Direct CP violation in charmed meson decays

Hai-Yang Cheng

Academia Sinica, Taipei

In collaboration with Cheng-Wei Chiang

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Experiment

Time-dependent CP asymmetry $A_{CP}(f(t)) = \frac{\Gamma(D^0 \to f(t)) - \Gamma(\overline{D}^0 \to f(t))}{\Gamma(D^0 \to f(t)) + \Gamma(\overline{D}^0 \to f(t))}$

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}

$\Delta A_{CP} = -(0.62 \pm 0.21 \pm 0.10)\%$ **2.7σ effect**

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

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

Expt	Year	$\Delta A_{CP}(\%)$	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

$D^{*+} \to D^0 \pi^+$

$B \to D^0 \mu^- \nu_\mu X$

LHCb (14'+16'+19') ⇒ ΔA_{CP} = (- 0.154±0.029)% 5.3σ effect

Δa_{CP}^{dir} = (- 0.156±0.029)%

Recall that LHCb ('11) ⇒ Δa_{CP}^{dir} = (- 0.82±0.24)%

Is this consistent with the SM prediction?

Consider tree T and penguin P amplitudes

$$A(D^0 \to \pi^+\pi^-) = \lambda_d(T + P_d) + \lambda_s P_s \qquad \lambda_p = V_{cp}^* V_{up}$$

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

$\Delta\mathrm{U} = 1$ $\quad$ $\Delta\mathrm{U} = 0$

with $\quad \Delta\mathrm{P} = \mathrm{P_d} - \mathrm{P_s}, \quad \Sigma\mathrm{P} = \mathrm{P_d} + \mathrm{P_s}$

$$A(D^0 \to K^+K^-) = \lambda_d P_d + \lambda_s(T + P_s)$$

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

$$a_{CP}^{dir}(\pi\pi) = Im\left(\frac{2\lambda_b}{\lambda_d - \lambda_s}\right) Im\left(\frac{T + \Sigma\mathrm{P}}{T + \Delta\mathrm{P}}\right) = 1.3 \times 10^{-3} \left|\frac{P}{T}\right| sin\delta_{\pi\pi}$$

$$a_{CP}^{dir}(KK) = Im\left(\frac{2\lambda_b}{\lambda_d - \lambda_s}\right) Im\left(\frac{T + \Sigma\mathrm{P}}{T - \Delta\mathrm{P}}\right) = -1.3 \times 10^{-3} \left|\frac{P}{T}\right| sin\delta_{KK}$$

It appears that direct CP asymmetries in $D^0 \to \pi^+\pi^-, K^+K^-$ are both smaller than 10^{-4} if |P/T| = O($\alpha_s(m_c)/\pi$) ~ 0.1

To evaluate various amplitudes we rely on topological approach for tree amplitudes (T, C, E, A) and QCD-inspired approach (e.g. QCD factorization, pQCD) for short-distance penguin amplitudes

Topological tree amplitudes

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

T = 3.113 ± 0.011 (taken to be real)

C = $(2.767 \pm 0.029)\, \exp[i\,(-151.3 \pm 0.3)^o]$

E = $(1.48 \pm 0.04)\, \exp[i\,(120.9 \pm 0.4)^o]$

A = $(0.55 \pm 0.03)\, \exp[i\,(23^{+7}_{-10})^o]$

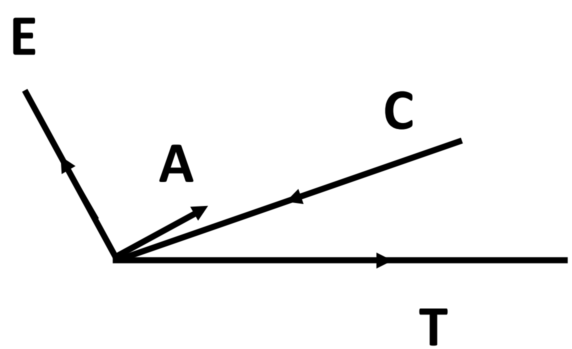
Rosner ('99)

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 ⇒ 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 ⇒ magnitude and strong phase of each topological tree amplitude are determined

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

Based on LCSR, Khodjamirian and Petrov ('17) obtained

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

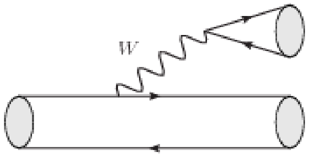
close to naïve expectation of P/T=O($\alpha_s(m_c)/\pi$) ~ 0.1, but

$$\left(\frac{P}{T}\right)_{\pi\pi} \approx 0.23 e^{-i150^\circ}, \qquad \left(\frac{P}{T}\right)_{KK} \approx 0.22 e^{-i150^\circ}$$

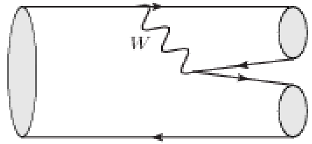
in QCDF+ topological approach [HYC & Chiang ('12)], and

$$\left(\frac{P}{T}\right)_{\pi\pi} \approx 0.30 e^{i110^\circ}, \qquad \left(\frac{P}{T}\right)_{KK} \approx 0.24 e^{i110^\circ}$$

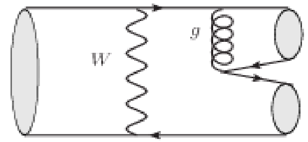
in pQCD + factorization-assisted topological amplitude (FAT)
[Li, Lu, Yu ('12)]



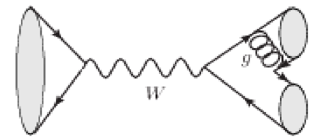
T (tree)



C (color-suppressed)

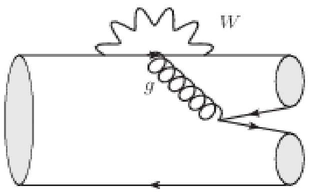


E (W-exchange)

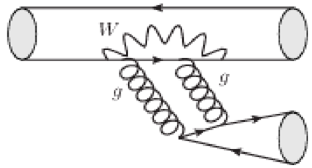


A (W-annihilation)

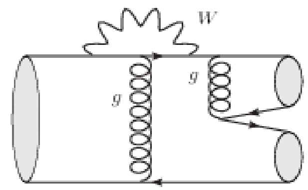
HYC, Oh ('11)



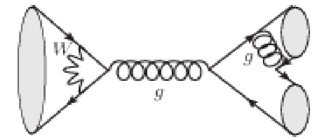
P, P^c_{EW}



S, P_{EW}



PE, PE_{EW}



PA, PA_{EW}

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

$$= \frac{1}{2}(\lambda_d - \lambda_s)\left(T + E_d + \Delta\mathrm{P}\right) - \frac{1}{2}\lambda_b(T + E_d + \Sigma\mathrm{P})$$

$$A(D^0 \to K^+K^-) = \lambda_d(P_d + PE_d + PA_d) + \lambda_s(T + E_s + P_s + PE_s + PA_s)$$

$$= \frac{1}{2}(\lambda_d - \lambda_s)\left(T + E_s - \Delta\mathrm{P}\right) - \frac{1}{2}\lambda_b(T + E_s + \Sigma\mathrm{P})$$

$$\Delta a_{CP}^{\rm dir} = -1.30 \times 10^{-3} \left(\left| \frac{P^d + PE^d + PA^d}{T + E^s - \Delta P} \right|_{KK} \sin \delta_{KK} + \left| \frac{P^s + PE^s + PA^s}{T + E^d + \Delta P} \right|_{\pi\pi} \sin \delta_{\pi\pi} \right)$$

$$= -1.30 \times 10^{-3} (C_{KK}\, sin\delta_{KK} + C_{\pi\pi}\, sin\delta_{\pi\pi})$$

In SU(3) limit, $C_{KK} = C_{\pi\pi}, \ \delta_{KK} = \delta_{\pi\pi}$

(i) $\boldsymbol{C \sim O(0.10 - 0.30)}$ **if only T and P are considered**

(ii) $\boldsymbol{C \sin\delta \sim 0.60 \pm 0.11}$ **from 2019 LHCb data**

(iii) $\boldsymbol{C \sin\delta \sim 3.2 \pm 0.9}$ **from 2011 LHCb data**

Case (ii) which is called ΔU=0 rule by Grossman and Schacht can be achieved in the SM.

- pQCD + FAT [Li, Lu, Yu ('12)]

$$\left(\frac{P}{T}\right)_{\pi\pi} \approx 0.30 e^{i110^\circ} \quad \Rightarrow \quad \left(\frac{P^s + PE^s + PA^s}{T + E^d + \Delta P}\right)_{\pi\pi} = 0.66\, e^{i134^\circ}$$

$$\left(\frac{P}{T}\right)_{KK} \approx 0.24 e^{i110^\circ} \quad \Rightarrow \quad \left(\frac{P^d + PE^d + PA^d}{T + E^s - \Delta P}\right)_{KK} = 0.45\, e^{i131^\circ}$$

ratio enhanced by a factor of 2

$\Rightarrow \quad \Delta a_{CP}^{dir} \approx -1.0 \times 10^{-3}$ **Li, Lu, Yu ('12)**

- QCDF + topological approach

$$\left(\frac{P^s + PE^s + PA^s}{T + E^d + \Delta P}\right)_{\pi\pi} = 0.40\, e^{i176^\circ}, \quad \left(\frac{P^d + PE^d + PA^d}{T + E^s - \Delta P}\right)_{KK} = \begin{cases} 0.29\, e^{-i164^\circ} \\ 0.29\, e^{i178^\circ} \end{cases}$$

SU(3) violation in E amplitudes is fixed from $D^0 \to K^0\underline{K}^0, K^+K^-, \pi^+\pi^-, \pi^0\pi^0$

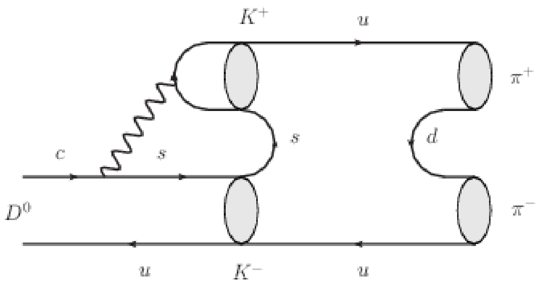
$$\mathrm{I}: \quad E^d = 1.10\, e^{i15.1^\circ} E\,, \qquad E^s = 0.62\, e^{-i19.7^\circ} E$$

$$\mathrm{II}: \quad E^d = 1.10\, e^{i15.1^\circ} E\,, \qquad E^s = 1.42\, e^{-i13.5^\circ} E$$

$E^q: c\bar{u} \to q\bar{q}$

$$\Rightarrow \quad \Delta a_{CP}^{dir} \approx \begin{cases} 6.8 \times 10^{-5} & (I) \\ -4.9 \times 10^{-5} & (II) \end{cases}$$

phases close to π !



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

HYC, Chiang ('12)

It is reasonable to assume $(P+PE)^{LD} \sim E$

Ansatz justified recently by Di Wang ⇒ L(C) : L(E) : L(P) = -2 : 1 : 1

$$\left(\frac{P^s + PE^s + PA^s + (P+PE)^{\rm LD}}{T + E^d + \Delta P}\right)_{\pi\pi} = 0.81\, e^{i119^\circ}$$

$$\left(\frac{P^d + PE^d + PA^d + (P+PE)^{\rm LD}}{T + E^s - \Delta P}\right)_{KK} = \begin{cases} 0.48\, e^{i143^\circ} \\ 0.48\, e^{i126^\circ} \end{cases}$$

$$\Rightarrow \quad \Delta a_{CP}^{dir} \approx \begin{cases} (-0.139 \pm 0.004)\% & (I) \\ (-0.151 \pm 0.004)\% & (II) \end{cases}$$

('12)

It is the interference between tree and long-distance penguin that pushes Δa_{CP}^{dir} up to the per mille level

- If Δa_{CP}^{dir} were not measured by LHCb, what would be the size of DCPV expected in D system?

$$A(D_s^+ \to K^+\eta) = \frac{1}{\sqrt{2}}\left[\lambda_d(C + P_d) + \lambda_s(A + P_s)\right] \cos\phi$$
$$-\left[\lambda_d P_d + \lambda_s(T + C + A + P_s)\right] \sin\phi$$

Large DCPV at tree level arises from interference between T & C

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

$$\Rightarrow\ a_{CP}^{tree} = (-0.75 \pm 0.01)10^{-3}, \quad a_{CP}^{total} = (-0.81 \pm 0.08)10^{-3}$$

$\Rightarrow$ **tree DCPC at per mille level**

- Another example: $D^0 \to K_S K_S$

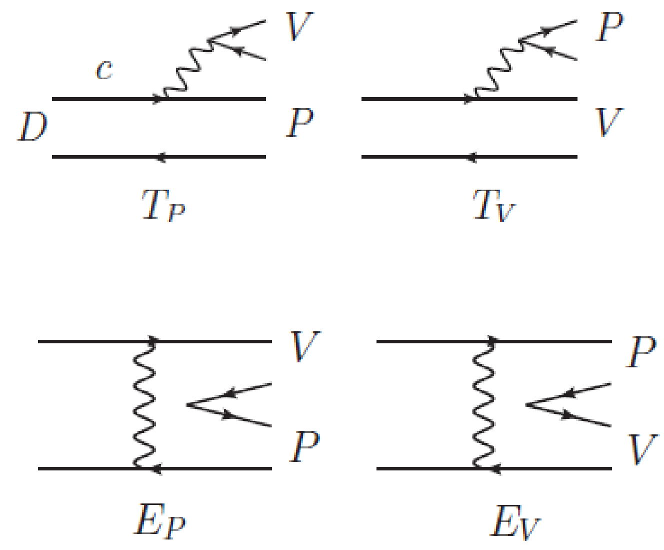
$$a_{\rm dir}^{\rm (tree)}(D^0 \to K_S K_S) = \begin{cases} -1.05 \times 10^{-3} & \text{Solution I} \\ -1.99 \times 10^{-3} & \text{Solution II} \end{cases}$$

If DCPV of $D^0 \to K_S K_S$ is seen at percent level $\Rightarrow$ new physics

D→ VP decays

Meson	Mode	Representation
D^0	$K^{*-}\pi^+$	$Y_{sd}(T_V+E_P)$
	$K^-\rho^+$	$Y_{sd}(T_P+E_V)$
	$\overline{K}^{*0}\pi^0$	$\frac{1}{\sqrt{2}}Y_{sd}(C_P-E_P)$
	$\overline{K}^0\rho^0$	$\frac{1}{\sqrt{2}}Y_{sd}(C_V-E_V)$
	$\overline{K}^{*0}\eta$	$Y_{sd}(\frac{1}{\sqrt{2}}(C_P+E_P)c_\phi-E_Vs_\phi)$
	$\overline{K}^{*0}\eta'$	$-Y_{sd}(\frac{1}{\sqrt{2}}(C_P+E_P)s_\phi+E_Vc_\phi)$
	$\overline{K}^0\omega$	$-\frac{1}{\sqrt{2}}Y_{sd}(C_V+E_V)$
	$\overline{K}^0\phi$	$-Y_{sd}E_P$
D^+	$\overline{K}^{*0}\pi^+$	$Y_{sd}(T_V+C_P)$
	$\overline{K}^0\rho^+$	$Y_{sd}(T_P+C_V)$
D_s^+	$\overline{K}^{*0}K^+$	$Y_{sd}(C_P+A_V)$
	$\overline{K}^0K^{*+}$	$Y_{sd}(C_V+A_P)$
	$\rho^+\pi^0$	$\frac{1}{\sqrt{2}}Y_{sd}(A_P-A_V)$
	$\rho^+\eta$	$-Y_{sd}(\frac{1}{\sqrt{2}}(A_P+A_V)c_\phi-T_Ps_\phi)$
	$\rho^+\eta'$	$Y_{sd}(\frac{1}{\sqrt{2}}(A_P+A_V)s_\phi+T_Pc_\phi)$
	$\pi^+\rho^0$	$\frac{1}{\sqrt{2}}Y_{sd}(A_V-A_P)$
	$\pi^+\omega$	$\frac{1}{\sqrt{2}}Y_{sd}(A_V+A_P)$
	$\pi^+\phi$	$Y_{sd}T_V$

CF



T_P, C_P: P contains q of D meson

T_V, C_V: V contains q of D meson

E_P, A_P: P contains q_2 of q_1q_2 configuration

E_V, A_V: V contains q_2 of q_1q_2

Five solutions with $\chi^2_{min} < 10$

in units of $10^{-6}(\epsilon . p_D)$

Set	$\|T_V\|$ $\|E_P\|$	$\|T_P\|$ δ_{E_P}	δ_{T_P} $\|A_V\|$	$\|C_V\|$ δ_{A_V}	δ_{C_V} $\|A_P\|$	$\|C_P\|$ δ_{A_P}	δ_{C_P} $\chi^2_{\rm min}$	$\|E_V\|$ fit quality	δ_{E_V}
(S1')	2.19 ± 0.03	3.32 ± 0.06	100 ± 3	1.75 ± 0.04	312 ± 3	2.10 ± 0.02	201 ± 1	0.29 ± 0.04	334^{+14}_{-22}
	1.69 ± 0.03	109 ± 2	0.20 ± 0.02	32^{+8}_{-11}	0.21 ± 0.03	357^{+12}_{-9}	5.88	11.74%	
(S2')	2.19 ± 0.03	3.23 ± 0.06	264 ± 3	1.74 ± 0.04	50 ± 3	2.07 ± 0.02	201 ± 1	0.36 ± 0.05	8^{+9}_{-8}
	1.69 ± 0.03	109 ± 2	0.20 ± 0.02	349^{+9}_{-7}	0.22 ± 0.03	23^{+9}_{-12}	6.39	9.41%	
(S3')	2.19 ± 0.03	3.56 ± 0.06	61 ± 5	1.69 ± 0.04	220 ± 3	2.02 ± 0.02	201 ± 1	0.58 ± 0.06	283 ± 5
	1.69 ± 0.03	108 ± 3	0.23 ± 0.02	77 ± 5	0.18 ± 0.03	111^{+13}_{-10}	7.06	6.99%	
(S4')	2.19 ± 0.03	3.50 ± 0.06	106^{+3}_{-4}	1.74 ± 0.04	262^{+4}_{-3}	2.09 ± 0.02	201 ± 1	0.38 ± 0.05	308^{+8}_{-10}
	1.69 ± 0.03	109 ± 2	0.25 ± 0.02	62^{+6}_{-7}	0.14 ± 0.03	44^{+50}_{-16}	7.34	6.19%	
(S5')	2.19 ± 0.03	3.54 ± 0.06	268^{+5}_{-4}	1.67 ± 0.04	107^{+3}_{-4}	2.04 ± 0.02	201 ± 1	$0.62^{+0.06}_{-0.07}$	43 ± 4
	1.69 ± 0.03	108 ± 2	0.26 ± 0.02	324 ± 5	0.13 ± 0.02	329^{+24}_{-32}	8.57	3.56%	

Size of each amplitude is similar in all five solutions, but strong phases vary.

All five solutions fit CF modes well, but may lead to very different predictions for some of SCS modes, especially $D^0 \to \pi^0\omega$, $D^+ \to \pi^+\omega$ and $D^+ \to \pi^+\rho^0$

	BF(10^{-3})	S1’	S2’	S3’	S4’	S5’
$D^0 \to \pi^0\omega$	0.117±0.035	1.46	3.28	0.13	0.64	2.59
$D^+ \to \pi^+\omega$	0.28±0.06	0.87	0.98	0.22	0.43	1.38

Solution (S3’) gives a best accommodation of SCS data, while other solutions are ruled out.

in units of 10^{-3}

Mode	$\mathcal{B}_{\text{theory}}$	$\mathcal{B}_{\text{exp}}$	Mode	$\mathcal{B}_{\text{theory}}$	$\mathcal{B}_{\text{exp}}$
$D^0 \to \pi^+\rho^-$	5.15 ± 0.21	5.15 ± 0.25	$D^0 \to \pi^0\omega$	0.13 ± 0.02	0.117 ± 0.035
$D^0 \to \pi^-\rho^+$	10.10 ± 0.37	10.1 ± 0.4	$D^0 \to \pi^0\phi$	0.95 ± 0.02	1.20 ± 0.04
$D^0 \to \pi^0\rho^0$	3.79 ± 0.12	3.86 ± 0.23	$D^0 \to \eta\omega$	2.09 ± 0.09	1.98 ± 0.18
$D^0 \to K^+K^{*-}$	1.65 ± 0.06	1.65 ± 0.11	$D^0 \to \eta'\omega$	0.02 ± 0.00	—
$D^0 \to K^-K^{*+}$	4.56 ± 0.15	4.56 ± 0.21	$D^0 \to \eta\phi$	0.19 ± 0.02	0.181 ± 0.034^c
$D^0 \to K^0\overline{K}^{*0}$	0.25 ± 0.01	0.246 ± 0.048	$D^0 \to \eta\rho^0$	0.59 ± 0.06	—
$D^0 \to \overline{K}^0 K^{*0}$	0.34 ± 0.06	0.336 ± 0.063	$D^0 \to \eta'\rho^0$	0.06 ± 0.00	—
$D^+ \to \pi^+\rho^0$	0.68 ± 0.09	0.83 ± 0.15	$D^+ \to \eta\rho^+$	0.94 ± 0.42	—
$D^+ \to \pi^0\rho^+$	4.44 ± 0.59	—	$D^+ \to \eta'\rho^+$	1.23 ± 0.11	—
$D^+ \to \pi^+\omega$	0.22 ± 0.05	0.28 ± 0.06	$D^+ \to K^+\overline{K}^{*0}$	5.92 ± 0.18	3.71 ± 0.16^d
$D^+ \to \pi^+\phi$	4.87 ± 0.10	5.59 ± 0.10	$D^+ \to \overline{K}^0 K^{*+}$	16.28 ± 0.61	34 ± 16
$D_s^+ \to \pi^+K^{*0}$	2.06 ± 0.08	2.23 ± 0.33^a	$D_s^+ \to \eta K^{*+}$	0.46 ± 0.19	—
$D_s^+ \to \pi^0K^{*+}$	0.92 ± 0.06		$D_s^+ \to \eta' K^{*+}$	0.41 ± 0.02	—
$D_s^+ \to K^+\rho^0$	1.22 ± 0.06	2.5 ± 0.4	$D_s^+ \to K^+\omega$	0.99 ± 0.05	0.87 ± 0.25
$D_s^+ \to K^0\rho^+$	7.64 ± 0.33		$D_s^+ \to K^+\phi$	0.12 ± 0.02	0.18 ± 0.04

BFs of $D_s^+ \to \pi^0 K^{*+}, K^0\rho^+$ absent in 2020 PDG, $Br(D^+ \to \overline{K}^0 K^{*+}) = 34 \pm 16$ poorly measured. The gap was filled by BESIII in 2021.

In our approach, all SCS data can be accommodated by solution S3' except

$D^+ \to K^+ \overline{K}^{*0}$**: 5.92 $\pm$ 0.18 (theory) vs 3.71 $\pm$ 0.16 (expt),**

$D_s^+ \to K^+ \rho^0$ **: 1.22 $\pm$ 0.06 (theory) vs 2.5 $\pm$ 0.4 (expt).**

Needs to be clarified in near future

Direct CP violation

- **As in the case of D $\to$ PP, we assume long-distance contributions to $(P_{V,P}+PE_{V,P})$ are of same order as $E_{P,V}$**

$$(P_V + PE_V)^{LD} \approx E_P(S3'), \qquad (P_P + PE_P)^{LD} \approx E_V(S3'),$$

- **Six golden modes:** $D^0 \to \pi^+\rho^-,\ \ K^+K^{*-},$
  $D^+ \to K^+\overline{K}^{*0},\ \ \eta\rho^+,$
  $D_s^+ \to \pi^+K^{*0},\ \ \pi^0K^{*+}$

- **Due to LD penguin contributions, our predictions of DCPV in D$\to$ VP are in general substantially larger than that of pQCD + FAT**

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

FAT

Mode	$a_{dir}^{(tree)}$	$a_{dir}^{(t+p)}$	$a_{dir}^{(t+pe+pa+s)}$	$a_{dir}^{(t+pe^{LD})}$	$a_{dir}^{(tot)}$	$a_{dir}^{(tot)}$ [24]
$D^0 \to \pi^+\rho^-$	0	-0.00 ± 0.00	-0.011 ± 0.000	0.77 ± 0.22	0.76 ± 0.22	-0.03
$D^0 \to \pi^-\rho^+$	0	0.01 ± 0.00	0.008 ± 0.001	-0.13 ± 0.08	-0.11 ± 0.08	-0.01
$D^0 \to \pi^0\rho^0$	0	-0.01 ± 0.00	-0.004 ± 0.000	0.28 ± 0.16	0.27 ± 0.16	-0.03
$D^0 \to K^+K^{*-}$	0	-0.01 ± 0.01	0.011 ± 0.000	-0.85 ± 0.24	-0.85 ± 0.24	-0.01
$D^0 \to K^-K^{*+}$	0	-0.03 ± 0.00	-0.009 ± 0.000	0.08 ± 0.09	0.04 ± 0.09	0
$D^0 \to K^0\overline{K}^{*0}$	-0.03 ± 0.02	-0.03 ± 0.02	-0.03 ± 0.02	-0.03 ± 0.02	-0.03 ± 0.02	-0.7
$D^0 \to \overline{K}^0 K^{*0}$	1.07 ± 0.12	1.07 ± 0.12	1.07 ± 0.12	1.07 ± 0.12	1.07 ± 0.12	-0.7
$D^0 \to \pi^0\omega$	0	0.04 ± 0.00	0.04 ± 0.01	-1.51 ± 0.87	-1.43 ± 0.87	0.02
$D^0 \to \pi^0\phi$	0	0	-0.004	0	-0.004	-0.0002
$D^0 \to \eta\omega$	-0.13 ± 0.01	-0.12 ± 0.01	-0.13 ± 0.01	-0.35 ± 0.10	-0.35 ± 0.10	-0.1
$D^0 \to \eta'\omega$	2.06 ± 0.11	1.93 ± 0.11	1.93 ± 0.11	1.48 ± 0.61	1.23 ± 0.60	2.2
$D^0 \to \eta\phi$	0	0	0.009	0	0.009	0.003
$D^0 \to \eta\rho^0$	0.45 ± 0.03	0.51 ± 0.03	0.49 ± 0.03	0.16 ± 0.30	0.26 ± 0.31	1.0
$D^0 \to \eta'\rho^0$	-0.65 ± 0.06	-0.63 ± 0.06	-0.62 ± 0.06	-0.17 ± 0.23	-0.13 ± 0.23	-0.1

$$a_{CP}(K^+K^{*-}) - a_{CP}(\pi^+\rho^-) = (-1.61 \pm 0.33) \times 10^{-3}$$

Recall that $a_{CP}(D^0 \to K^+K^-) - a_{CP}(D^0 \to \pi^+\pi^-) = (-1.56 \pm 0.29) \times 10^{-3}$

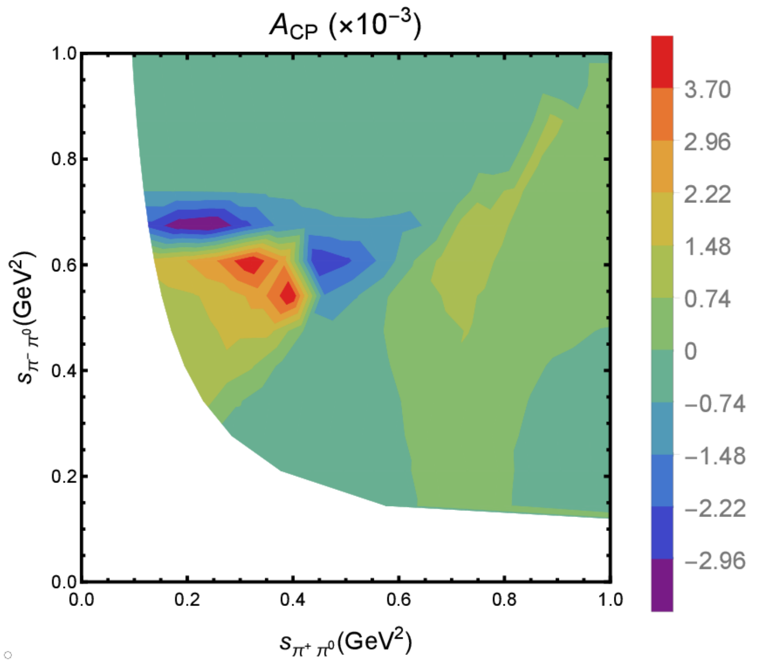
$$a_{CP}(D^0 \to K_S K^{*0}) = (1.07 \pm 0.12) \times 10^{-3}$$

Mode	$a_{dir}^{(tree)}$	$a_{dir}^{(t+p)}$	$a_{dir}^{(t+pe+pa+s)}$	$a_{dir}^{(t+pe^{LD})}$	$a_{dir}^{(tot)}$	$a_{dir}^{(tot)}$ [24]
$D^+ \to \pi^+\rho^0$	0	0.33 ± 0.02	0.10 ± 0.01	0.83 ± 1.36	1.26 ± 1.34	0.5
$D^+ \to \pi^0\rho^+$	0	0.10 ± 0.01	0.04 ± 0.00	-0.58 ± 0.52	-0.44 ± 0.52	0.2
$D^+ \to \pi^+\omega$	0	0.01 ± 0.01	0.08 ± 0.01	0.93 ± 2.28	1.03 ± 2.28	-0.05
$D^+ \to \pi^+\phi$	0	0	-0.004	0	-0.004	-0.0001
$D^+ \to \eta\rho^+$	-1.85 ± 0.51	-1.97 ± 0.54	-1.93 ± 0.55	-2.31 ± 0.92	-2.50 ± 0.98	-0.6
$D^+ \to \eta'\rho^+$	0.23 ± 0.05	0.20 ± 0.05	0.21 ± 0.05	0.39 ± 0.16	0.34 ± 0.15	0.5
$D^+ \to K^+\overline{K}^{*0}$	-0.11 ± 0.01	-0.14 ± 0.01	-0.11 ± 0.01	-0.77 ± 0.24	-0.80 ± 0.24	0.2
$D^+ \to \overline{K}^0 K^{*+}$	-0.04 ± 0.01	-0.05 ± 0.01	-0.05 ± 0.01	-0.06 ± 0.06	0.04 ± 0.07	0.04
$D_s^+ \to \pi^+K^{*0}$	0.18 ± 0.02	0.24 ± 0.02	0.19 ± 0.02	1.25 ± 0.41	1.32 ± 0.41	-0.1
$D_s^+ \to \pi^0K^{*+}$	0.13 ± 0.02	0.12 ± 0.03	0.11 ± 0.03	1.35 ± 0.40	1.31 ± 0.40	-0.2
$D_s^+ \to K^+\rho^0$	0.14 ± 0.03	0.11 ± 0.02	0.15 ± 0.03	-0.26 ± 0.12	-0.29 ± 0.12	0.3
$D_s^+ \to K^0\rho^+$	0.06 ± 0.02	0.08 ± 0.02	0.08 ± 0.02	-0.10 ± 0.10	-0.07 ± 0.10	0.3
$D_s^+ \to \eta K^{*+}$	1.18 ± 0.23	0.86 ± 0.16	0.95 ± 0.18	0.95 ± 0.75	0.40 ± 0.70	1.1
$D_s^+ \to \eta' K^{*+}$	-0.19 ± 0.04	-0.16 ± 0.04	0.14 ± 0.04	-0.33 ± 0.19	-0.24 ± 0.19	-0.5
$D_s^+ \to K^+\omega$	-0.15 ± 0.03	-0.14 ± 0.03	-0.16 ± 0.03	0.27 ± 0.14	0.28 ± 0.14	-2.3
$D_s^+ \to K^+\phi$	0	-0.32 ± 0.02	-0.14 ± 0.01	-0.88 ± 1.61	-1.33 ± 1.59	-0.8

Golden modes: $D^+ \to K^+\,\overline{K}^{*0}, \eta\rho^+,\ \ D_s^+ \to \pi^+K^{*0}, \pi^0K^{*+}$

DCPV in 3-body D decays

BaBar (`07) $\Rightarrow D^0 \to \pi^+\pi^-\pi^0$ is almost saturated by $\rho^+\pi^-, \rho^-\pi^+, \rho^0\pi^0$



Magnitude & sign of local CP asymmetries vary from region to region

It can reach 4×10^{-3} level in some region & becomes very negative of order -5×10^{-3} in other region due to interference

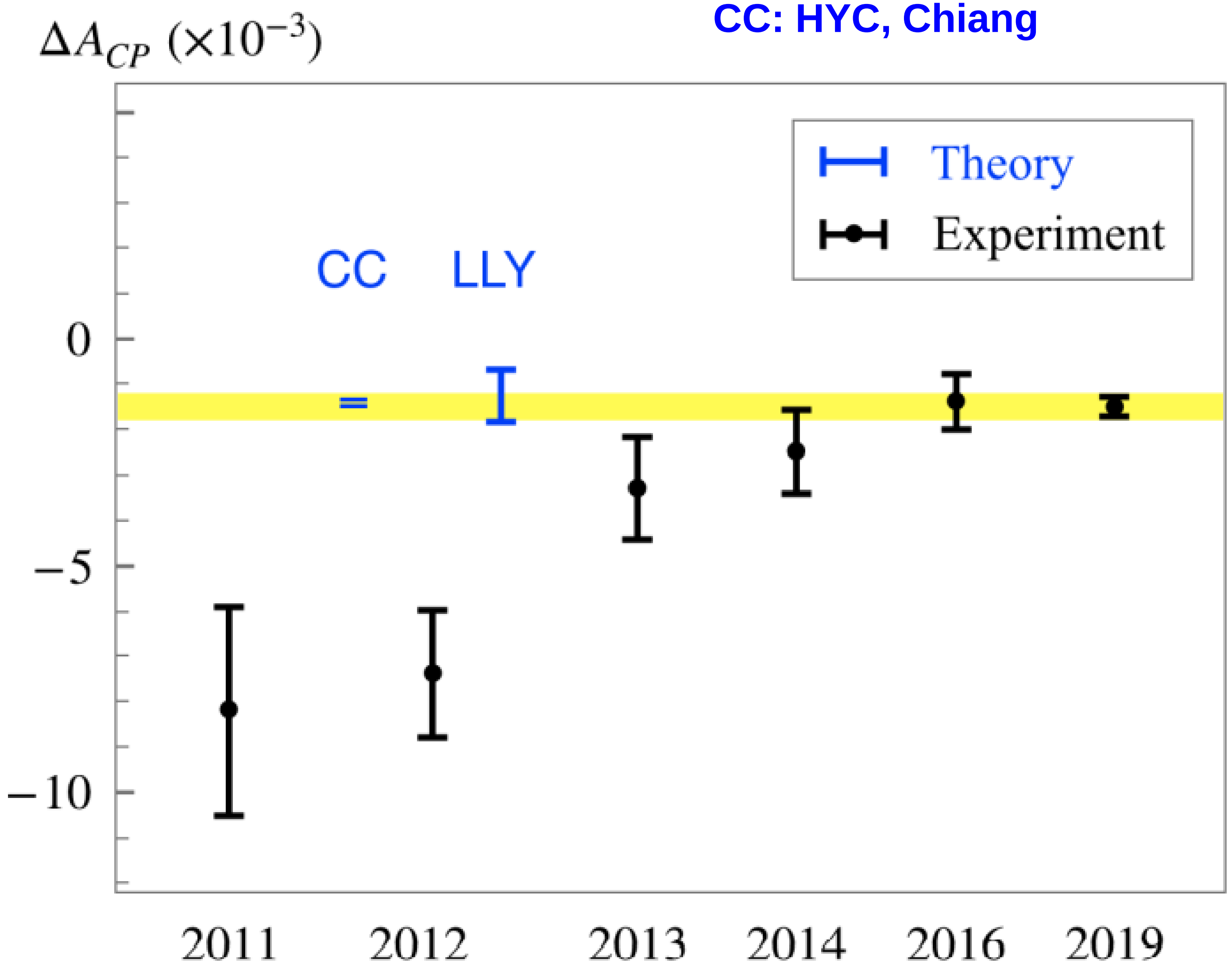
Conclusions

- The diagrammatical approach is very useful for analyzing hadronic D decays
- Interference between tree and long-distance penguin accounts for Δa_{CP} at per mille level in both PP & VP decays
- Six golden modes in $D \to VP$ decays
- CP asymmetry difference between K^+K^{*-} and $\pi^+\rho^-$ is very similar to the observed CP violation in K^+K^- and $\pi^+\pi^-$,
$$a_{CP}(K^+K^{*-}) - a_{CP}(\pi^+\rho^-) = (-1.61 \pm 0.33) \times 10^{-3}$$
- Dalitz plot of CP asymmetry distribution of 3-body D decays is studied. Local asymmetry varies in magnitude and sign from region to region

from M Saur & Fu-Sheng Yu

LLY: Li, Lu, Yu

CC: HYC, Chiang



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