New Physics signature in $D^0(\bar{D}^0) \rightarrow f$ effective width asymmetries

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Abstract

In this paper, the approach given in Ref.$^1$ is generalized and a new contribution to the effective time-integrated CP asymmetry $A_{\Gamma}^{CP}$ is obtained. We show that the new contribution is directly proportional to the weak phase responsible for the direct CP violation. As an illustration we apply this approach to $D^0 \rightarrow K^-\pi^+$ decay channel. We show that the large direct CP asymmetry that can be produced in some extensions of the Standard Model such as Left-Rigth models induces a $A_{\Gamma}^{CP}$ around $10^{-4}$ very close to the experimental limit. We also show that the weak phases that appears in the direct CP violation can induce a $A_{\Gamma}^{CP} \neq 0$ even if the strong phases are not large enough to generate an observable direct CP violation.

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I. INTRODUCTION

In $D$ mesons, a lot of experimental work has been done looking for direct or indirect CP Violation (CPV) \cite{2}. For instance, the time-integrated CPV $A_{\Gamma}(D^0 \to f)$ asymmetries in the effective widths for $D_0$ and $\bar{D}_0$ and direct CPV asymmetry ($A^{D_{CP}}_{CP}$) have been measured and their values are given as:

\[
A_{\Gamma}(K^-K^+) = (-0.134 \pm 0.077^{+0.026}_{-0.034}) \% \tag{3}
\]
\[
A_{\Gamma}(\pi^-\pi^+) = (-0.092 \pm 0.145^{+0.025}_{-0.033}) \% \tag{2}
\]
\[
A_{\Gamma}(K^-\pi^+) = (0.009 \pm 0.032) \% \tag{3}
\]
\[
A^{D_{CP}}_{CP}(D^0 \to K^-\pi^+) = (-0.7 \pm 1.9) \% \tag{4}
\]
\[
\Delta A_{CP} \equiv A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = 0.14 \pm 0.16 \pm 0.08\% \tag{5}
\]

The two first processes are simple Cabibbo suppressed (SCS) and the Standard Model (SM) contributions to these asymmetries are expected to be of order $10^{-4}$ \cite{6–9}. The last one is Cabibbo favored (CF). The Cabibbo favored (CF) processes have the great advantage that the Standard Model contributions to CP observables are strongly suppressed \cite{10}. So any observation of CPV in these CF channels will be a strong hint for New Physics. At present time, all results are compatible with no direct or indirect CPV \cite{3–5, 11–13}.

CP Violation and time dependence in decay amplitude due to mixing between neutral mesons have been clearly observed in $K$ and $B$ mesons \cite{2}. In $D$ mesons, the mixing between $D^0$ and $\bar{D}^0$ has been well established \cite{4, 14–19}. But the situation is more difficult as the slow mixing rate between $D^0$ and $\bar{D}^0$ doesn’t permit to measure directly the time-dependence of the $D^0$, $\bar{D}^0$ decays. It is only possible to measure the direct CPV and an effective time-integrated width which usually is assumed to depend on interference between indirect CPV and neutral mesons mixing \cite{20–22}. In Ref. \cite{1}, it has been showed that the situation is much more intricate and that these effective time-integrated widths are also depending on the direct CPV.

In the literature, the study of the interference between direct CPV and mixing has been performed through the introduction of a non-universal weak phase defined as $\delta_f \equiv -\arg(\bar{A}_f/A_f)$ where $A_f$ is the $A(D^0 \to f)$ amplitude \cite{23–25}. It is important to notice that this weak phase is irrelevant for the direct CPV as direct CPV is proportional to $|A_f|^2 - |\bar{A}_f|^2$. To get an observable direct CPV it is necessary that the amplitude, $A_f$, can be written as
the sum of at least two amplitudes with different relative weak and strong phases. So, we
generalize the approach adopted in Ref. [1] to take into account the structure of the direct
CPV and to show that these relative weak and strong phases are contributing to the CPV
in the effective decay widths. Moreover we show that even if the strong phases are too small
to generate an observable direct CPV, the relative weak phase will contribute to the CPV
in the effective decay widths and can compete with Standard Model contributions in some
$D^0 \to f$ decay channels.

The paper is organized as follows: in section II we review the general formalism to treat
the interference between $D^0 - \bar{D}^0$ mixing and different CP violation sources keeping open
the possibilities to have direct or indirect CP violation and generalize the approach used in
Ref. [1] taking into account the structure of direct CPV. We show that even without CPV
in mixing or without observable direct CPV, the New Physics weak phases can contribute
to the effective time-integrated asymmetries. These contributions are new and should be
included in the experimental data analysis as it could mimic the effects of indirect CPV. In
section III we apply our generalized approach to the Cabibbo favored process $D^0 \to K^-\pi^+$.
Finally we conclude in section IV.

II. GENERAL FORMALISM OF CP VIOLATION IN INTERFERENCE BETWEEN $D^0 - \bar{D}^0$ MIXING AND DIFFERENT CP VIOLATION SOURCES

As for the $K$ and $B$ neutral mesons, the mass eigenstates of the neutral $D$ mesones, called
$|D_{1,2}>$, with respective masses $m_{1,2}$ and total widths $\Gamma_{1,2}$, are linear combinations of the
flavor eigenstates $|D^0>$ and $|\bar{D}^0>$ defined as follows:

$$
|D_{1,2}> = p|D0> \pm q|\bar{D}^0>
$$

with the normalization condition imposes $|p|^2 + |q|^2 = 1$. We consider the decay modes
$D^0 \to f$ and $\bar{D}^0 \to f$, with $f$ a CP eigenstate like $f = \bar{f} = K^+K^-, \pi^+\pi^-$ or $K^-\pi^+ + K^+\pi^-
where for the last case, it is used the fact that the process $D^0 \to K^+\pi^-$ is double Cabibbo
suppressed compared to $D^0 \to K^-\pi^+$ which is Cabibbo favored. Using the general formalism
for $D^0 - \bar{D}^0$ mixing, it is possible to compute the respective widths as a function of time
\[ \Gamma_f(t) = \Gamma(D^0 \rightarrow f)(t) \text{ and } \Gamma_f(t) = \Gamma(D^0 \rightarrow f)(t): \]

\[ \Gamma_f(t) = |A_f(t)|^2 = \left| g_+ A_f + \frac{q}{p} g_- A_f \right|^2 \]

\[ = |A_f|^2 \left[ |g_+|^2 + |g_-\lambda_f|^2 + 2\text{Re} \left( g_+^* g_- \lambda_f \right) \right] \]

\[ = \frac{e^{-\Gamma t}}{2} |A_f|^2 \left[ (1 + |\lambda_f|^2) \cosh y \Gamma t + (1 - |\lambda_f|^2) \cos x \Gamma t + 2\text{Re} \lambda_f \sinh y \Gamma t - 2\text{Im} \lambda_f \sin x \Gamma t \right] \]

where \( \Gamma \) is the mean \( D^0 \) width and

\[ |g_\pm|^2 = \frac{1}{2} e^{-\Gamma t} [\cosh y \Gamma t \pm \cos x \Gamma t], \]

\[ g_-^* g_+ = \frac{1}{2} e^{-\Gamma t} [\sinh y \Gamma t - i \sin x \Gamma t], \]

\[ \lambda_f = \frac{q \bar{A}_f}{p A_f} \]

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

where one defines \( A_f = A(D^0 \rightarrow f) \) and \( \bar{A}_f = A(\bar{D}^0 \rightarrow f) \) and \( \Gamma = (\Gamma_1 + \Gamma_2)/2 \) is the average width.

\[ \bar{\Gamma}_f(t) = |\bar{A}_f(t)|^2 = \left| \frac{p}{q} g_-(t) A_f + g_+(t) \bar{A}_f \right|^2 = |\bar{A}_f|^2 \left| g_+(t) + g_-(t) \lambda_f^{-1} \right|^2 \]

\[ = \frac{e^{-\Gamma t}}{2} |\bar{A}_f|^2 \left[ (1 + |\lambda_f^{-1}|^2) \cosh y \Gamma t + (1 - |\lambda_f^{-1}|^2) \cos x \Gamma t + 2\text{Re} (\lambda_f^{-1}) \sinh y \Gamma t - 2\text{Im} (\lambda_f^{-1}) \sin x \Gamma t \right] \]

In the case of \( D \) mesons, these equations can be easily expanded and, to a good approximation, one can keep the terms up to the linear terms in time:

\[ \Gamma_f(t) = e^{-\Gamma t} |A_f|^2 \left[ 1 + (y \text{Re} \lambda_f - x \text{Im} \lambda_f) \Gamma t \right] \]

\[ = e^{-\Gamma t} |A_f|^2 \left[ 1 + |\lambda_f| \left( y \cos \phi_f - x \sin \phi_f \right) \Gamma t \right] \simeq |A_f|^2 e^{-\bar{\Gamma}_f t} \]

\[ \bar{\Gamma}_f(t) = e^{-\Gamma t} |\bar{A}_f|^2 \left[ 1 + (y \text{Re} \lambda_f^{-1} - x \text{Im} \lambda_f^{-1}) \Gamma t \right] \]

\[ = e^{-\Gamma t} |\bar{A}_f|^2 \left[ 1 + |\lambda_f^{-1}| \left( y \cos \phi_f + x \sin \phi_f \right) \Gamma t \right] \simeq |\bar{A}_f|^2 e^{-\bar{\Gamma}_f t} \]  

(13)

with \( \bar{A}_f/A_f = -\eta_f \sqrt{R_f} e^{-i\delta_f} \), so \( \lambda_f = -\eta_f |q/p| \sqrt{R_f} e^{i(\delta - \delta_f)} \equiv -\eta_f |q/p| \sqrt{R_f} e^{i\phi_f} \). The CP eigenvalue of \( f \) is \( \eta_f \). Given that \( e^{-\Gamma t}[1 + b \Gamma t] \simeq e^{-\Gamma(1-b)t} \), so \( \tau \simeq (1 + b)/\Gamma \) and the
effective widths become

$$\hat{\Gamma}_f = \Gamma \left[ 1 - |\lambda_f| (y \cos \phi_f - x \sin \phi_f) \right]$$

$$\hat{\bar{\Gamma}}_f = \Gamma \left[ 1 - |\lambda_f^{-1}| (y \cos \phi_f + x \sin \phi_f) \right]$$

(14)

Now, one can define the following CP observables:

$$A_f^\Gamma = \frac{\tau(D^0 \to f) - \tau(D^0 \to \bar{f})}{\tau(D^0 \to f) + \tau(D^0 \to \bar{f})} = \frac{\hat{\Gamma}_f - \hat{\bar{\Gamma}}_f}{2\Gamma} \approx \frac{\hat{\Gamma}_f - \hat{\bar{\Gamma}}_f}{2\Gamma}$$

$$y_{CP} = \frac{\tau(D^0 \to K^-\pi^+)}{[\tau(D^0 \to f) + \tau(D^0 \to \bar{f})]/2} - 1 \approx \frac{\hat{\Gamma}_f + \hat{\bar{\Gamma}}_f}{2\Gamma} - 1$$

(15)

$$A_f = |A_0| e^{i(\delta_0 + \alpha_0)} + |A_1| e^{i(\delta_1 + \alpha_1)}$$

(17)

$$\bar{A}_f = |A_0| e^{i(-\delta_0 + \alpha_0)} + |A_1| e^{i(-\delta_1 + \alpha_1)}$$

(18)

with \( |\lambda_f| = |q/p| \sqrt{R_f} \to |q/p| \) if no direct CP violation is present. If \( A_f/\bar{A}_f \neq 1 \), a direct CP asymmetry can be generated in the presence of the required strong and weak phases. Let us define

$$A_f = |A_0| e^{i(\delta_0 + \alpha_0)} + |A_1| e^{i(\delta_1 + \alpha_1)}$$

$$\bar{A}_f = |A_0| e^{i(-\delta_0 + \alpha_0)} + |A_1| e^{i(-\delta_1 + \alpha_1)}$$

(17)

where \( \delta_{0,1} \) are the weak phases and \( \alpha_{0,1} \) are the strong CP conserving phases. Here we assume that the amplitude \( A_0 \) comes from the Standard Model and that \( A_1 \) comes from radiative corrections to Standard Model or from New Physics contributions. Thus for \( |A_1/A_0| = \epsilon \ll 1 \), the corresponding CP asymmetry can be expressed, at first order in \( \epsilon \), as:

$$a_{CP}^D = \frac{|A_f|^2 - |\bar{A}_f|^2}{|A_f|^2 + |\bar{A}_f|^2} \approx 2\epsilon \sin \delta \quad \sin \alpha$$

(19)

(20)

where \( \delta = \delta_1 - \delta_0 \) and \( \alpha = \alpha_1 - \alpha_0 \). Using our definition of \( \bar{A}_f/A_f = -\eta_f \sqrt{R_f} e^{-i\delta_f} \), one has

$$R_f = \frac{1 - a_{CP}^D}{1 + a_{CP}^D} \approx 1 - 2 a_{CP}^D$$

(21)

(22)

$$\delta_f \approx 2\delta_0 + 2 \epsilon \cos \alpha \sin \delta$$

(23)

$$\phi_f = \phi - \delta_f$$

(24)
where $\phi = \arg(q/p)$ is the CP violation coming from the neutral mesons mixing.

The experimental values for the mixing and CPV parameters in $D$ neutral mesons are given as \[26\]

$$
\begin{align*}
  x &= 0.41^{+0.14}_{-0.15}\% \\
  y &= 0.63^{+0.07}_{-0.08}\% \\
  a_{CP}^D &= -0.71^{+0.92}_{-0.95} \\
  |q/p| &= 0.93^{+0.09}_{-0.08} \\
  \phi &= -8.7^{+8.7}_{-9.1} \\
  A_f^{K^+\pi^+} &= (0.009 \pm 0.032)\% \ \ \ \text{(30)}
\end{align*}
$$

where the fit assuming all floating parameters is used and $\phi$ is expressed in degree.

Using these expression in Eq.(15), it is possible to evaluate the contribution to $A_f^{f\Gamma}$ coming from the Direct CP asymmetry. In next section, we apply this formalism to the special case of the Cabibbo favored decay $D^0 \rightarrow K^-\pi^+$.

III. $D^0 \rightarrow K^-\pi^+$

The amplitude of the Cabibbo favored $D^0 \rightarrow K^-\pi^+$ decay mode is dominated by the tree-level Standard Model contribution with no weak phase at this order. Radiative corrections to the tree-level amplitude can generate a weak phase. However these corrections are very suppressed \[10\]. So, to a very good approximation, we can set $\delta_0 = 0$. To generate large weak phases, required for large direct CP asymmetry, it is necessary to go beyond Standard Model. In Ref.\[10\], a direct CP asymmetry in this channel of order $10^{-2}$ could be obtained in some class of Left-Right models still compatible with present experimental constraints.

In order to illustrate our approach, we assume that there is no CP violation in the mixing which means that $\phi = 0$ and $|q/p| = 1$. In this case, one has

$$
\phi_f = -\delta_f = -2 \epsilon \cos \alpha \sin \delta \ \ \ \text{(32)}
$$

Using eq.(15), we obtain

$$
A_f^{f\Gamma} \approx 2 \epsilon \sin \delta \left( x \cos \alpha - y \sin \alpha \right) \ \ \ \text{(33)}
$$
The second term is a contribution which is directly proportional to direct CP asymmetry. This contribution has already been noticed in Ref. [1]. The first term is new and usually it is not taken into account. It is important to emphasize that the second term will vanish upon setting $\alpha \approx 0$. However, for $\alpha \approx 0$, the first term can generate a non-zero contribution to $A^D_{f}$ thanks to the weak phase $\delta$. This contribution is given as

$$A^f_\Gamma \approx 2 \epsilon x \sin \delta \quad (34)$$

In such a case, using the experimental limit for the mixing parameters and assuming $\epsilon$ to be of order $0.01$ and a maximal $\delta$ CP violating phase, one obtains

$$A^f_\Gamma \approx 0.82 \times 10^{-4} \quad (35)$$

which is very close to its experimental limit. These values can be easily obtained in non-manifest left right models as it has been shown in Ref. [10].

If it is possible experimentally to measure the effective time-integrated CP asymmetry and the Direct CP asymmetry, it will be possible to get access to the strong phase via the relation

$$\tan \alpha \approx \frac{x a^D_{CP}}{A^f_\Gamma + y a^D_{CP}} \quad (36)$$

IV. CONCLUSION

In this work we have generalized the approach given in Ref. [1] where the interplay between direct and indirect CPV has been studied. Usually, the non-universality in the weak phase $\phi_f$ is taken into account but the relative weak phase between $A_f$ and $\bar{A}_f$ is irrelevant for direct CPV. We have studied the CP asymmetry $A^{CP}_{f}$ in the time-integrated effective widths and the effects of the weak and strong phases needed to generate direct CPV. The interference between this weak phase and the mixing induces a contribution to $A^{CP}_{f}$.

We have shown that the $A^{CP}_{f}$ gets three and not only two different contributions:

- $\arg(p/q) \neq 0$ or $\pi$ which is the well-known contribution coming from CPV in mixing and should be the same for all $D^0 \to f$ decay channels.

- $A^{D}_{CP} \neq 0$, where $A^{D}_{CP}$ is any direct CPV as it has been shown in Ref. [1].
\( \delta \neq 0 \) or \( \pi \) where \( \delta \) is the relative weak phase between two amplitudes contributing to \( A_f \) or \( \bar{A}_f \). One important point of our results is that this contribution still exists even if the strong phases responsible for the direct CPV are set to zero which implies \( A^D_{CP} = 0 \)

This last contribution is usually not taken into account even if in some extension of the Standard Model, this contribution could be as large as the one coming from mixing. For instance, we have shown that for the \( D^0 \to K^- \pi^+ \) in a non manifest left right model, a \( A^D_{CP} \) of order \( 10^{-4} \) can be generated.

In conclusion, the CPV in time-integrated effective widths is very sensitive to both the scale and weak phases of New Physics. Particularly, if the scale of New Physics implies that \( \epsilon \) is around 0.01 which means typically \( TeV \) scale, this new contribution to the CPV in the effective widths could give contributions of the same order or larger than the one expected from CPV in mixing or from Standard Model radiative corrections.

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