Direct CP violation in charm decays: general considerations within and beyond the SM

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[*INFN, Frascati & CERN*]

- A closer look to Δa_{CP} within the SM
- Considerations on possible NP contributions

▶ A closer look to Δa_{CP} within the SM

Let's consider the relevant SM effective Hamiltonian ($|\Delta c|=1$, $|\Delta s|=0$) renormalized at a scale $m_c < \mu < m_b$

$$\mathcal{H}^{\rm eff}_{|\Delta c|=1} = \lambda_d\, \mathcal{H}^{d}_{|\Delta c|=1} + \lambda_s\, \mathcal{H}^{s}_{|\Delta c|=1} + \lambda_b\, \mathcal{H}^{\rm peng}_{|\Delta c|=1}$$

$$\mathcal{H}^{q}_{|\Delta c|=1} = \frac{G_F}{\sqrt{2}} \sum_{i=1,2} C^q_i Q^s_i + \text{H.c.}\,,$$

$$Q^q_1 = (\bar u q)_{V-A}\, (\bar q c)_{V-A}$$

$$Q^q_2 = (\bar u_\alpha q_\beta)_{V-A}\, (\bar q_\beta c_\alpha)_{V-A}$$

O(1) Wilson coeff.

Standard basis of four QCD penguin ops.

Tiny coefficients for μ in the perturbative regime: $C_i \sim \alpha_s(\mu)/\pi$

$$\lambda_q = V^*_{cq} V_{uq} = \begin{cases} +\lambda + \ldots & (q=d) \\ -\lambda + \ldots & (q=s) \\ \sigma A^2 \lambda^5 e^{-i\gamma} & (q=b) \end{cases}$$

$$\lambda_d + \lambda_s + \lambda_b = 0$$

$$\lambda = \sin(\theta_c) \approx 0.225$$

A closer look to $\Delta a_{\rm CP}$ within the SM

To a good approximation, for sufficiently heavy μ:

$$\mathcal{H}^{\rm eff}_{|\Delta c|=1} \approx \lambda_d\, \mathcal{H}^{d}_{|\Delta c|=1} + \lambda_s\, \mathcal{H}^{s}_{|\Delta c|=1}$$

▶ A closer look to Δa_{CP} within the SM

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$$= +\lambda_d \left(\mathcal{H}^{d}_{|\Delta c|=1} - \mathcal{H}^{s}_{|\Delta c|=1} \right) - \lambda_b \mathcal{H}^{s}_{|\Delta c|=1}$$

$$= -\lambda_s \left(\mathcal{H}^{d}_{|\Delta c|=1} - \mathcal{H}^{s}_{|\Delta c|=1} \right) - \lambda_b \mathcal{H}^{d}_{|\Delta c|=1}$$

- Cabibbo-suppressed
- No tree-level in K^+K^- or $\pi^+\pi^-$
- *Penguin contractions allowed*

- Cabibbo-leading structure
- Tree-level amplitude in both K^+K^- and $\pi^+\pi^-$
- Both $\Delta I=1/2$ and $\Delta I=3/2$ components
- No penguin contractions in the SU(3) limit

A closer look to Δa_{CP} within the SM

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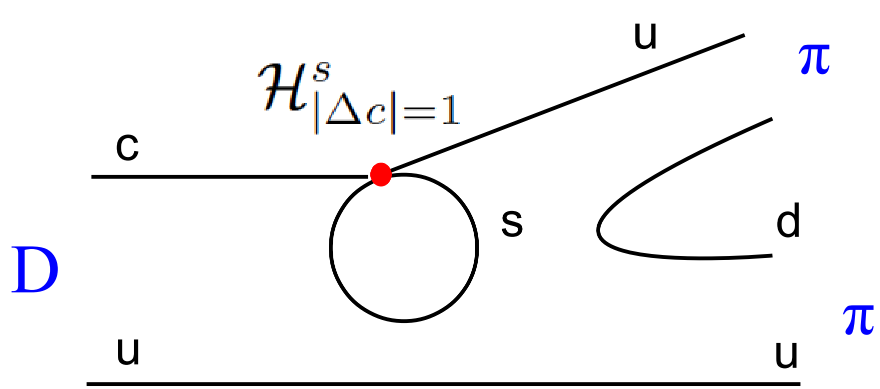
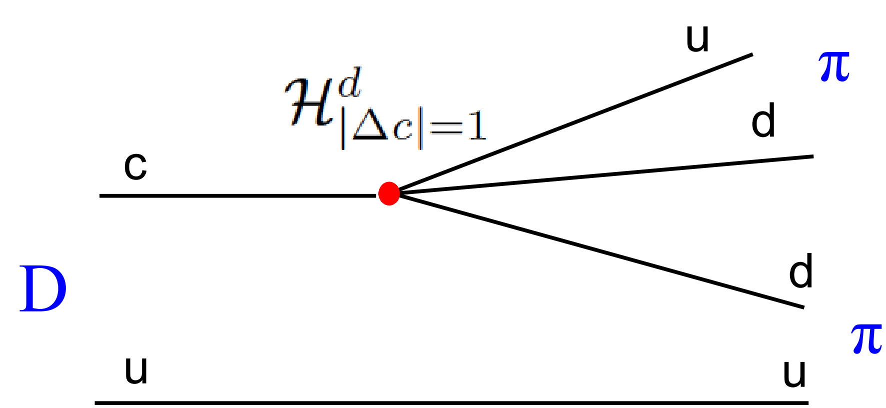


"Penguin contractions"



"Tree-level topologies"

A closer look to Δa_{CP} within the SM

In order to account for the observed asymmetry the penguin contractions need to be ~ 2-5 times larger than the tree-level topologies.

$$A_f = \lambda_d A^d{}_f + \lambda_s A^s{}_f + \lambda_b A^b{}_f$$

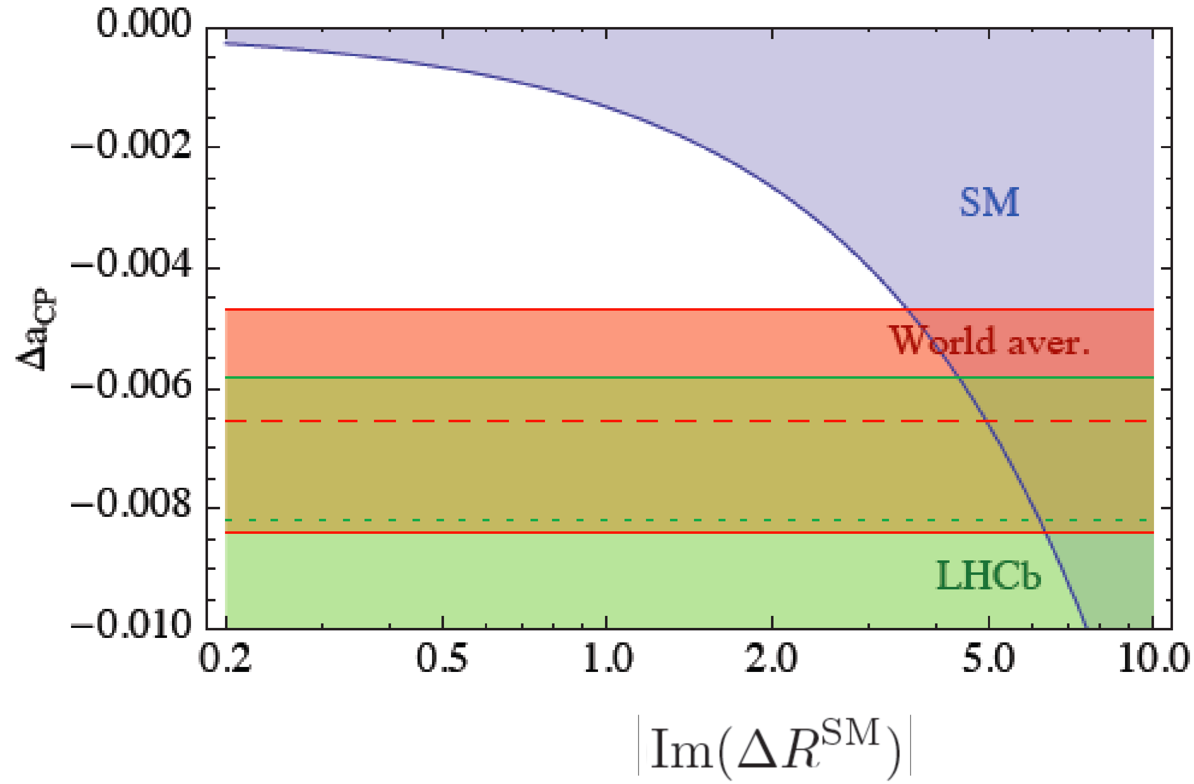
$$R_\pi^{SM} = \frac{A_\pi^b - A_\pi^s}{A_\pi^d - A_\pi^s}$$

$$R_K^{SM} = \frac{A_K^b - A_K^d}{A_K^s - A_K^d}$$

tree-level

$$\Delta R^{SM} = R_K^{SM} + R_\pi^{SM}$$

G.I., Kamenik, Ligeti, Perez, '11



In the SU(3) limit: $R_K^{SM} = R_\pi^{SM}$

▶ *A closer look to Δa_{CP} within the SM*

In order to account for the observed asymmetry the penguin contractions need to be ~ 2-5 times larger than the tree-level topologies.

This is not what expected if $m_c \gg \Lambda_{QCD}$, but is not surprising if we treat the charm as a light quark: enhancement of a_{CP} similar to the $\Delta I=1/2$ enhancement in kaon decays [*very similar operator structure* – Golden & Grinstein '89]

N.B.: the "penguin enhancement" has an opposite effect in K and D decays:

- In $K\to\pi\pi$ it enhances the leading A_0 ampl. → suppression of direct CPV.
- In $D\to KK, \pi\pi$ it affects only the sub-leading terms with different CKM phase → enhancement of direct CPV.

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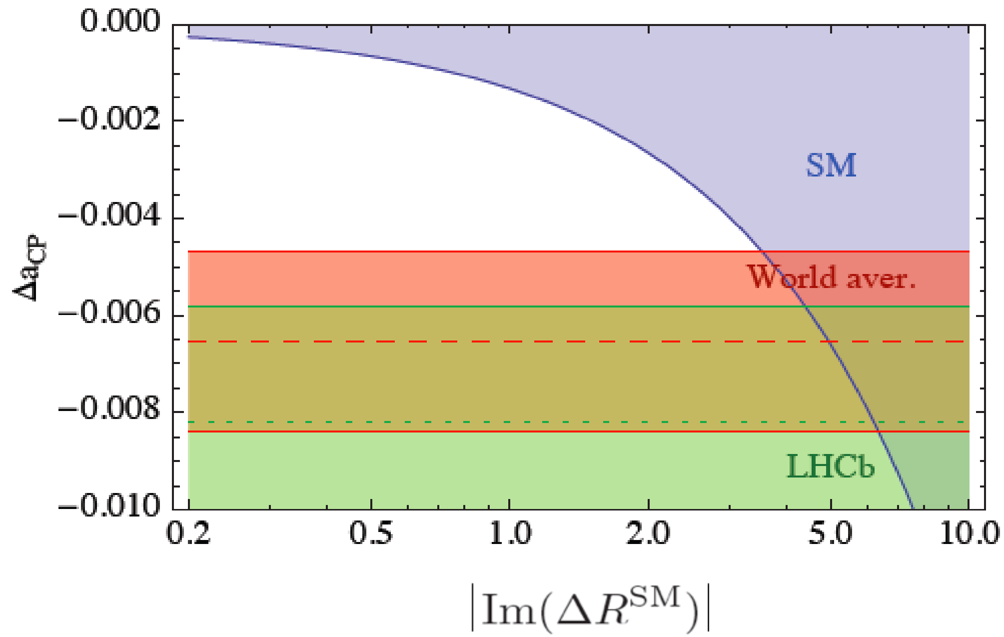
Arguments in favor of sizable corrections with respect to the leading terms in the Λ_{QCD}/m_c expansions presented by Bord et al. [Brod, Kagan & Zupan '11], based on the (non) suppression of $\Gamma(D\to K^0K^0)$ and other CPC observables.

However...

- The structure of H_{eff} is such that is not possible to access the size of the penguin contractions from data on the rates only (Cabibbo suppression)
- The size of the sub-leading Λ_{QCD}/m_c terms so far identified is not sufficient to explain the central value of the CP asymmetry measured by LHCb.

Considerations on possible NP contributions

Assuming that the SM does not saturates the exp. value, what can be said about NP?



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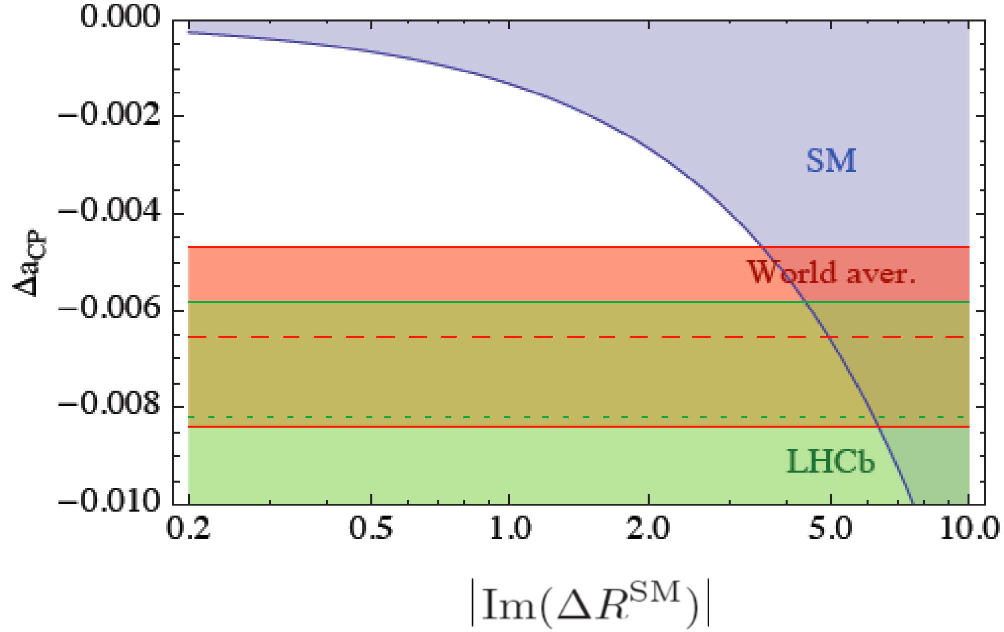


$$\Delta a_{CP} \approx (0.13\%)\mathrm{Im}(\Delta R^{\mathrm{SM}}) + 9\sum_i \mathrm{Im}(C_i^{\mathrm{NP}})\,\mathrm{Im}(\Delta R_i^{\mathrm{NP}})$$

$$\mathcal{H}^{\mathrm{eff-NP}}_{|\Delta c|=1} = \frac{G_F}{\sqrt{2}} \sum_i C_i^{\mathrm{NP}} Q_i$$

Ratio of NP/treel-level SM amplitudes, facotrizing-out the NP Wilson coeff

I. General considerations on the NP scale:

$$\mathrm{Im}(C_i^{\mathrm{NP}}) = \frac{\mathrm{v}^2}{\Lambda^2} \quad \Rightarrow \quad \frac{(10\ \mathrm{TeV})^2}{\Lambda^2} = \frac{(0.61 \pm 0.17) - 0.12\,\mathrm{Im}(\Delta R^{\mathrm{SM}})}{\mathrm{Im}(\Delta R^{\mathrm{NP}})}$$

Considerations on possible NP contributions

Despite 10 TeV is a large scale, several of the possible |Dc|=1 operators around or above the electroweak scale are constrained in a model-independent way by other low-energy constraints after "dressing" with SM weak interactions

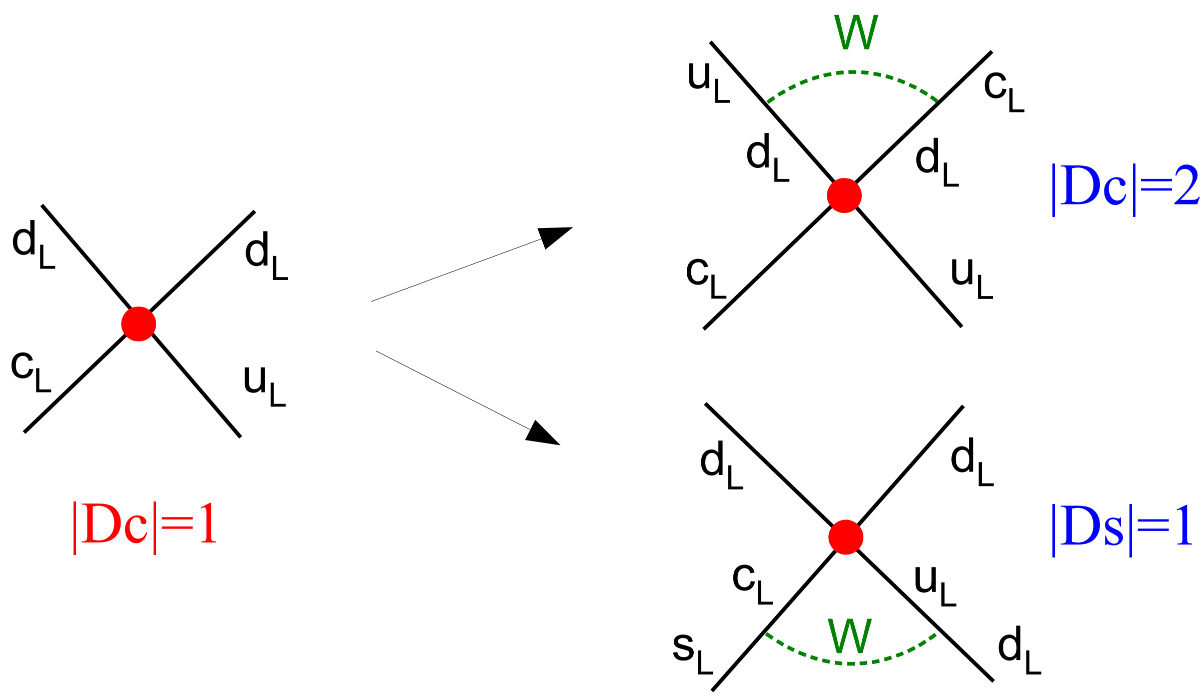
$$T\{\mathcal{H}^{\text{eff}-\text{NP}}_{|\Delta c|=1}(x)\,\mathcal{H}^{\text{SM}}(0)\}$$

→ |Dc|=2 (D-Dbar mixing)

→ CPV in |Ds|=1 (ε'/ε):

G.I., Kamenik, Ligeti, Perez, '11

E.g.:



Interesting exercise of EFT and RGE techniques

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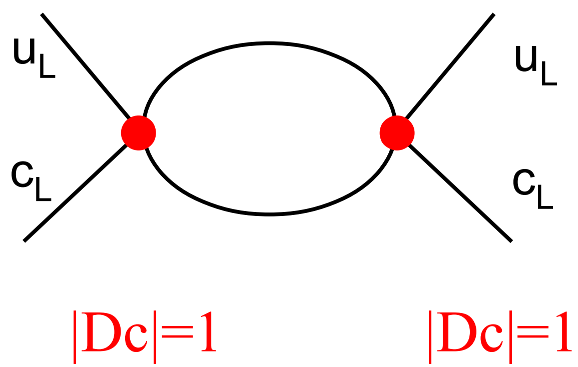
Or considering the NP interaction twice:



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▶ *Considerations on possible NP contributions*

Complete basis of |Dc|=1 operators:

$$\mathcal{H}^{\rm eff-NP}_{|\Delta c|=1} = \frac{G_F}{\sqrt{2}} \sum_{i=1,2,5,6} \sum_q (C_i^q Q_i^q + C_i^{q\prime} Q_i^{q\prime}) + \frac{G_F}{\sqrt{2}} \sum_{i=7,8} (C_i Q_i + C_i^\prime Q_i^\prime) + {\rm H.c.}$$

$$\begin{aligned} Q_1^q &= (\bar{u}q)_{V-A}\,(\bar{q}c)_{V-A} \\ Q_2^q &= (\bar{u}_\alpha q_\beta)_{V-A}\,(\bar{q}_\beta c_\alpha)_{V-A} \\ Q_5^q &= (\bar{u}c)_{V-A}\,(\bar{q}q)_{V+A} \\ Q_6^q &= (\bar{u}_\alpha c_\beta)_{V-A}\,(\bar{q}_\beta q_\alpha)_{V+A} \end{aligned}$$

4 x 5 x 2 four-fermion

$$\begin{aligned} Q_7 &= -\frac{e}{8\pi^2}\, m_c\, \bar{u}\sigma_{\mu\nu}(1+\gamma_5)F^{\mu\nu}\, c \\ Q_8 &= -\frac{g_s}{8\pi^2}\, m_c\, \bar{u}\sigma_{\mu\nu}(1+\gamma_5)T^a G_a^{\mu\nu} c \end{aligned}$$

2 x 2 dipoles

Considerations on possible NP contributions

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After “SM dressing” (W+gluons) we find that

- LL – ops. essentially ruled out
- LR – ops. borderline (potentially visible effects in D-meson mixing and/or ε'/ε)
- RR – ops. not constrained in a model-indep. way, but potentially very dangerous in D-meson mix. in explicit models (quadratic div. from NPxNP)

$$\begin{aligned} Q_7 &= -\frac{e}{8\pi^2}\, m_c\, \bar u \sigma_{\mu\nu}(1+\gamma_5) F^{\mu\nu}\, c \\ Q_8 &= -\frac{g_s}{8\pi^2}\, m_c\, \bar u \sigma_{\mu\nu}(1+\gamma_5) T^a G_a^{\mu\nu}\, c \end{aligned}$$

- only the dipole ops. could “naturally” explain the effect. (weak constraints from edms)

Conclusions

- The central value of Δa_{CP} measured by LHCb is larger than its natural expectation within the SM. However, given the present knowledge of the charm system, it cannot be considered (yet) a clear signal of physics beyond the SM.

- Hard to improve the SM predictions of Δa_{CP} using data on the rates (or the Lattice), while there is some hope to improve our understanding with the help of additional data on other CPV observables [*with the help of additional CPV observables it should be possible to construct observables that would unambiguously falsify the SM*].

- Assuming a sizable fraction of the measured Δa_{CP} is due to NP, only a few effective operators could explain the effect, due to the tight constraints from D-Dbar mixing and ε'/ε. The $|Dc=1|$ chromo-mangnetic operators are the most natural candidates from an effective-theory point of view.