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# ANGULAR CORRELATIONS IN $D\bar{D} \to (VV)(VV)$ coherent decays

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We report on our recent proposal to consider correlated $D^0\bar{D}^0$ decays to vector mesons. Thanks to the quantum and angular correlations, we show that new observables appear, that allow either to search for CP-violation or to extract the hadronic phase in $D \to K\pi$.

## 1. Introduction

Recent analyses at charm factories have started to exploit coherent decays of $D^0\bar{D}^0$ meson pairs, that lead to new fruitful information on the underlying fundamental processes. The main application is the extraction of phases, that can be of hadronic origin (final state interactions) or short-distance CP-violating couplings.

In these proceedings we report on Ref. 1 that extends the needed formalism to the case of final states with two vector mesons or more.

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## 2. Basic formalism

We consider an antisymmetric coherent state produced at a charm factory running at the $\psi(3770)$ resonance. Focusing on final states with light pseudoscalar ($P$) or vector ($V$) mesons we have the following possibilities:

- $(PP)(PP)$, $(PP)(VP)$, $(VP)(VP)$: the only observable is the total rate, since the helicities are fixed by angular momentum conservation
- $(PP)(VV)$, $(VP)(VV)$: $(VV)$ has three helicity states, which adds new angular (interference) observables; with $(PP) = (K\pi)$ it is used below for the measurement of hadronic parameters
- $(VV)(VV)$: both meson pairs exhibit non-trivial angular dependence, which is exploited below for the study of CP-violation

The helicity formalism to extract the angular dependence of the channels with at least one pair of vector mesons is standard. The full formulae can be found in the original paper [1]. The key point is that the angular structure allows the measurement of relative phases between the three helicy amplitudes.

### 2.1. *CP-forbidden transitions*

Correlated $D^0\bar{D}^0$ decay to a pair $f_a f_b$ of CP eigenstates of the same parity violate the CP symmetry [2]. It can readily be seen from the expression of the rate [a]

$$\mathcal{B}(D^0\bar{D}^0 \to f_a f_b) = 2\mathcal{B}_a\mathcal{B}_b|\rho_a - \rho_b|^2 \tag{1}$$

with $\rho_f = A(\bar{D}^0 \to f)/A(D^0 \to f)$. Thus CP is violated if $\rho_a \neq \rho_b$ (in particular $a \neq b$). This pattern of CP-violation is different from the more usual CP-asymmetries in decays: it is well possible that the individual decay $D \to f$ conserves CP ($|\rho_f| = 1$) while not the correlated $D^0\bar{D}^0 \to f_a f_b$ ($\rho_a \neq \rho_b$).

In practice though, if both types of CP-violation are of the same order, the CP-forbidden correlated $D^0\bar{D}^0$ decays are expected to be strongly suppressed because of the present bounds on CP-asymmetries in the $D$ system: one thus needs to study and combine as many channels as possible to improve the sensitivity to potential New Physics effects. In addition to $D \to PP$, $D \to PV$ and $D \to VV$ are worth the effort, thanks to the sizable branching ratios for some of them (see Table 1).

As pointed out above the $D \to VV$ transition is described by three helicity or transversity amplitudes. The transversity amplitudes $A_0$, $A_\perp$ and $A_{||}$ have CP-eigenvalues $+1$, $+1$ and $-1$. Thus CP conservation implies that only the $(0, \perp)$ and $(0, ||)$ combinations are allowed in $D^0\bar{D}^0 \to (VV)(VV)$. Both CP-allowed and CP-forbidden combinations can be extracted from a full angular likelihood fit. On the other hand each individual term can be readily obtained from a specific weighted integral of the differential rate. For example the longitudinal-longitudinal product

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[a] For simplicity, $D^0\bar{D}^0$ mixing is neglected throughout.

Table 1. Individual branching ratios and detection efficiencies for selected $D$ decays to a vector meson pair.

| $VV$ | $\mathcal{B}$ (%) | $\epsilon^2$ |
|---|---|---|
| $\rho^0\rho^0$ | 0.18 | 0.24 |
| $K^{*0}_{CP}\rho^0$ | 0.27 | 0.12 |
| $\rho^0\phi$ | 0.14 | 0.07 |
| $K^{*0}_{CP}\omega$ | 0.33 | 0.09 |
| $\rho^+\rho^-$ | [$\sim$ 0.6] | 0.18 |
| $\rho^0\omega$ | [$\sim$ 0] | 0.18 |
| $K^{*+}K^{*-}$ | [0.08] | 0.07 |
| $K^{*0}_{CP}\bar{K}^{*0}_{CP}$ | 0.003 | 0.09 |

in $D^0\bar{D}^0 \to (V_1V_2)(V_3V_4)$ reads

$$\begin{aligned}&\int d\Gamma_{4V}\frac{1}{128}(5\cos^2\theta_1-1)(5\cos^2\theta_2-1)(5\cos^2\theta_3-1)(5\cos^2\theta_4-1)\\&\sim |A(D^0->V_1V_2|^2|A(D^0->V_3V_4|^2\times|\rho^0_{V_1V_2}-\rho^0_{V_3V_4}|^2\end{aligned}\tag{2}$$

while the longitudinal-parallel product in the decay to $D^0\bar{D}^0 \to (V_1V_2)(V_1V_2)$ is given by

$$\begin{aligned}&\int d\Gamma_{4V}\prod_{i=1}^{4}(5\cos^2\theta_i-1)(5\cos^2\theta_i-3)(4\cos^2\Phi_{12}-1)(4\cos^2\Phi_{34}-1)\\&\sim |A(D^0->V_1V_2|^2|A(D^0->V_1V_2|^2\times|\rho^0_{V_1V_2}-\rho^{||}_{V_1V_2}|^2\end{aligned}\tag{3}$$

To see that the CP-violating terms that we discussed are actually driven by weak phases one parametrizes $\rho_f$ with $\rho_f = \eta_f(1+\delta_f)\exp(i\alpha_f)$ where $\delta_f$ represents CP-violation in decay, and $\alpha_f$ is a CP-odd phase. Then the rate becomes proportional to (assuming $\delta_f = 0$ for simplicity)

$$|\rho_a-\rho_b|^2 = 4\sin^2\frac{\alpha_a-\alpha_b}{2}\tag{4}$$

At the BES-III experiment, with about 20 fb$^{-1}$ of data, one would get from the non observation of the CP-violating terms in $(\rho^0\rho^0)(K^{*0}_{\rm CP}\rho^0)$ the upper bound

$$|\alpha_{\rho\rho}-\alpha_{K^*\rho}| < 4^\circ\tag{5}$$

that represents only the purely statistical uncertainty [1]. In addition to this one will have to take into account the experimental systematics, and in particular the effect of the finite width of the resonances that induces a non eigen-CP component in the final state.

### 2.2. $D\bar{D} \to (K\pi)(VV)$ and the phase $\delta$

The ratio of Cabibbo-suppressed to Cabibbo-allowed amplitudes

$$re^{i\delta} \equiv \frac{A(\bar{D}^0 \to K^+\pi^-)}{A(D^0 \to K^+\pi^-)} \tag{6}$$

is an important input to the extraction of the CKM angle $\gamma$ in $B$ decays to $DK$ final states [3,4]. In particular the hadronic phase $\delta$ still comes with a sizable uncertainty, $\cos\delta = 1.10 \pm 0.36$ [5].

Replacing one $VV$ pair in the previous section by $K\pi$, which technically amounts to select one of the transversity amplitudes, one finds that the differential $D^0\bar{D}^0 \to (K^\pm\pi^\mp)(VV)$ decay rate depends on the following three combinations of amplitudes

$$M_{0,||} = A_{0,||}(1 + re^{i\delta})\,, \quad M_\perp = A_\perp(1 - re^{i\delta})\,. \tag{7}$$

From the full angular dependence one gets independently the ratio $r$, as well as $\cos\delta$ and $|\sin\delta|$. The latter sensitivity on the sine is welcome as $\delta$ is small and thus the cosine is only quadratically dependent on the phase. Other ways to measure $\sin\delta$ involves keeping $D\bar{D}$ mixing terms, and/or analysing multibody decays such as $D\bar{D} \to (K\pi)(K\pi\pi)$ [4].

Numerically, with 20 $\text{fb}^{-1}$ of data at the BES-III experiment, one expects an uncertainty on $\delta$ extracted from $D \to (K\pi)(VV)$ of about a few degrees, from purely statistical arguments. Again the systematics should be estimated from the realistics simulation of the experimental environment in order to draw a more definite number.

## 3. Conclusion

Correlated $D^0\bar{D}^0$ decays to final states with at least one pair of vector mesons provide new interference terms that are sensitive to the phases of the underlying amplitudes.

In $D\bar{D} \to (VV)(VV)$ CP-forbidden correlations are a nice test of the Standard Model, and are a different manifestation of the violation of the CP-symmetry.

On the other hand in $D\bar{D} \to (K\pi)(VV)$ one can extract simultaneously $r$, $\cos\delta$ and $|\sin\delta|$ that are valuable inputs to the extraction of the CP-phase $\gamma$ in $B$ decays.

From the pure statistical point of view the prospects at the BES-III experiment are promising, with an uncertainty on the phases of about a few degrees. A realistic estimate of the systematics, and in particular of the impact of the finite resonance widths, is however needed.

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