Charm mixing and CP violation at LHCb

Artur Ukleja
National Centre for Nuclear Studies, Warsaw, PL
for the LHCb Collaboration
E-mail: artur.ukleja@fuw.edu.pl

Abstract. In $pp$ collisions at the LHC the LHCb experiment has collected the world’s largest sample of charmed hadrons. Using data of an integrated luminosity of $1.0 \ fb^{-1}$ recorded in 2011 a measurement of direct and indirect CP violation in the charm sector and of $D^0$ mixing parameters was performed. Results from several decay modes are presented with complementary time-dependent and time-integrated analyses.

1. Introduction
The charm sector of particle physics is a promising place to probe for the presence of Physics beyond the Standard Model (NP) because CP violation in the charm sector is expected to be small in the Standard Model (SM). Since evidence of $D^0 - \bar{D}^0$ oscillations was first reported [1, 2, 3, 4] there was growing interest in this subject. No single measurement reached a precision above $5\sigma$ significance in combinations of all measurements however, a $10\sigma$ significance of $D^0 - \bar{D}^0$ oscillations could be reached [5]. Discovery in a single measurement was presented for the first time by the LHCb experiment [6]. Details of this measurement are discussed in Section 3. The time integrated CP asymmetry measurements in multi-body charm decays with pions and/or kaons in the final states are discussed for two, three and four body decays in Sections 4, 5 and 6, respectively.

2. LHCb detector
The LHCb detector [7] is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, designed for the study of particles containing $b$ or $c$ quarks. The detector has a very good particle identification for $\pi$ and $K$, where misidentification is smaller than $5\%$. Displaced vertices of $c$-hadron decays can be measured with $20 \ \mu m$ resolution. A decay time resolution $0.1$ of the $D$ meson lifetime using a silicon vertex locator is achieved. The tracking system measures the charged particles with momentum resolution $\Delta p/p$ that varies from $0.4\%$ at $5 \ GeV$ to $0.6\%$ at $100 \ GeV$ corresponding to a typical mass resolution of approximately $8 \ MeV$ for a two body charm meson decay. The $c\bar{c}$ cross-section in $pp$ collisions of $\sim 6 \ mb$ [8] measured with the LHCb detector at $\sqrt{s} = 7 \ TeV$ is about 20 times larger than the $b\bar{b}$ cross-section. Therefore, the LHCb experiment has a great potential in charm physics studies.

3. First observation of $D^0 - \bar{D}^0$ oscillations
In order to measure $D^0 - \bar{D}^0$ oscillations the $D$ flavour has to be identified at both the production and decay. The flavour of the $D^0$ meson of production time is identified in the process of
$D^{*+} \rightarrow D^0(\rightarrow hh)\pi^+_s$ decays, with $h = \pi$ or $K$, in which the sign of the slow pion $\pi_s$ tags the initial $D^0$ or $\bar{D}^0$. The flavour at decay is tagged by the charge of the $K$ meson. The $D^0 \rightarrow K^+\pi^-$ decays called wrong-sign (WS) and the $D^0 \rightarrow K^-\pi^+$ decays called right-sign (RS) are considered. The RS decays are dominated by the Cabibbo-favoured (CF) decay amplitude, whereas the WS amplitude includes contributions from both the doubly-Cabibbo-suppressed (DCS) $D^0 \rightarrow K^+\pi^-$ decay and $D^0 - \bar{D}^0$ mixing followed by the favoured $D^0 \rightarrow K^+\pi^-$ decay. In the limit of small mixing and assuming negligible CP violation, the time-dependent ratio, $R$, of WS to RS decay rates is approximated by [9]

$$R(t) = R_D + \sqrt{R_D} \frac{t}{\tau} + \frac{x^2 + y^2}{4} \frac{(t/\tau)^2}{\Gamma}, \quad (1)$$

where $t/\tau$ is the decay time expressed in units of the average $D^0$ lifetime, $\tau$, $R_D$ is the ratio of DCS to CF decay rates, $x' = x \cos\delta + y \sin\delta$, $y' = y \cos\delta - x \sin\delta$, where $\delta$ is the strong phase difference between the DCS and the CF amplitudes and $x = \Delta m/\Gamma$, $y = \Delta\Gamma/2\Gamma$, where $\Delta m$ and $\Delta\Gamma$ are the mass and decay width differences between the two mass eigenstates and $\Gamma$ is the average $D^0$ decay width.

3.1. Data set and selection

The measurement is performed with 1.0 fb$^{-1}$ of data recorded by the LHCb detector during 2011. Events are selected by the signature of charm decays based on two oppositely charged tracks to form a $D^0$ candidate with a decay vertex well separated from the associated $pp$ collision vertex. Further criteria on the quality of the reconstructed tracks are applied and described in [6].

The time-integrated $D^0\pi^+_s$ mass distributions, $M(D^0\pi^+_s)$, for the selected RS and WS candidates are shown in Fig. 1. A binned $\chi^2$ fit is used to separate the $D^{*+}$ signal and the background component. From the fits about $3.6 \times 10^4$ WS and $8.4 \times 10^6$ RS decays are found.

![Figure 1](image.png)

Figure 1. Time-integrated $D^0\pi^+_s$ mass distributions for the selected RS $D^0 \rightarrow K^-\pi^+$ (left) and WS $D^0 \rightarrow K^+\pi^-$ (right) candidates with fit projections overlaid. The bottom plots show the residuals between the data points and the fits.

3.2. Results

The measurement of the time-dependent WS/RS ratio is performed in bins of $D^0$ decay time. The data is divided into thirteen bins, chosen to have a similar number of candidates in each. The number of RS and WS decays are determined using fits to the $M(D^0\pi^+_s)$ distributions in the thirteen bins to calculate the WS/RS ratios. The measured WS/RS ratios are shown in...
The fit to the WS/RS ratio with the no-mixing hypothesis does not describe the data (dashed line) fits overlaid. Fig. 2 [6]. From the binned $\chi^2$ fit to the time-dependence given in Eq. 1 (solid line in Fig. 2) the mixing parameters are obtained and are listed in Table 1.

Most of the systematic uncertainties cancel in the ratio of WS and RS since the WS and RS events are expected to have the same decay time acceptance. Two main sources of systematic uncertainties have been identified. One of them is related to the secondary $D$ decays. It was found that when the secondary component is not subtracted the measured WS/RS ratio could be biased less than 3%.

A second source of the systematic uncertainty is related to background from charm decays where both daughters are reconstructed with the wrong particle type which gives a peak in $M(D^0\pi^+)$. This is not accounted for in the mass fit. The background is suppressed by the use of tight particle identification and two body mass requirements. It was found that the dominant peaking background is from RS events that survive the requirements of the WS selection. They are estimated to constitute $(0.4\pm 0.2)\%$ of the WS signal. The measurements are dominated by the statistical uncertainties.

The fit to the WS/RS ratio with the no-mixing hypothesis does not describe the data (dashed line in Fig. 2). The $\chi^2$ difference between mixing and no-mixing assumption excludes the no-mixing hypothesis with a probability corresponding to 9.1 standard deviations. This is the first observation of $D^0 - \bar{D}^0$ oscillations in a single measurement. In Fig. 3 the $1\sigma$, $3\sigma$ and $5\sigma$ confidence regions of the measured mixing parameters $x^2$ and $y'$ are shown. They are compatible with and have substantially better precision than those from previous measurements [1, 3, 10].

### 4. Evidence for CPV in $D^0 \rightarrow h^- h^+$ decays

The time-integrated CP asymmetry has two contributions: an indirect and a direct component. The indirect component is universal for CP eigenstates in the SM and is expected to be
Table 1: Results of the time-dependent fit to the data. The uncertainties include statistical
and systematic sources; ndf indicates the number of degrees of freedom.

| Fit type Parameter | Fit result | Correlation coe |
|--------------------|------------|-----------------|
| $A_{\text{CP}}$ $(\%)$ | $-0.05$ | 0.05 |
| $A_{D}$(CP) $(\%)$ | $0.03$ | 0.03 |
| $A_{P}$(CP) $(\%)$ | $0.04$ | 0.04 |
| $\Delta f_{\text{eff}}$ $(\%)$ | $0.02$ | 0.02 |

small. The direct component depends in general on the final state. In the SM direct CPV
in $D^0 \to K^-K^+$ and the $D^0 \to \pi^-\pi^+$ decays is expected to be $10^{-3}$ or less [11]. In the presence
of the NP, however, the rate of CPV could be enhanced. Similar to the $D^0 - \bar{D}^0$ oscillation
measurements tagged $D^0$ decays are analysed.

The measured raw time-integrated asymmetry may be written as a sum of various components
both from physics and detector effects

$$A_{\text{RAW}}(f) = A_{\text{CP}}(f) + A_{D}(f) + A_{D}(\pi^+) + A_{P}(D^{*+}),$$

(2)

where $A_{\text{CP}}(f)$ is an intrinsic physics CP asymmetry, $A_{D}(f)$ is the asymmetry for selecting the
$D^0$ decay into the final state $f$, $A_{D}(\pi^+)$ is the asymmetry for selecting a slow pion from the
$D^{*+}$ decay chain. The $A_{P}(D^{*+})$ is the production asymmetry of the $D^{*+}$ mesons.

Since the decays $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ are symmetric the $D^0$ detection
asymmetries cancel. The asymmetries $A_{D}(\pi^+)$ and $A_{P}(D^{*+})$ are independent of the final
state and therefore the terms cancel in the subtraction. For this reason, the difference
$\Delta A_{\text{CP}} = A_{\text{RAW}}(K^-K^+) - A_{\text{RAW}}(\pi^-\pi^+)$ is measured and the quantity $\Delta A_{\text{CP}}$ is a difference of
CP asymmetries, $\Delta A_{\text{CP}} = A_{\text{CP}}(K^-K^+) - A_{\text{CP}}(\pi^-\pi^+)$. 

4.1. Data set and selection

The measurement is performed with 0.62 fb$^{-1}$ of LHCb data. The selection criteria applied
are related to the decay time to isolate the decays of interest, the track quality, the vertex
quality, the transverse momentum, the angle between the $D^0$ momentum in the lab frame and
its daughters’ momenta in the rest frame. The full selection description can be found in [12].

The invariant mass spectra of the selected $D \to K^-K^+$ and $D \to \pi^-\pi^+$ candidates are shown in Fig. 4. The half width at half maximum of the signal line shape is 8.6 MeV/c$^2$
for the $D \to K^-K^+$ and 11.2 MeV/c$^2$ for the $D \to \pi^-\pi^+$. The mass difference spectra,$\delta m \equiv m(h^-h^+\pi^+) - m(h^-h^+ \pi^+), h = K, \pi$, of selected candidates are shown in Fig. 5. The candidates are required to lie inside a wide $\delta m$ window of 0 − 15 MeV and a $D^0$ mass signal
window of 1844 − 1884 MeV/c$^2$. Approximately $1.44 \times 10^6$ candidates are found in the $K^-K^+$
sample and $0.38 \times 10^6$ in the $\pi^-\pi^+$ sample.

4.2. Results

The production and the detection asymmetries vary with $p_T$, pseudorapidity, $\eta$, and the detection
efficiency of the two different $D^0$ decays. Therefore, the analysis is performed in bins of $p_T$, the
$\eta$ of the $D^{*+}$ candidates and the momentum of the slow pion. In total, there are 216 statistically
independent measurements for each decay mode. A value of $\Delta A_{\text{CP}}$ is determined in each bin.
The analysis is performed in 54 kinematic bins, divided by charm from...

Combining these in quadrature, we obtain the background-subtracted average decay time of $D^{*+}$ candidates, the momentum of the slow pion, and whether the initial trajectory of selected $\pi^-\pi^+$ and satisfying $0 < \Delta^+ < 15\text{ MeV}/c^2$. The vertical lines indicate the signal window of $1844 - 1884\text{ MeV}/c^2$.

No systematic dependence of $\Delta A_{CP}$ is observed with respect to the kinematic variables. The weighted average yields

$$\Delta A_{CP} = [-0.82 \pm 0.21(stat) \pm 0.11(syst)]\%.$$  

Systematic uncertainties are assigned by changing the selection criteria, repeating the analysis with the asymmetry extracted through the sideband subtraction in $\delta m$ instead of a fit, removing all candidates but one (chosen at random) in events with multiple candidates and comparing with the result obtained without kinematic binning.

Combining statistical and systematic uncertainties in quadrature, the result is consistent at the $1\sigma$ level with the current HFAG world average [5]. Dividing the central value by the sum in quadrature of the statistical and systematic uncertainties, the significance of the measured deviation from zero is $3.5\sigma$. This is the first evidence for CPV in the charm sector.

4.3. Result interpretation

The CP asymmetry of each final state, $A_{CP}(f)$, can be expressed in terms of two contributions, a direct component associated with CPV in the decay amplitudes and an indirect component associated with CPV in the mixing or in the interference between mixing and decay. It can be written to the first order as [13]

$$A_{CP}(f) = a_{CP}^{dir}(f) + \frac{(t)}{\tau} a_{CP}^{ind},$$  (3)
where $a_{CP}^{dir}(f)$ is a direct CPV for the decay, $\langle t \rangle$ is the average proper time of the reconstructed sample, $\tau$ is a $D^0$ lifetime, and $a_{CP}^{ind}$ is an indirect CPV originating from the mixing and/or the interference between mixing and decay.

The measured quantity $\Delta A_{CP}$ can be related to the direct and indirect CPV

$$\Delta A_{CP} \equiv A_{CP}(K^-K^+) - A_{CP}(\pi^+\pi^-) = [a_{CP}^{dir}(K^-K^+) - a_{CP}^{dir}(\pi^+\pi^-)] + \frac{\Delta(t)}{\tau} a_{CP}^{ind},$$

where $\Delta(t)$ is the difference in average proper time of the $D^0$ mesons in the $K^-K^+$ and the $\pi^+\pi^-$ samples. In the limit that $\Delta(t)$ vanishes, $\Delta A_{CP}$ probes the difference in direct CPV between the two decays. Since indirect CPV is universal (up to $10^{-2}$) [14], its contribution would cancel in the difference. The fractional difference $\Delta(t)/\tau$ is obtained as $\Delta(t)/\tau = (9.83 \pm 0.22(stat) \pm 0.19(syst))\%$, the measured $\Delta A_{CP}$ is primarily sensitive to direct CPV.

5. Search for CPV in $D^+ \to K^-K^+\pi^+$ decays

Multi body charm meson decays are dominated by intermediate resonant states. The interference between resonances in the two dimensional phase space can lead to observable CP asymmetries which vary across the Dalitz plot for the Cabibbo suppressed decay $D^+ \to K^-K^+\pi^+$. Previously, CPV asymmetries in the Dalitz plot in three body charm decays were investigated by BABAR [15], CLEO-c [16] and BELLE [17]. No CPV has been observed in $D$ decays.

A direct model independent comparison between the $D^+$ and the $D^-$ Dalitz plots can be done on a bin by bin basis. For each bin, a local CP asymmetry is defined as [18]

$$S_{CP}^i = \frac{N^i(D^+) - \alpha N^i(D^-)}{\sqrt{N^i(D^+) + \alpha^2 N^i(D^-)}},$$

where $N^i(D^+)$ and $N^i(D^-)$ are the numbers of the $D^+$ and the $D^-$ candidates in the $i$th bin and the parameter $\alpha$ accounts for a global asymmetry which is the ratio between the total reconstructed $D^+$ and $D^-$ candidates, $\alpha = N_{tot}(D^+)/N_{tot}(D^-)$.

In the absence of the Dalitz plot dependent asymmetries, the $S_{CP}^i$ values are distributed according to a Gaussian distribution with zero mean and unit width. CPV manifests itself by deviations from this behaviour. The numerical comparison is performed with a $\chi^2$ test, $\chi^2 = \Sigma(S_{CP}^i)^2$, and a $p$–value calculation.

5.1. Data set and selection

These measurements are performed with 35 pb$^{-1}$ of LHCh data collected in 2010. The event selection is based on many criteria, the relative log-likelihood for pion and kaon hypothesis, the fit quality for each particle reconstructed in the final state, the primary and secondary vertex reconstruction and the flight distance variable [19].

The reconstructed invariant mass distribution of the $K^-K^+\pi^+$ is shown in Fig. 6. From a simultaneous fit to the invariant mass distributions of the $D^+$ and the $D^-$, a total number of 403894 candidates (signal and background) is obtained. Within a $D^+$ mass window of 1856.7 – 1882.1 MeV/c$^2$, about 8.6% of events are background and 200336 $D^+$ and 203558 $D^-$ candidates.

5.2. Results

The measured $S_{CP}^i$ distribution in $D^+ \to K^-K^+\pi^+$ decays is shown in Fig. 7 for two binning schemes: uniform and adaptive. For the adaptive, two different numbers of different size bins were used, 25 bins (Adaptive I) and 106 bins (Adaptive II). For the uniform, two different numbers of equal size bins were used, 200 bins (Uniform I) and 530 bins (Uniform II). Results
Charm Physics in the LHCb Experiment, First Evidence for CP Violation...

In the absence of the Dalitz plot dependent asymmetries, the fitted mass windows and sidebands defined in the text are labelled.

D and horizontal two-body resonances plus one track are expected. Charm

FIG. 1. Fitted mass spectra of (a) $K\pi\pi$ and (b) $K\pi\pi$ candidates. The signal mass windows and sidebands defined in the text are labelled.

are listed in Table 2. The calculated $p$-values are above 10% and the fits are consistent with Gaussian distributions with zero mean and unit width. The $p$-values indicate that there is no evidence for CPV.

FIG. 6. The fitted mass distribution of $D^+ \to K^- K^+ \pi^+$ candidates.

Figure 7. Distribution of $S_{CP}$ fitted to Gaussian functions for (a) Adaptive I, (b) Adaptive II, (c) Uniform I and (d) Uniform II.

Table 2. Fitted means and widths, $\chi^2/ndf$ and $p$-values for $D^+ \to K^- K^+ \pi^+$ decays with four different binning schemes.

| Binning      | Fitted mean $\pm$ (GeV/c) | Fitted width $\pm$ (GeV/c) | $\chi^2/ndf$ | $p$-value (%) |
|--------------|---------------------------|-----------------------------|--------------|---------------|
| Adaptive I   | $0.01 \pm 0.23$           | $1.13 \pm 0.16$            | 32.0/24      | 12.7          |
| Adaptive II  | $-0.024 \pm 0.010$        | $1.078 \pm 0.074$          | 123.4/105    | 10.6          |
| Uniform I    | $-0.043 \pm 0.073$        | $0.929 \pm 0.051$          | 191.3/198    | 82.1          |
| Uniform II   | $-0.039 \pm 0.045$        | $1.011 \pm 0.034$          | 519.5/529    | 60.5          |

6. Search for CPV in $D^+ \to \pi^- \pi^+ \pi^- \pi^+$ decays

While the three body decay kinematics can be described fully by a two dimensional Dalitz plot, a four body decay needs a five dimensional phase space description. In this study, the same model independent method is used as for three body charm decays (Section 5). The analysis
is performed with 1 fb⁻¹ of LHCb data collected in 2011. About 180k $D^+ \rightarrow \pi^-\pi^+\pi^+$ candidates with a signal purity of 95.8% have been found. The analysis has been performed on three different adaptive binnings, 15, 29 and 66. The $S_{CP}$ distribution for 66 adaptive bins is shown in Fig. 8. The $p$-values are 97.1%, 95.6% and 99.8%, respectively [20] and the measurements are consistent with the hypothesis of no CPV.

![Figure 8](image_url)

**Figure 8.** The $S_{CP}$ distribution of $D^+ \rightarrow \pi^-\pi^+\pi^+$ decays for 66 adaptive bins. The full line shows Gaussian distribution with the assumption of no CPV.

7. Conclusions
Using data of 1 fb⁻¹ collected with the LHCb experiment in 2011 $D^0 - \bar{D}^0$ oscillations are observed for the first time in a single measurement evaluating the time-dependence of the ratio of $D^0 \rightarrow K^+\pi^-$ and $D^0 \rightarrow K^-\pi^+$ decays. The no-mixing hypothesis is excluded at 9.1 standard deviations. The time-integrated difference in CP asymmetry of $D^0 \rightarrow K^-K^+$ and the $D^0 \rightarrow \pi^-\pi^+$ decays has been measured using 0.62 fb⁻¹ of data

$$\Delta A_{CP} = [-0.82 \pm 0.21(stat) \pm 0.11(syst)] \%.$$  

The measured $\Delta A_{CP}$ is mainly sensitive to the presence of direct CP violation.

No evidence for CP violation is found with a model independent search for direct CP violation in the Cabibbo suppressed decays, $D^+ \rightarrow K^-K^+\pi^+$ with 35 pb⁻¹ (2010 data) and $D^+ \rightarrow \pi^-\pi^+\pi^-\pi^+$ with 1 fb⁻¹ (2011 data).

References
[1] Aubert B et al. (BABAR Collaboration) 2007 *Phys.Rev.Lett.* 98 211802 (Preprint hep-ex/0703020)
[2] Staric M et al. (Belle Collaboration) 2007 *Phys.Rev.Lett.* 98 211803 (Preprint hep-ex/0703036)
[3] Aaltonen T et al. (CDF Collaboration) 2008 *Phys.Rev.Lett.* 100 121802 (Preprint 0712.1587)
[4] Aubert B et al. (BABAR Collaboration) 2009 *Phys.Rev.* D80 071103 (Preprint 0908.0761)
[5] Asner D et al. (Heavy Flavor Averaging Group) 2010 (Preprint 1010.1589)
[6] Aaij R et al. (LHCb Collaboration) 2012 (Preprint 1211.1230)
[7] Alves A Augusto J et al. (LHCb Collaboration) 2008 *JINST* 3 S08005
[8] Aaij R et al. (LHCb Collaboration) 2010 *LHCb-CONF-2010-013*
[9] Bianco S, Fabbrì F, Benson D and Bigi I 2003 *Riv.Nuovo Cim.* 26N7 1-200 (Preprint hep-ex/0309021)
[10] Zhang L et al. (BELLE Collaboration) 2006 *Phys.Rev.Lett.* 96 151801 (Preprint hep-ex/0601029)
[11] Grossman Y, Kagan A L and Nir Y 2007 *Phys.Rev.* D75 036008 (Preprint hep-ph/0609178)
[12] Aaij R et al. (LHCb Collaboration) 2012 *Phys.Rev.Lett.* 108 111602 (Preprint 1112.0938)
[13] Bigi I, Paul A and Recksiegel S 2011 *JHEP* 1106 089 (Preprint 1103.5785)
[14] Gersabeck M 2012 *Mod.Phys.Lett.* A27 1230026 (Preprint 1207.2195)
[15] Aubert B et al. (BABAR Collaboration) 2005 *Phys.Rev.* D71 091103 (Preprint hep-ex/0501075)
[16] Rubin P et al. (CLEO Collaboration) 2008 *Phys.Rev.* D78 072003 (Preprint 0807.4545)
[17] Staric M et al. (Belle Collaboration) 2011 (Preprint 1110.0694)
[18] Bediaga I et al. 2009 *Phys.Rev.* D 80 096006
[19] Aaij R et al. (LHCb Collaboration) 2011 *Phys.Rev.* D84 112008 (Preprint 1110.3970)
[20] Aaij R et al. (LHCb Collaboration) 2012 *LHCb-CONF-2012-019*