Karlsruher Institut für Technologie

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Branching fractions and CP asymmetries in charm meson decays

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Outline

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- Overview
- Two-body D decays: decay rates
- Two-body D decays: CP asymmetries
- Summary and outlook

Overview

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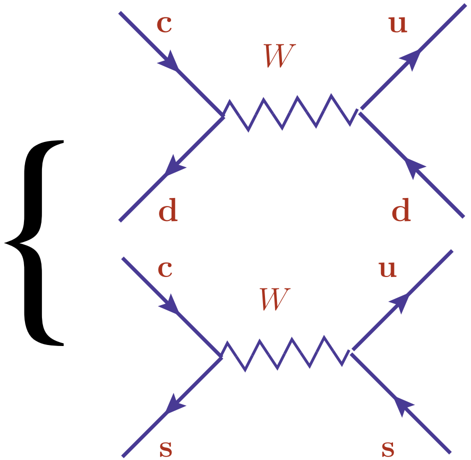
- Cabibbo-Kobayashi-Maskawa (CKM) matrix:

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \simeq \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

  with Wolfenstein parameters λ, A, ρ, η.
- Charm decays involve the red and blue parameters and
  - 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.

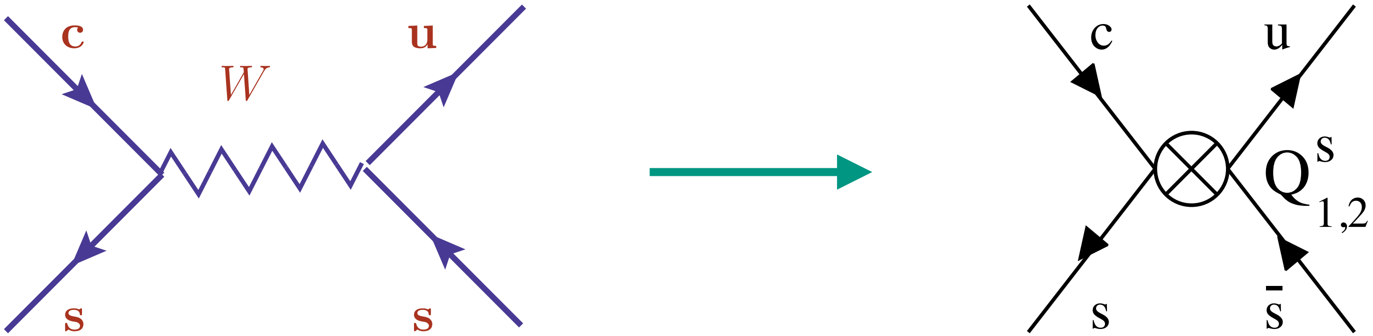
Overview

- I discuss decays of D^0, D^+, D_s^+ mesons into two pseudoscalar mesons or a pseudoscalar and a vector meson, $D \to PP'$ or $D \to PV$.
- All these decays are dominated by a W-mediated tree amplitude, categorised by the power of the Wolfenstein parameter $\lambda \simeq |V_{us}|$=0.225.
  - Cabibbo-favoured (CF), $\mathcal{O}(\lambda^0)$: $c \to s\bar{d}u$
  - Singly Cabibbo-suppressed, $\mathcal{O}(\lambda^1)$: $c \to d\bar{d}u$ or $c \to s\bar{s}u$
  - Doubly Cabibbo-suppressed, $\mathcal{O}(\lambda^2)$: $c \to d\bar{s}u$



Overview

- *W*-mediated interactions are described by local four-quark interactions à la Fermi theory:



Overview

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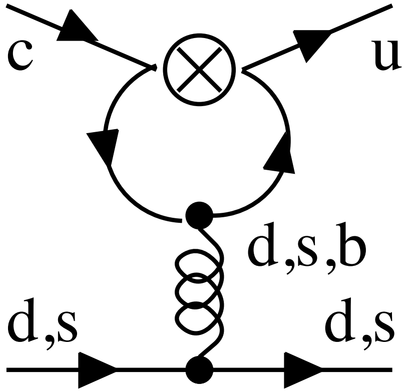
- Branching fractions in $D \to PP'$ or $D \to PV$ decays are insensitive to new physics and “bread and butter” physics to test the calculational tools and check the data for consistency.

- CP asymmetries are tiny in the Standard Model and very sensitive to new physics. SCS decays involve

$$\lambda_d = V_{cd}^* V_{ud}, \;\; \lambda_s = V_{cs}^* V_{us}, \;\; \lambda_b = V_{cb}^* V_{ub}$$

and $|\lambda_d| \simeq |\lambda_s| \gg |\lambda_b|$. Use $\lambda_d = -\lambda_s - \lambda_b$ to find all SM CP asymmetries proportional to

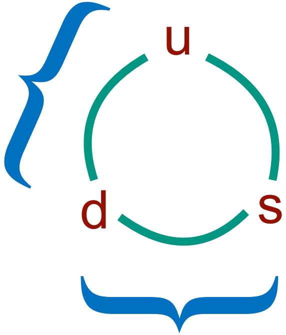
$$\text{Im}\,\frac{\lambda_b}{\lambda_s} = -6 \cdot 10^{-4}.$$



$SU(3)_F$ symmetry

Theorists love symmetries!

Isospin:
unitary rotations
of $\begin{pmatrix} u \\ d \end{pmatrix}$



U-spin:
unitary rotations
of $\begin{pmatrix} s \\ d \end{pmatrix}$

$SU(3)_F$: unitary rotations of $\begin{pmatrix} u \\ d \\ s \end{pmatrix}$

Useful because s and d have same charge, U-spin connects e.g. K^+ with π^+.
Only approximate symmetry of QCD, because $m_s \neq m_d$.

Two-body D decays: decay rates

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- Global SU(3)$_\mathrm{F}$ analyses of $D \to PP'$ or $D \to PV$ branching fractions, where $D = D^0, D^+, D_s^+$, have a long tradition. It is possible to include linear SU(3)$_\mathrm{F}$ breaking to reduce the intrinsic uncertainty from $\mathcal{O}(30\%)$ to $\mathcal{O}(10\%)$ in some cases. Gronau 1995, Grossman, Robinson 2012, Müller, UN, Schacht 2015.

- Final states with η or η' meson are usually treated with a mixing angle

$$|\eta_8\rangle = \quad |\eta\rangle\cos\theta + |\eta'\rangle\sin\theta \quad \longleftarrow \quad \text{SU(3)}_\mathrm{F} \text{ octet state}$$

$$|\eta_1\rangle = -|\eta\rangle\sin\theta + |\eta'\rangle\cos\theta \quad \longleftarrow \quad \text{SU(3)}_\mathrm{F} \text{ singlet state}$$

η-η' mixing angle

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- The η-η' mixing angle θ vanishes in the limit of exact $SU(3)_F$ symmetry.

- It is not possible to define a universal mixing angle θ such that

$$\langle \eta \ldots | \ldots | \ldots \rangle = \langle \eta_8 \ldots | \ldots | \ldots \rangle \cos\theta - \langle \eta_1 \ldots | \ldots | \ldots \rangle \sin\theta.$$

Leutwyler 1997, Feldmann, Kroll and Stech 1998

η-η' mixing angle

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- In D decays: Cannot relate final states with η' to those with η:

$$\langle P\eta | H | D\rangle = \cos\theta \langle P\eta_8 H | D\rangle - \sin\theta \langle P\eta_1 | H | D\rangle$$
$$\langle P\eta' | H | D\rangle = \sin\theta \langle P\eta_8 H | D\rangle' + \cos\theta \langle P\eta_1 | H | D\rangle'$$

Matrix elements are three-point functions and depend on kinematic variables. But $p_\eta \neq p_{\eta'}$, because $M_\eta \neq M_{\eta'}$. Thus

$$\langle P\eta_8 | H | D\rangle' \neq \langle P\eta_8 H | D\rangle$$
$$\langle P\eta_1 | H | D\rangle' \neq \langle P\eta_1 H | D\rangle$$

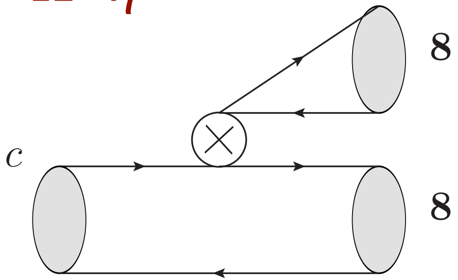
Bolognani, UN, Schacht, Vos 2024

Global fit for $D \to P\eta'$

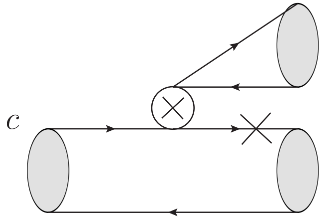
Still possible: Global fit to branching ratios of

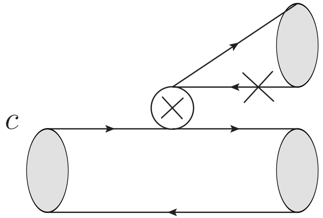
$$D^0 \to \pi^0\eta',\ D^0 \to \eta\eta',\ \ D^+ \to \pi^+\eta',\ D_s^+ \to K^+\eta',$$
$$D^0 \to \bar{K}^0\eta', D_s^+ \to \pi^+\eta', D^0 \to K^0\eta',\ D^+ \to K^+\eta'$$

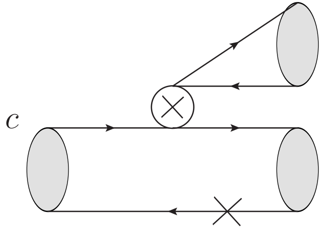
- Topological amplitudes: $\mathrm{SU(3)_F}$ limit: E.g.



- Linear ~~$\mathrm{SU(3)_F}$~~ breaking: E.g.







Cross: s-quark line

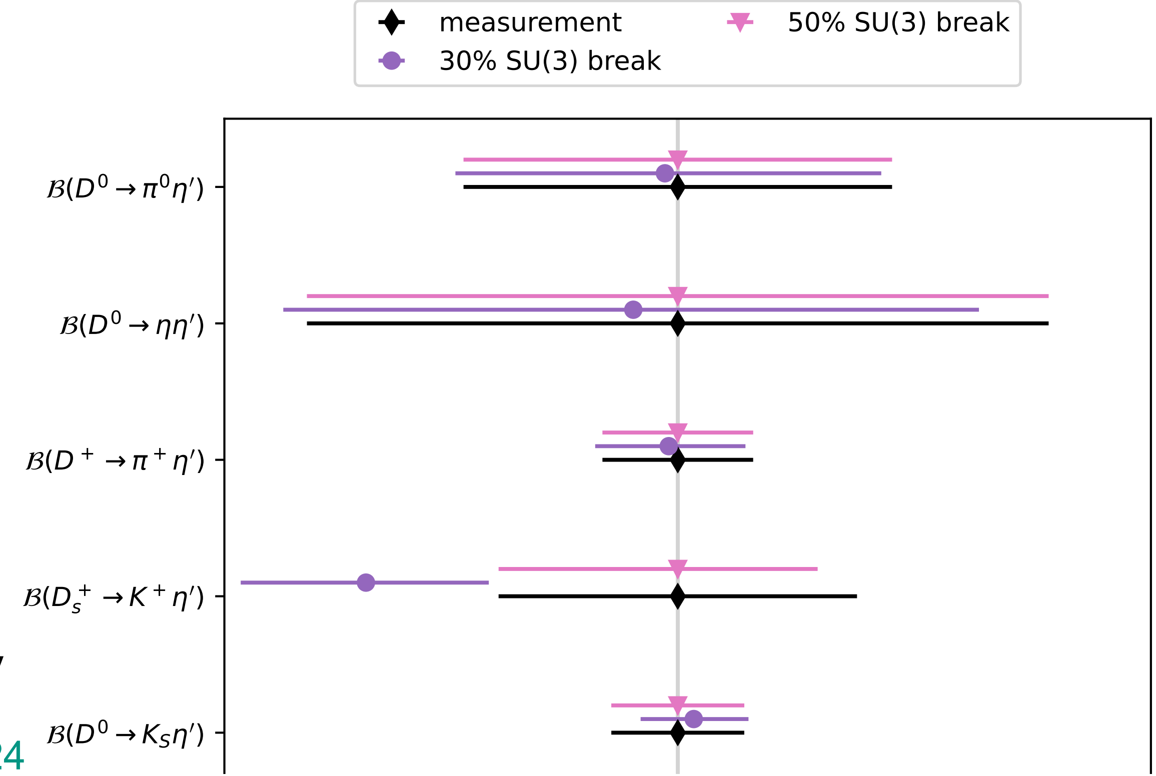
Global fit for $D \to P\eta'$

Results:

The global fit is consistent with $\leq$ 30% $SU(3)_F$ breaking in the amplitudes.

The fit predicts the branching fractions of $D_s^+ \to K^+\eta'$ and $D^+ \to K^+\eta'$ by 1σ too low and too high, respectively.

The $SU(3)_F$ limit is ruled out by 5.6σ. Bolognani, UN, Schacht, Vos 2024



Two-body D decays: CP asymmetries

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decay amplitude

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

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

More commonly used:

"tree" $\simeq A_{sd}$

"penguin" $\simeq -\frac{A_b}{2}$

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

U-spin triplet

U-spin singlet

Direct CP violation stems from the interference of A_b with A_{sd}.

March 21, 2019:

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

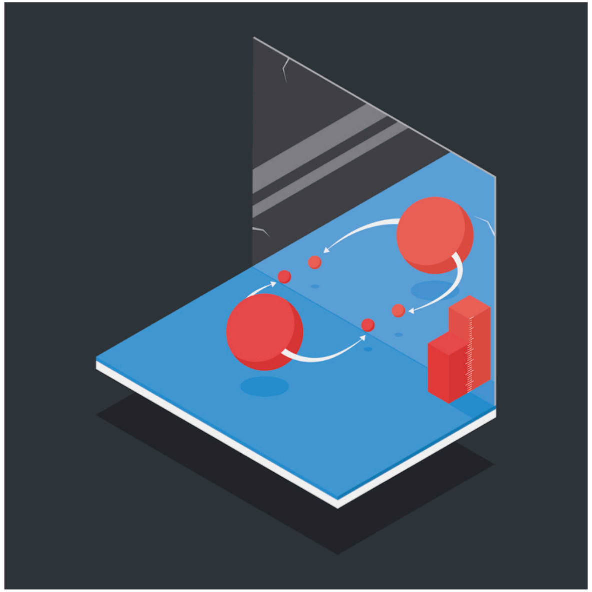
$$= (-15.4 \pm 2.9) \cdot 10^{-4}$$

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



Direct CP asymmetries

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

tree penguin

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

For U-spin limit $m_s = m_d$:

$$A_b(D^0 \to K^+K^-) = A_b(D^0 \to \pi^+\pi^-)$$

and

$$A_{sd}(D^0 \to K^+K^-) = -A_{sd}(D^0 \to \pi^+\pi^-),$$

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

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

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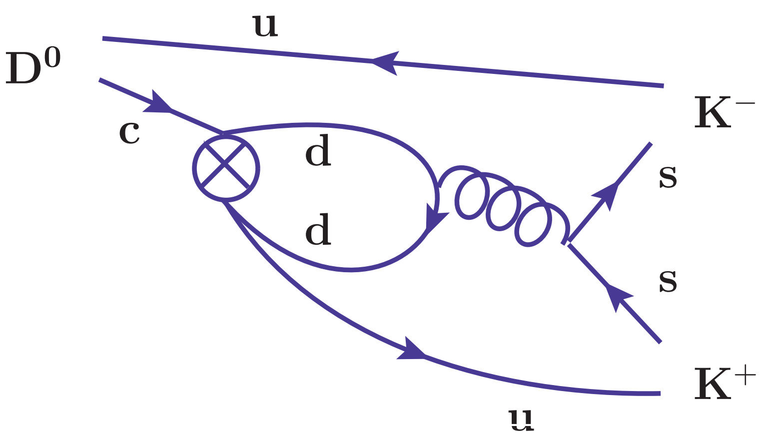
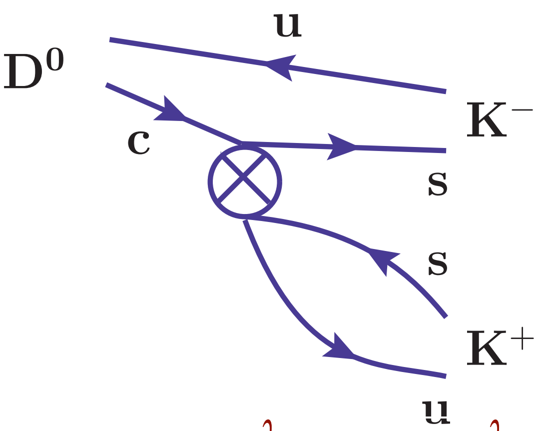
Interference of A_b with $A_{\rm sd}$:





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

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

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

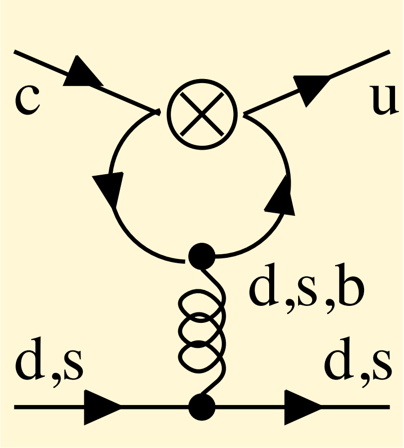
Prediction using QCD sum rules: $|\Delta a_{CP}| \leq (2.0 \pm 0.3) \cdot 10^{-4}$

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

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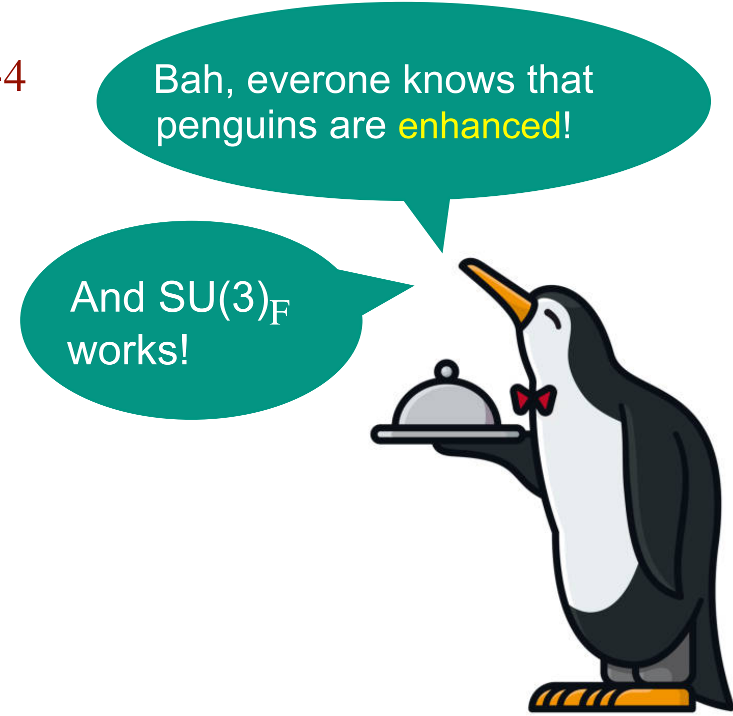
"I summon the spirits of long-distance enhancement"

Two-body D decays: CP asymmetries

- LHCb 2019: $\Delta a_{CP} = (-15.4 \pm 2.9) \cdot 10^{-4}$
- U-spin symmetry prediction:
  $a_{\mathrm{CP}}(D^0 \to K^+K^-) \approx -\, a_{\mathrm{CP}}(D^0 \to \pi^+\pi^-)$



Two-body D decays: CP asymmetries

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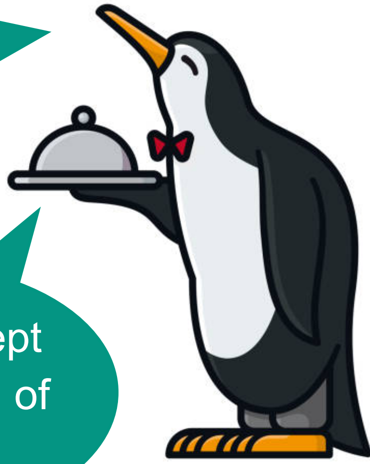
- LHCb 2019: $\Delta a_{CP} = (-15.4 \pm 2.9) \cdot 10^{-4}$
- U-spin symmetry prediction:

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

- LHCb 2022:

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

$$\Rightarrow \;\; a_{\mathrm{CP}}(D^0 \to \pi^+\pi^-) = (23.1 \pm 6.1) \cdot 10^{-4}$$



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

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

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

- $a_{CP}(D^0 \to K^+K^-)$ 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 $|\Delta a_{\rm CP}|$ 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:

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

with complex coupling a, neglecting SM penguin.

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

Two generic scenarios:

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

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

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

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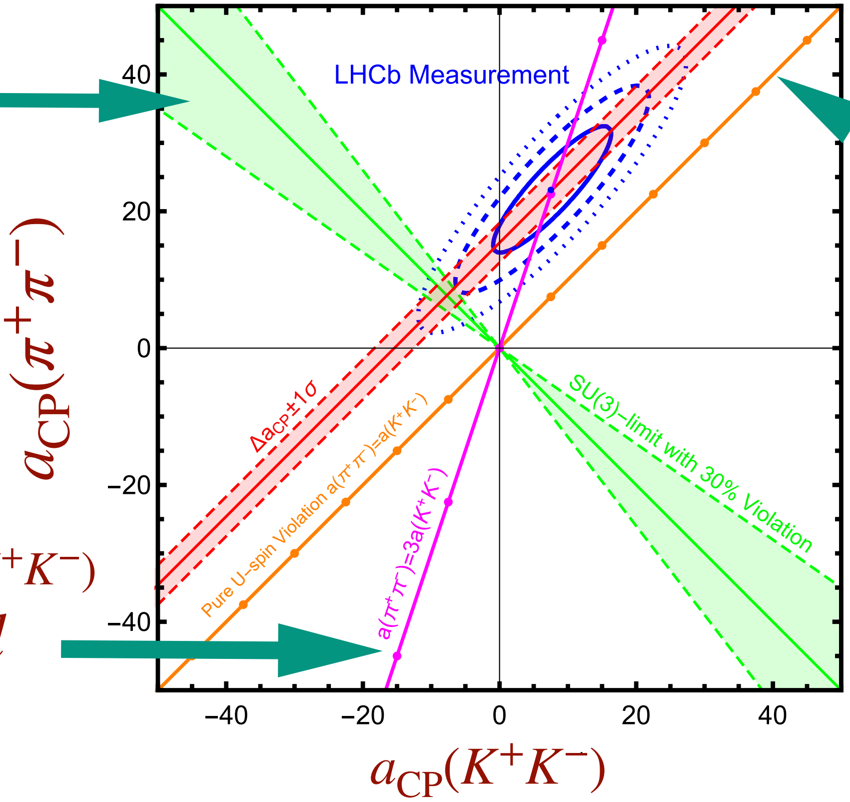
green wedge:
$\Delta U = 0$ with 30% U-spin breaking



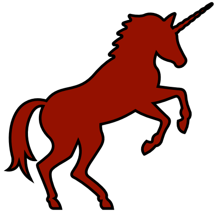
$\Delta U = 1$
NP only

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

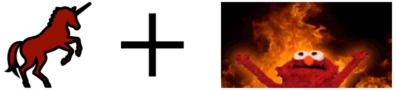
Iguro, UN, Overduin, Schüssler, 2024

What if?

- If $a_{\rm CP}(D^0 \to \pi^+\pi^-)$ is governed by the SM…
  - …the QCD sum rule calculation does not work and
  - …either U-spin symmetry fails for A_b or in future measurements $a_{CP}^{\rm dir}(D^0 \to K^+K^-)$ will move by 2σ and flip sign.



- If $a_{\rm CP}(D^0 \to \pi^+\pi^-)$ is dominated by NP…
  - …the NP contribution necessarily has a $\Delta U = 1$ contribution and
  - …either also a $\Delta U = 0$ NP contribution or some enhancement over the QCD sum rule prediction.



a_{CP} sum rules

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“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.

New physics scenarios

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- $\Delta U = 0$ hamiltonian. We take complete $SU(3)_F$ singlet:

$$H^{\text{NP,singlet}} = \frac{G_f}{\sqrt{2}} C^{\text{NP},\Delta\text{U}=0} \bar{u}\Gamma c(\bar{u}\Gamma' u + \bar{d}\Gamma' d + \bar{s}\Gamma' s)$$

Unspecified Dirac structure

Usual SM penguin is special case.

- $\Delta U = 1$ hamiltonian. We take

$$H^{\text{NP},\Delta\text{U}=1} = \frac{G_f}{\sqrt{2}} C^{\text{NP},\Delta\text{U}=0} \bar{u}\Gamma c(\bar{s}\Gamma' s - \bar{d}\Gamma' d)$$

same $SU(3)_F$ quantum numbers as SM A_{sd}

Iguro, UN, Overduin, Schüssler, 2024

a_{CP} sum rules

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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

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

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$\Delta U = 0$	$\Delta U = 1$
$\delta_{\text{CP}}(D^0 \to K^+K^-) + \delta_{\text{CP}}(D^0 \to \pi^+\pi^-) = 0$	$\delta_{\text{CP}}(D^0 \to K^+K^-) - \delta_{\text{CP}}(D^0 \to \pi^+\pi^-) = 0$
$\delta_{\text{CP}}(D_s^+ \to K^0\pi^+) + \delta_{\text{CP}}(D^+ \to \bar{K}^0K^+) = 0$	$\delta_{\text{CP}}(D_s^+ \to K^0\pi^+) - \delta_{\text{CP}}(D^+ \to \bar{K}^0K^+) = 0$

and many more with π^0's or η's, which are difficult for LHCb.

Here $\quad \text{Im}\,\delta_{\text{CP}}(D \to f) \propto a_{\text{CP}}(D \to f)\Gamma(D \to f)$.

Iguro, UN, Overduin, Schüssler, 2024

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

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$\Delta U = 0$	$\Delta U = 1$
$\delta_{\rm CP}(D^0 \to K^0 \bar{K}^{*0}) + \delta_{\rm CP}(D^0 \to \bar{K}^0 K^{*0}) = 0$	$\delta_{\rm CP}(D^0 \to K^0 \bar{K}^{*0}) - \delta_{\rm CP}(D^0 \to \bar{K}^0 K^{*0}) = 0$
$\delta_{\rm CP}(D_s^+ \to K^{*0} \pi^+) + \delta_{\rm CP}(D^+ \to \bar{K}^{*0} K^+) = 0$	$\delta_{\rm CP}(D_s^+ \to K^{*0} \pi^+) - \delta_{\rm CP}(D^+ \to \bar{K}^{*0} K^+) = 0$

and many more.

Iguro, UN, Overduin, Schüssler, 2024

Summary

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- A universal $\eta-\eta'$ mixing angle defined through unitary rotations of matrix elements with η_8 and η_1 is known since 27 years to be ill-defined. It is nevertheless commonly used in global $\mathrm{SU(3)_F}$ analyses of D or B decay data.
- We have devised a consistent treatment of $\eta-\eta'$ mixing, which permits a global analysis of $D \to P\eta'$ or $D \to P\eta$ data, while it is not possible to relate the former to the latter.
- A global fit to $D^0 \to \pi^0\eta'$, $D^0 \to \eta\eta'$, $D^+ \to \pi^+\eta'$, $D_s^+ \to K^+\eta'$, $D^0 \to \bar{K}^0\eta'$, $D_s^+ \to \pi^+\eta'$, $D^0 \to K^0\eta'$, $D^+ \to K^+\eta'$ branching ratios complies with $\leq 30\%$ $\mathrm{SU(3)_F}$ breaking, with slight tensions in $D_s^+ \to K^+\eta'$ and $D^+ \to K^+\eta'$.

Summary

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- The 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
- Especially interesting for LHCb are sum rules with $a_{\rm CP}(D_s^+ \to K^0\pi^+)$ and $a_{\rm CP}(D^+ \to \bar{K}^{*0}K^+)$ as well as sum rules with CP asymmetries in $D^0 \to K^0\bar{K}^{*0}$, $D^0 \to \bar{K}^0 K^{*0}$, $D_s^+ \to K^{*0}\pi^+$, and $D^+ \to \bar{K}^{*0}K^+$.

Outlook

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- Theory parallel talk:
  - Eleftheria Solomonidi, Tuesday 16:30 h, Urška 4:
    Implications of cascade topologies for rare charm decays and CP violation

- Experimental parallel talks:
  - Luca Balzani, Tuesday 16:45 h, Urška 4:
    Particle-antiparticle asymmetries in hadronic charm decays at LHCb
    ⟶ $D - \bar{D}$ mixing and CP violation
  - Marco Colonna, Tuesday 17:00 h, Urška 4:
    Rare charm decays at LHCb
    ⟶ $D \to hh'e^+e^-$ and more