CP violation in the charm sector within the Standard Model and beyond

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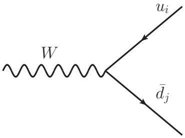
based on ArXiv:1903.10490

- The quark flavour-changing weak interactions are described by:



$$\mathcal{L}_{Wq} = \frac{g}{\sqrt{2}}(\bar{u}_L, \bar{c}_L, \bar{t}_L)\gamma^\mu \underbrace{\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}}_{V_{\rm CKM}} \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} W_\mu^\dagger + \text{h.c.}$$

- V_{CKM} - quark-mixing Cabibbo-Kobayashi-Maskawa (CKM) matrix
- In terms of three mixing angles $\theta_{12}, \theta_{13}, \theta_{23}$ and one *CP*-violating phase δ

$$V_{\rm CKM} = \begin{pmatrix} c_{12}\, c_{13} & s_{12}\, c_{13} & s_{13}\, e^{-i\delta} \\ -s_{12}\, c_{23} - c_{12}\, s_{23}\, s_{13}\, e^{i\delta} & c_{12}\, c_{23} - s_{12}\, s_{23}\, s_{13}\, e^{i\delta} & s_{23}\, c_{13} \\ s_{12}\, s_{23} - c_{12}\, c_{23}\, s_{13}\, e^{i\delta} & -c_{12}\, s_{23} - s_{12}\, c_{23}\, s_{13}\, e^{i\delta} & c_{23}\, c_{13} \end{pmatrix}$$

$$s_{ij} = \sin\theta_{ij},\ c_{ij} = \cos\theta_{ij}.$$

Direct CP asymmetry

- Definition of the direct CP-asymmetry:

$$A_{CP} = \frac{\Gamma(H \to f) - \Gamma(\bar{H} \to \bar{f})}{\Gamma(H \to f) + \Gamma(\bar{H} \to \bar{f})}$$

- Decomposing an amplitude

$$A(H \to f) = \underbrace{\lambda_1 e^{i\alpha_1}}_{\text{weak int.}} \underbrace{A_1 e^{i\phi_1}}_{\text{QCD}} + \underbrace{\lambda_2 e^{i\alpha_2}}_{\text{weak int.}} \underbrace{A_2 e^{i\phi_2}}_{\text{QCD}}$$

- The amplitude of the CP-conjugated mode

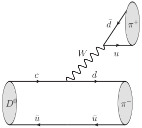
$$A(\bar{H} \to \bar{f}) = \underbrace{\lambda_1 e^{-i\alpha_1}}_{\text{weak int.}} \underbrace{A_1 e^{i\phi_1}}_{\text{QCD}} + \underbrace{\lambda_2 e^{-i\alpha_2}}_{\text{weak int.}} \underbrace{A_2 e^{i\phi_2}}_{\text{QCD}}$$

- Direct CP-asymmetry

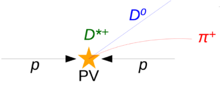
$$A_{CP} = \frac{-2\left|\frac{\lambda_1}{\lambda_2}\right| \sin(\alpha_1 - \alpha_2) \left|\frac{A_1}{A_2}\right| \sin(\phi_1 - \phi_2)}{1 + 2\left|\frac{\lambda_1}{\lambda_2}\right| \cos(\alpha_1 - \alpha_2) \left|\frac{A_1}{A_2}\right| \cos(\phi_1 - \phi_2) + \left|\frac{\lambda_1}{\lambda_2}\right|^2 \left|\frac{A_1}{A_2}\right|^2}$$

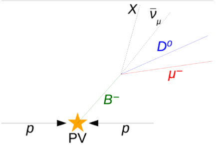
ΔA_{CP}: the history of measurements

- Consider non-leptonic $D^0 \to PP$ decays ($P = \pi, K$)
- Definition: $\Delta A_{CP} = A_{CP}(K^- K^+) - A_{CP}(\pi^- \pi^+)$



Experiment	$\Delta A_{CP} \times 10^4$	Tag	arXiv
BaBar	$+24 \pm 62 \pm 26$	pion	0709.2715
LHCb	$-82 \pm 21 \pm 11$	pion	1112.0938
CDF	$-62 \pm 21 \pm 10$	pion	1207.2158
Belle	$-87 \pm 41 \pm 6$	pion	1212.1975
LHCb	$+49 \pm 30 \pm 14$	muon	1303.2614
LHCb	$+14 \pm 16 \pm 8$	muon	1405.2797
LHCb	$-10 \pm 8 \pm 3$	pion	1602.03160
LHCb	$-18.2 \pm 3.2 \pm 0.9$	pion	1903.08726
LHCb	$-9 \pm 8 \pm 5$	muon	1903.08726



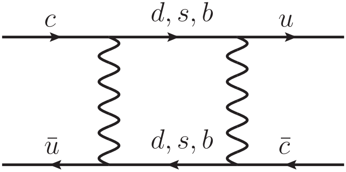


Federico Betti's talk

Moriond'19

- LHCb, Moriond 2019: $\Delta A_{CP}^{\text{Exp}} = (-15.4 \pm 2.9) \times 10^{-4}$ (5.3σ from 0)

Mixing in the charm sector



- Diagonalisation of the 2×2 matrix yields:

$$\Delta M_D^2 - \frac{1}{4}\Delta\Gamma_D^2 = 4\left|M_{12}^D\right|^2 - \left|\Gamma_{12}^D\right|^2, \quad \Delta M_D \Delta\Gamma_D = 4\left|M_{12}^D\right|\left|\Gamma_{12}^D\right|\cos(\phi_{12}^D)$$

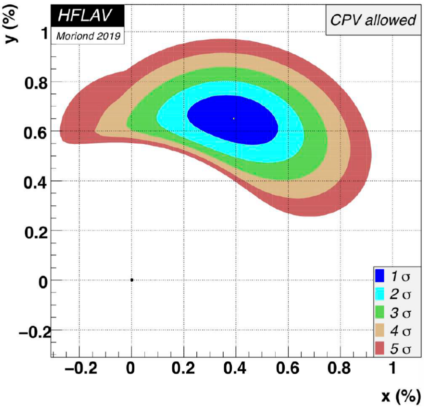
  - ▷ $\Delta M_D = M_1 - M_2$ - mass difference
  - ▷ $\Delta\Gamma_D = \Gamma_2 - \Gamma_1$ - decay widths difference of the mass eigenstates
  - ▷ Γ_{12}^D - absorptive part of box diagram (on-shell)
  - ▷ M_{12}^D - dispersive part of box diagram (off-shell)
  - ▷ $\phi_{12}^D = -\arg(-M_{12}^D/\Gamma_{12}^D)$ - relative phase

Mixing in the charm sector

- Experimental data on

$$x \equiv \Delta M_D/\Gamma_D = \left(0.39^{+0.11}_{-0.12}\right)\,\%$$
$$y \equiv \Delta\Gamma_D/(2\Gamma_D) = \left(0.651^{+0.063}_{-0.069}\right)\,\%$$

- Future experimental sensitivity for x and y will reach the order of 0.005 %



Mixing in the charm sector

- The on-shell contribution from box diagrams yields

$$\Gamma_{12}^D = -\lambda_s^2 \left(\Gamma_{ss}^D - 2\Gamma_{sd}^D + \Gamma_{dd}^D\right) + 2\lambda_s\lambda_b \left(\Gamma_{sd}^D - \Gamma_{dd}^D\right) - \lambda_b^2\Gamma_{dd}^D$$

$$\lambda_x = V_{cx}V_{ux}^*, \qquad \lambda_d \sim \lambda_s \sim \lambda, \qquad \lambda_b \sim \lambda^5, \qquad \lambda_d + \lambda_s + \lambda_b = 0$$

- The off-shell contribution from box diagrams yields

$$M_{12}^D = \lambda_s^2 \left[M_{ss}^D - 2M_{sd}^D + M_{dd}^D\right] + 2\lambda_s\lambda_b \left[M_{bs}^D - M_{bd}^D - M_{sd}^D + M_{dd}^D\right] + \lambda_b^2 \left[M_{bb}^D - 2M_{bd}^D + M_{dd}^D\right]$$

- Computing a single diagram

$$\lambda_s^2 \Gamma_{12}^{ss}/\Gamma_D \approx 3.7 \times 10^{-2} \approx 5.7\, y_D^{\rm exp}$$

- But combining everything together

$$y_D^{\rm HQE} \approx \lambda_s^2 \left(\Gamma_{12}^{ss} - 2\Gamma_{12}^{sd} + \Gamma_{12}^{dd}\right) \approx 1.7 \times 10^{-4}\, y_D^{\rm exp} \rightarrow \text{severe GIM cancellation !}$$

- To accommodate the data phase space dependent violations of duality of order 20 % is sufficient → no need in large non-perturbative effects

Lifetimes of the charm hadrons

- Experimental value of the D-meson lifetimes ratio

$$\left.\frac{\tau(D^+)}{\tau(D^0)}\right|_{\text{Exp.}} = \frac{(1040 \pm 7)\,\text{fs}}{(410.1 \pm 1.5)\,\text{fs}} = 2.536 \pm 0.019$$

- Heavy quark expansion (HQE)

$$\frac{1}{\tau} = \Gamma = \Gamma_0 + \frac{\Lambda^2}{m_Q^2}\Gamma_2 + \frac{\Lambda^3}{m_Q^3}\Gamma_3 + \frac{\Lambda^4}{m_Q^4}\Gamma_4 + \ldots$$

- Each of Γ_i is presented as

$$\Gamma_i = \underbrace{\left[\Gamma_i^{(0)} + \frac{\alpha_s}{4\pi}\Gamma_i^{(1)} + \frac{\alpha_s^2}{(4\pi)^2}\Gamma_i^{(2)} + \ldots\right]}_{\text{Perturbatively calculable part}} \times \underbrace{\langle O^{d=i+3}\rangle}_{\text{Nonperturbative matrix element}}$$

Lifetimes of the charm hadrons

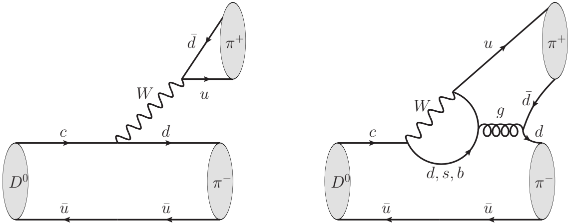
- Including $\Gamma_3^{(1)}$, $\Gamma_4^{(0)}$ [Lenz, Rauh, 1305.3588] and $\langle O^{d=6} \rangle$ from 3-loop HQET Sum Rules [Kirk, Lenz, Rauh, 1711.02100]

$$\left.\frac{\tau(D^+)}{\tau(D^0)}\right|_{\rm HQE} = 2.70^{+0.74}_{-0.82} = \left[1 + 16\pi^2 (0.25)^3 (1 - 0.34)\right]^{+0.74}_{-0.82}$$

  - ▷ $16\pi^2 \rightarrow$ loop enhancement factor
  - ▷ $(0.25)^3 \rightarrow$ HQE
  - ▷ 1 from dim-6
  - ▷ 0.34 from dim-7 (in the vacuum insertion approximation)

- Indicates an expansion parameter $\Lambda/m_c \approx 0.25 \ldots 0.34$
- HQE works reasonably well in computation of charm-hadron lifetimes!
- More prediction for lifetimes to come, next one is $\tau(D_s^+)/\tau(D^0)$

Theory of ΔA_{CP}



- The amplitude of the $D^0 \to \pi^+\pi^-$ decay

$$A(D^0 \to \pi^+\pi^-) = \lambda_d \left(A_{\rm Tree} + A^d_{\rm Peng}\right) + \lambda_s\, A^s_{\rm Peng} + \lambda_b\, A^b_{\rm Peng}$$

- Using unitarity of the CKM matrix

$$A \equiv \frac{G_F}{\sqrt{2}} \lambda_d\, T \left[1 + \frac{\lambda_b}{\lambda_d} \frac{P}{T}\right]$$

- Note that $\lambda_b/\lambda_d \sim \lambda^4 \ll 1 \quad \Rightarrow \quad$ small direct CP-asymmetry

Theory of ΔA_{CP}

- Branching fraction

$$\mathrm{BR} \propto \frac{G_F^2}{2} |\lambda_d|^2 |T|^2 \left| 1 + \frac{\lambda_b}{\lambda_d} \frac{P}{T} \right|^2$$

mostly given by the tree level amplitude T

- Direct CP-asymmetry

$$a_{CP}^{\mathrm{dir}} = \frac{-2 \left|\frac{\lambda_b}{\lambda_d}\right| \sin\gamma \left|\frac{P}{T}\right| \sin\phi}{1 - 2\left|\frac{\lambda_b}{\lambda_d}\right| \cos\gamma \left|\frac{P}{T}\right| \cos\phi + \left|\frac{\lambda_b}{\lambda_d}\right|^2 \left|\frac{P}{T}\right|^2} \approx -13 \times 10^{-4} \left|\frac{P}{T}\right| \sin\phi$$

sensitive to the differences of both strong and weak phases as well as P/T-ratio

Theory of ΔA_{CP}

- In the SM:

$$|\Delta A_{CP}| \approx 13 \times 10^{-4} \left| \left|\frac{P}{T}\right|_{K^+K^-} \sin\phi_{K^+K^-} + \left|\frac{P}{T}\right|_{\pi^+\pi^-} \sin\phi_{\pi^+\pi^-} \right|$$

- From naive estimate of $P/T \sim 0.1$:

$$|\Delta A_{CP}| \leq 2.6 \times 10^{-4}$$

- To be compared with the measurement

$$\Delta A_{CP}^{\mathrm{Exp}} = (-15.4 \pm 2.9) \times 10^{-4}$$

- To accommodate the experimental value one needs (at least)

$$\frac{P}{T} \sim 0.6$$

- Strong penguins? Or New Physics effects?

Light-cone sum rule (LCSR) prediction

[Khodjamirian, Petrov, 1706.07780]

- Tree level amplitudes T fixed from the data on

$$\begin{aligned} \mathrm{Br}(D^0 \to K^+ K^-) &= (3.97 \pm 0.07) \times 10^{-3} \\ \mathrm{Br}(D^0 \to \pi^+ \pi^-) &= (1.407 \pm 0.025) \times 10^{-3} \end{aligned}$$

- From LCSR for penquin amplitudes P (also their phases)

$$\left|\frac{P}{T}\right|_{\pi^+\pi^-} = 0.093 \pm 0.056, \qquad \left|\frac{P}{T}\right|_{K^+K^-} = 0.075 \pm 0.048$$

- Compatible with the naive estimate $P/T \sim 0.1$
- Relative strong phases not predicted (remain as arbitrary parameters)

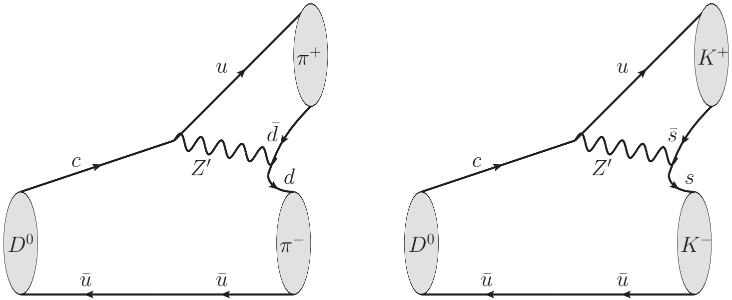
$$|\Delta A_{CP}| \leq (2.2 \pm 1.4) \times 10^{-4} \leq 3.6 \times 10^{-4}$$

- Uncertainty above is not just pure parametric one but also includes estimates of the higher twist effects, perturbative α_s corrections, etc.

New Physics?

- Consider an extension of the SM with Z'-boson

$$\mathcal{L}_{BSM} = \frac{1}{2} m_{Z'}^2 Z'_\mu Z'^\mu + Z'_\mu \left[g_{dd} \bar{d}_L \gamma^\mu d_L + g_{ss} \bar{s}_L \gamma^\mu s_L + (g_{cu} \bar{u}_L \gamma^\mu c_L + \text{h.c.}) \right]$$

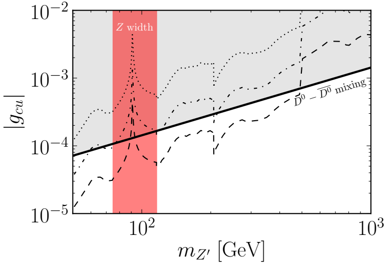


New Physics?

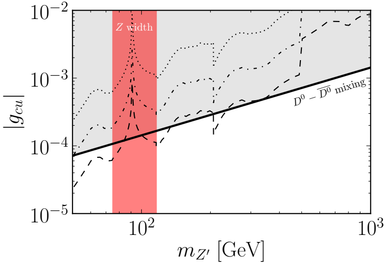
- Assuming that the whole effect originates in the K^+K^- final state

$$|g_{cu}| = \Delta_{NP} \frac{\sqrt{2} G_F \lambda_s m_{Z'}^2}{g_{ss}} \left(\left| \frac{A_{BSM}^s}{T} \right| \sin \delta_{BSM}^s \sin \phi_{BSM}^s \right)^{-1}$$

$$\Delta_{NP} = \Delta A_{CP}^{\mathrm{exp}} - \Delta A_{CP}^{\mathrm{SM}}$$



$\Delta_{\mathrm{NP}} = -11.8 \times 10^{-4}$



$\Delta_{\mathrm{NP}} = -6.0 \times 10^{-4}$

Conclusion

- Theory of charm decay is extremely complicated due to large (approx. 0.3) expansion parameters Λ/m_c and $\alpha_s(m_c)/\pi$ in combination with severe numerical cancellations
- Nevertheless, HQE looks promising in computation of charm-hadron lifetimes (albeit large uncertainties)
- To accommodate large exp. value one needs enhanced $(\mathcal{O}(10))$ penguins contributions in the SM
- A complete (including computation of both tree and penguin contributions and their relative phase) Standard Model prediction for ΔA_{CP} (based on non-perturbative method e.g. LCSR) is needed

Backup

$\Delta I = 1/2$ rule in $K \to \pi\pi$

- In the $K \to \pi\pi$ decays

$$\frac{A_0(K \to \pi\pi)}{A_2(K \to \pi\pi)} \approx 22.5$$

A_I – amplitude of the K-meson decay to two pions with isospin $I = 0, 2$

- Strong penguin contributions enhancing A_0?
- Lattice simulation: no enhancement of penguins contributions seen, but there are severe cancellations of tree level contributions [RBC and UKQCD Collab., 1212.1474, 1505.07863]
- The $\Delta I = 1/2$ rule does not motivate for penguin enhancement