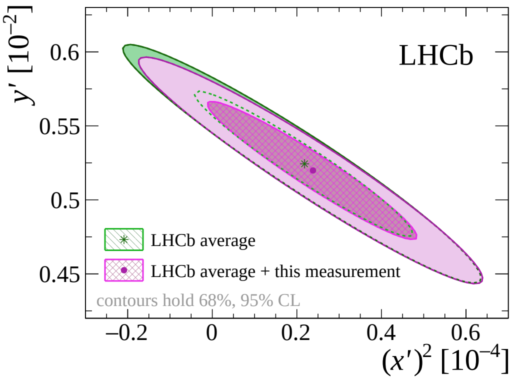

Figure 4: Correlation between the mixing parameters y' and $(x')^2$ illustrating the LHCb average before (green) and after (pink) including the semileptonically tagged result [16].

much cleaner environment with respect to prompt decays. This allows for a higher sensitivity to low decay times, with the downside of having a much lower statistics with respect to the one of prompt decays. Recently LHCb released a measurement of mixing and *CP* violation observables in semileptonically tagged $D^0 \to K^+\pi^-$ and $D^0 \to K^-\pi^+$ decays, using data collected between 2016 and 2018, for a total integrated luminosity of 5.4 fb^{-1} [16]. Results are compatible with previous results from LHCb, including the prompt analysis results [14], as shown in Fig. 4. A particularly remarkable achievement of this analysis is that, despite having a data sample which is approximately just 1% the size of the data sample used for the prompt analysis [14], its results improve the LHCb average for the mixing observables by factors spanning between 4.8% and 6.4%.

References

[1] S. L. Glashow, J. Iliopoulos, and L. Maiani, *Weak Interactions with Lepton-Hadron Symmetry*, Phys. Rev. D **2**, 7.

[2] N. Cabibbo, *Unitary Symmetry and Leptonic Decays*, Phys. Rev. Lett. **10**, 12.

[3] M. Kobayashi and T. Maskawa, *CP-Violation in the Renormalizable Theory of Weak Interaction*, Progress of Theoretical Physics **49**, 2.

[4] LHCb collaboration, *Observation of CP Violation in Charm Decays*, Phys. Rev. Lett. **122**, 21.

[5] LHCb collaboration, *Measurement of the Time-Integrated CP Asymmetry in $D^0 \to K^-K^+$ Decays*, Phys. Rev. Lett. **131**, 9.

[6] LHCb collaboration, *The LHCb Detector at the LHC*, Journal of Instrumentation **3**, 08.

[7] R.H. Dalitz, *CXII. On the analysis of τ-meson data and the nature of the τ-meson*, The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science **44**, 357.

[8] LHCb collaboration, *Observation of Several Sources of CP Violation in $B^+ \to \pi^+\pi^+\pi^-$ Decays*, Phys. Rev. Lett. **124**, 3.

[9] LHCb collaboration, *Measurement of CP Violation Observables in $D^+ \to K^-K^+\pi^+$ Decays*, Phys. Rev. Lett. **133**, 25.

[10] LHCb collaboration, *Search for CP violation in $D^+ \to \phi\pi^+$ and $D_s^+ \to K_S^0\pi^+$ decays*, Journal of High Energy Physics **2013**, 6.

[11] A. L. Kagan and L. Silvestrini, *Dispersive and absorptive CP violation in $D^0 - \overline{D}^0$ mixing*, Phys. Rev. D **103**, 5.

[12] S. Bergmann and Y. Nir, *New physics effects in doubly Cabibbo suppressed D decays*, Journal of High Energy Physics **1999**, 09.

[13] Y. Grossman, A. L. Kagan, and Y. Nir, *New Physics and CP Violation in Singly Cabibbo Suppressed D Decays*, Physical Review D **75**, 3.

[14] LHCb collaboration, *Measurement of $D^0 - \overline{D}^0$ mixing and search for CP violation with $D^0 \to K^+\pi^-$ decays*, Phys. Rev. D **111**, 1.

[15] LHCb collaboration, *Updated determination of $D^0 - \overline{D}^0$ mixing and CP violation parameters with $D^0 \to K^+\pi^-$ decays*, Physical Review D **97**, 3.

[16] LHCb collaboration, *Search for charge-parity violation in semileptonically tagged $D^0 \to K^+\pi^-$ decays*, arXiv **2501.11635**.