On large CP-violation in charm

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

$$= \begin{cases} -0.65(18)\cdot 10^{-2} & \text{World average} \\ -0.82(21)(11)\cdot 10^{-2} & \text{LHCb} \end{cases}$$

$$A_{\rm CP}^f \equiv \frac{\Gamma[D^0 \to f] - \Gamma[\bar{D}^0 \to f]}{\Gamma[D^0 \to f] + \Gamma[\bar{D}^0 \to f]}$$

Why difference $\Delta A_{\rm CP}$?

- time dependent part cancel
- experimental systematics cancel

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Overview

(A) $D^0 \Rightarrow \pi\pi/KK$

- topologies
- basics direct CP-violation
- why CP-violation ought to be small
- where to go with

theory: it's tough
(has always been)

↓

(B) $D^0 \Rightarrow V\gamma$ (CP-violation)

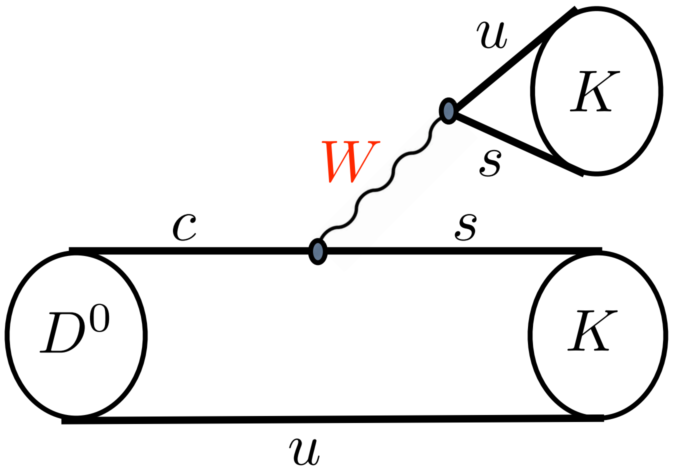
- topologies
- chromomagnetic operator large phase
- predictions
- outlook

theory: it's doable

Basic weak topologies of D→ππ/KK

- the flavour microscope (partly QCD blind) there two basic topologies

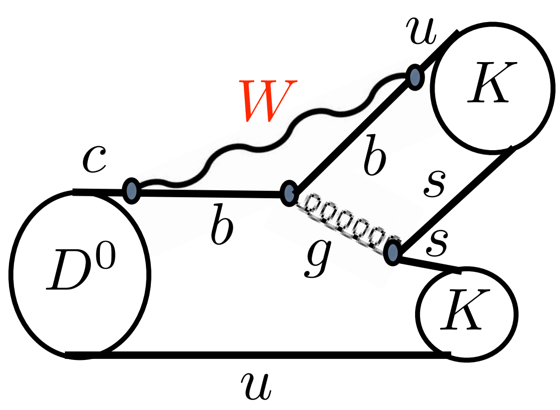
Tree T_s



$\sim \lambda_s T_s$

U-spin
$\pi \leftrightarrow K$
$d \leftrightarrow s$

Penguin P



$\sim \lambda_b P$

$\lambda_x \equiv V^*_{cx} V_{ux} \; , x = d, s, b$

Basics of (time indep.) CP-violation

strong phase (CP-even, cuts)

weak phase (CP-odd, CKM)

- generic amplitude and its CP transformed part read:

$$\begin{aligned} \mathcal{A}(B \to CD) &= A_1 e^{i\delta_1} e^{+i\phi_1} + A_2 e^{i\delta_2} e^{+i\phi_2} + \ldots \\ \bar{\mathcal{A}}(\bar{B} \to \bar{C}\bar{D}) &\sim A_1 e^{i\delta_1} e^{-i\phi_1} + A_2 e^{i\delta_2} e^{-i\phi_2} + \ldots \end{aligned}$$

- $A_{\rm CP} \sim |\mathcal{A}|^2 - |\overline{\mathcal{A}}|^2 \Rightarrow$ CP-violation if (at least) two amplitudes

$$\boxed{\mathcal{A}_{\rm CP} = \frac{2\Delta \sin(\delta_1 - \delta_2)\sin(\phi_1 - \phi_2)}{1 + 2\Delta\cos(\delta_1 - \delta_2)\cos(\phi_1 - \phi_2) + \Delta^2}} \qquad \Delta \equiv \frac{A_2}{A_1}$$

- 3 ingredients: 1) weak & 2) strong phase difference & 3) sizeable Δ

CP-violation in charm (c⇒u transitions)

- generic: - expect δ large through ππ/KK-rescattering (*uncalculable*)
  - b-quark decouples (*CKM hierarchy*) ⇒ small CP-violation in SM

1. decouple? $|\lambda_b| : |\lambda_{d,s}| \simeq 1 : 6 \times 10^{-4}$, (Recall: $\lambda_x \equiv V_{cx}^* V_{ux}$)
2. unitarity: $\lambda_d + \lambda_s + \lambda_b = 0$, $\Rightarrow$ $\lambda_d \simeq -\lambda_s$, weak-alignment

- $\Delta A_{CP}=0.6\times 10^{-2}$ is larger than 6×10^{-4}, but not than much ⇒ retain b-quark

$$\mathcal{A} = \lambda_b a_b + \lambda_s a_s + \lambda_d a_d = \lambda_b(a_b - a_d) + \lambda_s(a_s - a_d) = \lambda_b(P - T_d) + \lambda_s(T_s - T_d)$$

Penguin & Tree topologies

$$\boxed{\Delta A_{\rm CP} = 2\Delta \underbrace{\sin\gamma}_{\simeq 0.9}\ \underbrace{\sin\delta}_{\text{"large"}} + \mathcal{O}(\Delta^2)\ , \quad \Delta = \underbrace{\left|\frac{\lambda_b}{\lambda_s}\right|}_{6\times 10^{-4}} \underbrace{\left|\frac{P - T_d}{T_s - T_d}\right|}_{x_H}}$$

- $\Delta A_{CP}=0.6\times 10^{-2}$ ⇒ $x_H \approx 5$; $x_H = P/T \approx \alpha_s(m_c)/\pi \approx 0.1$ other ways 0.3 ⇒ **puzzle(d)**

Where to go from here

If $\Delta A_{CP}=0.6\times 10^{-2}$ remains

SM ("unexpected" dynamics)
À la $\Delta I=1/2$-rule $K \Rightarrow \pi\pi$

BSM: Generic $H^{eff}(c \Rightarrow u)$ with $\Delta I=1/2$ & $3/2$

investigate constraints (Isidori, Kamenik, Ligeti, Perez'1

e.g. D^0-mixing $\Delta c=1$, ε'/ε $\Delta s=1$
a favourite emerged: "enhance penguin" $\Delta I = 1/2$

Isospin tests $\Delta I=3/2$-case (Grossman, Kagan, Zupan'12)

$$A_{\rm CP}(D^+ \to \pi^+\pi^0) = \begin{cases} 0 (SM \ \& \ a_{1/2}^{BSM}) \\ a_{3/2}^{BSM} \end{cases}$$

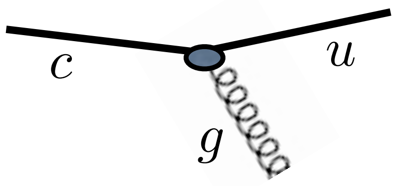
models give rise to it

effects elsewhere

rest talk

Let's name the suspect

- chromomagnetic operator



$$H^{\text{eff}} = \frac{G_F}{\sqrt{2}} C_8 \mathcal{O}_8 + \ldots \qquad \mathcal{O}_8' \equiv -\frac{g m_c}{2\pi^2} \, \bar{u} \sigma \cdot G c_{LR}$$

$$C_8^{\text{SM}} \simeq (0.3 - 0.8i) \cdot 10^{-5} \quad C_8'^{\text{SM}} \simeq \frac{m_u}{m_c} C_8^{\text{SM}}$$

$$\Delta A_{\text{CP}} = -0.6 \cdot 10^{-2} \Rightarrow \text{Im}[C_8^{\text{NP}} - C_8'^{\text{NP}}] \sin\delta = 0.3 \cdot 10^{-2}$$

Have introduced new weak (CP-odd) phase that accounts for ΔA_{CP}=-0.6×10^{-2} in naive factorisation and is not in conflict with any other experimental data.

- effects elsewhere: -- prime candidate: CP-violation -- look strong phase!
  - electric dipole moment (Giudice Isidori, Paradisi '12)
  - $A_{CP}(D^0 \Rightarrow \rho^0/\omega\gamma)$ indirect through O_7 (Isidori, Kamenik '12)
  - time dependent & direct through O_8 & $A_{CP}(D^+ \Rightarrow V^+\gamma)(t)$ (Lyon, RZ '12)

D⇒Vγ under the microscope

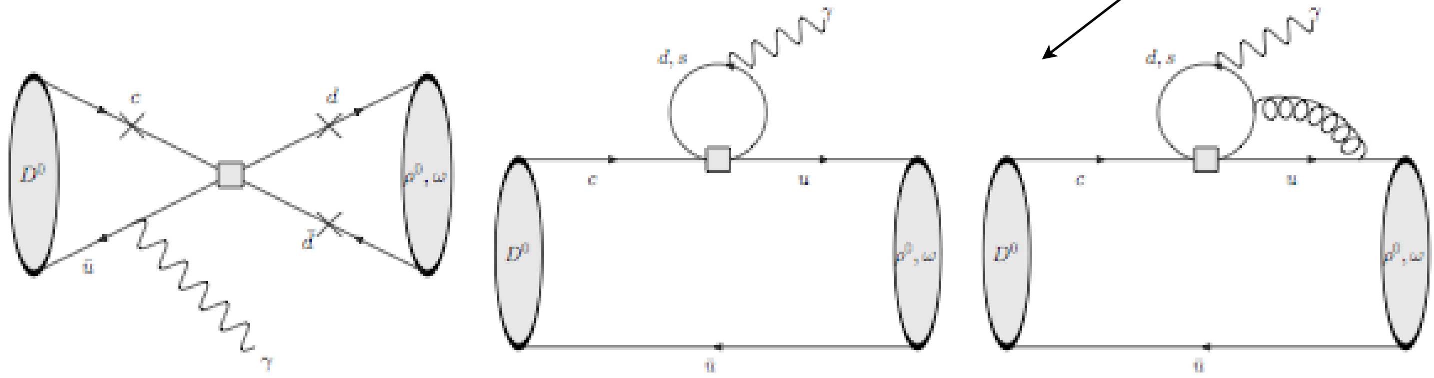
- Consensus: B⇒Vγ short distance (SD) dominated (penguin)

  D⇒Vγ long distance (LD) dominated

Why? -CKM-hierarchies
-large top mas

our view

A)



same Wilson coeff.
CKM-factors

Weak Annihilation (WA)	*Quarkloops (QL)*	
tree	1-loop	2-loop
1	0 gauge invariance	ca 10^{-2}

B) Computation LO α_s WA: 1) approx. saturates known rates $D^0 \Rightarrow \bar{K}^{*0}\gamma$, $D^0 \Rightarrow \phi\gamma$

2) chiral limit & no strong phase by virtue of $\partial \cdot J_{weak} = 0$

delicate colour suppressed
(enhanced NLO?)

In search of interfering amplitude

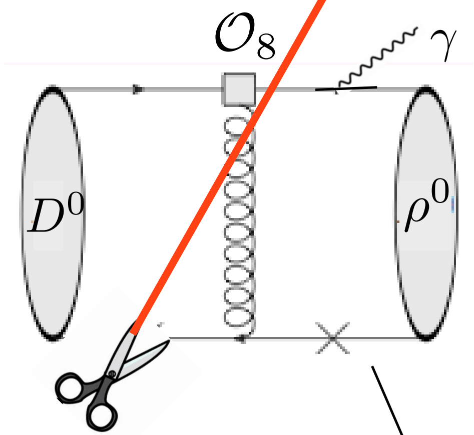
- Need interfering amplitude with large strong phase

$$\mathcal{A}(D^0 \to \rho^0 \gamma) = \lambda_d e^{i\delta_{WA}} |A_{WA}| + \dots \,, \delta_{WA} = 0 + \mathcal{O}(\alpha_s)$$

- That's where the chromomagnetic contribution comes in

$\langle \gamma \rho^0 | \mathcal{O}_8 | D^0 \rangle$

large strong phase

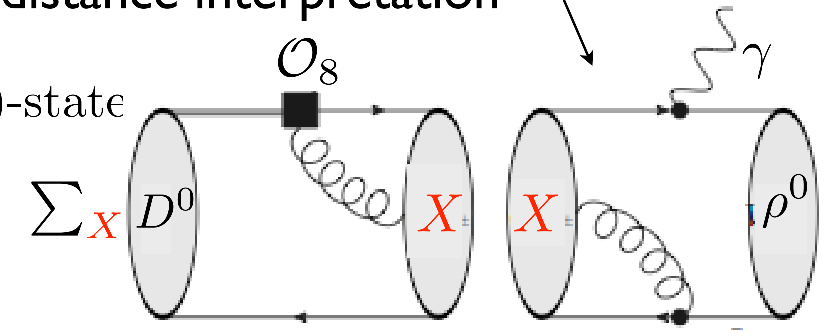


First "complete" computation free of IR-divergences (Dimou Lyon, RZ '12) by LCSR

- Strong phase call long distance interpretation

X is any (multiparticle)-state

- q-number $(\bar{u}u)_{0^\pm}$
- $m_X^2 = m_{D^0}^2$



Results

$$A_{\rm CP}(D^0 \to (\rho^0,\omega)\gamma) = \left(-1.5\% \left(\frac{\mathrm{Im}[C_8^{NP}]}{0.4\cdot 10^{-2}}\right) - 0.4\% \left(\frac{\mathrm{Im}[C_8'^{NP}]}{0.4\cdot 10^{-2}}\right)\right) c_{\mathcal{B}}$$

$$A_{\rm CP}(D^+_{(d,s)} \to (\rho^+,K^{*+})\gamma) = \left(3.9\% \left(\frac{\mathrm{Im}[C_8^{NP}]}{0.4\cdot 10^{-2}}\right) + 0.2\% \left(\frac{\mathrm{Im}[C_8'^{NP}]}{0.4\cdot 10^{-2}}\right)\right) c_{\mathcal{B}}$$

correction factor for (measured) branching ratio

- CP-asymmetries in the percent-range 1) uncertainties ca 45%
  2) SM estimate 2 orders of magnitude lower

- There are further opportunities e.g. time dependent CP-asymmetry
  ⇒ Measure chirality structure of WA amplitudes ⇒ check theory tools

time is short &
we are a bit tired

What have we achieved ...

... in going from $D^0 \Rightarrow \pi\pi/KK$ to $D^0 \Rightarrow V\gamma$?

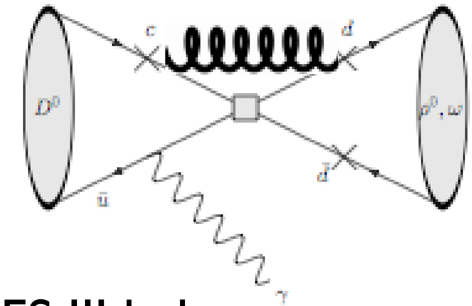
We have a prediction for strong phases and size of amplitude and thus a prediction for A_{CP}. This allows, in principle, to set bounds on ImC8.

interplay of theory and experiment can make it more robust

Outlook

Experiment

- Current $D^0 \Rightarrow \rho^0\gamma$ -- 2 orders of magnitude away from prediction
- BES III: should reach $D^0 \Rightarrow \rho^0\gamma$ this year -- $D^+ \Rightarrow \rho^+\gamma$ come close to prediction
- LHCb: photon not optimal $\Rightarrow$ extend $D \Rightarrow V ll$ (under investigation)
- SuperB: KEK II (not in physics book -- to be seen)
- Super tau-charm: please build!



Theory

- Colour suppression of neutral modes delicate
  - α_s-correction colour suppression relieved: large? certainly difficult!
  - large cancellation in Wilson coefficients -- $D^+ \Rightarrow \rho^+\gamma$ BES III helps
- Personal impression: matrix element under better control than thought of Yet I have a few question marks with Wilson coefficients. It's possible to to crosscheck them through experiment. (Plus flavour physics many channels)
- Nice if lattice could join matrix elements. Yet strong phases $\Rightarrow$ challenging

The End -- Thank You