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CP violation in $D \to \pi\pi$ and $D \to KK$

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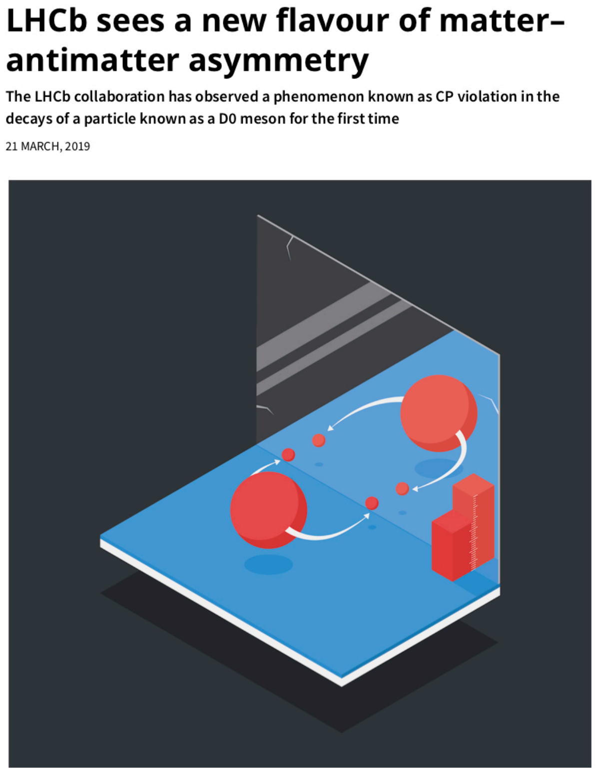
$$\Delta a_{CP} \equiv \quad a_{CP}^{\mathrm{dir}}(D^0 \to K^+K^-) \\ - a_{CP}^{\mathrm{dir}}(D^0 \to \pi^+\pi^-)$$

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

discovery of CP violation in charm decays



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

Role of charm physics

Charm decays

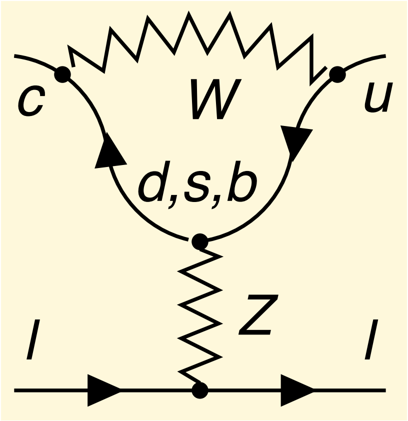
- have no stakes in Standard-Model CKM metrology, but
- have a unique role to probe new physics in the flavor sector of up-type quarks.

Problem of charm physics

FCNC example $D^0 \to \ell^+\ell^-$:

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

$$\frac{G_F}{M_Z^2}\cdot\underbrace{(m_s-m_d)}_{\overbrace{\begin{array}{c}\text{U-spin}\\ \text{breaking}\\ \text{GIM}\end{array}}}\quad\cdot\quad\underbrace{(m_s+m_d)}_{\overbrace{\begin{array}{c}\text{artefact of}\\ \text{perturbation theory}\end{array}}}$$



- No successful calculation of charm FCNC amplitudes.

U-spin symmetry: unitary rotations

of $\begin{pmatrix} s \\ d \end{pmatrix}$, exact for $m_s = m_d$.

CKM elements

$D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$ are singly Cabbibo-suppressed (SCS) decays.

In 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
$\lambda_d + \lambda_s + \lambda_b = 0$ is invoked to eliminate one of these.

Decay amplitude

Recall: $\lambda_j = V_{cj}^* V_{uj}$

decay amplitude

Commonly used: $\mathscr{A}^{\mathrm{SCS}} \equiv \lambda_{sd} A_{sd} - \dfrac{\lambda_b}{2} A_b$

with $\lambda_{sd} = \dfrac{\lambda_s - \lambda_d}{2} \simeq \lambda_s$ and $-\dfrac{\lambda_b}{2} = \dfrac{\lambda_s + \lambda_d}{2}$.

U-spin triplet

U-spin singlet

Since $|\lambda_b|/|\lambda_{sd}| \sim 10^{-3}$, only A_{sd} is relevant for decay rates.

CP asymmetries

In the Standard Model all CP asymmetries in hadronic charm decays are proportional to $\mathrm{Im}\,\frac{\lambda_b}{\lambda_{sd}} = -6 \cdot 10^{-4}$.

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

tree ↗ penguin ↑

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

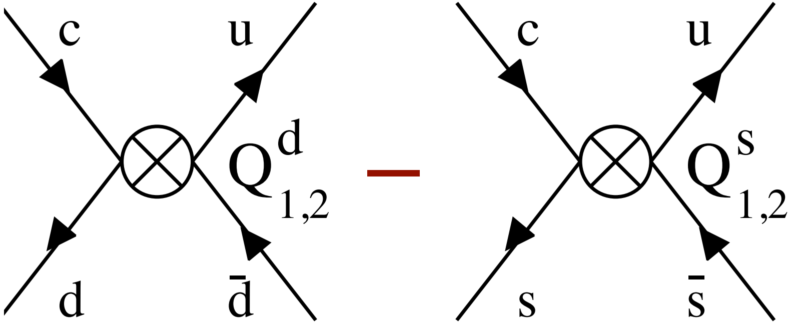
U-spin limit: $A_b(D^0 \to K^+K^-) = A_b(D^0 \to \pi^+\pi^-)$ and $A_{sd}(D^0 \to K^+K^-) = -A_{sd}(D^0 \to \pi^+\pi^-)$,

so that $\Delta a_{\rm CP} = 2a_{\rm CP}(D^0 \to K^+K^-) = -2a_{\rm CP}(D^0 \to \pi^+\pi^-)$.

$D^0 \to K^+K^-, \pi^+\pi^-$ amplitudes

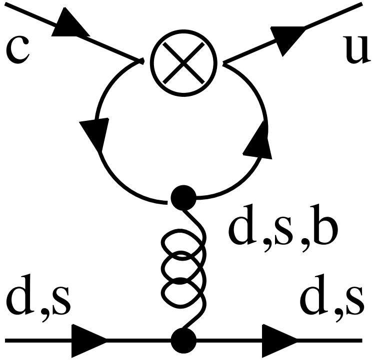
Recall $\mathscr{A}^{\mathrm{SCS}} \equiv \lambda_{sd} A_{sd} - \frac{\lambda_b}{2} A_b$

A_{sd} ("tree") from W exchange:



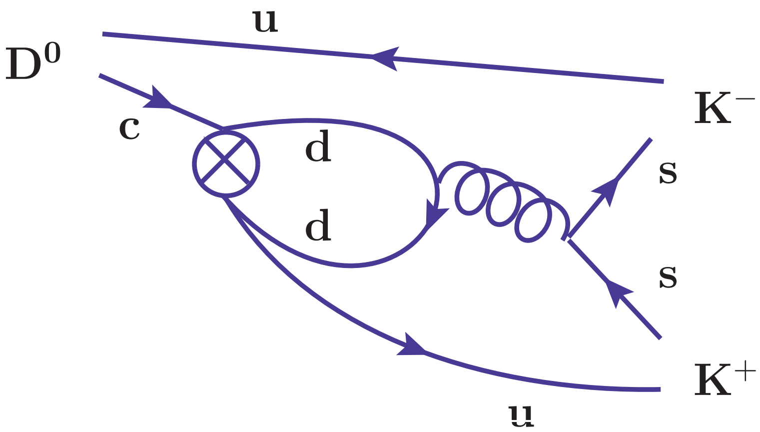
$\lambda_s \simeq -\lambda_d \Rightarrow KK$ and $\pi\pi$ dominantly produced from triplet amplitude A_{sd}

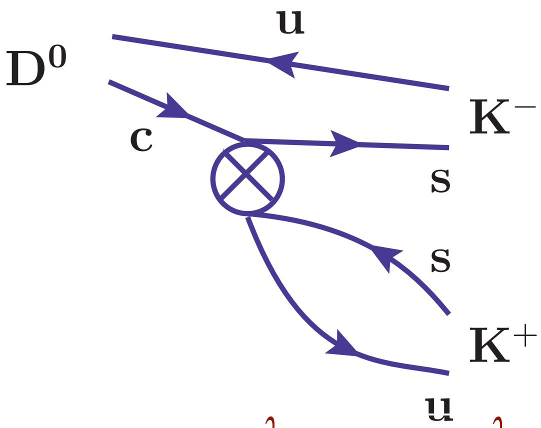
Small A_b dominantly from penguin topology:



CP asymmetry in $D^0 \to K^+K^-$

Interference of A_b with $A_{\rm sd}$:





The penguin diagram involves $\lambda_d = -\lambda_s - \lambda_b$ and $a_{\rm CP} \propto {\rm Im}\, \dfrac{\lambda_d}{\lambda_s} = -{\rm Im}\, \dfrac{\lambda_b}{\lambda_s}$.

Its absorptive part leads to ${\rm Im}\, \dfrac{A_b}{A_{sd}} \neq 0$.

Theory always at your service

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!

And we are not stubborn at all: “New data —- new opinions!”

Δa_{CP}

LHCb 2019: $\Delta a_{CP} = (-15.4 \pm 2.9) \cdot 10^{-4}$

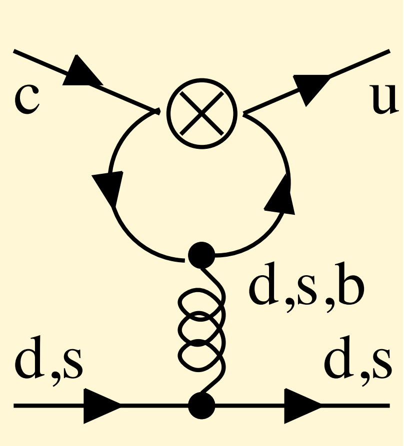
Prediction using QCD sum rules: $|\Delta a_{CP}| \leq (2.0 \pm 0.3) \cdot 10^{-4}$

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

Difference by a factor of 7.

New physics?

Or poorly understood QCD dynamics enhancing the penguin contribution?



Long-distance QCD

“I summon the spirits of long-distance enhancement”

2022: $a_{\mathrm{CP}}(D^0 \to K^+K^-)$

LHCb 2022: $a_{CP}(D^0 \to K^+K^-) = (7.7 \pm 5.7) \cdot 10^{-4}$.

Thus Δa_{CP} implies $a_{\mathrm{CP}}(D^0 \to \pi^+\pi^-) = (23.1 \pm 6.1) \cdot 10^{-4}$.

- $a_{CP}(D^0 \to K^+K^-)$ complies with the calculation of Khodjamirian and Petrov.
- For approximate U-spin limit $a_{CP}(D^0 \to K^+K^-) \approx -a_{CP}(D^0 \to \pi^+\pi^-)$ to work, with future data $a_{CP}(D^0 \to K^+K^-)$ must flip sign.
- Will future data decrease $|\Delta a_{\mathrm{CP}}|$ and will the 5σ discovery eventually go away?
- Or did LHCb discover new physics in 2019?

New physics

New physics amplitude interfering with Standard-Model (SM) tree amplitude:

$$\mathscr{A}^{\text{SCS}} \equiv \lambda_{sd} A_{sd} + a A_{\text{NP}}$$ with complex coupling a,

neglecting SM penguin.

$$a_{CP}^{\text{dir}} = -2\,\text{Im}\frac{a}{\lambda_{sd}}\;\text{Im}\frac{A_{\text{NP}}}{A_{sd}}$$

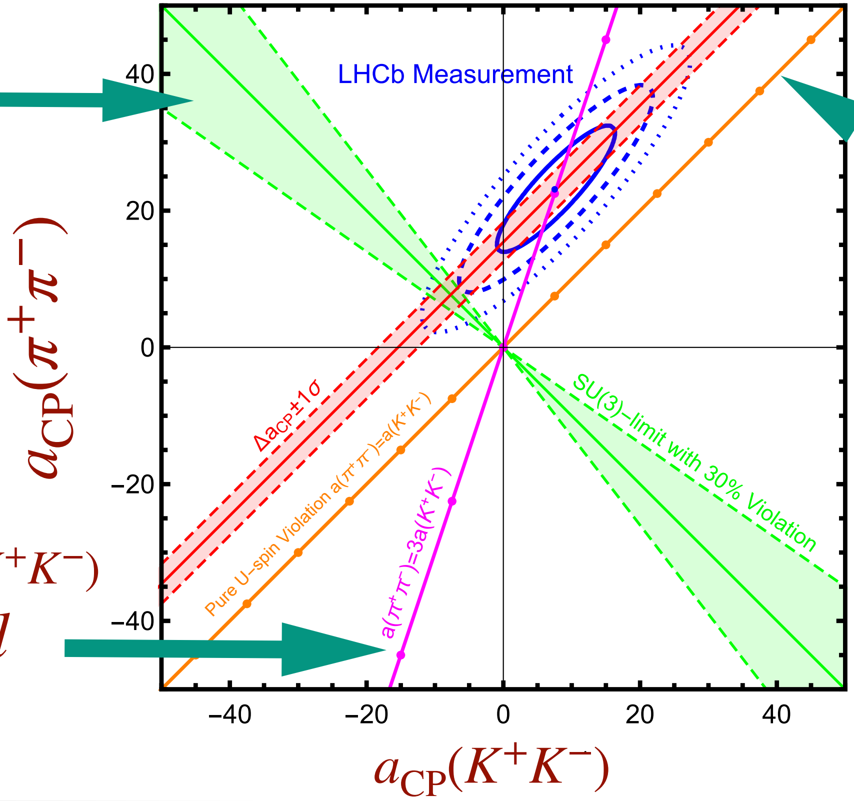
Two generic scenarios:

A_{NP} is $\Delta U = 0$ amplitude → indistinguishable from SM penguin enhancement

A_{NP} is $\Delta U = 1$ amplitude → same sign of $a_{\text{CP}}(D^0 \to K^+K^-)$ and $a_{\text{CP}}(D^0 \to \pi^+\pi^-)$

$a_{\text{CP}}(D^0 \to \pi^+\pi^-)$ vs. $a_{\text{CP}}(D^0 \to K^+K^-)$

green wedge:
$\Delta U = 0$ with
30% U-spin
breaking



$\Delta U = 1$
NP only

$a_{\text{CP}}(D^0 \to \pi^+\pi^-) = 3a_{\text{CP}}(D^0 \to K^+K^-)$
inspired by NP in $c \to u\bar{d}d$

from Bachelor
thesis of
Maurice Schüßler,
KIT, 2022

a_{CP} sum rules

> “Extraordinary claims require extraordinary evidence.”
>
> *(Sherlock Holmes in The Sign of Four)*

Derive sum rules between further CP asymmetries; distinguish between the $\Delta U = 0$ and $\Delta U = 1$ cases.

$\left.\begin{array}{l}\text{Emil Overduin}\\\text{Maurice Schüßler}\end{array}\right\}$ Bachelor theses

Syuhei Iguro
Ulrich Nierste

a_{CP} sum rules

Recall: $\mathscr{A}^{\mathrm{SCS}} \equiv \lambda_{sd} A_{sd} + a A_{\mathrm{NP}}$

Tool: Use Wigner Eckart theorem to express A_{sd} and A_{NP} in terms of Clebsch-Gordan coefficients (related to U-spin SU(2)) and reduced matrix elements.
Known from SM analysis.

Grossman, Ligeti, Robinson, *JHEP* 01 (2014) 066

$D^0, D^+_{(s)}$ → two pseudoscalars

KCETA

Institut für Theoretische Teilchenphysik (KIT)

$\Delta U = 0$	$\Delta U = 1$
$a_{\mathrm{CP}}(K^+K^-) + a_{\mathrm{CP}}(\pi^+\pi^-) = 0$	$a_{\mathrm{CP}}(K^+K^-) - a_{\mathrm{CP}}(\pi^+\pi^-) = 0$
$a_{\mathrm{CP}}(K^0\pi^+) + a_{\mathrm{CP}}(\bar{K}^0K^+) = 0$	$a_{\mathrm{CP}}(K^0\pi^+) - a_{\mathrm{CP}}(\bar{K}^0K^+) = 0$
$a_{\mathrm{CP}}(\eta\eta) + a_{\mathrm{CP}}(\pi^0\pi^0) + 2a_{\mathrm{CP}}(\eta\pi^0) = 0$	$a_{\mathrm{CP}}(\eta\eta) - a_{\mathrm{CP}}(\pi^0\pi^0) = 0$
$a_{\mathrm{CP}}(\eta K^+) + a_{\mathrm{CP}}(\eta\pi^+) + a_{\mathrm{CP}}(\pi^0K^+) = 0$	$a_{\mathrm{CP}}(\eta\eta) - a_{\mathrm{CP}}(\eta\pi^0) = 0$
$3a_{\mathrm{CP}}(\eta K^+) - 3a_{\mathrm{CP}}(\pi^0K^+) + a_{\mathrm{CP}}(K^0\pi^+) = 0$	two sum rules connecting four modes each

$D^0, D^+_{(s)} \rightarrow$ two pseudoscalars

Remarkable: One sum rule holds for both $\Delta U = 0$ and $\Delta U = 1$:

$$6a_{\text{CP}}(\pi^0\pi^+) - 3a_{\text{CP}}(\eta K^+) + 3a_{\text{CP}}(\pi^0 K^+) - a_{\text{CP}}(K^0\pi^+) = 0$$

→ consistency check of experiment and test of quality of U-spin symmetry

$D^0, D^+_{(s)}$ → pseudoscalar + vector

$\Delta U = 0$	$\Delta U = 1$
$a_{\rm CP}(K^0\bar{K}^{*0}) + a_{\rm CP}(\bar{K}^0 K^{*0}) = 0$	$a_{\rm CP}(K^0\bar{K}^{*0}) - a_{\rm CP}(\bar{K}^0 K^{*0}) = 0$
$a_{\rm CP}(K^\mp K^{*\pm}) + a_{\rm CP}(\pi^\mp \rho^\pm) = 0$	$a_{\rm CP}(K^\mp K^{*\pm}) - a_{\rm CP}(\pi^\mp \rho^\pm) = 0$
$a_{\rm CP}(K^{*0}\pi^+) + a_{\rm CP}(\bar{K}^{*0} K^+) = 0$	$a_{\rm CP}(K^{*0}\pi^+) - a_{\rm CP}(\bar{K}^{*0} K^+) = 0$
$a_{\rm CP}(\pi^0 K^{*+}) + a_{\rm CP}(\eta K^{*+})$	$a_{\rm CP}(\pi^0 K^{*+}) + a_{\rm CP}(\eta K^{*+})$
$+a_{\rm CP}(\pi^0\rho^+) + a_{\rm CP}(\eta\rho^+) = 0$	$-a_{\rm CP}(\pi^0\rho^+) - a_{\rm CP}(\eta\rho^+) = 0$

and more.

Summary

- LHCb measurements $\Delta a_{CP} = (-15.4 \pm 2.9) \cdot 10^{-4}$ and $a_{CP}(D^0 \to K^+K^-) = (7.7 \pm 5.7) \cdot 10^{-4}$ are not consistent with SM and U-spin symmetry.
- New physics explanations involve a $\Delta U = 1$ amplitude (with a different phase than $V_{cs}^* V_{us}$) and a $\Delta U = 0$ amplitude (SM or NP) as well.
- One can check this in the future in other decay modes in which CP asymmetries are not yet measured to be non-zero.
  → sum rules between CP asymmetries
- D decays into two pseudoscalars obey a sum rule which holds in the SM and for both $\Delta U = 0$ and $\Delta U = 1$ new physics.
  → consistency check, probing quality of U-spin symmetry