Direct $CP$ violation in $D$ meson decays

Joachim Brod

in collaboration with Yuval Grossman, Alexander L. Kagan, Jure Zupan

Recontres de Moriond, QCD session
March 13th, 2012


see also A. Kagan, talk at FPCP 2011, May 2011
Introduction

Singly Cabibbo-suppressed (SCS) $D$-meson decays $D^0 \rightarrow \pi^+\pi^-$, $D^0 \rightarrow K^+K^-$

$CP$ violation in SCS $D$-meson decays is

- sensitive to new physics (NP) in the up-quark sector
- suppressed in the standard model (SM):
  - two-generation dominance
  - loop suppression (penguin amplitudes)
  - GIM mechanism

Naively, expect effects of $\mathcal{O} \left( \frac{V_{ub} V_{cb}}{V_{us} V_{cs}} \frac{\alpha_s}{\pi} \right) \sim 0.01\%$. 
Definitions

\[ A_f \equiv A(D^0 \rightarrow f) = A_f^T \left[ 1 + r_f e^{i(\delta_f - \phi_f)} \right], \]
\[ \bar{A}_f \equiv A(\bar{D}^0 \rightarrow f) = A_f^T \left[ 1 + r_f e^{i(\delta_f + \phi_f)} \right] \]

\( r_f \) relative magnitude of subleading (penguin) amplitude with relative strong phase \( \delta_f \), weak phase \( \phi_f \).

\[ A^\text{dir}_f := \frac{|A_f|^2 - |\bar{A}_f|^2}{|A_f|^2 + |\bar{A}_f|^2} = 2r_f \sin \phi_f \sin \delta_f \]

(Universal) indirect contribution \( A^\text{ind}_f \) cancels to good approximation in

\[ \Delta A_{CP} := A^\text{dir}_{K^+K^-} - A^\text{dir}_{\pi^+\pi^-} \]
Measurements

First significant measurements of $CP$ violation in the up-quark sector

**LHCb** [R. Aaij et al., 1112.0938]:

$$\Delta A_{CP} = (-0.82 \pm 0.21 \pm 0.11)\%$$

**CDF** [La Thuile 2012]:

$$\Delta A_{CP} = (-0.62 \pm 0.21 \pm 0.10)\%$$

leading to new world average [La Thuile 2012]:

$$\Delta A_{CP} = (-0.67 \pm 0.16)\%$$

- Can it be standard model (SM)?
- Can it be new physics (NP)?
- Can we distinguish NP from SM?
“There one typically finds asymmetries $\sim \mathcal{O}(10^{-4})$, i.e. somewhat smaller than the rough benchmark stated above. Yet $10^{-3}$ effects are conceivable, and even 1% effects cannot be ruled out completely.”

[D. Benson et al., hep-ex/0309021]

“This would lead to gigantic CP violations, an asymmetry of order 1. This is of course very unlikely [..]”


Can we be more specific?
Integrate out $M_W$, $m_b$, evolve down to charm scale $\mu_c$, use GIM:

$$H_{\text{eff}}^{\text{SCS}} = \frac{G_F}{\sqrt{2}} \left\{ V_{cs} V_{us}^* \sum_{i=1,2} C_i (Q_i^{ss} - Q_i^{dd}) - V_{cb} V_{ub}^* \sum_{i=3}^{6} C_i Q_i + C_{8g} Q_{8g} \right\} + \text{h.c.}$$

- Wilson coefficients: perturbative
- Matrix elements: leading power and power corrections in $1/m_c$
- Estimate tree amplitude $A^T$ from data
- Relate penguin amplitude $A^P$ to $A^T$
Leading power ("Naive factorization" + $\mathcal{O}(\alpha_s)$ corrections):

\[
r_f^{\text{LP}} = \left| \frac{A_f^{\text{P}}(\text{leading power})}{A_f^{\text{T}}(\text{experiment})} \right|
\]

\[
 r_{K^+K^-}^{\text{LP}} \approx (0.01 - 0.02)\%, \quad r_{\pi^+\pi^-}^{\text{LP}} \approx (0.015 - 0.03)\%
\]

Expect \( \text{sign}(A_{K^+K^-}^{\text{dir}}) = -\text{sign}(A_{\pi^+\pi^-}^{\text{dir}}) \) (if SU(3)$_F$ breaking is not too large). Cf. global averages [HFAG]

\[
 A_{K^+K^-} = (-0.23 \pm 0.17)\%, \quad A_{\pi^+\pi^-} = (0.20 \pm 0.22)\%
\]

For \( \phi_f = \gamma \approx 67^\circ \) and $\mathcal{O}(1)$ strong phases

\[
 \Delta A_{CP}(\text{leading power}) \sim 4r_f = \mathcal{O}(0.1\%).
\]

Order of magnitude below measurement!
From $SU(3)_F$ fits [Cheng, Chiang, 1001.0987, 1201.0785; Bhattacharya, Gronau, Rosner, 1201.2351; Pirtskhalava, Uttayarat, 1112.5451] we know

$$\mathcal{O}(1) = T_f \sim E_f = \mathcal{O}(1/m_c)$$

Signals breakdown of $1/m_c$ expansion

**Power corrections**: look at two specific contributions - insertions of $Q_4$, $Q_6$
SM: Large penguin power corrections

Associated penguin contractions of $Q_1$ cancel scheme and scale dependence

Single hard gluon exchange leads to “effective Wilson coefficients” $C_{4}^{\text{eff}}$ and $C_{6}^{\text{eff}}$ depending on the gluon virtuality $q^2$.

Setting $A^T(\text{exp}) = E_f$ in

$$
\left| \frac{A^P_f (\text{power correction})}{A^T_f (\text{experiment})} \right|
$$

and $N_c$ counting leads to

$$
\begin{align*}
    r_{f,1} & \sim 2N_c |V_{cb} V_{ub} C_{6}^{\text{eff}}| / (C_1 \sin \theta_c), \\
    r_{f,2} & \sim 2 |V_{cb} V_{ub} (C_{4}^{\text{eff}} + C_{6}^{\text{eff}})| / (C_1 \sin \theta_c).
\end{align*}
$$
SM: Large penguin power corrections

\[ r_{\pi^+\pi^-,i} \text{ (black)} \] and \[ r_{K^+K^-,i} \text{ (blue)} \] for \( \mu = 1 \text{ GeV}, m_c, m_D \)

\[ \Delta A_{CP}(P_{f,1}) = \mathcal{O}(0.3\%), \quad \Delta A_{CP}(P_{f,2}) = \mathcal{O}(0.2\%) \]

\[ \Rightarrow \] a SM explanation is plausible.
Uncertainties

- Extraction of annihilation amplitudes $E_f$ from data
- Neglected contributions to $E_f$
- $N_c$ counting
- Modeling of penguin contraction matrix elements
- Neglected additional penguin contractions

Cumulative uncertainty of a factor of a few; much larger effects are unlikely.

Can we trust it?
SM: Consistent picture

Another observation: from $\text{Br}(D^0 \to K^+ K^-) \approx 2.8 \times \text{Br}(D^0 \to \pi^+ \pi^-)$

$$|A(D^0 \to K^+ K^-)| = 1.8 \times |A(D^0 \to \pi^+ \pi^-)|$$

- Should be the same in $SU(3)_F$ limit
- Usually interpreted as a sign of large $O(1)$ $SU(3)_F$ breaking

But note that

$$|A(D^0 \to K^- \pi^+)| = 1.15 \times |A(D^0 \to K^+ \pi^-)|$$

for Cabibbo-favored (CF) decay $D^0 \to K^- \pi^+$ and doubly Cabibbo-suppressed (DCS) decay $D^0 \to K^+ \pi^-.$

$$H_{\text{eff}}^{\text{CF}} = \frac{G_F}{\sqrt{2}} V_{cs} V_{ud}^* \sum_{i=1,2} C_i Q_i \bar{d}s + \text{h.c.}$$
Weak Hamiltonian, written differently

\[ T_{KK} = T_{KK}^s + P_{KK}^{T,s} - P_{KK}^{T,d} \]
\[ T_{\pi\pi} = -T_{\pi\pi}^d + P_{\pi\pi}^{T,s} - P_{\pi\pi}^{T,d} \]

- Broken penguin \( P_{\text{break}} \) violates \( U \) spin (\( s \leftrightarrow d \))

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

- Penguin \( P \) violates \( CP \)
**$U$-spin decomposition**

- $D^0 \rightarrow K^-\pi^+, K^+K^-, \pi^+\pi^-, K^+\pi^-$
- Assume nominal $U$-spin breaking $\propto \epsilon_U \sim 0.2 - 0.3$
- Additional assumption: $T = O(1)$, $P = O(1/\epsilon)$, where $\epsilon \sim 0.2 - 0.3$

For $\epsilon \sim 0.3$ we have naturally

$$r_f = \frac{|V_{cb}V_{ub}|}{|V_{cs}V_{us}|} \frac{P}{T} \sim \frac{|V_{cb}V_{ub}|}{|V_{cs}V_{us}|} \frac{1}{\epsilon} \sim 0.2\%$$

- Right order of magnitude to explain $\Delta A_{CP}$
- $P_{\text{break}} = \epsilon_U P \sim \epsilon_U/\epsilon \sim O(1)$ explains $\text{Br}(K^+K^-) = 2.8 \times \text{Br}(\pi^+\pi^-)$
- Test by performing a fit to branching ratios and $CP$ asymmetries.
Fit to data

\[ P_{\text{break}} \lesssim T \]

- Nominal \( \epsilon_U \)
- \( P \sim T/\epsilon \)
$\Delta A_{CP}$ from fit

![Plot of $\Delta A_{CP}$ versus $\epsilon_{sd}^{(1)}$]
Relations to other modes

By exchanging the spectator quark,

- $D^+ \rightarrow K^+ K^0$
- $D_s^+ \rightarrow \pi^+ K^0$

receive contributions from

$\Rightarrow$ expect direct $CP$ asymmetries of same order
NP: viable models

Constraints from $D$ mixing, Kaon mixing, direct searches . . .

- (More) Model-independent operator analysis
  [Isodori, Kamenik, Ligeti, Perez 1111.4987]

- Supersymmetric examples ($Q_{8g} = -g_s/4\pi^2 m_c \bar{u}_L \sigma_{\mu\nu} G^{\mu\nu} c_R$)

[Diagrams by A. Kagan]

- Tree-level exchanges
  [Hochberg, Nir 1112.5268; Altmannshofer, Primulando, Yu, Yu 1202.2866]
How to distinguish NP from SM

NP models that have $\Delta I = 3/2$ contributions:

- SM tree operators have both $\Delta I = 1/2$ and $\Delta I = 3/2$ contributions
- SM penguin operators ($\propto \sum \bar{q}q, g$) have only $\Delta I = 1/2$ contributions
- E.g. $D^+ \rightarrow \pi^+\pi^0$ has $I = 2$ final state $\Rightarrow$ no SM contribution to $A^{\text{dir}}$.
- Example: Single scalar exchange could explain both $A_{FB}(t\bar{t})$ and $\Delta A_{\text{CP}}$ [Hochberg, Nir 1112.5268]

NP models that have only $\Delta I = 1/2$ contributions:

- Build models and look for collider signatures. In many cases allowed parameters are close to experimental sensitivity
  [Altmannshofer, Primulando, Yu, Yu 1202.2866; see also Feldmann, Nandi, Soni 1202.3795]
- Example: LR contributions to $Q_{8g}$ in SUSY
Conclusion

- Enhanced penguin contributions in the SM can naturally explain both $\Delta A_{CP}$ and $\text{Br}(K^+K^-) = 2.8 \times \text{Br}(\pi^+\pi^-)$ – plausible and consistent.
- NP contributions not excluded, viable and testable models exist.
Experiments measure

\[ A_f := \frac{\Gamma(D^0 \rightarrow f) - \Gamma(D^0 \rightarrow \bar{f})}{\Gamma(D^0 \rightarrow f) + \Gamma(D^0 \rightarrow \bar{f})} \approx A_f^{\text{dir}} + \frac{\langle t(f) \rangle}{\tau} A_f^{\text{ind}} \]

CDF: \( A_f^{\text{ind}} = (-0.02 \pm 0.22)\% \)
Penguin matrix elements

\[ P_{f,1} = \frac{G_F}{\sqrt{2}} V_{cb} V_{ub} C_6 \times \langle f | - 2(\bar{u}u)_{S+P} \otimes^A (\bar{u}c)_{S-P} | D^0 \rangle \]

\[ P_{f,2} = \frac{G_F}{\sqrt{2}} V_{cb} V_{ub} 2(C_4 + C_6) \times \langle f | (\bar{q}_\alpha q_\beta)_{V\pm A} \otimes^A (\bar{u}_\beta c_\alpha)_{V-A} | D^0 \rangle \]

\[ C_{4(6)}^{\text{eff}}(\mu, q^2) = C_{4(6)}(\mu) + C_1(\mu) \frac{\alpha_s}{2\pi} \left[ \frac{1}{6} + \frac{1}{3} \log \left( \frac{m_c}{\mu} \right) - \frac{1}{8} G \left( \frac{m_s^2}{m_c^2}, \frac{m_d^2}{m_c^2}, \frac{q^2}{m_c^2} \right) \right] \]

\[ \frac{\langle f | (\bar{u}u)_{S+P} \otimes^A (\bar{u}c)_{S-P} | D^0 \rangle}{\langle f | (\bar{s}_\alpha s_\beta - \bar{d}_\alpha d_\beta)_{V-A} \otimes^A (\bar{u}_\beta c_\alpha)_{V-A} | D^0 \rangle} = \mathcal{O}(N_c), \]

\[ \frac{\langle f | (\bar{u}_\alpha u_\beta)_{V\pm A} \otimes^A (\bar{u}_\beta c_\alpha)_{V-A} | D^0 \rangle}{\langle f | (\bar{s}_\alpha s_\beta - \bar{d}_\alpha d_\beta)_{V-A} \otimes^A (\bar{u}_\beta c_\alpha)_{V-A} | D^0 \rangle} = \mathcal{O}(1). \]
CP asymmetries from fit

![Graph showing CP asymmetries from fit](image-url)
\( A(\bar{D}^0 \to K^+\pi^-) = V_{cs} V_{ud}^* T (1 - \frac{1}{2} \epsilon_1' T), \)

\[
A(\bar{D}^0 \to \pi^+\pi^-) = \frac{1}{2} \left( V_{cd} V_{ud}^* - V_{cs} V_{us}^* \right) \left( T (1 + \frac{1}{2} \epsilon_1 T) - P_{\text{break}} (1 - \frac{1}{2} \epsilon_{sd}^{(2)}) \right) \\
- V_{cb}^* V_{ub} \left( T/2 (1 + \frac{1}{2} \epsilon_1 T) + P (1 - \frac{1}{2} \epsilon_P) \right),
\]

\[
A(\bar{D}^0 \to K^+K^-) = \frac{1}{2} \left( V_{cs} V_{us}^* - V_{cd} V_{ud}^* \right) \left( T (1 - \frac{1}{2} \epsilon_1 T) + P_{\text{break}} (1 + \frac{1}{2} \epsilon_{sd}^{(2)}) \right) \\
- V_{cb}^* V_{ub} \left( T/2 (1 - \frac{1}{2} \epsilon_1 T) + P (1 + \frac{1}{2} \epsilon_P) \right),
\]

\[
A(\bar{D}^0 \to \pi^+K^-) = V_{cd} V_{us}^* T (1 + \frac{1}{2} \epsilon_1' T).
\]
(Barbieri-Giudice-) Fine tuning

\[ \text{tuning in } \Delta A_{CP} \]

\[ \begin{array}{c}
\text{4.0} \\
\text{3.5} \\
\text{3.0} \\
\text{2.5} \\
\text{2.0} \\
\text{1.5} \\
\text{1.0} \\
\text{0.5} \\
\end{array} \]

\[ \begin{array}{c}
\text{5} \\
\text{6} \\
\text{7} \\
\text{8} \\
\text{9} \\
\text{10} \\
\end{array} \]