How to discover charm CP violation

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Heavy Quarks through the Looking Glass
Siegen, 5 October 2018

Today is Thomas' 60.003th birthday!

I met Thomas for the first time in Munich in 1992, where he was introduced to us as an expert on "$1/m$ expansion"

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He brought his PhD student with him:

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In that year, Robert Fleischer and I, both beginning PhD students, started to learn HQET, but soon drifted off into the worlds of penguins and boxes, respectively.

According to INSPIRE the papers co-authored by Thomas and me have collected 491 citation on average.

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All the best for the next 39.997 years!

1. CP violation in D decays
2. How not to discover charm CP violation
3. How to discover charm CP violation
4. How to really discover charm CP violation
5. Summary

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

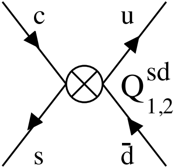
$$D^+ \sim c\overline{d}, \qquad D^0 \sim c\overline{u}, \qquad D_s^+ \sim c\overline{s},$$

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

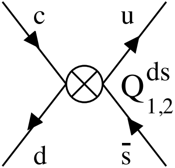
Decays are classified in terms of powers of the Wolfenstein parameter

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

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



Cabibbo-favoured (CF), $A \propto \lambda^0$



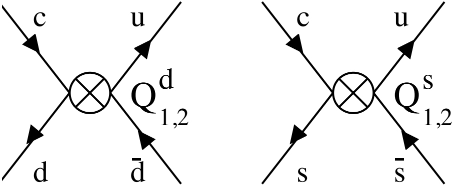
doubly Cabibbo-suppressed (DCS), $A \propto \lambda^2$

Number of D^+, D^0, D_s^+ decay modes:

4 Cabibbo-favoured,

5 doubly Cabibbo-suppressed,

8 singly Cabibbo-suppressed.



singly Cabibbo-suppressed (SCS), $A \propto \lambda^1$

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

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

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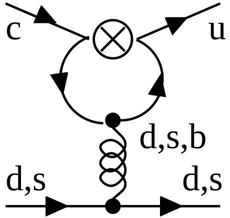
In view of $|\lambda_b|/|\lambda_{sd}| \sim 10^{-3}$ only A_{sd} is relevant for branching ratios.

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!

CP asymmetries in D decays

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

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

Recall: $|A_{sd}| = |\mathcal{A}|/|\lambda_{sd}|$ is fixed from measured branching ratios.

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

All SM predictions for CP asymmetries involve a suppression by $\mathrm{Im}\frac{\lambda_b}{\lambda_{sd}} = -6 \cdot 10^{-4}$. This is also true for mixing-induced CP asymmetries or the semileptonic CP asymmetry, which quantifies CP violation (CPV) in mixing.

CPV discovery vs. new-physics discovery

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In the pre-LHC era CPV could have only been discovered if there was a substantial enhancement by new physics, with $\mathrm{Im}\frac{\lambda_b}{\lambda_{sd}}$ replaced by some $\mathcal{O}(1)$ factor. Thus the "CPV discovery channels" were identical to the "new-physics discovery channels".

With LHCb probing CP asymmetries down to SM predictions, the goals

(a) "discover CPV if there is no physics beyond the SM"
and

(b) "discover new physics"

require different strategies:

For (a) need decay modes with large SM predictions for a_{CP}^{dir}.
For (b) need decay modes with clean SM predictions for a_{CP}^{dir}.

CPV discovery channels in the SM

$$a_{CP}^{\rm dir} = {\rm Im}\frac{\lambda_b}{\lambda_{sd}}\ {\rm Im}\frac{A_b}{A_{sd}}$$
$$= -6\cdot 10^{-4}\ \underbrace{{\rm Im}\frac{A_b}{A_{sd}}}$$

can be $\mathcal{O}(10)$ in the SM,
if A_{sd} is suppressed.

Typical SM values of $a_{CP}^{\rm dir}$ are below 10^{-3}, thus identifying decays with large $\left|\frac{A_b}{A_{sd}}\right|$ is important. (The phase $\arg\frac{A_b}{A_{sd}}$ is unpredictable, so one must be lucky.)

A_{sd} sausage factory

To learn as much as possible about A_{sd} for the various decay modes, do a correlated analysis of all available data on 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 $\delta_{K\pi} = 6.45^\circ \pm 10.65^\circ$.

This gives essentially one ingredient of the CP asymmetries, $|A_{sd}|$, but gives no information on $|A_b|$ and $\arg(A_b/A_{sd})$.

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 $m_{u,d,s} \ll \Lambda_{\mathrm{QCD}}$ 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

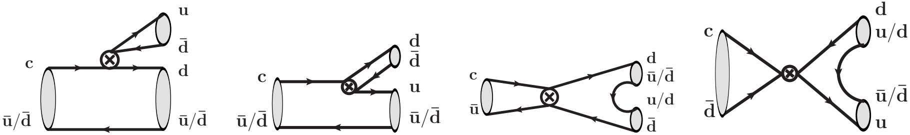
$$\mathcal{B}(D^0 \to \pi^+\pi^-) = \mathcal{B}(D^0 \to K^+K^-).$$

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.

Topological amplitudes

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

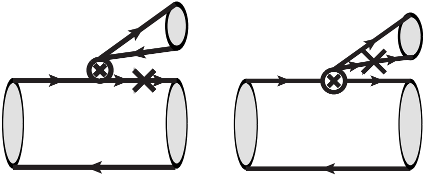
$SU(3)_F$ limit:



tree (T) color-suppressed tree (C) exchange (E) annihilation (A)

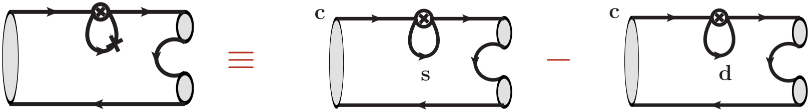
$SU(3)_F$ breaking

Feynman rule from $H_{\not{\mathrm{SU(3)}}_F} = (m_s - m_d)\bar{s}s$: dot on s-quark line.
Find 14 new topological amplitudes such as



T_1 T_2 …

Important:



penguin (P_{break})

Predict CP asymmetries in D decays

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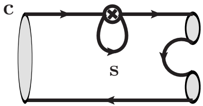
Every measurement hinting at some non-zero CP asymmetry was successfully postdicted offering interpretations both

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

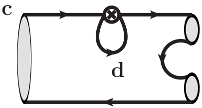
Generic problem: For CP asymmetries we need A_b which involves new hadronic quantities which do not appear in A_{sd} and are therefore not constrained by branching fractions.

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 $P_s + P_d - 2P_b$.

Experimentally $a_{CP}^{\mathrm{dir}}(D^0 \to \pi^+\pi^-)$ and $a_{CP}^{\mathrm{dir}}(D^0 \to K^+K^-)$ are well constrained. Status of 2015:

$$\Delta a_{CP}^{\mathrm{dir}} \equiv a_{CP}^{\mathrm{dir}}(D^0 \to K^+K^-) - a_{CP}^{\mathrm{dir}}(D^0 \to \pi^+\pi^-) = -0.00253 \pm 0.00104$$
$$\Sigma a_{CP}^{\mathrm{dir}} \equiv a_{CP}^{\mathrm{dir}}(D^0 \to K^+K^-) + a_{CP}^{\mathrm{dir}}(D^0 \to \pi^+\pi^-) = -0.0011 \pm 0.0026$$

Topological amplitudes:

$$\mathcal{A}_{sd}(D^0 \to \pi^+\pi^-) = -T - E + P_{\mathrm{break}}$$
$$\mathcal{A}_b(D^0 \to \pi^+\pi^-) = T + E + P + PA$$

It is useful to eliminate $T + E$ in $\mathcal{A}_b$ in favour of $\mathcal{A}_{sd}$:

$$\mathcal{A}_b(D^0 \to \pi^+\pi^-) = -\mathcal{A}_{sd}(D^0 \to \pi^+\pi^-) + P_{\rm break} + P + PA$$
$$\Rightarrow \qquad \mathrm{Im}\,\frac{A_b(\pi^+\pi^-)}{A_{sd}(\pi^+\pi^-)} = \mathrm{Im}\,\frac{P_{\rm break} + P + PA}{A_{sd}(\pi^+\pi^-)}$$

Similarly for $D^0 \to K^+K^-$ (up to $\mathrm{SU(3)}_F$ breaking):

$$\mathrm{Im}\,\frac{A_b(K^+K^-)}{A_{sd}(K^+K^-)} = \mathrm{Im}\,\frac{P_{\rm break} - P - PA}{A_{sd}(\pi^+\pi^-)}$$

Thus $\Delta a_{CP}^{\rm dir}$ rules out spectacular enhancements of $P + PA$ and $\Sigma a_{CP}^{\rm dir}$ likewise constrains $P_{\rm break}$.

$\Rightarrow$ To find CPV look for alternatives to P, PA!

Discovering SM CP violation

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

Special feature I:

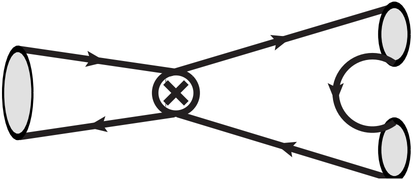
In the $SU(3)_F$ limit: $\mathcal{A}_{sd} = 0$ while $\mathcal{A}_b \neq 0$

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

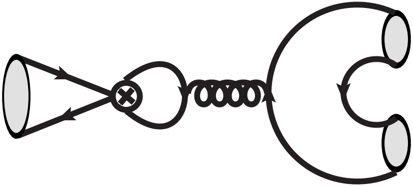
enhanced $a_{CP}^{\mathrm{dir}} \propto \mathrm{Im} \dfrac{A_b}{A_{sd}}$

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.

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

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

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

UN, St. Schacht, Phys.Rev.Lett. 119 (2017) 251801

Two $D^0 \to KK^*$ decays:

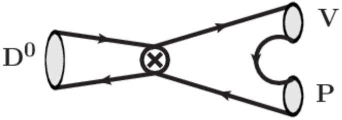
$$D^0 \to \overline{K}^{*0}[\to K^-\pi^+]K^0$$
$$D^0 \to K^{*0}[\to K^+\pi^-]\overline{K}^0$$

with the K^0, $\overline{K}^0$ hadronising into K_S.

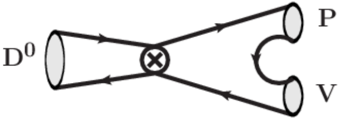
Write shortly:

$$\mathcal{A}(\overline{K}^{*0}) \equiv \mathcal{A}(D^0 \to \overline{K}^{*0}K^0)$$
$$\mathcal{A}(K^{*0}) \equiv \mathcal{A}(D^0 \to K^{*0}\overline{K}^0).$$

Each diagram comes in two variants, e.g.



E_P



E_V

Topological amplitudes:

$$\mathcal{A}_{sd}(K^{*0}) = \quad E_P - E_V + E_{P3} - E_{V1} - E_{V2} - PA_{PV}^{\text{break}}$$

$$\mathcal{A}_b(K^{*0}) = -E_P - E_V - E_{P3} - E_{V1} - E_{V2} - PA_{PV}$$

$$= \mathcal{A}_{sd}(K^{*0}) - 2E_P - 2E_{P3} - PA_{PV} + PA_{PV}^{\text{break}},$$

$$\mathcal{A}_{sd}(\overline{K}^{*0}) = -E_P + E_V - E_{P1} - E_{P2} + E_{V3} - PA_{PV}^{\text{break}},$$

$$\mathcal{A}_b(\overline{K}^{*0}) = -E_P - E_V - E_{P1} - E_{P2} - E_{V3} - PA_{PV}$$

$$= \mathcal{A}_{sd}(\overline{K}^{*0}) - 2E_V - 2E_{V3} - PA_{PV} + PA_{PV}^{\text{break}}.$$

$$\Rightarrow \quad a_{CP}^{\text{dir}}(D^0 \to \overline{K}^{*0} K^0) = \text{Im}\frac{\lambda_b}{\lambda_{sd}}\ \text{Im}\frac{A_b(\overline{K}^{*0})}{A_{sd}(\overline{K}^{*0})}$$

$$\approx -\text{Im}\frac{\lambda_b}{\lambda_{sd}}\ \text{Im}\frac{A_b(K^{*0})}{A_{sd}(K^{*0})} = -a_{CP}^{\text{dir}}(D^0 \to K^{*0}\overline{K}^0) = a_{CP}^{\text{dir}}(\overline{D}^0 \to \overline{K}^{*0} K^0)$$

$D^0 \to KK^*$

$a_{CP}^{\rm dir}(D^0 \to \overline{K}^{*0} K^0) \approx a_{CP}^{\rm dir}(\bar{D}^0 \to \overline{K}^{*0} K^0)$ means that no flavour tagging is needed:

$$a_{CP}^{\rm dir}(\overset{(-)}{D} \to K_S K^{0*}) \approx a_{CP}^{\rm dir}(D^0 \to K_S K^{0*})$$

Using

$$\mathcal{B}^{\rm exp}(D^0 \to K^{*0} K_S) = (1.1 \pm 0.2) \cdot 10^{-4}\,,$$
$$\mathcal{B}^{\rm exp}(D^0 \to \overline{K}^{*0} K_S) = (0.9 \pm 0.2) \cdot 10^{-4}\,.$$

from experiment to determine $|E_P - E_V| = (1.6 \pm 0.2) \cdot 10^{-6}$ we find

$$|a_{CP}^{\text{dir, untag}}| \lesssim 0.003\,.$$

The maximum corresponds to $\arg(E_V/E_P) = 0.14\,\pi$.

Another goodie: One can scan the $K^+\pi^- K_S$ Dalitz plot near the K^{*0} resonance for a favourable $\arg(E_V/E_P)$.

- "Charm CPV discovery within the SM" and "New-physics discovery through CPV" require different strategies.
- Within the Standard Model the direct CP asymmetry in the charm decay in $D^0 \to K_S K_S$ can be as large as 1.1%.
  $a_{CP}^{\rm dir}(D^0 \to K_S K_S)$ is dominated by the exchange diagram, which involves no loop suppression. View $D^0 \to K_S K_S$ as a discovery channel for charm CP violation.
- The same is true for $D^0 \to K^{*0} K_S$, which moreover requires no tagging to measure $a_{CP}^{\rm dir}$. $a_{CP}^{\text{dir, untag}}(D^0 \to K^{*0} K_S)$ can be as large as 0.3%.