

CP asymmetries in D decays to two pseudoscalars

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D decays to two pseudoscalars

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

$$D^+ \sim c\bar{d}, \quad D^0 \sim c\bar{u}, \quad D_s^+ \sim c\bar{s},$$

Examples: $D^+ \rightarrow \bar{K}^0\pi^+$, $D^0 \rightarrow \pi^+\pi^-$, $D^+ \rightarrow K^0\pi^+$.

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

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

with

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

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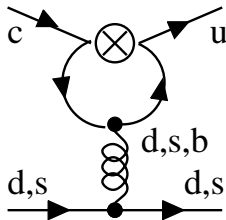
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In view of $|\lambda_b|/|\lambda_{sd}| \sim 10^{-3}$ only A_{sd} is relevant for branching ratios.

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



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- ... and probe **new physics** in flavour transitions of **up-type** quarks,
- ... 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 $D^0 \rightarrow K^+K^-, D^0 \rightarrow \pi^+\pi^-, D^0 \rightarrow K_S K_S, D^0 \rightarrow \pi^0\pi^0, D^+ \rightarrow \pi^0\pi^+, D^+ \rightarrow K_S K^+, D_s^+ \rightarrow K_S \pi^+, D_s^+ \rightarrow K^+\pi^0, D^0 \rightarrow K^-\pi^+, D^0 \rightarrow K_S \pi^0, D^0 \rightarrow K_L \pi^0, D^+ \rightarrow K_S \pi^+, D^+ \rightarrow K_L \pi^+, D_s^+ \rightarrow K_S K^+, D^0 \rightarrow K^+\pi^-, D^+ \rightarrow K^+\pi^0$, 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 $m_{u,d,s} \ll \Lambda_{\text{QCD}}$ hadronic amplitudes are approximately invariant under unitary rotations of

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

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

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

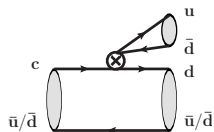
$$\mathcal{B}(D^0 \rightarrow \pi^+\pi^-) = \mathcal{B}(D^0 \rightarrow K^+K^-).$$

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.

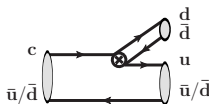
Topological amplitudes

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

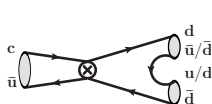
$SU(3)_F$ limit:



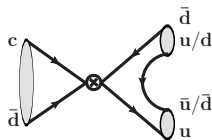
tree (T)



color-suppressed tree (C)



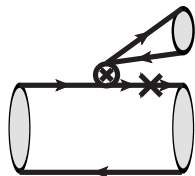
exchange (E)



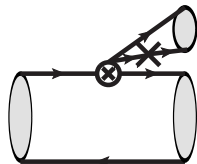
annihilation (A)

$SU(3)_F$ breaking

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



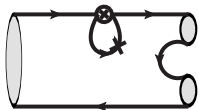
T_1



T_2

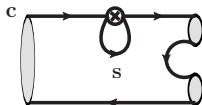
...

Important:

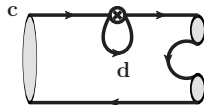


penguin (P_{break})

\equiv



$-$



Direct CP asymmetries in singly Cabibbo-suppressed decays:

With $\mathcal{A}^{\text{SCS}} = \mathcal{A}$ write

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

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

Find

$$\begin{aligned} a_{CP}^{\text{dir}} &\equiv \frac{|\mathcal{A}|^2 - |\bar{\mathcal{A}}|^2}{|\mathcal{A}|^2 + |\bar{\mathcal{A}}|^2} \\ &= \frac{\text{Im } \lambda_b}{|\mathcal{A}|} \text{Im} \frac{A_b}{A_{sd}} |A_{sd}|. \end{aligned}$$

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

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

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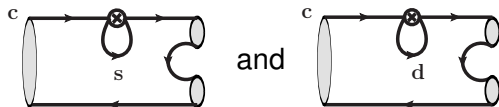
- within the **Standard Model**
and
- as evidence for **new physics!**

CP asymmetries

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:



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

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**.

→ **sum rules** among CP asymmetries.

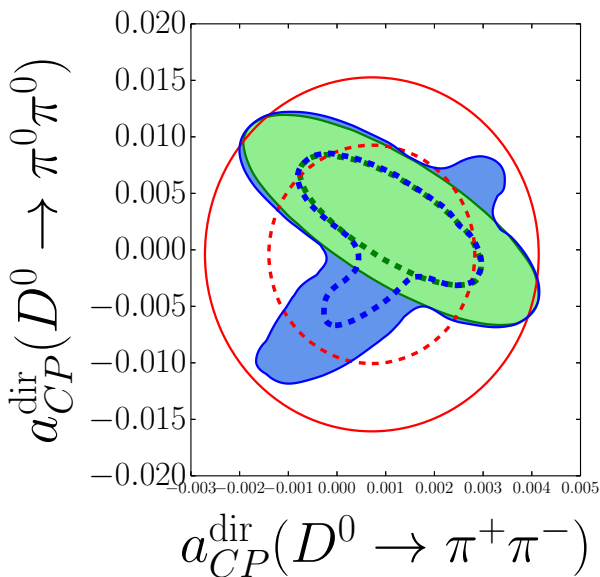
Our finding: Two sum rules each correlating **three** direct CP asymmetries in

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

II $D^+ \rightarrow \bar{K}^0K^+$, $D_s^+ \rightarrow K^0\pi^+$, and $D_s^+ \rightarrow K^+\pi^0$.

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
 $a_{CP}^{dir}(D^0 \rightarrow K^+ K^-)$ as
today.

Light green:

95% CL from global fit

Dark green dashed:

68% CL from global fit

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

Special feature I:

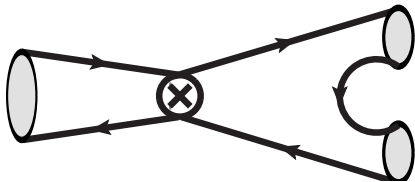
In the $SU(3)_F$ limit: $\mathcal{A}_{sd} = 0$ while $\mathcal{A}_b \neq 0$

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

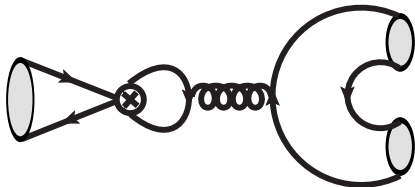
enhanced $a_{CP}^{\text{dir}} \propto \text{Im} \frac{A_b}{A_{sd}}$

Special feature II:

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



exchange diagram



penguin annihilation diagram

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

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

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

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

Experiment determines

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

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

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

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

- **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**.
→ **sum rules**
- The sum rules test the quality of $SU(3)_F$ in penguin amplitudes and/or 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%. $a_{CP}^{\text{dir}}(D^0 \rightarrow K_S K_S)$ 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**?