Applying LCSRs to CP violation in charm decays

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color meets flavor

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CP-violation in charm decays

- The (direct) CP asymmetry in singly-Cabibbo-suppressed (SCS) D - meson decays into two pseudoscalars

$$A_{CP}(P_1 P_2) = \frac{\Gamma(D \to P_1 P_2) - \Gamma(\overline{D} \to \bar{P}_1 \bar{P}_2)}{\Gamma(D \to P_1 P_2) + \Gamma(\overline{D} \to \bar{P}_1 \bar{P}_2)}$$

- SCS D^0 decays into two pions or kaons

Mode	$BR_{exp}\,[10^{-3}]$	$A_{CP}\,[10^{-3}]$	ref.
$D^0 \to \pi^+\pi^-$	1.454 ± 0.024	2.32 ± 0.61	LHCb'22
$D^0 \to K^+K^-$	4.08 ± 0.06	0.77 ± 0.57	LHCb'22
$D^0 \to \pi^0\pi^0$	0.826 ± 0.025	0 ± 60	[PDG aver.]
$D^0 \to K_S K_S$	0.141 ± 0.005	$62 \pm 30 \pm 20 \pm 8$	[CMS '24]
		$-3.7 \pm 7.8 \pm 2.9$	[LHCb'26 average]

- substantial evidence that $A_{CP}(\pi^+\pi^-) \neq 0$ and $A_{CP}(K_s K_s) \neq 0$

☐ CP asymmetry in Standard Model

- the effective Hamiltonian for *SCS* decays

$$\mathcal{H}_{eff}^{(SCS)} = \frac{G_F}{\sqrt{2}} \left\{ \sum_{q=d,s} \lambda_q \underbrace{\left[C_1(\mu) O_1^q + C_2(\mu) O_2^q \right]}_{\mathcal{O}^q_{(1,2)}} - \lambda_b \underbrace{\sum_{i=3,4,5,6,8g} C_i(\mu) O_i]}_{\mathcal{O}_{(P)}} \right\},$$

- combinations of CKM parameters

$$\lambda_q = (V_{uq} V_{cq}^*) \,, \quad (q = d, s), \qquad \lambda_b = (V_{ub} V_{cb}^*), \qquad |\lambda_b| \ll |\lambda_d| \simeq |\lambda_s|$$

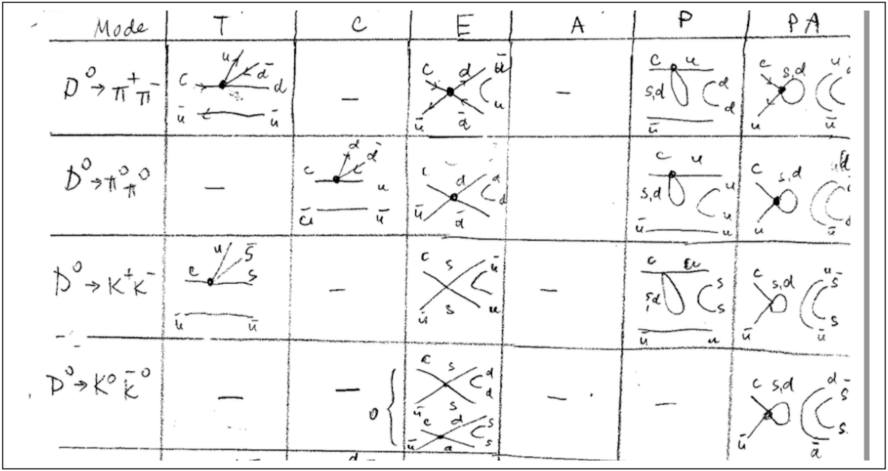
- CKM unitarity in SM: replacing $\lambda_d = -(\lambda_s + \lambda_b)$
- isolating the part of the amplitude with CKM-phase

$$\mathcal{A}(D \to P_1 P_2) = \frac{G_F}{\sqrt{2}} \Big\{ -\lambda_s \left[\langle P_1 P_2 | \mathcal{O}^d_{(1,2)} | D_{(s)} \rangle - \langle P_1 P_2 | \mathcal{O}^s_{(1,2)} | D_{(s)} \rangle \right]$$
$$- \lambda_b \left[\langle P_1 P_2 | \mathcal{O}^d_{(1,2)} | D_{(s)} \rangle + \langle P_1 P_2 | \mathcal{O}_{(P)} | D_{(s)} \rangle \right] \Big\}.$$

- $A_{CP}(P_1, P_2)$ easily calculated, knowing hadronic matrix elements
- but, calculating all of them in QCD is next to impossible

(interplay of topologies, nonfactorizable, $SU(3)$ broken, FSI, scalar resonances)

Quark topologies



- last update of T, C, E, A fit, H.-Y. Cheng and C.-W. Chiang, 2401.06316
- a long history, among very early papers: AK, Yad.Fiz. 30 (1979) 824-836
- nontrivial due to O_i mixing : A.Buras, L.Silvestrini , hep-ph/9812392,
- U-spin analysis (data driven) e.g., S. Schacht's 2405.09299
- combination of QCDf, symmetry and data R.Fleischer et al, 2512.10911

□ Minimizing calculable hadronic input

AK, A.Petrov, arXiv:1706.07780 [hep-ph].

- leave penguins alone !
- rearrange the $\sim \lambda_b$ part to include only "penguin topology"

$$A(D^0 \to \pi^+\pi^-) = -\lambda_s \mathcal{A}_{\pi\pi} \left\{ 1 + \frac{\lambda_b}{\lambda_s} \left(1 + \left| \frac{\mathcal{P}^s_{\pi\pi}}{\mathcal{A}_{\pi\pi}} \right| \exp(i\delta_\pi) \right) \right\},$$

$$A(D^0 \to K^+K^-) = \lambda_s \mathcal{A}_{KK} \left\{ 1 - \frac{\lambda_b}{\lambda_s} \left| \frac{\mathcal{P}^d_{KK}}{\mathcal{A}_{KK}} \right| \exp(i\delta_K) \right\},$$

- the notation:

$$\mathcal{A}_{\pi\pi} = \langle \pi^+\pi^- | \mathcal{O}^d_{(1,2)} | D^0 \rangle - \langle \pi^+\pi^- | \mathcal{O}^s_{(1,2)} | D^0 \rangle ,$$

$$\mathcal{A}_{KK} = \langle K^+K^- | \mathcal{O}^s_{(1,2)} | D^0 \rangle - \langle K^+K^- | \mathcal{O}^d_{(1,2)} | D^0 \rangle ,$$

- the "penguin" hadronic matrix elements:

$$\mathcal{P}^s_{\pi\pi} = \langle \pi^+\pi^- | \mathcal{O}^s | D^0 \rangle , \quad \mathcal{P}^d_{KK} = \langle K^+K^- | \mathcal{O}^d | D^0 \rangle ,$$

- the resulting CP asymmetry: (the same for kaons with $\pi \to K$)

$$A_{CP}(\pi^+\pi^-) = 2 \left| \frac{\lambda_b}{\lambda_s} \right| \sin\gamma \left(\left| \frac{\mathcal{P}^s_{\pi\pi}}{\mathcal{A}_{\pi\pi}} \right| \sin\delta_\pi \right) + O(\lambda_b^2) .$$

□ Why penguins alone are suffificent?

- a very accurate approximation:

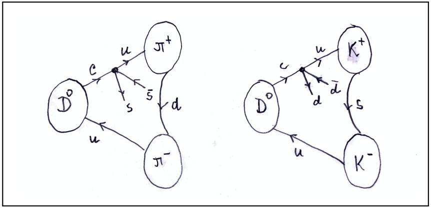
$$-\lambda_s \mathcal{A}_{\pi\pi} \simeq A(D^0 \to \pi^+\pi^-)\,, \;\; \lambda_s \mathcal{A}_{KK} \simeq A(D^0 \to K^+K^-)$$

- a calculation of $\mathcal{P}^s_{\pi\pi}$ and $\mathcal{P}^d_{KK}$ is necessary and suffficient,

$\mathcal{A}_{\pi\pi}$ and $\mathcal{A}_{KK}$ extracted from the measured branching fractions:

- a generic definition: in a "pengiun" hadronic matrix element
- there is a $\bar{q}q$ in the four-quark operator
- no flavour q in the valence content of the hadrons,

otherwise no relation to "topological (quark flow)" diagrams



- definition valid only if we use a method in which mesons or their intepolating currents have a definite valence content.

□ LCSR calculation of the penguin amplitude

AK, A.Petrov, arXiv:1706.07780 [hep-ph].

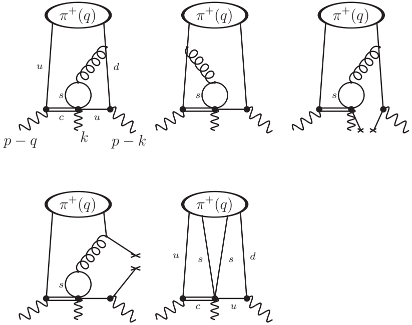
- the method formulated and used earlier for the $B \to \pi\pi$ decays

AK, Nucl.Phys. **B605**, 558, (2001),

AK, T. Mannel and B. Melic, Phys. Lett. B **571** (2003) 75

- correlation function for $D \to \pi^+\pi^-$ ($\pi \to K$, $s \leftrightarrow d$ for $D \to K^+K^-$)
- OPE diagrams

in terms of pion LCDAs:



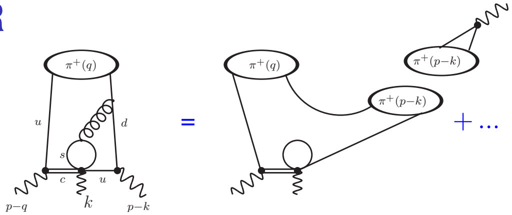
- some details:
- finite quark masses m_c, m_s
- $SU(3)$ not used, only isospin
- tw 2,3 accuracy, fact. tw 5,6
- selection of diagrams

(see eariler $B \to \pi\pi$ papers)

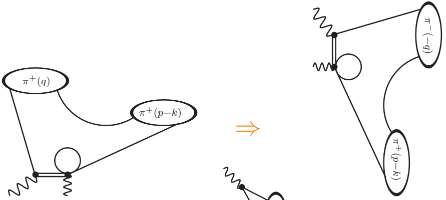
- LCSR's for $D \to \pi, K$ form factors

□ Obtaining LCSR

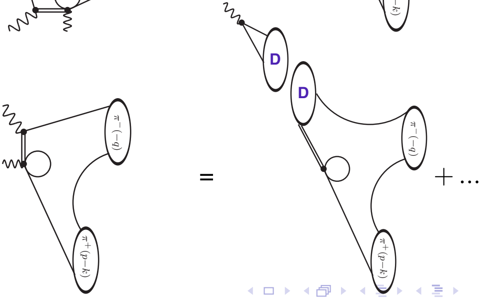
- step 1:
  Dispersion relation
  in the pion channel
  ⊕ duality



- step 2:
  Analytic continuation
  $P^2 = (p - q - k)^2 < 0 \Rightarrow \quad P^2 = m_D^2$



- step 3:
  Dispersion relation
  in the D channel ⊕
  duality



□ Results for CP asymmetry

AK, A.Petrov 1706.07780 [hep-ph]

- numerical results obtained from LCSRs:

$$|\mathcal{P}^s_{\pi\pi}| = (1.96 \pm 0.23) \times 10^{-7}\text{GeV}\,, \quad |\mathcal{P}^d_{KK}| = (2.86 \pm 0.56) \times 10^{-7}\text{GeV}\,,$$

- using measured branching fractions of $D \to \pi^+\pi^-$, and $D \to K^+K^-$ for $\mathcal{A}_{\pi\pi}$ and $\mathcal{A}_{KK}$:

$$\frac{|\mathcal{P}^s_{\pi\pi}|}{|\mathcal{A}_{\pi\pi}|} = 0.093 \pm 0.011\,, \qquad \frac{|\mathcal{P}^d_{KK}|}{|\mathcal{A}_{KK}|} = 0.075 \pm 0.015\,.$$

- the resulting upper limits: (independent of strong phases)

$$\left|A_{CP}(\pi^+\pi^-)\right| < 0.12 \pm 0.01 \times 10^{-3} \quad \left|A_{CP}(K^+K^-)\right| < 0.09 \pm 0.02 \times 10^{-3},$$
$$|\Delta A_{CP}| < 0.2 \pm 0.3 \times 10^{-3}\,.$$

- much smaller than the LHCb results especially for the pion mode:

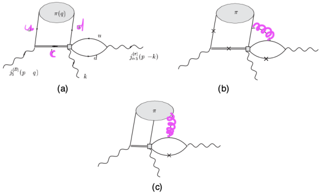
- LCSR estimate of the emission-topology amplitudes ($T \oplus C$) for $D \to PP$, in agreement with experiment

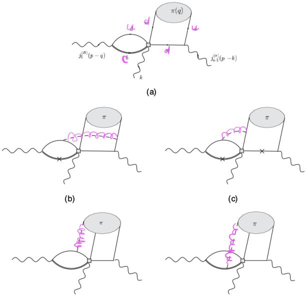
A. Lenz, M. L. Piscopo and A. V. Rusov, [arXiv:2312.13245 [hep-ph]].

□ Can we do more with LCSRs?

ongoing project with A.Bansal, E.Solomonidi and Th.Mannel

- LCSR diagrams for the emission and annihilation topologies,
used for $B \to \pi\pi$ in A.K., T. Mannel, M. Melcher and B. Melic, hep-ph/0509049
and easiliy transformed to $D \to P_1 P_2$ $(P_{1,2} = \pi, K)$





- aiming at the matrix elements of quark-penguin operators
(leading emission topology)

$$\mathcal{P}_{(\pi^+\pi^-)} = \langle \pi^+\pi^- | \mathcal{O}^s_{(1,2)} | D^0 \rangle + \langle \pi^+\pi^- | \mathcal{O}_{(P)} | D^0 \rangle$$

$$\mathcal{P}_{(K^+K^-)} = \langle K^+K^- | \mathcal{O}^d_{(1,2)} | D^0 \rangle + \langle K^+K^- | \mathcal{O}_{(P)} | D^0 \rangle \,,$$

Can we do more with LCSRs ?

- annihilation topology: factorizable (O_6), soft-gluon and hard-gluon contributions

- extend LCSR analysis to other $D \to P_1 P_2$ modes, first of all to $D^0 \to K_S K_S$

- try to merge LCSRs with alternative, purely hadronic and data-driven approach

A. Pich, E. Solomonidi and L. Vale Silva, [arXiv:2305.11951 [hep-ph]].

which yields both $A_{CP}(K^+K^-)$, $A_{CP}(\pi^+\pi^-)$ at the same level of 10^{-4}

- concluding:

tension between measured CP violation in certain D decays and theory remains and needs further hard work from the side of theory