Direct $\not{C}\!\!\not{P}$ in charm decays

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□ Single Cabibbo-Suppressed $D^0 \to h^+ h^-$ decays

$h^+ h^- = \pi^+\pi^-,\ K^+K^-;\ \pi^\pm\rho^\mp, K^\pm K^{*\mp}$

- The direct $\not{CP}$ asymmetry:

$$a_{CP}^{dir}(h^+h^-) = \frac{\Gamma(D^0 \to h^+h^-) - \Gamma(\bar{D}^0 \to h^-h^+)}{\Gamma(D^0 \to h^+h^-) + \Gamma(\bar{D}^0 \to h^-h^+)}$$

- In what follows: (see also the talk by S.Schacht)

- to obtain $a_{CP}^{dir}(h^+h^-)$ in SM, it is necessary and sufficient to calculate a single hadronic matrix element ("penguin amplitude").
- penguin amplitudes from QCD Light-cone sum rules (LCSR),
- how important are intermediate f_0 resonances in $D \to h^+h^-$?

□ Realization of direct $\not{CP}$ in $D^0 \to h^+ h^-$ decays

- Single Cabibbo-suppressed decays satisfy the conditions for direct $\not{C}$P:

$$A(D^0 \to h^+ h^-) = A_h^{(1)} e^{i\delta_1} e^{i\phi_1} + A_h^{(2)} e^{i\delta_2} e^{i\phi_2},$$
$$A(\bar{D}^0 \to h^- h^+) = A_h^{(1)} e^{i\delta_1} e^{-i\phi_1} + A_h^{(2)} e^{i\delta_2} e^{-i\phi_2},$$

the decay amplitude with two parts, weak $\phi_1 \neq \phi_2$ and strong $\delta_1 \neq \delta_2$ phases

- the asymmetry $$a_{CP}^{dir}(h^+ h^-) \sim \frac{A_h^{(1)}}{A_h^{(2)}} \sin(\delta_1 - \delta_2) \sin(\phi_1 - \phi_2).$$

- in more detail:

$$A(D^0 \to \pi^+ \pi^-) = \lambda_d \langle \pi^+ \pi^- | \mathcal{O}^d | D^0 \rangle + \lambda_s \langle \pi^+ \pi^- | \mathcal{O}^s | D^0 \rangle \,,$$
$$A(D^0 \to K^+ K^-) = \lambda_s \langle K^+ K^- | \mathcal{O}^s | D^0 \rangle + \lambda_d \langle K^+ K^- | \mathcal{O}^d | D^0 \rangle \,,$$

- SCS four-quark operators, a compact notation

$$H_{eff} = \underbrace{V_{ud} V_{cd}^*}_{\lambda_d} \underbrace{\frac{G_F}{\sqrt{2}} \left[c_1 \, (\bar{u} \Gamma_\mu d) \, (\bar{d} \Gamma^\mu c) + c_2 \, (\bar{d} \Gamma_\mu d) \, (\bar{u} \Gamma^\mu c) \right]}_{\mathcal{O}^d} + \{d \to s\}$$

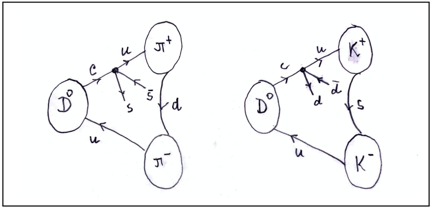
neglected $O_{i \geq 3}$ with $c_i \ll c_{1,2}$

"Penguin" amplitudes

- the "penguin" hadronic matrix elements:
  $\mathcal{P}^s_{\pi\pi} = \langle \pi^+\pi^-|\mathcal{O}^s|D^0\rangle\,, \quad \mathcal{P}^d_{KK} = \langle K^+K^-|\mathcal{O}^d|D^0\rangle\,,$

- 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.

□ Penguins in the direct *CP*-asymmetry

- CKM unitarity in SM: $\lambda_d = -(\lambda_s + \lambda_b)$, $\lambda_b = (V_{ub}V_{cb}^*) \ll \lambda_{s,d}$,
- separating the $O(\lambda_b)$ contribution with CP-phase

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

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

the notation: $\frac{\lambda_b}{\lambda_s} \equiv r_b e^{-i\gamma}$, $r_b = \left|\frac{V_{ub}V_{cb}^*}{V_{us}V_{cs}^*}\right|$.

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

$$r_\pi = \left|\frac{\mathcal{P}^s_{\pi\pi}}{\mathcal{A}_{\pi\pi}}\right|, \quad r_K = \left|\frac{\mathcal{P}^d_{KK}}{\mathcal{A}_{KK}}\right|, \quad \delta_{\pi(K)} = arg[\mathcal{P}^{s(d)}_{\pi\pi(KK)}] - arg[\mathcal{A}_{\pi\pi(KK)}]$$

- a "clean" observable (after time-integration)

$$\Delta a^{dir}_{CP} = a^{dir}_{CP}(K^+K^-) - a^{dir}_{CP}(\pi^+\pi^-) = -2r_b \sin\gamma(r_K \sin\delta_K + r_\pi \sin\delta_\pi) + O(r_b^2)\,.$$

- 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 sufffficient, combined with $\mathcal{A}_{\pi\pi}$ and $\mathcal{A}_{KK}$ extracted from experiment

□ Calculation of the “penguin” matrix elements

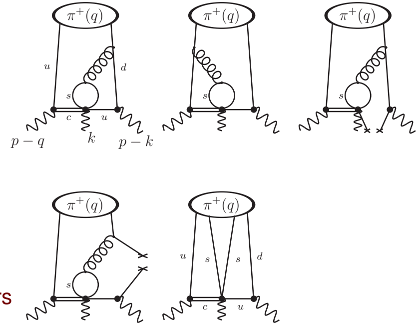
AK, A.Petrov Phys. Lett. B **774** (2017), 235 [arXiv:1706.07780 [hep-ph]].

- 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

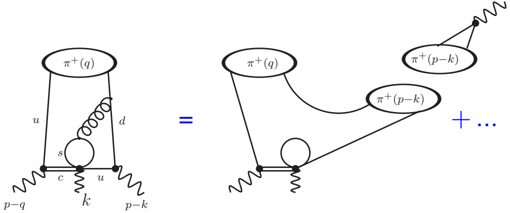
- correlation function for $D \to \pi^+\pi^-$ ($\pi \to K$, $s \leftrightarrow d$ for $D \to K^+K^-$)
- OPE diagrams
  in terms of pion LCDAs:



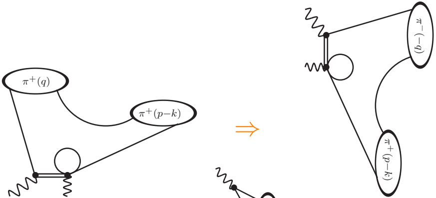
- some details:
  - finite quark masses m_c, m_s
  - $SU(3)$ not used, only isospin
  - tw 2,3 accuracy, fact. tw 5,6
  - selection of diagrams
    (see eariler $B \to \pi\pi$ papers)
  - LCSR’s for $D \to \pi, K$ form factors
- LCSR input: quark masses, pion, kaon DAs, parameters used in the LCSR calculation of $D \to \pi$, $D \to K$ and pion e.m. form factor

□ Obtaining LCSR

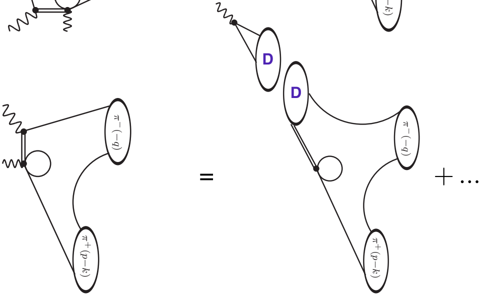
- **step 1:**
  Dispersion relation
  in the pion channel
  ⊕ duality



- **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 direct CP asymmetry

- numerical results obtained from LCSRs:

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

the uncertainties are only parametrical !

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

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

- CKM averages yield $r_b\, sin\gamma = 0.64 \times 10^{-3}$,
- the difference of asymmetries:

$$\Delta a^{dir}_{CP} = -2 r_b \sin\gamma (r_K \sin\delta_K + r_\pi \sin\delta_\pi)$$

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

$$\left|a^{dir}_{CP}(\pi^-\pi^+)\right| < 0.012 \pm 0.001\%, \quad \left|a^{dir}_{CP}(K^-K^+)\right| < 0.009 \pm 0.002\%,$$

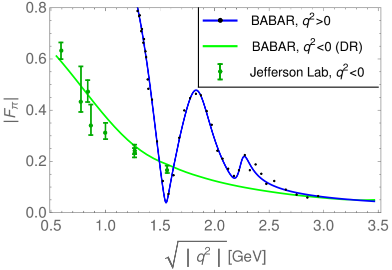
$$\left|\Delta a^{dir}_{CP}\right| < 0.020 \pm 0.003\%\,.$$

- much smaller than the LHCb collaboration result:

$\Delta a^{dir}_{CP} = (-0.154 \pm 0.029)\%$ R. Aaij *et al.* [LHCb], 1903.08726 [hep-ex] (2019)

□ Accuracy of the LCSR prediction

- parametric accuracy of LCSR: higher twists, perturbative corrections –need dedicated calculations,
- systematic errors from semilocal duality in π and D channels
  – controlled by the pion e.m. and $D \to \pi, K$ form factor LCSRs
- we do not calculate the total amplitude of $D \to \pi^+\pi^-, K^+K^-$ in which several "topologies" contribute,
- the strong phase difference is not yet accessible
- How accurate is the local duality approximation ?
- cf. the spacelike $\to$ timelike transition for the pion e.m. form factor:
- f_0 resonances $(J^P = 0^+, I = 0)$ near D_0 may locally enhance or suppress the effect (local duality violation)



[AK, S.Cheng, A.Rusov, 2007.05550]

□ How important are f_0 resonances ?

- $f_0(1710)$ enhances $\not{CP}$ S. Schacht, A. Soni , 2110.07619 (2021)
- in general:
  - hadronic unitarity and dispersion relation
  - intermediate states dominated by f_0 resonances

$$\mathcal{P}^s_{\pi\pi} = \int_{4m_pi^2}^{\infty} ds \frac{\mathrm{Im}\mathcal{P}^s_{\pi\pi}}{s - m_D^2} = \sum_{f_0} \frac{\langle \pi^+\pi^- | f_0 \rangle \langle f_0 | \widetilde{O}_2^s | D^0 \rangle}{m_{f_0}^2 - m_D^2 - i m_{f_0} \Gamma_{f0}}$$

- there are many f_0's:

  ' Five isoscalar resonances are established: the very broad $f_0(500)$, the $f_0(980)$, the broad $f_0(1370)$, and the comparatively narrow $f_0(1500)$ and $f_0(1710)$'

  [PDG minireview]

  in addition $f_0(2020)$ updated from the analysis of $B \to J/\psi\pi\pi$

  S. Ropertz, C. Hanhart and B. Kubis, 1809.06867

- taking them into account in the LCSR: model-dependent resonance ansatz fitted to the correlator in the spacelike region

Summary and outlook

- using QCD-based tools (QCD light-cone sum rules, quark-hadron duality) it is possible to estimate hadronic matrix elements for nonleptonic charm decays

- the magnitude of direct CP-violation in $D \to \pi^+\pi^-$ and $D \to K^+K^-$ was estimated; the result is significantly smaller than the latest LHCb result

Disclaimer:
- our calculation is not a "short-distance" one
- we do not "predict/confirm new physics" !

- future possibilities of LCSR applicaitons:
  - $D^0 \to \rho^\pm\pi^\mp, K^{*\pm}K^\mp$,
  - other $D_{(s)}$ modes including other topologies,
  - $\not{CP}$ in charmed baryon modes, (in progress)
  - including resonances, assessing the duality violation

- wishlist :
  - lattice QCD calculation of penguin amplitudes
  - f_0 resonances in the S-wave of $B^- \to \pi^+\pi^-\ell^-\bar{\nu}_\ell$
  - measuring direct CP asymmetries in $D^0 \to \rho^\pm\pi^\mp, K^{*\pm}K^\mp$

LOI submitted by Siegen group

Letter of Interest - SNOWMASS 2021
RARE PROCESSES AND PRECISION MEASUREMENTS
RF1: Weak decays of b and c quarks
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High Precision SM Predictions for Quark Flavor Observables

Guido Bell[(a)], Oscar Cata[(a)], Thorsten Feldmann[(a)], Tobias Huber[(a)], Alexander Khodjamirian[(a)], Wolfgang Kilian[(a)], Thomas Mannel[(a)], Björn Lange[(a)], Alexander Lenz[(a)], Jan Piclum[(a)], Alexei Pivovarov[(a)] and Oliver Witzel[(b)].

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Abstract

Quark flavor physics provides the possibility to search with precision measurements for effects of new particles that are beyond the direct reach of current accelerators. For the unambiguous identification of new physics effects a pro-