$CP$ content of $D^0 \to h^+h^-\pi^0$

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Quantum-correlated $\psi(3770) \to DD$ decays collected by the CLEO-c experiment are used to perform measurements of $F_+$, the fractional $CP$-even content of the self-conjugate decays $D \to \pi^+\pi^-\pi^0$ and $D \to K^+K^-\pi^0$. Values of $0.973 \pm 0.017$ and $0.732 \pm 0.055$ are obtained for $\pi^+\pi^-\pi^0$ and $K^+K^-\pi^0$, respectively. The high $CP$-even content of $D \to \pi^+\pi^-\pi^0$, in particular, makes this a promising mode for improving the precision on $\gamma$ and for measurements of $CP$ violation in $D$ decay.

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1 Introduction

A better determination of the unitarity triangle angle $\gamma = \arg(-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*)$ is required for testing the $CP$ violation mechanism within the Standard Model. Sensitivity to $\gamma$ can be obtained by studying $CP$-violating observables in $B^{\mp} \rightarrow D K^{\mp}$ decays, where $D$ indicates a neutral charm meson reconstructed in a final state common to both $D^0$ and $D^{*0}$ mesons, including $CP$-eigenstates [1]. The current world average precision on $\gamma$ is much worse than that of the other angles of the unitarity triangle [2]. Therefore, including additional $D$-meson final states is desirable to reduce the statistical uncertainty on $\gamma$ at current and future facilities.

In the case that the $D$ does not decay to a pure $CP$ eigenstate, information is required on the strong decay dynamics in order to relate the $CP$-violating observables to $\gamma$. This information can be obtained from studies of quantum-correlated $D \bar{D}$ mesons produced in $e^+e^-$ collisions at an energy corresponding to the mass of the $\psi(3770)$ [3, 4, 5, 6]. The decay $D \rightarrow \pi^+\pi^-\pi^0$ is a promising candidate to be added to the modes used in the $\gamma$ measurement. Its Dalitz plot has been studied by the CLEO and BaBar collaboration using flavour-tagged $D^0$ decays and exhibits a strikingly symmetric distribution that suggests the decay may be dominated by a single $CP$ eigenstate [7, 8]. An isospin analysis [9] of the amplitude model for $D^0 \rightarrow \pi^+\pi^-\pi^0$ presented in Ref. [8] concludes that the final state is almost exclusively $I = 0$. Therefore, given that the parity and $G$-parity of the three-pion final state is odd and $G = (-1)^I C$, the final state is expected to be $C = -1$ and $CP = +1$. As its branching ratio of $1.43 \pm 0.06\%$ [2] is significantly larger than those of the pure two-body $CP$-even modes, it has the potential to contribute strongly in any analysis making use of such decays. The channel $D \rightarrow K^+K^-\pi^0$ is a similar, but less abundant, self-conjugate mode that has also attracted interest [10, 11]. These proceedings present the first analysis of these decays using quantum-correlated $D \bar{D}$ decays, and measurements of their $CP$ content, making use of the CLEO-c $\psi(3770)$ data set. These measurements allow the inclusive decays to be included in future $B^{\mp} \rightarrow D K^{\mp}$ analyses in a straightforward and model-independent manner, thus allowing for an improved determination of the angle $\gamma$. Further it has been shown that improved determinations of $CP$ violating parameters in the charm sector can be made with these measurements [12].

These proceedings are based on Refs. [13] and [14] and are structured as follows. Section 2 describes how quantum-correlated $D$ decays are used to determine the $CP$ content. The results are presented in Sect. 3. In Sect. 4 the implications for the measurement of the unitarity triangle angle $\gamma$ are discussed. Section 5 gives the conclusions.
2 Measuring the CP content

Consider a $\psi(3770) \to D\bar{D}$ analysis in which the signal decay mode is $D \to h^+h^-\pi^0$. Let $M^+$ designate the number of “double-tagged” candidates, after background subtraction, where one $D$ meson is reconstructed in the signal mode of interest, and the other is reconstructed in a CP-odd eigenstate. The quantum-numbers of the $\psi(3770)$ resonance then require that the signal mode is in a CP-even state, hence the $+ \,$ superscript. The observable $M^-$ is defined in an analogous manner. Let $S^+$ ($S^-$) designate the number of “single-tagged” CP-odd (CP-even) candidates in the data sample, where a $D$ meson is reconstructed decaying to a CP eigenstate, with no requirement on the final state of the other $D$ meson in the event. The small effects of $D^0\bar{D}^0$ mixing are eliminated from the measurement [13].

On the assumption that for double-tagged candidates the reconstruction efficiencies of each $D$ meson are independent, then the quantity $N^+ \equiv M^+/S^+$ has no dependence on the branching fractions or reconstruction efficiencies of the CP-eigenstate modes, and can be directly compared with the analogous quantity $N^-$ to gain insight into the CP content of the signal mode. The $CP$ fraction is defined

$$F_+ \equiv \frac{N^+}{N^+ + N^-},$$

and is 1 (0) for a signal mode that is fully $CP$-even ($CP$-odd). The notation $F_+(\pi^+\pi^-\pi^0)$ and $F_+(K^+K^-\pi^0)$ is used in the discussion when it is necessary to distinguish between the two final states. In addition, tagging the final state with $K^0\pi^+\pi^-$ and measuring the yield in bins of the $K^0\pi^+\pi^-$ Dalitz of plot for which the strong phase parameters of the decay are known [15] yields further sensitivity to $F_+$ [14].

Amplitude models of $D^0 \to \pi^+\pi^-\pi^0$ and $D^0 \to K^+K^-\pi^0$ are available from studies of flavour-tagged $D^0$ decays performed by the BaBar collaboration [8 11]. These models can be used to calculate predictions for the CP content for each decay. Values of $F_+(\pi^+\pi^-\pi^0) = 0.92$ and $F_+(K^+K^-\pi^0) = 0.64$ are obtained.

3 Results

The data set analysed consists of $e^+e^-$ collisions produced by the Cornell Electron Storage Ring (CESR) at $\sqrt{s} = 3.77$ GeV and collected with the CLEO-c detector. The integrated luminosity of the data set is 818 pb$^{-1}$. The CLEO-c detector is described in detail elsewhere [16]. Simulated Monte Carlo (MC) samples of signal decays are used to estimate selection efficiencies. Possible background contributions are determined from a generic MC sample corresponding to approximately ten times the integrated luminosity of the data set. The EVTGEN generator [17] is used to
simulate the decays. The detector response is modelled using the GEANT software package [18].

Table 1 lists the reconstructed $D^0$ and $\bar{D}^0$ final states. The unstable final state particles are reconstructed in the following decay modes: $\pi^0 \to \gamma \gamma$, $K^0_S \to \pi^+ \pi^-$, $\omega \to \pi^+ \pi^- \pi^0$, $\eta \to \gamma \gamma$, $\eta \to \pi^+ \pi^- \pi^0$ and $\eta' \to \eta(\gamma \gamma) \pi^+ \pi^-$. The $\pi^0$, $K^0_S$, $\omega$, $\eta$ and $\eta'$ reconstruction procedure is identical to that used in Ref. [19].

| Type         | Final states                  |
|--------------|-------------------------------|
| Signal       | $\pi^+ \pi^- \pi^0$, $K^+ K^- \pi^0$ |
| $CP$-even    | $K^0 S \pi^0$, $K^0 \pi^0$, $K^0_\omega$, $K^0_\eta$, $K^0_\eta'$ |
| $CP$-odd     | $K^0 S \pi^0$, $K^0 \pi^0$, $K^0_\omega$, $K^0_\eta$, $K^0_\eta'$ |
| Mixed CP     | $K^0_\omega$, $K^0_\eta$, $K^0_\eta'$ |

Final states that do not contain a $K^0_L$ are fully reconstructed via two kinematic variables: the beam-constrained candidate mass, $M_{bc} \equiv \sqrt{s/4c^4} - p_D^2/c^2$, where $p_D$ is the $D$-candidate momentum, and $\Delta E \equiv E_D - \sqrt{s}/2$, where $E_D$ is the $D$-candidate energy. The $M_{bc}$ and $\Delta E$ distributions of correctly reconstructed $D$-meson candidates will peak at the nominal $D^0$ mass and zero, respectively. Neither $\Delta E$ nor $M_{bc}$ distributions exhibit any peaking structure for combinatoric background. The double-tagged yield is determined from counting events in signal and sideband regions of $M_{bc}$ after placing requirements on $\Delta E$. The yield determination procedure is identical to that presented in Refs. [20, 19].

The selection procedures are almost identical to those presented in Refs. [20, 19]; additional details of the selection can be found in Ref. [13]. Figure 1 shows the $M_{bc}$ distributions for $CP$-tagged signal candidates, summed over all $CP$-even and $CP$-odd tags, respectively, where the $CP$-tag final state does not contain a $K^0_L$ meson. No significant signal is seen in any of the modes tagged by a $CP$-even eigenstate, whereas significant signals are seen in most modes tagged by $CP$-odd eigenstates.

Many $K^0_L$ mesons produced do not deposit any reconstructible signal in the detector. However, double-tag candidates can be fully reconstructed using a missing-mass squared ($M_{miss}^2$) technique [21] for tags containing a single $K^0_L$ meson. Yields are extracted from the signal and sideband regions of the $M_{miss}^2$ distribution. Figure 2 shows the $M_{miss}^2$ distributions for candidates tagged with either a $K^0_L \pi^0$ or $K^0_\omega$ tag.

It is also necessary to know the single-tag yield for the $CP$-eigenstates to normalise the double-tagged yields appropriately to obtain a value of $F_+$. The details of this selection can be found in Ref. [13].

The yields of double-tagged and single $CP$-tag candidates are used to determine the quantities $N^+$ and $N^-$, and from these the $CP$ fraction $F_+$. The values for
$N^+$ and $N^-$ are calculated from the ensemble of $CP$-odd and $CP$-even tags, respectively, accounting for statistical and systematic uncertainties, and allowing for the correlations that exist between certain systematic components.

The measured values for $N^+$ and $N^-$ for the two signal modes are displayed in Fig. 3. It can be seen that there is consistency between the individual $CP$ tags for each measurement. From these results it is determined that $F_+(\pi^+\pi^-\pi^0) = 0.968 \pm 0.017 \pm 0.006$ and $F_+(K^+K^-\pi^0) = 0.731 \pm 0.058 \pm 0.021$, where the first uncertainty is statistical and the second is systematic. In addition, the binned yields from the $K^0_{L,S}\pi^+\pi^-$ tagged are used to determine values of $F_+$ which are found to be consistent with those from the $CP$ tags alone [14]. The combined values are $0.973 \pm 0.017$ and $0.732 \pm 0.055$ for $\pi^+\pi^-\pi^0$ and $K^+K^-\pi^0$, respectively [14]. These values are slightly higher than, but compatible with, the model predictions reported in Sect. 2.

4 Implications for the measurement of $\gamma$

Sensitivity to the unitarity triangle angle $\gamma$ is obtained by measuring the relative rates of $B^\pm \to D(h^+h^-\pi^0)K^\mp$ decays and related observables. These partial widths and those involving flavour-specific $D$ meson decays can be used to construct the partial-widths ratio $R_{F_+}$ and $CP$-asymmetry $A_{F_+}$:

$$R_{F_+} \equiv \frac{\Gamma(B^- \to D_{F_+}K^-) + \Gamma(B^+ \to D_{F_+}K^+)}{\Gamma(B^- \to D^0K^-) + \Gamma(B^+ \to D^0K^+)}.$$

Figure 1: $M_{bc}$ distributions for $D \to \pi^+\pi^-\pi^0$ candidates tagged by $CP$-even (a) and $CP$-odd (b) eigenstates. Tags involving a $K^0_L$ are not included. The vertical dotted lines indicate the applied signal window.
Figure 2: $M^2_{\text{miss}}$ distributions for $D \to \pi^+ \pi^- \pi^0$. The shaded histogram indicates the peaking background. The vertical dotted lines indicate the applied signal window.

\[
A_{F^+} \equiv \frac{\Gamma(B^- \to D_{F^+} K^-) - \Gamma(B^+ \to D_{F^+} K^+)}{\Gamma(B^- \to D_{F^+} K^-) + \Gamma(B^+ \to D_{F^+} K^+)},
\]

where $D_{F^+}$ indicates a $D$ meson of $CP$-even content $F^+$, established through its decay into the final state $h^+ h^- \pi^0$. These observables are directly analogous to the usual so-called GLW [1] observables $R_{CP^\pm}$ and $A_{CP^\pm}$, where the $D$ meson is reconstructed in a pure $CP$ eigenstate.

Then $R_{F^+}$ and $A_{F^+}$ are found [13] to have the following dependence on the underlying physics parameters:

\[
R_{F^+} = 1 + r^2_B + (2F^+ - 1) \cdot 2r_B \cos \delta_B \cos \gamma,
\]
\[
A_{F^+} = (2F^+ - 1) \cdot 2r_B \sin \delta_B \sin \gamma/R_{F^+},
\]

which reduces to the equivalent expressions for $R_{CP^\pm}$ and $A_{CP^\pm}$ in the case $F^+$ is 1 or 0. Therefore inclusive final states such as $h^+ h^- \pi^0$ may be cleanly interpreted in terms of $\gamma$ and the other parameters of interest, provided that $F^+$ is known. At leading order the only difference that the $CP$ asymmetry $A_{F^+}$ has with respect to the pure $CP$-eigenstate case is a dilution factor of $(2F^+ - 1)$.

5 Conclusion

Data corresponding to an integrated luminosity of 818 pb$^{-1}$ collected by the CLEO-c experiment in $e^+e^-$ collisions at the $\psi(3770)$ resonance have been analysed for
the decays $D \to \pi^+\pi^-\pi^0$ and $D \to K^+K^-\pi^0$. Measurements of $F_+$, the fractional $CP$-even content of each decay have been performed showing that $D^0 \to \pi^+\pi^-\pi^0$ is nearly a pure $CP$-even eigenstate. It has been demonstrated that such self-conjugate inclusive channels can be cleanly included in measurements of the unitarity-triangle angle $\gamma$, using $B^\mp \to DK^\pm$ decays. The high value of $F_+$ obtained for $D \to \pi^+\pi^-\pi^0$ makes this channel, in particular, a valuable addition to the suite of $D$-decay modes used in the measurement of $\gamma$ at LHCb and Belle-II. Improved precision on the $F_+$ parameters can be obtained using the larger $\psi(3770)$ data set available at BESIII, and similar measurements can also be performed for other self-conjugate final states.

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