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?*

First Things First:
Data!

Short summary of data news: LHCb and CDF

LHCb (1112.0938) measures:

$$A_{\rm raw}(D^0 \to K^+ K^-) - A_{\rm raw}(D^0 \to \pi^+ \pi^-)$$
$$= (-0.82 \pm 0.21 \pm 0.11)\%$$
$$\simeq A_{CP}^{\rm dir}(D^0 \to K^+ K^-) - A_{CP}^{\rm dir}(D^0 \to \pi^+ \pi^-)$$

- 3.5σ away from the hypothesis of CP conservation
- Based on 620/pb of analyzed data. LHCb has now almost 2x on tape

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- Most precise single-exp determinations
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☞ **Note** that 3 asymmetries appear in the above discussion:

- $A_{\rm raw}$: it is the experimental asymmetry.

  Generally $A_{\rm raw}$ = {instrumental CP asymmetry} + {physics CP asymmetry}

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

It needs to be subtracted away in order to isolate the physics CP asymmetry.

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

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This is the actual quantity of interest

More on the various asymmetries

- For each final state *f*, the quantity A_{raw} is defined as:

$$A_{raw}(D^0 \to f) = \frac{N_{obs}(D^0 \to f) - N_{obs}(\bar{D}^0 \to f)}{N_{obs}(D^0 \to f) + N_{obs}(\bar{D}^0 \to f)}$$

To get this number:

- Identify a decay event, occurring at time t, of a neutral D meson, tagged at t = 0 (prod'n) to be a D^0
- Sum over all t (hence "time-integrated" asymmetry)

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3. any detector effect not perfectly CP symmetric → Instrumental

"Physical" CPV (Direct CPV and indirect CPV)

Indirect CPV: small

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

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

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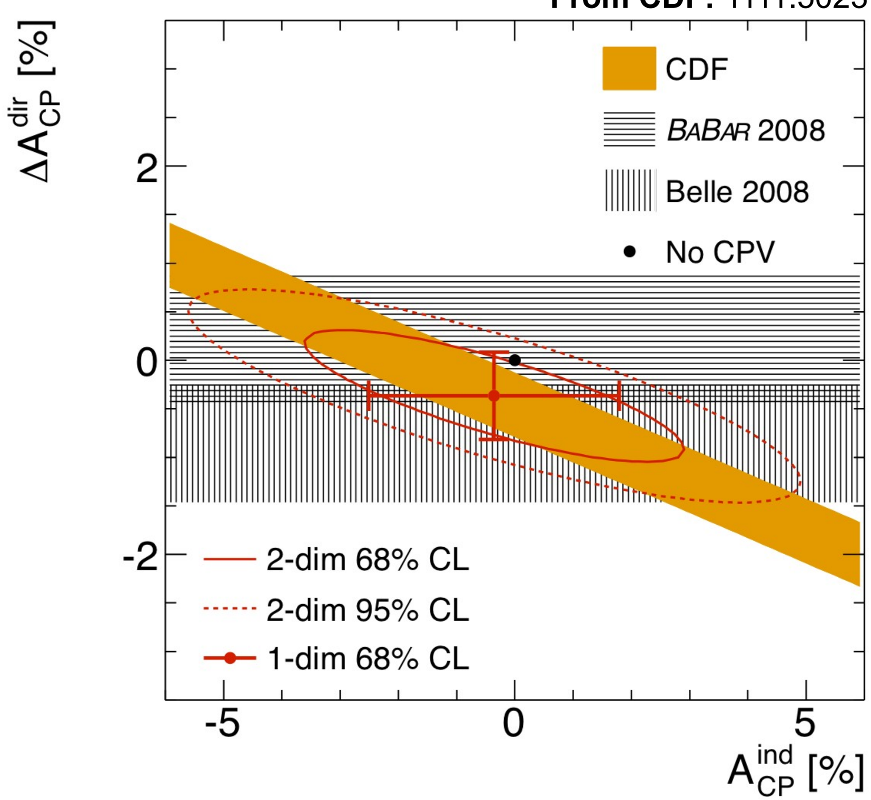
   CDF quotes:

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

From CDF: 1111.5023



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

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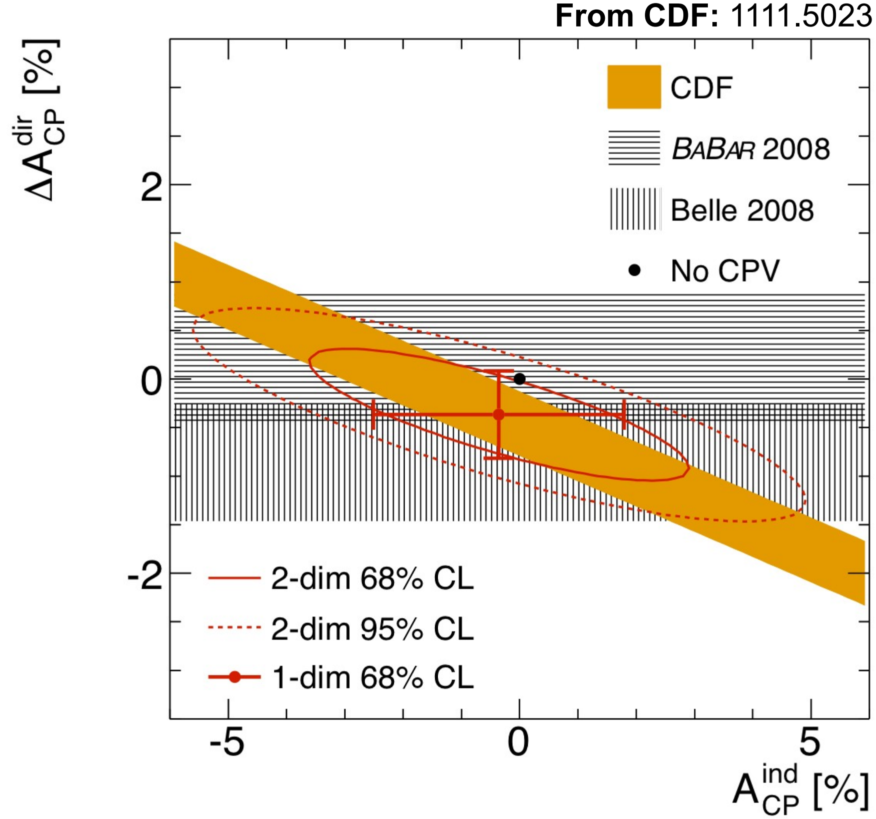

Theory Implications

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 (A_f^T): its phase is taken to be zero

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

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

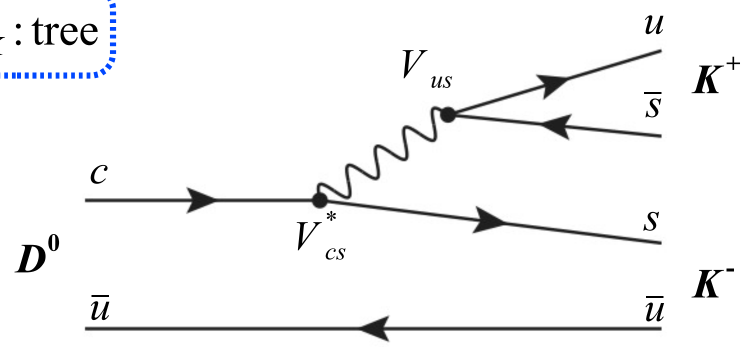
$$A_{CP}^{\mathrm{dir}}(D \to f) \simeq -2\, r_f \sin\delta_f \sin\phi_f$$

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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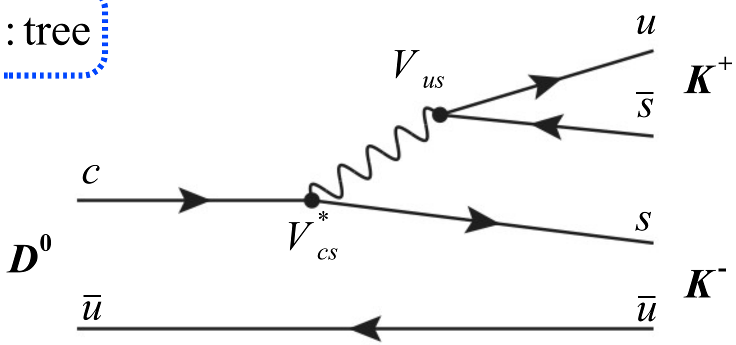

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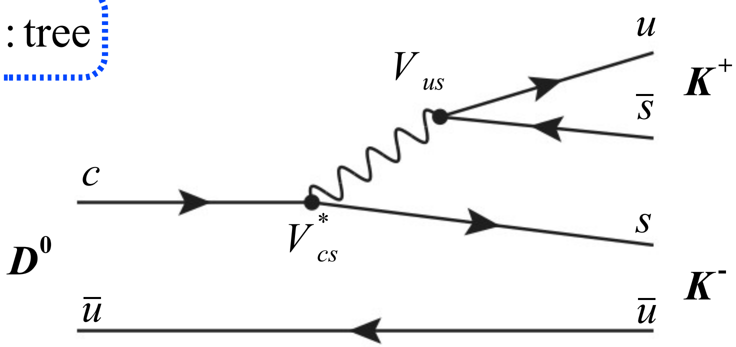

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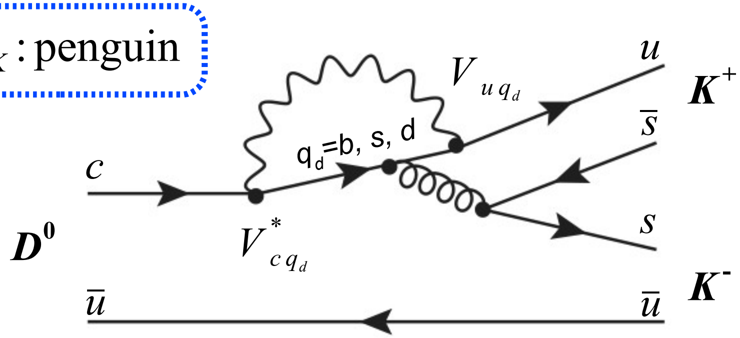

$$a^P_{KK} \sim \underbrace{V^*_{cb} V_{ub}}_{\lambda_C^2 \,\cdot\, \lambda_C^3} P^b_{KK} + \underbrace{V^*_{cs} V_{us}}_{1 \,\cdot\, \lambda_C} P^s_{KK} + \underbrace{V^*_{cd} V_{ud}}_{\lambda_C \,\cdot\, 1} P^d_{KK}$$

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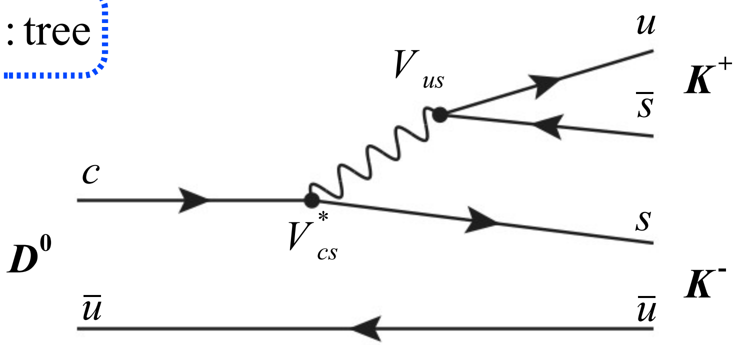

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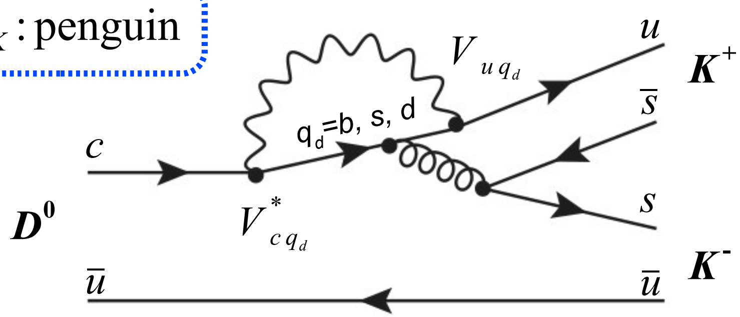

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$$\lambda_C^2 \cdot \lambda_C^3 \qquad 1 \cdot \lambda_C \qquad \lambda_C \cdot 1$$

- 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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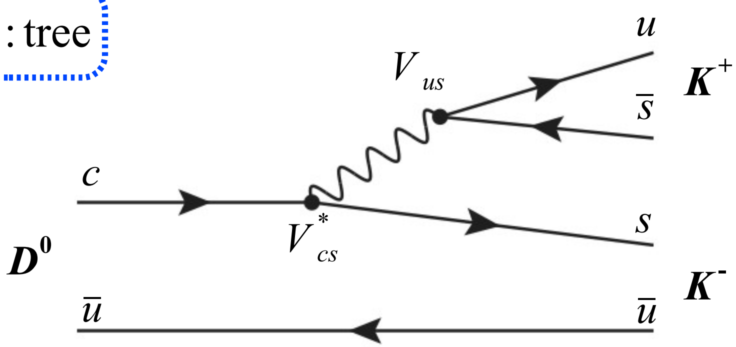

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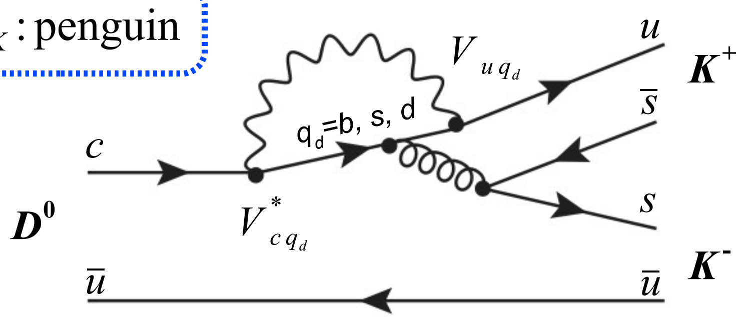

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Hence the amplitude ratio estimate: $r_f \sim A^P_{KK} / A^T_{KK} \sim \lambda_C^4 \, \alpha_s(m_c)/\pi \sim 10^{-4}$

ΔA_{CP} : heuristic estimate

- Now let us go back to the formula

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

- Recall that:

1. The strong phase is expected to be large: $\sin\delta = O(1)$
2. The weak phase is minus $\gamma \simeq 67°$: $\sin\gamma = O(1)$
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:

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

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

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

It follows:

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

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

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

This resembles the "$\Delta I = 1/2$ rule" in $K \to \pi \pi$ matrix elements, at work in ϵ'/ϵ

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This resembles the "$\Delta I = ½$ rule" in $K \to \pi\pi$ matrix elements, at work in ϵ'/ϵ

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

- **Aim:** analysis of the amplitudes $D \to 2$ pseudoscalars, focusing on CPV effects, and including QCD corrections (running)

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   - Consider all the structures of the kind $(\bar{q}^{\,i}\ \Gamma_1\ c)\ (\bar{q}^{\,j}\ \Gamma_2\ q^k)$, with i, j, k = $SU(3)_{\rm flavor}$ indices.
   - Classify these structures according to irreps of $SU(3)_{\rm flavor}$. One arrives at $H_{|\Delta C| = 1}(\mu = M_W)$.

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   For the decays of interest to us, one arrives 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

Golden-Grinstein: continued

Main observation

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

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

- 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 ($\Delta I = 1/2$ rule).

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

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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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Expected solution: $SU(3)_{flavor}$ – breaking effects may well be large, and need be incorporated in the above analysis

Pirtskhalava-Uttayarat follow-up (1112.5451):

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

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Under the assumptions (fairly general) that:

1. only leading (= linear) $SU(3)_{flavor}$ – breaking effects need be retained
2. operators belonging to lower $SU(3)_{flavor}$ representations have somewhat enhanced matrix elements

the Golden-Grinstein amplitudes are modified as follows:

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

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Bottom line

By inclusion of the leading $SU(3)_{flavor}$ corrections,

the ΔA_{CP} measurement by LHCb & the observed partial-widths' ratio

can be simultaneously explained with an enhancement of triplet operators' matrix elements of O(10), i.e. a reasonable one

Selected Theory Work after LHCb results

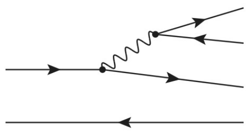
(Apologies for the not represented work)


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, but in practice known to be sizable.

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

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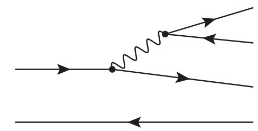
Besides the tree amplitude seen before, namely:  ("*W*-emission" topology)

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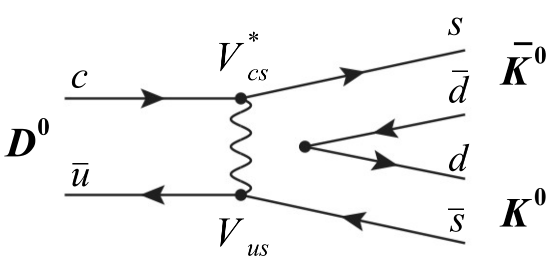
What does sizable mean in practice? Example.

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.



+ { diagram with s ↔ d }

$$= V^*_{cs} V_{us} E^s_{KK} + V^*_{cd} V_{ud} E^d_{KK}$$

$$\simeq \lambda_C \left(E^s_{KK} - E^d_{KK} \right)$$

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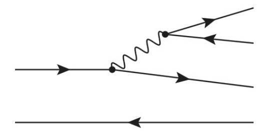
Besides the tree amplitude seen before, namely:  ("*W*-emission" topology)

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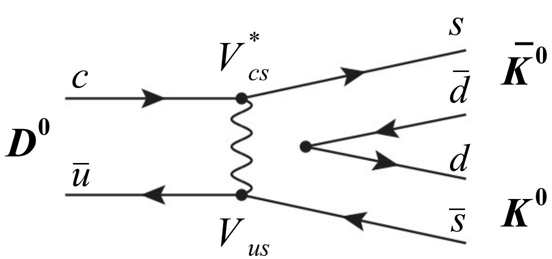

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Data (PDG)

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

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

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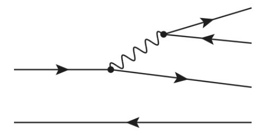

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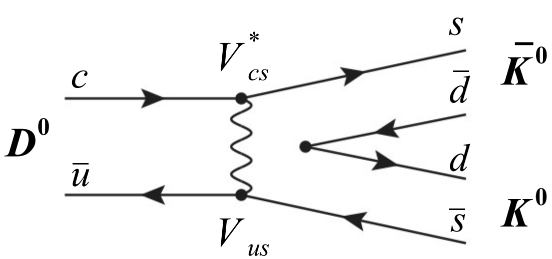

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This suggests that:

- 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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- the $\Delta C = 1$ effective Hamiltonian at NLO within the SM
- "naïve" factorization + $O(\alpha_s)$ corrections

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Including renorm. scale variation, they get:

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

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consistent with the heuristic estimate seen before

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Beware:

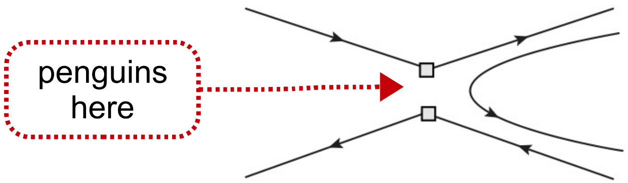
- It is well known that the charm mass is too light for factorization theorems to hold (and much too heavy for chiral symmetry).
  Therefore, the $1/m_c$ expansion and factorization are, here and below, mostly used as guidance.
- The corresponding results require of course plenty of assumptions (e.g. on the matrix elements).
  Results should be taken with relative errors of O(1).

Brod, Kagan, Zupan: continued

❷ **The (formally) power-suppressed amplitudes**

Estimate of:

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



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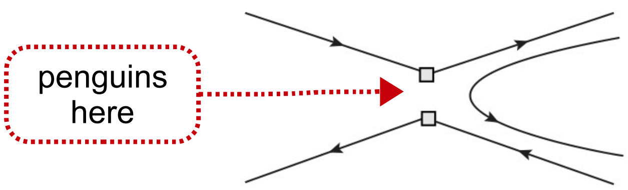
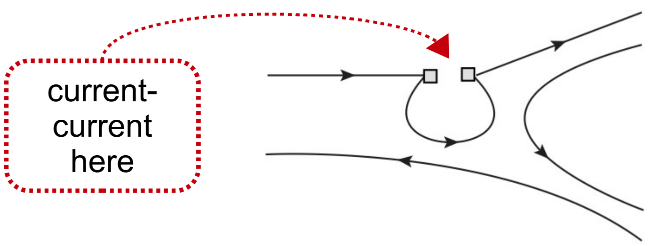


(b) Penguin contractions of current-current operators. Example:



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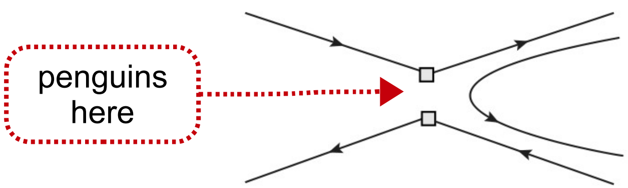

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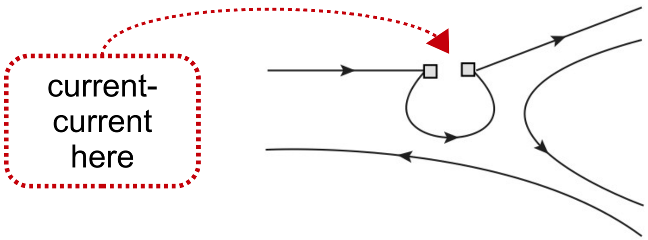

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A contribution to ΔA_{CP} from each of these amplitudes of:

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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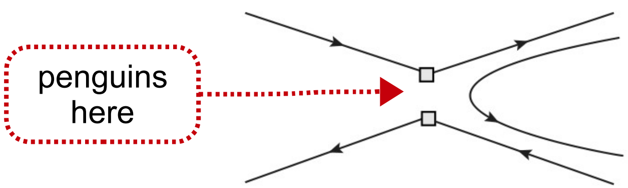

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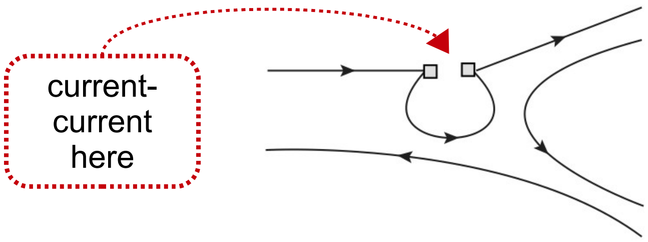

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❷ The whole approach is testable in two ways:

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

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

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

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

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

- ξ_f: ratio of CKM factors
- R_f^{SM}, $R_{f,i}^{\rm NP}$: ratio between hadronic amplitudes
- $C_i^{\rm NP}$: non-SM Wilson coefficients (normalized to the tree amplitude CKM suppression)

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

Isidori et al.: continued

Constraint equation

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$$\mathrm{Im}\left(C_{\mathrm{NDA}}\right)\frac{(10\,\mathrm{TeV})^2}{\Lambda^2_{\mathrm{NDA}}} = \frac{(0.61\pm0.17) - 0.12\,\mathrm{Im}\left(\Delta R^{\mathrm{SM}}\right)}{\mathrm{Im}\left(\Delta R^{\mathrm{NP}}\right)}$$

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

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It follows that:

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

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

Isidori et al.: continued

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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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Isidori et al.: continued

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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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LHCb update on ΔA_{CP} with full 2011 dataset

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  More into the question: can this be sheer SM?

  - *Classification of other decay modes where similar enhancements would be expected.*
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- ☑ **Data 2**

  Data on these modes