CP Violation in hadronic two-body charm-meson decays

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In collaboration with Antonio Pich and Eleftheria Solomonidi (IFIC, UV – CSIC)

based on 2305.11951 (PRD 108 (2023) 3, 036026), and upcoming work

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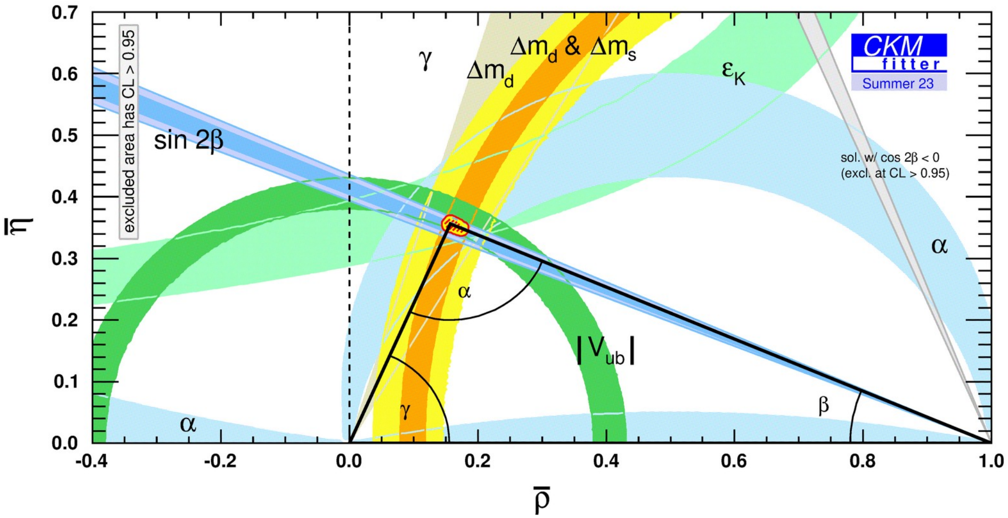
Charm-flavour physics

- Flavour physics of the **up-type**: complementary, but less well known than **down-type** strange and bottom sectors
  - QCD @ intermediate regime $M_K \ll m_c \ll m_b$ [consolidated theoretical tools for the two extrema, χPT_3 and HQET; slower behaviour of the $1/m_c$ perturbative series]
  - EW sector largely uncharted; more effective GIM mechanism: potential to identify BSM

- CKM: a single CP-odd phase responsible for CPV phenomena in all quark flavour sectors of the SM

b : $|V_{ub}|$, α, β, γ, Δm_d, Δm_s

s : ε_K



Measurement of direct CPV

- Major discovery by LHCb in 2019:

$$\Delta A_{CP} = A_{CP}(K^- K^+) - A_{CP}(\pi^- \pi^+) \neq 0$$

D^0 to $K^- K^+$ asym. D^0 to $\pi^- \pi^+$ asym.

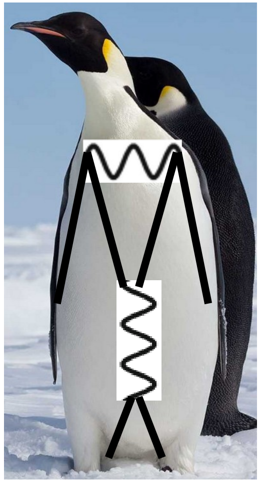
[I will neglect indirect CPV throughout this talk]

- Bounds in many other cases: $\pi^+\pi^-$ and K^+K^- (individually), $\pi^0\pi^0$, $\pi^+\pi^0$, $K_S K_S$, K^+K_S, etc.

[LHCb '22] [LHCb, BABAR, Belle, ...]

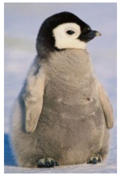
- Much progress is expected in this decade: LHCb Upgrade I and Belle II; about 3-fold better sensitivity to CPV in ΔA_{CP}

Direct CPV from "penguin topologies"



Present exp. sensitivity to penguins

LHCb UI



LHCb UII

Future exp. sensitivity to penguins

SM description of direct CPV

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- **Theory has to match experimental progress**

amplitude moduli (schematic)

$$A_{CP}^{i\to f} \equiv \frac{|\langle f|T|i\rangle|^2 - |\langle \bar{f}|T|\bar{i}\rangle|^2}{|\langle f|T|i\rangle|^2 + |\langle \bar{f}|T|\bar{i}\rangle|^2} \approx -2\frac{B}{A}\sin(\delta_1-\delta_2)\sin(\phi_1-\phi_2)$$

$$\mathcal{H}_{\rm eff} = \frac{G_F}{\sqrt{2}}\left[\sum_{i=1}^{2} \underbrace{C_i(\mu)\left(\lambda_d Q_i^d + \lambda_s Q_i^s\right)}_{\text{current-current operators}} - \lambda_b \sum_{i=3}^{6} \underbrace{C_i(\mu) Q_i}_{\text{penguin operators}}\right] + h.c.$$

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

(CKM factors)

μ~2 GeV for charm

[Buchalla, Buras, Lautenbacher '95]

- We need both strong-phase (=δ) and weak-phase (=ϕ) differences
- Strong-phases enhance A_{CP}, but also make its description more challenging
- **HERE**: discussion of non-perturbative QCD effects, their extraction from data, and physical impact on direct CPV in the charm sector

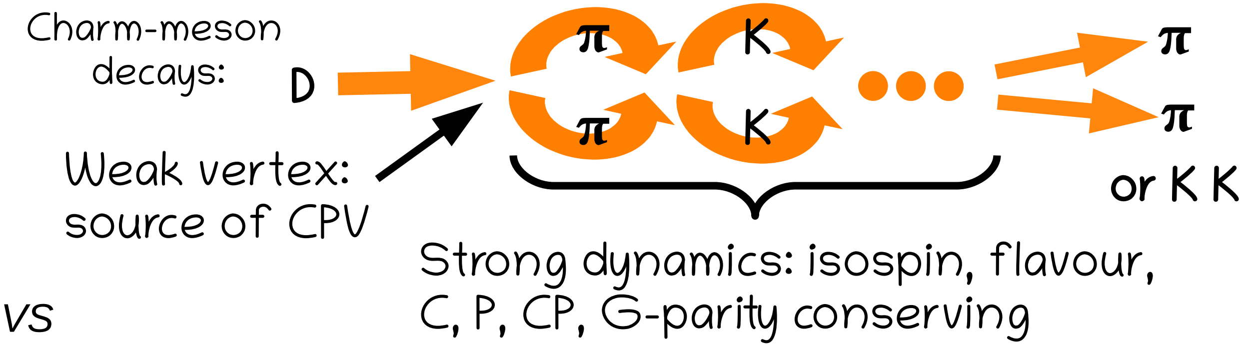
[see also: Brod, Grossman, Kagan, Zupan '12; Li, Lu, Yu '12; Franco, Mishima, Silvestrini '12; Cheng, Chiang '12; Khodjamirian, Petrov '17; Soni '19; Schacht, Soni '21; Lenz, Piscopo, Rusov '23; etc., etc.]

Rescattering in weak decays

- Rescattering among stable on-shell particles produces a CP-even (strong) phase; elastic limit: Watson theorem

$$\text{phase of the } \pi \text{ FF} = (\text{phase-shift } \pi\pi \to \pi\pi) \bmod 180^\circ\,, \quad @ \text{ elastic region above } \pi\pi \text{ threshold}$$

- Separate strong and weak dynamics; final-state rescattering in transition amplitude encoded in process-independent Ω
- Relate dispersive and absorptive parts based on **analyticity** of the amplitudes (Mandelstam variables)



(dispersive) (absorptive)

$$\mathrm{Re}[\Omega(s)] = \frac{1}{\pi}\int_{4M_\pi^2}^{\infty} \frac{\mathrm{Im}[\Omega(s')]}{s'-s}\,ds'$$

Dispersion Relation (DR) for Ω entering the transition amplitude

LVS

Omnes factor

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- Elastic limit, explicit solution of the integral equation:

[Muskhelishvili ‘46; Omnes ‘58]

Explicit solution to the DR (isospin=I, total angular mom.=J), once-subtracted @ s_0:

$$A^I_J(s) = \underbrace{\overline{A}^I_J(s)}_{\text{polynomial ambiguity}} \overbrace{\exp\{i\,\delta^I_J(s)\}}^{\text{Watson theorem}} \underbrace{\exp\left\{\frac{s-s_0}{\pi}\int_{4M_\pi^2}^{\infty}\frac{dz}{z-s_0}\frac{\delta^I_J(z)}{z-s}\right\}}_{\text{Omnes factor }|\Omega|}$$

Watson theorem

polynomial ambiguity
= subtraction constant

Omnes factor |Ω|:
behaviour dictated by δ

- **IR**: phase-shift and Omnes factor embody the effects of rescattering in the amplitudes of weak decays
- **UV**: polynomial ambiguity (analytical properties of Ω unchanged), requires some physical input [e.g., in K to ππ, employ χPT_3]

[Pallante, Pich ‘99 ‘00; Pallante, Pich, Scimemi ‘01; Gisbert, Pich ‘17]

Two-channel analysis of rescattering 6

- Inelastic case: set of integral equations (DRs) related by **unitarity**; no explicit solution known; DRs have to be solved numerically

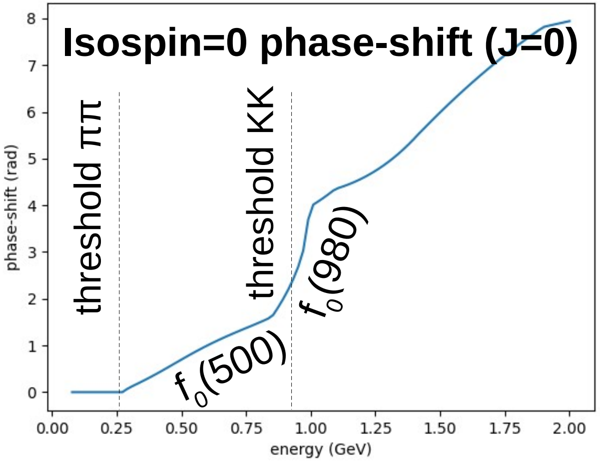
[Moussallam ‘00; Descotes-Genon ‘03]

$$R(s) = R(s_0) + \frac{s - s_0}{\pi} \int_{4M_\pi^2}^{\infty} ds' \frac{1}{s' - s} \frac{X(s') R(s')}{s' - s_0}$$

R: real part of amplitudes
X: 2-by-2 rescattering matrix
[X = tan(δ) in the elastic limit]

- Neglect the effect of further channels
- Experimental input for (ππ, KK) phase-shifts and inelasticity (ππ↔KK) in isospin=0 available

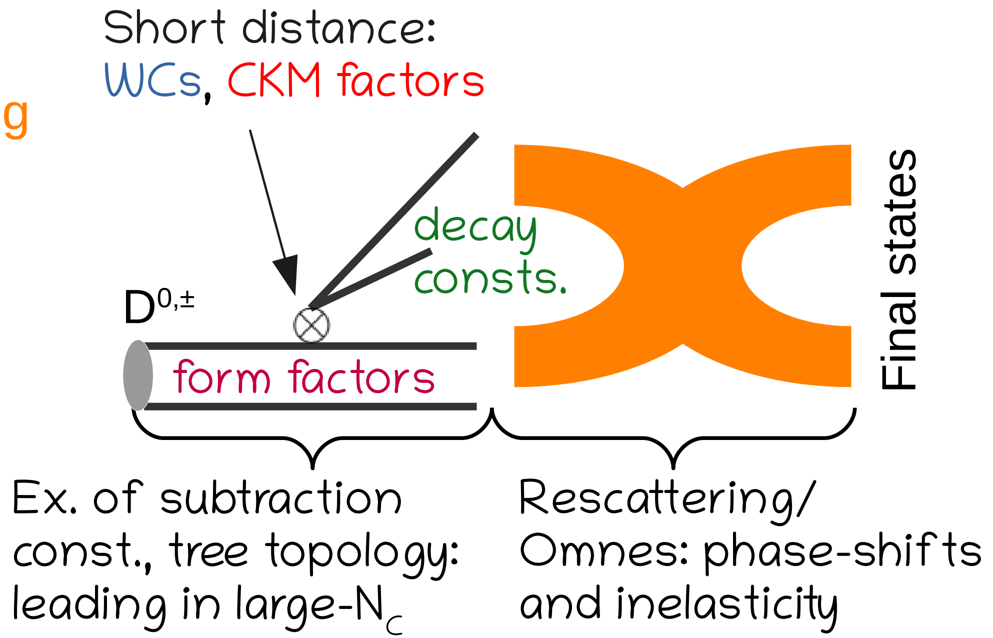
[Garcia-Martin, Kaminski, Pelaez, Ruiz de Elvira, Yndurain ‘11; Pelaez, Rodas, Ruiz De Elvira ‘19; Pelaez, Rodas ‘20][Buettiker, Descotes-Genon, Moussallam ‘04]



Further physical inputs

- Subtraction constant of DRs taken from large-N_C; improvement given by rescattering (sub-leading in large-N_C)
- Decay constants and form factors (independent sub-leading large-N_C effects)
- Large perturbative QCD effects $\alpha_s(\mu)*\log(\mu/M_W)$ are included in Wilson Coefficients (RGE improvement)

[Buras, Gerard, Rueckl ‘85; Bauer, Stech, Wirbel ‘86; Buras, Silvestrini ‘00; Mueller, Nierste, Schacht ‘15]



- Isospin analysis: information from D^+ to $\pi^+\pi^0$, K^+K_S branching ratios into D^0 decays; phase-shifts of final states with isospin=1 and =2 undetermined

CP-even amplitudes and BRs

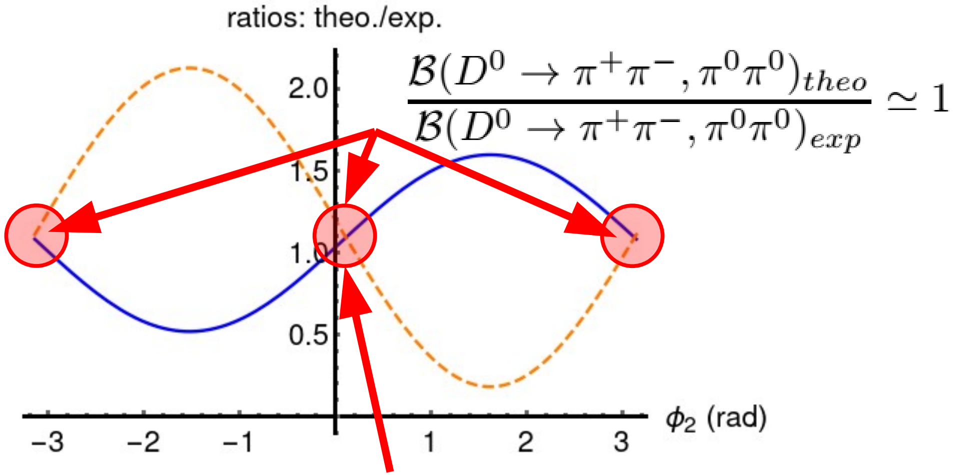
WCs , DCs , FFs , rescattering factors , and D^+ BRs

isospin decomposition: A_0^π , A_2^π , A_0^K , A_{11}^K , A_{13}^K

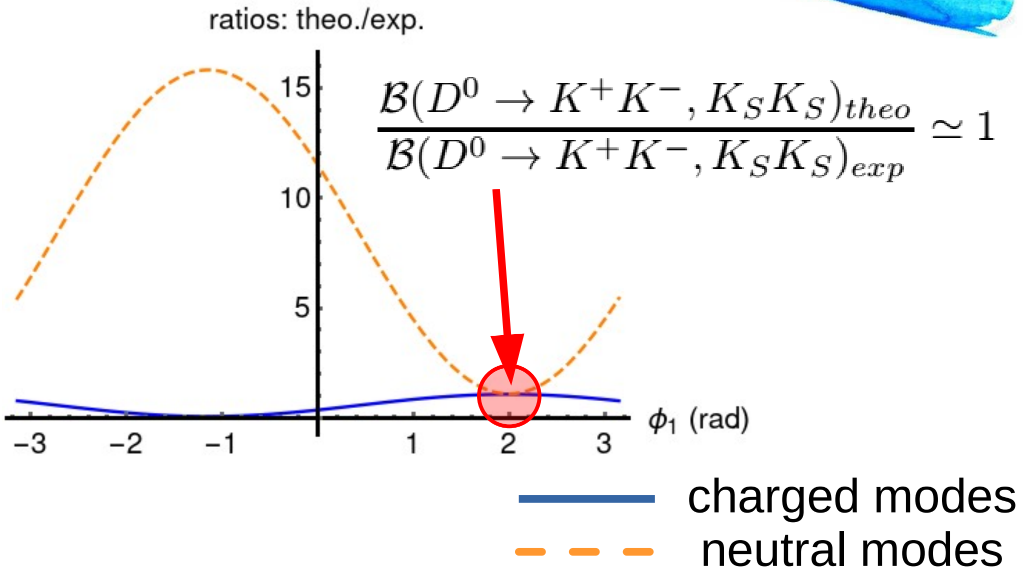
$\mathcal{B}(D^0 \to \pi^+\pi^-, \pi^0\pi^0)_{theo}$ $\mathcal{B}(D^0 \to K^+K^-, K_S K_S)_{theo}$

- **$BR_{theo} \sim BR_{exp}$** can be found; however, large uncertainties are present
- Inelasticity is the main source of uncertainties
- Use BRs to control uncs. of dispersive inputs: better prediction for A_{CP}

CP-even amplitudes and BRs



[favored by Durusoy et al. '73]



- Phase-shifts of final states with isospin=2 and =1 adjusted
- Isospin=0: source of breaking of symmetry between pions and kaons, of size similar to f_K/f_π & $F^{DK}/F^{D\pi}$
- Other sources of breaking: I=2 (from D^+ to $\pi^+\pi^0$), I=1 (from D^+ to K^+K_S)

Mechanisms of CPV

Isospin=0:

rescattering factors

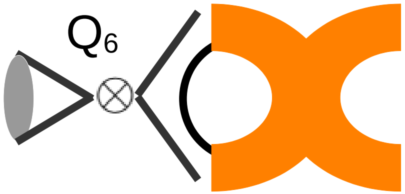
$$\begin{pmatrix} A_0^\pi + i\, B_0^\pi \\ A_0^K + i\, B_0^K \end{pmatrix} = \Omega(M_D^2) \begin{pmatrix} \lambda_d\, T_{\pi\pi}^{CC} - \lambda_b\, T_{\pi\pi}^{P} \\ \lambda_s\, T_{KK}^{CC} - \lambda_b\, T_{KK}^{P} \end{pmatrix}$$

CKM factors, WCs, DCs, FFs

similar expressions for I=2 (pions) and I=1 (kaons), which are treated elastically

- CPV from different interference terms between amplitudes
- I=0/I=0: possible due to rescattering;

  correlation in pions and kaons: CPV[ππ]+CPV[KK]=0
- I=0 interference with exotic states: I=2 (pions), I=1 (kaons)
- scalar+/-pseudoscalar structure: small WC, but enhanced



$$\frac{2\,M_\pi^2}{(m_u + m_d)\, m_c}\,, \quad \frac{2\,M_K^2}{m_s\, m_c} \sim 5$$

@ μ ~ 2 GeV

[cf. Li, Lu, Yu ‘12; Cheng, Chiang ‘12; Soni ‘19]

CP-odd amplitudes and CP asym.

WCs , DCs , FFs , rescattering factors , and BRs

isospin decomposition: $A_0^\pi\,,\ B_0^\pi\,,\ A_2^\pi\,,\ B_2^\pi\,,\quad A_0^K\,,\ B_0^K\,,\ A_{11}^K\,,\ B_{11}^K\,,\ A_{13}^K\,,\ B_{13}^K$

$$\Delta A_{CP}^{theo} \approx -2\,\Sigma_{i=K,\pi} \underbrace{\left(\frac{B_i}{A_i}\,\sin(\delta_1-\delta_2)\right)_i}_{\text{rescattering } \mathcal{O}(0.1)} \underbrace{\frac{\text{Jarlskog}}{|\lambda_d|^2}}_{=6.2\times10^{-3}} \sim -4\times10^{-4} \quad \ll \quad \Delta A_{CP}^{exp} \simeq -2\times10^{-3}$$

A_i, B_i: full amplitude moduli (schematic)

↑ mainly from D^0 to $\pi^+\pi^-$ [LHCb '22]

- Weak-phase: rephasing-invariant Jarlskog/$|\lambda_d|^2$ from <u>bottom & strange</u>
- Small CPV: rescattering effects not large enough
- It seems difficult to explain the measured CPV based on this approach

Summary & Conclusions

- **Data-driven approach**: isospin=0 rescattering effects through DRs; isospin=2 & isospin=1 rescattering effects from D^+ to $\pi^+\pi^0$, K^+K_S BRs

  subtraction constants given by large-N_C

- Exp. values of $\pi^+\pi^-$, $\pi^0\pi^0$ and K^+K^-, K_SK_S BRs used to control uncertainties

- Predicted CP asymmetries are too small

Outlook

- Constrain ΔA_{CP} based on unitarity, CPT and DRs
  [Pich, Solomonidi, LVS, in progress]
- Test use of DRs in Cabibbo allowed and doubly Cabibbo suppressed modes
  [Camarasa Domene, LVS, in progress]
- Complementary signs of CPV: look into decay modes with higher multiplicity → LHCb, Belle II, BESIII, STCF
- Apply DRs in the description of rare charm-meson decay modes
  [see Fajfer, Solomonidi, LVS, 2312.07501]

Many thanks!, *XièXie!*

Fit of isospin amplitudes

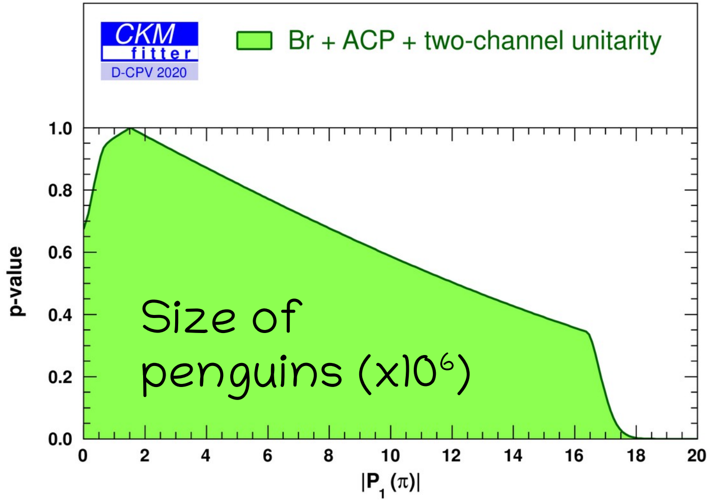
App 1

[not including LHCb ‘22]

isospin decomposition: $A_0^\pi\,,\ B_0^\pi\,,\ A_2^\pi\,,\quad A_0^K\,,\ B_0^K\,,\ A_{11}^K\,,\ B_{11}^K\,,\ A_{13}^K$ [Franco, Mishima, Silvestrini ‘12]

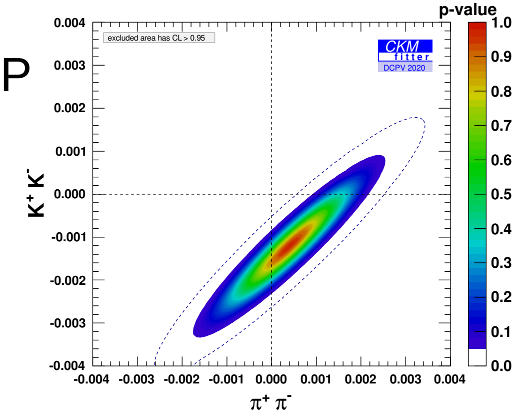
- Incorporate unitarity @ m_D only
- Amplitudes satisfy relations involving phase-shifts and inelasticity, that can be implemented in the isospin fit
- Fit includes also BRs and CP asyms.

Global fit combination of D to $\pi\pi$ and D to KK branching ratios & CP asymmetries



Penguin still largely unconstrained

Results for the CP asymmetries in charged modes



[for inclusion of phase-shifts and inelasticity @ m_D see also: Bediaga, Frederico, Magalhaes ‘22]

Operator basis and CPV

App 2

- One effect of CPV comes from non-unitarity of the 2-by-2 CKM sub-matrix; CP-odd contribution comes from loop topologies with insertions of current-current operators (light flavours in the loop, i.e., long-distance effect)
- WCs of penguin operators are tiny (aka GIM mechanism), but their contribution may be enhanced
- The quantity Q_{udcs} is rephasing-invariant and has an imaginary part, namely, the Jarlskog

μ	C_1	C_2	C_3	C_4	C_5	C_6
m_c	1.22	−0.40	0.021	−0.055	0.0088	−0.060
2 GeV	1.18	−0.32	0.011	−0.031	0.0068	−0.032

[Buchalla, Buras, Lautenbacher ‘95]

$$\lambda_d \lambda_s^* = V_{ud} V_{cs} V_{us}^* V_{cd}^* = Q_{udcs}$$

Implications of a Large Phase Shift

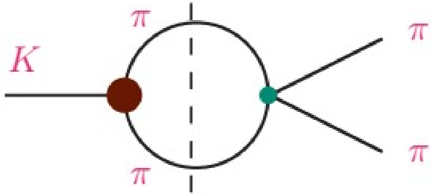
App 3

Slide from Antonio Pich, "Kaon decays & CP Violation", FPCP 2020 (virtual)

Important difference with charm physics: analogous kaon process is elastic; moreover, in charm, e.g.: $\arg(A_2^{\pi}/A_0^{\pi}) \sim \pm 90^{o}$

$$\mathcal{A}_I \equiv A_I\, e^{i\delta_I} = \mathrm{Dis}\,(\mathcal{A}_I) + i\,\mathrm{Abs}\,(\mathcal{A}_I)$$

❶ **Unitarity:** $\delta_0(M_K) = (39.2 \pm 1.5)^\circ$ ➡ $A_0 \approx 1.3 \times \mathrm{Dis}\,(\mathcal{A}_0)$



$$\tan\delta_I = \frac{\mathrm{Abs}\,(\mathcal{A}_I)}{\mathrm{Dis}\,(\mathcal{A}_I)}$$

$$A_I = \mathrm{Dis}\,(\mathcal{A}_I)\,\sqrt{1 + \tan^2\delta_I}$$

❷ **Analyticity:** $\Delta\,\mathrm{Dis}\,(\mathcal{A}_I)[s] = \frac{1}{\pi}\int dt\, \frac{\mathrm{Abs}\,(\mathcal{A}_I)[t]}{t - s - i\epsilon} + \text{subtractions}$

Large δ_0 ➡ Large $\mathrm{Abs}\,(\mathcal{A}_0)$ ➡ Large correction to $\mathrm{Dis}\,(\mathcal{A}_0)$