Direct CP violation in SCS D meson decays

Joachim Brod

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

UNIVERSITY OF Cincinnati

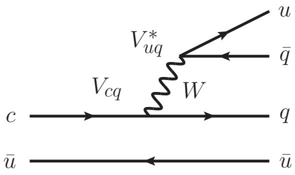
CKM workshop
Cincinnati, September 30th, 2012

Phys.Rev. D86 (2012) 014023 [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 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.

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

(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 [arXiv:1112.0938]:

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

CDF [arXiv:1207.2158]:

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

leading to new world average [HFAG 2012]:

$$\Delta\mathcal{A}_{CP} = (-0.678 \pm 0.147)\%$$

Could it have been expected?

"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, S. Bianco, I. Bigi, F. L. Fabbri, hep-ex/0309021]

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

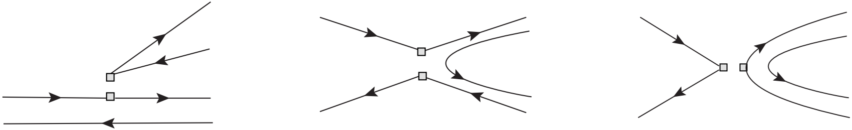
[M. Golden, B. Grinstein, Phys. Lett. B 222]

Can we be more specific?

SM weak effective Hamiltonian

$$H_{\rm eff}^{\rm SCS} = \frac{G_F}{\sqrt{2}} \Bigg\{ (V_{cs} V_{us}^* - V_{cd} V_{ud}^*) \sum_{i=1,2} C_i \left(Q_i^{\bar{s}s} - Q_i^{\bar{d}d} \right) /2$$

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



- Wilson coefficients: perturbative
- Matrix elements: leading power and power corrections in $1/m_c$

SM: Large penguin power corrections

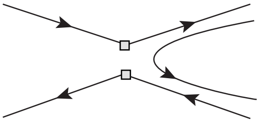
Leading power ("Naive factorization" + $\mathcal{O}(\alpha_s)$ corrections):
For $\phi_f = \gamma \approx 67°$ and $\mathcal{O}(1)$ strong phases

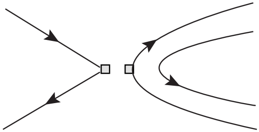
$$\Delta\mathcal{A}_{CP}(\text{leading power}) \sim 4r_f = \mathcal{O}(0.1\%)\,.$$

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 that power corrections are large.
Signals breakdown of $1/m_c$ expansion

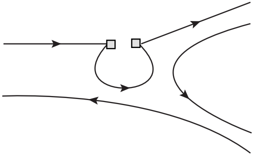
Power corrections: look at two specific contributions - insertions of Q_4, Q_6

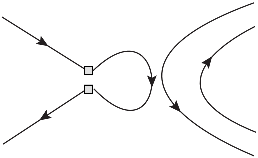




SM: Large penguin power corrections

Associated penguin contractions of Q_1 cancel scheme and scale dependence





- Extract annihilation amplitudes E_f from data
- N_c counting
- modeling penguin contraction matrix elements

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

$\Rightarrow$ a SM explanation is plausible.

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

Decay rate difference

From $\text{Br}(D^0 \to K^+K^-) \approx 2.8 \times \text{Br}(D^0 \to \pi^+\pi^-)$ we infer

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

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

- Analogous to "$\Delta I = 1/2$ rule" in K decays?

U-spin decomposition of Hamiltonian and states

- D^0 is U-spin ($s \leftrightarrow d$ symmetry) singlet
- triplet $(\langle K^+\pi^-|, (\langle K^+K^-| - \langle\pi^+\pi^-|)/\sqrt{2}, \langle K^-\pi^+|)$, singlet $(\langle K^+K^-| + \langle\pi^+\pi^-|)/\sqrt{2}$
- triplet $(Q_i^{\bar{d}s}, (Q_i^{\bar{s}s} - Q_i^{\bar{d}d})/\sqrt{2}, Q_i^{\bar{s}d})$, singlet $(Q_i^{\bar{s}s} + Q_i^{\bar{d}d})/\sqrt{2}$

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

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

U-spin decomposition – amplitudes

- Assume nominal U-spin breaking, originating from $m_s \bar{s} s$, of order $\epsilon_U \sim 20\% \sim f_K/f_\pi - 1$
- Additional assumption: $T = \mathcal{O}(1)$, $P = \mathcal{O}(1/\epsilon')$, where $\epsilon' \ll 1$

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

U-spin decomposition – $\mathcal{O}(1)$

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

$$
\begin{aligned}
T &= -\frac{1}{2}\big(\langle K^+K^-|C_i(Q_i^{\bar{s}s} - Q_i^{\bar{d}d})|\bar{D}^0\rangle - \langle \pi^+\pi^-|C_i(Q_i^{\bar{s}s} - Q_i^{\bar{d}d})|\bar{D}^0\rangle\big)\\
&= \langle K^+\pi^-|C_iQ_i^{\bar{d}s}|\bar{D}^0\rangle = \langle \pi^+K^-|C_iQ_i^{\bar{s}d}|\bar{D}^0\rangle \sim \mathcal{O}(1)\,.
\end{aligned}
$$

- All four rates are equal to $\mathcal{O}(\epsilon_U^0)$

U-spin decomposition – $\mathcal{O}(1/\epsilon')$

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

$$
\begin{aligned}
P = \langle K^+K^-|C_iQ_i^{\bar{d}d}|\bar{D}^0\rangle = \langle \pi^+\pi^-|C_iQ_i^{\bar{s}s}|\bar{D}^0\rangle \sim \mathcal{O}(1/\epsilon')\,,\\
T + P = \langle K^+K^-|C_iQ_i^{\bar{s}s}|\bar{D}^0\rangle = \langle \pi^+\pi^-|C_iQ_i^{\bar{d}d}|\bar{D}^0\rangle \sim \mathcal{O}(1/\epsilon')\,.
\end{aligned}
$$

- separate CP asymmetries have opposite sign to $\mathcal{O}(\epsilon^0)$
- $\Delta\mathcal{A}_{CP}$ enhanced by U-spin invariant penguin $P \sim \mathcal{O}(1/\epsilon')$

U-spin decomposition – $\mathcal{O}(\epsilon_U/\epsilon')$

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

$$
\begin{aligned}
P_{\rm break} =& \frac{1}{2}\big(\langle K^+K^-|C_i(Q_i^{\bar{s}s} - Q_i^{\bar{d}d})|\bar{D}^0\rangle + \langle\pi^+\pi^-|C_i(Q_i^{\bar{s}s} - Q_i^{\bar{d}d})|\bar{D}^0\rangle\big)\\
&\sim \mathcal{O}(\epsilon_U/\epsilon')\,.
\end{aligned}
$$

- $P_{\rm break} = \epsilon_{\rm sd}^{(1)} P$ violates U spin, explains $\mathrm{Br}(K^+K^-) = 2.8 \times \mathrm{Br}(\pi^+\pi^-)$

U-spin decomposition – $\mathcal{O}(\epsilon_U)$

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

$$A(\bar{D}^0 \to \pi^+\pi^-) = - V_{cs} V_{us}^* \big[T(1 + \tfrac{1}{2}\epsilon_{1T}) - P_{\mathrm{break}}(1 - \tfrac{1}{2}\epsilon_{sd}^{(2)})\big] - V_{cb}^* V_{ub}(T/2(1 + \tfrac{1}{2}\epsilon_{1T}) + P(1 - \tfrac{1}{2}\epsilon_P)),$$

$$A(\bar{D}^0 \to K^+K^-) = V_{cs} V_{us}^* \big[T(1 - \tfrac{1}{2}\epsilon_{1T}) + P_{\mathrm{break}}(1 + \tfrac{1}{2}\epsilon_{sd}^{(2)})\big] - V_{cb}^* V_{ub}(T/2(1 - \tfrac{1}{2}\epsilon_{1T}) + P(1 + \tfrac{1}{2}\epsilon_P)),$$

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

- Difference of $K^+\pi^-$ and π^+K^- decay rates arises at $\mathcal{O}(\epsilon_U)$

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:

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

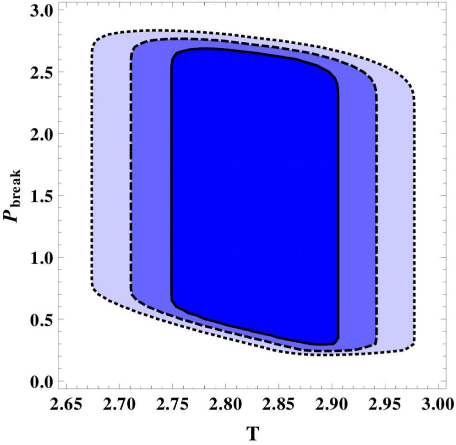
- Gets corrections linear in U-spin breaking
- Solutions with small tuning of strong phases only for nominal U-spin breaking!

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

Fit to branching ratios

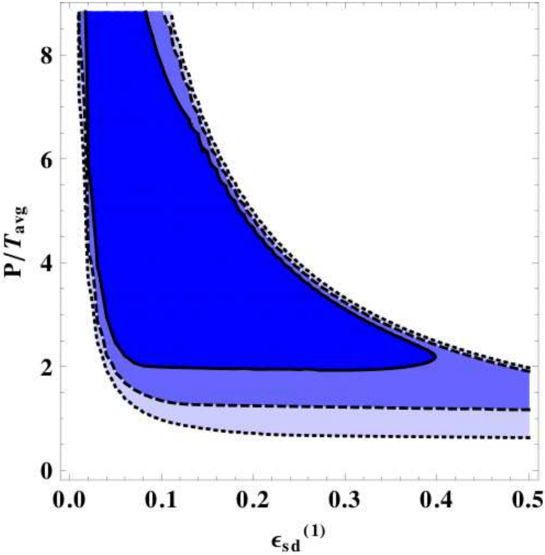


- Fit shows $P_{\text{break}} \sim T/2$
- Recall $P_{\text{break}} = \epsilon_U P$
- For $\epsilon_U = 0.2$:

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

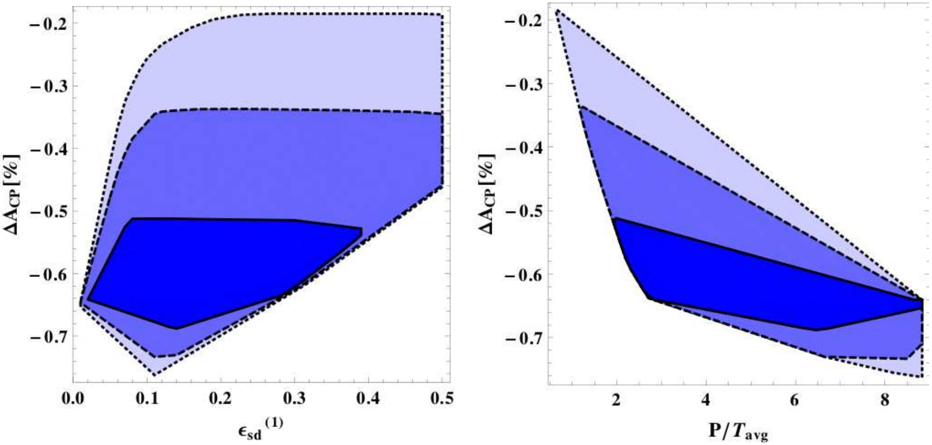
- Right order of magnitude to explain $\Delta \mathcal{A}_{CP}$!

Fit including CP asymmetries



- $P_{\text{break}} = \epsilon_{\text{sd}}^{(1)} P$

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

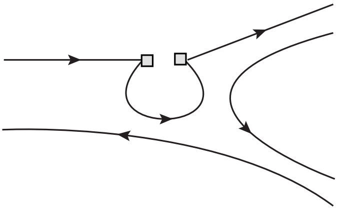


Relations to other modes

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, explains rate difference in $D \to K\pi, \pi K$
- "Broken penguin" then explains rate difference in $D \to KK, \pi\pi$
- Related large penguin contractions imply large $\Delta\mathcal{A}_{CP}$

Backup slides

Penguin matrix elements

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

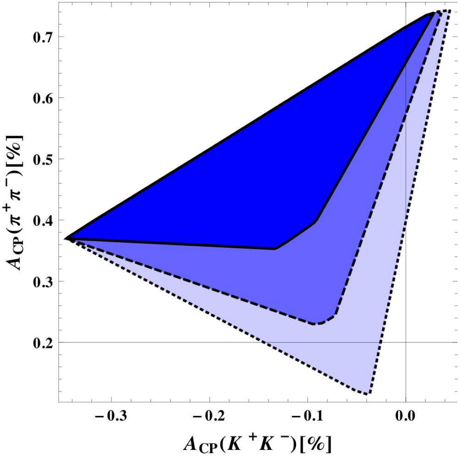
$$P_{f,2} = \frac{G_F}{\sqrt{2}} V_{cb} V_{ub}^* 2(C_4 + C_6) \times \langle f | (\bar{q}_\alpha q_\beta)_{V\pm A} \otimes^A (\bar{u}_\beta c_\alpha)_{V-A} | D^0 \rangle$$

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

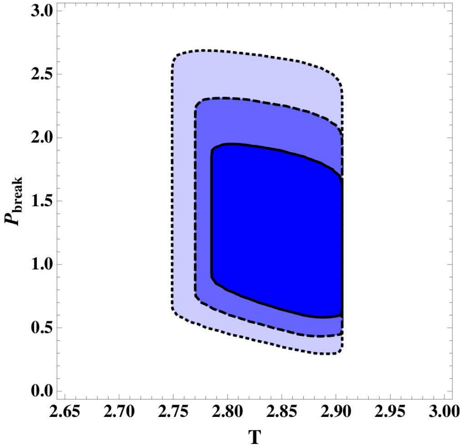
$$\frac{\langle f | (\bar{u}u)_{S+P} \otimes^A (\bar{u}c)_{S-P} | D^0 \rangle}{\langle f | (\bar{s}_\alpha s_\beta - \bar{d}_\alpha d_\beta)_{V-A} \otimes^A (\bar{u}_\beta c_\alpha)_{V-A} | D^0 \rangle} = \mathcal{O}(N_c)\,,$$

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

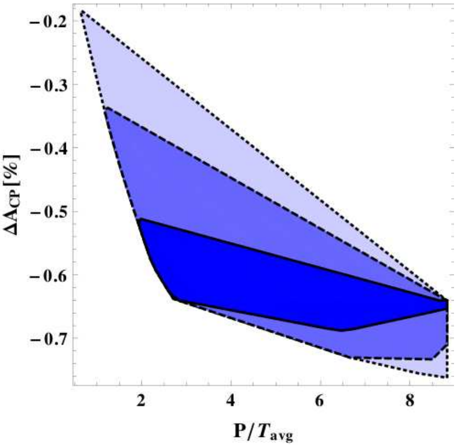
CP asymmetries from fit

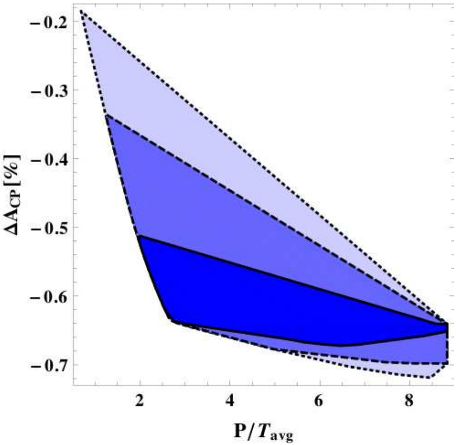


Different ranges of ϵ_U



Restricted range of ϵ_U





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