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Measurements of mixing and CP violation in two body charm decays

Mark Smith on behalf of the LHCb collaboration

Abstract

Two-body charm decays provide an intriguing avenue of exploration in the search for new sources of CP violation. Four recent results concerning this subject from LHCb analyses of data collected in 2011 and 2012 are presented; all are consistent with CP conservation.

Keywords: Charm, mixing, CP violation, LHCb

1. Introduction

Charmed mesons provide the only sector where one would expect to find neutral meson mixing and CP violating transitions involving the up quark. They therefore provide an important environment in the search for new physics, complementing the bottom and strange decays. From the Standard Model one expects both mixing and CP violation in charm to be small. The degeneracy of the quark masses leads to sizeable GIM suppression and as the initial and final states involve only the first two quark generations, CP violating phases due to interactions with the third would need to be introduced via intermediate loops. New physics could enhance both the mixing and decay amplitudes.

Mixing in charm was discovered in 2007 through a combination of results from BABAR [1], Belle [2] and CDF [3]. In 2012 the first individual measurement of mixing in charm with greater than 5σ significance was made at LHCb [4], a result that has subsequently been updated and is discussed below. There have been no unambiguous signs of CP violation in the charm sector, either direct or indirect.

One defines the mass eigenstates of the neutral charm mesons in terms of the flavour states in the usual manner,

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

with $p = q = \frac{1}{\sqrt{2}}$ if there is no CP violation in mixing. The mixing parameters are

$$x = \frac{\Delta m}{\Gamma}, \quad y = \frac{\Delta\Gamma}{2\Gamma}, \tag{2}$$

where Δm and $\Delta\Gamma$ are the differences of the masses and lifetimes of the mass states. CP violation can can arise in mixing via different magnitudes of q and p,

$$\left|\frac{q}{p}\right|^{\pm 2} \approx 1 \pm A_m, \tag{3}$$

where A_m is the asymmetry in mixing. Alternatively the decay amplitudes may be different for D^0 and $\overline{D}^0$ leading to direct CP violation,

$$\left|\frac{\bar{A}_f}{A_f}\right|^{\pm 2} \approx 1 \pm A_d, \tag{4}$$

with A_d being the asymmetry in decay. Finally there may be interference between mixing and decay through a phase ϕ that is not 0 or a multiple of π. Collectively CP violation from mixing and interference are referred to as indirect CP violation, which for the CP asymmetry can be written as

$$a_{CP}^{ind} = -\frac{A_m}{2} y\cos\phi + x\sin\phi. \tag{5}$$

CP violating observables in charm feature contributions from both direct and indirect CP violation[5]; the extraction of the charm parameters is made through a combination of several complementary measurements.

Here four results are presented using data collected in 2011 and 2012 by the LHCb detector, comprised of 1fb^{-1} of proton-proton collisions at 7TeV and 2fb^{-1} at 8TeV respectively. D candidates are selected from two sources; they can be produced at the interaction point in which case they are referred to as prompt, or by the decay of B particles with an associated muon whereby they are given the moniker semi-leptonic. For prompt candidates the initial flavour of a neutral D^0 is ascertained by searching for the strong decay $D^{*+} \to D^0\pi^+$ (and its charge conjugate), the charge of the pion indicating the flavour. Semi-leptonic candidates are produced in the decay $\bar{B} \to D^0\mu^- X$ (again with the charge conjugate), the muon charge in this instance indicating the D^0 flavour.

2. Indirect CP violation

The first single measurement of mixing in charm came from the study of wrong-sign (WS) $D^0 \to K^+\pi^+$ decays with respect to the Cabibbo favoured right-sign (RS) $D^0 \to K^-\pi^+$ mode [4]. In the event of mixing the ratio of their yields develops with decay time t as

$$R(t) = \frac{N_{WS}(t)}{N_{RS}(t)} = R_D + \sqrt{R_D}y't + \frac{x'^2 + y'^2}{4}t, \quad (6)$$

where R_D is the ratio of the decay amplitudes. x' and y' are the mixing parameters modified by the strong phase between the Cabibbo favoured (CF) and doubly Cabibbo suppressed (DCS) transitions, δ.

The analysis of the prompt 2011 data set excluded the no mixing hypothesis with a significance of 9.1σ. The analysis was updated with the 2011 and 2012 combined data (again only prompt D^0) to include a search for CP violation [6]. The ratio $R(t)$ was measured separately for D^0 (R^+) and $\bar{D}^0$ (R^-) candidates giving access to indirect CP violation via

$$x'^{\pm} = \left(\frac{1 \pm A_m}{1 \mp A_m}\right)^{\frac{1}{4}} (x' \cos\phi \pm y' \sin\phi)$$
$$y'^{\pm} = \left(\frac{1 \pm A_m}{1 \mp A_m}\right)^{\frac{1}{4}} (x' \sin\phi \mp x' \sin\phi). \quad (7)$$

Additionally one can compare the extracted decay amplitude ratios $R_D^{\pm}$ to search for direct CP violation,

$$A_D = \frac{R_D^+ - R_D^-}{R_D^+ + R_D^-}. \quad (8)$$

$R^{\pm}(t)$ is fitted with three hypotheses: CP violation allowed, only indirect CP violation and no CP violation.

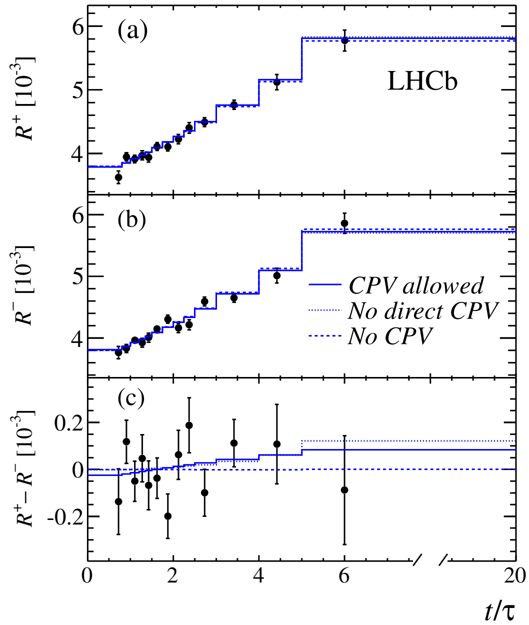

Figure 1: The time evolution of the ratio of WS to RS decays for D^0 tagged (top) and $\bar{D}^0$ tagged (middle) decays. Overlaid in the data are fits of $R(t)$ allowing for CP violation and without CP violation. The bottom plot shows the difference between the two, corrected for their efficiencies.

The fits are shown in Figures 1(a) and (b). The bottom plot presents the time evolution of the difference between R^+ and R^-. The hypotheses with and without CP violation fit the data equally well; the difference plot shows a flat line suggesting there is no CP violation in the mixing at this sensitivity. The results of the fit give $A_D = (-1.3 \pm 1.9)\%$ and $0.75 < \left|\frac{q}{p}\right| < 1.24$ and the 68% confidence level.

Contour plots of x'^2 and y' can be seen in Figure 2; the fit with no CP violation represents an improvement by a factor of ~ 2.5 with respect to the previous results for these variables[4].

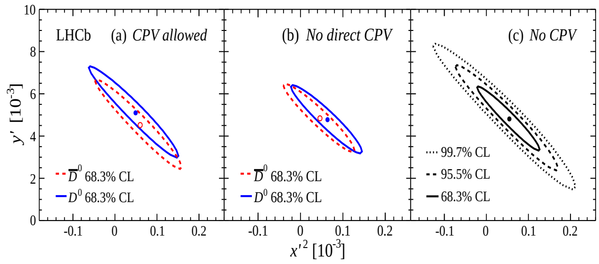

Figure 2: Contour plots of x'^2 and y' under the three fitted hypotheses.

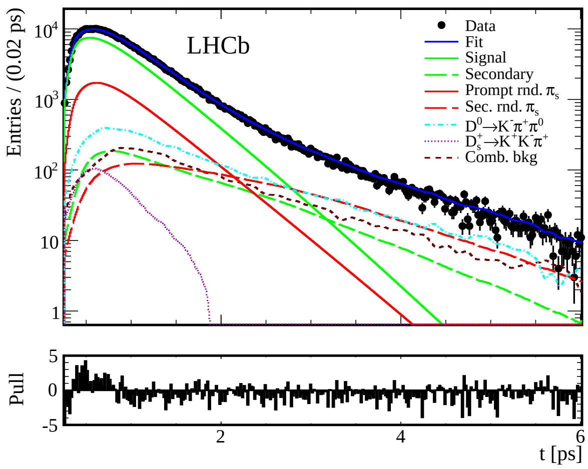

Figure 3: A fit to the measured decay times of $\bar{D}^0 \to K^+K^-$ candidates.

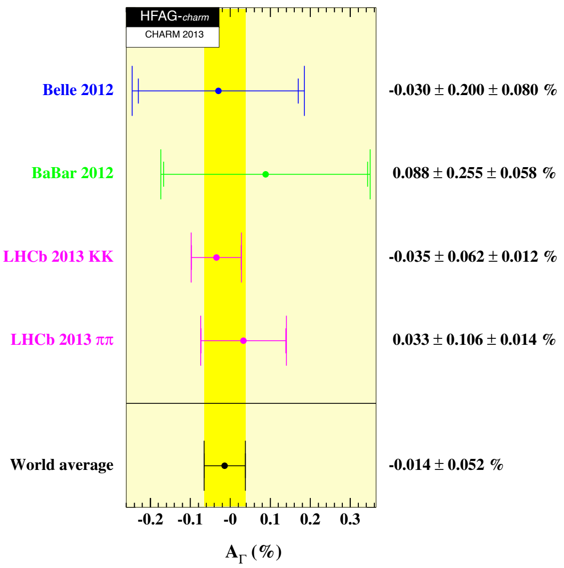

Figure 4: The HFAG average for A_Γ [9].

The observable A_Γ provides another method for probing indirect CP violation. It is defined as the difference in decay rates between D^0 and $\bar{D}^0$ decaying to a CP eigenstate, K^+K^- or $\pi^+\pi^-$;

$$A_\Gamma(KK) = \frac{\hat{\Gamma}\left(D^0 \to K^+K^-\right) - \hat{\Gamma}\left(\bar{D}^0 \to K^+K^-\right)}{\hat{\Gamma}\left(D^0 \to K^+K^-\right) + \hat{\Gamma}\left(\bar{D}^0 \to K^+K^-\right)} \approx \frac{A_m + A_d}{2} y \cos\phi - x \sin\phi. \quad (9)$$

This is mostly a measure of indirect CP violation as the term involving A_d is expected to be small. In the Standard Model A_Γ is expected to be small and roughly final state independent. New physics could enhance A_Γ or make the phase ϕ final state dependent. Therefore the two final states are measured independently.

The decay rates are extracted by measuring the effective lifetimes $\hat{\tau}$ ($\hat{\Gamma} = \frac{1}{\hat{\tau}}$) through a fit to the decay times of the D^0. The analysis was performed on $1 \mathrm{fb}^{-1}$ of data collected in 2011 using only prompt candidates. Lifetime acceptance biases introduced by the selection of the data are corrected for using the "swimming" method [7]. An example of the fitted decay time distribution for $\bar{D}^0 \to K^+K^-$ candidates is shown in Figure 3.

The results of are [8]

$$A_\Gamma(KK) = (-0.35 \pm 0.62_{stat} \pm 0.12_{syst}) \times 10^{-3}$$
$$A_\Gamma(\pi\pi) = (0.33 \pm 1.06_{stat} \pm 0.14_{syst}) \times 10^{-3}. \quad (10)$$

The two final states are consistent with each other and show no CP violation within the experimental uncertainties. The Heavy Flavour Averaging Group (HFAG)[9] average in Figure 4 shows that these results for A_Γ are the most precise to date by a significant margin. This is also the first time that the two final states have been presented separately.

The results from these analyses contribute to the extraction of parameters q and p in the HFAG fit for their relative magnitude and phase shown in Figure 5; as can be seen the fit is consistent with no indirect CP violation.

3. Direct CP violation in neutral charm decays

Direct CP violation can be measured with time integrated analyses of the same modes as A_Γ. The time-integrated asymmetries in yields of the decays to a final state (K^+K^- or $\pi^+\pi^-$) include spurious production and detection asymmetries as well as the physics asymmetry, A_{CP}, of interest:

$$A_{raw}(f) = \frac{N(D^0 \to f) - N(\bar{D}^0 \to f)}{N(D^0 \to f) + N(\bar{D}^0 \to f)} = A_{CP} + A^{prod} + A^{det}. \quad (11)$$

In order to negate these nuisances the difference between the asymmetries in K^+K^- and $\pi^+\pi^-$ is taken to

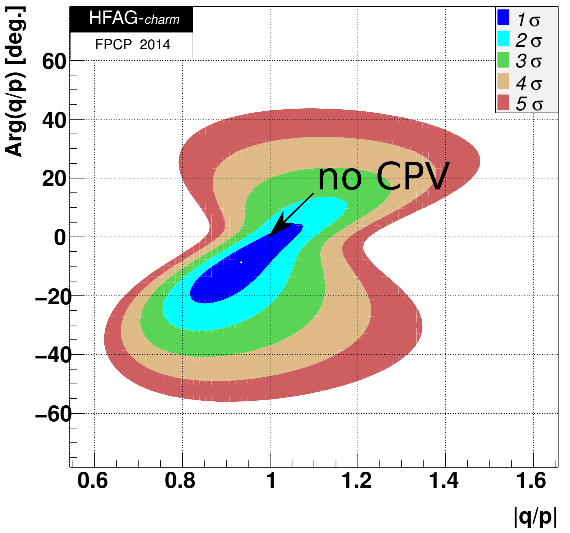

Figure 5: The HFAG fit for the relative magnitudes and phase of the parameters q and p, from May 2014. The no CP violation point has been highlighted and lies within the 1σ contour.

give the observable ΔA_{CP},

$$\begin{aligned}\Delta A_{CP} &= A_{KK} - A_{\pi\pi} \\ &\approx \Delta a_{CP}^{dir}\left(1 + y_{CP}\frac{\langle\bar{t}\rangle}{\tau}\right) + a_{CP}^{ind}\frac{\Delta\langle t\rangle}{\tau}, \end{aligned} \tag{12}$$

which is to a good approximation a measurement of direct CP violation.

An initial ΔA_{CP} measurement with 0.6fb^{-1} of the prompt 2011 data had indicated some tension with the CP conservation hypothesis [10], a result supported by CDF [11]. An update on the full 2011 data set supersedes that result and is more consistent with no CP violation [12],

$$\Delta A_{CP} = (-0.34 \pm 0.15_{stat} \pm 0.10_{syst})\%. \tag{13}$$

Additionally a ΔA_{CP} measurement has been carried out using semi-leptonic candidates from the whole 3fb^{-1} data set [13]. As with the prompt analysis the result is consistent with no CP violation:

$$\Delta A_{CP} = (+0.14 \pm 0.16_{stat} \pm 0.08_{syst})\%. \tag{14}$$

Having obtained ΔA_{CP} one may wish to disentangle the two individual asymmetries. To do so with the semi-leptonic analysis requires one to deal with the charged B production asymmetry, $A_{prod}(B)$, and the detection asymmetry of the tagging muon, $A_{det}(\mu)$. To that end the asymmetries of various Cabibbo favoured control modes are measured and combined.

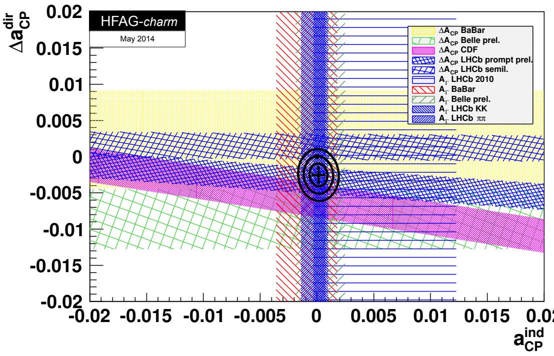

Figure 6: The HFAG fit for direct and indirect CP violation, from May 2014.

The asymmetry in the decay $\bar{B} \to D^0(K^-\pi^+)\mu^- X$ includes $A_{prod}(B)$ and $A_{det}(\mu)$ with a $K^-\pi^+$ detection asymmetry which can be accounted for through a combination of prompt $D^+ \to K^-\pi^+\pi^+$ and $D^+ \to \bar{K}^0\pi^+$. The use of $\bar{K}^0$ introduces another nuisance term due to kaon CP violation and regeneration in the material of the detector. The physics of these is well know and so using a careful detector simulation $A(\bar{K}^0)$ can be estimated.

Putting these together leads to

$$\begin{aligned} A_{CP}(KK) &= (-0.06 \pm 0.15_{stat} \pm 0.10_{syst})\% \\ A_{CP}(\pi\pi) &= (-0.20 \pm 0.19_{stat} \pm 0.10_{syst})\%. \end{aligned} \tag{15}$$

These represent the first LHCb measurement of individual charm asymmetries and are the most accurate to date. The LHCb prompt and semi-leptonic ΔA_{CP} and A_Γ are included in the HFAG combined fit for a_{CP}^{ind} and Δa_{CP}^{dir} shown in Figure 6. The efficacy of the LHCb results in constraining possible CP violation in charm is apparent.

4. Direct CP violation in charged charm decays

CP violation can be expected in charged two body charm decays, the measurement of which presents similar challenges to neutral decays with regards nuisance asymmetries. CP violation has been searched for in the singly Cabibbo suppressed prompt decays $D^\pm \to K_S^0 K^\pm$ and $D_s^\pm \to K_S^0\pi^\pm$ [14]. Unwanted asymmetries arise in the $D_{(s)}^\pm$ production, charged hadron detection and K_S^0 behaviour.

In a similar manner to ΔA_{CP} the nuisances can be negated by calculating the difference in asymmetries between modes, this time with some CF modes included.

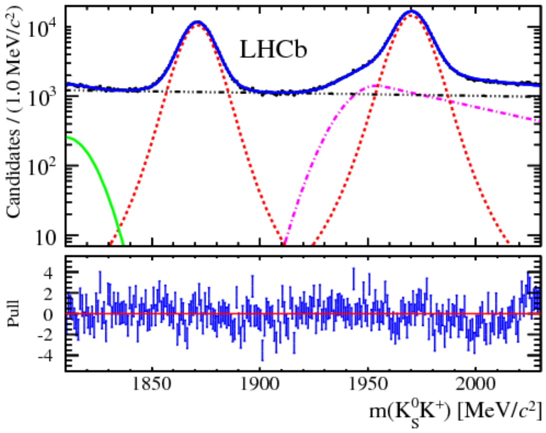

Figure 7: A fit to the reconstructed $K_S^0K^+$ invariant mass to extract the D^+ and D_s^+ yields. A low-mass background from mis-reconstructed multi-body decays is in green (solid) and a cross-feed from $D^\pm \to K_S^0\pi^\pm$ is represented by the magenta (dot-dashed) curve.

The single measured asymmetry is

$$A_{meas}(D^\pm_{(s)} \to K_S^0 h^\pm) \approx A_{CP}(D^\pm_{(s)} \to K_S^0 h^\pm) + A_{prod}(D^\pm_{(s)}) + A_{det}(h^\pm) + A(K^0/\overline{K}^0). \quad (16)$$

Using the Cabibbo favoured modes $D_s^\pm \to K_S^0K^\pm$ and $D^\pm \to K_S^0\pi^\pm$ and taking two differences the *double difference* is constructed which leaves the sum of the physics asymmetries:

$$\begin{aligned} A_{CP}^{DD} &= \left[A_{meas}^{D_s^\pm\to K_S^0\pi^\pm} - A_{meas}^{D_s^\pm\to K_S^0K^\pm}\right] \\ &- \left[A_{meas}^{D^\pm\to K_S^0\pi^\pm} - A_{meas}^{D^\pm\to K_S^0K^\pm}\right] - 2A_{K^0} \\ &= A_{CP}^{D^\pm\to K_S^0K^\pm} + A_{CP}^{D_s^\pm\to K_S^0\pi^\pm}. \end{aligned} \quad (17)$$

Additionally the individual asymmetries can be extracted via the Cabibbo favoured decay $D_s^\pm \to \phi\pi^\pm$ by

$$\begin{aligned} A_{CP}^{D^\pm\to K_S^0K^\pm} &= \left[A_{meas}^{D^\pm\to K_S^0K^\pm} - A_{meas}^{D_s^\pm\to K_S^0K^\pm}\right] \\ &- \left[A_{meas}^{D^\pm\to K_S^0\pi^\pm} - A_{meas}^{D_s^\pm\to \phi\pi^\pm}\right] - A_{K^0} \end{aligned} \quad (18)$$

and

$$A_{CP}^{D_s^\pm\to K_S^0\pi^\pm} = A_{meas}^{D_s^\pm\to K_S^0\pi^\pm} - A_{meas}^{D_s^\pm\to \phi\pi^\pm} - A_{K^0}. \quad (19)$$

The yields used to calculate these observables are extracted using a fit to the reconstructed invariant masses of the daughter particles, as shown for example in Figure 7. The measurement of these quantities with the full 3fb^{-1} data set yields

$$\begin{aligned} A_{CP}^{D^\pm\to K_S^0K^\pm} + A_{CP}^{D_s^\pm\to K_S^0\pi^\pm} &= (+0.41 \pm 0.49 \pm 0.26)\% \\ A_{CP}^{D^\pm\to K_S^0K^\pm} &= (+0.03 \pm 0.17 \pm 0.14)\% \\ A_{CP}^{D_s^\pm\to K_S^0\pi^\pm} &= (+0.38 \pm 0.46 \pm 0.17)\%, \end{aligned} \quad (20)$$

where the first uncertainty is statistical and the second is systematic. All three figures are consistent with CP conservation and represent the most precise measurement of CP violating asymmetries in $D^\pm_{(s)} \to K_S^0 h^\pm$ decays thus far.

5. Conclusions

From its first two full years of data taking LHCb has made the first individual measurement of charm mixing as well as several of the most precise measurements of CP violation in two-body charm decays. These have led to considerable improvements on the constraints for the values of the charm mixing and CP violation parameters. Thus far all results are consistent with CP conservation in charm.

There is much more to come from LHCb in the future with regard two-body charm measurements. From run 1 of the LHC a semi-leptonic A_Γ measurement is to follow, as are updates with the 2012 data of the prompt A_Γ and ΔA_{CP} results. Additionally one expects great improvements in precision with the data collected in run 2.

References

[1] B. Aubert, et al., Evidence for D^0-$\overline{D}^0$ Mixing, Phys. Rev. Lett. 98 (2007) 211802. doi:10.1103/PhysRevLett.98.211802.

[2] M. Starič, et al., Evidence for D^0-$\overline{D}^0$ Mixing, Phys. Rev. Lett. 98 (2007) 211803. doi:10.1103/PhysRevLett.98.211803.

[3] T. Aaltonen, et al., Evidence for $D^0 - \overline{D}^0$ Mixing Using the CDF II Detector, Phys. Rev. Lett. 100 (2008) 121802. doi:10.1103/PhysRevLett.100.121802.

[4] R. Aaij, et al., Observation of D^0–$\overline{D}^0$ Oscillations, Phys. Rev. Lett. 110 (2013) 101802. doi:10.1103/PhysRevLett.110.101802.

[5] M. Gersabeck, M. Alexander, S. Borghi, V. Gligorov, C. Parkes, On the interplay of direct and indirect CP violation in the charm sector, J.Phys. G39 (2012) 045005. arXiv:1111.6515, doi:10.1088/0954-3899/39/4/045005.

[6] R. Aaij, et al., Measurement of D^0-$\overline{D}^0$ Mixing Parameters and Search for CP Violation Using $D^0 \to K^+\pi^-$ Decays, Phys. Rev. Lett. 111 (2013) 251801. doi:10.1103/PhysRevLett.111.251801.

[7] R. Aaij, et al., Measurement of mixing and CP violation parameters in two-body charm decays, Journal of High Energy Physics 2012 (4). doi:10.1007/JHEP04(2012)129.

[8] R. Aaij, et al., Measurements of Indirect CP Asymmetries in $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ Decays, Phys. Rev. Lett. 112 (2014) 041801. doi:10.1103/PhysRevLett.112.041801.

[9] Y. A. et al., Averages of b-hadron, c-hadron, and tau-lepton properties as of early 2012, online update at http://www.slac.stanford.edu/xorg/hfagarXiv:1207.1158.

[10] R. Aaij, et al., Evidence for CP Violation in Time-Integrated $D^0 \to h^-h^+$ Decay Rates, Phys. Rev. Lett. 108 (2012) 111602. doi:10.1103/PhysRevLett.108.111602.

[11] T. Aaltonen, et al., Measurement of the Difference in CP-Violating Asymmetries in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ Decays at CDF, Phys. Rev. Lett. 109 (2012) 111801. doi:10.1103/PhysRevLett.109.111801.

[12] A search for time-integrated CP violation in $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decaysLinked to LHCb-ANA-2012-034.

[13] R. Aaij, et al., Measurement of CP asymmetry in D 0 K K + and D 0 + decays, Journal of High Energy Physics 2014 (7). doi:10.1007/JHEP07(2014)041.
URL http://dx.doi.org/10.1007/JHEP07%282014%29041

[14] R. Aaij, et al., Search for CP violation in $D^\pm \to K^0_S K^\pm$ and $D^\pm_s \to K^0_S \pi^\pm$ decays, Tech. Rep. arXiv:1406.2624. LHCB-PAPER-2014-018. CERN-PH-EP-2014-125, CERN, Geneva (Jun 2014).