CP violation in D decays to two pseudoscalars: A SM-based calculation

Eleftheria Solomonidi

In collaboration with Antonio Pich & Luiz Vale Silva

Instituto de Física Corpuscular-University of Valencia/CSIC

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C(ytryno-)P(omarańczowa) violation [Gierymski 1881]

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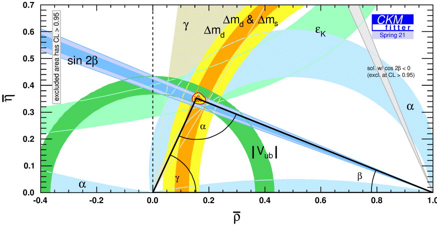
CP violation in D decays: just a SM system or gateway to New Physics?

$$\Delta A_{CP}^{exp} \equiv A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-) = (-1.54 \pm 0.29) \cdot 10^{-3}$$

$$\Delta A_{CP}^{dir,exp} = (-1.57 \pm 0.29) \cdot 10^{-3}$$ [LHCb 2019]

- Is the full SM theoretical prediction in agreement?

- Weak sector (CKM parameters) already probed by kaons, B mesons

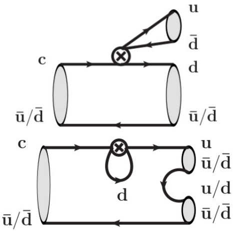


- Strong sector (hadronic uncertainties) problematic

CPV in D: the strong sector

- Does a beyond-naive estimation of hadronic effects matter?

$$A(D^0 \to f) = T(f) + i r_{CKM} P(f)$$
$$A(\overline{D^0} \to f) = T(f) - i r_{CKM} P(f)$$
$$a_{CP}^{dir} \approx 2 r_{CKM} \frac{|P(f)|}{|T(f)|} \cdot \sin\arg \frac{T(f)}{P(f)}$$
$$\left(r_{CKM} = Im \frac{V_{cb}^* V_{ub}}{V_{cd}^* V_{ud}}\right)$$

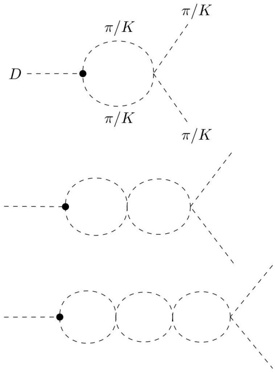


[Other approaches: 1506.04121, 1706.07780]

In K decays: Chiral Perturbation Theory. In B decays: HQET.
$\Lambda_{\chi PT} \approx m_\rho < m_D = 1865$ MeV, $\frac{\Lambda_{QCD}}{m_c} = \mathcal{O}(1)$
$\to$ neither approach would be valid in charm!

A way to look at the problem: rescattering

- Strong process, blind to T or P
- Isospin (u$\leftrightarrow$d) is a good symmetry of strong interactions
- In I=0, two channels:



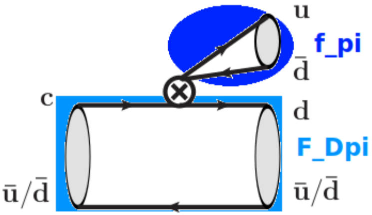
$$S_{strong} = \begin{pmatrix} \pi\pi \to \pi\pi & \pi\pi \to KK \\ KK \to \pi\pi & KK \to KK \end{pmatrix}$$

Rescattering & what we learn about strong phases

- S matrix is **unitary**, as well as strong sub-matrix (approximately)
- For I=0: $$\begin{pmatrix} A(D\to\pi\pi) \\ A(D\to KK)\end{pmatrix} = \underbrace{\begin{pmatrix} \eta e^{i2\delta_1} & i\sqrt{1-\eta^2}e^{i(\delta_1+\delta_2)} \\ i\sqrt{1-\eta^2}e^{i(\delta_1+\delta_2)} & \eta e^{i2\delta_2}\end{pmatrix}}_{S_{strong}} \cdot \begin{pmatrix} A^*(D\to\pi\pi) \\ A^*(D\to KK)\end{pmatrix}$$
- The phases are related to the rescattering phases **which are known from data/other experiments**
- Watson's theorem (elastic rescattering limit): $argA(D\to\pi\pi) = argA(\pi\pi\to\pi\pi) mod\pi$
- With inelasticities: more complicated, phase-shifts dependent on magnitudes of the amplitudes too

What about magnitudes?

- Does rescattering also affect the *magnitudes* of amplitudes, apart from the *phases*?
- An estimate for magnitudes: factorisation/large number-of-colors (N_C)



CKM $\times$ Wilson coefficient $\times$factorisation

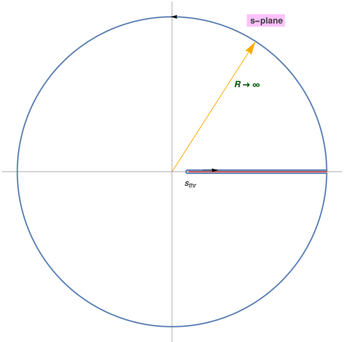
- Does not take rescattering into account
- Decay constant and form factor come from data

Basic property of scattering amplitudes: analyticity

- Fundamental, model-independent property related to **causality**
- Cauchy's theorem: $A(s) = \frac{1}{2\pi i} \oint_C ds' \frac{A(s')}{s'-s}$ leads to

$$ReA(s) = \frac{1}{\pi} \int_{s_{thr}}^{\infty} ds' \frac{ImA(s')}{s' - s}$$

(Dispersion relation)



- Unitarity of S-matrix & dispersion relation:

$$\underbrace{ReA(s)}_{\text{Re at a point}} = \frac{1}{\pi} \underbrace{\int_{s_{thr}}^{\infty} ds' \frac{\tan \delta(s')}{s' - s} ReA(s')}_{\text{integral of Re along the physical region}}$$

Analyticity & what we learn about magnitudes

- Integral equation, studied by Muskhelishvili-Omnes
- One subtraction: needs one piece of physical information
- Single channel case (& one subtraction at s_0), **physical** solution:

$$|A_I(s)| = A_I(s_0)\,\underbrace{exp\{\frac{s-s_0}{\pi} PV \int_{4M_\pi^2}^{\infty} dz \frac{\delta_I(z)}{(z-s_0)(z-s)}\}}_{\text{Omnes factor } \Omega}$$

We need more than just large N_C!

$|A_I(s=m_D^2)| = (\text{large } N_C \text{ result}) \times (\text{Omnes factor})_I$

- More channels: Equally more solutions. No analytical solution

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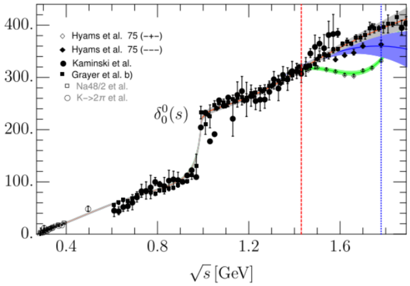
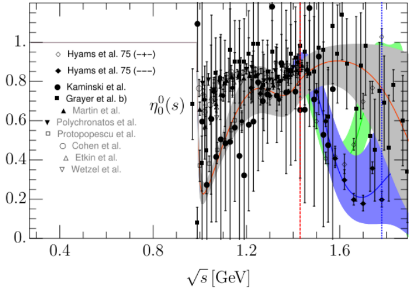
Summary of our method

- Separate CP-even (T) and odd (P) part
- Flavour basis to isospin
- Isospin blocks:
  - I=0 with 2 channels: $\pi\pi$ and KK
  - I=1 with KK elastic rescattering
  - I=2 with $\pi\pi$ elastic rescattering
- Isospin amplitudes treated with dispersion relations calculated numerically (based on Moussallam et al. [hep-ph/9909292])
- Physical input: unitarity (for integrand), large N_C limit (for polynomial ambiguity/subtraction point)

Data deployed: phase-shifts & inelasticities





- Rely on inelasticity and phase-shift parametrisations by others

  [Pelaez et al., 1907.13162],[Pelaez et al., 2010.11222]
- Parametrisations available up to energies $\sim m_D$ - extrapolate for higher & vary relevant parameters for uncertainties
- For I=1 and 2, extract Omnes factors from Br's of $A(D^+ \to \pi^+\pi^0) \sim A_{I=2}, A(D^+ \to K^+\overline{K^0}) \sim A_{I=1}$

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Omnes factors

For the isospin=0 channels we **calculate** numerically the Omnes matrix at $s = m_D^2$:

$$\Omega_{I=0} = \begin{pmatrix} -0.11 + 0.55i & -0.12 - 0.69i \\ 0.12 - 0.54i & -0.42 + 0.50i \end{pmatrix}$$

(In data: inelasticity taken from $\pi\pi$ rescattering)

The **physical solution** is

$$\begin{pmatrix} \mathbf{T}(D \to \pi\pi) \\ \mathbf{T}(D \to KK) \end{pmatrix} = \Omega_{I=0} \cdot \begin{pmatrix} \mathbf{T}_{\text{factorisation}}(D \to \pi\pi) \\ \mathbf{T}_{\text{factorisation}}(D \to KK) \end{pmatrix}$$

(Same for **P** instead of **T**)

It turns out:

Isospin=0 amplitudes are modified significantly compared to pure large-N_C/factorisation result!

Branching fration predictions

Decay channel	$\frac{Br_{theo}}{Br_{exp}}$
$D^0 \to \pi^+\pi^-$	~ 1
$D^0 \to \pi^0\pi^0$	~ 1
$D^0 \to K^+K^-$	~ 1
$D^0 \to K^0\overline{K^0}$	~ 1

- We *calculate* these based on our method (often extracted directly from fits)
- Can adjust $\delta^{\pi\pi}_{I=2}, \delta^{KK}_{I=1}$ so that all Br's are close to experiment

CP asymmetries

$\Delta A_{CP}^{dir,exp} = (-1.57 \pm 0.29) \cdot 10^{-3}$ [LHCb 2019]

We get $\Delta A_{CP}^{dir,theo} \leq \mathscr{O}(10^{-4})$!!

- Remember $a_{CP}^{dir} \approx 2 \underbrace{r_{CKM}}_{\sim 6 \cdot 10^{-4}} \underbrace{\frac{|P(f)|}{|T(f)|}}_{\text{needs be } \mathscr{O}(1)} \cdot \underbrace{\sin \arg \frac{T(f)}{P(f)}}_{\text{needs be close to 1}}$
- Wilson coefficients for penguin operators at least 10 times smaller than for T's
- We **do not** find a sufficient enough enhancement of P's

Summary

- SM approach deploying
  1. S-matrix unitarity, scattering amplitude analyticity, isospin symmetry and factorisation
  2. as much data as possible (rescattering, form factors and decay constants, Br's of D^+ decays)
- We succeed in calculating the branching fractions in reasonable agreement with experiment, from scratch
- We still estimate the CP asymmetry **an order of magnitude too small** compared to the experimental value!
- Preliminary results, but seems difficult to accommodate the current value in our SM calculation...

Thank you very much!

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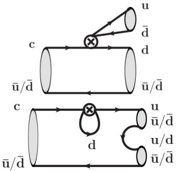
CPV in mesons: Direct vs indirect

$$A_{CP}(f) = \frac{\Gamma(D^0 \to f) - \Gamma(\overline{D^0} \to \overline{f})}{\Gamma(D^0 \to f) - \Gamma(\overline{D^0} \to \overline{f})}$$

$$\approx \frac{A(D^0 \to f) - A(\overline{D^0} \to \overline{f})}{A(D^0 \to f) - A(\overline{D^0} \to \overline{f})} + \frac{< t_f >}{\tau_{D^0}} a_{CP}^{ind}$$

- $A_\Gamma = -a_{CP}^{ind} = (-2.8 \pm 2.8) \cdot 10^{-4}$

D mesons: Parameters into play



- For the decay $D^0 \to \pi^+\pi^-$: apply unitarity of the CKM matrix
  $A(D^0 \to \pi^+\pi^-) = \lambda_d A_d + \lambda_b A_b$
  $\to a_{CP}^{dir} \sim |\lambda_d||\lambda_b||A_d||A_b| \sin arg \frac{V_{cd}^* V_{ud}}{V_{cb}^* V_{ub}} \cdot \sin arg \frac{A_d}{A_b}$

Relevant quantities

- Compare $m_D = 1865$ MeV to $\Lambda_{\chi PT} \approx m_\rho = 775$ MeV
- $\overline{m_c}(\overline{m_c}) = 1.278$ GeV

Isospin decomposition

- $\pi\pi$ states can have isospin=0,2. KK can have isospin=0,1.

$$\begin{pmatrix} A(\pi^+\pi^-) \\ A(\pi^0\pi^0) \\ A(K^+K^-) \\ A(K^0\overline{K}^0) \end{pmatrix} = \begin{pmatrix} 1/\sqrt{6} & -1/\sqrt{3} & 0 & 0 \\ \sqrt{2/3} & 1/\sqrt{3} & 0 & 0 \\ 0 & 0 & 1/2 & -1/2 \\ 0 & 0 & 1/2 & 1/2 \end{pmatrix} \begin{pmatrix} A_\pi^2 \\ A_\pi^0 \\ A_K^1 \\ A_K^0 \end{pmatrix}$$

Analyticity-Dispersion relations 2: Omnes solutions and properties

- Behaviour at ∞ determined by phase in integral: $A \to \frac{1}{s^n}$, $n = \frac{\delta(\infty)-\delta(s_{thr})}{\pi}$
- As many solutions as there are involved channels
- 2 channels: Omnes matrix $\begin{pmatrix} \Omega_{11} & \Omega_{12} \\ \Omega_{21} & \Omega_{22} \end{pmatrix}$ multiplied by appropriate polynomials

Large N_C limit

- $T_{fac}(D^0 \to \pi^+\pi^-) = \lambda_d C_1 \frac{G_F}{\sqrt{2}} F_0^{D\pi}(m_\pi^2) f_\pi \cdot (m_D^2 - m_\pi^2)$
- $P_{fac}(D^0 \to \pi^+\pi^-) =$ $\lambda_d (C_4 - 2C_6 \frac{M_\pi^2}{(m_u+m_d)(m_c+m_d)}) \frac{G_F}{\sqrt{2}} F_0^{D\pi}(m_\pi^2) f_\pi \cdot (m_D^2 - m_\pi^2)$
- $C_1 = 1.21$, $C_2 = -0.41$, $C_3 = 0.02$, $C_4 = -0.04$, $C_5 = 0.01$, $C_6 = -0.05$
- $\lambda_d = V_{cd}^* V_{ud} \approx 0.22$

Omnes numerical calculation