MEASUREMENT OF CP VIOLATION IN $D^0/\bar{D}^0$

MICHAEL J. MORELLO
Scuola Normale Superiore, Piazza dei Cavalieri 7
Pisa, 56127, Italy
michael.morello@sns.it

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Charm physics has played all along a central role in particle physics, however the level of attention on it has tremendously increased in the last years because of the observation of “fast” $D^0 - \bar{D}^0$ flavour oscillations and because of very recent observed hints of $CP$ violation. While in the past these would have been unambiguously interpreted as signs of New Physics, the revisitation of theoretical expectations, prompted by the latest experimental measurements, makes the picture not clear. This brief review covers the current status of $CP$-violating measurements in the $D^0 - \bar{D}^0$ system, both on the experimental and theoretical side.

Keywords: Charm physics; Meson mixing; $CP$ violation.

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1. Introduction

The $CP$ transformation combines the charge conjugation $C$ with the parity $P$. Under $C$ operator particles and antiparticles are interchanged by conjugating all internal quantum numbers (e.g., $Q \rightarrow -Q$ for electromagnetic charge), while under $P$ the handedness of space is reversed, $x \rightarrow -\bar{x}$. So far most phenomena observed in Nature are $C$- and $P$-symmetric, and therefore, also $CP$-symmetric. Gravitational, electromagnetic, and strong interactions are invariant under $C$, $P$ and then under the $CP$ transformation, while the weak interactions violate $C$ and $P$ separately in the strongest possible way. For a long time physicists believed that weak interactions were $CP$-symmetric, since the invariance under the $CP$ operator is preserved in most weak processes. However the $CP$ symmetry is also violated in certain rare weak processes, as discovered in neutral $K$ decays in 1964 [1], and observed in recent years in $B$ decays [2]. These effects are related to $K^0 - \bar{K}^0$ and $B^0 - \bar{B}^0$ mixing, but $CP$ violation arising solely from decay amplitudes has also been observed, first in $K \rightarrow \pi\pi$ decays [3] and more recently in various neutral [4] and charged [5] $B$ decays.

Within the Standard Model the $CP$ symmetry is broken through the well-known Kobayashi-Maskawa (KM) mechanism [11], by a single complex phase which ap-
pears in the $3 \times 3$ unitary matrix that gives the $W$-boson couplings to an up-type antiquark and a down-type quark, in the basis of mass eigenstates. The theory agrees with all measurements to date, providing a strong proof that the Cabibbo-Kobayashi-Maskawa (CKM) phase is different from zero, and that the matrix of three-generation quark mixing is the dominant source of $CP$ violation observed in the meson decays. However this is not sufficient to explain the matter-antimatter asymmetry observed in our Universe. That asymmetry tells us New Physics (NP) with $CP$ violation has to exist. The usual candidate for finding the dynamics underlying the Universes baryonic asymmetry is neutrino oscillation with $CP$ violation, however the heavy flavour sectors have not yet been fully covered by experiments so far. For instance, the Standard Model (SM) predicts very small $CP$ violation for charm decays, therefore the dynamics of this quark can be well probed for the existence and analyses of NP without too much SM “background”. Moreover the neutral $D$ mesons system is the only one where up-sector quarks are involved in the initial state. Thus it probes scenarios where up-type quarks play a special role, such as supersymmetric models where the down quark and the squark mass matrices are aligned and, more generally, models in which CKM mixing is generated in the up-quark sector. The interest in charm dynamics has increased recently with the observation of charm oscillations. The current measurements indicate $O(10^{-2})$ magnitudes for the parameters governing their phenomenology. Such values are on the upper end of most theory predictions. Charm oscillations could be enhanced by a broad class of non-SM physics processes. Any generic non-SM contribution to the mixing would naturally carry additional $CP$-violating phases, which could enhance the observed $CP$ violating asymmetries relative to SM predictions.

2. Formalism

The decay amplitudes of a $D$ meson (charged or neutral) and its $CP$ conjugate $\bar{D}$ to a multi–particle final state $f$ and its $CP$ conjugate $\bar{f}$ are defined as

$$ A_f = \langle f | H | D \rangle, \quad \bar{A}_f = \langle f | H | \bar{D} \rangle, \quad A_{\bar{f}} = \langle \bar{f} | H | D \rangle, \quad \bar{A}_{\bar{f}} = \langle \bar{f} | H | \bar{D} \rangle $$

where $H$ is the decay Hamiltonian. There are two types of phases that may appear in $A_f$ and $\bar{A}_{\bar{f}}$. Complex parameters in any Lagrangian term that contributes to the amplitude will appear in complex conjugate form in the $CP$–conjugate amplitude. Thus their phases appear in $A_f$ and $\bar{A}_{\bar{f}}$ with opposite signs. In the Standard Model these phases occur only in the CKM matrix which is part of the electroweak sector of the theory, hence these are often called “weak phases”. A second type of phase can appear in scattering or decay amplitudes even when the Lagrangian is real. Such phases do not violate $CP$ and they appear in $A_f$ and $\bar{A}_{\bar{f}}$ with the same sign. Their origin is the possible contribution from intermediate on–shell states in the decay process, that is an absorptive part of an amplitude that has contributions from coupled channels. Usually the dominant rescattering is due to strong interactions and hence the designation “strong phases” for the phase shifts so induced.
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$CP$ violation in the decay appears as a result of interference among various terms in the decay amplitude, and will not occur unless at least two terms have different weak phases and different strong phases. As an example, let us consider a decay process which can proceed through several amplitudes:

$$A_f = \sum_j |A_j| e^{i(\delta_j + \phi_j)}, \quad \overline{A_f} = \sum_j |A_j| e^{i(\delta_j - \phi_j)},$$

where $\delta_j$ and $\phi_j$ are strong ($CP$ conserving) and weak ($CP$ violating) phases, respectively. To observe $CP$ violation one needs $|A_f| \neq |\overline{A_f}|$, i.e. there must be a contribution from at least two processes with different weak and strong phases in order to have a non vanishing interference term

$$|A_f|^2 - |\overline{A_f}|^2 = -2 \sum_{i,j} |A_i||A_j| \sin(\delta_i - \delta_j) \sin(\phi_i - \phi_j).$$

The phenomenology of $CP$ violation in neutral flavored meson decays is enriched by the possibility that, besides the decay, it is also possible to have $D^0 \leftrightarrow \bar{D}^0$ transitions, also known as flavor mixing or oscillations. Particle–antiparticle mixing has been observed in all four flavored neutral meson systems, i.e., in neutral kaon, both neutral $B$ meson systems and neutral $D$ meson system. The particle–antiparticle mixing phenomenon causes an initial (at time $t = 0$), pure $D^0$ meson state to evolve in time to a linear combination of $D^0$ and $\bar{D}^0$ states. If the times $t$ in which we are interested are much larger than the typical strong interaction scale, then the time evolution can be described by the approximate Schrödinger equation:

$$i \frac{d}{dt} \begin{pmatrix} D^0(t) \\ \bar{D}^0(t) \end{pmatrix} = \begin{pmatrix} M - i \frac{\Gamma}{2} & 0 \\ 0 & M + i \frac{\Gamma}{2} \end{pmatrix} \begin{pmatrix} D^0(t) \\ \bar{D}^0(t) \end{pmatrix},$$

where $M$ and $\Gamma$ are $2 \times 2$ Hermitian matrices,

$$M = \begin{pmatrix} M_{11} & M_{12} \\ M_{12}^* & M_{22} \end{pmatrix} \quad \text{and} \quad \Gamma = \begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_{22} \end{pmatrix},$$

associated with transitions via off–shell (dispersive) and on–shell (absorptive) intermediate states, respectively. Diagonal elements of $H_{\text{eff}} = M - i \Gamma/2$ are associated with the flavor–conserving transitions $D^0 \rightarrow D^0$ and $\bar{D}^0 \rightarrow \bar{D}^0$ while off–diagonal elements are associated with flavor–changing transitions $D^0 \leftrightarrow \bar{D}^0$. The matrix elements of $M$ and $\Gamma$ must satisfy $M_{11} = M_{22}$ and $\Gamma_{11} = \Gamma_{22}$ in order to be consistent with $CPT$ invariance.

The eigenstates of the effective Hamiltonian $H_{\text{eff}}$ are

$$|D_{L,H}\rangle = p \ |D^0\rangle \pm q \ |\bar{D}^0\rangle$$

while the corresponding eigenvalues are

$$\lambda_{L,H} = \left(M_{11} - \frac{i}{2}\Gamma_{11}\right) \pm \frac{q}{p} \left(M_{12} - \frac{i}{2}\Gamma_{12}\right) \equiv m_{L,H} - \frac{i}{2}\Gamma_{L,H}.$$
The coefficients $p$ and $q$ are complex coefficients, satisfying $|p|^2 + |q|^2 = 1$, and

$$q = \frac{\sqrt{M_{12}^* - \frac{i}{2} \Gamma_{12}^*}}{M_{12} - \frac{i}{2} \Gamma_{12}} = \frac{|q|}{p} e^{i \phi}.$$  

The real parts of the eigenvalues $\lambda_{1,2}$ represent masses, $m_{L,H}$, and their imaginary parts represent the widths $\Gamma_{L,H}$ of the two eigenstates $|D_{L,H}\rangle$, respectively. The sub–scripts $H$ (heavy) and $L$ (light) are here used because by convention we choose $\Delta m = m_H - m_L > 0$, while the sign of $\Delta \Gamma = \Gamma_L - \Gamma_H$ is not known a priori and needs to be experimentally determined.

The time–dependent decay amplitude of an initially pure $D^0$ state decaying to final state $f$ is then given by

$$\langle f | H | D^0(t) \rangle = A_f \ g_+ (t) + \bar{A}_f \ \frac{q}{p} \ g_- (t),$$

where

$$|g_+ (t)|^2 = \frac{1}{2} \ e^{-t/\tau} \left[ \cos \left( \frac{xt}{\tau} \right) \pm \cosh \left( \frac{yt}{\tau} \right) \right]$$

represents the time–dependent probability to conserve the initial flavor ($+$) or oscillate into the opposite flavor ($-$) and $x$, $y$ are dimensionless mixing parameters defined as

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

and $\Gamma = (\Gamma_L + \Gamma_H)/2 = 1/\tau$ is the mean decay width.

The time–dependent decay rate, proportional to $|\langle f | H | D^0(t) \rangle|^2$, is then

$$\frac{d \Gamma}{dt} (D^0(t) \to f) \propto |A_f|^2 \left[ (1 - |\lambda_f|^2) \cos \left( \frac{xt}{\tau} \right) + (1 + |\lambda_f|^2) \cosh \left( \frac{yt}{\tau} \right) \right.$$

$$- 2 \Im (\lambda_f) \sin \left( \frac{xt}{\tau} \right) + 2 \Re (\lambda_f) \sinh \left( \frac{yt}{\tau} \right) \Big].$$

with

$$\lambda_f = \frac{q}{p} \frac{\bar{A}_f}{A_f}.$$

In analogy with this treatment one can show that for an initial pure $\bar{D}^0$ eigenstate the decay rate is

$$\frac{d \Gamma}{dt} (\bar{D}^0(t) \to f) \propto |\bar{A}_f|^2 \left[ (1 - |\lambda_f^{-1}|^2) \cos \left( \frac{xt}{\tau} \right) + (1 + |\lambda_f^{-1}|^2) \cosh \left( \frac{yt}{\tau} \right) \right.$$

$$- 2 \Im (\lambda_f^{-1}) \sin \left( \frac{xt}{\tau} \right) + 2 \Re (\lambda_f^{-1}) \sinh \left( \frac{yt}{\tau} \right) \Big].$$

Decay rates to the CP–conjugate final state $\bar{f}$ are obtained analogously, with the substitutions $A_f \to A_{\bar{f}}$ and $\bar{A}_f \to \bar{A}_{\bar{f}}$ in the above equations. Terms proportional to $|A_f|^2$ or $|\bar{A}_f|^2$ are associated with decays that occur without any net $D^0 \leftrightarrow \bar{D}^0$. 


oscillation, while terms proportional to $|\lambda_f|^2$ or $|\lambda_f^{-1}|^2$ are associated with decays following a net oscillation; the $\sin(xt/\tau)$ and $\sinh(yt/\tau)$ terms are instead associated with the interference between these two cases.

While $CP$ violation in charged meson decays depends only on $A_f$ and $\overline{A_f}$, in the case of neutral mesons, because of the possibility of flavor oscillations, $CP$ violating effects have additional dependences on the values of $|q/p|$ and $\lambda_f$. We then distinguish three types of $CP$ violating effects in meson decays:

(1) $CP$ violation in the decay is defined by

$$|\overline{A_f}/A_f| \neq 1.$$  

In charged meson decays, where mixing effects are absent, this is the only possible source of $CP$ asymmetries:

$$A_{CP}(D \rightarrow f) = \frac{\Gamma(D \rightarrow f) - \Gamma(D \rightarrow \overline{f})}{\Gamma(D \rightarrow f) + \Gamma(D \rightarrow \overline{f})} = \frac{1 - |\overline{A_f}/A_f|^2}{1 + |\overline{A_f}/A_f|^2} \quad (3)$$

(2) $CP$ violation in mixing is defined by

$$|q/p| \neq 1.$$  

In this case, in place of Eq. (3) it is useful to define the time–dependent asymmetry

$$A_{CP}(D^0 \rightarrow f; t) = \frac{d\Gamma(D^0(t) \rightarrow f)/dt - d\Gamma(D^0(t) \rightarrow \overline{f})/dt}{d\Gamma(D^0(t) \rightarrow f)/dt + d\Gamma(D^0(t) \rightarrow \overline{f})/dt}, \quad (4)$$

(3) $CP$ violation in interference between a decay without mixing, $D^0 \rightarrow f$, and a decay with mixing, $D^0 \rightarrow D^0 \rightarrow f$ (such an effect occurs only in decays to final states that are common to both $D^0$ and $\overline{D^0}$, including all $CP$ eigenstates), is defined by

$$\Im m\lambda_f \neq 0$$

Usually type (1) is also known as direct $CP$ violation, while type (2) and (3) are referred as indirect $CP$ violation.

3. Neutral charmed mesons decays: $D$ mixing

The interest in charm dynamics has increased recently with the evidence of charm oscillations reported by three different experiments\cite{14,15,16}, which, when combined together with all other available experimental information, established the existence of mixing at the $10\sigma$ level\cite{17}. In the Standard Model mixing in neutral $D$ meson system can proceed through a double weak boson exchange (short distance contributions) represented by box diagrams, or through intermediate states that are accessible to both $D^0$ and $\overline{D^0}$ (long distance effects), as represented in Fig. [1]. Potentially large long distance contributions are non–perturbative and therefore difficult
Fig. 1. Examples of Feynman diagrams which describe “short” (left) and “long distance” (right) contributions to the $D^0 - \bar{D}^0$ mixing amplitude. In the Standard Model the latter diagrams dominate over the “short distance” ones which are negligible compared to the first because of the small CKM coupling to the $b$ quark and of GIM suppression of the remaining two light–quark loops.

to estimate, hence the predictions for the mixing parameters $x$ and $y$ within the Standard Model span several orders of magnitude between $10^{-8}$ and $10^{-2}$ \cite{18}. The measured values of $x$ and $y$, as averaged by the Heavy Flavor Averaging Group (HFAG) when CP violation is allowed \cite{17}, are

$$x = (0.63^{+0.19}_{-0.20})\%$$ and $$y = (0.75 \pm 0.12)\%.$$ \hspace{1cm} (5)

The large uncertainties of the Standard Model mixing predictions make it difficult to identify New Physics contributions (a clear hint would be, if $x$ is found to be much larger than $y$), however since current measurements are on the upper end of most theory predictions \cite{18}, they could be interpreted as a possible hint for New Physics.

Charm oscillations could be enhanced by a broad class of non–Standard Model physics processes \cite{19}, i.e., models with extra fermions like a forth generation down–type quark, with flavor changing neutral currents at tree level mediated by additional gauge bosons or in general with new symmetry of the theory like in Supersymmetry (SUSY). Any generic New Physics contribution to the mixing would naturally carry additional CP–violating phases, which could enhance the observed CP–violating asymmetries relative to Standard Model predictions. Moreover, since charmed hadrons are the only hadrons, presently accessible to experiment, composed of a heavy charged $+2/3$ quark\footnote{The top quark decays before it forms a hadron and therefore cannot oscillate; the absence of flavor mixing reduces significantly the possibility to study CP violating effects involving the other down–type quarks.}, they provides the sole window of opportunity to examine scenarios where up–type quarks play a special role, such as SUSY models where the down quark and the squark mass matrices are aligned \cite{12,13} and, more generally, models in which CKM mixing is generated in the up–quark sector.

4. Cabibbo–suppressed $D^0 \rightarrow \pi^+\pi^-$ and $D^0 \rightarrow K^+K^-$ decays

Examples of clean channels where to study both direct and indirect CP violation in the charm system are the neutral singly–Cabibbo–suppressed decays into CP–
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eigenstates, such as $D^0 \rightarrow \pi^+\pi^-$ and $D^0 \rightarrow K^+K^-$ (collectively referred to as $D^0 \rightarrow h^+h^-$ in the following). Owing to the slow mixing rate of charm mesons, the time–dependent asymmetry of Eq. 4 can be approximated to first order as the sum of two terms:

$$A_{CP}(D^0 \rightarrow f; t) = A_{dir}^{CP}(D^0 \rightarrow f) + \frac{t}{\tau} A_{ind}^{CP}(D^0 \rightarrow f) \quad (x, y \ll \tau/t)$$  \hspace{1cm} (6)$$

where $A_{dir}^{CP}$ and $A_{ind}^{CP}$ represents direct and indirect CP asymmetries, respectively. In the case $f$ is a CP eigenstate, as for $D^0 \rightarrow h^+h^-$ decays, then

$$A_{dir}^{CP}(D^0 \rightarrow f) = \left| \frac{A_{f}/A_{\bar{f}}}{1 + |A_{f}/A_{\bar{f}}|^2} \right|^2$$  \hspace{1cm} (7)$$

$$A_{ind}^{CP}(D^0 \rightarrow f) = \frac{1}{2} \left[ y \Re(\lambda_f - \lambda_{\bar{f}}^{-1}) - x \Im(\lambda_f - \lambda_{\bar{f}}^{-1}) \right]$$  \hspace{1cm} (8)$$

Within the Standard Model direct CP violation can occur in singly–Cabibbo–suppressed charm decays ($c \rightarrow u\bar{q}q$ with $q = d, s$) because the final state particles contain at least one pair of quark and antiquark of the same flavor, which makes a contribution from penguin–type or box amplitudes induced by virtual $b$–quarks possible in addition to the tree amplitudes. However, as shown in the Feynman diagrams of Fig. 2, the contribution of these second order amplitudes are strongly suppressed by the small combination of CKM matrix elements $V_{cb}V_{ub}^*$ and $V_{cd}V_{ud}^*$, which is real in Wolfenstein parametrization up to $O(\lambda^2)$ and $O(\lambda^6)$. Hence to first order one would expect to observe an asymmetry consistent only with the mixing phase $\phi$, with no decay phase contribution:

$$A_{CP}(D^0 \rightarrow h^+h^-) \approx A_{ind}^{CP}(D^0 \rightarrow h^+h^-)$$

$$\approx \frac{\eta_{CP}}{2} \left[ -y \left( \frac{|q|}{p} - \frac{|\bar{p}|}{|q|} \right) \cos \phi + x \left( \frac{|p|}{|q|} + \frac{|\bar{p}|}{|q|} \right) \sin \phi \right]$$

Conversely, in the Standard Model, it is not possible to have direct CP violation in Cabibbo–favored ($c \rightarrow s\bar{u}\pi$) or doubly–Cabibbo–suppressed ($c \rightarrow d\bar{u}\pi$) charm decays.
where $\eta_{CP} = +1$ is the CP eigenvalue of the $h^+ h^-$ final state. The Standard Model dynamics predicts indirect CP asymmetries around $O(10^{-3})$, being suppressed by the value of $x$ and $y$ (see Eq. [5]), while direct CP violation produces asymmetries one order of magnitude smaller. In addition, in the limit of $U$–spin symmetry, the direct component is equal in magnitude and opposite in sign for $D^0 \to K^+ K^-$ and $D^0 \to \pi^+ \pi^-$. 

As already mentioned in the previous section, New Physics contributions to the charm mixing would, in general, also exhibit larger CP violation. This mixing–induced effects, in many scenarios beyond the Standard Model, would in addition provide sources of direct CP violation in $D^0 \to h^+ h^-$ decays both at tree level (extra quark in Standard Model vector–like representation, SUSY without R–parity models, two Higgs doublet models) or at one–loop (QCD penguin and dipole operators, flavor changing neutral currents in supersymmetric flavor models) as described in Ref. [22]. While the first group of models can produce an effect that is much less than 1%, the processes having one–loop can even reach the percent level, producing effects that are clearly not expected in the Standard Model.

In the absence of large new weak phases in the decay amplitudes, i.e., negligible direct CP violation from New Physics, the CP asymmetries in singly–Cabibbo–suppressed decays into final CP eigenstates would be dominated by mixing–induced effects and thus universal, i.e., independent of the final state. So if different asymmetries are observed between $D^0 \to \pi^+ \pi^-$ and $D^0 \to K^+ K^-$ decays, then direct CP violation must be present.

5. Measurement of time–integrated CP asymmetries

The sources of a possible asymmetry in neutral $D$ meson decays can be distinguished by their dependence on the decay–time, so a time–dependent analysis seems necessary. However sensitivity to indirect CP violation can be achieved also with time–integrated measurements, if the detector acceptance allows to collect samples of $D^0$ mesons with decay–times longer than $\tau$. In fact, the time–integrated asymmetry is the integral of Eq. [6] over the observed distribution of proper decay time, $D(t)$:

$$A_{CP}(D^0 \to h^+ h^-) = A_{CP}^{\text{dir}}(D^0 \to h^+ h^-) + A_{CP}^{\text{ind}}(D^0 \to h^+ h^-) \int_0^\infty \frac{t}{\tau} D(t)dt$$

$$= A_{CP}^{\text{dir}}(D^0 \to h^+ h^-) + \frac{\langle t \rangle}{\tau} A_{CP}^{\text{ind}}(D^0 \to h^+ h^-). \quad (9)$$

Since the value of $\langle t \rangle$ depends on $D(t)$, different values of time–integrated asymmetry may be observed in different experimental environments because of different detector acceptances as a function of decay time, thus providing different sensitivities to $A_{CP}^{\text{dir}}$ or $A_{CP}^{\text{ind}}$. In experiments where the reconstruction efficiency does not depend on proper decay time ($D(t) = 1$), as it is the case at the $B$–factories, the factor $\langle t \rangle/\tau$ equals unity resulting in the same sensitivity to direct and indirect CP.
violation. On the contrary, in experiments where data are collected with an online event selection (trigger), that imposes requirements on the displacement of the $D^0$ meson decay point from the production point, as it is the case at the CDF and LHCb, results $(t)/\tau > 1$. This makes measurements, performed in hadronic environment, as CDF and LHCb, more sensitive to mixing–induced CP violation. In addition, combination of these results with those from Belle and BABAR provides discrimination between the two contributions to the asymmetry.

From the experimental point of view the flavour of neutral $D$ mesons at production is tagged by reconstructing $D^{\ast +} \to D^0 \pi^+_s$ decays in which the charge of the low momentum pion, $\pi^+_s$, determines the flavour of the $D^0$ meson. The measured asymmetry,

$$ A_{hh}^{\text{rec}} = \frac{N(D^0 \to h^+ h^-) - N(\bar{D}^0 \to h^+ h^-)}{N(D^0 \to h^+ h^-) + N(\bar{D}^0 \to h^+ h^-)}, $$

with $N$ denoting the number of reconstructed decays, can be written, in general, as a sum of several (assumed small) contributions:

$$ A_{hh}^{\text{rec}} = A_p + A_{hh}^{\text{CP}} + A_{\pi}^{\epsilon}. $$

(10)

where $A_{hh}^{\text{CP}}$ is the intrinsic CP asymmetry, $A_{\pi}^{\epsilon}$ is a contribution due to an asymmetry in the reconstruction efficiencies of oppositely charged $\pi_s$ and $A_p$ a contribution from a production asymmetry depending on the experimental environment. Since the final state $h^+ h^-$ is self-conjugate, its reconstruction efficiency does not affect measured asymmetry $A_{hh}^{\text{rec}}$.

At the Tevatron, charm and anticharm mesons are expected to be created in almost equal numbers. Since the overwhelming majority of them are produced by CP–conserving strong interactions, and the $p\bar{p}$ initial state is CP symmetric, any small difference between the abundance of charm and anti-charm flavor is constrained to be antisymmetric in pseudorapidity. As a consequence, the net effect of any possible charge asymmetry in the production cancels out ($A_p = 0$), as long as the distribution of the decays is symmetric in pseudorapidity $^{26}$.

In the production of $D^{\ast +}$ mesons in $e^+ e^- \to c\bar{c}$, instead, there is a forward-backward asymmetry, which arises from $\gamma - Z^0$ interference and higher order QED effects $^{30,31,32}$. This term is an odd function of the cosine of the $D^{\ast +}$ production polar angle in the center-of-mass (CM) system ($\cos \theta^*$). Since detector acceptance, in $e^+ e^-$ machines, is not symmetric with respect to $\cos \theta^*$, the measurement is performed in bins of $\cos \theta^*$, allowing to correct for the acceptance and extract both $A_p$ and $A_{hh}^{\text{CP}}$ $^{24,25}$.

One of the main experimental difficulty of these measurements comes from the small differences in the detection efficiencies of tracks of opposite charge $A_{\pi}^{\epsilon}$ which may lead, if not properly taken into account, to spuriously-measured charge asymmetries. Relevant instrumental effects include differences in interaction cross sections with matter between positive and negative low-momentum hadrons and the geometry of the main tracking system. This must be corrected to better than one per
to match the expected statistical precision of the current measurements. To reliably determine \( A_\pi^* \) all experiments adopt a similar fully data-driven technique, based on an appropriate combination of charge-asymmetries observed in different event samples. In addition to the \( D^0 \to h^+h^- \) modes mentioned above, two \( D^0 \to K^-\pi^+ \) samples are reconstructed: one consisting of \( D \) mesons with tagged initial flavour, and one consisting of untagged candidates. The measured asymmetries for these modes can be written as

\[
A^{\text{tag}}_{\pi^\pm} = A_p + A^{K\pi}_{\text{CP}} + A^{K\pi}_\pi + A_\pi^*,
\]

\[
A^{\text{untag}}_{\pi^\pm} = A_p + A^{K\pi}_{\text{CP}} + A^{K\pi}_\pi.
\]

(11)

A notable difference with (10) is that this final state is not self-conjugate and thus an additional term \( A^{K\pi}_\pi \) appears as a consequence of a possible asymmetry in the reconstruction efficiency of the \( D^0 \to K^-\pi^+ \) decays. The two measurements in (11) are used to determine \( A_\pi^* \) at the Tevatron where \( A_p \) is null, and \( A_\pi^* + A_p \) at the B-Factories. The fact that \( A_p \) is antisymmetric with respect to \( \cos\theta^* \) and \( A^{hh}_{\text{CP}} \) is independent of this variable allows to disentangle the two contributions at the \( e^+e^- \) environment. Then the result is inserted into (10) to extract \( A^{hh}_{\text{CP}} \).

Table 1. Summary of recent experimental measurements of \( CP \) violating asymmetries in two–body singly–Cabibbo–suppressed decays of \( D^0 \) mesons.

| Experiment | \( A_{\text{CP}}(D^0 \to \pi^+\pi^-) \) (%) | \( A_{\text{CP}}(D^0 \to K^+K^-) \) (%) |
|------------|------------------------------------------|------------------------------------------|
| BABAR 2008 | \(-0.24 \pm 0.52 \pm 0.22\) | \(+0.00 \pm 0.34 \pm 0.13\) |
| Belle 2008 | \(+0.43 \pm 0.52 \pm 0.12\) | \(-0.43 \pm 0.30 \pm 0.11\) |
| CDF 2012   | \(+0.22 \pm 0.24 \pm 0.11\) | \(-0.24 \pm 0.22 \pm 0.09\) |
| Belle 2012 | \(+0.55 \pm 0.36 \pm 0.09\) | \(-0.32 \pm 0.21 \pm 0.09\) |

The individual measurements of the time-integrated \( CP \) asymmetries in the singly-Cabibbo-suppressed decays into \( CP \)-eigenstates are reported in Tab. 1. As reference we report the results of the combined fit of the tagged \( D^0 \to \pi^+\pi^- \) and \( \bar{D}^0 \to \pi^+\pi^- \) samples at CDF in Fig. 3 where the fit results are overlaid to the distribution of \( D^0 \pi \) mass. The signal yields are about 106 000 decays of \( D^0 \to \pi^+\pi^- \) and 110 000 of \( \bar{D}^0 \to \pi^+\pi^- \).

A useful comparison with results from different experiments is achieved by expressing the observed asymmetry as a linear combination (Eq. (10)) of a direct component, \( A^{\text{dir}}_{\text{CP}} \), and an indirect component, \( A^{\text{ind}}_{\text{CP}} \), through a coefficient that is the mean proper decay time of charm mesons in the data sample used. Each measurements defines a band in the \( (A^{\text{ind}}_{\text{CP}}, A^{\text{dir}}_{\text{CP}}) \) plane with slope \( -t / \tau \) (Eq. (10)). CDF determines a mean decay time of \( 2.40 \pm 0.03 \) and \( 2.65 \pm 0.03 \) in units of \( D^0 \) lifetime, for \( D^0 \to \pi^+\pi^- \) and \( D^0 \to K^+K^- \) decays, respectively. The same holds for \( \text{BABAR} \) and Belle measurements, with slope \( -1 \), due to unbiased acceptance in decay time. The most recent results are shown in Fig. 4 which displays their relationship. The bands represent \( \pm 1\sigma \) uncertainties and show that all measurements
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**Fig. 3.** Results of the combined fit of the tagged $D^0 \rightarrow \pi^+\pi^-$ and $D^0 \rightarrow \pi^+\pi^-$ samples at CDF. Distribution of $D^0\pi_s$ mass for (a) charm and (b) anti-charm decays. Fit results are overlaid.

**Fig. 4.** Comparison of the present results with Belle, BABAR and CDF measurements of time-integrated $CP$–violating asymmetry in (a) $D^0 \rightarrow \pi^+\pi^-$ and (b) $D^0 \rightarrow K^+K^-$ decays displayed in the $(A^{\text{ind}}_{CP}, A^{\text{dir}}_{CP})$ plane. The point with error bars denotes the central value of the combination of the three measurements with one-dimensional 68% confidence level uncertainties. Figures are extracted from Ref. [26]. Very recent measurement from Belle [27] is not included in the average.

are compatible with $CP$ conservation (origin in the two-dimensional plane). The results of the three experiments can be combined assuming Gaussian uncertainties, to construct a combined confidence regions in the $(A^{\text{ind}}_{CP}, A^{\text{dir}}_{CP})$ plane, denoted with
68% and 95% confidence level ellipses. The corresponding values for the asymmetries are $A_{\text{dir}}^{CP}(D^0 \rightarrow \pi^+\pi^-) = (0.04 \pm 0.60)\%$, $A_{\text{ind}}^{CP}(D^0 \rightarrow \pi^+\pi^-) = (0.08 \pm 0.34)\%$, $A_{\text{dir}}^{CP}(D^0 \rightarrow K^+K^-) = (-0.24 \pm 0.41)\%$, and $A_{\text{ind}}^{CP}(D^0 \rightarrow K^+K^-) = (0.00 \pm 0.20)\%$, in which the uncertainties represent one-dimensional 68% confidence level intervals.

6. Measurement of $\Delta A_{CP}$

At LHC charm and anticharm mesons are produced by $CP$-conserving strong interactions, through $pp$ initial state, which has a net charge of $+2e$, which is not $CP$ symmetric. This produces a small net effect different from zero in the asymmetry production $A_p$, difficult to measure or cancel out in the measurement of the individual $CP$ asymmetries. The production asymmetry cannot be “easily” disentangled from the intrinsic $CP$ asymmetry, and so far LHCb did not provide any individual measurement of the time-integrated $CP$ asymmetry in the singly-Cabibbo-suppressed decay modes. However this term cancels out in the measurement of the difference

$$\Delta A_{CP} \equiv A_{CP}(D^0 \rightarrow K^+K^-) - A_{CP}(D^0 \rightarrow \pi^+\pi^-),$$

which could be maximally sensitive to $CP$ violation since the individual asymmetries are expected to have opposite sign, if the invariance under the interchange of $d$ with $s$ quark is even approximately valid. From Eq. 9 the difference $\Delta A_{CP}$ can be written as

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

and in the limit that $\Delta(t)$ vanishes, $\Delta A_{CP}$ is equal to the difference in the direct $CP$ asymmetry between the two decays $\Delta A_{\text{dir}}^{CP}$. Tab. 2 reports the most recent measurements of $\Delta A_{CP}$ with the relative uncertainties, where the deviation from zero is calculated by adding in quadrature the statistical and systematic uncertainty, assumed to be independent and Gaussian-distributed. All measurements are consistent. In particular LHCb result strongly indicate, for the first time, the presence of $CP$ violation in the charm sector, since $\Delta A_{CP}$ deviates from zero by and 3.5$\sigma$, confirmed by CDF results 2.7$\sigma$ from zero. The two results have comparable accuracy.

| Experiment | $A_{CP}(D^0 \rightarrow K^+K^-) - A_{CP}(D^0 \rightarrow \pi^+\pi^-)$ (%) | significance |
|------------|-------------------------------------------------|--------------|
| BABAR 2008 | $-0.24 \pm 0.62 \pm 0.26$ | 0.4$\sigma$ |
| Belle 2008 | $-0.86 \pm 0.60 \pm 0.07$ | 1.4$\sigma$ |
| LHCb 2012  | $-0.82 \pm 0.21 \pm 0.11$ | 3.5$\sigma$ |
| CDF 2012   | $-0.62 \pm 0.21 \pm 0.10$ | 2.7$\sigma$ |
| Belle 2012 | $-0.87 \pm 0.41 \pm 0.06$ | 2.1$\sigma$ |
and less than 1σ different in central value. The combined results of the two experiments provide substantial evidence for CP violation in the charm sector with a size larger than most predictions\textsuperscript{33,34}, possibly suggestive of the presence of non-SM dynamics. Figure 6 shows the $\Delta A_{\text{CP}}$ measurements as a function of $A_{\text{ind}}^{\text{CP}}$.

7. Measurement of $A_{\Gamma}$

The singly-Cabibbo-suppressed $D^0 \to h^+h^-$ decays probes CP violation effects also through the observable $A_{\Gamma}$, given by the asymmetry of effective lifetimes as

$$A_{\Gamma} \equiv \frac{\tau(D^0 \to h^+h^-) - \tau(D^0 \to h^+h^-)}{\tau(D^0 \to h^+h^-) + \tau(D^0 \to h^+h^-)}.$$  

(13)

where effective lifetime refers to the value measured using a single exponential model. Given the experimental constrains $x, y \ll 1$ and assuming $|A_f/A_f| \approx 1$ one can write\textsuperscript{22}

$$A_{\Gamma} \approx -A_{\text{ind}}^{\text{CP}}.$$  

(14)

The measurement of $A_{\Gamma}$ is, therefore, described in most literature as a determination of indirect CP violation. However, because of the very recent measurements of $\Delta A_{\text{CP}}$, the direct CP violation, which seems to be at the level of $10^{-2}$ cannot be neglected in the calculations. It can have a contribution to $A_{\Gamma}$ at the level of $10^{-4}$.

$A_{\Gamma}$ can be then expressed\textsuperscript{35} as

$$A_{\Gamma} \approx -A_{\text{ind}}^{\text{CP}} - A_{\text{dir}}^{\text{CP}} y_{CP} \cos \phi \approx -A_{\text{ind}}^{\text{CP}} - A_{\text{dir}}^{\text{CP}} y_{CP}.$$  

(15)

where $y_{CP}$ is the deviation from unity of the ratio of effective lifetimes in the decay modes $D^0 \to h^+h^-$ and $D^0 \to K^-\pi^+$

$$y_{CP} \equiv \frac{\tau(D^0 \to K^+K^-)}{\tau(D^0 \to K^-\pi^+)} - 1.$$  

(16)

In the limit of no CP violation $y_{CP}$ is equal to $y$ and hence becomes a pure mixing parameter. The most recent measurement for $A_{\Gamma}$ and $y_{CP}$ are reported in Tab. 3

The latest from BABAR and Belle were presented very recently in 2012, confirming the presence of charm mixing, respectively at $3.3\sigma$ and $4.8\sigma$, and a value for $A_{\Gamma}$ consistent with zero.

| Experiment | $y_{CP}$ [\%] | $A_{\Gamma}$ [\%] |
|------------|----------------|------------------|
| BABAR 2007\textsuperscript{35} | 1.24 ± 0.39 ± 0.13 | -0.26 ± 0.36 ± 0.08 |
| Belle 2007\textsuperscript{15} | 1.31 ± 0.32 ± 0.25 | +0.01 ± 0.30 ± 0.15 |
| LHCb 2012\textsuperscript{27} | 0.55 ± 0.63 ± 0.41 | -0.59 ± 0.59 ± 0.21 |
| BABAR 2012\textsuperscript{39} | 0.72 ± 0.18 ± 0.12 | +0.09 ± 0.26 ± 0.06 |
| Belle 2012\textsuperscript{39} | 1.11 ± 0.22 ± 0.11 | -0.03 ± 0.20 ± 0.08 |
As for the measurement of the time-integrated CP asymmetry, it is necessary to reconstruct the $D^{*+} \rightarrow D^0 \pi^+$ decays with a characteristic slow pion $\pi_s$, and $D^0 \rightarrow K^- \pi^+$, $K^- \pi^+$, and $\pi^+ \pi^-$. To select pion and kaon candidates, standard particle identification criteria are imposed. $D^0$ daughter tracks are refitted to a common vertex, and the $D^0$ production vertex is found by constraining its momentum vector and the $\pi_s$ track to originate from the $e^+e^-$ interaction region. The proper decay time of the $D^0$ candidate is then calculated from the projection of the vector joining the two vertices, $\vec{L}$, onto the $D^0$ momentum vector, $t = m_{D^0} \vec{L} \cdot \vec{p}/p^2$, where $m_{D^0}$ is the nominal $D^0$ mass. The decay time uncertainty $\sigma_t$ is evaluated event-by-event from the covariance matrices of the production and decay vertices. Figure 5 reports the results of the simultaneous fit to decay time distributions of $D^0 \rightarrow K^+ K^-$, $D^0 \rightarrow K^- \pi^+$ and $D^0 \rightarrow \pi^+ \pi^-$ decays at Belle. Similar distributions are obtained at BABAR and LHCb. For all experiments the main challenges are the extraction of the time resolution function and the acceptance variations with the decay time. In particular the last is crucial in LHCb where a lifetime-biasing selection is applied.

Figure 6 shows the current knowledge on CP violation in $D^0 \rightarrow h^+ h^-$ decays in the plane $(A_{CP}^{\text{dir}}, \Delta A_{CP}^{\text{dir}})$, where all measurements of $\Delta A_{CP}$ and $A_{CP}$ are reported. A $\chi^2$ fit is performed to combine all measurements reported in Tab. 2 and 3. Statistical
and systematic uncertainties are added in quadrature when calculating the $\chi^2$. The current world average value $y_{CP} = (1.064 \pm 0.209)\%$ [17] is used since it appears in the expression for $A_{\Gamma}$ of Eq. 15. Moreover using the same approximation of Eq. 15 the difference of time-integrated CP asymmetries of Eq. 12 must be written as

$$\Delta A_{CP} \approx \Delta A_{CP}^{\text{dir}} \left(1 + y_{CP} \frac{\langle t \rangle}{\tau}\right) + \frac{\Delta \langle t \rangle}{\tau} A_{CP}^{\text{ind}}$$

(17)

where $\Delta \langle t \rangle$ is the difference between the averaged quantity $\langle t \rangle$ for the $KK$ and $\pi\pi$ final state and $\langle t \rangle$ is their average. The bands represent $\pm 1\sigma$ intervals, the point of no CP violation $(0,0)$ is shown as a filled circle, and two-dimensional 68% C.L., 95% C.L., and 99.7% C.L. regions are plotted as ellipses with the best fit value as a cross indicating the one-dimensional uncertainties in their center. From the fit, the change in $\chi^2$ from the minimum value for the no-CPV point $(0,0)$ is 21.7; this corresponds to a C.L. of $2 \times 10^{-5}$ for two degrees of freedom. Thus the data is consistent with no CP violation at 0.002% C.L. The central values and $\pm 1\sigma$ errors for the individual parameters are:

$$A_{CP}^{\text{ind}} = (-0.027 \pm 0.163)%$$

(18)

$$\Delta A_{CP}^{\text{dir}} = (-0.678 \pm 0.147)%$$

(19)

Details can be found in Ref. [17].

8. Conclusions

Recent charm physics measurements reached for the first time an interesting precision after many years of the discovery of $c$ quark. The size of the available data samples of charmed mesons decays allows a first exploration of the the Standard Model predictions in this territory, in fact the first evidence for CP violation has already opened a privileged door for probing effects of New Physics. The observation
of the $CP$ violation in the charm sector is a near term goal, achievable in a short
time scale, if current hints will be confirmed. Instead, the real long term challenge
will be the interpretation of the observed effects, where the relatively small charm
quark mass and the large cancellations in this system, makes it very hard. In partic-
ular more precise determinations of the individual asymmetries in $D^0 \rightarrow \pi^+\pi^-$
and $D^0 \rightarrow K^+K$ decays and extension of the precise experimental exploration to
other charm decays may help in understanding whether the observed effect can be
attributed to significant hadronic corrections to the SM weak amplitudes or to new,
non-SM sources of $CP$ violation. Therefore precise measurements of both time-
dependent and time-integrated asymmetries are necessary to reveal the nature of
$CP$ violating effects in the $D^0$ system.

Since B factories, CLEO-c and CDF are analysing their final datasets, while
LHCb and BESII are currently taking data, new results are expected to come soon.
However to deeply explore the very interesting territory of charm CP violation, we
will need the next generation experiments, the LHCb upgrade and the the future
$e^+e^-$ collider experiments.

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