CP-symmetry violation in charm decays: QCD-based estimates

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CP violation: puzzles

- *CP*-violation in the quark-flavour sector of Standard Model (SM) is not sufficient for baryon asymmetry
- *CP*-violation due to $G^a_{\mu\nu}\widetilde{G}^{a\mu\nu}$ in QCD is strongly suppressed:
  e.d.m. bounds (axion?)
- most of BSM scenarios predict new *CP*-violating effects
- *CP*-violation in lepton sector ? (future neutrino studies)

to disentangle new sources of CP-violation we need accurate predictions of the CP-violating asymmetries in SM

CP violation in SM: challenges

- Source of *CP*-asymmetries in SM:
  - three generations of quarks:

$$\begin{pmatrix} U \\ D \end{pmatrix} = \begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$$

  - quark-flavour mixing in the weak interactions;

$$\mathcal{L}_W = \frac{g}{2\sqrt{2}} \sum_{U=u,c,t;D=d,s,b} \left(V_{UD} \bar{U} \Gamma_\mu D W^\mu + V^*_{UD} \bar{D} \Gamma_\mu U W^{\dagger\mu} \right)$$

  - unremovable complex phase in V_{UD} [Kobayashi,Maskawa]
- to observe the *CP*-asymmetries, one needs additional (*CP*-symmetric) phases of hadronic matrix elements in weak decays.
- *CP*-violating effects measured in kaon and *B*-meson decays,
- not yet in *D*-meson decays,
  predicted small in SM, but how small they should be?

Hadronic matrix elements in nonleptonic decays

- generally determined by QCD interactions in nonperturbative domain, especially difficult to assess their phases,
- QCD-based methods to calculate hadronic matrix elements ?
  - lattice QCD combined with ChPT:

recent promising results for kaon nonleptonic decays,

  - non-lattice approaches:

applicable for weak decays of heavy hadrons ($m_b, m_c \gg \Lambda_{QCD}$)

Direct *CP* asymmetry in charm decays

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

- the most straightforward *CP*-violation effect:
  difference of the decay widths of D and $\bar{D}$ mesons
- selected weak decay modes $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$:
- the width:

$$\Gamma(D \to P^+P^-) = \frac{p^*_{D\to PP}}{8\pi m_D^2}|A(D \to P^+P^-)|^2\,, \quad P = \pi, K\,.$$

$p^*_{D\to PP}$ - the decay 3-momentum in the D rest frame

- The asymmetry

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

Conditions for nonvanishing direct *CP*-asymmetry

- $a_{CP}^{dir}(P^+P^-) \neq 0$ is realized if the decay amplitude of $D \to f$ can be separated into at least two different parts,

$$A_f = A_f^{(1)} e^{i\delta_1} e^{i\phi_1} + A_f^{(2)} e^{i\delta_2} e^{i\phi_2},$$

$\phi_1 \neq \phi_2$ - the weak phases (odd under *CP*),
$\delta_1 \neq \delta_2$ - the strong phases (even under *CP*):

$$\bar{A}_{\bar{f}} = A_f^{(1)} e^{i\delta_1} e^{-i\phi_1} + A_f^{(2)} e^{i\delta_2} e^{-i\phi_2},$$

- The CP-violating asymmetry:

$$a_{\rm CP}^{\rm dir}(f) \sim \frac{A_f^{(1)}}{A_f^{(2)}} \sin(\delta_1 - \delta_2) \sin(\phi_1 - \phi_2).$$

- Such an amplitude pattern emerges,e.g.,
  in $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$
- Can we make a quantitative estimate of this asymmetry in SM?
  how small it should be in SM?

Single Cabibbo-suppressed (SCS) decays

- the effective Hamiltonian:

$$H_{eff} = \frac{G_F}{\sqrt{2}}\Big\{\lambda_d\big(c_1\ O_1^d + c_2\ O_2^d\big) + \lambda_s\big(c_1\ O_1^s + c_2\ O_2^s\big) - \lambda_b \sum_{i=3,\dots,6,8g} c_i O_i\Big\}\,,$$

$$O_1^d = (\bar{u}\Gamma_\mu d)\left(\bar{d}\Gamma^\mu c\right)\,,\ O_2^d = \left(\bar{d}\Gamma_\mu d\right)(\bar{u}\Gamma^\mu c) \underset{d\to s}{\Longrightarrow}\ O_1^s\,,\ O_2^s$$

$$\lambda_D = V_{uD}V^*_{cD},\ \ (D = d, s, b)\,,\qquad \lambda_b \ll \lambda_{s,d},\ \ \mathrm{Im}(\lambda_b) \neq 0$$

- the CKM unitarity in SM:

$$\sum_{D=d,s,b} \lambda_D = 0\,,\quad \text{or}\quad \lambda_d = -(\lambda_s + \lambda_b)\,.$$

- we hereafter neglect $O_{i\leq 3}$ with $c_i \ll c_{1,2}$

Decomposition of decay amplitudes

- separating the contributions of $O^d_{1,2}$ and $O^s_{1,2}$ operators

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

using a compact notation:

$$\mathcal{O}^D \equiv \frac{G_F}{\sqrt{2}} \sum_{i=1,2} c_i O_i^D \,, \quad (D = d, s) \,.$$

- replacing $\lambda_d = -(\lambda_s + \lambda_b)$
- "penguin" type amplitudes - the central object of our interest

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

"penguin" indicates that the operator contains a quark-antiquark pair not belonging to the valence content of final state,

Decomposition of decay amplitudes

- separating the $O(\lambda_b)$ contribution with CP-phase

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

where the notation:

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

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

- to a good approximation

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

The direct *CP*-asymmetry

- In terms of the parameters entering the decomposition:

$$a_{CP}^{dir}(K^+K^-) = \frac{-2r_b r_K \sin\delta_K \sin\gamma}{1-2r_b r_K \cos\gamma\cos\delta_K + r_b^2 r_K^2}\,,$$

$$a_{CP}^{dir}(\pi^+\pi^-) = \frac{2r_b r_\pi \sin\delta_\pi \sin\gamma}{1+2r_b\cos\gamma(1+r_\pi\cos\delta_\pi)+r_b^2(1+2r_\pi\cos\delta_\pi+r_\pi^2)}\,,$$

- the CKM elements involved

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

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

$$\begin{aligned}\Delta a_{CP}^{dir} &= a_{CP}^{dir}(K^+K^-) - a_{CP}^{dir}(\pi^+\pi^-)\\ &= -2r_b\sin\gamma(r_K\sin\delta_K + r_\pi\sin\delta_\pi) + O(r_b^2)\,.\end{aligned}$$

- a QCD-based calculation of $\mathcal{P}^s_{\pi\pi}$ and $\mathcal{P}^d_{KK}$
- combined with $\mathcal{A}_{\pi\pi}$ and $\mathcal{A}_{KK}$ extracted from experiment

  $\Rightarrow$ an estimate of r_π and r_K

Calculation of the "penguin" hadronic matrix element

- The method employing QCD Light-Cone Sum Rules (LCSRs) used earler for the $B \to \pi\pi$ decays:

  AK, Nucl. Phys. B ***605*** *(2001) 558 [hep-ph/0012271];*

  AK, T. Mannel and B. Melic, Phys. Lett. B ***571*** *(2003) 75 [hep-ph/0304179];*

  AK, T. Mannel, M. Melcher and B. Melic, Phys. Rev. D ***72*** *(2005) 094012 [hep-ph/0509049].*

- reproduce the magnitudes of branching fractions, also for penguin dominated $B \to K\pi$ modes

  M.Jung, AK, B.Melic, work in progress

Some details of the calculation

- the correlation function for $D \to \pi^+\pi^-$ case

$$F_\alpha(p,q,k) =$$
$$i^2 \int d^4x\, e^{-i(p-q)x} \int d^4y\, e^{-i(p-k)y} \langle 0|T\{j^{(\pi)}_{\alpha 5}(y) O^s_{1,2}(0) j^{(D)}_5(x)\}|\pi^+(q)\rangle$$

- sorting out the operators:

$$c_1 O^s_1 + c_2 O^s_2 = 2c_1 \widetilde{O}^s_2 + \left(\frac{c_1}{3} + c_2\right) O^s_2\,,$$

- the colour-octet operator provides dominant contribution

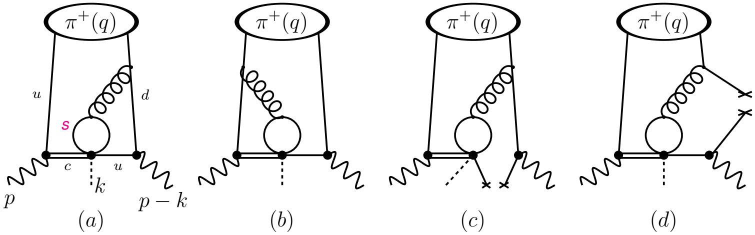
$$\widetilde{O}^s_2 = \left(\bar{s}\Gamma_\mu \frac{\lambda^a}{2} s\right)\left(\bar{u}\Gamma^\mu \frac{\lambda^a}{2} c\right)\,,$$

- the hadronic matrix element entering r_π :

$$\mathcal{P}^s_{\pi\pi} \simeq 2c_1 \frac{G_F}{\sqrt{2}} \langle \pi^+\pi^-|\widetilde{O}^s_2|D^0\rangle\,.$$

Some details of the calculation

- the dominant diagrams for $D \to \pi^+\pi^-$ case:



- The method, adapted to $D \to PP$ ($D = \pi, K$):
  - calculate a series of OPE diagrams in terms of light-cone distribution amplitude of pion(kaon)
  - interpolate the second pion(kaon) and D-meson by quark currents.
  - switch from the spacelike region of P^2 (artifitial 4-momentum $k \neq 0$) the final state invariant mass and analytically continue to $P^2 = m_D^2$, relying on the local quark-hadron duality

The light-cone sum rule

$$\langle \pi^+\pi^- | \widetilde{O}_2^s | D^0 \rangle = -i \frac{\alpha_s C_F m_c^2}{8\pi^3 m_D^2 f_D} \Bigg[\int_0^{s_0^\pi} ds e^{-s/M_1^2} \int_{u_0^D}^1 \frac{du}{u} e^{\left(m_D^2 - \frac{m_c^2}{u}\right)/M_2^2}$$

$$\times \Bigg\{ P^2 \int_0^1 dz I(zuP^2, m_s^2) \Bigg(z(1-z)\varphi_\pi(u)$$

$$+(1-z)\frac{\mu_\pi}{2m_c}\left[\left(2z + \frac{m_c^2}{uP^2}\right) u\varphi_p(u) + \frac{1}{3}\left(2z - \frac{m_c^2}{uP^2}\right)\left(\varphi_\sigma(u) - \frac{u\varphi'_\sigma(u)}{2}\right)\right]\Bigg)$$

$$-\frac{\mu_\pi m_c}{4} \int_0^1 dz I(-z\bar{u}m_c^2/u, m_s^2) \frac{\bar{u}^2}{u} \left[\left(1 + \frac{3m_c^2}{uP^2}\right)\varphi_p(1) + \left(1 - \frac{5m_c^2}{uP^2}\right)\frac{\varphi'_\sigma(1)}{6}\right]\Bigg\}$$

$$+\frac{2\pi^2}{3} m_c(-\langle \bar{q}q \rangle) \int_{u_0^D}^1 \frac{du}{u^2} e^{\left(m_D^2 - \frac{m_c^2}{u}\right)/M_2^2} \Bigg\{ I(uP^2, m_s^2) \Bigg(2\varphi_\pi(u) + \frac{\mu_\pi}{m_c}\Big[3u\varphi_p(u)$$

$$+\frac{\varphi_\sigma(u)}{3} - \frac{u\varphi'_\sigma(u)}{6}\Big]\Bigg)\Bigg\}\Bigg]_{P^2 \to m_D^2},$$

the loop integral: $I(\ell^2, m_q^2) = \frac{1}{6} + \int_0^1 dx x(1-x) \ln\left[\frac{m_q^2 - x(1-x)\ell^2}{\mu^2}\right]$.

Numerical estimates

- LCSR input: quark masses, pion, kaon DAs, Borel scales, effective thresholds from the LCSR calculation of $D \to \pi$, $D \to K$ and pion form factor
- the hadronic matrix element calculated from the sum rule

$$\langle \pi^+\pi^-|\widetilde{\mathcal{Q}}_2^s|D^0\rangle = (9.50 \pm 1.13) \times 10^{-3} \exp[i(-97.5^o \pm 11.6)]\,\mathrm{GeV}^3\,,$$
$$\langle K^+K^-|\widetilde{\mathcal{Q}}_2^d|D^0\rangle = (13.9 \pm 2.70) \times 10^{-3} \exp[i(-71.6^o \pm 29.5)]\,\mathrm{GeV}^3\,,$$

- converting to the estimate of the penguin amplitude:

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

- To predict the ratios r_K and r_π from our calculations we use the experimentally measured branching fractions from PDG, and obtain:

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

Comparing with experiment

- the CKM averages [PDG] yield $r_b\, sin\gamma = 0.64 \times 10^{-3}$,
  $|V_{ub}| = 0.00357$, $|V_{cb}| = 0.0411$, $|V_{us}| = 0.22506$, $|V_{cs}| = 0.97351$, $\gamma = 73.2^o$
- the difference of asymmetries: (indirect asymmetries largely cancel)

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

- we predict the upper limits: (independent of strong phases)

$$\left|a_{CP}^{dir}(\pi^-\pi^+)\right| < 0.012 \pm 0.001\%, \quad \left|a_{CP}^{dir}(K^-K^+)\right| < 0.009 \pm 0.002\%,$$
$$\left|\Delta a_{CP}^{dir}\right| < 0.020 \pm 0.003\%\,.$$

- Assuming that the phases δ_π and δ_K are given by the calculated phases of $\mathcal{P}^s_{\pi\pi}$ and $\mathcal{P}^d_{KK}$:

$$a_{CP}^{dir}(\pi^-\pi^+) = -0.011 \pm 0.001\%, \quad a_{CP}^{dir}(K^-K^+) = 0.009 \pm 0.002\%,$$
$$\Delta a_{CP}^{dir} = 0.020 \pm 0.003\%\,.$$

- The most recent LHCb collaboration result:

$$\Delta a_{CP}^{dir} = (-0.10 \pm 0.08 \pm 0.03)\%$$

R. Aaij *et al.* [LHCb Collaboration], PRL 116,191601 (2016)

Summary

- using QCD-based tools (QCD light-cone sum rules, quark-hadron duality) it is possible to estimate hadronic matrix elements for heavy hadron decays
- the magnitude of direct CP-violation in $D \to \pi^+\pi^-$ and $D \to K^+K^-$ can be predicted and constrained
- if more accurate future measurements of $\left|\Delta a_{CP}^{dir}\right|$ stay at the level of 0.1%, that may indicate a tension with SM
- future: extending the set of decay processes, improving the accuracy