Charm decays

Ulrich Nierste

Karlsruhe Institute of Technology
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Beauty 2019
Ljubljana, 3 October 2019

March 21, 2019:

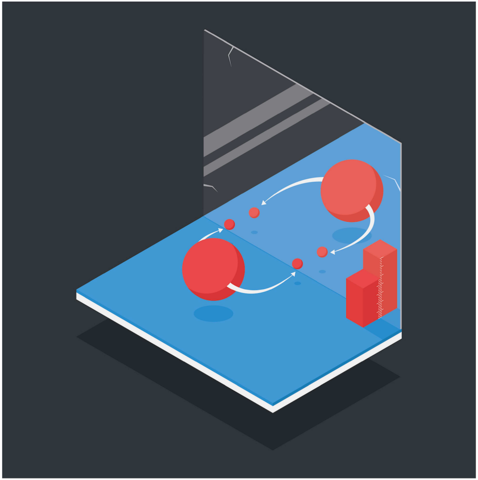
Discovery of CP violation in charm decays through

$$\Delta a_{CP} \equiv a_{CP}^{\rm dir}(D^0 \to K^+K^-) - a_{CP}^{\rm dir}(D^0 \to \pi^+\pi^-)$$

LHCb sees a new flavour of matter–antimatter asymmetry

The LHCb collaboration has observed a phenomenon known as CP violation in the decays of a particle known as a D0 meson for the first time

21 MARCH, 2019



Eight days earlier…

…I gave a talk to the LHCb charm group:

How to discover charm CP violation

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and stated:

A posteriori the experimental data tell us that CP violation from boxes and penguins is small, e.g.

$$\Delta a_{CP} \equiv a_{CP}^{\rm dir}(D^0 \to K^+K^-) - a_{CP}^{\rm dir}(D^0 \to \pi^+\pi^-) = -0.00134 \pm 0.00070$$ HFLAV 2016

$\longrightarrow$ focus on tree-tree interference $\longleftarrow$

Role of charm physics

Charm decays

- have no stakes in Standard-Model CKM metrology,
  but
- have a unique role to probe new physics in the flavor sector of up-type quarks.

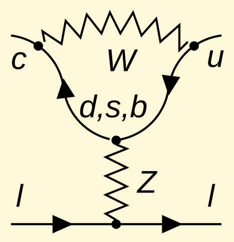
FCNC example $D^0 \to l\bar{l}$:

loop with b comes with small $|V_{cb}^* V_{ub}| = 1.6 \cdot 10^{-4}$
loops with d, s are proportional to

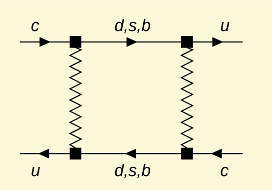
$$\frac{G_F}{M_Z^2} \cdot \underbrace{(m_s - m_d)} \cdot \underbrace{(m_s + m_d)}$$

$(m_s - m_d)$: U-spin breaking GIM

$(m_s - m_d) \cdot (m_s + m_d)$: artefact of perturbation theory



No successful attempt to calculate charm FCNC.



$D-\bar{D}$ mixing: mass difference Δm and width difference $\Delta\Gamma$ of mass eigenstates:

$$x = \frac{\Delta m}{\Gamma} = 0.43^{+0.10}_{-0.11}\%, \qquad y = \frac{\Delta\Gamma}{2\Gamma} = 0.63 \pm 0.06\%$$

HFLAV March 2019

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

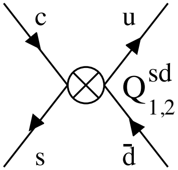
$$\lambda \simeq |V_{us}| \simeq |V_{cd}| \simeq 0.22.$$

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

Operators from W exchange, e.g.

$$Q_1^{sd} = \overline{s}_L^j \gamma_\mu c_L^k \, \overline{u}_L^k \gamma^\mu d_L^j$$
$$Q_2^{sd} = \overline{s}_L^j \gamma_\mu c_L^j \, \overline{u}_L^k \gamma^\mu d_L^k$$

with colour indices j, k.



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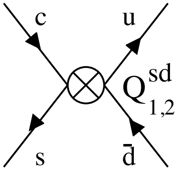

Strip CKM factors off the amplitudes:

$$\mathcal{A}^{\mathrm{CF}} \equiv V_{cs}^* V_{ud} A$$
$$\mathcal{A}^{\mathrm{DCS}} \equiv V_{cd}^* V_{us} A.$$

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

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

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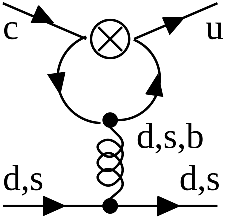
In view of $|\lambda_b|/|\lambda_{sd}| \sim 10^{-3}$ only A_{sd} is relevant for branching ratios.

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



CP asymmetries of hadronic charm decays …

- … are proportional to $\mathrm{Im}\,\frac{\lambda_b}{\lambda_{sd}} = -6 \cdot 10^{-4}$ in the Standard Model
  - … and probe new physics in flavour transitions of up-type quarks,
- … are very difficult to predict in the Standard Model.

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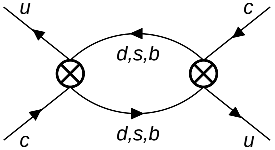
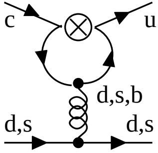
And we are not stubborn at all: After new measurements we eagerly change our opinions!

Detectable CP asymmetries stem from the interference of a tree diagram with a

box,

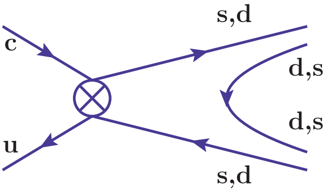


penguin,



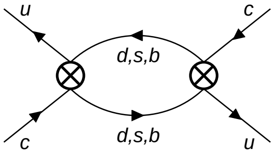
or tree-level diagram:

"(colour favoured) tree" (T),
"colour suppressed tree" (C),
or "exchange" (E).

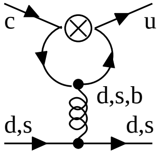


Observables (examples):

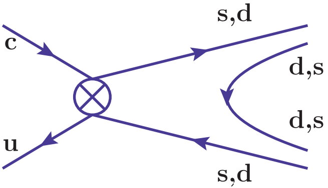
$a_{CP}^{\mathrm{mix}}(D^0(t) \to K^+\pi^-)$



$a_{CP}^{\mathrm{dir}}(D^0 \to \pi^+\pi^-)$
$a_{CP}^{\mathrm{dir}}(D^0 \to K^+K^-)$



$a_{CP}^{\mathrm{dir}}(D^0 \to K_S K_S)$
$a_{CP}^{\mathrm{dir}}(D^0 \to K_S K^{*0})$



In all cases find:

$$a_{CP} \propto \frac{\lambda_b}{\lambda_{sd}} = -6 \cdot 10^{-4}$$

The prefactor multiplying $\frac{\lambda_b}{\lambda_{sd}}$ cannot be precisely calculated in all three cases.

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

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

Branching ratios only fix $|A_{sd}| = |\mathcal{A}|/|\lambda_{sd}|$.

$\Rightarrow$ still need ${\rm Im} \frac{A_b}{A_{sd}}$ to predict $a_{CP}^{\rm dir}$.

CPV discovery channels in the SM

$$a_{CP}^{\rm dir} = \mathrm{Im}\frac{\lambda_b}{\lambda_{sd}}\ \mathrm{Im}\frac{A_b}{A_{sd}}$$

$$= -6 \cdot 10^{-4}\ \underbrace{\mathrm{Im}\frac{A_b}{A_{sd}}}$$

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.)

$SU(3)_F$ symmetry

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 $D \to K\pi$ decays.

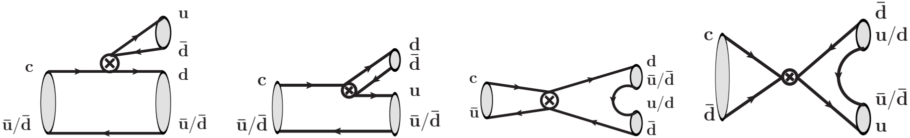
Example: In the limit of exact $SU(3)_F$ symmetry find

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

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)

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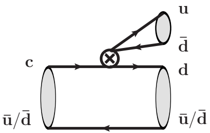
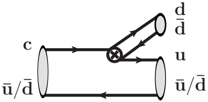
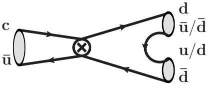


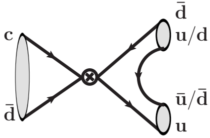
tree (T)



color-suppressed tree (C)



exchange (E)



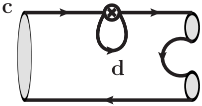
annihilation (A)

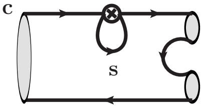
A global fit to all $D^0, D^+, D_s^+ \to KK, K\pi, \pi\pi$ branching ratios $\left\{\begin{array}{l}\text{without}\\ \text{including}\end{array}\right\}$ $\mathrm{SU(3)_F}$ breaking is $\left\{\begin{array}{l}\text{underconstrained}\\ \text{overconstrained}\end{array}\right\}$, and returns $\geq$ 28% $\mathrm{SU(3)_F}$ breaking in the amplitudes.

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

CP asymmetries

Already in the SU(3)$_F$ limit direct CP asymmetries involve topological amplitudes which are not constrained by branching fractions, importantly: With

$P_d \equiv$ 

$P_s \equiv$ 

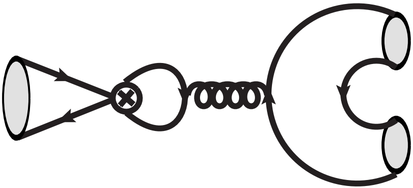
(and analogously defined P_b), the amplitude A_b entering CP asymmetries like $a_{CP}^{\rm dir}(D^0 \to K^+K^-, \pi^+\pi^-)$ involves

$$P \equiv P_d + P_s - 2P_b.$$

⇒ It is impossible to predict penguin-induced CP asymmetries from branching ratios with SU(3)$_F$ symmetry alone!

Other diagram entering A_b:

Penguin annihilation diagram PA:



In the $\mathrm{SU(3)_F}$ limit find $A_b(\pi^+\pi^-) = A_b(K^+K^-)$ and $A_{sd}(\pi^+\pi^-) = -A_{sd}(K^+K^-)$ and

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

LHCb has measured

$$\Delta a_{CP} \equiv a_{CP}^{\mathrm{dir}}(D^0 \to K^+K^-) - a_{CP}^{\mathrm{dir}}(D^0 \to \pi^+\pi^-) \overset{\text{SU(3) limit}}{=} 2a_{CP}^{\mathrm{dir}}(D^0 \to K^+K^-)$$

LHCb measurement of March 21, 2019:

$$\Delta a_{CP} = (-15.4 \pm 2.9) \cdot 10^{-4}$$

Previous world averages (HFLAV):

2016: $\Delta a_{CP} = (-13.4 \pm 7.0) \cdot 10^{-4}$

2015: $\Delta a_{CP} = (-25.3 \pm 10.4) \cdot 10^{-4}$

Previous LHCb measurements:

2016: $\Delta a_{CP} = (-10 \pm 8 \pm 3) \cdot 10^{-4}$

2014: $\Delta a_{CP} = (-14 \pm 16 \pm 8) \cdot 10^{-4}$

2011: $\Delta a_{CP} = (-82 \pm 21 \pm 11) \cdot 10^{-4}$

CP violation in tree-tree interference

Confronting

$$a_{CP}^{\text{dir}}(D^0 \to K^+K^-) \simeq \frac{1}{2}\Delta a_{CP} = \frac{1}{2}(-15.4 \pm 2.9) \cdot 10^{-4}$$

with

$$a_{CP}^{\text{dir}} = -6 \cdot 10^{-4} \text{Im} \frac{A_b}{A_{sd}}$$

one can solve for the imaginary part of the "penguin-to-tree ratio":

$$\frac{1}{2} \frac{A_b(K^+K^-)}{A_{sd}(K^+K^-)} \approx \frac{P_d}{A_{sd}(K^+K^-)}$$

Y. Grossman and St. Schacht (JHEP 1907 (2019) 020) find

$$\frac{1}{2} \frac{A_b(K^+K^-)}{A_{sd}(K^+K^-)} = 0.65 \pm 0.12$$

and conclude that a perturbative estimate of P_d does not work and advocate for a non-perturbative enhancement with a large strong phase of A_b/A_{sd}.

Prediction using QCD sum rules:

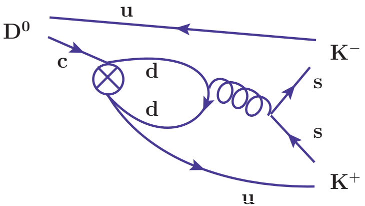
$$|\Delta a_{CP}| \leq (2.0 \pm 0.3) \cdot 10^{-4}$$

A. Khodjamirian, A. Petrov, Phys.Lett. B774 (2017) 235

Smaller than the measured value by a factor of 7!

QCD sum rules work well in B physics, could they fail completely in D physics?

Closer look:
We need $\mathrm{Im}\frac{A_b}{A_{sd}} = \frac{\mathrm{Im}\, A_b A_{sd}^*}{|A_{sd}|^2}$.
The numerator is the absorptive part of the penguin-tree interference term:



By the optical theorem this absorptive part is related to a $c \to ud\bar{d}$ decay followed by $d\bar{d} \to s\bar{s}$ rescattering. One contribution to this is $D^0 \to \pi^+\pi^- \to K^+K^-$. Each such contribution to $\mathrm{Im}\frac{A_b}{A_{sd}}$ is color-suppressed $\propto 1/N_c$ and suppressed by a factor of $\sim 1/\pi$ from the rescattering.

$\Rightarrow$ Need enhancement factor X such that $X \cdot \frac{1}{N_c\pi} \stackrel{!}{=} 0.65 \pm 0.12$.

$\Rightarrow$ $X \sim 6$.

New-physics explanations

Light Z': M. Chala, A. Lenz, A. V. Rusov, J. Scholtz, JHEP 1907 (2019) 161.
Various scenarios with heavy new particles: A. Dery, Y. Nir, 1909.11242

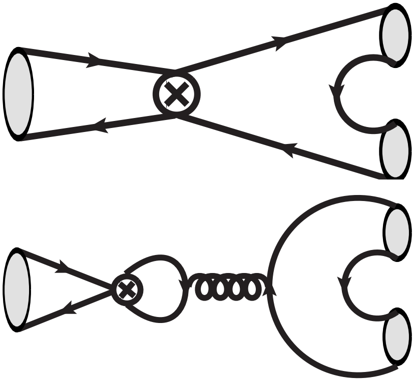
If the new physics couples differently to s and d quarks (i.e. if it violates U-spin symmetry), then $a_{CP}^{\rm dir}(K^+K^-) \approx -a_{CP}^{\rm dir}(\pi^+\pi^-)$ does not hold.

Whenever $c \to u\bar{d}d$ and $c \to u\bar{s}s$ interfere, the decay can have a non-vanishing direct CP asymmetry proportional to

$$\mathrm{Im}\,\frac{V_{ud}V_{cd}^*}{V_{us}V_{cs}^*} = \mathrm{Im}\,\frac{-V_{us}V_{cs}^* - V_{ub}V_{cb}^*}{V_{us}V_{cs}^*} = -\mathrm{Im}\,\frac{V_{ub}V_{cb}^*}{V_{us}V_{cs}^*} \simeq -\mathrm{Im}\,\frac{\lambda_b}{\lambda_{sd}} \simeq 6 \cdot 10^{-4}$$

Tree-tree interference occurs for final states with $\eta^{(\prime)}, \omega \ldots$ or with a pair of neutral Kaons like $K_S K_S, K_S K^{*0}, \ldots$ or for multibody final states containing all four $s, \bar{s}, d, \bar{d}$ quarks like $K^+K^-\pi^+\pi^-$.

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



Other CP asymmetry with tree-tree interference:
$a_{CP}^{\rm dir}(D^0 \to \overline{K}^{*0} K^0) \approx -a_{CP}^{\rm dir}(D^0 \to K^{*0} \overline{K}^0)$

Extracting *E* amplitudes from branching ratio data we find

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

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

and

$$|a_{CP}^{\rm dir}(D^0 \to \overline{K}^{*0} K_S)| \leq 0.003$$

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

Precise predictions are not possible because we have no information on the strong phase $\arg(A_b/A_{sd})$.

Summary

- The small CKM factor $\mathrm{Im}\,\frac{\lambda_b}{\lambda_{sd}} \simeq -6 \cdot 10^{-4}$ renders CP asymmetries in the charm sector sensitive to new physics.
- The LHCb measurement of

$$\Delta a_{CP} = (-15.4 \pm 2.9) \cdot 10^{-4}$$

  exceeds theory predictions by a factor of 7. The result will teach us either about unkown QCD effects or about new physics.
- If the new physics couples differently to $d\bar{d}$ and $s\bar{s}$, it is distinguishable from QCD effects.
- Next to discover: CP violation in tree-tree interference: $a_{CP}^{\mathrm{dir}}(D^0 \to K_S K_S)$ and $a_{CP}^{\mathrm{dir}}(D^0 \to \overline{K}^{*0} K_S)$.