Direct CP Violation in Charm: Recent Results

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LAPTh Annecy

Short Outline

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

First Things First:
Data!

Short summary of data news: LHCb and CDF

LHCb (1112.0938) measures:

$$A_{\mathrm{raw}}(D^0 \to K^+ K^-) - A_{\mathrm{raw}}(D^0 \to \pi^+ \pi^-)$$
$$= (-0.82 \pm 0.21 \pm 0.11)\%$$
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- $A_{\rm raw}$: it is the experimental asymmetry.

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The instrumental asymmetry is due to the detector response not being fully CP symmetric.

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- $A_{\rm CP}^{\rm dir}$ = {asymmetry from direct CPV}

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This is the actual quantity of interest

More on the various asymmetries

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3. any detector effect not perfectly CP symmetric → Instrumental

"Physical" CPV

cancels in the difference $A_{\mathrm{raw}}(D^0 \to K^+ K^-) - A_{\mathrm{raw}}(D^0 \to \pi^+ \pi^-)$, measured by LHCb

Therefore the LHCb measurement is the first evidence of direct CPV in the charm sector.

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$$\Delta A_{\rm raw} = \Delta A_{CP}^{\rm dir} + \frac{\Delta \langle t \rangle}{\tau} A_{CP}^{\rm ind}$$

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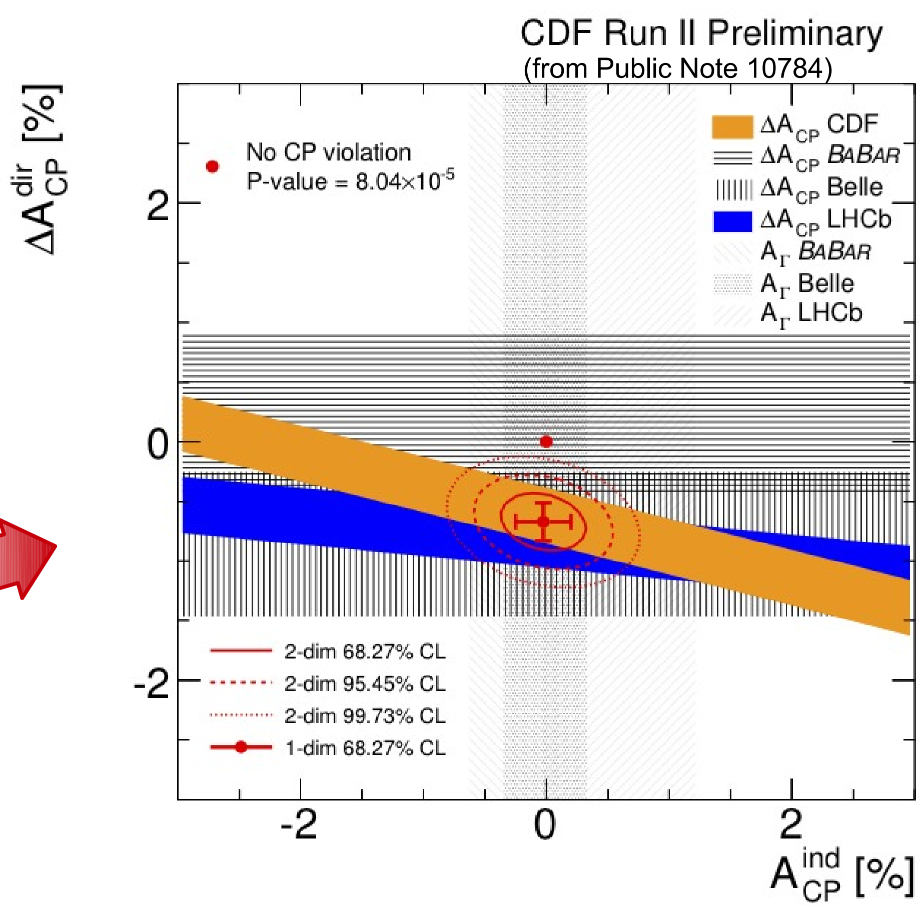

D. Guadagnoli, Direct CPV in Charm

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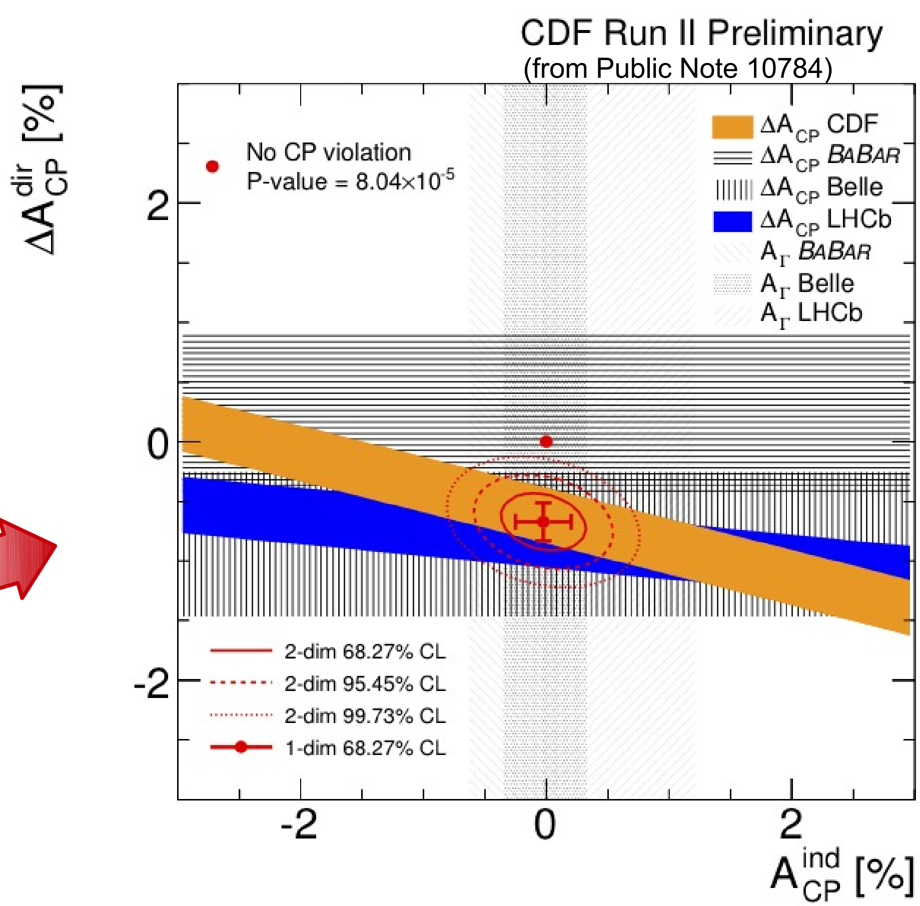
2. World Average: $\Delta A_{CP}^{dir} = (-0.67 \pm 0.16)\%$

Conclusion? We need more data.
In particular we await the LHCb update based on the full 2011 dataset



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:

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

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

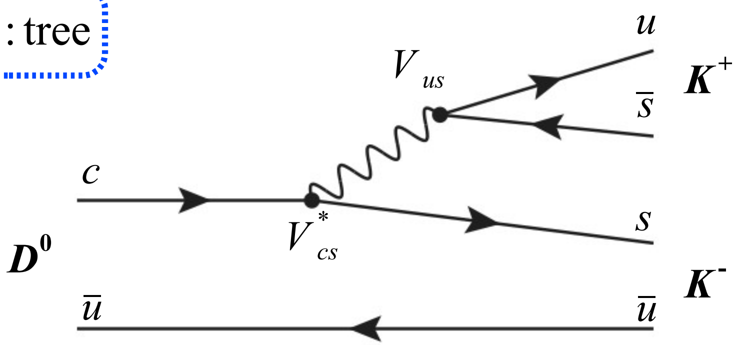
$$A_{CP}^{\rm dir}(D \to f) \simeq -2 \, r_f \sin\delta_f \sin\phi_f$$

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-emission) amplitude, as well as a loop ("penguin") one.

a^T_{KK} : tree



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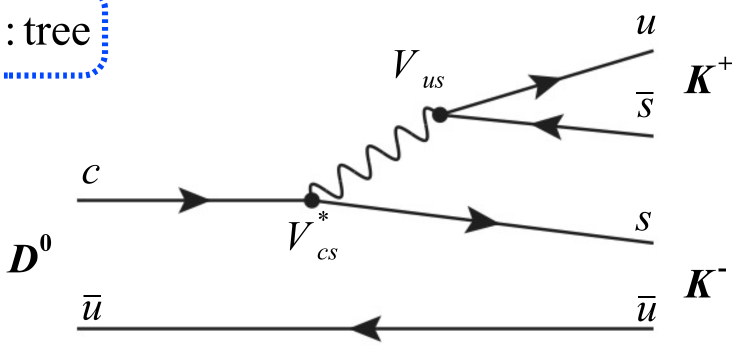

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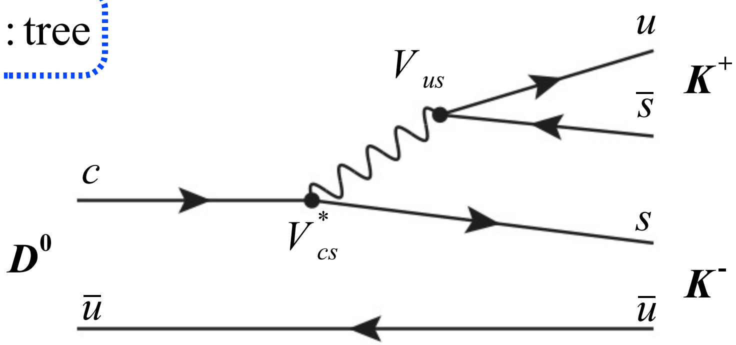

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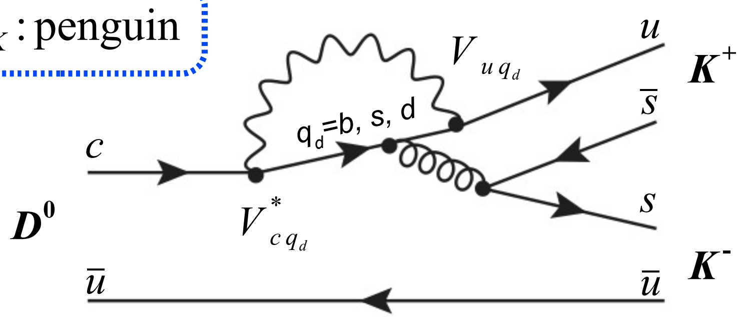

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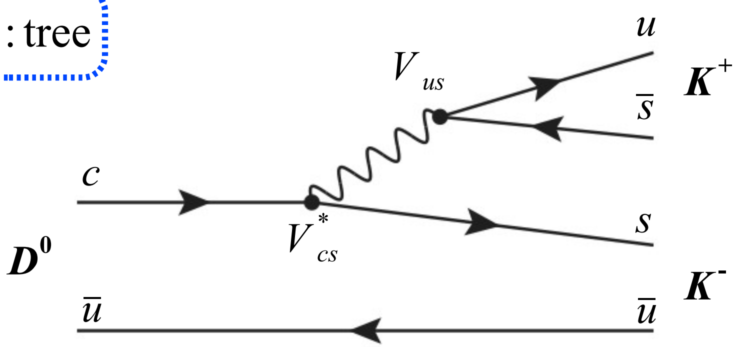

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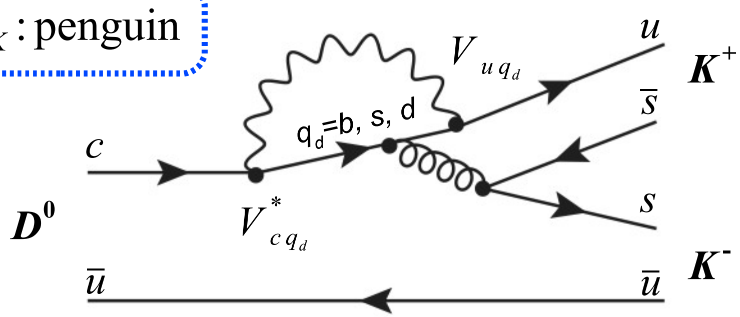

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- Using unitarity on the last term of the penguin amplitude, it follows:

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

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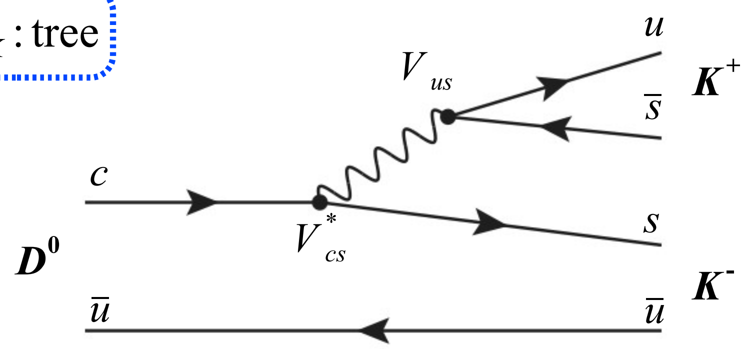

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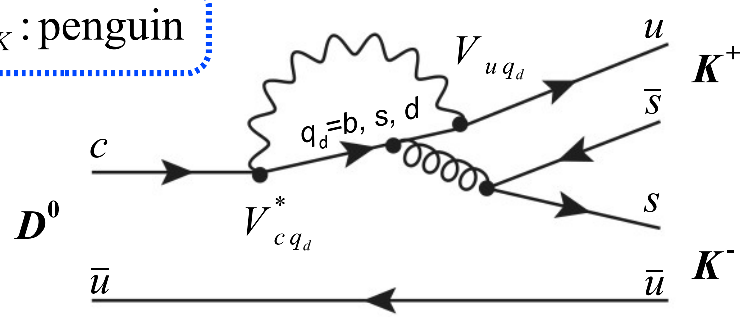

$$a^P_{KK} \sim \underbrace{V^*_{cb}\, V_{ub}}_{\lambda_C^2 \,\cdot\, \lambda_C^3} P^b_{KK} + \underbrace{V^*_{cs}\, V_{us}}_{1 \,\cdot\, \lambda_C} P^s_{KK} + \underbrace{V^*_{cd}\, V_{ud}}_{\lambda_C \,\cdot\, 1} P^d_{KK}$$

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

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

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

$$A_{CP}^{\mathrm{dir}}(D \to f) \simeq -2\, r_f \sin\delta_f \sin\phi_f \qquad \text{with } f = K^+K^- \text{ or } \pi^+\pi^-$$

- Recall that:

❶ The strong phase is expected to be large: sin δ = O(1)

❷ The weak phase is minus $\gamma \simeq 67°$: sin γ = O(1)

❸ 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:

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☞ It follows:

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

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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
Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, IL 60510, USA

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 $SU(3)_{\text{flavor}}$) <u>whose matrix elements may be enhanced</u> with respect to naïve expectations.

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This observation warrants further investigation:

- *on the Lattice QCD side:* estimate of the triplet operators' matrix elements
- *on the side of the assumptions specific to the Golden-Grinstein analysis.* Let's look closer at this issue

More on Golden-Grinstein

Amplitudes' formula

For the decays of interest to us, they arrive at the following amplitudes:

$$A(D^0 \to K^+ K^-) \;=\; a\,\Sigma + b\,\Delta$$

$$A(D^0 \to \pi^+ \pi^-) \;=\; -a\,\Sigma + b\,\Delta$$

with:

a, b = operator matrix elements

$$\Sigma = \left(V^*_{cs} V_{us} - V^*_{cd} V_{ud}\right)/2$$ approx. real

$$\Delta = \left(V^*_{cs} V_{us} + V^*_{cd} V_{ud}\right)/2$$ small in magnitude, but with large phase

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Crucial points

- Matrix elements from the lowest-dim irreps (= operator triplets) enter only in b, *not* in a
- Such matrix elements may well be enhanced with respect to naïve expectations, in analogy with the neutral-*K* case (Δ I = ½ rule).

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Conclusion

Since Δ has a large phase, and if b is indeed enhanced (say 10x) $\Longrightarrow$ A_{CP} may be large enough to be observable. Ballpark: $A_{CP} = O(10^{-3})$

More on Golden-Grinstein

Problem

Since $|\Sigma| / |\Delta| \sim 3000$, the above amplitudes would predict $\Gamma(D^0 \to K^+ K^-) \simeq \Gamma(D^0 \to \pi^+\pi^-)$.

On the other hand, experimentally, one finds: $\Gamma(D^0 \to K^+ K^-) \simeq 2.8 \cdot \Gamma(D^0 \to \pi^+\pi^-)$

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Inclusion of the leading $SU(3)_{flavor}$ – breaking effects into the Golden-Grinstein analysis

Main point

Under fairly general assumptions on the $SU(3)_{flavor}$ – breaking terms, the Golden-Grinstein amplitudes are modified as follows:

$$A(D^0 \to K^+ K^-) = (a + c)\,\Sigma + b\,\Delta$$

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Therefore:

Inclusion of these corrections can explain the widths' discrepancy, without spoiling Golden-Grinstein's argument on A_{CP}

Selected Theory Work after LHCb results

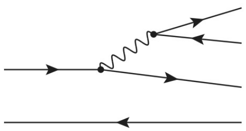
(Apologies for the not represented work)


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
hep-ph/0609178

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, <u>but in practice known to be sizable.</u>

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

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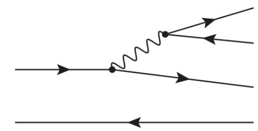
Besides the tree amplitude seen before, namely:  ("*W*-emission" topology)

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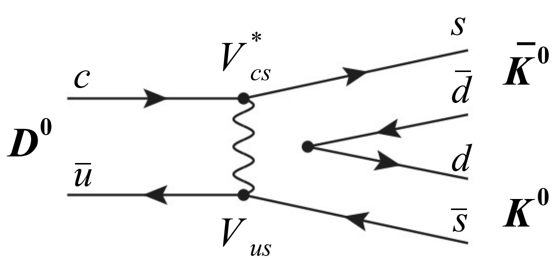
What does sizable mean in practice? Example.

The BR($D^0 \to K^0 \overline{K}^0$) 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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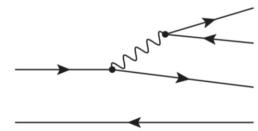
Besides the tree amplitude seen before, namely:  ("*W*-emission" topology)

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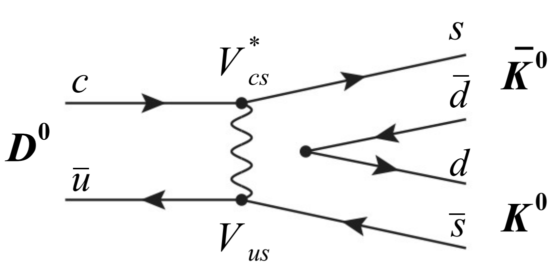

+ { diagram with s ↔ d }

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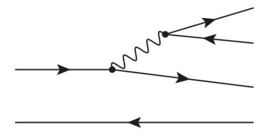
Besides the tree amplitude seen before, namely:  ("*W*-emission" topology)

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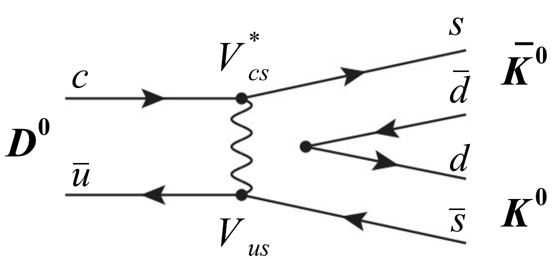

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This suggests that:

- ☑ the W-exchange amplitude is about ½ of the W-emission one (hence not so 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**

for the $D \to K^+ K^-$ and $D \to \pi^+ \pi^-$ decays

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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).

Brod, Kagan, Zupan: continued

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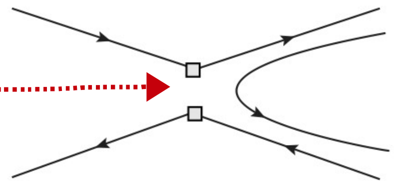
Estimate of:

(a) Annihilation topologies with insertions of QCD penguins. Example:

penguins here



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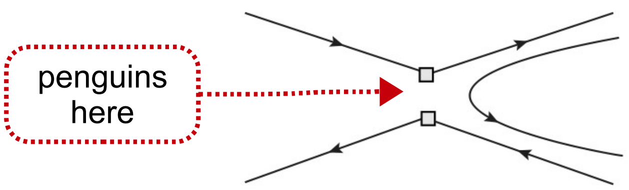
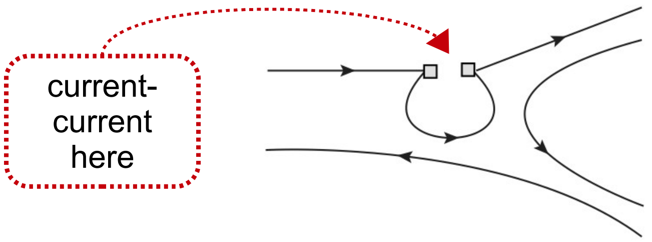


(b) Penguin contractions of current-current operators. Example:



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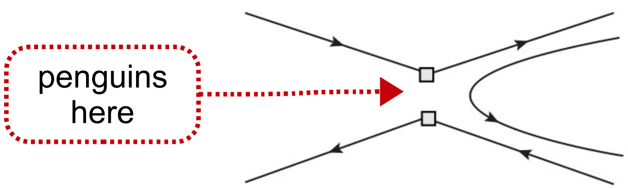

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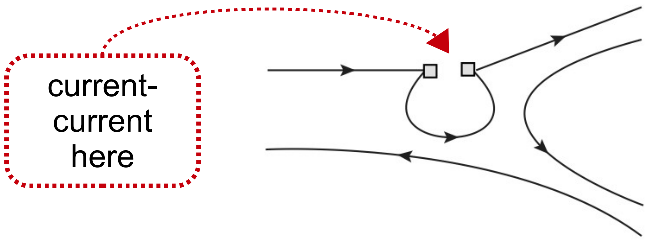

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A contribution to ΔA_{CP} from each of these amplitudes of:

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

It follows that the LHCb measurement can plausibly be saturated by the SM contributions

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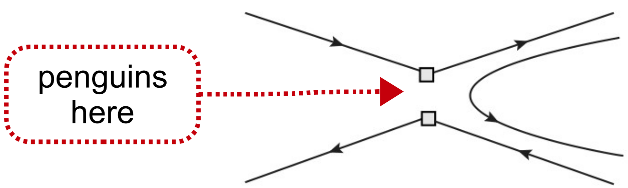

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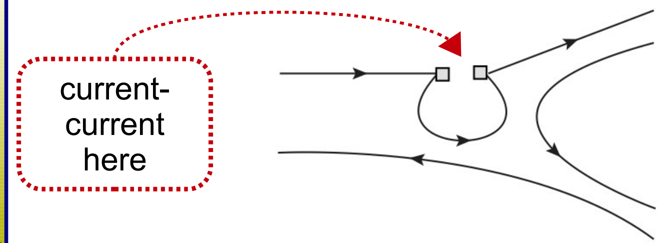

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❷ The whole approach is testable in two ways:

- 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* $\pi^+\pi^-$:

$$A_{CP}^{\mathrm{dir}}(D \to f) = -2\, \underbrace{r_f}_{\text{magnitude of the sub-leading to leading amplitudes ratio}} \sin \underbrace{\phi_f}_{\text{sub-leading to leading relative } CP\text{-odd phase}} \sin \underbrace{\delta_f}_{\text{sub-leading to leading relative strong phase}}$$

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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* $\pi^+ \pi^-$:

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

magnitude of the sub-leading to leading amplitudes ratio

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

sub-leading to leading relative *strong* phase

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

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

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:

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

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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It is naturally of O(1) if Λ_{NDA} is the Fermi scale

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- If { $\mathrm{Im}\,\Delta R^{\mathrm{NP}} \sim 1$, $|\Delta R^{\mathrm{SM}}|$ negligible; $C_{\mathrm{NDA}} \sim 1$ } $\Rightarrow$ $\Lambda_{\mathrm{NDA}} \sim 13$ TeV

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It follows that:

- If { Im $\Delta R^{NP} \sim 1$, $|\Delta R^{SM}|$ negligible; $C_{NDA} \sim 1$ } $\Longrightarrow$ $\Lambda_{NDA} \sim 13$ TeV
- If instead { $\Lambda_{NDA} \sim$ Fermi scale } $\Longrightarrow$ Im $C_{NDA} \sim 7 \cdot 10^{-4}$

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

Isidori et al.: continued

☑ **Full analysis**

(a) Write down the most general $|\Delta C| = 1$ effective Hamiltonian for non-SM contributions: $H^{\text{eff, NP}}_{|\Delta C|=1}$

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(b1) The double insertion $T\{H^{\text{eff, NP}}_{|\Delta C|=1}(x)\ H^{\text{eff, SM}}_{|\Delta F|=1}(0)\}$ generates an effective |ΔC| = 2 Hamiltonian. It is constrained by $D^0 - \overline{D}^0$ mixing

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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.

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However

Chromo-magnetic operators (at variance with 4-fermion ones) do actually largely circumvent this statement.

See the recent paper by *Giudice, Isidori and Paradisi* for a detailed account of this possibility

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

☑ **Data 1**

LHCb update on ΔA_{CP} with full 2011 dataset

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- **Data 2**

  Data on these modes