SM predictions for charm CP violation

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Introduction

Why study charm?

- Many challenges ...
  - The charm quark is not very heavy $\alpha_s(m_c) \sim 0.33$ $\frac{\Lambda_{QCD}}{m_c} \sim 0.30$
  - There is little room for CP violation (CPV)
  - The GIM mechanism is highly effective $m_b, m_s, m_d \ll m_W$
- ... that are also opportunities
  - Important testing ground for QCD methods
  - High sensitivity to potential New Physics (NP) effects
  - Only possibility to study mixing in the up-type quark sector

Complementarity to K- and B-mixing

CPV in charm

- CP violating effects in charm decays are *small* in the SM

see e.g. review [Lenz, Wilkinson '20]

$$\lambda_d = -0.21874 + 2.51 \times 10^{-5} i \qquad \lambda_s = +0.21890 + 0.13 \times 10^{-5}\, i$$

$$\lambda_b = 6.3 \times 10^{-5} - 1.4 \times 10^{-4}\, i$$

$\lambda_q \equiv V_{cq}^* V_{uq}$

- Relevant CKM parameters are *real* to good approximation

λ_b has largest relative imaginary part, but is very small in magnitude

  - Strong sensitivity to CP violating NP contributions

Experimental status

- Discovery of CP violation in D^0 decays by LHCb [arXiv:1903.08726]

$$\Delta A_{\mathrm{CP}} \equiv A_{\mathrm{CP}}(K^-K^+) - A_{\mathrm{CP}}(\pi^-\pi^+) = (-15.4 \pm 2.9) \times 10^{-4}$$

$$\Delta a_{\mathrm{CP}}^{\mathrm{dir}} = (-15.7 \pm 2.9) \times 10^{-4}$$

- Measurement by LHCb of $A_{\mathrm{CP}}(K^-K^+)$
  - Combination with ΔA_{CP} gives [arXiv:2209.03179]

$$a_{\mathrm{CP}}^{\mathrm{dir}}(K^-K^+) = (7.7 \pm 5.7) \times 10^{-4} \qquad a_{\mathrm{CP}}^{\mathrm{dir}}(\pi^-\pi^+) = (23.2 \pm 6.1) \times 10^{-4}$$

$$a_{\mathrm{CP}}^{\mathrm{dir}}(f) \equiv \frac{\Gamma(D^0(t) \to f) - \Gamma(\overline{D}^0(t) \to \bar{f})}{\Gamma(D^0(t) \to f) + \Gamma(\overline{D}^0(t) \to \bar{f})}$$

Theoretical status

- Estimate of $\Delta a_{\rm CP}^{\rm dir}$ based on LCSR* largely deviates from data

  [Khodjamirian, Petrov '17; Lenz, MLP, Rusov '23]

  - Triggered NP analyses e.g. [Chala, Lenz, et al. '19; Dery, Nir '19]

- Study of rescattering effects using dispersive methods

  - Results for CPV below the experimental values

  [Pich, Solomonidi, Vale Silva '23]

$$\Delta A_{\rm CP}^{\rm exp} \overset{?}{\gg} \Delta A_{\rm CP}^{\rm SM}$$

*Light-cone sum rules [Balitsky, Braun, Kolesnischenko '89]

Theoretical status

- But also possibility to accommodate $\Delta A_{\rm CP}$ in the SM
  - Using U-spin relations and $\mathrm{SU}(3)_{\rm F}$ symmetry e.g. [Grossman, Schacht '19]
    - However, opposite sign for CP asymmetries *"U-spin anomaly"* e.g. [Bause, Gisbert, Hiller et al. '22; Schacht '23]
  - From analyses of topological amplitudes, or final state interactions e.g. [Li, Lü, Yu '19; Cheng, Chiang '19; Bediaga, Frederico, Megahlães '22]

$$\Delta A_{\rm CP}^{\rm exp} \overset{?}{\sim} \Delta A_{\rm CP}^{\rm SM}$$

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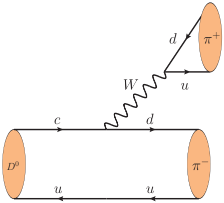
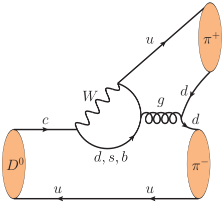
Big efforts towards unambiguous interpretation of experimental results

The SCS decays $D^0 \to \pi^+\pi^-$ *and* $D^0 \to K^+K^-$ *within LCSR*

The decay $D^0 \to \pi^-\pi^+$ *(and similarly for* $D^0 \to K^-K^+$*)*





- Theoretically very challenging, different topologies contribute
- From unitarity of CKM $\lambda_d + \lambda_s + \lambda_b = 0$ $\lambda_q = V^*_{cq} V_{uq}$

$$\mathcal{A}(D^0 \to \pi^-\pi^+) = \lambda_d\, \mathcal{A}_{\pi\pi} \left(1 - \frac{\lambda_b}{\lambda_d} \frac{\mathcal{P}_{\pi\pi}}{\mathcal{A}_{\pi\pi}}\right)$$

The decay $D^0 \to \pi^-\pi^+$ (and $D^0 \to K^-K^+$)

- Using $\lambda_b/\lambda_d \ll 1$, the branching ratio becomes

$$\mathcal{B}(D^0 \to \pi^-\pi^+) \simeq |\lambda_d|^2 |\mathcal{A}_{\pi\pi}|^2$$

- And the CP asymmetry

$$a_{\rm CP}^{\rm dir}(\pi^-\pi^+) \simeq 2\left|\frac{\lambda_b}{\lambda_d}\right| \sin\gamma \left|\frac{\mathcal{P}_{\pi\pi}}{\mathcal{A}_{\pi\pi}}\right| \sin\phi_{\pi\pi}$$

  - Sensitive to difference of weak and strong phases γ, $\phi_{\pi\pi}$, and $\left|\frac{\mathcal{P}_{\pi\pi}}{\mathcal{A}_{\pi\pi}}\right|$

- Similarly for $a_{\rm CP}^{\rm dir}(K^-K^+)$, but with opposite sign due to $\lambda_s \approx -\lambda_d$

Penguin amplitudes using LCSR

- Size of amplitudes $\mathcal{P}_{\pi\pi}, \mathcal{P}_{KK}$ determined using LCSR

  [Khodjamirian, Petrov '17]

- Values of $|\mathcal{A}_{\pi\pi}|, |\mathcal{A}_{KK}|$ extracted from precise data on $\mathcal{B}$

$$\mathcal{B}(D^0 \to \pi^+\pi^-)|_{\text{exp}} = (1.454 \pm 0.024) \times 10^{-3}$$

$$\mathcal{B}(D^0 \to K^+K^-)|_{\text{exp}} = (4.08 \pm 0.06) \times 10^{-3}$$

[PDG '24]

- Derived bound on $\Delta a_{\text{CP}}^{\text{dir}}$ assuming the SM

$$|\Delta a_{\text{CP}}^{\text{dir}}|_{\text{SM}} \leq 2.3 \times 10^{-4}$$

[Khodjamirian, Petrov '17]

- Can we obtain a prediction entirely in LCSR without using data?

And further test applicability of LCSR for these decays?

Decay amplitudes in naive factorisation

- Obtain predictions for branching fractions in NF [Lenz, MLP, Rusov '23]

$$\mathcal{B}(D^0 \to \pi^+\pi^-)\Big|_{\rm NF} = (1.90^{+0.28}_{-0.26}) \times 10^{-3} \qquad \mathcal{B}(D^0 \to K^+K^-)\Big|_{\rm NF} = (3.40^{+0.40}_{-0.35}) \times 10^{-3}$$

Using Lattice QCD for decay constants and form-factors

[FLAG '19]

$$\mathcal{B}(D^0 \to \pi^+\pi^-)|_{\rm exp} = (1.454 \pm 0.024) \times 10^{-3} \qquad \mathcal{B}(D^0 \to K^+K^-)|_{\rm exp} = (4.08 \pm 0.06) \times 10^{-3}$$

- Uncertainties only to the naive factorisation approximation

Errors not final, additional uncertainties not accounted

Estimate of $\Delta a_{\rm CP}^{\rm dir}$ *using LCSR*

- Compute tree-level topology for $\mathcal{A}_{\pi\pi}, \mathcal{A}_{KK}$ with 3-point LCSR

[Lenz, MLP, Rusov '23]

$$\frac{\mathcal{B}(D^0 \to K^+K^-)}{\mathcal{B}(D^0 \to \pi^+\pi^-)}\Big|_{\rm exp} = 2.81 \pm 0.06$$

$$\frac{\mathcal{B}(D^0 \to K^+K^-)}{\mathcal{B}(D^0 \to \pi^+\pi^-)}\Big|_{\rm LCSR} = 2.63 \pm 0.86$$

- The observed large $\mathrm{SU}(3)_F$ breaking is well reproduced

With no additional assumption on size of $\mathrm{SU}(3)_F$ breaking

- Combination with LCSR determination for $\mathcal{P}_{\pi\pi}$, $\mathcal{P}_{KK}$ gives

$$|\Delta a_{\rm CP}^{\rm dir}|_{\rm LCSR} \leq 2.4 \times 10^{-4}$$

- Same result as using precise experimental data

Possibility to account for correlations due to common framework/inputs

Conclusions

- Discovery of CP violation in D^0-meson decays
- Solid SM prediction needed for clear interpretation of the result
  - First estimate of leading penguin amplitude with LCSR [Khodjamirian, Petrov '17]
  - Use LCSR to also predict the branching ratios [Lenz, MLP, Rusov '23]
    - Determine $\Delta a_{CP}^{\rm dir}$ within the same framework
      Significant reduction of theory uncertainties
    - First step, additional contributions can be systematically included

Thanks for the attention