REVIEW OF D-MESON DALITZ PLOT ANALYSES

Revised April 2008 by D. Asner (Carleton University)

The formalism of Dalitz-Plot analysis is reviewed in the preceding note. Recent studies of multi-body decays of charm mesons probe a variety of physics including γ/ϕ_3, D^0–$\overline{D}^0$ mixing, searches for CP violation, doubly Cabibbo-suppressed decays, and properties of S-wave $\pi\pi$, $K\pi$, and KK resonances. In the following, we discuss: (1) $D^0 \to K^0_S\pi^+\pi^-$; (2) doubly Cabibbo-suppressed decays; and (3) CP violation.

$\boldsymbol{D^0 \to K^0_S\pi^+\pi^-}$: Several experiments have analyzed $D^0 \to K^0_S\pi^+\pi^-$ decay. A CLEO analysis [1] of this process included ten resonances: $K^0_S\rho^0$, $K^0_S\omega$, $K^0_S f_0(980)$, $K^0_S f_2(1270)$, $K^0_S f_0(1370)$, $K^*(892)^-\pi^+$, $K^*_0(1430)^-\pi^+$, $K^*_2(1430)^-\pi^+$, $K^*(1680)^-\pi^+$, and the doubly Cabibbo-suppressed (DCS) mode $K^*(892)^+\pi^-$. A BABAR analysis [2–4] added to these ten the $K^*(1410)^-\pi^+$, $K^0_S\rho(1450)$, the DCS resonances $K^*_0(1430)^+\pi^-$ and $K^*_2(1430)^+\pi^-$, and two Breit-Wigner $\pi\pi$ S-wave contributions. A Belle analysis [5–7] included all the components of BABAR and added two more DCS contributions, $K^*(1410)^+\pi^-$ and $K^*(1680)^+\pi^-$.

The primary motivation for the analysis of the decay $D^0 \to K^0_S\pi^+\pi^-$ is to study $D^0 - \overline{D}^0$ oscillations and the CKM angles. The quasi-two-body intermediate states include both CP-even and CP-odd eigenstates as well as doubly Cabibbo-suppressed channels. A time-dependent analysis of the Dalitz plot from CLEO [8] and Belle [9] allows simultaneous determination of the strong transition amplitudes and phases, the mixing parameters x and y without phase or sign ambiguity, and the CP-violating parameter $|q/p|$ and $\mathrm{Arg}(q/p)$. See the note on "$D^0 - \overline{D}^0$ Mixing" for a discussion.

The CKM angle γ/ϕ_3 [10] and the quark-mixing parameter $\cos 2\beta/\phi_1$ [11] can be determined with the process $B^- \to D^{(*)}K^{(*)-}$ and $\overline{B}^0 \to Dh^0$, respectively, followed by the decay $D \to K^0_S\pi^+\pi^-$. The Belle and BABAR experiments measured γ/ϕ_3 (Belle [5–7] and BABAR [2–4]) and $\cos 2\beta/\phi_1$ (Belle [12], BABAR [13]) . In these analyses, a large systematic uncertainty

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in the relative phase between the D^0 and $\overline{D}^0$ amplitudes point by point across the Dalitz plot remains to be fully understood.

The CLEO model with only ten submodes does not provide a good description of the higher-statistics BABAR and Belle data samples. An improved description is obtained in two ways: First, by adding more Breit-Wigner resonances, including two $\pi\pi$ resonances with arbitrary mass and width. Second, following the methodology of FOCUS [14], by applying a K-matrix model to the $\pi\pi$ S-wave [9,2].

The quantum entangled production of D's from $\psi(3770)$ enables a model-independent determination of the $D^0-\overline{D}^0$ relative phase. Studying CP-tagged Dalitz plots [15,16] provides sensivity to the cosine of the relative phase, while studying double-tagged Dalitz plots [16] probes both the cosine and sine of the $D^0-\overline{D}^0$ phase difference. CLEO analyzed [17] the $D^0 \to K^0_S\pi^+\pi^-$ and $D^0 \to K^0_L\pi^+\pi^-$ samples using the CP-even tag modes K^+K^-, $\pi^+\pi^-$, $K^0_L\pi^0$ (vs. $K^0_S\pi^+\pi^-$ only), the CP-odd tag modes $K^0_S\pi^0$, $K^0_S\eta$, and the double-tag modes $(K^0_S\pi^+\pi^-)^2$ and $(K^0_S\pi^+\pi^-)(K^0_L\pi^+\pi^-)$. These measurements can reduce the model uncertainty on γ/ϕ_3 to about 3°.

Doubly Cabibbo-Suppressed Decays: There are two classes of multibody doubly Cabibbo-suppressed (DCS) decays of D mesons. The first consists of those in which the DCS and corresponding Cabbibo-favored (CF) decays populate distinct Dalitz plots; the pairs $D^0 \to K^+\pi^-\pi^0$ and $D^0 \to K^-\pi^+\pi^0$, or $D^+ \to K^+\pi^+\pi^-$ and $D^+ \to K^-\pi^+\pi^+$, are examples. Our average of three measurements of $\Gamma(D^0 \to K^+\pi^-\pi^0)/\Gamma(D^0 \to K^-\pi^+\pi^0)$ is $(2.20 \pm 0.10) \times 10^{-3}$. Our average of three measurements of $\Gamma(D^+ \to K^+\pi^-\pi^+)/\Gamma(D^+ \to K^-\pi^+\pi^+)$ is $(6.8 \pm 0.8) \times 10^{-3}$; see the Particle Listings.

The second class consists of decays in which the DCS and CF modes populate the same Dalitz plot; for example, $D^0 \to K^{*-}\pi^+$ and $D^0 \to K^{*+}\pi^-$ both contribute to $D^0 \to K^0_S\pi^+\pi^-$. In this class, the potential for interference of DCS and CF amplitudes increases the sensitivity to the DCS amplitude and allows direct measurement of the relative strong phases between amplitudes. CLEO [1] and Belle [9] have measured the relative phase between $D^0 \to K^*(892)^+\pi^-$ and $D^0 \to K^*(892)^-\pi^+$ to be $(189 \pm 10 \pm 3^{+15}_{-5})^\circ$ and $(171.9 \pm 1.3)^\circ$ (statistical error only). These results are close to the 180° expected from Cabibbo factors and a small strong phase.

Additionally, Belle [9] has reported results for both the relative phase (statisical errors only) and ratio R (central values only) of the DCS fit fraction relative to the CF fit fractions for $K^*(892)^+\pi^-$, $K_0^*(1430)^+\pi^-$, $K_2^*(1430)^+\pi^-$, $K^*(1410)^+\pi^-$, and $K^*(1680)^+\pi^-$. The reported values for R, in units of $\tan^4\theta_c$, are 2.94 ± 0.12, 22.0 ± 1.6, 34 ± 4, 87 ± 13, and $(5 \pm 5) \times 10^2$. For $K^+\pi^-$, the corresponding value for R is $(1.28 \pm 0.02) \times \tan^4\theta_c$. Similarly, BABAR [2] has reported central values for R for $K^*(892)^+\pi^-$, $K_0^*(1430)^+\pi^-$, and $K_2^*(1430)^+\pi^-$. In units of $\tan^4\theta_c$, R is 3.45 ± 0.31, 7.7 ± 3.0, and 1.7 ± 1.7. The systematic uncertainties on these values remain to be evaluated. The large differences in R among these final states, if significant, could point to an interesting role for hadronic effects that deserves theoretical attention.

(There are other ways, not involving DCS decays, in which D^0 and $\overline{D}^0$ decays can populate the same Dalitz plot. Examples are D^0 and $\overline{D}^0$ decays to $K^0_S K^+\pi^-$, or to $K^0_S K^-\pi^+$. These final states can be used to study D^0–$\overline{D}^0$ mixing and the CKM angle γ/ϕ_3.)

CP* *Violation: In the limit of CP conservation, charge conjugate decays will have the same Dalitz-plot distribution. The $D^{*\pm}$ tag enables the discrimination between D^0 and $\overline{D}^0$. The integrated CP violation across the Dalitz plot is determined in two ways. The first uses

$$\mathcal{A}_{CP} = \int \left(\frac{|\mathcal{M}|^2 - |\overline{\mathcal{M}}|^2}{|\mathcal{M}|^2 + |\overline{\mathcal{M}}|^2} \right) dm^2_{ab}\, dm^2_{bc} \Bigg/ \int dm^2_{ab}\, dm^2_{bc} \,, \quad (1)$$

where $\mathcal{M}$ and $\overline{\mathcal{M}}$ are the D^0 and $\overline{D}^0$ Dalitz-plot amplitudes for the three-body decay $D \to abc$, and m_{ab} (m_{bc}) is the invariant mass of ab (bc). The second uses the asymmetry in the efficiency-corrected D^0 and $\overline{D}^0$ yields,

$$\mathcal{A}_{CP} = \frac{N_{D^0} - N_{\overline{D}^0}}{N_{D^0} + N_{\overline{D}^0}} \,. \quad (2)$$

These expressions are less sensitive to CP violation than are the individual resonant submodes [18]. Our Particle Listings give limits on CP violation for 11 D^+, 25 D^0, and 12 D_S^+ decay modes.

The possibility of interference between CP–conserving and CP–violating amplitudes provides a more sensitive probe of CP violation. The constraints on the square of the CP–violating amplitude obtained in the resonant submodes of $D^0 \to K_S^0\pi^+\pi^-$ range from 3.5×10^{-4} to 28.4×10^{-4} at 95% confidence level [18].

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