

Charm mixing and CP violation at LHCb

Artur Ukleja

National Centre for Nuclear Research, Warsaw, Poland

E-mail: artur.ukleja@fuw.edu.pl

Abstract. The LHCb experiment has collected the world's largest sample of charmed hadrons. Using data corresponding to an integrated luminosity of 3.0 fb^{-1} recorded in 2011 and 2012, measurements of direct and indirect CP violation in the charm sector and of D^0 mixing parameters were performed. Results from several decay modes are presented with complementary time-dependent and time-integrated analyses.

1. Introduction

The charm sector is a promising place to probe for the presence of physics beyond the Standard Model (SM) because CP violation (CPV) in the charm sector is expected to be very small in the SM [1]. Since evidence of $D^0 - \bar{D}^0$ oscillations was first reported [2, 3, 4] there is growing interest in this subject. Details of the measurement of $D^0 - \bar{D}^0$ oscillations achieved recently at the LHCb are discussed in Sec. 2. CPV arises when two or more amplitudes with different weak and strong phases contribute to the same final state. This is possible in the singly Cabibbo-suppressed (SCS) D decays, where significant tree and penguin contributions can be expected. The time-integrated CP asymmetry measurements in two-body SCS D^0 decays are discussed in Sec. 3. The searches for CP asymmetry in three-body SCS D^+ decays are discussed in Sec. 4. Conclusions are presented in Sec. 5.

2. Search for CP in $D^0 - \bar{D}^0$ oscillations

To measure $D^0 - \bar{D}^0$ oscillations, the D^0 flavour has to be identified at both the production and decay. The flavour of the D^0 meson at the production time is identified by the charge of the slow pion (π_s) from $D^{*+} \rightarrow D^0 \pi_s^+$ and $D^{*-} \rightarrow \bar{D}^0 \pi_s^-$ decays. The flavour at the time of decay is identified using the almost flavour-specific $K^\pm \pi^\mp$ final state. The $D^0 \rightarrow K^+ \pi^-$ decays are called wrong-sign (WS) decays and the $D^0 \rightarrow K^- \pi^+$ decays are called right-sign (RS) decays. 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 $\bar{D}^0 \rightarrow K^+ \pi^-$ decay. Assuming negligible CPV, the time-dependent ratio, R , of WS to RS decay rates is approximated by [1]

$$R(t) = R_D + \sqrt{R_D} y' \frac{t}{\tau} + \frac{x'^2 + y'^2}{4} \left(\frac{t}{\tau}\right)^2, \quad (1)$$

where t/τ is the decay time expressed in units of the average D^0 lifetime (τ), 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 δ is the strong phase difference between DCS and CF amplitudes. The parameters $x = \Delta m/\Gamma$ and $y = \Delta\Gamma/2\Gamma$, where Δm and $\Delta\Gamma$ are the mass and the decay width differences between the two mass eigenstates and Γ is the average D^0 decay width.

The measurement of the time-dependent WS/RS ratio is performed with 3 fb^{-1} in thirteen bins of D^0 decay time, chosen to have a similar number of candidates in each bin [5]. The

number of RS and WS decays are determined using fits to the $M(D^0\pi_s^+)$ distributions in each bin. The measured WS/RS ratios as a function of t/τ are fit separately for D^{*+} and D^{*-} decays to the time-dependence of Eq. 1. Three fits are performed to the data; the first allows direct and indirect CPV; the second allows only indirect CPV; and the third is a CP-conserving fit. Fig. 1 shows the central values and confidence regions in the (x'^2, y') plane. The resulting p -value, for the fit with direct and indirect (indirect only) CPV allowed, is 91% (81%), showing that the data are compatible with CP symmetry. This allows to limit the amount of CPV in $D^0 - \bar{D}^0$ mixing to $0.75 < |q/p| < 1.24$ at 68.3% CL and the amount of direct CPV in the DCS decay to $A_D = (R_D^+ - R_D^-)/(R_D^+ + R_D^-) = (-0.7 \pm 1.9)\%$, where R_D^+ (R_D^-) is the DCS/CF rate ratio for D^0 (\bar{D}^0) decays. Assuming CP conservation, the mixing parameters are measured to be $x'^2 = (5.5 \pm 4.9) \times 10^{-5}$, $y' = (4.8 \pm 1.0) \times 10^{-3}$ and $R_D = (3.568 \pm 0.066) \times 10^{-3}$.

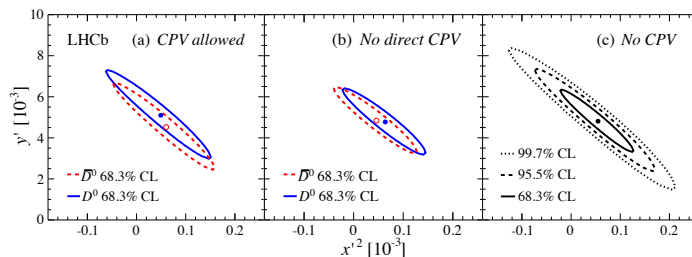


Figure 1. Two-dimensional confidence regions in the (x'^2, y') plane obtained (a) without any restriction on CPV, (b) assuming no direct CPV, and (c) assuming CP conservation. The dashed (solid) curves in (a) and (b) indicate the contours of the mixing parameters associated with \bar{D}^0 (D^0) decays. The best-fit values are shown with open or filled points.

3. A search for time-integrated CPV in $D^0 \rightarrow h^- h^+$ decays

The CP asymmetry of a decay of a D^0 meson to a CP eigenstate, $A_{CP}(f)$, 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 [6]

$$A_{CP}(f) = a_{CP}^{dir}(f) + \frac{\langle t \rangle}{\tau} a_{CP}^{ind}, \quad (2)$$

where $a_{CP}^{dir}(f)$ is a direct CPV for the decay, $\langle t \rangle$ is the average proper time of the reconstructed sample, and a_{CP}^{ind} is the indirect CPV. The indirect component is universal for CP eigenstates in the SM whilst the direct component depends in general on the final state.

The time-integrated CPV asymmetry difference between $D^0 \rightarrow K^- K^+$ and $D^0 \rightarrow \pi^- \pi^+$, ΔA_{CP} , is performed with 3 fb^{-1} in which the D^0 mesons are produced in inclusive semileptonic B meson decays to the $D^0 \mu^- \bar{\nu}_\mu X$ final state, where X means other possible particles [7]. The charge of the accompanying muon is used to identify the flavour of the D^0 meson ($\bar{B} \rightarrow D^0 \mu^- \bar{\nu}_\mu X$ or $B \rightarrow \bar{D}^0 \mu^+ \nu_\mu X$). The measured raw time-integrated asymmetry is a sum of physics and detector asymmetries,

$$A_{RAW}(f) = A_{CP}(f) + A_D(\mu^+) + A_P(B), \quad (3)$$

where $A_D(\mu^+)$ is the detection asymmetry for selecting a muon from semileptonic B decay chain and $A_P(B)$ is the production asymmetry of the B mesons. The detector and production asymmetries are removed by the difference of $A_{RAW}(K^- K^+)$ and $A_{RAW}(\pi^- \pi^+)$.

A binned maximum likelihood fit to the mass distributions is performed to determine the numbers of signal candidates as 2.1×10^3 for $D^0 \rightarrow K^- K^+$ decays and 0.77×10^3 for $D^0 \rightarrow \pi^- \pi^+$ decays. The fractional difference in an average decay time of the D^0 candidates for the two samples is $\Delta \langle t \rangle / \tau = 0.014 \pm 0.004$. The small value of $\Delta \langle t \rangle / \tau$ implies that the measured ΔA_{CP} is equal to the difference in direct CPV with negligible indirect CPV correction. For the first

time in LHCb, also the individual CP asymmetry in $D^0 \rightarrow K^-K^+$ decays is measured. In this case the determination of the detector and production asymmetries uses control samples of CF $\bar{B} \rightarrow D^0(\rightarrow K\pi)\mu\nu X$, $D^+ \rightarrow K\pi\pi$ and $D^+ \rightarrow \bar{K}^0(\rightarrow \pi\pi)\pi$ decays where CPV effects are negligible.

The measured value of ΔA_{CP} and the CP asymmetry in the $D^0 \rightarrow K^-K^+$ channel are found to be $\Delta A_{CP} = [+0.14 \pm 0.16(stat) \pm 0.08(syst)]\%$ and $A_{CP}(K^-K^+) = [-0.06 \pm 0.15(stat) \pm 0.10(syst)]\%$. By combining the above results, the CP asymmetry in the $D^0 \rightarrow \pi^-\pi^+$ decays is extracted as $A_{CP}(\pi^-\pi^+) = [-0.20 \pm 0.19(stat) \pm 0.10(syst)]\%$. The results show that there is no significant CPV in SCS $D^0 \rightarrow K^-K^+, \pi^-\pi^+$ decays at the level of 10^{-2} .

4. Search for CPV in the decay $D^+ \rightarrow \pi^-\pi^+\pi^+$

Many-body decays benefit from rich resonance structures with interfering amplitudes modulated by strong-phase variations across the phase space. Searches for localised asymmetries can bring complementary information on the nature of the CPV to the time-integrated decay rate measurements. The investigation of the Cabibbo-suppressed decay $D^+ \rightarrow \pi^-\pi^+\pi^+$ with 1 fb^{-1} is performed across the Dalitz plot using two model-independent techniques, one binned and the other unbinned searches [8].

The binned method, as employed in previous LHCb analyses [9, 10], is based on a bin-by-bin comparison between the D^+ and D^- Dalitz plots. For each bin of the Dalitz plot, the significance of the difference between the number of D^+ and D^- candidates, S_{CP}^i , is computed as

$$S_{CP}^i \equiv \frac{N_i^+ - \alpha N_i^-}{\sqrt{\alpha(N_i^+ + N_i^-)}}, \quad \alpha \equiv \frac{N^+}{N^-}, \quad (4)$$

where N_i^+ (N_i^-) is the number of D^+ (D^-) candidates in the i th bin and N^+ (N^-) is the sum of N_i^+ (N_i^-) over all bins. The parameter α removes the contribution of global asymmetries which may arise due to production and detection asymmetries, as well as from CPV. In the absence of localised asymmetries, the S_{CP}^i values follow a standard normal distribution. Therefore, CPV can be detected as a deviation from this behaviour.

Two binning schemes are used, a uniform grid with bins of equal size and an adaptive binning schemes where the bins have the same population (Fig. 2). No single bin in any of the binning schemes presents an absolute S_{CP}^i value larger than 3. Assuming no CPV, the probabilities of observing local asymmetries as large or larger than those are above 50% in all the tested binned schemes.

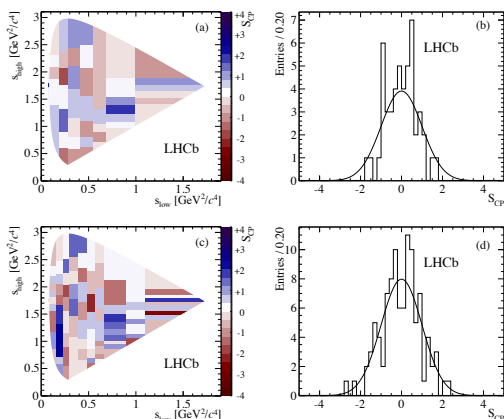


Figure 2. Distributions of S_{CP}^i across the D^+ Dalitz plot, with the adaptive binning scheme of uniform population for the total $D^+ \rightarrow \pi^-\pi^+\pi^+$ decays with (a) 49 and (c) 100 bins. The corresponding one-dimensional S_{CP}^i distributions (b) and (d) are shown with a standard normal function superimposed (solid line).

The unbinned method is based on the concept of nearest-neighbour events (kNN) in a combined D^+ and D^- sample to test whether they share the same parent distribution function [11, 12, 13]. A test statistic, T , is defined as the average fraction of like-charged neighbour pairs. For the null hypothesis of no CPV, this follows a Gaussian distribution

with predictable mean μ_T and variance σ_T^2 [8]. CPV can be detected as a deviation from this behaviour.

The kNN method is applied with the two region definitions (Fig. 3). The pull values of T and the corresponding p -values for the hypothesis of no CPV are shown in Fig. 4. All p -values are above 20%, consistent with no CP asymmetry.

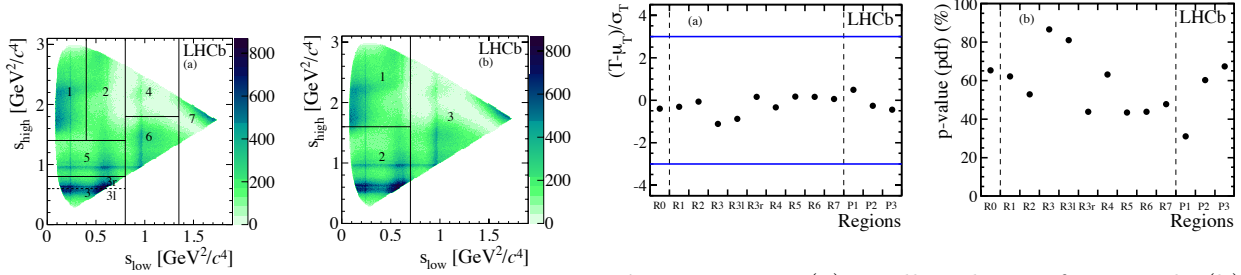


Figure 3. Dalitz plot for $D^+ \rightarrow \pi^- \pi^+ \pi^+$ candidates divided into (a) seven regions R1-R7 and (b) three regions P1-P3.

Figure 4. (a) Pull values of T and (b) the corresponding p -values for $D^+ \rightarrow \pi^- \pi^+ \pi^+$ candidates restricted to each region obtained the kNN method. The horizontal blue lines in (a) represents pull values -3 and $+3$. The region R0 corresponds to the full Dalitz plot.

5. Conclusions

Using data collected with the LHCb experiment in 2011 and 2012 $D^0 - \bar{D}^0$ oscillations are observed by evaluating the time-dependence of the ratio of $D^0 \rightarrow K^+ \pi^-$ and $D^0 \rightarrow K^- \pi^+$ decays. Assuming CP conservation, the mixing parameters are measured to be $x'^2 = (5.5 \pm 4.9) \times 10^{-5}$, $y' = (4.8 \pm 1.0) \times 10^{-3}$ and $R_D = (3.568 \pm 0.066) \times 10^{-3}$. Study of D^0 and \bar{D}^0 decays separately shows no evidence for CPV. The measurement of time-integrated difference in CP asymmetry between $D^0 \rightarrow K^- K^+$ and $D^0 \rightarrow \pi^- \pi^+$ decays also does not show evidence for direct CP violation. No evidence for CP violation is found in searches for CP asymmetries in three-body SCS decays $D^+ \rightarrow \pi^- \pi^+ \pi^+$.

References

- [1] S. Bianco, F. L. Fabbri, D. Benson and I. Bigi, *A Cicerone for the physics of charm*, *Riv.Nuovo Cim.* **26N7** (2003) 1-200.
- [2] B. Aubert *et al.* [BABAR Collaboration], *Evidence for D^0 -anti- D^0 Mixing*, *Phys.Rev.Lett.* **98** (2007) 211802.
- [3] M. Staric *et al.* [Belle Collaboration], *Evidence for $D^0 - \bar{D}^0$ Mixing*, *Phys.Rev.Lett.* **98** (2007) 211803.
- [4] T. Aaltonen *et al.* [CDF Collaboration], *Evidence for $D^0 - \bar{D}^0$ mixing using the CDF II Detector*, *Phys.Rev.Lett.* **100** (2008) 121802.
- [5] R. Aaij *et al.* [LHCb Collaboration], *Measurement of $D^0 - \bar{D}^0$ mixing parameters and search for CP violation using $D^0 \rightarrow K^+ \pi^-$ decays*, *Phys.Rev.Lett.* **111** (2013) 251801.
- [6] T. Aaltonen *et al.* [CDF Collaboration], *Measurement of CP-violating asymmetries in $D^0 \rightarrow \pi^+ \pi^-$ and $D^0 \rightarrow K^+ K^-$ decays at CDF*, *Phys.Rev.* **D85** (2012) 012009.
- [7] R. Aaij *et al.* [LHCb Collaboration], *Measurement of CP asymmetry in $D^0 \rightarrow K^- K^+$ and $D^0 \rightarrow \pi^- \pi^+$ decays*, *JHEP* **1407** (2014) 041.
- [8] R. Aaij *et al.* [LHCb Collaboration], *Search for CP violation in the decay $D^+ \rightarrow \pi^- \pi^+ \pi^+$* , *Phys.Lett.* **B728** (2014) 585.
- [9] R. Aaij *et al.* [LHCb Collaboration], *Search for CP violation in $D^+ \rightarrow K^- K^+ \pi^+$ decays*, *Phys.Rev.* **D84** (2011) 112008.
- [10] R. Aaij *et al.* [LHCb Collaboration], *Model-independent search for CP violation in $D^0 \rightarrow K^- K^+ \pi^- \pi^+$ and $D^0 \rightarrow \pi^- \pi^+ \pi^+ \pi^-$ decays*, *Phys.Lett.* **B726** (2013) 623.
- [11] N. Henze, *A multivariate two-sample test based on the number of nearest neighbor type coincidences*, *The Annals of Statistics* **16 No 2** (1988) 772.
- [12] M.F. Schilling, *Multivariate two-sample test based on the nearest neighbors*, *J.Am.Stat.Assoc* **81** (1986) 799.
- [13] M. Williams, *How good are your fits? Unbinned multivariate goodness-of-fit tests in high energy physics*, *JINST* **5** (2010) P09004.