Direct CP Violation in hadronic two-body charm-meson decays

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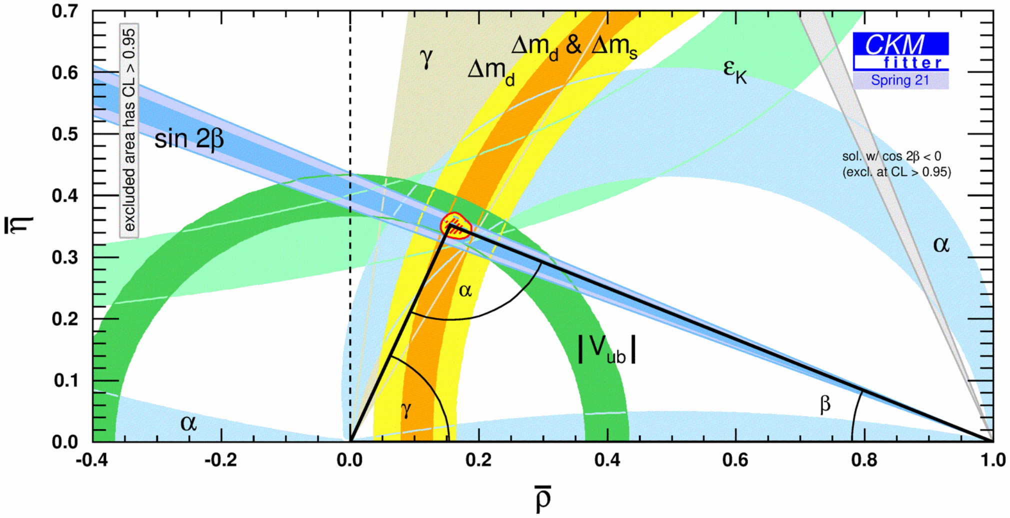
Charm-flavour physics

- Flavour physics of the **up-type**: complementary, but less well known than **down-type** strange and bottom sectors
  - QCD @ intermediate regime $m_K << m_c << m_b$ [consolidated theoretical tools for the two extrema, χPT_3 and HQET; $1/m_c$ converges more slowly]
  - EW sector largely uncharted; more effective GIM mechanism: potential for identifying BSM
- CKM: a single CP-odd phase responsible for CPV phenomena in all flavour sectors of the SM

b : $|V_{ub}|$, α, β, γ, Δm_d, Δm_s

s : ε_K



Measurement of direct CPV

②

- Major discovery by LHCb in 2019:

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

D to KK asym. D to $\pi\pi$ asym.

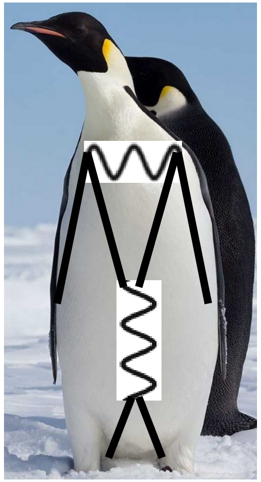
[I will neglect indirect CPV throughout this talk]

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

[LHCb, BABAR, Belle, ...]

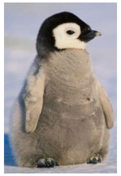
- Much progress is expected in this decade: LHCb Upgrade I and Belle II; about 3-fold better sensitivity to CPV in ΔA_{CP}

Direct CPV from “penguin topologies”



Present exp. sensitivity to penguins

LHCb UI



LHCb UII

Future exp. sensitivity to penguins

SM description of direct CPV ③

- **Theory has to match experimental progress**

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

amplitude moduli

$\lambda_q = V_{cq}^* V_{uq}$ (CKM factors)

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

[Buchalla, Buras, Lautenbacher '95]

μ~2 GeV for charm

- We need both strong-phase (=δ) and weak-phase (=ϕ) differences
- **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; Khodjamirian, Petrov '17; Soni '19; Grossman, Schacht '19; Chala, Lenz, Rusov, Scholtz '19; Schacht, Soni '21; ...]

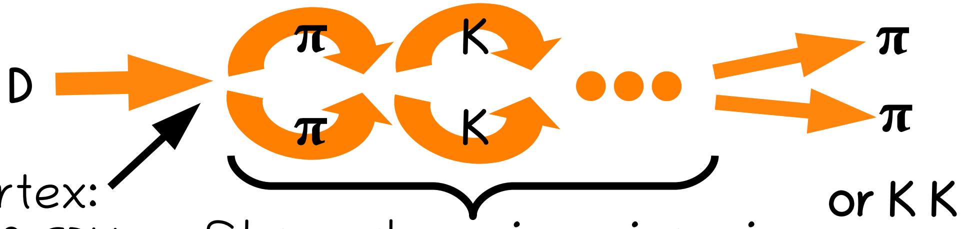
Rescattering in weak decays

- Strong and weak dynamics factorize (first order in weak interactions); <u>strong dynamics is blind to specifics of weak interactions</u>
- Rescattering among light stable final-state particles produces a CP-even (strong) phase; <u>elastic limit</u>: Fermi-Watson theorem

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

- Relate dispersive and absorptive parts based on analyticity of rescattering amplitude (Mandelstam variables)

Charm-meson decays:



Weak vertex: source of CPV

Strong dynamics: ≈isospin, flavour and CP conserving

(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

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:

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

Fermi-Watson theorem

polynomial ambiguity
= subtraction constant

Omnes factor Ω:
behaviour dictated by δ

- Phase-shift and Omnes factor embody the effects of rescattering in the amplitudes of weak decays
- Polynomial ambiguity (analytical properties 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]

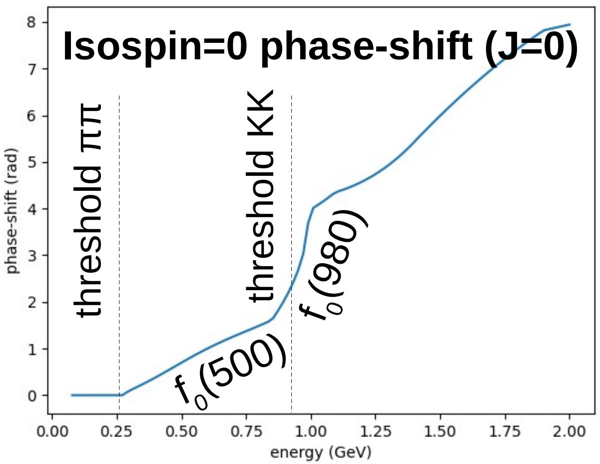
$$R(s) = R(s_0) + \frac{s-s_0}{\pi}\int_{4M_\pi^2}^{\infty} ds' \frac{1}{s'-s}\frac{X(s')R(s')}{s'-s_0}$$

R: real part of form factors
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 ("π↔K prob") in isospin=0 available

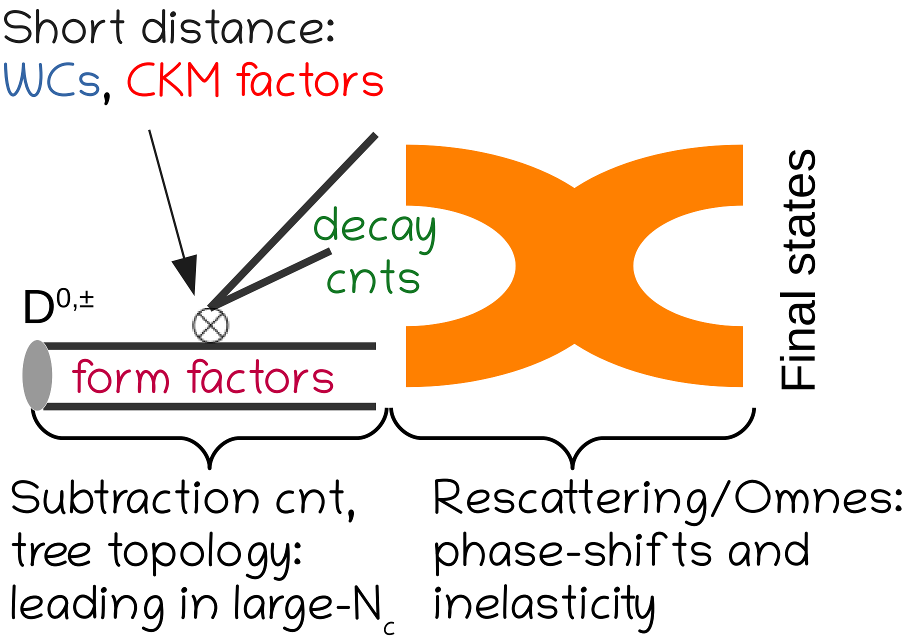
[Garcia-Martin, Kaminski, Pelaez, Ruiz de Elvira, Yndurain '11; Pelaez, Rodas, Ruiz De Elvira '19; Pelaez, Rodas '20][Buettiker, Descotes-Genon, Moussallam '04]



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 (include sub-leading effects in large-N_c)
- 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^+ into $\pi^+\pi^0$, K^+K_S branching ratios into D^0 decays; phase-shifts of final states with isospin=1 and =2 undetermined

Summary of results

- Predicted branching ratios are close to their experimental values, while CP asymmetries are small
- **Preliminary predictions**; ongoing: determination of error budget coming from phase-shift and inelasticity parameterizations
- Next: one particular set of input data for isospin=0 [inelasticity determined from pion-pion data]

CP-even amplitudes and BRs

WCs , DCs , FFs , rescattering factors

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

$$\frac{\mathcal{B}(D^0 \to \pi^+\pi^-, \pi^0\pi^0)_{theo}}{\mathcal{B}(D^0 \to \pi^+\pi^-, \pi^0\pi^0)_{exp}} \simeq 1\,, \qquad \frac{\mathcal{B}(D^0 \to K^+K^-, K_SK_S)_{theo}}{\mathcal{B}(D^0 \to K^+K^-, K_SK_S)_{exp}} \simeq 1$$

- Phase-shifts of final states with isospin=1 and =2 adjusted
- Right branching ratios ≡ CP-even amplitudes from isospin fit well reproduced
- Rescattering: another source of difference between pions and kaons, of size similar to f_K/f_π and $F^{DK}/F^{D\pi}$

[Franco, Mishima, Silvestrini ‘12]

CP-odd amplitudes and CP asym.

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$$\text{WCs}\;,\quad \text{DCs}\;,\quad \text{FFs}\;,\quad \text{rescattering factors}$$

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

$$\Delta A_{CP}^{theo} \approx -2\,\Sigma_{i=K,\pi} \underbrace{\frac{B_i}{A_i}\,\sin(\delta_1-\delta_2)_i}_{\text{rescattering } \mathcal{O}(0.1)} \underbrace{\frac{\text{Jarlskog}}{|\lambda_d|^2}}_{=6.2\times10^{-3}} \sim -\mathcal{O}(\text{few})\times 10^{-4}\,, \qquad \Delta A_{CP}^{exp} \simeq -2\times 10^{-3}$$

A_i, B_i: full amplitude moduli (schematic)

- Weak-phase: rephasing-invariant Jarlskog/$|\lambda_d|^2$ from bottom, strange and unflavoured
- Possible to have CPV from different interferences between amplitudes; no significant cancellation among different terms observed
- It seems difficult to explain the level of the measured CPV based on this approach

Conclusions

- **Data-driven approach**: isospin=0 rescattering effects through DRs, with subtraction constants given by large-N_c; isospin=1 & isospin=2 rescattering effects from D^+ into $\pi^+\pi^0$, K^+K_S BRs
- Right values for $\pi^+\pi^-$, $\pi^0\pi^0$ and K^+K^-, K_SK_S BRs
- CP asymmetries are too small
- Ongoing: error budget determination (main source: different parametrizations of the phase-shifts and inelasticity)

Many thanks!, Grazie mille!

BACK UP

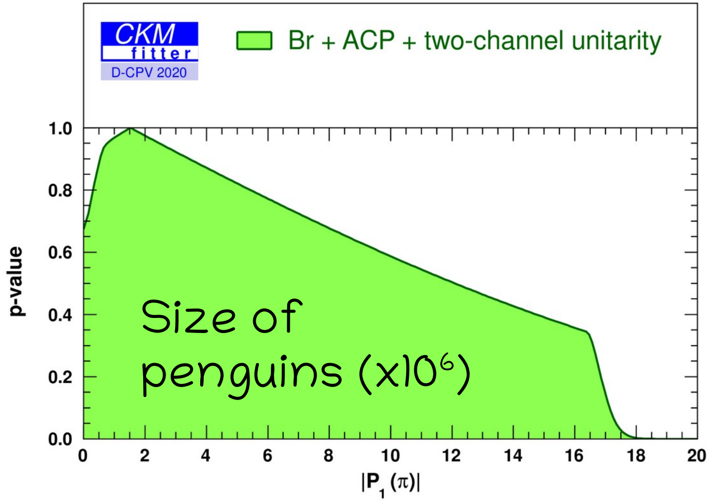
Fit of isospin amplitudes

App 1

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]

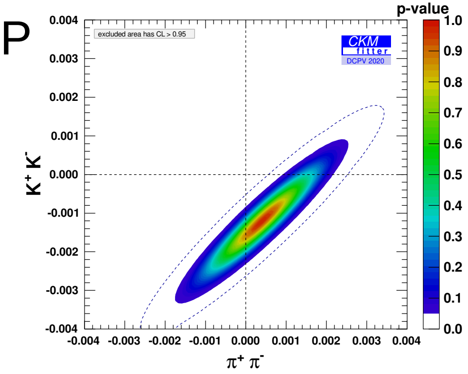
- Incorporate unitarity @ m_D only
- Amplitudes satisfy relations involving phase-shifts and inelasticity, that can be implemented in an isospin fit
- Fit includes also BRs and CP asyms.

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

App 2

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

	μ	z_1	z_2	v_3	v_4	v_5	v_6
NLO [Buras et al.]	1.3 GeV	1.21	−0.41	0.02	−0.06	0.02	−0.06
NLO [Buras et al.]	2 GeV	1.15	−0.31	0.01	−0.04	0.01	−0.03

[Buchalla, Buras, Lautenbacher '95]

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

[see also: Brod, Grossman, Kagan, Zupan '12; ...]

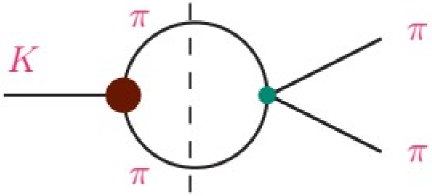
Slide from Antonio Pich, “Kaon decays & CP Violation”, FPCP 2020 (virtual)

Implications of a Large Phase Shift

App 3

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

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 $\mathrm{Dis}\,(\mathcal{A}_0)$

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