Implication of the $D^0$ Width Difference
On CP-Violation in $D^0$-$\bar{D}^0$ Mixing

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Abstract

Both BaBar and Belle have found evidence for a non-zero width difference in the $D^0$-$\bar{D}^0$ system. Although there is no direct experimental evidence for CP-violation in $D$ mixing (yet), we show that the measured values of the width difference $y \sim \Delta \Gamma$ already imply constraints on the CP-odd phase in $D$ mixing, which, if significantly different from zero, would be an unambiguous signal of new physics.

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The highlight of this year’s Moriond conference on electroweak interactions and unified theories arguably was the announcement by BaBar and Belle of experimental evidence for $D^0\bar{D}^0$ mixing [1, 2, 3], which was quickly followed by a number of theoretical analyses [4, 5, 6, 7, 8, 9]. While Refs. [4, 7, 8, 9] focused on the constraints posed, by the experimental results, on various new-physics models, Ref. [5] presented a first analysis of the implications of these results for the fundamental parameters describing $D$ mixing. The purpose of this letter is to show that the present experimental results already imply constraints on a sizeable CP-odd phase in $D$ mixing, which could only be due to new physics (NP).

To start with, let us shortly review the theoretical formalism of $D$ mixing and the experimental results, see Refs. [10, 11] for more detailed reviews. In complete analogy to $B$ mixing, $D$ mixing in the SM is due to box diagrams with internal quarks and $W$ bosons. In contrast to $B$, though, the internal quarks are down-type. Also in contrast to $B$ mixing, the GIM mechanism is much more effective, as the contribution of the heaviest down-type quark, the $b$, comes with a relative enhancement factor $(m_b^2 - m_s^2)/(m_u^2 - m_d^2)$, but also a large CKM-suppression factor $|V_{ub}V_{cb}^*|^2/|V_{us}V_{cs}^*|^2 \sim \lambda^8$, which renders its contribution to $D$ mixing $\sim 1\%$ and hence negligible. As a consequence, $D$ mixing is very sensitive to the potential intervention of NP. On the other hand, it is also rather difficult to calculate the SM “background” to $D$ mixing, as the loop-diagrams are dominated by $s$ and $d$ quarks and hence sensitive to the intervention of resonances and non-perturbative QCD. The quasi-decoupling of the 3rd quark generation also implies that CP violation in $D$ mixing is extremely small in the SM, and hence any observation of CP violation will be an unambiguous signal of new physics, independently of hadronic uncertainties.

The theoretical parameters describing $D$ mixing can be defined in complete analogy to those for $B$ mixing: the time evolution of the $D^0$ system is described by the Schrödinger equation

$$i \frac{\partial}{\partial t} \begin{pmatrix} D^0(t) \\ \bar{D}^0(t) \end{pmatrix} = \begin{pmatrix} M - i \frac{\Gamma}{2} \end{pmatrix} \begin{pmatrix} D^0(t) \\ \bar{D}^0(t) \end{pmatrix}$$

(1)

with Hermitian matrices $M$ and $\Gamma$. The off-diagonal elements of these matrices, $M_{12}$ and $\Gamma_{12}$, describe, respectively, the dispersive and absorptive parts of $D$ mixing. The flavour-eigenstates $D^0 = (c\bar{u})$, $\bar{D}^0 = (u\bar{c})$ are related to the mass-eigenstates $D_{1,2}$ by

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$$

(2)

with

$$\left( \frac{q}{p} \right)^2 = \frac{M_{12}^* - \frac{\Gamma}{2} \Gamma_{12}^*}{M_{12} - \frac{\Gamma}{2} \Gamma_{12}};$$

(3)

$|p|^2 + |q|^2 = 1$ by definition.

The basic observables in $D$ mixing are the mass and lifetime difference of $D_{1,2}$, which are usually normalised to the average lifetime $\Gamma = (\Gamma_1 + \Gamma_2)/2$:

$$x \equiv \frac{\Delta M}{\Gamma} = \frac{M_2 - M_1}{\Gamma_1 + \Gamma_2}, \quad y \equiv \frac{\Delta \Gamma}{2\Gamma} = \frac{\Gamma_2 - \Gamma_1}{2\Gamma_1}. $$

(4)
In this letter we follow the sign convention of Ref. [5], according to which \( x \) is positive by definition. The sign of \( y \) then has to be determined from experiment. In addition, if there is CP-violation in the \( D \) system, one also has

\[
\left| \frac{q}{p} \right| \neq 1, \quad \phi \equiv \arg(M_{12}/\Gamma_{12}) \neq 0. \tag{5}
\]

While previously only bounds on \( x \) and \( y \) were known, both BaBar and Belle have now found evidence for non-vanishing mixing in the \( D \) system. BaBar has obtained this evidence from the measurement of the doubly Cabibbo-suppressed decay \( D^0 \to K^+\pi^- \) (and its CP conjugate), yielding

\[
y' = (0.97 \pm 0.44(\text{stat}) \pm 0.31(\text{syst})) \times 10^{-2},
\]

\[
x'^2 = (-0.022 \pm 0.030(\text{stat}) \pm 0.021(\text{syst})) \times 10^{-2}, \tag{6}
\]

while Belle obtains

\[
y_{CP} = (1.31 \pm 0.32(\text{stat}) \pm 0.25(\text{syst})) \times 10^{-2} \tag{7}
\]

from \( D^0 \to K^+K^-, \pi^+\pi^- \) and

\[
x = (0.80 \pm 0.29(\text{stat}) \pm 0.17(\text{syst})) \times 10^{-2}, \quad y = (0.33 \pm 0.24(\text{stat}) \pm 0.15(\text{syst})) \times 10^{-2} \tag{8}
\]

from a Dalitz-plot analysis of \( D^0 \to K^0_S\pi^+\pi^- \). Here \( y_{CP} \to y \) in the limit of no CP violation in \( D \) mixing, while the primed quantities \( x', y' \) are related to \( x, y \) by a rotation by a strong phase \( \delta_{K\pi} \):

\[
y' = \cos \delta_{K\pi} - x \sin \delta_{K\pi}, \quad x' = x \cos \delta_{K\pi} + y \sin \delta_{K\pi}. \tag{9}
\]

Limited experimental information on this phase has been obtained at CLEO-c [12]:

\[
\cos \delta_{K\pi} = 1.09 \pm 0.66, \tag{10}
\]

which can be translated into \( \delta_{K\pi} = (0 \pm 65)^\circ \). An analysis with a larger data-set is underway at CLEO-c, with an expected uncertainty of \( \Delta \cos \delta_{K\pi} \approx 0.1 \) in the next couple of years [13]; BES-III is expected to reach \( \Delta \cos \delta_{K\pi} \approx 0.04 \) after 4 years of running [14]. The experimental result [10] agrees with theoretical expectations, \( \delta_{K\pi} = 0 \) in the SU(3)-limit and \( |\delta_{K\pi}| < 15^\circ \) from a calculation of the amplitudes in QCD factorisation [15]. Based on these experimental results, a preliminary HFAG-average was presented at the 2007 CERN workshop “Flavour in the Era of the LHC” [13]:

\[
x = (8.5^{+3.2}_{-3.1}) \times 10^{-3}, \quad y = (7.1^{+2.0}_{-2.3}) \times 10^{-3}. \tag{11}
\]

Adding errors in quadrature, this implies

\[
\frac{x}{y} = 1.2 \pm 0.6. \tag{12}
\]
The exact relations between $\Delta M$, $\Delta \Gamma$, $M_{12}$ and $\Gamma_{12}$ are given by

\[
(\Delta M)^2 - \frac{1}{4} (\Delta \Gamma)^2 = 4|M_{12}|^2 - |\Gamma_{12}|^2,
\]

\[
(\Delta M)(\Delta \Gamma) = 4\text{Re}(M_{12}^* \Gamma_{12}) = 4|M_{12}||\Gamma_{12}| \cos \phi.
\] (13)

Eq. (13) implies $x/y > 0$ for $|\phi| < \pi/2$ and $x/y < 0$ for $\pi/2 < |\phi| < 3\pi/2$. In view of the above experimental results, we assume $|\phi| < \pi/2$ from now on.

As for the CP-violating observables, $|q/p| \neq 1$ characterises CP-violation in mixing and can be measured for instance in flavour-specific decays $D^0 \to f$, where $\bar{D}^0 \to f$ is possible only via mixing. The prime example is semileptonic decays with

\[
A_{SL} = \frac{\Gamma(D^0 \to \ell^- X) - \Gamma(\bar{D}^0 \to \ell^+ X)}{\Gamma(D^0 \to \ell^- X) + \Gamma(\bar{D}^0 \to \ell^+ X)} = \frac{|q/p|^2 - |p/q|^2}{|q/p|^2 + |p/q|^2}.
\] (14)

Although the B factories may have some sensitivity to this asymmetry, its measurement is severely impaired by the fact that $D$ mixing proceeds only very slowly, resulting in a large suppression factor of the mixed vs. the unmixed rate:

\[
\frac{\Gamma(D^0 \to \ell^- X)}{\Gamma(D^0 \to \ell^+ X)} = \frac{x^2 + y^2}{2 + x^2 + y^2} \approx 6 \times 10^{-5}.
\] (15)

Both in the $K$ and the $B$ system the quantity

\[
A_M \equiv \left| \frac{q}{p} \right| - 1
\] (16)

is very small, which however need not necessarily be the case for $D$’s. From (3) one derives the general expression

\[
\left| \frac{q}{p} \right| = \sqrt{\left( \frac{4 + r^2 + 4r \sin \phi}{4 + r^2 - 4r \sin \phi} \right)^{1/2}}
\] (17)

with $r = |\Gamma_{12}/M_{12}|$ and the weak phase $\phi$ defined in (5). In the B system, one has $r \ll 1$ (the current up-to-date numbers are $r \approx 7 \times 10^{-3}$ for $B$ and $r \approx 5 \times 10^{-3}$ for $B$, [16]), so that upon expansion in $r$

\[
\left| \frac{q}{p} \right|_{B_{d,s}} = 1 + \frac{\Gamma_{12}}{M_{12}} |\phi| + O(r^2).
\] (18)

Note that this formula refers to the definition $\phi = \arg(M_{12}/\Gamma_{12})$, which differs by $+\pi$ from the one used in Ref. [16], $\phi = \arg(-M_{12}/\Gamma_{12})$. For the $K$ system, one finds $r \approx |\Delta \Gamma/\Delta M| \approx 2$ from experiment, but now the phase $\phi$ turns out to be small, so that

\[
\left| \frac{q}{p} \right|_K = 1 + \frac{4r}{4 + r^2} \phi + O(\phi^2) \approx 1 + \phi.
\] (19)

In both cases, $|q/p| \approx 1$ to a very good approximation. In the $D$ system, however, there is no natural hierarchy $r \ll 1$, and of course one hopes that NP-effects induce $|\phi| \gg 0$. In
Figure 1: $|q/p|^2$, Eq. (20), as a function of the CP-odd phase $\phi$ for the central experimental value $\tilde{r} = 7.1/8.5$. Solid line: full expression, dashed line: first order expansion around $\phi = 0$.

this case, and because $x$ and $y$ have been measured, while $|M_{12}|$ and $|\Gamma_{12}|$ are difficult to calculate, it is convenient to express $|q/p|$ in terms of $x$, $y$, $\phi$, using the exact relations (13). From (3), and defining $\tilde{r} = y/x$, we then obtain

$$
|q/p|^2 = \frac{1}{\sqrt{2}(1 + \tilde{r}^2)} \left\{ 2(1 + \tilde{r}^2)^2 + 16\tilde{r}^2 \tan^2 \phi + 8\tilde{r} \tan \phi \sec \phi \sqrt{(1 + \tilde{r}^2)^2 - (1 - \tilde{r}^2)^2 \sin^2 \phi} \right\}^{1/2}.
$$

(20)

Note that for finite $xy$ and $\phi = \pm \pi/2$, $|q/p|$ diverges because $xy \to 0$ for $\phi \to \pm \pi/2$ from (13). In Fig. 1 we plot $|q/p|^2$ as function of $\phi$, for the central experimental value from HFAG, $\tilde{r} = 7.1/8.5$, Eq. (11). It is obvious that even for moderate values of $\phi$ the small-$\phi$ expansion is not really reliable.

What is the currently available experimental information on CP-violating in $D$ mixing, i.e. $|q/p|$ and $\phi$? As already mentioned, the semileptonic CP-asymmetry (14) has not been measured yet. What has been measured, though, is the effect of CP-violation on the time-dependent rates of $D^0 \to K^+\pi^-$ and $\bar{D}^0 \to K^-\pi^+$. The BaBar collaboration has parametrised these rates as

$$
\Gamma(D^0(t) \to K^+\pi^-) \propto e^{-\Gamma t} \left[ R_D + \sqrt{R_D y_+^\prime \Gamma^t} + \frac{x_+^2 + y_+^2}{4} (\Gamma t)^2 \right],
$$

$$
\Gamma(\bar{D}^0(t) \to K^-\pi^+) \propto e^{-\Gamma t} \left[ R_D + \sqrt{R_D y_-^\prime \Gamma^t} + \frac{x_-^2 + y_-^2}{4} (\Gamma t)^2 \right]
$$

(21)

and fit the $D^0$ and $\bar{D}^0$ samples separately. They find

$$
y_+^\prime = (9.8 \pm 6.4 \text{(stat)} \pm 4.5 \text{(syst)}) \times 10^{-3},
$$

$$
y_-^\prime = (9.6 \pm 6.1 \text{(stat)} \pm 4.3 \text{(syst)}) \times 10^{-3}.
$$

(22)

Adding errors in quadrature, this means $y_+^\prime/y_-^\prime = 1.0 \pm 1.1$. BaBar also obtains values for $x_\pm^2$ which we do not quote here, because the sensitivity to the quadratic term in (21) is
less than that to the linear term in $y'_\pm$. $R_{D}^{1/2}$ is the ratio of the doubly Cabibbo-suppressed to the Cabibbo-favoured amplitude, $R_{D}^{1/2} = |A(D^0 \rightarrow K^+\pi^-)/A(D^0 \rightarrow K^-\pi^+)|$. $\delta_{K\pi}$ is the relative strong phase in the Cabibbo-favoured and suppressed amplitudes:

$$\frac{A(D^0 \rightarrow K^+\pi^-)}{A(D^0 \rightarrow K^-\pi^+)} = -\sqrt{R_{D}}e^{-i\delta_{K\pi}}; \quad (23)$$

the minus-sign comes from the relative sign between the CKM matrix elements $V_{cd}$ and $V_{us}$. In the limit of no CP-violation in the decay amplitude, one has $|A(D^0 \rightarrow K^-\pi^+)| = |A(\bar{D}^0 \rightarrow K^+\pi^-)|$, which is expected to be a very good approximation, in view of the fact that the decay is solely due to a tree-level amplitude. Then the relation of $y'_\pm$ to $x$, $y$ and $\phi$ is given by

$$y'_+ = \left| \frac{q}{p} \right| \{ (y \cos \delta_{K\pi} - x \sin \delta_{K\pi}) \cos \phi + (x \cos \delta_{K\pi} + y \sin \delta_{K\pi}) \sin \phi \},$$

$$y'_- = \left| \frac{p}{q} \right| \{ (y \cos \delta_{K\pi} - x \sin \delta_{K\pi}) \cos \phi - (x \cos \delta_{K\pi} + y \sin \delta_{K\pi}) \sin \phi \}. \quad (24)$$

Presently, the experimental result for $y'_+/y'_-$ is compatible with 1, although with considerable uncertainties. Any significant deviation from 1 would be a sign for new physics. In Fig. 2 we plot $y'_+/y'_-$ as function of $\phi$, for different values of $x/y$ and $\delta_{K\pi}$. The figures clearly show that the value of $y'_+/y'_-$ is very sensitive to the phase $\phi$, at least if $\delta_{K\pi}$ is not too close to $-65^\circ$, which corresponds to the nearly constant dashed line in Fig. 2b. The reason for this dependence on $\delta_{K\pi}$ becomes clearer if $y'_+/y'_-$ is expanded to first order in $\phi$:

$$\frac{y'_+}{y'_-} = 1 - 2\phi \frac{x(x^2 + 2y^2) \cos \delta_{K\pi} + y^2 \sin \delta_{K\pi}}{(x^2 + y^2)(x \sin \delta_{K\pi} - y \cos \delta_{K\pi})} + O(\phi^2). \quad (25)$$

For the central values of $x$ and $y$, Eq. (11), this amounts to $1 + 3.4\phi$ for $\delta_{K\pi} = 0$, $1 - 3.3\phi$ for $\delta_{K\pi} = +65^\circ$, and $1 + 0.45\phi$ for $\delta_{K\pi} = -65^\circ$, which explains the shape of the curves in Fig. 2b. Evidently it is important to reduce the uncertainty of $\delta_{K\pi}$, which, as mentioned
earlier, will be achieved within the next few years. On the other hand, as shown in Fig. 2a, $y'_+/y'_-$, which depends only on the ratio $x/y$, but not $x$ and $y$ separately, is not very sensitive to the precise value of that ratio, but very much so to $\phi$. The conclusion is that, even if $x/y$ itself cannot be determined very precisely, $y'_+/y'_-$ will nonetheless be a powerful tool to constrain $\phi$, at least once $\delta_{K\pi}$ will be known more precisely. Already now very large values $\phi \sim \pi/2$ are excluded.

Another, more theory-dependent constraint on $\phi$ can be derived from the value of $y$. This argument centers around the fact that (a) the experimental result (11) is at the top end of theoretical predictions $y_{SM} \sim 1\%$ [17] and (b) new physics indicated by a non-zero value of $\phi$ always reduces the lifetime difference, independently of the value of $x$. This observation is similar to what was found, some time ago, for the $B_s$ system [18]. In order to derive it, we assume that new physics does not affect $\Gamma_{12}$, so that $\Gamma_{12} = \Gamma_{12}^{SM}$. We then have $2|\Gamma_{12}| = \Delta \Gamma^{SM}$ and hence $|y_{SM}| = |\Gamma_{12}|/\Gamma$. Using the relations (13), we can then express the ratio $|\Delta \Gamma/\Delta \Gamma^{SM}|$ in terms of $y_{SM}$, $x$ and $\phi$:

$$\frac{|y|}{|y_{SM}|} = \left| \frac{\Delta \Gamma}{\Delta \Gamma^{SM}} \right| = \left( \frac{y_{SM}^2 + x^2}{y_{SM}^2 + x^2 / \cos^2 \phi} \right)^{1/2}. \quad (26)$$

This implies that new physics always reduces the lifetime difference, independently of the value of $x$ (and any new physics in the mass difference). In particular one has $y = 0$ for $\phi = \pm \pi/2$ and $x \neq 0$, which follows from the 2nd relation (13). Eq. (26) is the manifestation of the fact that one does not need to observe CP-violation in order to constrain it. A famous example for this is the unitarity triangle in $B$ physics, whose sides are determined from CP-conserving quantities only, but nonetheless allow a precise measurement of the size of CP-violation in the SM, via the angles and the area of the triangle. In Fig. 3 we plot $|\Delta \Gamma/\Delta \Gamma^{SM}|$ as a function of $r = x/y_{SM}$. The zero at $\phi = \pm \pi/2$ is clearly visible. The experimental value $|y/y_{SM}| = O(1)$ then excludes phases $\phi$ close to $\pm \pi/2$. In order to make more quantitative statements, apparently a more precise calculation of $y_{SM}$ is needed.

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Figure 3: Plot of $|\Delta \Gamma/\Delta \Gamma^{SM}|$, Eq. (26), as a function of $x/y_{SM}$ and $\phi$.

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1See, however, Ref. [19] for a discussion of the effect of tiny NP admixtures to $\Gamma_{12}$. 

6
Two more CP-sensitive observables related to $D^0 \to K^+K^-$ have been measured by the Belle collaboration [3]:

$$y_{CP} = \frac{1}{2\Gamma} \left[ \Gamma(D^0 \to K^+K^-) + \Gamma(\bar{D}^0 \to K^+K^-) \right] - 1$$

$$A_\Gamma = \frac{1}{2\Gamma} \left[ \Gamma(D^0 \to K^+K^-) - \Gamma(\bar{D}^0 \to K^+K^-) \right] - 1$$

The present experimental value of $y_{CP}$ is given in (7), that for $A_\Gamma$ is $(0.01 \pm 0.30 \text{(stat)} \pm 0.15 \text{(syst)}) \times 10^{-2}$. Again, we can study the dependence of these observables on $\phi$. In Fig. 4a we plot the ratio $y_{CP}/y$, which is a function of $x/y$ and $\phi$, in dependence on $\phi$. As it turns out, this quantity is far less sensitive to $\phi$ than $y'_+ / y'_-$, the reason being that its deviation from 1 is only a second-order effect in $\phi$:

$$y_{CP} = y \left\{ 1 + \phi^2 \frac{x^4 + x^2y^2 - y^4}{2(x^2 + y^2)^2} + O(\phi^4) \right\}.$$  

Hence, unless the experimental accuracy is dramatically increased, and because the results on $y'_+ / y'_-$ and $y / y_{SM}$ already exclude a large CP-odd phase $\phi \approx \pm \pi/2$, it is safe to interpret $y_{CP}$ as measurement of $y$. In Fig. 4b we plot the quantity $A_\Gamma / y_{CP}$. Also here there is a distinctive dependence on $\phi$, with $A_\Gamma / y \propto \phi$ for small $\phi$, but the effect is less dramatic than that in $y'_+ / y'_-$. 

In conclusion, we find that the experimental results on $D$ mixing reported by BaBar and Belle already exclude extreme values of the CP-odd phase $\phi$ close to $\pm \pi/2$. This follows from the result for $y$, which is close to the top end of theoretical predictions and can only be reduced by new physics, and from $y'_+ / y'_- \sim 1$. While $y'_+ / y'_- - 1$ vanishes in the limit of no CP-violation, $y \sim \Delta \Gamma$ is a CP-conserving observable, which demonstrates...
the usefulness of such quantities in constraining CP-odd phases. Also $y_{CP}$, $A_{T}$ and the ratio $A_{T}/y_{CP}$ can be useful in constraining $\phi$. As long as there is no major breakthrough in theoretical predictions for $D$ mixing, which are held back by the fact that the $D$ meson is at the same time too heavy and too light for current theoretical tools to get a proper grip on the problem, the long-distance SM contributions to $x$ will completely obscure any NP contributions and their detection. The observation of CP violation, however, presents a theoretically clean way for NP to manifest itself and it is to be hoped that in the near future, i.e. at the $B$ factories or the LHC, at least one of the plentiful opportunities for NP to show up in CP violation [20] will be realised.

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