CP asymmetries in $D$ decays to two pseudoscalars

Ulrich Nierste
Karlsruhe Institute of Technology
Institute for Theoretical Particle Physics

9th International Workshop on the CKM Unitarity Triangle (CKM2016)
Mumbai, 28 November 2016
$D$ 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: $D^+ \rightarrow \bar{K}^0\pi^+, \quad D^0 \rightarrow \pi^+\pi^-, \quad D^+ \rightarrow K^0\pi^+.$

Decays are classified in terms of powers of the Wolfenstein parameter

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

Amplitude $A \propto \left\{ \begin{array}{ll}
\lambda^0 & \text{Cabibbo-favoured} \\
\lambda^1 & \text{singly Cabibbo-suppressed} \\
\lambda^2 & \text{doubly Cabibbo-suppressed}
\end{array} \right.$$

Ulrich Nierste (TTP)
In the SCS amplitudes three CKM structures appear:

\[ \lambda_d = V_{cd}^* V_{ud}, \quad \lambda_s = V_{cs}^* V_{us}, \quad \lambda_b = V_{cb}^* V_{ub} \]

and CKM unitarity \( \lambda_d + \lambda_s + \lambda_b = 0 \) is invoked to eliminate one of these.

Commonly used

\[ A^{SCS} \equiv \lambda_{sd} A_{sd} - \frac{\lambda_b}{2} A_b \]

with

\[ \lambda_{sd} = \frac{\lambda_s - \lambda_d}{2} \quad \text{and} \quad -\frac{\lambda_b}{2} = \frac{\lambda_s + \lambda_d}{2} \]
In the SCS amplitudes three CKM structures appear:
\[ \lambda_d = V_{cd}^* V_{ud}, \quad \lambda_s = V_{cs}^* V_{us}, \quad \lambda_b = V_{cb}^* V_{ub} \]
and CKM unitarity \( \lambda_d + \lambda_s + \lambda_b = 0 \) is invoked to eliminate one of these.

Commonly used
\[ A^{SCS} \equiv \lambda_{sd} A_{sd} - \frac{\lambda_b}{2} A_b \]
with
\[ \lambda_{sd} = \frac{\lambda_s - \lambda_d}{2} \quad \text{and} \quad -\frac{\lambda_b}{2} = \frac{\lambda_s + \lambda_d}{2} \]

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: \( \propto (m_s^2 - m_d^2)/m_c^2 \)).
Branching ratios of hadronic charm decays . . .

. . . are “dull” tree-level quantities dominated by a single CKM amplitude
Branching ratios of hadronic charm decays . . .

. . . are “dull” tree-level quantities dominated by a single CKM amplitude

. . . and are therefore insensitive to new physics, but
Branching ratios of hadronic charm decays . . .

. . . are “dull” tree-level quantities dominated by a single CKM amplitude

. . . and are therefore insensitive to new physics, but

. . . are useful to test the calculational framework and
Branching ratios of hadronic charm decays . . .

. . . are “dull” tree-level quantities dominated by a single CKM amplitude

. . . and are therefore insensitive to new physics, but

. . . are useful to test the calculational framework and

. . . experimentally determine $|A_{sd}|$, an important ingredient to predict CP asymmetries.
Branching ratios of hadronic charm decays . . .

. . . are “dull” tree-level quantities dominated by a single CKM amplitude

. . . and are therefore insensitive to new physics, but

. . . are useful to test the calculational framework and

. . . experimentally determine $|A_{sd}|$, an important ingredient to predict CP asymmetries.
Branching ratios of hadronic charm decays . . .

. . . are “dull” tree-level quantities dominated by a single CKM amplitude

. . . and are therefore insensitive to new physics, but

. . . are useful to test the calculational framework and

. . . experimentally determine $|A_{sd}|$, an important ingredient to predict CP asymmetries.

CP asymmetries of hadronic charm decays . . .

. . . are proportional to $\text{Im} \frac{\lambda_b}{\lambda_{sd}} = -6 \cdot 10^{-4}$ in the Standard Model
Branching ratios of hadronic charm decays . . .

. . . are “dull” tree-level quantities dominated by a single CKM amplitude

. . . and are therefore insensitive to new physics, but

. . . are useful to test the calculational framework and

. . . experimentally determine $|A_{sd}|$, an important ingredient to predict CP asymmetries.

CP asymmetries of hadronic charm decays . . .

. . . are proportional to $\text{Im} \frac{\lambda_b}{\lambda_{sd}} = -6 \cdot 10^{-4}$ in the Standard Model

. . . and probe new physics in flavour transitions of up-type quarks,
Branching ratios of hadronic charm decays . . .

. . . are “dull” tree-level quantities dominated by a single CKM amplitude

. . . and are therefore insensitive to new physics, but

. . . are useful to test the calculational framework and

. . . experimentally determine $|A_{sd}|$, an important ingredient to predict CP asymmetries.

CP asymmetries of hadronic charm decays . . .

. . . are proportional to $\text{Im} \frac{\lambda_b}{\lambda_{sd}} = -6 \cdot 10^{-4}$ in the Standard Model

. . . and probe new physics in flavour transitions of up-type quarks,

. . . are very difficult to predict in the Standard Model,
Branching ratios of hadronic charm decays . . .

. . . are “dull” tree-level quantities dominated by a single CKM amplitude

. . . and are therefore insensitive to new physics, but

. . . are useful to test the calculational framework and

. . . experimentally determine $|A_{sd}|$, an important ingredient to predict CP asymmetries.

CP asymmetries of hadronic charm decays . . .

. . . are proportional to $\text{Im} \frac{\lambda_b}{\lambda_{sd}} = -6 \cdot 10^{-4}$ in the Standard Model

. . . 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
\( D^0 \to K^+K^- \), \( D^0 \to \pi^+\pi^- \), \( D^0 \to K_SK_S \), \( D^0 \to \pi^0\pi^0 \), \( D^+ \to \pi^0\pi^+ \),
\( D^+ \to K_SK^+ \), \( D_S^+ \to K_S\pi^+ \), \( D_S^+ \to K^+\pi^0 \), \( D^0 \to K^-\pi^+ \), \( D^0 \to K_S\pi^0 \),
\( D^0 \to K_L\pi^0 \), \( D^+ \to K_S\pi^+ \), \( D^+ \to K_L\pi^+ \), \( D_S^+ \to K_SK^+ \), \( D^0 \to K^+\pi^- \),
\( D^+ \to K^+\pi^0 \),
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
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

\[
\begin{pmatrix}
  u \\
  d \\
  s
\end{pmatrix}
\]

⇒ 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.
Topological amplitudes


$SU(3)_F$ limit:

- **Tree (T)**
- **Color-suppressed tree (C)**
- **Exchange (E)**
- **Annihilation (A)**
SU(3)_F breaking

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

Important:

penguin ($P_{\text{break}}$)
Direct CP asymmetries in singly Cabibbo-suppressed decays:

With $\mathcal{A}_{SCS} = \mathcal{A}$ 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

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

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

$\Rightarrow$ need $A_b$ and the phase of $A_{sd}$ to predict $a_{CP}^{\text{dir}}$. 
The theory community has delivered a perfect service to the experimental colleagues:
Predict CP asymmetries in $D$ decays

The theory community has delivered a perfect service to the experimental colleagues: Every measurement hinting at some non-zero CP asymmetry was successfully postdicted offering interpretations both
The theory community has delivered a **perfect service** to the experimental colleagues: **Every measurement** hinting at some non-zero CP asymmetry was **successfully postdicted** offering interpretations both

- 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:

![Diagram](image)

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

Ulrich Nierste (TTP)
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.

→ sum rules among CP asymmetries.

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

1. $D^0 \to K^+ K^-$, $D^0 \to \pi^+ \pi^-$, and $D^0 \to \pi^0 \pi^0$, and
2. $D^+ \to \bar{K}^0 K^+$, $D^+_s \to K^0 \pi^+$, 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 $O(1000\%)$ spread of past predictions.

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

Light green: 95% CL from global fit
Dark green dashed: 68% CL from global fit
$D^0 \rightarrow K_SK_S$

\[ \mathcal{A}(D^0 \rightarrow K_SK_S) = \lambda_{sd}A_{sd} - \frac{\lambda_b}{2}A_b. \]

**Special feature I:**

In the SU(3)$_F$ limit: $A_{sd} = 0$ while $A_b \neq 0$

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

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

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

- **exchange diagram**
- **penguin annihilation diagram**
Result: $a_{CP}^{\text{dir}}$ can be large. We find:

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

The CP violation in $K^-K^+$ 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 $\tau$ is the $D^0$ lifetime.

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

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

$$A_{CP}^{\text{Belle 2016}} = -0.0002 \pm 0.0153 \pm 0.0017$$
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 $D^0 \rightarrow K_SK_S$ can be as large as 1.1%. $a^\text{dir}_{CP}(D^0 \rightarrow K_SK_S)$ is dominated by the exchange diagram, which involves no loop suppression. Could $D^0 \rightarrow K_SK_S$ be a discovery channel for charm CP violation?