CP asymmetries in *D* decays to two pseudoscalars

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I discuss hadronic two-body weak decays of D^+, D^0, D_s^+ mesons.

$$D^+ \sim c\overline{d}, \qquad D^0 \sim c\overline{u}, \qquad D_s^+ \sim c\overline{s},$$

Examples: $D^+ \to \overline{K}^0\pi^+$, $D^0 \to \pi^+\pi^-$, $D^+ \to K^0\pi^+$.

Decays are classified in terms of powers of the Wolfenstein parameter

$$\lambda \simeq |V_{us}| \simeq |V_{cd}| \simeq 0.22.$$

$$\text{Amplitude } A \propto \begin{cases} \lambda^0 & \text{Cabibbo-favoured} \\ \lambda^1 & \text{singly Cabibbo-suppressed} \\ \lambda^2 & \text{doubly Cabibbo-suppressed} \end{cases}$$

In the SCS amplitudes three CKM structures appear: $\lambda_d = V_{cd}^* V_{ud}$, $\lambda_s = V_{cs}^* V_{us}$, $\lambda_b = V_{cb}^* V_{ub}$ and CKM unitarity $\lambda_d + \lambda_s + \lambda_b = 0$ is invoked to eliminate one of these.

Commonly used

$$\mathcal{A}^{\mathrm{SCS}} \equiv \lambda_{sd} A_{sd} - \frac{\lambda_b}{2} A_b$$

with

$$\lambda_{sd} = \frac{\lambda_s - \lambda_d}{2} \qquad \text{and} \qquad -\frac{\lambda_b}{2} = \frac{\lambda_s + \lambda_d}{2}$$

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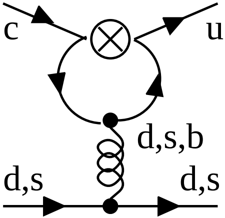
In view of $|\lambda_b|/|\lambda_{sd}| \sim 10^{-3}$ only A_{sd} is relevant for branching ratios.

Penguin loop contributions to A_{sd} are GIM-suppressed (naively: $\propto (m_s^2 - m_d^2)/m_c^2$).



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- ... are very difficult to predict in the Standard Model,
- ... are not discovered yet!

Goal: Get the most out of the measurements of the branching fractions of $D^0 \to K^+K^-$, $D^0 \to \pi^+\pi^-$, $D^0 \to K_S K_S$, $D^0 \to \pi^0\pi^0$, $D^+ \to \pi^0\pi^+$, $D^+ \to K_S K^+$, $D_s^+ \to K_S \pi^+$, $D_s^+ \to K^+\pi^0$, $D^0 \to K^-\pi^+$, $D^0 \to K_S\pi^0$, $D^0 \to K_L\pi^0$, $D^+ \to K_S\pi^+$, $D^+ \to K_L\pi^+$, $D_s^+ \to K_S K^+$, $D^0 \to K^+\pi^-$, $D^+ \to K^+\pi^0$,
and the $K^+\pi^-$ strong phase difference $\delta_{K\pi} = 6.45^\circ \pm 10.65^\circ$ to predict branching fractions and CP asymmetries in these decays.

S. Müller, UN, St. Schacht, Phys.Rev.D92(2015) 014004

S. Müller, UN, St. Schacht, Phys.Rev.Lett.115(2015) 251802

UN, St. Schacht, Phys.Rev.D92(2015) 054036

Use the approximate $SU(3)_F$ symmetry of QCD: Owing to $m_{u,d,s} \ll \Lambda_{\rm QCD}$ hadronic amplitudes are approximately invariant under unitary rotations of

$$\begin{pmatrix} u \\ d \\ s \end{pmatrix} .$$

$\Rightarrow$ One can correlate various $D \to K\pi$ decays.

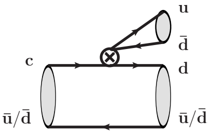
Example: In the limit of exact $SU(3)_F$ symmetry find

$$\mathcal{B}(D^0 \to \pi^+\pi^-) = \mathcal{B}(D^0 \to K^+K^-).$$

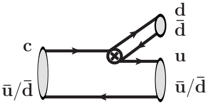
Data show $\mathcal{O}(30\%)$ $SU(3)_F$ breaking in the decay amplitudes. It is possible to include $SU(3)_F$ breaking to first order (linear breaking) in the decomposition of the decay amplitudes in terms of $SU(3)_F$ representations.

Combine topological amplitudes (Chau 1980,1982; Zeppenfeld 1981) with linear $SU(3)_F$ breaking (Gronau 1995).

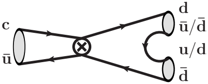
$SU(3)_F$ limit:



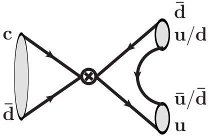
tree (T)



color-suppressed tree (C)

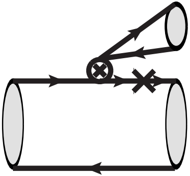


exchange (E)

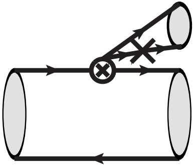


annihilation (A)

Feynman rule from $H_{\cancel{\mathrm{SU(3)}}_F} = (m_s - m_d)\bar{s}s$: dot on s-quark line.
Find 14 new topological amplitudes such as



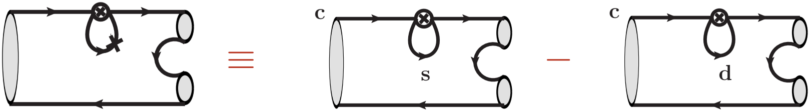
T_1



T_2

…

Important:



penguin (P_{break})

Direct CP asymmetries in singly Cabibbo-suppressed decays:
With $\mathcal{A}^{\rm SCS} = \mathcal{A}$ write

$$\mathcal{A} = \lambda_{sd} A_{sd} - \frac{\lambda_b}{2} A_b,$$

CP-conjugate decay: $$\overline{\mathcal{A}} = -\lambda_{sd}^* A_{sd} + \frac{\lambda_b^*}{2} A_b.$$

Find

$$a_{CP}^{\rm dir} \equiv \frac{|\mathcal{A}|^2 - |\overline{\mathcal{A}}|^2}{|\mathcal{A}|^2 + |\overline{\mathcal{A}}|^2} = \frac{\mathrm{Im}\,\lambda_b}{|\mathcal{A}|}\, \mathrm{Im} \frac{A_b}{A_{sd}} |A_{sd}|\,.$$

Recall: $|\mathcal{A}|$ is fixed from measured branching ratios.

$\Rightarrow$ need A_b and the phase of A_{sd} to predict $a_{CP}^{\rm dir}$.

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Predict CP asymmetries in D decays

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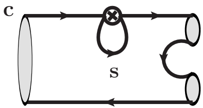
- within the Standard Model
  and
- as evidence for new physics!

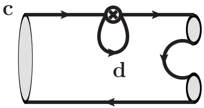
Generic problem: For CP asymmetries we need A_b which involves new hadronic quantities which do not appear in A_{sd} and are therefore not constrained by branching fractions.

E.g. new SU(3) representations or, in our analysis, new topological-amplitudes.

Prominent example:



and



Penguins P_s and P_d appear in other combinations than $P_{\rm break} = P_s - P_d$. We also need $P_s + P_d - 2P_b$.

Correlate CP asymmetries

Strategy: Build combinations out of several CP asymmetries containing only those topological amplitudes which can be extracted from the global fit to the branching ratios.

$\rightarrow$ sum rules among CP asymmetries.

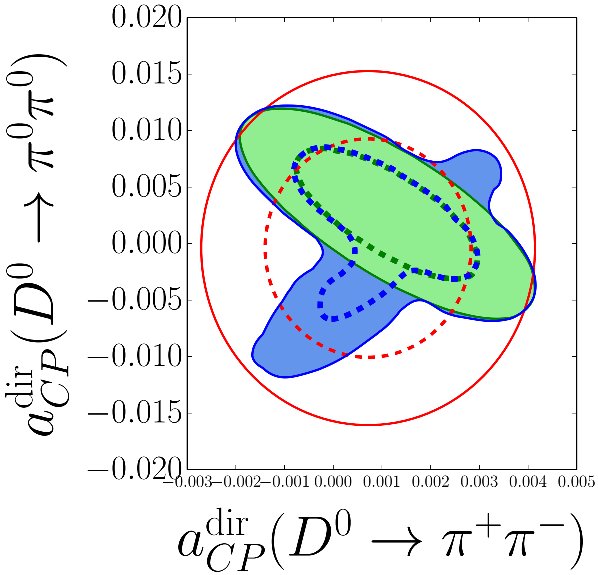
Our finding: Two sum rules each correlating three direct CP asymmetries in

I $D^0 \to K^+K^-$, $D^0 \to \pi^+\pi^-$, and $D^0 \to \pi^0\pi^0$,
and

II $D^+ \to \overline{K}^0K^+$, $D_s^+ \to K^0\pi^+$, and $D_s^+ \to K^+\pi^0$.

Theoretical accuracy of new-physics tests only limited by the assumed size of $SU(3)_F$ breaking; great progress compared to the $\mathcal{O}(1000\%)$ spread of past predictions.

S. Müller,UN,St. Schacht, Phys.Rev.Lett.115(2015) 251802.



Red solid:
95% CL measurement

Red dashed:
68% CL measurement

Present data:

Light blue:
95% CL from global fit

Dark blue dashed:
68% CL from global fit

Future scenario:

assume $\sqrt{50}$ better branching ratios, but $a_{CP}^{\mathrm{dir}}(D^0 \to K^+K^-)$ as today.

Light green:
95% CL from global fit

Dark green dashed:
68% CL from global fit

$$\mathcal{A}(D^0 \to K_S K_S) = \lambda_{sd} \mathcal{A}_{sd} - \frac{\lambda_b}{2} \mathcal{A}_b.$$

Special feature I:

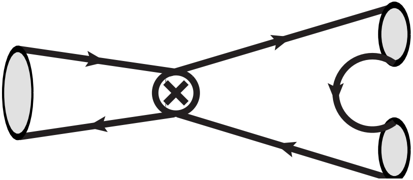
In the SU(3)$_F$ limit: $\mathcal{A}_{sd} = 0$ while $\mathcal{A}_b \neq 0$

$\Rightarrow$ suppressed $\mathcal{B}(D^0 \to K_S K_S) = (1.7 \pm 0.4) \cdot 10^{-4}$

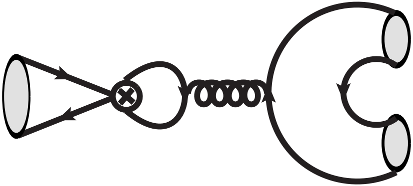
enhanced $a_{CP}^{\rm dir} \propto \mathrm{Im} \frac{A_b}{A_{sd}}$

Special feature II:

$a_{CP}^{\rm dir}(D^0 \to K_S K_S)$ receives contributions at tree level, from the (sizable!) exchange diagram:



exchange diagram



penguin annihilation diagram

Result: $a_{CP}^{\rm dir}$ can be large. We find:

$$|a_{CP}^{\rm dir}(D^0 \to K_S K_S)| \leq 1.1\% \qquad @95\% \text{ C.L.}$$

The CP violation in $\mathrm{K}-\overline{\mathrm{K}}$ mixing is meant to be subtracted.

UN, St. Schacht, Phys.Rev.D92(2015) 054036

Experiment determines

$$A_{CP} = a_{CP}^{\rm dir} - A_\Gamma \frac{\langle t \rangle}{\tau},$$

where $\langle t \rangle$ is the average decay time and τ is the D^0 lifetime.

$$A_{CP}^{\rm CLEO\ 2001} = -0.23 \pm 0.19$$

$$A_{CP}^{\rm LHCb\ 2015} = -0.029 \pm 0.052 \pm 0.022$$

$$A_{CP}^{\rm Belle\ 2016} = -0.0002 \pm 0.0153 \pm 0.0017$$

Summary

- CP asymmetries in D decays involve topological amplitudes not constrained by fits to branching ratio data. These can be eliminated by forming judicious combinations of several CP asymmetries.

  $\rightarrow$ sum rules
- The sum rules test the quality of $SU(3)_F$ in penguin amplitudes and/or new physics.
- Combine CP asymmetries in $D^0 \rightarrow K^+K^-$, $D^0 \rightarrow \pi^+\pi^-$, and $D^0 \rightarrow \pi^0\pi^0$ to probe new physics.
- Within the Standard Model the direct CP asymmetry in the charm decay in $D^0 \rightarrow K_S K_S$ can be as large as 1.1%. $a_{CP}^{\mathrm{dir}}(D^0 \rightarrow K_S K_S)$ is dominated by the exchange diagram, which involves no loop suppression. Could $D^0 \rightarrow K_S K_S$ be a discovery channel for charm CP violation?