DIRECT CP VIOLATION IN D-MESON DECAYS

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Recently, the LHCb and CDF collaborations reported a surprisingly large difference between the direct CP asymmetries, $\Delta\mathcal{A}_{CP}$, in the $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decay modes. An interesting question is whether this measurement can be explained within the standard model. In this review, I would like to convey two messages: First, large penguin contractions can plausibly account for this measurement and lead to a consistent picture, also explaining the difference between the decay rates of the two modes. Second, "new physics" contributions are by no means excluded; viable models exist and can possibly be tested.

1 Introduction

The $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays are induced by the weak interaction via an exchange of a virtual W boson and suppressed by a single power of the Cabibbo angle. Direct CP violation in singly Cabibbo-suppressed (SCS) D-meson decays is sensitive to contributions of new physics in the up-quark sector, since it is expected to be small in the standard model: the penguin amplitudes necessary for interference are down by a loop factor and small Cabibbo-Kobayashi-Maskawa (CKM) matrix elements, and there is no heavy virtual top quark which could provide substantial breaking of the Glashow-Iliopoulos-Maiani (GIM) mechanism. Naively, one would thus expect effects of order $\mathcal{O}([V_{cb}V_{ub}/V_{cs}V_{us}]\alpha_s/\pi) \sim 0.01\%$.

We define the amplitudes for final state f as

$$\begin{aligned} A_f &\equiv A(D \to f) = A_f^T\left[1 + r_f e^{i(\delta_f - \phi_f)}\right], \\ \overline{A}_f &\equiv A(\bar{D} \to f) = A_f^T\left[1 + r_f e^{i(\delta_f + \phi_f)}\right]. \end{aligned} \tag{1}$$

Here A_f^T is the dominant tree amplitude and r_f the relative magnitude of the subleading amplitude, carrying the weak phase ϕ_f and the strong phase δ_f. We can now define the direct CP asymmetry as

$$\mathcal{A}_f^{\rm dir} \equiv \frac{|A_f|^2 - |\bar{A}_f|^2}{|A_f|^2 + |\bar{A}_f|^2} = 2 r_f \sin\gamma \sin\delta_f\,, \tag{2}$$

where the last equality holds up to corrections of $\mathcal{O}(r_f^2)$. LHCb and CDF measure a time-integrated CP asymmetry. The approximately universal contribution of indirect CP violation cancels to good approximation in the difference

$$\Delta\mathcal{A}_{CP} = \mathcal{A}_{CP}(D \to K^+K^-) - \mathcal{A}_{CP}(D \to \pi^+\pi^-)\,. \tag{3}$$

The measurements of LHCb, $\Delta\mathcal{A}_{CP} = (-0.82 \pm 0.21 \pm 0.11)\%$ [1], CDF, $\Delta\mathcal{A}_{CP} = (-0.62 \pm 0.21 \pm 0.10)\%$ [2], and inclusion of the indirect CP asymmetry A_Γ [5,6], lead to the new world average (including the Babar [3], Belle [4], and CDF [7] measurements) $\Delta\mathcal{A}_{CP} = (-0.67 \pm 0.16)\%$ [2]. In the following, we will try to answer three questions: Can this measurement be accounted for by the standard model? Can it be new physics? Can we distinguish the two possibilities?

2 Setting the stage

As a first step, we take the size of the tree amplitudes A^T from data and then relate the tree amplitudes to the penguin amplitudes A^P to estimate the size of the latter [8]. The starting point of our analysis is the weak effective Hamiltonian

$$H_{\rm eff}^{\rm SCS} = \frac{G_F}{\sqrt{2}} \Bigg\{ (V_{cs}V_{us}^* - V_{cd}V_{ud}^*) \sum_{i=1,2} C_i \left(Q_i^{\bar{s}s} - Q_i^{\bar{d}d}\right)/2 \\ -V_{cb}V_{ub}^* \left[\sum_{i=1,2} C_i \left(Q_i^{\bar{s}s} + Q_i^{\bar{d}d}\right)/2 + \sum_{i=3}^{6} C_i Q_i + C_{8g} Q_{8g} \right] \Bigg\} + \text{h.c.}. \tag{4}$$

The Wilson coefficients of the tree operators $Q_1^{\bar{p}p'} = (\bar{p}u)_{V-A} \otimes (\bar{c}p')_{V-A}$, $Q_2^{\bar{p}p'} = (\bar{p}_\alpha u_\beta)_{V-A} \otimes (\bar{c}_\beta p'_\alpha)_{V-A}$, the penguin operators $Q_{3\ldots6}$, and the chromomagnetic operator Q_{8g}, can be calculated in perturbation theory. The hadronic matrix elements are harder to compute; we will estimate their size using experimental data. They receive leading power contributions and power corrections in $1/m_c$, which are expected to be large.

A leading power estimation, using naive factorization and $\mathcal{O}(\alpha_s)$ corrections, yields for the ratio $r_f^{\rm LP} \equiv |A_f^P(\text{leading power})/A_f^T(\text{experiment})|$: $r_{K^+K^-}^{\rm LP} \approx (0.01 - 0.02)\%$, $r_{\pi^+\pi^-}^{\rm LP} \approx (0.015 - 0.028)\%$. This is consistent with, yet slightly larger than the naive scaling estimate. We expect the signs of $\mathcal{A}_{K^+K^-}^{\rm dir}$ and $\mathcal{A}_{\pi^+\pi^-}^{\rm dir}$ to be opposite, if $SU(3)$ breaking is not too large; so for $\phi_f = \gamma \approx 67^\circ$ and $\mathcal{O}(1)$ strong phases we obtain $\Delta\mathcal{A}_{CP}(\text{leading power}) = \mathcal{O}(0.1\%)$, an order of magnitude smaller than the measurement.

However, we know from $SU(3)$ fits [9,10,11,12,13] that power corrections can be large. To be specific, we look at insertions of the penguin operators Q_4, Q_6 into power-suppressed annihilation amplitudes. The associated penguin contractions of Q_1 cancel the scale and scheme dependence. Estimating their size using the loop functions G, defined in [15], and using naive N_c counting to relate the penguin to the tree amplitudes, we arrive at $r_{f,1}^{\rm PC} \approx (0.04 - 0.08)\%$, $r_{f,2}^{\rm PC} \approx (0.03 - 0.04)\%$, where $r_{f,i}^{\rm PC} \equiv |A_f^P(\text{power correction})/A_f^T(\text{experiment})|$ and the subscripts $1, 2$ correspond to the insertions of Q_4, Q_6, respectively. Again assuming $\mathcal{O}(1)$ strong phases, this leads to $\Delta\mathcal{A}_{CP}(r_{f,1}) = \mathcal{O}(0.3\%)$ and $\Delta\mathcal{A}_{CP}(r_{f,2}) = \mathcal{O}(0.2\%)$ for the two insertions. Thus, a standard model explanation seems plausible.

Of course, the extraction of the annihilation amplitudes from data, neglected contributions to the annihilation amplitudes, N_c counting, the modeling of the penguin contraction amplitudes, and the neglected additional penguin contractions lead to an uncertainty of a factor of a few. So, can we trust the estimate?

3 A consistent picture

Another interesting observation is the large difference of SCS branching ratios, $\text{Br}(D^0 \to K^+K^-) \approx 2.8 \times \text{Br}(D^0 \to \pi^+\pi^-)$. It implies that the ratio of amplitudes (normalized to phase space) is $A(D^0 \to K^+K^-) \approx 1.8 \times A(D^0 \to \pi^+\pi^-)$, whereas they would be equal in the $SU(3)$ limit. This has often been interpreted as a sign of large $SU(3)$ breaking. On the other hand, the ratio of the Cabibbo-favored (CF) to the doubly Cabibbo-suppressed (DCS) amplitude is $A(D^0 \to K^-\pi^+) \approx 1.15 \times A(D^0 \to K^+\pi^-)$, after accounting for CKM factors, in accordance with nominal $SU(3)$ breaking of $\mathcal{O}(20\%)$.

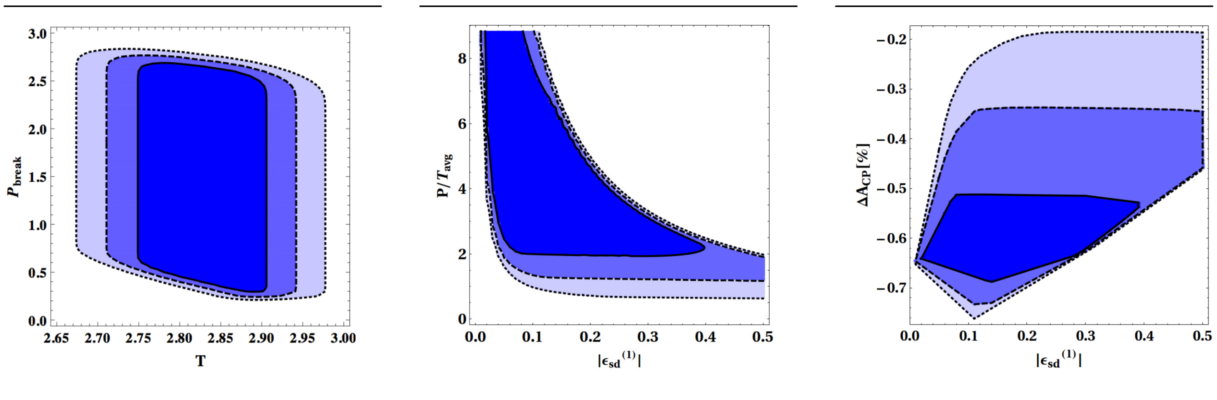

Figure 1: The results of our fit. Solid, dashed, and dotted lines denote one-, two-, and three-sigma contours, respectively. Left panel: A fit to the branching ratios only yields $P_{\rm break} \equiv \epsilon_{sd}^{(1)} P \sim T$, assuming nominal U-spin breaking. T is the tree amplitude. The lower bound of $P/T_{\rm avg}$ in the middle panel is directly related to the large difference of decay rates for the SCS modes. ($T_{\rm avg}$ is the average value of T from the fit). It translates into the upper bound on $\Delta\mathcal{A}_{CP}$ – the fit results can naturally accommodate the measured value (right panel).

A glance at the effective Hamiltonian (4) shows that the combination P of penguin contractions of $Q_{1,2}^{\bar{s}s}$ and $Q_{1,2}^{\bar{d}d}$ proportional to $V_{cb}V_{ub}^*$ is U-spin invariant, while $P_{\rm break}$, the combination contributing to the tree amplitude vanishes in the U-spin limit. $P_{\rm break}$ contributes with opposite sign to the two SCS decay rates, and P gives rise to a nonvanishing $\Delta\mathcal{A}_{CP}$. Guided by the considerations exposed in Section 2, we perform a U-spin decomposition of the amplitudes to all four (CF, SCS, DCS) decays, and fit these amplitudes to the data (branching ratios and CP asymmetries) under the additional assumption that penguin contractions are large, of order $\mathcal{O}(1/\epsilon)$, where $\epsilon \ll 1$.

Our main point is[14] that under the assumption of nominal U-spin breaking, a broken penguin $P_{\rm break}$ which explains the difference of the $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decay rates implies a $\Delta U = 0$ penguin P that naturally[a] yields the observed $\Delta\mathcal{A}_{CP}$. The scaling $P_{\rm break} \sim \epsilon_U P$ together with our fit result $P_{\rm break} \sim T/2$ (see Fig. 1) yields the estimate

$$r_{\pi^+\pi^-,K^+K^-} \simeq \left|\frac{V_{cb}V_{ub}}{V_{cs}V_{us}}\right| \cdot \left|\frac{P}{T \pm P_{\rm break}}\right| \sim \frac{|V_{cb}V_{ub}|}{|V_{cs}V_{us}|}\frac{1}{2\,\epsilon_U} \sim 0.2\%, \tag{5}$$

for $\epsilon_U \sim 0.2$. This is consistent with the measured $\Delta\mathcal{A}_{CP}$ for $\mathcal{O}(1)$ strong phases. Some results of our fit are shown in Figure 1.

By the same reasoning, exchanging the spectator quark we expect direct CP asymmetries of the same order ($\approx 0.5\%$) in the decay modes $D^+ \to K^+\overline{K^0}$, $D_s^+ \to \pi^+K^0$.

4 Can it be new physics?

Whereas a standard-model explanation seems plausible, it is not excluded that new physics contributes partly to $\Delta\mathcal{A}_{CP}$. Any new-physics explanation has to respect constraints from other observables like D- and K-meson mixing, or direct searches, but substantial contributions are still possible[16,17]. Can we discriminate them from the standard-model contributions?

Models of new physics that have $\Delta I = 3/2$ contributions could be separated from the standard-model background (an example would be a scalar color-singlet weak doublet[18]). To see this, note that the standard-model tree operators have both $\Delta I = 1/2$ and $\Delta I = 3/2$ contributions, while the standard-model penguin operators are pure $\Delta I = 1/2$ (apart from neglegible electroweak contributions). For instance, the $I = 2$ final state in $D^+ \to \pi^+\pi^0$ cannot

[a] An important side remark is that no fine tuning of strong phases is required[14].

be reached by standard-model penguin operators, so any observed direct CP asymmetry in this decay would be a clear signal of new physics. More sophisticated isospin sum rules can be constructed [19].

If new physics induces only $\Delta I = 1/2$ transitions, it seems necessary to build explicit models and look for their collider signatures. The most plausible models include chirally enhanced chromomagnetic penguin operators [20,21].

5 Conclusion

Large penguin contractions in the standard model can naturally explain both the large difference of decay rates in the $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ modes and the observed $\Delta\mathcal{A}_{CP}$. However, new-physics contributions are not excluded. Viable models exist and can possibly tested.

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