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# Studies of charm mixing and CP violation at LHCb

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Recent results on mixing and CP violation in charm decays are presented, based on an integrated luminosity of 1 $\mathrm{fb}^{-1}$ from $pp$-collision data taken at a centre-of-mass energy of 7 TeV with the LHCb detector. The hypothesis of no mixing in the $D^0 - \bar{D}^0$ system is excluded with a significance of $9.1\sigma$. Direct CP violation searches are reported in different modes. No indication of CP violation in charm is found.

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## 1. Introduction

The charm sector in the Cabibbo-Kobayashi-Maskawa matrix reveals unique properties. The $D^0-\bar{D}^0$ system is the only up-type quark meson system for which particle-antiparticle mixing is possible. Charge-parity ($CP$) violation through mixing, on the other hand, is expected to be very suppressed according to the standard model (SM) with estimated asymmetries of $\mathscr{O}(10^-4)$ or less. Direct $CP$ violation from Cabibbo-suppressed decays could reach a few per-mille level according to recent calculations [1].

Here we report results for mixing measurement and direct CP violation searches pursued with data collected by the LHCb detector during 2011, from $pp$ collisions at a centre-of-mass energy of 7 TeV, corresponding to 1 fb$^{-1}$ of integrated luminosity.



## 2. Observation of $D^0-\bar{D}^0$ mixing

The phenomena of mixing in neutral-meson systems occur when the flavour eigenstates differ from the mass eigenstates. The difference in the mass $\Delta m$ and in the widths $\Delta\Gamma$ of the two states are assessed through the measurement of the mixing parameters $x \equiv \Delta m/\Gamma$ and $y = \Delta\Gamma/2\Gamma$, where $\Gamma$ is the average decay width.

We present here a measurement of mixing parameters through the study of the time-dependent ratio of "wrong sign" (WS) $D^0 \to K^+\pi^-$ decay rate[1] with respect to that of the "right sign" (RS) $D^0 \to K^-\pi^+$ [2]. The RS process is essentially the Cabibbo-favoured (CF) decay, while the WS decay may proceed either directly via the Double-Cabibbo-suppressed (DCS) amplitude or via an oscillation followed by the CF decay. The knowledge of the initial flavour state of the $D^0$ meson at production is essential; the decay chain $D^{*+} \to D^0\pi^+$ gives this information by the charge of the companion $\pi^+$ (here referred to as slow pion, $\pi_s^+$, due to its low momentum).

Assuming the conservation of charge-parity ($CP$) symmetry and $|x|, |y| \ll 1$, the time-dependent ratio WS/RS is given by

$$R(t) \approx R_D + \sqrt{R_D}\, y' \frac{t}{\tau} + \frac{x'^2 + y'^2}{4}\left(\frac{t}{\tau}\right)^2 \tag{2.1}$$

where $R_D$ is the ratio of DCS to CF decay rates, $t$ is the measured $D$ decay time, $\tau$ is the $D$ lifetime, and $x'$ and $y'$ are related to $x$ and $y$ by a rotation through the strong phase between the CF and the DCS amplitudes.

We select a sample of $3.6\times10^4$ WS and $8.4\times10^6$ RS signal candidates obtained from fits to the $D^0\pi_s^+$ mass spectrum. The data is divided in 13 time decay-time intervals, with approximately the same number of events, and the ratio WS/RS decays is obtained for each interval. A binned $\chi^2$ fit is performed to this ratio distribution, as shown in Fig. 1, to determine the mixing parameters. We obtain $R_D = (3.52\pm0.15)\times10^{-3}$, $y' = (7.2\times2.4)\times10^{-3}$ and $x'^2 = (-0.09\pm0.13)\times10^{-3}$. The same distribution is fitted to a constant to obtain the significance of the mixing result. The no-mixing hypothesis is excluded at 9.1 standard deviations ($\sigma$), as can be seen also in Fig. 1. This is the first single-measurement observation of $D^0-\bar{D}^0$ mixing.

[1] Unless otherwise explicitly stated, charge conjugation states are implied through this text.

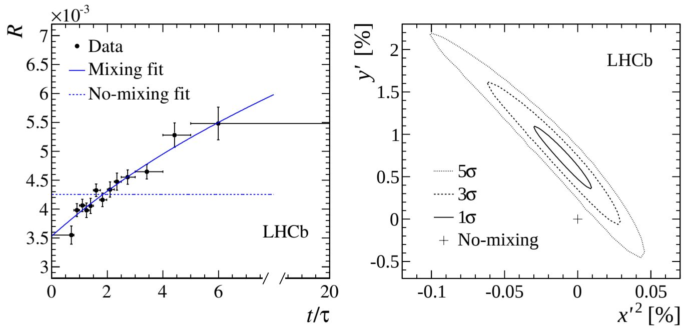


**Figure 1:** (left) Fit to the WS/RS ratio time intervals; (right) contours in the $x'^2 - y'$ plane and the no-mixing point.

## 3. Search for CP violation in 4-body $D^0$ decays

Multi-body Cabibbo-suppressed charm decays are interesting environments for the search of direct CP violation due to the rich, interfering resonant structure. The decay modes $D^0 \to K^-K^+\pi^-\pi^+$ and $D^0 \to \pi^-\pi^+\pi^-\pi^+$ are investigated for signs of localised CP effects within the five-dimensional (5D) phase space in a model-independent way. The Cabibbo-favored decay $D^0 \to K^-\pi^+\pi^-\pi^+$, with much higher statistics and for which no *CP* violation is expected, is used as a control mode to guarantee that no localised asymmetries due to production or detection are present. The flavour of the $D^0$ at production is identified through the decay chain $D^{*+} \to D^0\pi_s^+$.

After applying a selection criteria to reduce backgrounds (see details in [4]) a fit is performed to the samples and the *sPlot* tool [3] is used to assign signal weights to the candidates. There are $5.7 \times 10^4$ and $3.3 \times 10^5$ candidates for $D^0 \to K^-K^+\pi^-\pi^+$ and $D^0 \to \pi^-\pi^+\pi^-\pi^+$ signal channels, respectively, while there are $2.9 \times 10^6$ candidates for the control channel $D^0 \to K^-\pi^+\pi^-\pi^+$. The samples are searched for localised asymmetries by dividing the 5D the phase space into bins with the same occupancy (adaptive bins) and calculating the significance

$$S^i_{CP} = \frac{N_i(D^0) - \alpha N_i(\bar{D}^0)}{\sqrt{\alpha\left[\sigma_i^2(D^0) + \sigma_i^2(\bar{D}^0)\right]}}, \quad \alpha = \frac{\sum_i N_i(D^0)}{\sum_i N_i(\bar{D}^0)} \tag{3.1}$$

where $N_i$ is the sum of signal weights in bin $i$, $\sigma_i^2$ is the sum of squared weights, and the normalization factor $\alpha$ removes global asymmetries. A p-value for the no-*CP* violation hypothesis is obtained through a $\chi^2$ statistic, $\chi^2 = \sum_i \left(S^i_{CP}\right)^2$, with degrees of freedom equal to the total number of bins minus one.

Studies based on pseudo-experiments show that, with the current statistics, the method is sensitive to phase differences of $\mathcal{O}(10^\circ)$ or an amplitude difference greater than 5% between the main $D^0$ and $\bar{D}^0$ resonant channels appearing in the signal modes.

The method is first applied to the control channel to check for the possible presence of local asymmetries not related to *CP* violation and for different number of adaptive bins, 16, 128, and 1024. The p-values obtained are respectively 34.8, 80.0, and 22.1%, indicating the absence of local asymmetries. The distribution of the $S_{CP}$ values for the 128 adaptive bins is shown in Fig. 2

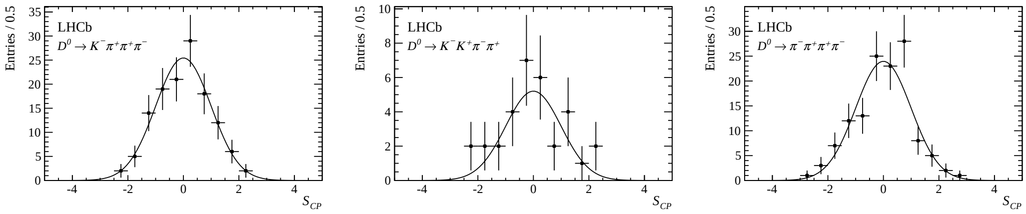


**Figure 2:** $S_{CP}$ distributions for (left to right) $D^0 \to K^-\pi^+\pi^-\pi^+$, $D^0 \to K^-K^+\pi^-\pi^+$ and $D^0 \to \pi^-\pi^+\pi^-\pi^+$.

showing agreement with a Gaussian distribution (overlaid) with zero mean and unit deviation, as it should be expected for $S_{CP}$ driven by statistical effects only.

The study is then performed for the signal channels. Due to the limited statistics, to gain sensitivity the choices for the number of adaptive binnings used for the $D^0 \to K^-K^+\pi^-\pi^+$ mode are 16, 32, and 64. The p-values are found to be respectively 9.1, 9.1, and 13.1%. For $D^0 \to \pi^-\pi^+\pi^-\pi^+$ mode, 64, 128, and 256 binnings are used and the p-values obtained are 28.8, 41.0, and 61.7%, respectively.

For both channels, these results show consistency with the hypothesis of no *CP* violation.

## 4. $\Delta A_{CP}(KK-\pi\pi)$ measurements

We review the results on the difference in time-integrated *CP* asymmetries between $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays. A previous measurement, with part of the 2011 data and using $D^{*+} \to D^0\pi_s^+$ chain to tag the $D^0$ flavour, has shown a $3.5\sigma$ evidence for a non-null difference [5]. Here we present a preliminary update of that analysis, with full 2011 data [6], as well as an independent analysis using semi-leptonic $B$ decays [7], where the charge of the muon tags the flavour of the $D^0$ meson at production. These two analyses will be referred to here as "$\pi_s$-tagged" and "$\mu$-tagged", respectively.

The decay-time-dependent *CP* asymmetry for $D^0$ decays to a *CP* eigenstate is defined as the difference in the decay widths for particle and antiparticle to that given final state over their sum.

The observable $\Delta A_{CP} \equiv A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+)$ is given to first order by

$$\Delta A_{CP} = a_{CP}^{\rm dir}(K^-K^+) - a_{CP}^{\rm dir}(\pi^-\pi^+) + \frac{\Delta\langle t\rangle}{\tau} a_{CP}^{\rm ind} \qquad (4.1)$$

where $a_{CP}^{\rm dir}(f)$ and $a_{CP}^{\rm ind}(f)$ represent the direct and induced *CP* violation asymmetry terms; the latter is expected to be small compared to the former, making this primarily a measurement sensitive to direct *CP* violation. On the other hand what is indeed measured is the *raw* asymmetry - e.g., the asymmetry in the observed number of $D^0$and $\bar{D}^0$ candidates. This asymmetry could receive contributions from production and detection mechanisms. Since both modes are self-conjugate final states, no detection asymmetry is expected for the $KK$ and $\pi\pi$ pairs. For the $\pi_s$-tagged analysis, the production asymmetry due to $D^{*+}$ and the detection asymmetry for $\pi_s^+$ are expected to cancel for $\Delta A_{CP}$ since they are common, to first order, to both modes. The same holds for the $B$ production and $\mu^+$ detection effects in the $\mu$-tagged analysis. Thus

$$\Delta A_{CP} \approx A_{\text{raw}}(K^-K^+) - A_{\text{raw}}(\pi^-\pi^+); \quad A_{\text{raw}}(f) = \frac{N(D^0 \to f) - N(\bar{D}^0 \to f)}{N(D^0 \to f) + N(\bar{D}^0 \to f)} \,. \tag{4.2}$$

After selection criteria are applied, for the $\pi_s$-tagged analysis there are $2.24 \times 10^6$ and $0.69 \times 10^6$ candidates for $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$, respectively. Details of the analysis can be found in [6]. The final result for the $\pi_s$-tagged analysis is

$$[\Delta A_{CP}]_{\pi_s-\text{tagged}} = (-0.34 \pm 0.15_{\text{stat}} \pm 0.10_{\text{sys}})\% \,.$$

The $\mu$-tagged analysis selects $5.89 \times 10^5$ and $2.22 \times 10^5$ candidates for $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$, respectively. Details of the analysis can be found in [7]. The final result for the $\mu$-tagged analysis is

$$[\Delta A_{CP}]_{\mu-\text{tagged}} = (+0.49 \pm 0.30_{\text{stat}} \pm 0.14_{\text{sys}})\% \,.$$

The two results can be combined to give the average $\Delta a_{CP}^{\text{dir}} = (-0.15 \pm 0.16)\%$. LHCb does not confirm the previous result on $\Delta A_{CP}$ [5]. No evidence for *CP* violation is found.

## 5. Search for *CP* violation in $D^+ \to \phi\pi^+$ and $D_s^+ \to K_S^0\pi^+$

A search for direct *CP* violation is performed in the Cabibbo-suppressed mode $D^+ \to K^-K^+\pi^+$ in the $\phi\pi^+$ region of the Dalitz plot, specifically requiring $1.00 < m_{KK} < 1.04$ GeV/$c^2$. We will be referring to this as simply $D^+ \to \phi\pi^+$. The Cabibbo-favoured mode $D^+ \to K_S^0\pi^+$ is used as a control channel. The *CP* asymmetry in the $D^+ \to \phi\pi^+$ is, to first order,

$$A_{CP}(D^+ \to \phi\pi^+) = A_{\text{raw}}(D^+ \to \phi\pi^+) - A_{\text{raw}}(D^+ \to K_S^0\pi^+) + A_{CP}(K^0/\overline{K}^0) \tag{5.1}$$

where the last term accounts for the expected *CP* asymmetry from neutral kaons an $A_{\text{raw}}$ is the raw asymmetry from the number of selected signal candidates for $D^+$ and $D^-$.

In addition, a search for *CP* violation is performed to the mode $D_s^+ \to K_S^0\pi^+$, also Cabibbo-suppressed. In this case the control channel used is $D_s^+ \to \phi\pi^+$ and similarly the *CP* asymmetry is given by

$$A_{CP}(D_s^+ \to K_S^0\pi^+) = A_{\text{raw}}(D_s^+ \to K_S^0\pi^+) - A_{\text{raw}}(D_s^+ \to \phi\pi^+) + A_{CP}(K^0/\overline{K}^0) \,. \tag{5.2}$$

In both measurements it is assumed that asymmetries from production and detection of $D^+$ and $D^-$ cancel in the difference between signal and control channel raw asymmetries.

A third measurement is performed by taking advantage by the rapidly-varying strong phase across the $\phi\pi^+$ region in the $D^+ \to K^-K^+\pi^+$ Dalitz plot. A constant *CP*-violating asymmetry would be modulated by this strong phase and there could be a cancellation when computing $A_{CP}$ (Eq. 5.1) when different parts of the $\phi\pi^+$ are added. A complementary observable is defined as

$$A_{CP|S} = \frac{1}{2}\left[(A_{\text{raw}}^A + A_{\text{raw}}^C) - (A_{\text{raw}}^B + A_{\text{raw}}^D)\right] \tag{5.3}$$

where the regions $A, B, C, D$, for which the raw asymmetries are calculated, are shown in Fig. 3.

Details of the analysis can be found at [8]. The results are

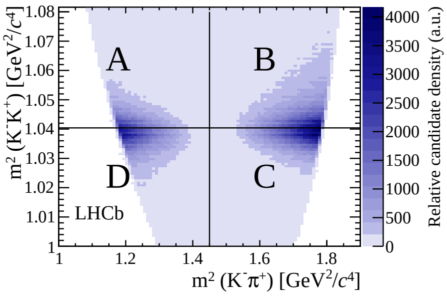


**Figure 3:** Definition of the four regions $A, B, C, D$ around the $\phi\pi^+$ region of the $D^+ \to K^-K^+\pi^+$ Dalitz plot. The distribution is the observed density of selected candidates.

$$
\begin{aligned}
A_{CP}(D^+ \to \phi\pi^+) &= (-0.04 \pm 0.14 \pm 0.14)\% \\
A_{CP|S}(D^+ \to \phi\pi^+) &= (-0.18 \pm 0.17 \pm 0.18)\% \\
A_{CP}(D_s^+ \to K_S^0\pi^+) &= (+0.61 \pm 0.83 \pm 0.14)\%
\end{aligned}
$$

No evidence for *CP* violation is found in these modes.

## 6. Conclusion

We have presented here results for mixing and searches for *CP* violation in charm decays with data from LHCb experiment collected during 2011, corresponding to 1 fb$^{-1}$ in *pp*-collisions at 7 TeV. No evidence for *CP* violation in charm was found. Mixing in $D^0 - \overline{D}^0$ system is observed, with the no-mixing hypothesis excluded at $9.1\sigma$.

## References


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