Direct CP violation in charmed meson decays

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- Diagrammatical approach
- SU(3) breaking
- CP violation at tree and loop levels

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Experiment

Time-dependent CP asymmetry

$$A_{CP}(f(t)) = \frac{\Gamma(D \to f(t)) - \Gamma(\overline{D} \to \bar{f}(t))}{\Gamma(D \to f(t)) + \Gamma(\overline{D} \to \bar{f}(t))}$$

Time-integrated asymmetry

$$A_{CP}(f) = a_{CP}^{dir}(f) + \frac{\langle t \rangle}{\tau} a_{CP}^{ind}(f)$$

LHCb: (11/14/2011) 0.92 fb^{-1} based on 60% of 2011 data

$\Delta A_{CP} \equiv A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-) = -(0.82 \pm 0.21 \pm 0.11)\%$

3.5σ effect: first evidence of CPV in charm sector

CDF: (2/29/2012) 9.7 fb^{-1}

$\Delta A_{CP} = -(2.33 \pm 0.14)\% - (-1.71 \pm 0.15)\%$

$= -(0.62 \pm 0.21 \pm 0.10)\%$ **2.7σ effect**

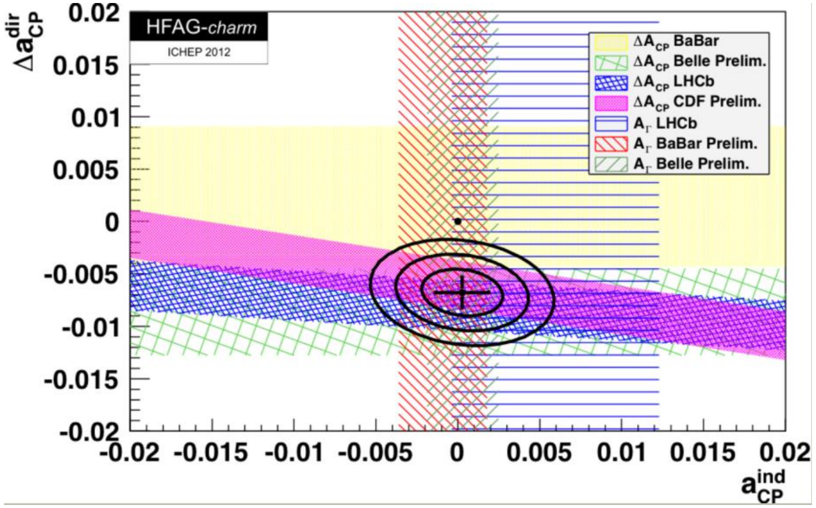
Belle: (ICHEP2012) 540 fb^{-1}

$\Delta A_{CP} = -(0.87 \pm 0.41 \pm 0.06)\%$ **2.1σ effect**

World averages of LHCb + CDF + BaBar + Belle

Δa_{CP}^{dir} = -(0.678±0.147)%, 4.6σ effect

a_{CP}^{ind} = -(0.027±0.163)%



Fermilab Today, Dec 13, 2012:

"Another charm revolution?"

The discovery of the charm quark is known in physicists' lingo as the "November revolution" .   (1974)

This measurement (of CP violating asymmetry parameter) puts much pressure on the need for revising and improving the prediction techniques to make a clear distinction between the contributions expected from Standard Model physics and those from possible new interaction forces.

Ideas for new precision measurements are likely to turn out as well. Our hope is that this is the beginning of a second revolution in charm physics.

Another November revolution?

Isidori, Kamenik, Ligeti, Perez [1111.4987]

Brod, Kagan, Zupan [1111.5000]

Wang, Zhu [1111.5196]

Rozanov, Vysotsky [1111.6949]

Hochberg, Nir [1112.5268]

Pirtskhalava, Uttayarat [1112.5451]

Cheng, Chiang [1201.0785]

Bhattacharya, Gronau, Rosner [1201.2351]

Chang, Du, Liu, Lu, Yang [1201.2565]

Giudice, Isidori, Paradisi [1201.6204]

Altmannshofer, Primulando, C. Yu, F. Yu [1202.2866]

Chen, Geng, Wang [1202.3300]

Feldmann, Nandi, Soni [1202.3795]

Li, Lu, Yu [1203.3120]

Franco, Mishima, Silvestrini [1203.3131]

Brod, Grossman, Kagan, Zupan [1203.6659]

Hiller, Hochberg, Nir [1204.1046]

Grossman, Kagan, Zupan [1204.3557]

Cheng, Chiang [1205.0580]

Chen, Geng, Wang [1206.5158]

Delaunay, Kamenik, Perez, Randall [1207.0474]

Da Rold, Delaunay, Grojean, Perez [1208.1499]

Lyon, Zwicky [1210.6546]

Atwood, Soni [1211.1026]

Hiller, Jung, Schacht [1211.3734]

Delepine, Faisel, Ramirez [1212.6281]

Muller, Nierste, Schacht [1506.04121]

Nierste, Schacht [1508.00074]

Buccella, Paul, Santorelli [1902.05564]

Attempts for SM interpretation

Golden, Grinstein ('89): hadronic matrix elements enhanced as in $\Delta I=1/2$ rule.

However, $D\to \pi\pi$ data do not show large $\Delta I=1/2$ enhancement over $\Delta I=3/2$ one.

Moreover, $|A_0/A_2|=2.5$ in D decays is dominated by tree amplitudes.

Brod, Kagan, Zupan: PE and PA amplitudes considered

Pirtskhalava, Uttayarat : SU(3) breaking with hadronic m.e. enhanced

Bhattacharya, Gronau, Rosner : P_b enhanced by unforeseen QCD effects

Feldmann, Nandi, Soni : U-spin breaking with hadronic m.e. enhanced

Brod, Grossman, Kagan, Zupan: penguin enhanced

Franco, Mishima, Silvestrini: marginally accommodated

New Physics interpretation

- **Model-independent analysis of NP effects** Isidori, Kamenik, Ligeti, Perez
- **Tree level (applied to some of SCS modes)**

In SM, $\Delta a_{CP}^{dir} = 0$ at tree level

- **FCNC Z** Giudice, Isidori, Paradisi; Altmannshofer, Primulando, C. Yu, F. Yu
- **FCNC Z' (a leptophobic massive gauge boson)** Wang, Zhu; Altmannshofer et al.
- **2 Higgs-doublet model: charged Higgs** Altmannshofer et al.
- **Left-right mixing** Chen, Geng, Wang; Delepine, Faisel, Ramirez
- **Color-singlet scalar** Hochberg, Nir
- **Color-sextet scalar (diquark scalar)** Altmannshofer et al; Chen, Geng, Wang
- **Color-octet scalar** Altmannshofer et al.
- **4^{th} generation** Rozanov, Vysotsky; Feldmann, Nandi, Soni

NP models are highly constrained from D-$\bar{D}$ mixing, K-$\bar{K}$ mixing, ε'/ε,…
Tree-level models are either ruled out or in tension with other experiments.

■ Loop level (applied to all SCS modes)

Large ΔC=1 chromomagnetic operator with large imaginary coefficient

$$O_{8g} = -\frac{g_s}{8\pi^2} m_c \bar{u} \sigma_{\mu\nu} (1+\gamma_5) G^{\mu\nu} c$$

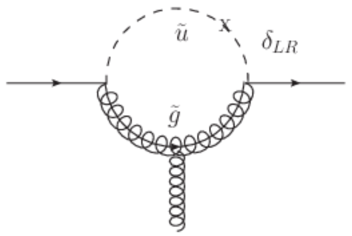
Giudice, Isidori, Paradisi

is least constrained by low-energy data and can accommodate large $\Delta A_{CP.}$
$\langle PP|O_{8g}|D\rangle$ is enhanced by $O(v/m_c)$. However, D^0-$\underline{D}^0$ mixing induced by O_{8g} is suppressed by $O(m_c^2/v^2)$. Need NP to enhance c_{8g} by $O(v/m_c)$

It can be realized in SUSY models

- gluino-squark loops   Grossman, Kagan, Nir

$$c_{8g}^{NP} = G(x) \frac{m_{\tilde{g}}}{m_c} \delta_{LR}$$



- new sources of flavor violation from disoriented A terms, split families

Giudice, Isidori, Paradisi

- trilinear scalar coupling   Hiller, Hochberg, Nir
- RS flavor anarchy warped extra dimension models

Delaunay, Kamenik, Perez, Randall

Expt	Year	ΔA_{CP}(%)	Tag
LHCb	2011	- 0.82±0.24	π
CDF	2012	- 0.62±0.23	π
Belle	2012	- 0.87±0.41	π
LHCb	2013	0.49±0.33	μ
LHCb	2014	0.14±0.18	μ
LHCb	2016	- 0.10±0.09	π
LHCb	2019	- 0.182±0.033	π
LHCb	2019	- 0.090±0.079	μ

LHCb (14'+16'+19') $\Rightarrow \Delta A_{CP}$ = (- 0.154±0.029)% 5.3σ effect

Δa_{CP}^{dir} = (- 0.156±0.029)% **1903.08726**

Recall that LHCb ('11) $\Rightarrow \Delta a_{CP}^{dir}$ = (- 0.82±0.24)%

Is this consistent with the SM prediction?

A brief history of estimating Δa_{CP} in SM:

- **We (Cheng-Wei Chiang and HYC) obtained Δa_{CP} ~ -0.13% in 2012**
- **A few months later, Hsiang-nan Li, Cai-Dian Lu, Fu-Sheng Yu found Δa_{CP} ~ -0.10% or (-0.57 ~ -1.87) $\times 10^{-3}$**
- **We improved the estimate and obtained two solutions in May, 2012**

$$\Delta a_{CP}^{dir} = -0.139 \pm 0.004\% \text{ (I)}$$

$$-0.151 \pm 0.004\% \text{ (II)}$$

The 2nd solution agrees almost exactly with LHCb, - 0.156±0.029%.

- **In 2017, Khodjamirian & Petrov estimated Δa_{CP} using LCSR and obtained an upper bound $\Delta a_{CP}^{dir} \leq (2.0 \pm 0.3) \times 10^{-4}$**

  Chala et al. reinforced the notation that this implies new physics!

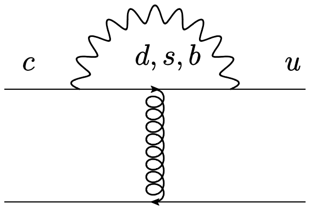
Why singly Cabibbo-suppressed decays ?

DCPV requires nontrival strong and weak phase difference

In SM, DCPV occurs only in singly Cabibbo-suppressed decays

It is expected to be very small in charm sector within SM

Amp = $V^*_{cd}V_{ud}$ (tree + penguin) + $V^*_{cs}V_{us}$ (tree' + penguin)



Tree-induced CP violation depends on strong phases in tree diagrams

DCPV induced by the interference of penguin & tree amplitudes

$$a_{CP}^{dir} = \frac{2\,\mathrm{Im}(V_{cd}^*V_{ud}V_{cs}V_{us}^*)}{|V_{cd}^*V_{ud}|^2}\left|\frac{P}{T}\right|\sin\delta = 2\left|\frac{V_{cb}^*V_{ub}}{V_{cd}^*V_{ud}}\right|\sin\gamma\left|\frac{P}{T}\right|\sin\delta = 1.3\times10^{-3}\left|\frac{P}{T}\right|\sin\delta$$

δ: strong phase

DCPV is expected to be the order of $10^{-3} \sim 10^{-5}$

Theoretical framework

◆ Effective Hamiltonian approach

pQCD: Li, Tseng ('97); Du, Y. Li, C.D. Lu ('05)

QCDF: Du, H. Gong, J.F. Sun ('01)

X.Y. Wu, X.G. Yin, D.B. Chen, Y.Q. Guo, Y. Zeng ('04)

J.H. Lai, K.C. Yang ('05); D.N. Gao ('06)

Grossman, Kagan, Nir ('07)

X.Y. Wu, B.Z. Zhang, H.B. Li, X.J. Liu, B. Liu, J.W. Li, Y.Q. Gao ('09)

However, it doesn't make much sense to apply pQCD & QCDF to charm decays due to huge $1/m_c$ power corrections

QCD sum rules: Blok, Shifman ('87); Khodjamirian, Ruckl; Halperin ('95)

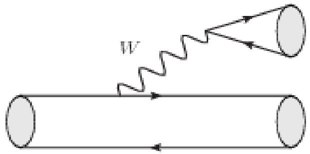
Khodjamirian, Petrov ('17)

◆ Lattice QCD: ultimate tool but a formidable task now

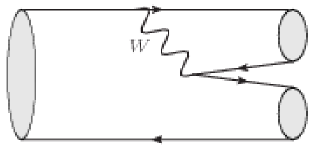
◆ Model-independent diagrammatical approach

Diagrammatic Approach

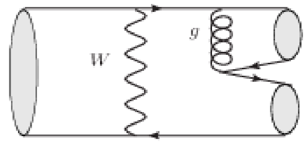
All two-body hadronic decays of heavy mesons can be expressed in terms of several distinct topological diagrams [Chau ('80); Chau, HYC('86)]



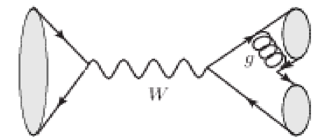
T (tree)



C (color-suppressed)

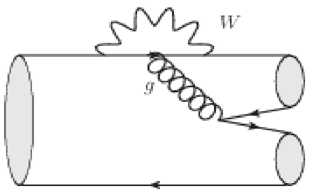


E (W-exchange)

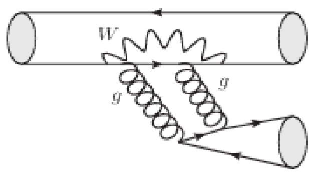


A (W-annihilation)

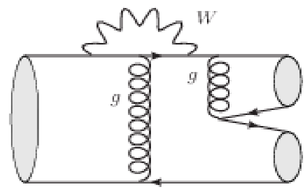
HYC, Oh ('11)



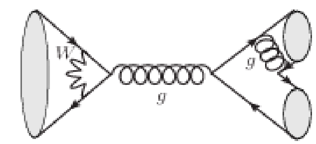
P, P^c_{EW}



S, P_{EW}



PE, PE_{EW}



PA, PA_{EW}

All quark graphs are topological and meant to have all strong interactions encoded and hence they are not Feynman graphs. And SU(3) flavor symmetry is assumed.

Cabibbo-allowed decays

For Cabibbo-allowed $D \to PP$ decays (in units of 10^{-6} GeV)

T = 3.14 ± 0.01 (taken to be real)

C = $(2.66 \pm 0.03)\ \exp[i(-152 \pm 0.3)^o]$

E = $(1.53 \pm 0.04)\ \exp[i(122 \pm 0.4)^o]$

A = $(0.44 \pm 0.03)\ \exp[i(29^{+7}_{-10})^o]$

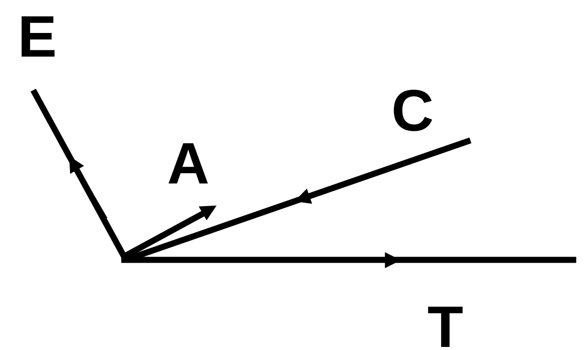
Rosner ('99)

Wu, Zhong, Zhou ('04)

Bhattacharya, Rosner ('08,'10)

HYC, Chiang ('10, '19)

- Phase between **C** & **T** ~ 150^o
- W-exchange **E** is sizable with a large phase $\Rightarrow$ importance of $1/m_c$ power corrections
- W-annihilation **A** is smaller than **E** and almost perpendicular to **E**



The great merit & strong point of this approach $\Rightarrow$ magnitude and strong phase of each topological tree amplitude are determined

All topological tree amplitude except T are dominated by nonfactorizable long-distance effects.

SCS

Meson	Mode	Representation	$\mathcal{B}_{\rm exp}$ ($\times 10^{-3}$)	$\mathcal{B}_{\rm theory}$ ($\times 10^{-3}$)
D^0	$\pi^+\pi^-$	$V_{cd}^*V_{ud}(T'+E')$	1.45 ± 0.05	2.24 ± 0.10
	$\pi^0\pi^0$	$\frac{1}{\sqrt{2}}V_{cd}^*V_{ud}(C'-E')$	0.81 ± 0.05	1.35 ± 0.05
	$\pi^0\eta$	$-V_{cd}^*V_{ud}E'\cos\phi - \frac{1}{\sqrt{2}}V_{cs}^*V_{us}C'\sin\phi$	0.68 ± 0.07	0.75 ± 0.02
	$\pi^0\eta'$	$-V_{cd}^*V_{ud}E'\sin\phi + \frac{1}{\sqrt{2}}V_{cs}^*V_{us}C'\cos\phi$	0.91 ± 0.13	0.74 ± 0.02
	$\eta\eta$	$-\frac{1}{\sqrt{2}}V_{cd}^*V_{ud}(C'+E')\cos^2\phi + V_{cs}^*V_{us}(2E'\sin^2\phi - \frac{1}{\sqrt{2}}C'\sin 2\phi)$	1.67 ± 0.18	1.44 ± 0.08
	$\eta\eta'$	$-\frac{1}{2}V_{cd}^*V_{ud}(C'+E')\sin 2\phi + V_{cs}^*V_{us}(E'\sin 2\phi - \frac{1}{\sqrt{2}}C'\cos 2\phi)$	1.05 ± 0.26	1.19 ± 0.07
	K^+K^-	$V_{cs}^*V_{us}(T'+E')$	4.07 ± 0.10	1.92 ± 0.08
	$K^0\bar{K}^0$	$V_{cd}^*V_{ud}E'_s + V_{cs}^*V_{us}E'_d$ [a]	0.64 ± 0.08	0
D^+	$\pi^+\pi^0$	$\frac{1}{\sqrt{2}}V_{cd}^*V_{ud}(T'+C')$	1.18 ± 0.07	0.88 ± 0.10
	$\pi^+\eta$	$\frac{1}{\sqrt{2}}V_{cd}^*V_{ud}(T'+C'+2A')\cos\phi - V_{cs}^*V_{us}C'\sin\phi$	3.54 ± 0.21	1.48 ± 0.26
	$\pi^+\eta'$	$\frac{1}{\sqrt{2}}V_{cd}^*V_{ud}(T'+C'+2A')\sin\phi + V_{cs}^*V_{us}C'\cos\phi$	4.68 ± 0.30	3.70 ± 0.37
	$K^+\bar{K}^0$	$V_{cd}^*V_{ud}A' + V_{cs}^*V_{us}T'$	6.12 ± 0.22 [b]	5.46 ± 0.53
D_s^+	π^+K^0	$V_{cd}^*V_{ud}T' + V_{cs}^*V_{us}A'$	2.52 ± 0.27 [c]	2.73 ± 0.26
	π^0K^+	$\frac{1}{\sqrt{2}}(V_{cd}^*V_{ud}C' - V_{cs}^*V_{us}A')$	0.62 ± 0.23	0.86 ± 0.09
	$K^+\eta$	$\frac{1}{\sqrt{2}}(V_{cd}^*V_{ud}C' + V_{cs}^*V_{us}A')\cos\phi - V_{cs}^*V_{us}(T'+C'+A')\sin\phi$	1.76 ± 0.36	0.78 ± 0.09
	$K^+\eta'$	$\frac{1}{\sqrt{2}}(V_{cd}^*V_{ud}C' + V_{cs}^*V_{us}A')\sin\phi + V_{cs}^*V_{us}(T'+C'+A')\cos\phi$	1.80 ± 0.52	1.07 ± 0.17

Sizable SU(3) breaking in some SCS modes

SU(3) flavor symmetry breaking

A long standing puzzle: $R=\Gamma(D^0\to K^+K^-)/\Gamma(D^0\to \pi^+\pi^-) \approx 2.8$
expected to be unity in SU(3) limit

$\lambda_p = V^*_{cp} V_{up}$

$$A(D^0 \to \pi^+\pi^-) = \lambda_d (T + E + P_d + PE_d + PA_d)_{\pi\pi} + \lambda_s (P_s + PE_s + PA_s)_{\pi\pi}$$

$$= \frac{1}{2}(\lambda_d - \lambda_s)(T + E + \Delta P)_{\pi\pi} - \frac{1}{2}\lambda_b (T + E + \Sigma P)_{\pi\pi}$$

$$A(D^0 \to K^+K^-) = \lambda_d (P_d + PE_d + PA_d)_{KK} + \lambda_s (T + E + P_s + PE_s + PA_s)_{KK}$$

$$= \frac{1}{2}(\lambda_d - \lambda_s)(T + E - \Delta P)_{KK} - \frac{1}{2}\lambda_b (T + E + \Sigma P)_{KK}$$

with $\Delta P \equiv (P_d + PE_d + PA_d) - (P_s + PE_s + PA_s)$, $\quad \Sigma P \equiv (P_d + PE_d + PA_d) + (P_s + PE_s + PA_s)$

Possible scenarios for seemingly large SU(3) violation:

- **Large ΔP**

A fit to data yields $\Delta P = 1.54 \exp(-i202^o)$ $\Rightarrow$ $|\Delta P/T| \sim 0.5$

Brod, Grossman, Kagan, Zupan

Need a large ΔP contributing constructively to K^+K^- & destructively to $\pi^+\pi^-$

■ Nominal SU(3) breaking in both T & E, while ΔP negligible

SU(3) symmetry must be broken in amplitudes E & PA

$A(D^0 \to K^0 \underline{K}^0) = \lambda_d(E_d + 2PA_d) + \lambda_s(E_s + 2PA_s)$ almost vanishes in SU(3) limit

Neglecting ΔP, E_d & E_s fixed from $D^0 \to K^+K^-$, $\pi^+\pi^-$, $\pi^0\pi^0$, $K^0\underline{K}^0$ to be

$$\text{(I)} \quad E_d = 1.15 e^{i14.1^\circ} E, \quad E_s = 0.72 e^{-i18.3^\circ} E$$

$$\text{(II)} \quad E_d = 1.15 e^{i14.1^\circ} E, \quad E_s = 1.45 e^{-i12.7^\circ} E$$

Accumulation of several small SU(3) breaking effects leads to apparently large SU(3) violation seen in K^+K^- and $\pi^+\pi^-$ modes

Singly Cabibbo-suppressed D→ PP decays

Decay Mode	$\mathcal{B}_{SU(3)}$	$\mathcal{B}_{SU(3)-breaking}$	$\mathcal{B}_{PDG}$
$D^0 \to \pi^+\pi^-$ ➡	2.28 ± 0.02	1.47 ± 0.02	1.455 ± 0.024
$D^0 \to \pi^0\pi^0$ ➡	1.41 ± 0.03	0.82 ± 0.02	0.826 ± 0.025
$D^0 \to \pi^0\eta$	0.78 ± 0.02	0.91 ± 0.02	0.63 ± 0.06
$D^0 \to \pi^0\eta'$	0.75 ± 0.02	1.25 ± 0.03	0.92 ± 0.10
$D^0 \to \eta\eta$	1.49 ± 0.03	1.90 ± 0.04	2.11 ± 0.19
	1.49 ± 0.03	2.05 ± 0.04	
$D^0 \to \eta\eta'$	1.19 ± 0.05	0.74 ± 0.03	1.01 ± 0.19
	1.19 ± 0.05	1.73 ± 0.08	
$D^0 \to K^+K^-$ ➡	1.91 ± 0.02	4.02 ± 0.03	4.08 ± 0.06
	1.91 ± 0.02	4.04 ± 0.05	
$D^0 \to K_S K_S$ ➡	0	0.139 ± 0.007	0.141 ± 0.005
	0	0.141 ± 0.007	
$D^+ \to \pi^+\pi^0$	0.89 ± 0.02	0.97 ± 0.02	1.247 ± 0.033
$D^+ \to \pi^+\eta$ ➡	1.54 ± 0.12	3.34 ± 0.14	3.77 ± 0.09
$D^+ \to \pi^+\eta'$ ➡	3.92 ± 0.11	4.64 ± 0.08	4.97 ± 0.19
$D^+ \to K^+K_S$	2.55 ± 0.18	4.57 ± 0.20	3.04 ± 0.09
$D_s^+ \to \pi^+K_S$	1.34 ± 0.05	1.39 ± 0.04	1.22 ± 0.06
$D_s^+ \to \pi^0K^+$	0.86 ± 0.03	0.56 ± 0.02	0.63 ± 0.21
$D_s^+ \to K^+\eta$	0.84 ± 0.03	0.76 ± 0.03	1.77 ± 0.35
$D_s^+ \to K^+\eta'$	1.09 ± 0.06	1.37 ± 0.08	1.8 ± 0.6

Tree-level direct CP violation

- $A(D_s^+ \to K^0\pi^+) = \lambda_d(T + P_d + PE_d) + \lambda_s(A + P_s + PE_s)$, $\lambda_p = V^*_{cp}V_{up}$

  DCPV in $D_s^+ \to K^0\pi^+$ arises from interference between T & A

$$a_{dir}^{(\text{tree})}(D_s^+ \to K^0\pi^+) = \frac{2\text{Im}(\lambda_d\lambda_s^*)}{|\lambda_d|^2}\frac{\text{Im}(T^*A)}{|T-A|^2} \approx 1.2\times 10^{-3}\left|\frac{A}{T}\right|\sin\delta_{AT} \approx 10^{-4}$$

- Larger DCPV at tree level occurs in interference between T & C (e.g. $D_s^+ \to K^+\eta$, -0.80×10^{-3}) or C & E (e.g. $D^0 \to \pi^0\eta$, -0.85×10^{-3})

- $A(D^0 \to K^0\underline{K}^0) = \lambda_d(E_d + 2PA_d) + \lambda_s(E_s + 2PA_s)$

$$a_{dir}^{(\text{tree})}(D^0 \to K_SK_S) = \frac{2\text{Im}(\lambda_d\lambda_s^*)}{|\lambda_d|^2}\frac{\text{Im}(E_d^*E_s)}{|E_d-E_s|^2} = 1.3\times10^{-3}\frac{|E_dE_s|}{|E_d-E_s|^2}\sin\delta_{ds}$$

$$a_{dir}^{(\text{tree})}(D^0 \to K_SK_S) = \begin{cases} -1.25\times10^{-3} & \text{Solution I}, \\ -2.14\times10^{-3} & \text{Solution II} \end{cases}$$

DCPV at tree level can be reliably estimated in diagrammatic approach as magnitude & phase of tree amplitudes can be extracted from data

Decay	a_{CP}^{tree}
$D^0 \to \pi^+\pi^-$	0
$D^0 \to \pi^0\pi^0$	0
$D^0 \to \pi^0\eta$	0.85±0.23
$D^0 \to \pi^0\eta'$	-0.43±0.01
$D^0 \to \eta\eta$	-0.32±0.01 -0.42±0.01
$D^0 \to \eta\eta'$	0.59±0.01 0.46±0.01
$D^0 \to K^+K^-$	0
$D^0 \to K_S K_S$	-1.25 -2.14
$D^+ \to \pi^+ \eta$	0.40±0.03
$D^+ \to \pi^+\eta'$	-0.24±0.01
$D^+ \to K^+\underline{K}^0$	-0.04±0.02
$D_s^+ \to \pi^+K^0$	0.09±0.02
$D_s^+ \to \pi^0K^+$	0.01±0.05
$D_s^+ \to K^+\eta$	-0.80±0.02
$D_s^+ \to K^+\eta'$	0.33±0.01

Tree-level DCPV $a_{CP}^{(tree)}$ in units of per mille

$$10^{-3} > a_{dir}^{(tree)} > 10^{-4}$$

Largest tree-level DCPV in D→PP:

$$D^0 \to K_S K_S$$

$$a_{dir}^{(tree)} = (-1.25 \sim -2.14)\times 10^{-3}$$

$$A_{CP}(K_S K_S) = \begin{cases} (-2.9 \pm 5.2 \pm 2.2)\%, & \text{LHCb} \\ (4.3 \pm 3.4 \pm 1.0)\%, & \text{LHCb} \\ (-0.02 \pm 1.53 \pm 0.17)\%, & \text{Belle} \end{cases}$$

Penguin-induced CP violation

$$A(D^0 \to \pi^+\pi^-) = \lambda_d (T + E + P_d + PE_d + PA_d)_{\pi\pi} + \lambda_s (P_s + PE_s + PA_s)_{\pi\pi}$$

$$A(D^0 \to K^+K^-) = \lambda_d (P_d + PE_d + PA_d)_{KK} + \lambda_s (T + E + P_s + PE_s + PA_s)_{KK}$$

$$A(D^0 \to \pi^+\pi^-) = \frac{1}{2}(\lambda_d - \lambda_s)(T + E + \Delta P)_{\pi\pi} - \frac{1}{2}\lambda_b (T + E + \Sigma P)_{\pi\pi}$$

$$A(D^0 \to K^+K^-) = \frac{1}{2}(\lambda_s - \lambda_d)(T + E - \Delta P)_{KK} - \frac{1}{2}\lambda_b (T + E + \Sigma P)_{KK}$$

DCPV in $D^0 \to \pi^+\pi^-$, K^+K^- arises from interference between tree and penguin

$$\Delta a_{\rm CP}^{\rm dir} = -1.30 \times 10^{-3} \left(\left| \frac{P_d + PE_d + PA_d}{T + E - \Delta P} \right|_{KK} \sin\delta_{KK} + \left| \frac{P_s + PE_s + PA_s}{T + E + \Delta P} \right|_{\pi\pi} \sin\delta_{\pi\pi} \right)$$

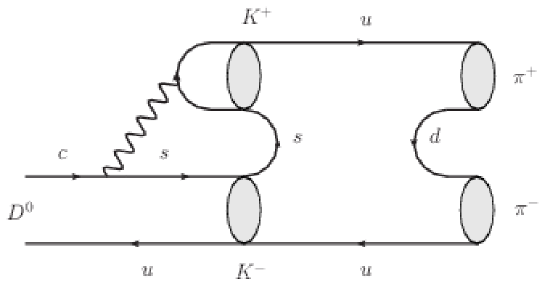
While QCD-penguin amplitudes are estimated to NLO in QCD factorization, $PE_{d,s}$ & $PA_{d,s}$ are subject to end-point divergences beyond control

$$\left(\frac{P_s}{T + E_s + \Delta P} \right)_{\pi\pi} = 0.32 e^{i173^0}, \qquad \left(\frac{P_d}{T + E_d + \Delta P} \right)_{KK} = \begin{cases} 0.23 e^{-i167^0} \\ 0.23 e^{i177^0} \end{cases}$$

DCPV from QCD penguin is small for $D^0 \to K^+K^-$ & $\pi^+\pi^-$ due to almost trivial strong phase ~ 175^o

$$\Delta a_{CP}^{\rm dir} = \begin{cases} 0.02 \times 10^{-3} & \text{Solution I,} \\ -0.07 \times 10^{-3} & \text{Solution II} \end{cases}$$

How about power corrections to QCD penguin ?



Large LD contribution to PE can arise from $D^0 \to K^+K^-$ followed by a resonantlike final-state rescattering

HYC, Chiang ('12)

It is reasonable to assume PE ~ E. It should be stressed that PE cannot be larger than T

$$(PE)_{LD} = (1.60 \pm 0.32) \times 10^{-6} e^{i(115\pm30)^0}\,\mathrm{GeV}$$

$$\left(\frac{P_s + PE}{T + E_s + \Delta P}\right)_{\pi\pi} = 0.80 e^{i111^0}, \qquad \left(\frac{P_d + PE}{T + E_d + \Delta P}\right)_{KK} = \begin{cases} 0.46 e^{i135^0} \\ 0.46 e^{i118^0} \end{cases}$$

$$\Delta a_{CP}^{\rm dir} = \begin{cases} (-1.22 \pm 0.27) \times 10^{-3} & \text{Solution I,} \\ (-1.32 \pm 0.26) \times 10^{-3} & \text{Solution II} \end{cases}$$

Δa_{CP} arises mainly from long-distance PE!

Li, Lu, Yu obtained

$$\left(\frac{P_s}{T+E_s}\right)_{\pi\pi}=0.41e^{i148^0},\qquad \left(\frac{P_d}{T+E_d}\right)_{KK}=0.31e^{i153^0},$$

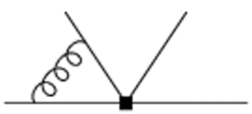
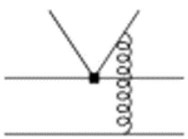
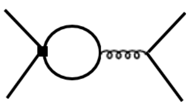
$$\left(\frac{P_s+PE_s+PA_s}{T+E_s}\right)_{\pi\pi}=0.66e^{i134^0},\qquad \left(\frac{P_d+PE_d+PA_d}{T+E_d}\right)_{KK}=0.45e^{i131^0},$$

⇒ Δa_{CP} ~ -0.10%

Consider penguin contribution first

$$P_{P_1P_2}=\frac{G_F}{\sqrt{2}}[a_4(P_1P_2)+r_\chi^{P_2}a_6(P_1P_2)]f_{P_2}(m_D^2-m_{P_1}^2)\ F_0^{DP_1}(m_{P_2}^2)$$

$$a_6(P_1P_2)\ =\ \left(c_6+\frac{c_5}{N_c}\right)+\frac{c_5}{N_c}\frac{C_F\alpha_s}{4\pi}[V_6(P_2)+\frac{4\pi^2}{N_c}H_6(P_1P_2)]+\mathcal{P}_6(P_2)$$

vertex corrections | hard spectator interactions | penguin contractions

Instead of evaluating vertex, hard spectator and penguin corrections, Li, Lu and Yu parametrized them as $\chi_{nf} e^{i\phi}$

$$a_6 = c_6 + c_5 \left[\frac{1}{N_c} + \chi_{nf} e^{i\phi}\right], \qquad a_2 = c_2 + c_1 \left[\frac{1}{N_c} + \chi_{nf} e^{i\phi}\right]$$

$$\boldsymbol{\chi_{nf} = -0.59, \qquad \phi = -0.62}$$

Penguin-exchange and penguin annihilation

$$PE_{P_1P_2} = c_3 \chi^E_{q,s} e^{i\phi^E_{q,s}} f_D m_D^2 \left(\frac{f_{P_1} f_{P_2}}{f_\pi^2}\right) + 2\left[c_6(\mu) + \frac{c_5(\mu)}{N_c}\right] g_S B_S(m_D^2) m_S \bar{f}_S f_D \frac{m_D^2}{m_c}$$

$$PA_{P_1P_2} = [c_4(\mu) + c_6(\mu)] \chi^A_{q,s} e^{i\phi^A_{q,s}} f_D m_D^2 \left(\frac{f_{P_1} f_{P_2}}{f_\pi^2}\right).$$

Decay	a_{CP}^{tree}	a_{CP}^{total}
$D^0 \to \pi^+\pi^-$	0	0.86±0.23
$D^0 \to \pi^0\pi^0$	0	0.91±0.32
$D^0 \to \pi^0\eta$	0.85±0.23	0.03±0.30
$D^0 \to \pi^0\eta'$	-0.43±0.01	-0.11±0.18
$D^0 \to \eta\eta$	-0.32±0.01 -0.42±0.01	-0.57±0.08 -0.69±0.07
$D^0 \to \eta\eta'$	0.59±0.01 0.46±0.01	0.51±0.22 0.36±0.15
$D^0 \to K^+K^-$	0	-0.35±0.14 -0.47±0.13
$D^0 \to K_S K_S$	-1.25 -2.14	-1.15 -2.21
$D^+ \to \pi^+ \eta$	0.40±0.03	-0.68±0.27
$D^+ \to \pi^+\eta'$	-0.24±0.01	0.21±0.18
$D^+ \to K^+\bar{K}^0$	-0.04±0.02	-0.27±0.18
$D_s^+ \to \pi^+K^0$	0.09±0.02	0.41±0.24
$D_s^+ \to \pi^0K^+$	0.01±0.05	0.97±0.28
$D_s^+ \to K^+\eta$	-0.80±0.02	-0.67±0.06
$D_s^+ \to K^+\eta'$	0.33±0.01	-0.06±0.28

a_{CP}^{dir} (10^{-3})

Δa_{CP}^{dir}= -0.122±0.027% (I)

-0.132±0.026% (II)

consistent with LHCb result

Δa_{CP}^{dir} = (- 0.156±0.029)%

The analysis of $D \to VP$ modes in the diagrammatic approach is much more involved. The study is near completion.

HYC, Chiang ('19)

Light-cone sum rules by Khodjamirian, Petrov ('17) lead to

$$\left|\frac{P}{T+E}\right|_{\pi\pi} = 0.093 \pm 0.011, \qquad \left|\frac{P}{T+E}\right|_{KK} = 0.075 \pm 0.015$$

$$\left|\Delta A_{CP}^{SM}\right| \leq (2.0 \pm 0.3) \times 10^{-4}$$

Chala, Lenz, Rusov, Scholtz ('19) considered higher twist corrections

$$\left|\Delta A_{CP}^{SM}\right| \leq (2.0 \pm 1.0) \times 10^{-4} \qquad \Rightarrow \textbf{New Physics}$$

- Khodjamirian & Petrov kept only c_1 and c_2 and neglected all other Wilson coefficients

$$a_6^p(P_1P_2) = \left(c_6 + \frac{c_5}{N_c}\right) + \frac{c_5}{N_c}\frac{C_F\alpha_s}{4\pi}\left[V_6(P_2) + \frac{4\pi^2}{N_c}H_6(P_1P_2)\right] + \mathcal{P}_6^p(P_2)$$

$$a_4^p = a_6^p \approx \frac{C_F\alpha_s}{4\pi N_c}c_1\left[\frac{4}{3}\ln\frac{m_c}{\mu} + \frac{2}{3} - G_{M_2}(s_p)\right]$$

- Penguin annihilation (PE & PA) and **especially LD effects** haven't been considered in LCSR calculations

Conclusions

- DCPV measured by LHCb $\Rightarrow$ importance of penguin effects in the charm sector

- The diagrammatical approach is very useful for analyzing hadronic D decays

- DCPV in charm decays is studied in the diagrammatic approach. It can be reliably estimated at tree level. Our estimate of Δa_{CP} = (- 0.122±0.027)% or (- 0.132±0.026)% is consistent with LHCb

- DCPV in $D^0 \to K_S K_S$ is predicted to be large and negative

CP asymmetries with $D^0 \to h^+h^-$ decays

- Observed (raw) asymmetries suffer from instrumental and production effects

$$\frac{N(D^0 \to h^+h^-) - N(\bar{D}^0 \to h^+h^-)}{N(D^0 \to h^+h^-) + N(\bar{D}^0 \to h^+h^-)}$$

$$A(h^+h^-) = A_{CP}(h^+h^-) + A_D + A_P$$

The CP asymmetry you want to measure

Detection asymmetry of tagging track (π^+ or μ^-)

Production asymmetry of parent hadron (D* or B)

- Difference of raw asymmetries to cancel unwanted effects

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

- Similar strategy for most of other CP asymmetry measurements — one or more suitable additional modes are needed to remove detection/production asymmetries

Taken from Angelo Di Canto, talk presented at "Towards the Ultimate Precision in Flavor Physics", Durham, April, 2019

After LHCb's new announcement on charm CP violation:

Z. Z. Xing [1903.09566]

Chala, Lenz, Rusov, Scholtz [1903.10490]

H. N. Li, C. D. Lu, F. S. Yu [1903.10638]

Grossman, Schacht [1903.10952]

Soni [1905.00907]