Direct CP Violation in Charm: Recent Results

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Short Outline

- ☑ **Data news:** evidence for direct CPV in charm
- ☑ **Interpretation:**
  - *New physics?*
  - *Or a hardly calculable SM contribution?*

Short summary of data news: LHCb and CDF

LHCb (1112.0938) measures:

$$A_{\mathrm{raw}}(D^0 \to K^+ K^-) - A_{\mathrm{raw}}(D^0 \to \pi^+ \pi^-)$$

$$= (-0.82 \pm 0.21 \pm 0.11)\%$$

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

- 3.5σ away from the hypothesis of CP conservation
- Based on 580/pb of analyzed data. LHCb has now 2x on tape

CDF (1111.5023) measures separately $A_{CP}(D^0 \to K^+ K^-)$ and $A_{CP}(D^0 \to \pi^+ \pi^-)$, reporting

$$A_{CP}(D^0 \to K^+ K^-) = (-0.24 \pm 0.22 \pm 0.09)\%$$

$$A_{CP}(D^0 \to \pi^+ \pi^-) = (+0.22 \pm 0.24 \pm 0.11)\%$$

- Based on 5.9/fb of analyzed data.
- Most precise single-exp determinations
- Consistent with CP conservation

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One main comment for a comparison

- Note that A_{CP} from CDF includes direct and indirect CPV contributions.

  In the limit of equal decay-time acceptance between the K^+K^- and $\pi^+\pi^-$ modes, this contribution cancels in the difference, also measured by LHCb.

  CDF quotes:

$$A_{CP}(D^0 \to K^+ K^-) - A_{CP}(D^0 \to \pi^+ \pi^-) = (-0.46 \pm 0.31 \pm 0.12)\%$$

- Conclusion? We need more data.
  To start with we need the measurements of the separate CP asymmetries by LHCb

Theory Implications

Direct CPV and Direct CP Asymmetries

- CP violation in decay occurs when the decay rate $M \to f$ differs from the decay rate involving the CP-conjugate states.
- Since decay width $\propto$ | amplitude $|^2$, for this to occur, the amplitude needs consist of at least two terms, with a relative (hence convention-independent) weak (hence CP-odd) phase.

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- So let's consider the amplitude for $D \to f$, where $f = K^+ K^-$ *or* $\pi^+ \pi^-$.
  It can be expanded into a leading + a sub-leading term as follows:

$$A_f = A_f^T \left(1 + r_f \, e^{i(\delta_f + \phi_f)}\right)$$

Leading amplitude: its phase is taken to be zero

Sub-leading amplitude:
it comes with a relative weak (ϕ_f) and strong (δ_f) phase

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CPV in the decay $D \to f$ can be quantified by the direct CP asymmetry, defined as:

$$A_{CP}^{\mathrm{dir}}(D \to f) = \frac{|A_f|^2 - |\bar{A}_{\bar{f}}|^2}{|A_f|^2 + |\bar{A}_{\bar{f}}|^2}$$

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To leading order in $r_f \ll 1$, one gets:

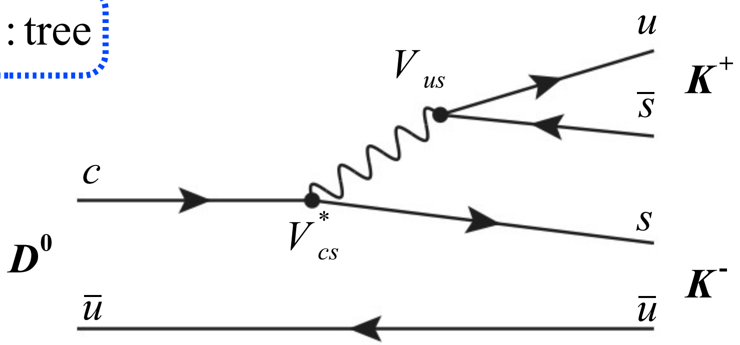
$$A_{CP}^{\rm dir}(D \to f) \simeq -2 \, r_f \sin\delta_f \sin\phi_f$$

For large phases, the asymmetry goes down as the magnitude of the sub-leading / leading amplitude ratio.

Amplitude ratio: heuristic estimate

Let us take the D → $K^+ K^-$ decay. At the level of dim-6 operators, one can write down a tree (W-exchange) amplitude, as well as a loop ("penguin") one.

a^T_{KK} : tree



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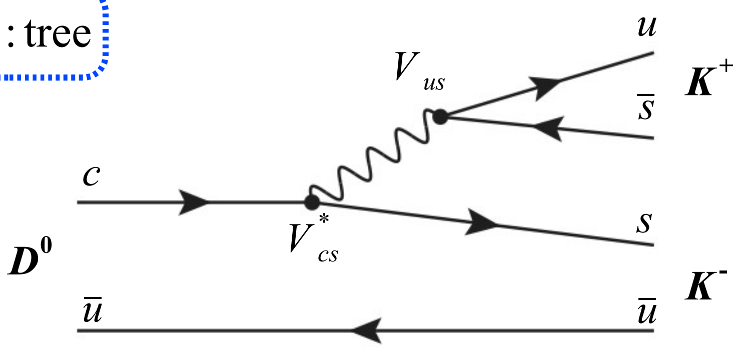

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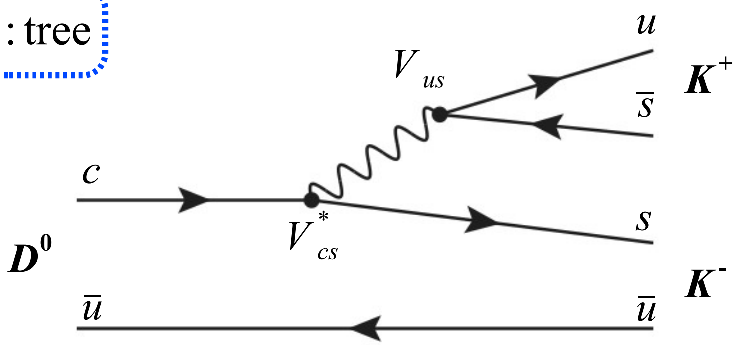

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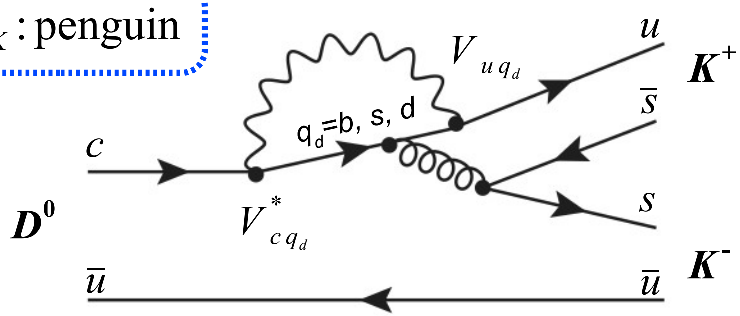

$$a^P_{KK} \sim \underset{\lambda_C^2\,\cdot\,\lambda_C^3}{V^*_{cb}\,V_{ub}}\,P^b_{KK} + \underset{1\,\cdot\,\lambda_C}{V^*_{cs}\,V_{us}}\,P^s_{KK} + \underset{\lambda_C\,\cdot\,1}{V^*_{cd}\,V_{ud}}\,P^d_{KK}$$

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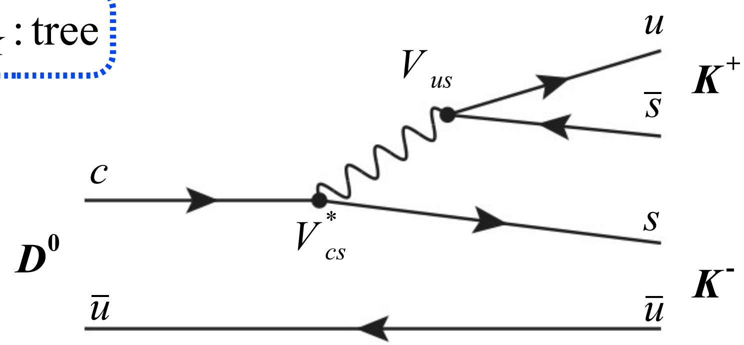

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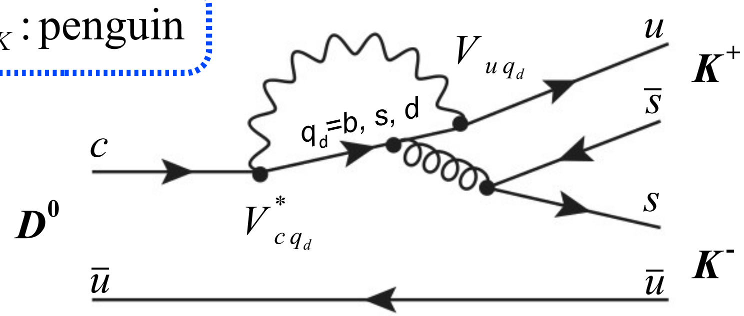

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- Using unitarity on the last term of the penguin amplitude, it follows:

$$A_{KK} = a^T_{KK} + a^P_{KK} = \underbrace{V^*_{cs}\,V_{us}\left(T_{KK} + P^s_{KK} - P^d_{KK}\right)}_{A^T_{KK}} + \underbrace{V^*_{cb}\,V_{ub}\left(P^b_{KK} - P^d_{KK}\right)}_{A^P_{KK}}$$

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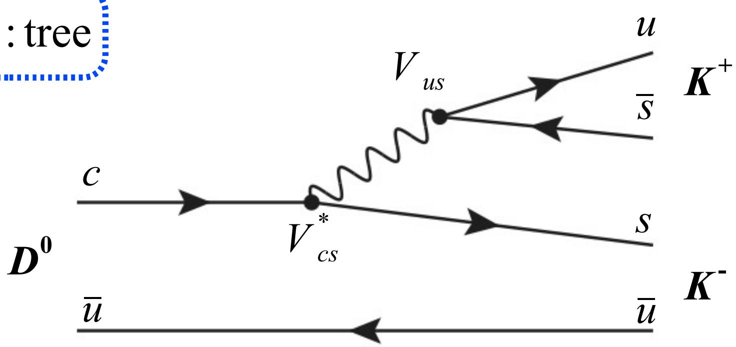

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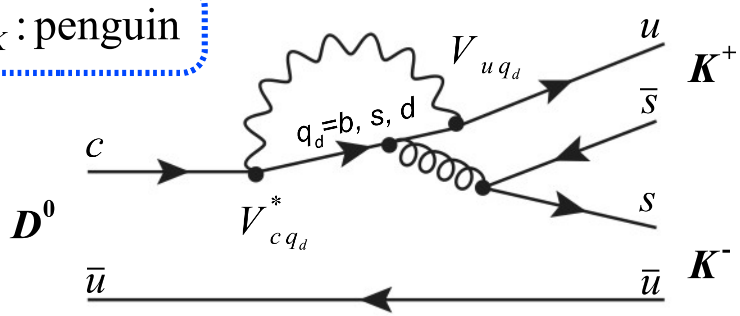

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Hence the amplitude ratio estimate: $\boxed{r_f \sim A^P_{KK} / A^T_{KK} \sim \lambda_C^4 \, \alpha_s(m_c)/\pi \sim 10^{-4}}$

ΔA_{CP} : heuristic estimate

- Now let us go back to the formula

$$A_{CP}^{\mathrm{dir}}(D \to f) \simeq -2\, r_f \sin\delta_f \sin\phi_f$$

with $f = K^+ K^-$ *or* $\pi^+\pi^-$

- Recall that:

1. The strong phase is expected to be large: sin δ = O(1)
2. The weak phase is minus $\gamma \simeq 67°$: sin γ = O(1)
3. In the U-spin symmetric limit (s $\leftrightarrow$ d quarks), the only difference between the KK and the $\pi\pi$ amplitudes is the sign of the tree-level contribution. Hence:

$$r_{\pi^+\pi^-} \simeq -r_{K^+K^-}$$

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It follows:

$$|A_{CP}^{\mathrm{dir}}(D \to K^+K^-) - A_{CP}^{\mathrm{dir}}(D \to \pi^+\pi^-)| \approx -2(r_{K^+K^-} - r_{\pi^+\pi^-}) \approx -4\, r_{K^+K^-} \sim 4 \cdot O(10^{-4})$$

Namely this (heuristic) estimate returns a figure about one order of magnitude below LHCb's measurement

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Two main questions arise:

(a) Can this estimate be missing the actual SM order of magnitude? What enhancements are possible?

(b) How plausibly can non-SM physics explain this signal?

First: An old observation to keep in mind

Volume 222, number 3,4 PHYSICS LETTERS B 25 May 1989

ENHANCED *CP* VIOLATIONS IN HADRONIC CHARM DECAYS

Michell GOLDEN and Benjamin GRINSTEIN
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Received 6 March 1989

☑ **Observation:**

The CKM structure responsible for large CPV in the $|\Delta C| = 1$ Hamiltonian ($V_{cb}^* \ V_{ub}$) multiplies certain operators (transforming as triplets under SU(3)) <u>whose matrix elements may be enhanced</u> with respect to naïve expectations.

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(To my knowledge) this issue has not been clarified by the <u>data collected</u> in the meantime, nor by <u>lattice QCD estimates</u>.

What a better opportunity than the LHCb data to reappraise this?

Recent Work
(after LHCb results)


Here's where
the quickest gun rules

(Instant) paper 1: *"On the size of direct CPV in Singly Cabibbo-Suppressed decays"*
SM *Brod, Kagan, Zupan (1111.5000)*

Grossman, Kagan, Nir
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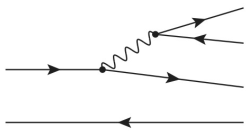
Main observation to get to their point:

Besides the tree amplitude seen before, namely:  ("*W*-emission" topology)

there are further topologies, formally $1/m_c$ suppressed, but in practice known to be sizable.

For example, topologies known as "*W*-exchange annihilation".

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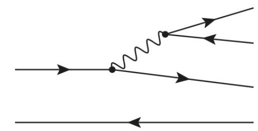
Besides the tree amplitude seen before, namely:  ("*W*-emission" topology)

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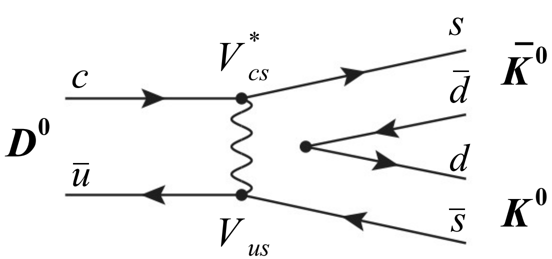
What does sizable mean in practice? Example.

The BR($D^0 \to K^0\, \bar{K}^0$) vanishes to leading power. Its amplitude receives two sub-leading contributions from *W*-exchange annihilation.

Note that they would cancel in the SU(3) limit.



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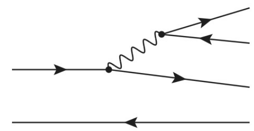
Besides the tree amplitude seen before, namely:  ("*W*-emission" topology)

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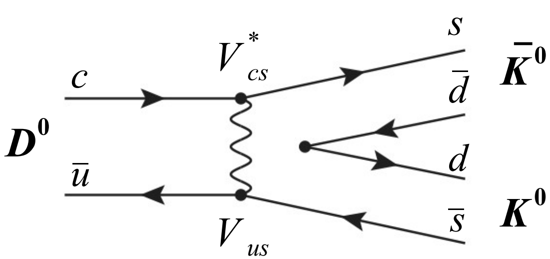

+ { diagram with s $\leftrightarrow$ d }

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Data (PDG)

BR($D^0 \to K^0 \bar{K}^0$) = $0.69(12) \times 10^{-3}$ vs. BR($D^0 \to K^+ K^-$) = $3.96(8) \times 10^{-3}$

$$\boxed{\frac{\mathrm{Ampl}\left(D^0 \to K^0 \bar{K}^0\right)}{\mathrm{Ampl}\left(D^0 \to K^+ K^-\right)} \sim \sqrt{\frac{0.69}{3.96}} \simeq 0.4}$$

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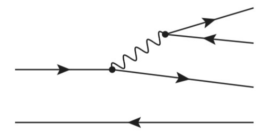
Besides the tree amplitude seen before, namely:  ("*W*-emission" topology)

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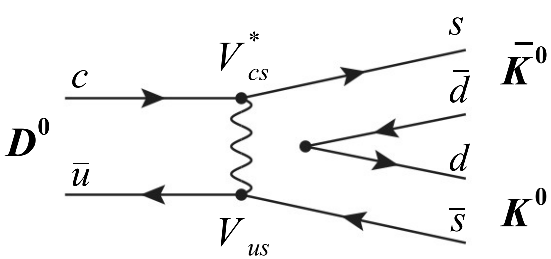

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This suggests that:

- the W-exchange amplitude is about ½ of the W-emission one (hence not so much suppressed)
- the SU(3) symmetry may not be working so well here

Brod, Kagan, Zupan: continued

Results

The previous observations can be made more quantitative, and used to give an estimate of:

➊ **The (formally) leading-power penguin amplitudes**

➋ **The (formally) power-suppressed annihilation amplitudes**

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Use of:

- the ΔC = 1 effective Hamiltonian at NLO within the SM
- “naïve” factorization + O(α_s) corrections

Including renorm. scale variation, they get:

$$r_{K^+K^-} \approx (0.01-0.02)\%$$
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Beware:

It is well known that the charm mass is too light for factorization theorems to hold (and much too heavy for chiral symmetry).
Therefore, the $1/m_c$ expansion and factorization are, here and below, mostly used as guidance.

The corresponding results require of course plenty of assumptions (e.g. on the matrix elements).
Results should be taken with relative errors of O(1).

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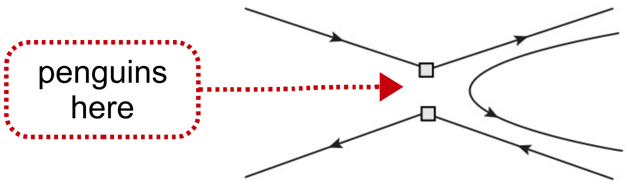

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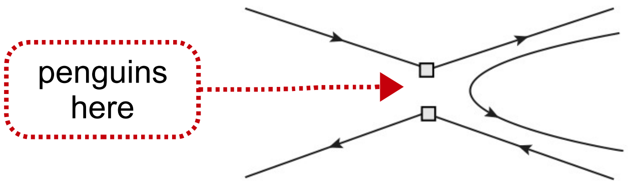

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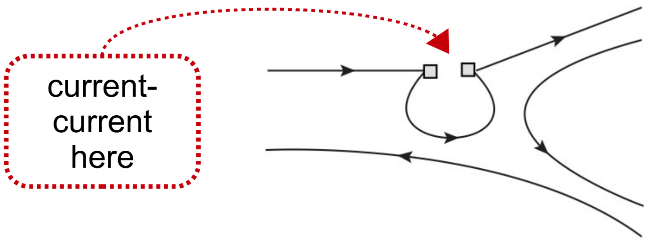

Brod, Kagan, Zupan: continued

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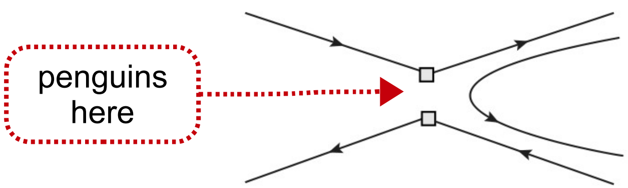

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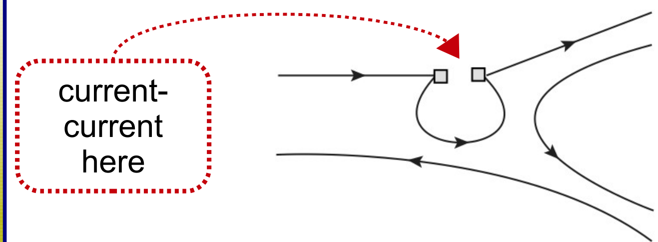

Conclusions

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A contribution to ΔA_{CP} from each of these amplitudes of:

ΔA_{CP}(single ampl.) $\sim$ few x 0.1 %

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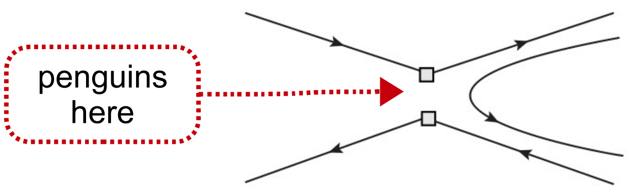

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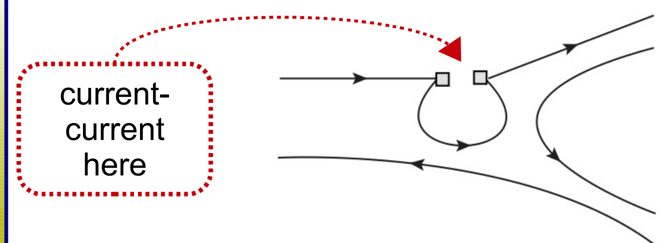

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❷ The whole approach is testable in two ways:

- Similarly large SM effects should be visible in $D^+ \to K^+ K^0$ and in $D_s^+ \to \pi^+ K^0$, that differ from the K^+K^- and $\pi^+ \pi^-$ decays only in the spectator quark
- The modes $D^+ \to \pi^+ \pi^0$ and $D_s^+ \to K^+ \pi^0$ are not polluted by QCD penguins, hence they are suited for non-SM searches

(Instant) paper 2: mostly beyond SM

"Implications of the LHCb Evidence for Charm CPV"
Isidori, Kamenik, Ligeti, Perez (1111.4987)

☑ **Main idea**

Write down the most general $|\Delta C| = 1$ effective Hamiltonian (including non-SM operators).
Address the question of what operators may plausibly generate the LHCb signal, taking into account the relevant constraints ($D^0 - \overline{D}^0$ mixing and ϵ'/ϵ)

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Parameterizing non-SM contributions

Recall again the direct CP asymmetry formula for the channel $D \to f$, where $f = K^+ K^-$ or $\pi^+\pi^-$:

$$A_{CP}^{\text{dir}}(D \to f) = -2\, r_f \sin\phi_f \sin\delta_f$$

r_f: magnitude of the sub-leading to leading amplitudes ratio

ϕ_f: sub-leading to leading relative *CP-odd* phase

δ_f: sub-leading to leading relative *strong* phase

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This formula can be generalized to include the case of contributions from non-SM operators:

$$A_{CP}^{\rm dir}(D \to f) = 2\left[\xi_f \, \mathrm{Im}(R_f^{SM}) + \frac{1}{\lambda_C} \sum_i \mathrm{Im}(C_i^{\rm NP}) \, \mathrm{Im}(R_{f,i}^{\rm NP})\right]$$

Here "ratio" means between the sub-leading and the leading amplitude

ratio of CKM factors

ratio between hadronic amplitudes

non-SM Wilson coefficients (normalized to the tree amplitude CKM suppression)

Isidori et al.: continued

Constraint equation

The previous relation, written down explicitly for the K^+K^- and $\pi^+\pi^-$ decays, and after use of the ΔA_{CP} measurement, leads to the following equation:

$$\mathrm{Im}\left(C_{\mathrm{NDA}}\right)\frac{(10\,\mathrm{TeV})^2}{\Lambda^2_{\mathrm{NDA}}} = \frac{\boxed{(0.61 \pm 0.17)} - 0.12\,\mathrm{Im}\left(\Delta R^{\mathrm{SM}}\right)}{\mathrm{Im}\left(\Delta R^{\mathrm{NP}}\right)}$$

hadronic amplitudes ratio for the difference between the K^+K^- and $\pi^+\pi^-$ channels

New world average (HFAG) for $\Delta A_{CP} = -(0.65 \pm 0.18)\%$ (rescaled by a numerical factor)

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- If instead { $\Lambda_{\mathrm{NDA}} \sim$ Fermi scale } $\Longrightarrow$ $\mathrm{Im}\,C_{\mathrm{NDA}} \sim 7 \cdot 10^{-4}$

These bounds hold before including any other constraint, in particular from $D^0 - \overline{D}^0$ mixing and ϵ'/ϵ

Isidori et al.: continued

Full analysis

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Conclusions

- Operators where the bilinear containing the charm quark is of $V - A$ structure are severely constrained by $D^0 - \overline{D}^0$ mixing and ϵ'/ϵ.
- In cases where non-SM contributions are allowed to be large, one expects correspondingly large contributions to CPV in $D^0 - \overline{D}^0$ mixing and/or ϵ'/ϵ.

Outlook: *we need more data and more theory work*

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  Measurement of the separate CP asymmetries by LHCb

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☑ **Data 2**

Data on these modes