Direct $CP$ violation in $D$ meson decays

Joachim Brod

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

Implications of LHCb measurements and future prospects
April 17th, 2012

arXiv:1111.5000 [hep-ph]; arXiv:1203.6659 [hep-ph]
see also A. Kagan, talk at FPCP 2011, May 2011
Singly Cabibbo-suppressed (SCS) $D$-meson decays $D^0 \rightarrow \pi^+\pi^-$, $D^0 \rightarrow K^+K^-$

$V^{*}\bar{u}\bar{q}u\bar{c}qW$

$CP$ 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 $O \left( \frac{V_{ub} V_{cb}}{V_{us} V_{cs}} \frac{\alpha_s}{\pi} \right) \sim 0.01\%$. 
Definitions

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

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

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

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

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

$$\Delta A_{CP} = (-0.67 \pm 0.16)\%$$
"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 [. . . ].”

[M. Golden, B. Grinstein, Phys. Lett. B 222]

Can we be more specific?
Part I: Rough estimate of penguin contractions
SM weak effective Hamiltonian

Integrate out $M_W$, $m_b$, evolve down to charm scale $\mu_c$, use GIM:

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

- 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 $A^T$
**$P/T$ at leading power**

Leading power ("Naive factorization" $+ \mathcal{O}(\alpha_s)$ corrections):

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

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

Expect 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!
SM: Large penguin power corrections

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

![Diagram of penguin contractions]

- 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

$$r_f^{\text{PC}} = \left| \frac{A_f^{\text{P}}(\text{power correction})}{A_f^{\text{T}}(\text{experiment})} \right|$$

and $N_c$ counting leads to

$$r_{f,1} \sim 2N_c |V_{cb} V_{ub} C_6^{\text{eff}}|/(C_1 \sin \theta_c),$$

$$r_{f,2} \sim 2 |V_{cb} V_{ub} (C_4^{\text{eff}} + C_6^{\text{eff}})|/(C_1 \sin \theta_c).$$
SM: Large penguin power corrections

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

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

⇒ 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?
Part II: Consistent picture
Decay rate difference

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 $D^0 \to K^+ \pi^-$. 

$$H^\text{CF}_{\text{eff}} = \frac{G_F}{\sqrt{2}} V_{cs} V_{ud}^* \sum_{i=1,2} C_i Q_i \bar{d}s + \text{h.c.}$$
U-spin sum rule

- U-spin decomposition implies one linear relation of amplitudes
  \[ A_{K^-\pi^+} + A_{K^+\pi^-} = A_{K^+K^-} + A_{\pi^+\pi^-} \]

- We have the following experimental relation:
  \[
  \frac{|A(D^0 \rightarrow K^+K^-)| + |A(D^0 \rightarrow \pi^+\pi^-)|}{|A(D^0 \rightarrow K^+\pi^-)| + |A(D^0 \rightarrow K^-\pi^+)|} - 1 = (4.0 \pm 1.6)\%
  \]

- Gets corrections linear in U-spin breaking

- Solutions with small tuning of strong phases only for nominal U-spin breaking!
The following consistent and natural picture arises:

- $D \to K\pi$ rates and sum rule hint at nominal $U$-spin breaking.
- Thus need large penguin contractions to explain the $KK, \pi\pi$ rate difference.
- The large penguins account for large $\Delta A_{CP}$. 
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 \((s \leftrightarrow d)\)

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

- 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: $T = \mathcal{O}(1), P = \mathcal{O}(1/\epsilon)$, where $\epsilon \ll 1$
- $P_{\text{break}} = \epsilon_U P \sim \epsilon_U/\epsilon \sim \mathcal{O}(1)$ explains Br($K^+K^-$) = 2.8 $\times$ Br($\pi^+\pi^-$)
Fit to data

- Fit shows $P_{\text{break}} \sim T/2$
- For $\epsilon_U = 0.2$

$$r_f = \frac{|V_{cb} V_{ub}|}{|V_{cs} V_{us}|} \frac{P}{|T \pm P_{\text{break}}|} \sim \frac{|V_{cb} V_{ub}|}{|V_{cs} V_{us}|} \frac{1}{2\epsilon_U} \sim 0.2\%$$

- Right order of magnitude to explain $\Delta A_{CP}$!
Fit to data
$\Delta A_{CP}$ from fit

$\Delta A_{CP}$ vs $\epsilon_{sd}^{(1)}$

$\Delta A_{CP}$ vs $P/T_{avg}$
Relations to other modes

By exchanging the spectator quark,

- \( D^+ \rightarrow K^+ \bar{K}^0 \)
- \( D_s^+ \rightarrow \pi^+ K^0 \)

receive contributions from

⇒ expect direct \( CP \) asymmetries of same order
Conclusion

- Penguin matrix elements can plausibly be large in the SM
- Nominal $U$-spin breaking is natural
- “Broken penguin” then explains rate difference in $D \rightarrow KK, \pi\pi$
- Related large penguin contractions imply large $\Delta A_{CP}$
Definitions

Experiments measure

\[ \mathcal{A}_f := \frac{\Gamma(D^0 \to f) - \Gamma(D^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(D^0 \to f)} \approx \mathcal{A}^\text{dir}_f + \frac{\langle t(f) \rangle}{\tau} \mathcal{A}^\text{ind}_f \]

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

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

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

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

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

\[ \frac{\langle f | (\bar{u}_\alpha u_\beta)_{V\pm A} \otimes^A (\bar{u}_\beta c_\alpha)_{V-A} | D^0 \rangle}{\langle f | (\bar{s}_\alpha s_\beta - \bar{d}_\alpha d_\beta)_{V\pm A} \otimes^A (\bar{u}_\beta c_\alpha)_{V-A} | D^0 \rangle} = \mathcal{O}(1). \]
Large penguins in $D \to K^0\bar{K}^0$?

- $D \to K^0\bar{K}^0$ proceeds only via “exchange topologies” $E_{K^0\bar{K}^0}^d - E_{K^0\bar{K}^0}^s$ and corresponding penguin contractions $P_{K^0\bar{K}^0}^{E,d} - P_{K^0\bar{K}^0}^{E,s}$

- For nominal $U$-spin breaking expect $E \sim T/2$
  
  [see for instance Bhattacharya, Gronau, Rosner, 1201.2351]

- Thus $E_{K^0\bar{K}^0}^d - E_{K^0\bar{K}^0}^s \sim \epsilon_U E \sim 0.1 T \sim 0.3\text{keV}$

- Bhattacharya et al. find $|P_{K^0\bar{K}^0}^{E,d} - P_{K^0\bar{K}^0}^{E,s}| \sim 1\text{keV}$

- We find $|P_{K^0\bar{K}^0}^{T,d} - P_{K^0\bar{K}^0}^{T,s} + P_{K^0\bar{K}^0}^{E,d} - P_{K^0\bar{K}^0}^{E,s}| \sim 1.5\text{keV}$

- In any case, penguins contributions dominate

- Expect large $CP$ asymmetries in $D \to K_SK_S$
$CP$ asymmetries from fit

![Graph showing $A_{CP}(\pi^+\pi^-)$ vs $A_{CP}(K^+K^-)$]
Different ranges of $\epsilon_U$
Restricted range of $\epsilon_U$

$\epsilon_U \leq 0.4$

$\epsilon_U \leq 0.3$
Fitting for indirect CP violation

$\Delta A_{CP}$ [%] vs $A_{CP}^{ind}$ [%]

$A_{CP}(\pi^+ \pi^-)$ [%] vs $A_{CP}^{ind}$ [%]

$A_{CP}(K^+ K^-)$ [%] vs $A_{CP}^{ind}$ [%]
$U$-spin decomposition

$A(\bar{D}^0 \to K^+ \pi^-) = V_{cs} V^*_{ud} \ T(1 - \frac{1}{2} \epsilon'_{1T}),$

$A(\bar{D}^0 \to \pi^+ \pi^-) = \frac{1}{2} \ (V_{cd} V^*_{ud} - V_{cs} V^*_{us}) \ (T(1 + \frac{1}{2} \epsilon_{1T}) - P_{\text{break}}(1 - \frac{1}{2} \epsilon^{(2)}_{sd}))$

$- V^*_{cb} V_{ub} (T/2(1 + \frac{1}{2} \epsilon_{1T}) + P(1 - \frac{1}{2} \epsilon_P)),$

$A(\bar{D}^0 \to K^+ K^-) = \frac{1}{2} \ (V_{cs} V^*_{us} - V_{cd} V^*_{ud}) \ (T(1 - \frac{1}{2} \epsilon_{1T}) + P_{\text{break}}(1 + \frac{1}{2} \epsilon^{(2)}_{sd}))$

$- V^*_{cb} V_{ub} (T/2(1 - \frac{1}{2} \epsilon_{1T}) + P(1 + \frac{1}{2} \epsilon_P)),$

$A(\bar{D}^0 \to \pi^+ K^-) = V_{cd} V^*_{us} \ T(1 + \frac{1}{2} \epsilon'_{1T}).$