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# $CP$ violation in $D$ meson decays at hadron colliders

S. Perazzini
*INFN, Sezione di Bologna - Bologna, Italy*

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**Summary.** — The search for $CP$ violation in charmed meson decays represents an important test of the Standard Model and hence a promising sector where to look for New Physics. In this paper, the first observation of $D^0$ mixing with a significance of more than 5 standard deviations performed by a single experiment is presented. The measured mixing parameters are: $R_D = (3.52 \pm 0.15) \times 10^{-3}$, $y' = (7.2 \pm 2.4) \times 10^{-3}$, $x'^2 = (-0.09 \pm 0.13) \times 10^{-3}$. Furthermore, the recent measurements of the difference between the $CP$ asymmetries of the $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays ($\Delta A_{CP}$) are discussed.

PACS 12.15.Hh – Determination of Cabibbo-Kobayashi & Maskawa (CKM) matrix.
PACS 13.25.Ft – Decays of charmed mesons.

## 1. – Introduction

The non-invariance of the weak interactions with respect to the combined application of charge conjugation ($C$) and parity ($P$) transformations is explained within the Standard Model (SM), by the Cabibbo-Kobayashi-Maskawa (CKM) mechanism [1]. Despite its great success in describing experimental observations in the mesons decays, the SM predicts a size of $CP$ violation which is not sufficient to explain the observed cosmological imbalance between matter and anti-matter in our Universe. Therefore some new interactions at very high energies must give rise to new sources of $CP$ violation. Nowdays $CP$ violation is well established in $K^0$, $B^0$ and $B_s^0$ meson systems, but has never been observed in charmed meson decays, since the expected amount of $CP$ violation in this sector is generally expected to be much smaller than 1% [2]. Only very recently experimental sensitivity approached the necessary level to probe the charm sector, in fact first evidence of $D^0$ mixing was recently reported [3], as well as a first evidence at 3.5 standard deviations significance for direct $CP$ violation in two-body, singly-Cabibbo-suppressed, $D^0$ decays [4]. In this short report we present a summary of recent experimental results on $CP$ violation in the charm sector, obtained at hadron colliders.

## 2. – First observation of $D^0$ mixing

Evidence of $D^0$ mixing has been reported by three experiments using different decay channels, but only the combination of these measurements proves the presence of $D^0$ oscillations with significance of more than $5\sigma$. Thanks to the large charm production cross-section in $pp$ collisions at 7 TeV and to its excellent capabilities in triggering, reconstructing and selecting hadronic final states, the LHCb experiment [5] collected unprecedented samples of $D$-meson hadronic decays during the 2011 LHC run. Such a sample, corresponding to $1\,\text{fb}^{-1}$ of integrated luminosity, has been used to search for $D^0$ oscillations, by measuring the time-dependent ratio between the doubly-Cabibbo-suppressed (DCS) $D^0 \to K^+\pi^-$ and the Cabibbo-favoured (CF) $D^0 \to K^-\pi^+$ decay rates. Charge-conjugate states are implied throughout, unless explicitly stated. In order to distinguish the two decays, the $D^0$ flavour at the production is tagged using the charge of the low-momentum pion ($\pi_s^+$) in the $D^{*+} \to D^0\pi_s^+$ decay. Due to the much larger branching ratio the $D^{*+} \to D^0(\to K^-\pi^+)\pi_s^+$ process will be referred to as the Right-Sign (RS) decay, whereas the $D^{*+} \to D^0(\to K^+\pi^-)\pi_s^+$ process will be labeled as Wrong-Sign (WS) decay. The parameters governing the $D^0$ oscillations are the mass difference ($x$) and the decay width difference ($y$) between the two $D^0$ mass eignstate. Assuming small values for $x$ and $y$ ($x, y \ll 1$) and negligible $CP$ violation, the ratio between WS and RS decay rates can be approximated by

$$R(t) = \frac{\Gamma_{WS}}{\Gamma_{RS}} \approx R_D + \sqrt{R_D}y'\frac{t}{\tau} + \frac{x'^2 + y'^2}{4}\left(\frac{t}{\tau}\right)^2,$$

where $t$ is the decay time, $\tau$ is the $D^0$ lifetime, $R_D$ is the ratio between the DCS and CF decay rates, $x'$ and $y'$ are the mixing parameters rotated by the strong phase difference between the DCS and CF amplitudes. The analysis strategy consists in separating the sample into intervals of $t/\tau$ and determining the yields of the WS and RS decays by means of fits to the $D^0\pi_s^+$ invariant mass spectra in each bin. Then $R_D$, $x'$ and $y'$ are determined from a binned $\chi^2$ fit to the observed decay-time dependence of the WS/RS ratio. Figure 1 (left) shows the determined WS/RS ratio as a function of decay-time with the result of the fit superimposed. Since WS and RS events are expected to have the same decay-time acceptance and $M(D^0\pi_s^+)$ distributions, most of the systematic uncertainties affecting the determination of signal yields cancel out in the ratio. Possible residual biases, due to asymmetries in detection efficiencies and production rates or uncertainties in the determination of the flight distance of the $D^0$ meson, are found to be negligible at the current level of precision. The main sources of systematic uncertainty are the contamination of $D$ mesons from $b$-hadron decays and peaking backgrounds from charm decays reconstructed with wrong particle identification assignments. Studying the distribution of the $\chi^2$ of the impact parameter of the $D^0$ with respect to the $pp$ interaction vertex ($\chi^2_{\text{IP}}$), the pollution due to secondary $D^0$ mesons is determined. Such pollution is firstly reduced applying hard requirements on $\chi^2_{\text{IP}}$, then the largest possible effect due to the residual contamination is inserted into the function used to fit $R(t)$. A set of pseudo experiments is then used to control that the introduced bias is much smaller than the increase in the systematic uncertainty. The RS events where both the $D^0$ daughters have been mis-identified, and thus considered as WS candidates, are found to be the main source of peaking backgrounds. Such a component is parameterized inside

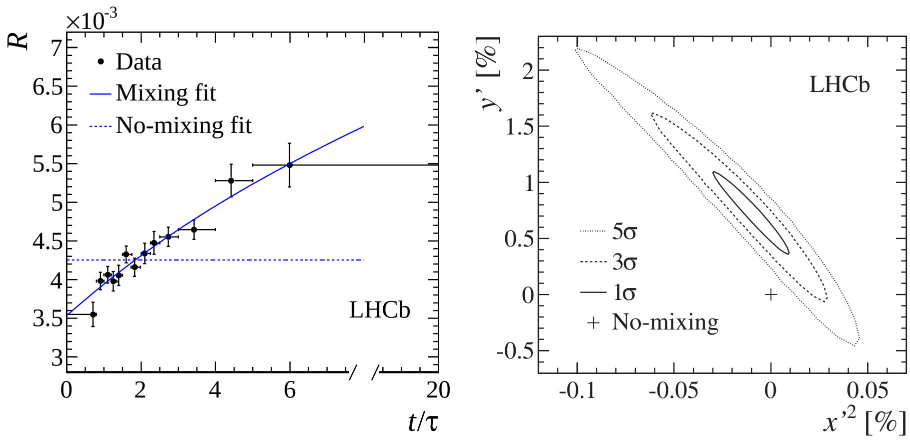


Fig. 1. – Left: decay-time evolution of the ratio, $R$, of WS over RS yields (points) with the projection of the mixing allowed (solid line) and no-mixing (dashed line) fits overlaid. Right: estimated confidence level regions in the $(x'^2, y')$ with systematic uncertainties included. The cross indicates the no-mixing point.

the function used to fit $R(t)$. The results are

$$\begin{aligned} R_D &= (3.52 \pm 0.15) \times 10^{-3}, \\ y' &= (7.2 \pm 2.4) \times 10^{-3}, \\ x'^2 &= (-0.09 \pm 0.13) \times 10^{-3}. \end{aligned}$$

To evaluate the associated significance, the change in the fit $\chi^2$ is determined also under the assumption of the no-mixing hypothesis, *i.e.* $R(t) = $ constant. The variation of the $\chi^2$ is found to correspond to a $p$-value of $5.7 \times 10^{-20}$, which excludes the no-mixing hypothesis at 9.1 standard deviations. This is the first observation of $D^0$ mixing in a single measurement.

## 3. – Search for direct $CP$ violation in $D^0 \to h^+h^-$ modes

After the evidence of a non-zero difference between the $CP$ asymmetries of $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays ($\Delta A_{CP} = A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)$) reported by the LHCb Collaboration in ref. [4], also the CDF Collaboration measured such a quantity [6]. The two experiments measured $\Delta A_{CP} = (-0.82 \pm 0.21(\text{stat.}) \pm 0.11(\text{syst.}))\%$ and $\Delta A_{CP} = (-0.62 \pm 0.21(\text{stat.}) \pm 0.10(\text{syst.}))\%$, respectively. In both analyses, the charge of the low-momentum pion in the $D^{*+} \to D^0\pi_s^+$ decay was used to tag the initial flavour of the $D^0$ meson. At the beginning of 2013 LHCb presented an update of the measurement, increasing the statistics from $0.6\,\text{fb}^{-1}$ to $1\,\text{fb}^{-1}$. The $D^*$ meson was constrained to come from the primary $pp$ vertex, achieving a better invariant mass resolution. Simultaneously, LHCb performed another analysis using the same integrated luminosity but exploiting the charge of the accompanying muon in the semileptonic $b$ hadron decay to the $D\mu\nu_\mu X$ final state to tag the flavour of the charmed meson (the $X$ denotes other particles produced in the semileptonic decay). From now on we will refer to these two analyses as $D^*$-tagged and semileptonic, respectively. Once the initial flavour of the $D^0$ is determined, the signal yields extracted from invariant mass fits are used to build the raw asymmetries defined as

$$A_{\mathrm{raw}} = \frac{N(D^0 \to f) - N(\bar{D}^0 \to f)}{N(D^0 \to f) + N(\bar{D}^0 \to f)}\,.$$

In the $D^*$-tagged analysis the observable $\delta m = m(h^+h^-\pi^\pm) - m(h^+h^-) - m(\pi^\pm)$ is used, while in the semileptonic analysis the $m(h^+h^-)$ observable is used ($h = \pi, K$). Neglecting second- and higher-order terms, $A_{\mathrm{raw}}$ is related to the $CP$ asymmetry by the relation

$$A_{\mathrm{raw}} \approx A_{CP} + A_D + A_P,$$

where $A_D$ is the asymmetry between the detection efficiencies of oppositely charged pions or muons and $A_P$ is the asymmetry between the production rates of $c$- or $b$-hadrons, depending on the technique used to tag the flavour of the $D^0$. Taking the difference between the raw asymmetries measured for the $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays, detection and production asymmetries cancel, yielding a robust measurement. In order to take into account possible effects related to the data taking conditions, in both analyses $A_{\mathrm{raw}}$ is measured from exclusive subsamples, separated depending on the magnet polarity and the trigger that selected the events. The final value for $A_{\mathrm{raw}}$ is computed from a weighted average of the subsamples. Since the detection and production asymmetries may have kinematic dependences, the cancellation is only valid in case of equal kinematic distributions for the tagging muon and pion in both $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$. As the $D^0$ kinematic is correlated with the tagging particle, the different phase space and particle identification criteria applied to the two decays may lead to differences in the kinematics of tagging particles for the two decays. In order to equalize the kinematic distributions both analyses use a reweighting procedure. The ratio between the two decay modes has been determined as a function of $D^0$ kinematic variables, using background subtracted events. Then the ratio is used as an event-by-event weight and the raw asymmetries are determined from invariant mass fits to the weighted samples. A final correction needs to be applied to $\Delta A_{CP}$ obtained from the semileptonic analysis, due to the probability to mistag the $D^0$ flavour. The mistag probability has been estimated from a sample of $D^0 \to K^-\pi^+$ decays. The final results from the two analyses are

$$\Delta A_{CP} = (-0.34 \pm 0.15(\mathrm{stat.}) \pm 0.10(\mathrm{syst.}))\%, \quad \text{ref. [7]},$$
$$\Delta A_{CP} = (0.49 \pm 0.30(\mathrm{stat.}) \pm 0.14(\mathrm{syst.}))\%, \quad \text{ref. [8]},$$

for the $D^*$-tagged analysis and semileptonic analysis, respectively. Neglecting the indirect $CP$ asymmetry the two measurements differ by 2.2 standard deviation. Because of this discrepancy an extensive set of cross-checks has been performed to verify the stability of the results. $\Delta A_{CP}$ has been found to be stable with respect to several reconstructed quantities and particle identification requirements. In the case of the semileptonic analysis a variation of $\Delta A_{CP}$ of 0.11% is found when removing events with negative decay time of the $D^0$. Such a difference contributes as the dominant source of systematic uncertainty. In the case of the $D^*$-tagged analysis the main systematic uncertainty comes from the variation observed removing the events with a large $\chi^2$ of the impact parameter of the soft pion with respect to the primary vertex.

The statistical correlation between the data samples used by the two analyses is negligible, and due to the different production environment and tagging technique the systematic uncertainties are also uncorrelated. Because of this, and assuming a negligible indirect $CP$ violation contribution, it is possible to combine the results performing a simple weighted average. The result of such a combination is

$$\Delta A_{CP} = (-0.15 \pm 0.16)\%,$$

showing no evidence for $CP$ violation. More precise measurements of $\Delta A_{CP}$ are needed to establish whether $CP$ violation at the level of $\mathcal{O}(10^{-3})$ in two-body $D$ meson decays exists. The LHCb Collaboration has the possibility to achieve the needed sensitivity analysing the $2\,\mathrm{fb}^{-1}$ of data collected during the 2012 LHC run at an center-of-mass energy of 8 TeV.

## REFERENCES


[1] Cabibbo N., *Phys. Rev. Lett.*, **10** (1963) 531; Kobayashi M. and Maskawa T., *Prog. Theor. Phys.*, **49** (1973) 652.
[2] Bianco F. *et al.*, *Riv. Nuovo Cimento*, **26**, No. 7 (2003); Grossman Y. *et al.*, *Phys. Rev. D*, **75** (2007) 036008.
[3] Aubert B. *et al.* (BaBar Collaboration), *Phys. Rev. Lett.*, **98** (2007) 211802; Staric M. *et al.* (Belle Collaboration), *Phys. Rev. Lett.*, **98** (2007) 211803; Aaltonen T. *et al.* (CDF Collaboration), *Phys. Rev. Lett.*, **100** (2008) 011105.
[4] Aaij R. *et al.* (LHCb Collaboration), *Phys. Rev. Lett.*, **108** (2012) 111602.
[5] Aaij R. *et al.* (LHCb Collaboration), *JINST*, **8** (2013) P04022.
[6] Aaltonen T. *et al.* (CDF Collaboration), *Phys. Rev. Lett.*, **109** (2012) 111801.
[7] Aaij R. *et al.* (LHCb Collaboration), LHCb-CONF-2013-003.
[8] Aaij R. *et al.*, *Phys. Rev. Lett.*, **108** (2012) 111602.