Direct *CP* violation in *D* meson decays

Joachim Brod

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

UNIVERSITY OF Cincinnati

Implications of LHCb measurements and future prospects
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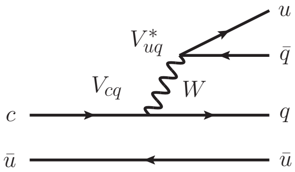
arXiv:1111.5000 [hep-ph]; arXiv:1203.6659 [hep-ph]

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

Introduction

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



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

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

r_f relative magnitude of subleading (penguin) amplitude with relative strong phase δ_f, weak phase ϕ_f.

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

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

$$\Delta\mathcal{A}_{CP} := \mathcal{A}_{K^+K^-}^{\text{dir}} - \mathcal{A}_{\pi^+\pi^-}^{\text{dir}}$$

Measurements

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

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

$$\Delta\mathcal{A}_{CP} = (-0.82 \pm 0.21 \pm 0.11)\%$$

CDF [La Thuile 2012]:

$$\Delta\mathcal{A}_{CP} = (-0.62 \pm 0.21 \pm 0.10)\%$$

leading to new world average [La Thuile 2012]:

$$\Delta\mathcal{A}_{CP} = (-0.67 \pm 0.16)\%$$

Can it be 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 [. . .]"

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

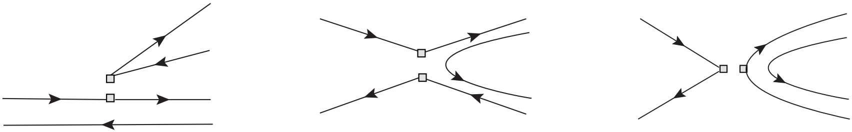
Can we be more specific?

Part I: Rough estimate of penguin contractions

SM weak effective Hamiltonian

Integrate out M_W, m_b, evolve down to charm scale μ_c, use GIM:

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



- 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):

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

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

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

$$\mathcal{A}_{K^+K^-} = (-0.23 \pm 0.17)\%\,, \quad \mathcal{A}_{\pi^+\pi^-} = (0.20 \pm 0.22)\%$$

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

$$\Delta\mathcal{A}_{CP}(\text{leading power}) \sim 4 r_f = \mathcal{O}(0.1\%)\,.$$

Order of magnitude below measurement!

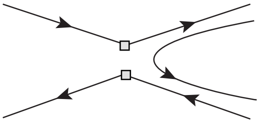
SM: Large penguin power corrections

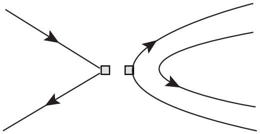
From $SU(3)_F$ fits [Cheng, Chiang, 1001.0987, 1201.0785; Bhattacharya, Gronau, Rosner, 1201.2351; Pirtskhalava, Uttayarat, 1112.5451] we know

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

Signals breakdown of $1/m_c$ expansion

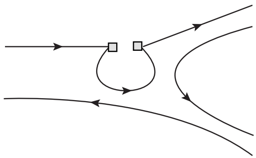
Power corrections: look at two specific contributions - insertions of Q_4, Q_6

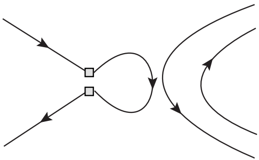




SM: Large penguin power corrections

Associated penguin contractions of Q_1 cancel scheme and scale dependence





- Single hard gluon exchange leads to “effective Wilson coefficients” $C_4^{\rm eff}$ and $C_6^{\rm eff}$ depending on the gluon virtuality q^2.

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

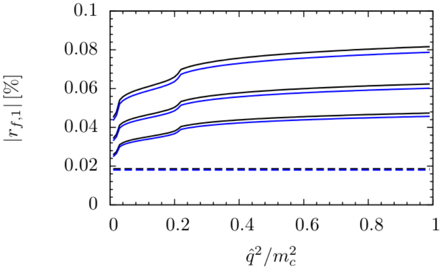
$$r_f^{\rm PC} = \left| \frac{A_f^P(\text{power correction})}{A_f^T(\text{experiment})} \right|$$

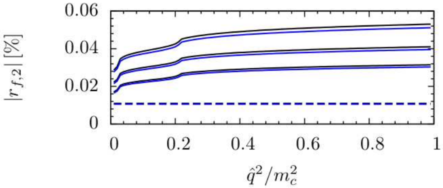
and N_c counting leads to

$$r_{f,1} \sim 2N_c |V_{cb} V_{ub} C_6^{\rm eff}| / (C_1 \sin\theta_c)\,,$$
$$r_{f,2} \sim 2|V_{cb} V_{ub} (C_4^{\rm eff} + C_6^{\rm eff})| / (C_1 \sin\theta_c)\,.$$

SM: Large penguin power corrections

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





$$\Delta\mathcal{A}_{CP}(P_{f,1}) = \mathcal{O}(0.3\%)\,, \quad \Delta\mathcal{A}_{CP}(P_{f,2}) = \mathcal{O}(0.2\%)$$

$\Rightarrow$ 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?

Part II: Consistent picture

Decay rate difference

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

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

- Should be the same in $SU(3)_F$ limit
- Usually interpreted as a sign of large $\mathcal{O}(1)$ $SU(3)_F$ 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 $D^0 \to K^+\pi^-$.

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

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:

$$\frac{|A(D^0 \to K^+K^-)| + |A(D^0 \to \pi^+\pi^-)|}{|A(D^0 \to K^+\pi^-)| + |A(D^0 \to K^-\pi^+)|} - 1 = (4.0 \pm 1.6)\%$$

- Gets corrections linear in U-spin breaking
- Solutions with small tuning of strong phases only for nominal U-spin breaking!

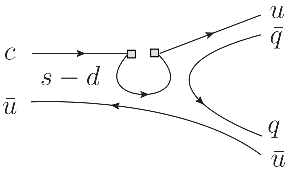
Consistent picture

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 $\Delta\mathcal{A}_{CP}$.

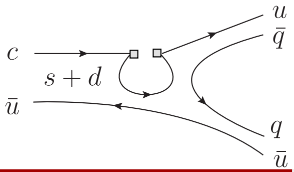
Weak Hamiltonian, written differently

$$T_{KK} = T^s_{KK} + P^{T,s}_{KK} - P^{T,d}_{KK}$$
$$T_{\pi\pi} = -T^d_{\pi\pi} + P^{T,s}_{\pi\pi} - P^{T,d}_{\pi\pi}$$



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

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

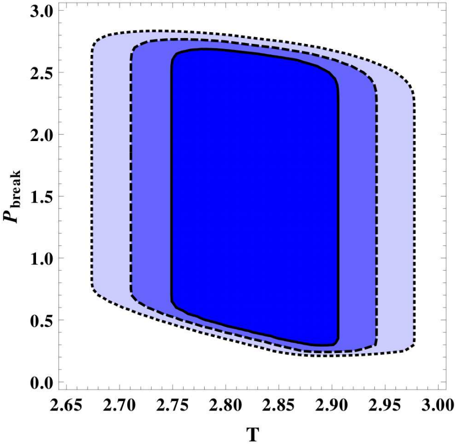


- Penguin P violates CP

U-spin decomposition

- $D^0 \to K^-\pi^+, K^+K^-, \pi^+\pi^-, K^+\pi^-$
- 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 $\text{Br}(K^+K^-) = 2.8 \times \text{Br}(\pi^+\pi^-)$

Fit to data

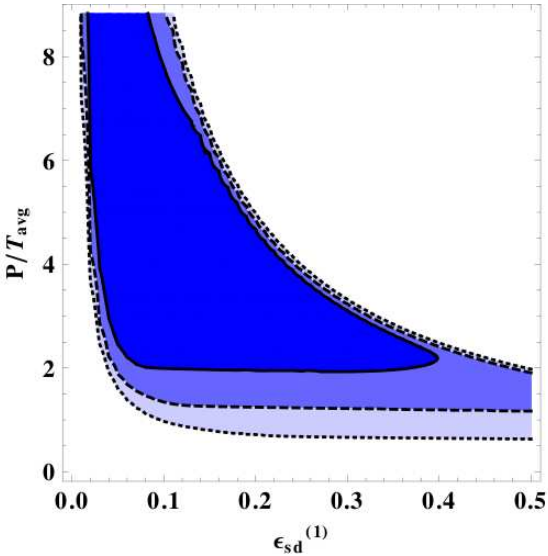


- Fit shows $P_{\text{break}} \sim T/2$
- For $\epsilon_U = 0.2$

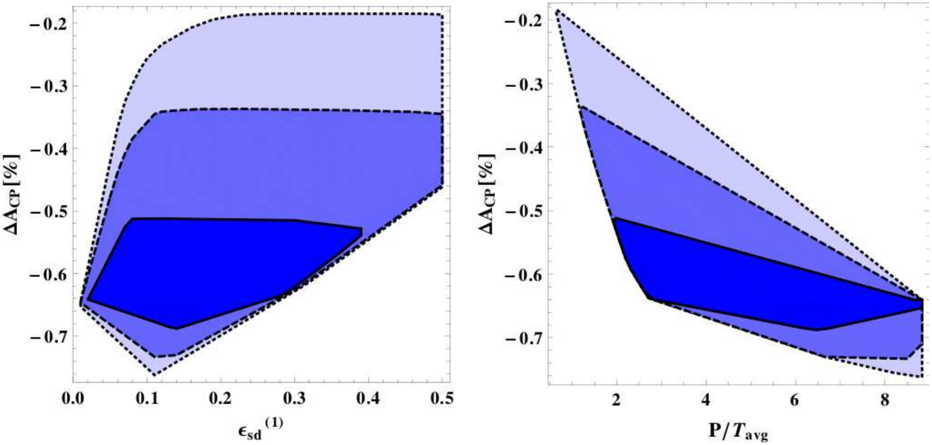
$$r_f = \frac{|V_{cb} V_{ub}|}{|V_{cs} V_{us}|} \frac{P}{|T \pm P_{\text{break}}|} \sim \frac{|V_{cb} V_{ub}|}{|V_{cs} V_{us}|} \frac{1}{2\,\epsilon_U} \sim 0.2\%$$

- Right order of magnitude to explain $\Delta\mathcal{A}_{CP}$!

Fit to data



$\Delta\mathcal{A}_{CP}$ from fit

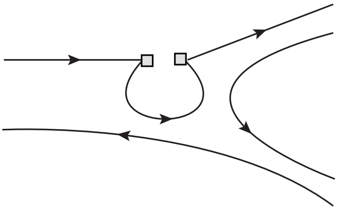


Relations to other modes

By exchanging the spectator quark,

- $D^+ \to K^+ \overline{K^0}$
- $D_s^+ \to \pi^+ K^0$

receive contributions from



$\Rightarrow$ 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 $D \to KK, \pi\pi$
- Related large penguin contractions imply large $\Delta\mathcal{A}_{CP}$

Backup slides

Definitions

Experiments measure

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

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

Penguin matrix elements

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

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

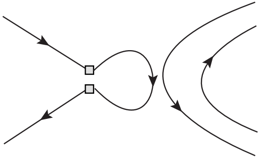
$$C_{4(6)}^{\text{eff}}(\mu, q^2) = C_{4(6)}(\mu) + C_1(\mu)\frac{\alpha_s}{2\pi}\left[\frac{1}{6} + \frac{1}{3}\log\left(\frac{m_c}{\mu}\right) - \frac{1}{8}G\left(\frac{m_s^2}{m_c^2}, \frac{m_d^2}{m_c^2}, \frac{q^2}{m_c^2}\right)\right]$$

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

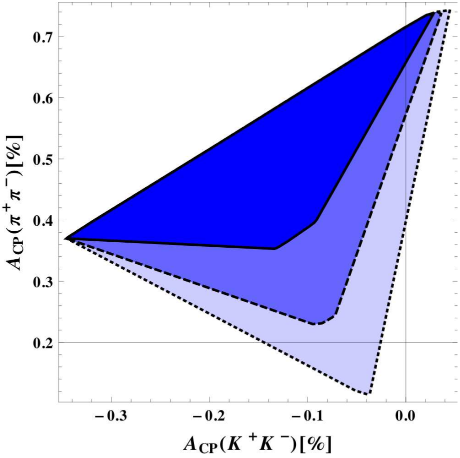
$$\frac{\langle f|(\bar{u}_\alpha u_\beta)_{V\pm A} \otimes^A (\bar{u}_\beta c_\alpha)_{V-A}|D^0\rangle}{\langle f|(\bar{s}_\alpha s_\beta - \bar{d}_\alpha d_\beta)_{V-A} \otimes^A (\bar{u}_\beta c_\alpha)_{V-A}|D^0\rangle} = \mathcal{O}(1)\,.$$

Large penguins in $D \to K^0\overline{K^0}$?

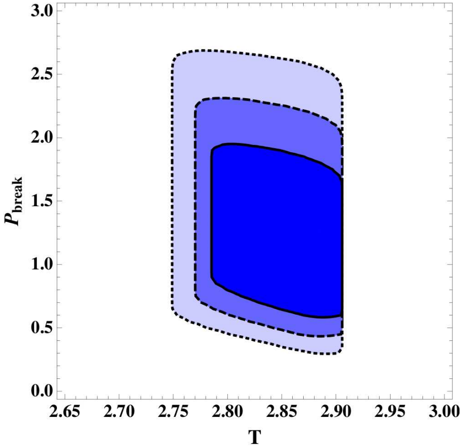
- $D \to K^0\overline{K^0}$ proceeds only via "exchange topologies" $E^d_{K^0\overline{K^0}} - E^s_{K^0\overline{K^0}}$ and corresponding penguin contractions $P^{E,d}_{K^0\overline{K^0}} - P^{E,s}_{K^0\overline{K^0}}$
- For nominal U-spin breaking expect $E \sim T/2$
  [see for instance Bhattacharya, Gronau, Rosner, 1201.2351]
- Thus $E^d_{K^0\overline{K^0}} - E^s_{K^0\overline{K^0}} \sim \epsilon_U E \sim 0.1T \sim 0.3\text{keV}$
- Bhattacharya et al. find $|P^{E,d}_{K^0\overline{K^0}} - P^{E,s}_{K^0\overline{K^0}}| \sim 1\text{keV}$
- We find $|P^{T,d}_{K^0\overline{K^0}} - P^{T,s}_{K^0\overline{K^0}} + P^{E,d}_{K^0\overline{K^0}} - P^{E,s}_{K^0\overline{K^0}}| \sim 1.5\text{keV}$
- In any case, penguins contributions dominate
- Expect large CP asymmetries in $D \to K_S K_S$



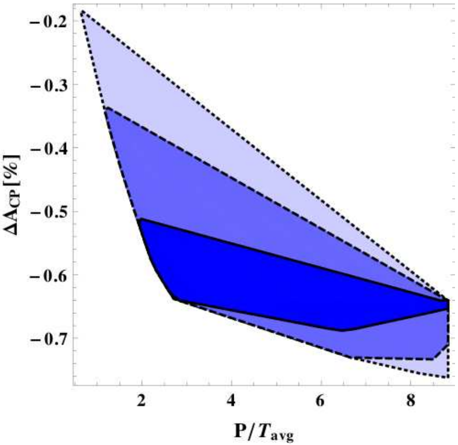
CP asymmetries from fit

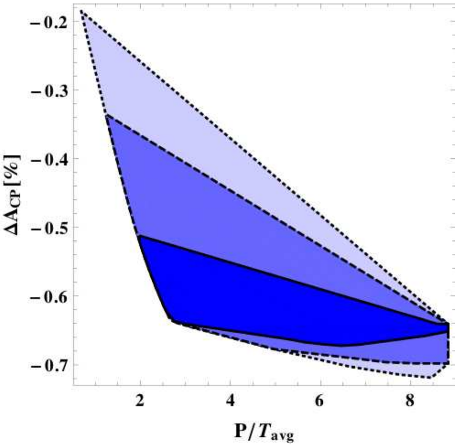


Different ranges of ϵ_U



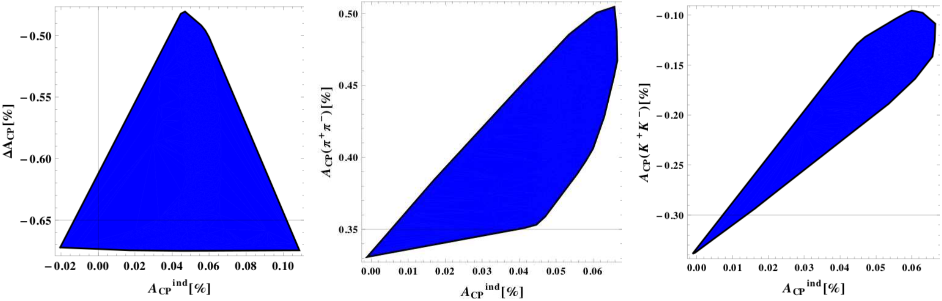
Restricted range of ϵ_U





- $\epsilon_U \leq 0.4$
- $\epsilon_U \leq 0.3$

Fitting for indirect CP violation



U-spin decomposition

$$
\begin{aligned}
A(\bar{D}^0 \to K^+\pi^-) =& V_{cs} V_{ud}^* T(1 - \tfrac{1}{2}\epsilon'_{1T}),\\
A(\bar{D}^0 \to \pi^+\pi^-) =& \tfrac{1}{2}\left(V_{cd} V_{ud}^* - V_{cs} V_{us}^*\right)\left(T(1 + \tfrac{1}{2}\epsilon_{1T}) - P_{\mathrm{break}}(1 - \tfrac{1}{2}\epsilon_{sd}^{(2)})\right)\\
& - V_{cb}^* V_{ub}(T/2(1 + \tfrac{1}{2}\epsilon_{1T}) + P(1 - \tfrac{1}{2}\epsilon_P)),\\
A(\bar{D}^0 \to K^+K^-) =& \tfrac{1}{2}\left(V_{cs} V_{us}^* - V_{cd} V_{ud}^*\right)\left(T(1 - \tfrac{1}{2}\epsilon_{1T}) + P_{\mathrm{break}}(1 + \tfrac{1}{2}\epsilon_{sd}^{(2)})\right)\\
& - V_{cb}^* V_{ub}(T/2(1 - \tfrac{1}{2}\epsilon_{1T}) + P(1 + \tfrac{1}{2}\epsilon_P)),\\
A(\bar{D}^0 \to \pi^+K^-) =& V_{cd} V_{us}^* T(1 + \tfrac{1}{2}\epsilon'_{1T}).
\end{aligned}
$$