Searches for $CP$ violation in charm at LHCb

Paras P. Nair$^\dagger$

H.H. Wills Physics Laboratory
University of Bristol, Bristol BS8 1TL, United Kingdom

LHCb has collected the world’s largest sample of charmed hadrons. This sample is used to search for direct and indirect $CP$ violation in charm. Recent and updated measurements from several decay modes are presented.

PRESENTED AT

The 7th International Workshop on Charm Physics
(CHARM 2015)
Detroit, Michigan, U.S.A., 18-22 May, 2015

$^\dagger$on behalf of the LHCb collaboration.
1 Introduction

Studies of $CP$ violation are a primary goal of the LHCb Experiment \cite{1} at CERN. $CP$ violation in charm decays is expected to be very small in the Standard Model \cite{2,3}. However, asymmetries at a few times $10^{-3}$ within the Standard Model cannot be excluded \cite{4,6}. A significant excess of $CP$ violation with respect to the theoretical predictions would be a signature of physics beyond the Standard Model. The study of $CP$ violation in singly Cabibbo-suppressed (SCS) charm decays is uniquely sensitive to physics beyond the Standard Model, in particular through new contributions to $\Delta C = 1$ strong penguin and chromomagnetic dipole operators \cite{3}. The analysis of the following decay channels allows us several opportunities to probe both integrated and localized $CP$ violation in different regions of decay phase space. Large $CP$ violation has been observed in regions of meson decay phase space not associated to a resonance, further motivating localized searches \cite{7}. To date, no $CP$ violation has been observed in the charm quark system.

2 Searches for direct $CP$ violation in charm

2.1 $D_{(s)}^+ \rightarrow K_S^0 h^+$

The measured time-integrated $CP$ asymmetry for a meson ($Q$) decay to a final state $f$ can be given by:

$$A_{\text{raw}}(Q \rightarrow f) = \frac{N(Q \rightarrow f) - N(\bar{Q} \rightarrow \bar{f})}{N(Q \rightarrow f) + N(\bar{Q} \rightarrow \bar{f})},$$  \hspace{1cm} (1)

where $N$ indicates the number of reconstructed events of a given decay after background subtraction. We study the decays $D_{(s)}^+ \rightarrow K_S^0 h^+$, where $h = \pi$ or $K$. $CP$ violation is only expected to be measurable in the SCS subset of these decays. The analysis is performed using promptly produced $D$ mesons from the full 3 fb$^{-1}$ LHCb Run 1 data sample, which consists of 1 fb$^{-1}$ of proton-proton collision data taken in 2011 at $\sqrt{s} = 7$ TeV, and 2 fb$^{-1}$ of proton-proton collision data taken in 2012 at $\sqrt{s} = 8$ TeV.

These measured (or “raw”) asymmetries are a sum of several independent asymmetries:

$$A_{\text{raw}}(K_S^0 h^+) = A_{\text{CP}}(K_S^0 h^+) + A_P(D_{(s)}^+) + A_D(h^+) + A_{\text{CP/int}},$$  \hspace{1cm} (2)

where $A_{\text{CP}}$ is the physical $CP$ asymmetry, $A_P$ is the production asymmetry of the decay particle, $A_D$ is the detection asymmetry of the charged daughter hadron, and $A_{\text{CP/int}}$ represents the detection asymmetry between a $K^0$ and a $\bar{K}^0$, due to the
presence of mixing and CP violation in the kaon system and the different interaction rates of $K^0$ and $\bar{K}^0$ in the detector material \[5\].

The quantities of interest can then be determined by forming differences that result in the cancellation of production and detection asymmetries:

$$ A_{CP}(D^+_S \rightarrow K^0_S \pi^+) = A_{raw}(D^+_s \rightarrow K^0_s \pi^+) - A_{raw}(D^+_s \rightarrow \phi \pi^+) $$ (3)

and

$$ A_{CP}(D^+ \rightarrow K^0_S K^+) = (A_{raw}(D^+ \rightarrow K^0_S K^+) - A_{raw}(D^+_s \rightarrow K^0_S \phi^+)) - (A_{raw}(D^+ \rightarrow K^0_S \pi^+) - A_{raw}(D^+_s \rightarrow \phi \pi^+)), $$ (4)

where we assume the Standard Model expectation of no CP violation in the Cabibbo-favored (CF) $D^+_s \rightarrow \phi \pi^+$ decay mode.

As a cross check, a double difference of asymmetries largely insensitive to production and instrumental asymmetries may also be formed:

$$ A_{DD}^{CP} = (A_{raw}(D^+_s \rightarrow K^0_S \pi^+) - A_{raw}(D^+_s \rightarrow K^0_S K^+)) - (A_{raw}(D^+_s \rightarrow K^0_S \pi^+) - A_{raw}(D^+_s \rightarrow \phi \pi^+)), $$ (5)

In Equations 3-5 above, the neutral kaon asymmetry is not shown, but is accounted for in the final results. As the production and detection asymmetries depend on the kinematic distributions, weights are assigned to the candidates such that the kinematic distributions are equalized.

The analysis is performed separately for 2011 and 2012 data, and for both LHCb magnet polarities; consistent results are obtained. The combined results \[9\]

$$ A_{CP}(D^+ \rightarrow K^0_S K^+) = (0.03 \pm 0.17\text{(stat)} \pm 0.14\text{(syst)})\%, $$ (6)

$$ A_{CP}(D^+_s \rightarrow K^0_S \pi^+) = (0.38 \pm 0.46\text{(stat)} \pm 0.17\text{(syst)})\%, $$ (7)

and

$$ A_{CP}(D^+ \rightarrow K^0_S K^+) + A_{CP}(D^+_s \rightarrow K^0_S \pi^+) = (0.41 \pm 0.49\text{(stat)} \pm 0.26\text{(syst)})\%, $$ (8)

show no indication of CP violation. These are the most precise measurements of these quantities.

### 2.2 $D^0 \rightarrow h^+h^-$ ($\Delta A_{CP}$)

A search for a time-integrated CP asymmetry in $D^0 \rightarrow h^+h^-$ decays is performed using the full LHCb Run 1 data sample (3 fb$^{-1}$). The flavor of the initial $D^0$ state
is tagged by the charge of the muon in semileptonic $B \to D^0 \mu^- \overline{\nu}_\mu X$ decays, where $B$ is a $B^-$ or $B^0$. The measured asymmetry for tagged neutral $D$ mesons to a $CP$ conjugate final state $f$ is given by:

$$A_{\text{raw}}(f) = \frac{N(B \to D^0 \mu^- X') - N(B \to D^0 \mu^+ X')}{N(B \to D^0 \mu^- X') + N(B \to D^0 \mu^+ X')}$$

(9)

where $N$ indicates the number of reconstructed events of a given decay after background subtraction and $X'$ represents the set of undetected final state particles from the semileptonic $B$ decay.

The measured asymmetry is a sum of the physical $CP$ asymmetry ($A_{CP}(f)$), the production asymmetry ($A_P(B)$) and detection asymmetry ($A_D(\mu)$):

$$A_{\text{raw}}(f) = A_{CP}(f) + A_P(B) + A_D(\mu).$$

(10)

An experimentally robust variable may be constructed, $\Delta A_{CP}$, by taking the difference of the measured asymmetries in $D^0 \to K^+ K^-$ and $D^0 \to \pi^+ \pi^-$ decays:

$$\Delta A_{CP} = A_{\text{raw}}(KK) - A_{\text{raw}}(\pi\pi),$$

(11)

as the production and the muon detection asymmetries cancel to first order.

Alternatively, for extracting $A_{CP}(KK)$, the detection and production asymmetries can be measured using CF $B \to D^0(\to K^- \pi^+) \mu^- X$ decays where no $CP$ violation is expected. An additional detection asymmetry, $A_D(K\pi)$, arises due to the different interaction rates of the charged kaon with matter. To remove this asymmetry, the CF control channels $D^+ \to K^- \pi^+ \pi^+$ and $D^+ \to \overline{K}^0 \pi^+$ (for which we assume negligible $CP$ violation) are used. In the $D^+ \to \overline{K}^0 \pi^+$ decays, $A_{CP/int}$ is estimated from simulation and subtracted from the measured asymmetry. Once $\Delta A_{CP}$ and $A_{CP}(KK)$ are measured, the individual asymmetry $A_{CP}(\pi\pi) = \Delta A_{CP} - A_{CP}(KK)$ can be computed.

The analysis is performed separately for the 2011 and the 2012 data, and for the two magnet polarities; consistent results are obtained. The combined results for the asymmetries $[8]$:

$$\Delta A_{CP} = (+0.14 \pm 0.16(\text{stat}) \pm 0.08(\text{syst}))\%,$$

(12)

$$A_{CP}(KK) = (-0.06 \pm 0.15(\text{stat}) \pm 0.10(\text{syst}))\%,$$

(13)

and, with correlation $\rho = 0.28$,

$$A_{CP}(\pi\pi) = (-0.20 \pm 0.19(\text{stat}) \pm 0.10(\text{syst}))\%,$$

(14)

are compatible with $CP$ conservation.

The $A_{CP}(hh)$ asymmetries are the most precise measurement of these individual asymmetries to date. The precision of $\Delta A_{CP}$ is comparable to the preliminary result for $\Delta A_{CP}$ measured using prompt $D^0$ decays reconstructed in 1 fb$^{-1}$ of LHCb Run 1 data from 2011 $[10]$.  

3
2.3 $D^0 \to \pi^+\pi^-\pi^0$ (Energy Test)

The energy test [11] is an unbinned model-independent statistical method than can be used to search for time-integrated $CP$ violation in $D^0 \to \pi^-\pi^+\pi^0$ decays. This method relies on the comparison of $D^0$ and $\bar{D}^0$ flavor samples and is sensitive to $CP$ violation localized in the phase-space of the multi-body final state.

The flavor of the prompt $D^0$ is tagged by the charge of the slow pion in the decay $D^* \to D^0\pi_s$. For the reconstruction of the $D^0$, two categories of reconstructed neutral pions are used: pions for which both final state photons are reconstructed separately (resolved pions), as well as pions that have higher momentum (typically $p_T > 2$ GeV/$c$) and thus a smaller opening angle of the two photons (merged pions).

The energy test is used to assign a $p$-value for a non-zero $CP$ violation hypothesis. In this method, a test statistic $T$ is used to compare the average distances based on the metric function $\psi$. The test statistic is defined as

$$T = \sum_{i,j>i} \frac{\psi_{ij}}{n(n-1)} + \sum_{i,j>i} \frac{\psi_{ij}}{n(n-1)} - \sum_{i,j} \frac{\psi_{ij}}{nn},$$  \hspace{1cm} (15)$$

and the metric function $\psi_{ij} \equiv \psi(d_{ij}) = e^{-d_{ij}^2/2\sigma^2}$ is chosen as a Gaussian function with a tunable parameter $\sigma$. $T$ compares the average distances of pairs of events belonging to two samples of opposite flavor. The normalization factor removes the impact of global asymmetries. The distance between two points in phase space is given by $d_{ij} = (m_{12}^2 - m_{12}^2, m_{23}^2 - m_{23}^2, m_{13}^2 - m_{13}^2)$, where the subscripts $\{1, 2, 3\}$ indicate the final-state particles.

If there is $CP$ violation, $T$ is expected to be larger than zero. This technique calculates a $p$-value under the hypothesis of $CP$ symmetry by comparing the nominal $T$ value observed in data to a distribution of $T$ values obtained from permutation samples, where the flavor of the $D^0$ is randomly reassigned to simulate samples without $CP$ violation. The $p$-value for the no $CP$ violation hypothesis is obtained as the fraction of permutation $T$ values greater than the nominal $T$ value in the data.

We study the data sample of 2 fb$^{-1}$ collected by LHCb during 2012, and find a $p$-value of $(2.6 \pm 0.5) \times 10^{-2}$ [12]. This result is based on 1000 permutations. The data sample has been split according to various criteria to test the stability of the results. Analyses of sub-samples with opposite magnet polarity, with different trigger configurations, and with fiducial selection requirements removing areas of high local asymmetry of the tagging soft pion from the $D^{*+}$ decay all provide consistent results. Various checks have been performed to ensure there are no asymmetries arising from background events or detector related asymmetries. Varying the metric parameter $\sigma$ results in similar $p$-values at the $10^{-2}$ level.

This analysis provides the world’s best sensitivity from a single experiment to local $CP$ violation in $D^0 \to \pi^-\pi^+\pi^0$ decays.
2.4 $D^0 \rightarrow K^+K^-\pi^+\pi^-$ (Triple product asymmetries)

Multi-body $D$ decays are sensitive to $CP$ violation due to the interference of several resonances across the multi-body phase space. In $D^0 \rightarrow K^+K^-\pi^+\pi^-$ decays, triple products of final state particle momenta in the $D^0$ rest frame, defined as $C_T \equiv \vec{p}_{K^+} \cdot (\vec{p}_{\pi^+} \times \vec{p}_{\pi^-})$ and $\overline{C}_T \equiv \vec{p}_{K^-} \cdot (\vec{p}_{\pi^-} \times \vec{p}_{\pi^+})$ for $D^0$ and $\overline{D}^0$ mesons, respectively, are quantities which are $P$-odd (and $T$-odd). The decay rate asymmetries:

$$A_T \equiv \frac{\Gamma(C_T > 0) - \Gamma(C_T < 0)}{\Gamma(C_T > 0) + \Gamma(C_T < 0)} \quad \overline{A}_T \equiv \frac{\Gamma(-\overline{C}_T > 0) - \Gamma(-\overline{C}_T < 0)}{\Gamma(-\overline{C}_T > 0) + \Gamma(-\overline{C}_T < 0)}$$

are thus sensitive to $CP$ violation. However, final state interactions significantly alter the measured asymmetries, and so the difference $a_{CP}^{T-odd} \equiv \frac{1}{2}(A_T - \overline{A}_T)$ is used to access the $CP$ asymmetry of the $D^0$ meson by canceling final state interaction effects.

The observable $a_{CP}^{T-odd}$ is, by definition, insensitive to production and detection asymmetries, and is thus very robust against systematic uncertainties. Using the full LHCb Run 1 data sample (3 fb$^{-1}$), the phase space integrated measurements of the asymmetries are $[13]$:

$$A_T = (-7.18 \pm 0.41(stat) \pm 0.13(syst))\%,$$  \hspace{1cm} \hspace{1cm} (17)

$$\overline{A}_T = (-7.55 \pm 0.41(stat) \pm 0.12(syst))\%,$$  \hspace{1cm} \hspace{1cm} (18)

and

$$a_{CP}^{T-odd} = ( 0.18 \pm 0.29(stat) \pm 0.04(syst))\%.$$  \hspace{1cm} \hspace{1cm} (19)

These results show no evidence of global $CP$ violation in these decays, but achieve a significant improvement in precision over previous measurements $[14]$.

The same measurements are also performed in 32 bins of the five-dimensional phase space. The asymmetries are extracted in each bin and $a_{CP}^{T-odd}$ calculated. A $\chi^2$ test for consistency across the phase space is performed, yielding a $p$-value of 74%. Thus there is no evidence for direct local $CP$ violation in this decay.

Similarly, binning in the decay time of the $D^0$ candidates and performing the same test gives sensitivity to indirect $CP$ violation. This yields a $p$-value of 72%; no evidence for indirect $CP$ violation was found.

3 Searches for indirect $CP$ violation in charm

3.1 $D^0 \rightarrow h^+h^-$ ($A_T$)

A measurement of the indirect $CP$ violation in $D^0$ mixing can be performed in the study of two-body hadronic charm decays to $CP$ eigenstates ($D^0 \rightarrow K^+K^-$ or...
Figure 1: Raw CP asymmetry as a function of decay time for $D^0 \rightarrow K^+ K^-$ decays (left) and of $D^0 \rightarrow \pi^+ \pi^-$ decays (right), and corresponding pull plots $^{[15]}$.  

$D^0 \rightarrow \pi^+ \pi^-$. It can be evaluated by the asymmetry in the effective lifetimes ($\tau$) of flavor-tagged decays and expressed by the following equation with the assumption of negligible direct CP-violating contribution:

$$A_{\Gamma} = \frac{\tau(D^0 \rightarrow f) - \tau(D^0 \rightarrow \bar{f})}{\tau(D^0 \rightarrow f) + \tau(D^0 \rightarrow \bar{f})} \approx \frac{1}{2} A_m \cos \phi - x \sin \phi$$  \hspace{1cm} (20)$$

where $A_m$ is defined by $|q/p|^{\pm 2} \approx 1 \pm A_m$. A measurement of $A_{\Gamma}$ differing significantly from zero is a manifestation of indirect CP violation as it requires a non-zero value for $A_m$ or $\phi = \text{arg}(q/p)$.

A measurement of $A_{\Gamma}$ at LHCb is performed using 3 fb$^{-1}$ of data from the full LHCb Run 1 data sample $^{[15]}$. In this analysis, $D^0$ decays are obtained from $B \rightarrow D^0 \mu^- \nu_\mu X$ decays and the neutral $D$ meson is tagged by the charge of the muon. $A_{\Gamma}$ is determined through a $\chi^2$ fit to the time-dependent raw CP asymmetry $A_{raw CP}^t(t)$:

$$A_{raw CP}^t(t) \approx A_D - A_{\Gamma}\frac{t}{\tau}$$  \hspace{1cm} (21)$$

The raw CP asymmetry is determined from simultaneous fits to $m_{h^+h^-}$ in bins of decay time for both $D^0$ and $\bar{D}^0$ samples, as seen in Figure 1.

Systematic uncertainties include uncertainty in the $D^0$ mass fit model, the decay time resolution, mixing in the beauty quark system, detection and production asymmetries, and the time-dependent efficiency. The main contributions to the systematic uncertainty result from the mistag probability (the probability that the neutral $D$ meson was tagged with the wrong flavor) and the mistag asymmetry (differences in positive and negative muon mistag probability), which are studied using a control sample of $D^0 \rightarrow K^- \pi^+$ decays. The mistag asymmetry is the dominant contribution to the systematic uncertainty.
We find:

\[ A_\Gamma(K\bar{K}) = (-0.134 \pm 0.077^{+0.026}_{-0.034})\% \]  
\[ A_\Gamma(\pi\pi) = (-0.092 \pm 0.145^{+0.025}_{-0.033})\% , \]

where the uncertainties are statistical and systematic, respectively. This measurement is consistent with no indirect CP violation in the charm system, and has comparable precision to LHCb’s previous result using neutral \( D \) mesons from prompt \( D^* \) decays obtained from 1 fb\(^{-1} \) of LHCb Run 1 data from 2011 [16].

### 3.2 “Wrong-sign” \( D^0 \to K\pi \) (CP violation via mixing)

At LHCb, charm mixing parameters are determined by the time-dependent ratio of \( D^0 \to K^+\pi^- \) (“wrong” sign, WS) to \( D^0 \to K^-\pi^+ \) (“right sign”, RS) decay rates. The RS decay rate is dominated by its CF amplitude. The WS rate arises from the interfering amplitudes of the doubly Cabibbo-suppressed decay (DCS) and the CF decay following \( D^0 - \bar{D}^0 \) oscillation.

Assuming no CP violation and small charm mixing parameters (\( |x| \) and \( |y| \ll 1 \)), this ratio is:

\[ R(t) \approx R_D + \sqrt{R_D} y' \frac{t}{\tau} + \frac{x'^2 + y'^2}{4} \left( \frac{t}{\tau} \right)^2 \]  
\[ (24) \]

where \( x' = x \cos \delta + y \sin \delta \), \( y' = y \cos \delta - x \sin \delta \), \( R_D \) is the ratio of suppressed-to-favored decay rates, and \( \delta \) is the strong phase difference between the DCS decays and the CF decays \( \left( \mathcal{A}(D^0 \to K^+\pi^-)/\mathcal{A}(D^0 \to K^-\pi^+) = -\sqrt{R_D} e^{-i\phi} \right) \).

We can search for CP violation in these decays by comparing the time-dependent ratios evaluated separately for \( D^0 \) and \( \bar{D}^0 \). A difference in the \( R_D \) parameter for \( D^0 \) and \( \bar{D}^0 \) would be a sign of direct CP violation, while a difference in \( x'^2 \) and \( y' \) parameters would imply indirect CP violation (\( |q/p| \neq 1 \) or \( \phi \neq 0 \)). The data are fit under three hypotheses: CP is conserved, only an indirect CP contribution is allowed, and both direct and indirect CP contributions are allowed.

The full LHCb Run 1 data sample (3 fb\(^{-1} \)) is used to perform these measurements. The sample is obtained from \( D^{\pm} \to D^0\pi^{\mp} \) decays, which allow the determination of the flavor of the neutral \( D \) meson. Assuming CP conservation, the mixing parameters are measured to be \( R_D = (3.568 \pm 0.058 \pm 0.033) \cdot 10^{-3} \), \( y' = (4.8 \pm 0.8 \pm 0.5) \cdot 10^{-3} \) and \( x'^2 = (5.5 \pm 4.2 \pm 2.6) \cdot 10^{-5} \) where the first uncertainty is statistical and the second systematic [17]. In the other scenarios, the direct CP asymmetry is \( A_D = (-0.7 \pm 1.9)\% \), and the magnitude of \( q/p \) is determined to be 0.75 < \( |q/p| < 1.24 \) and 0.67 < \( |q/p| < 1.52 \) at 68.3% and 95.5% confidence level (C.L.), respectively. The results of the measurements of mixing parameters, and of the confidence regions, are shown in Figure 2 for the three scenarios. The results are compatible with CP conservation and provide the most stringent bounds on the parameter \( |q/p| \) from a single experiment.
Figure 2: Two-dimensional confidence regions in the ($x'^2$, $y'$) plane obtained (a) allowing both direct and indirect $CP$ violation, (b) assuming no direct $CP$ violation and (c) assuming $CP$ conservation. The solid (dashed) curves in (a) and (b) indicate the contours of the mixing parameters associated with $D^0$ ($\bar{D}^0$) decays. The solid, dashed and dotted curves in (c) indicate the contours of $CP$-averaged mixing parameters at 68.3%, 95.5% and 99.7% C.L. The best-fit value is shown with a point [17].

References

[1] A. Alves et al. The LHCb Detector at the LHC. *JINST*, 3:S08005, 2008.
[2] S. Bianco, F.L. Fabbri, D. Benson, and I. Bigi. A Cicerone for the physics of charm. *Riv.Nuovo Cim.*, 26N7:1–200, 2003.
[3] Y. Grossman, A.L. Kagan, and Y. Nir. New physics and $CP$ violation in singly Cabibbo suppressed $D$ decays. *Phys.Rev.*, D75:036008, 2007.
[4] T. Feldmann, S. Nandi, and A. Soni. Repercussions of Flavour Symmetry Breaking on $CP$ Violation in $D$-Meson Decays. *JHEP*, 1206:007, 2012.
[5] J. Brod, A.L. Kagan, and J. Zupan. Size of direct $CP$ violation in singly Cabibbo-suppressed $D$ decays. *Phys.Rev.*, D86:014023, 2012.
[6] B. Bhattacharya, M. Gronau, and J.L. Rosner. $CP$ asymmetries in singly-Cabibbo-suppressed $D$ decays to two pseudoscalar mesons. *Phys.Rev.*, D85:054014, 2012.
[7] R. Aaij et al. Measurements of $CP$ violation in the three-body phase space of charmless $B^\pm$ decays. *Phys.Rev.*, D90(11):112004, 2014.
[8] R. Aaij et al. Measurement of $CP$ asymmetry in $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays. *JHEP*, 07:041, 2014.
[9] R. Aaij et al. Search for CP violation in $D^\pm \rightarrow K_S^0K^\pm$ and $D_s^\pm \rightarrow K_S^0\pi^\pm$ decays. JHEP, 10:25, 2014.

[10] R. Aaij et al. A search for time-integrated CP violation in $D^0 \rightarrow K^-K^+$ and $D^0 \rightarrow \pi^-\pi^+$ decays. LHCb-CONF-2013-003, 2013.

[11] M. Williams. Observing CP Violation in Many-Body Decays. Phys. Rev., D84:054015, 2011.

[12] R. Aaij et al. Search for CP violation in $D^0 \rightarrow \pi^-\pi^+\pi^0$ decays with the energy test. Phys. Lett., B740:158, 2015.

[13] R. Aaij et al. Search for CP violation using $T$-odd correlations in $D^0 \rightarrow K^+K^-\pi^+\pi^-$ decays. JHEP, 10:005, 2014.

[14] Y. Amhis et al. Averages of $b$-hadron, $c$-hadron, and $\tau$-lepton properties as of summer 2014. arXiv:1412.7515, 2014.

[15] R. Aaij et al. Measurement of indirect CP asymmetries in $D^0 \rightarrow K^-K^+$ and $D^0 \rightarrow \pi^-\pi^+$ decays using semileptonic $B$ decays. JHEP, 04:043, 2015.

[16] R. Aaij et al. Measurements of indirect CP asymmetries in $D^0 \rightarrow K^-K^+$ and $D^0 \rightarrow \pi^-\pi^+$ decays. Phys. Rev. Lett., 112(4):041801, 2014.

[17] R. Aaij et al. Measurement of $D^0 - \overline{D}^0$ Mixing Parameters and Search for CP Violation Using $D^0 \rightarrow K^+\pi^-$ Decays. Phys. Rev. Lett., 111(25):251801, 2013.