Direct *CP* Asymmetries in *D* decays

Fu-Sheng Yu (于福升)

Hsiang-nan Li and Cai-Dian Lu

PRD86,036012(2012)

Institute of High Energy Physics, CAS

10th HFCPV@ Qingdao

Oct 26, 2012

Outline

- Motivation
- Branching Ratios
- Predict direct CP asymmetries
- Summary

Evidence of CP Violation

- **First evidence** of CP violation in charm decays by LHCb, with 3.5 σ [PRL 2012]

$$\Delta A_{CP} \equiv A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-) = (-0.82 \pm 0.25)\%$$

- World average from LHCb, CDF and Belle [ICHEP2012]

$$\Delta A_{CP} = (-0.74 \pm 0.15)\%$$

- Naively expected smaller in the SM

$$A_{CP}^{dir} \approx \frac{|V_{cb}^* V_{ub}|}{|V_{cs}^* V_{us}|} \frac{\alpha_s}{\pi} \approx 10^{-4}$$

- Necessary to predict more precisely in the SM.

Dynamics of *D* decays

- To predict *CPV*
- **Decay mechanism**

  to be well understood
- **Branching ratios**

  to be well explained

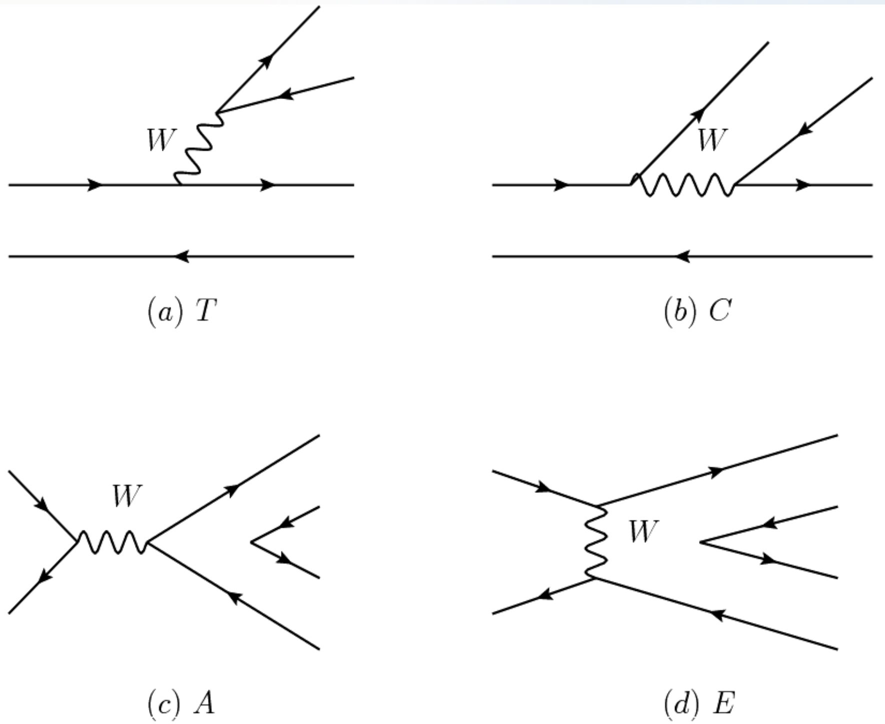
➢ ***A long-standing puzzle:***

$$R = \frac{Br(D^0 \to K^+K^-)}{Br(D^0 \to \pi^+\pi^-)} \approx 2.8$$

- But *R=1* in the SU(3) flavor symmetry

Large SU(3) Breaking Effects

Guidelines



Topological amplitudes in **factorization** :

- Short-distance dynamics: Wilson coefficients
- Long-distance dynamics: hadronic matrix elements

$m_c \sim 1.3 GeV$

Parameterized by **Non-perturbative** quantities

➢Include large **SU(3) breaking** effects

Mode-dependent dynamics

SU(3) breaking effects

◆**Evolution of Wilson coefficients** depending on **energy release**

$M_{\eta'} \sim 1$ GeV

- Masses of η' can not be neglected

$M_D \sim 1.8$ GeV

◆**Glauber strong phase** associated with **pion** in nonfactorizable amplitudes [H.n Li, S. Mishima, 2009]

- Pion: as a $q\bar{q}$ bound state, and as a massless Nambu-Goldstone boson?
- Multi-parton in pion => soft cloud => Glauber phase
- **Pion is unique**, distinguished from other final states

Branching ratios

Tree parameterization

$$O_1 = (\bar{u}_\alpha q_{2\beta})_{V-A}(\bar{q}_{1\beta} c_\alpha)_{V-A}$$

$$O_2 = (\bar{u}_\alpha q_{2\alpha})_{V-A}(\bar{q}_{1\beta} c_\beta)_{V-A}$$

Penguin contributions are negligible

Tree-level Amplitudes

Glauber phase

$$\mathcal{A}(D^0 \to \pi^+\pi^-) = \frac{G_F}{\sqrt{2}}\lambda_d\left(T^{\pi\pi} + E^{\pi\pi}\right)$$

$$= \frac{G_F}{\sqrt{2}}V_{cd}^* V_{ud}\left[a_1(\mu)(m_D^2 - m_\pi^2)f_\pi F_0^{D\pi}(m_\pi^2) + C_2(\mu)e^{i(\phi_q^E + 2S_\pi)}\chi_q^E f_D m_D^2\right]$$

$$\mathcal{A}(D^0 \to K^+K^-) = \frac{G_F}{\sqrt{2}}\lambda_s\left(T^{KK} + E^{KK}\right)$$

$$= \frac{G_F}{\sqrt{2}}V_{cs}^* V_{us}\left[a_1(\mu)(m_D^2 - m_K^2)f_K F_0^{DK}(m_K^2) + C_2(\mu)e^{i\phi_q^E}\chi_q^E f_D m_D^2 \frac{f_K^2}{f_\pi^2}\right]$$

Cabibbo-suppressed BRs : well agree with exp

Our advantage : SU(3) breaking effects included

Modes	Br(FSI)	Br(diagram)	Br(pole)	Br(exp)	Br(this work)
$D^0 \to \pi^+\pi^-$	1.59	2.24 ± 0.10	2.2 ± 0.5	1.45 ± 0.05	1.43 ⬅
$D^0 \to K^+K^-$	4.56	1.92 ± 0.08	3.0 ± 0.8	4.07 ± 0.10	4.19 ⬅
$D^0 \to K^0\bar{K}^0$	0.93	0	0.3 ± 0.1	0.320 ± 0.038	0.36
$D^0 \to \pi^0\pi^0$	1.16	1.35 ± 0.05	0.8 ± 0.2	0.81 ± 0.05	0.57
$D^0 \to \pi^0\eta$	0.58	0.75 ± 0.02	1.1 ± 0.3	0.68 ± 0.07	0.94
$D^0 \to \pi^0\eta'$	1.7	0.74 ± 0.02	0.6 ± 0.2	0.91 ± 0.13	0.65
$D^0 \to \eta\eta$	1.0	1.44 ± 0.08	1.3 ± 0.4	1.67 ± 0.18	1.48
$D^0 \to \eta\eta'$	2.2	1.19 ± 0.07	1.1 ± 0.1	1.05 ± 0.26	1.54
$D^+ \to \pi^+\pi^0$	1.7	0.88 ± 0.10	1.0 ± 0.5	1.18 ± 0.07	0.89
$D^+ \to K^+\bar{K}^0$	8.6	5.46 ± 0.53	8.4 ± 1.6	6.12 ± 0.22	5.95
$D^+ \to \pi^+\eta$	3.6	1.48 ± 0.26	1.6 ± 1.0	3.54 ± 0.21	3.39
$D^+ \to \pi^+\eta'$	7.9	3.70 ± 0.37	5.5 ± 0.8	4.68 ± 0.29	4.58 ⬅
$D_S^+ \to \pi^0K^+$	1.6	0.86 ± 0.09	0.5 ± 0.2	0.62 ± 0.23	0.67
$D_S^+ \to \pi^+K^0$	4.3	2.73 ± 0.26	2.8 ± 0.6	2.52 ± 0.27	2.21
$D_S^+ \to K^+\eta$	2.7	0.78 ± 0.09	0.8 ± 0.5	1.76 ± 0.36	1.00
$D_S^+ \to K^+\eta'$	5.2	1.07 ± 0.17	1.4 ± 0.4	1.8 ± 0.5	1.92

$D^0 \to \pi^+\pi^-$ vs $D^0 \to K^+K^-$

Puzzle

- Revisited: R_{exp} =2.8,   R=1 in SU(3) flavor symmetry

Modes	Br(FSI)	Br(diagram)	Br(pole)	Br(exp)	Br(this work)
$D^0 \to \pi^+\pi^-$	1.59	2.24 ± 0.10	2.2 ± 0.5	1.45 ± 0.05	1.43
$D^0 \to K^+K^-$	4.56	1.92 ± 0.08	3.0 ± 0.8	4.07 ± 0.10	4.19

➢ **Glauber phase** associated with **pions** in nonfactorizable annihilation contribution

- dominate the difference between the two modes

$$T^{\pi\pi} = 2.73, \qquad E^{\pi\pi} = 0.82e^{-i142^\circ},$$

$$T^{KK} = 3.65, \qquad E^{KK} = 1.2e^{-i85^\circ},$$

Improvement of BRs involving η'

- Mass-dependent Wilson coefficients
- η' involved predictions are improved

Modes	Br(FSI)	Br(diagram)	Br(pole)	Br(exp)	Br(this work)
$D^0 \to \overline{K}^0 \eta'$	1.51	1.91±0.09	1.9 ± 0.3	1.90±0.11	1.73
$D_S^+ \to \pi^+ \eta'$	5.89	3.82±0.36	4.6 ± 0.6	3.95±0.34	3.44
$D^0 \to \pi^0 \eta'$	1.7	0.74±0.02	0.6 ± 0.2	0.91±0.13	0.65
$D^0 \to \eta \eta'$	2.2	1.19±0.07	1.1 ± 0.1	1.05±0.26	1.54
$D^+ \to \pi^+ \eta'$	7.9	3.70±0.37	5.5 ± 0.8	4.68±0.29	4.58
$D_S^+ \to K^+ \eta'$	5.2	1.07±0.17	1.4 ± 0.4	1.8±0.5	1.92
$D^+ \to K^+ \eta'$		0.91±0.17	1.0 ± 0.1	1.76±0.22	1.14

Branching ratios well explained otherwise, some important dynamics may be missed

↓

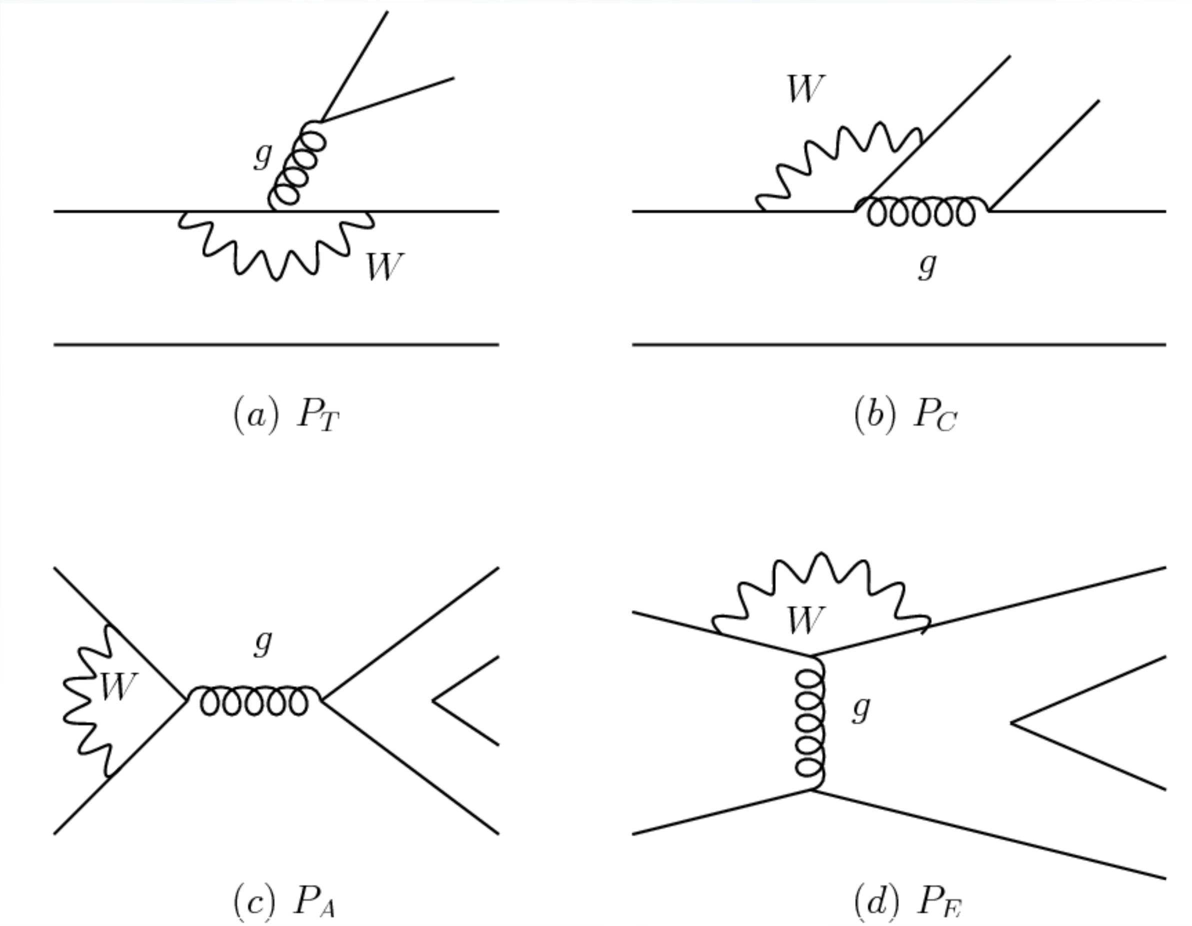
penguin parameterization
& predict direct CP asymmetries

$$\Delta A_{CP} = -2r\sin\gamma\left(\frac{|\mathcal{P}^{KK}|}{|\mathcal{T}^{KK}|}\sin\delta^{KK} + \frac{|\mathcal{P}^{\pi\pi}|}{|\mathcal{T}^{\pi\pi}|}\sin\delta^{\pi\pi}\right),$$

$$r = \frac{|V_{cb}^{*}V_{ub}|}{|V_{cs}^{*}V_{us}|} \sim \lambda^4$$

Penguin topologies

- All topological penguin diagrams for D->PP



Penguin parameterization

- **Factorization**
- **Long-distance** hadronic parameters, related to tree level, fixed by BRs
- **Short-distance** dynamics associated with penguin Wilson coefficients
- Then predict direct CP asymmetries

Penguin operators

$$O_3 = \sum_{q'=u,d,s} (\bar{u}_\alpha c_\alpha)_{V-A} (\bar{q}'_\beta q'_\beta)_{V-A},$$

(V-A)(V-A)

$$O_4 = \sum_{q'=u,d,s} (\bar{u}_\alpha c_\beta)_{V-A} (\bar{q}'_\beta q'_\alpha)_{V-A},$$

$$O_5 = \sum_{q'=u,d,s} (\bar{u}_\alpha c_\alpha)_{V-A} (\bar{q}'_\beta q'_\beta)_{V+A},$$

(V-A)(V+A)

$$O_6 = \sum_{q'=u,d,s} (\bar{u}_\alpha c_\beta)_{V-A} (\bar{q}'_\beta q'_\alpha)_{V+A},$$

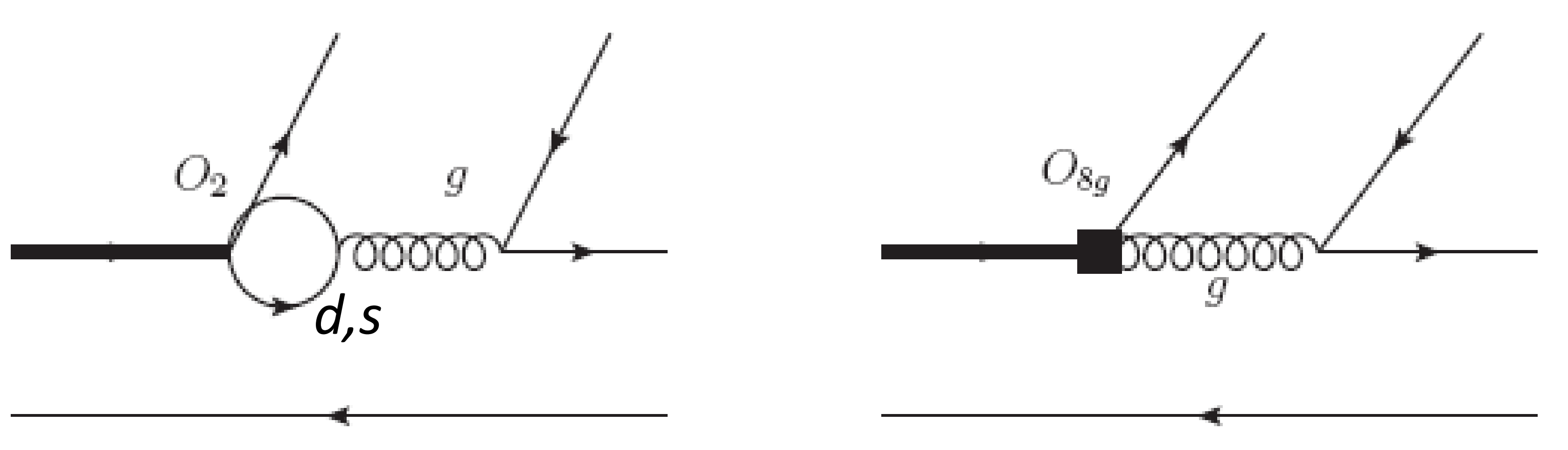
(S+P)(S-P)

Hadronic Parameterization: relate penguin to tree

- At **tree** level, operators are all **(*V-A*)(*V-A*)**
- For **penguin** hadronic matrix elements
  - **<(*V-A*)(*V-A*)>** are the same as tree level
  - **<(*V-A*)(*V+A*)>** related to tree by a sign, since either *V* or *A* contributes to *P->PP*
  - **<(*S-P*)(*S+P*)>** are either factorizable and related to tree by chiral enhancement , or neglected by power suppression

Quark loops & Magnetic penguin

- absorbed into short-distance Wilson coefficients



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

$$\mathcal{A}(D^0 \to \pi^+\pi^-)$$

$$= \frac{G_F}{\sqrt{2}}\left[\lambda_d (T+E) - \lambda_b \left(P_C + 2P_A^d + P_E^d\right)\right],$$

$$= \frac{G_F}{\sqrt{2}}\Big\{V_{cd}^* V_{ud}\left[a_1(\mu)(m_D^2 - m_\pi^2) f_\pi F_0^{D\pi}(m_\pi^2) + C_2(\mu) e^{i(\phi_q^E + 2S_\pi)} \chi_q^E f_D m_D^2\right]$$

$$-V_{cb}^* V_{ub}\Big[a_{P_C}(\mu)(m_D^2 - m_\pi^2) f_\pi F_0^{D\pi}(m_\pi^2) + 2a_{P_A}(\mu) e^{i(\phi_q^A + 2S_\pi)} \chi_q^A f_D m_D^2$$

$$+C_3(\mu) e^{i(\phi_q^E + 2S_\pi)} \chi_q^E f_D m_D^2 + 2a_6'(\mu) g_S f_D \frac{m_D^2}{m_c} \sum_{f_0} B_{f_0}(m_D^2) m_{f_0} \bar{f}_{f_0}\Big]\Big\},$$

$$a_{P_C}(\mu) = [a_4(\mu) + a_6(\mu) r_\chi]\, e^{i\phi},$$
$$a_{P_A}(\mu) = C_4(\mu) + C_6(\mu),$$
$$a_6'(\mu) = C_6(\mu) + \frac{C_5(\mu)}{N_c}.$$

$$r_\chi = \frac{2m_{P_2}^2}{m_c(m_u + m_q)},$$

- (S+P)(S-P)
- Factorizable

Resonances dominated

$$B_S(q^2) = \frac{1}{q^2 - m_S^2 + i m_S \Gamma_S(q^2)}.$$

Predictions of CPV

- **Penguin** contributions are formulated without any new free parameters
  - Either related to tree level (fixed by BRs),
  - Or factorizable and calculable,
  - Or power suppressed
- **Unambiguous** predictions of direct CP asymmetries
- Dominate contribution: $\langle (S+P)(S-P) \rangle$ in P_C and P_E by chiral enhancement

Predictions of Direct CPV (10^{-3})

Modes	A_{CP}(FSI)	A_{CP}(diagram)	A_{CP}^{tree}	A_{CP}^{tot}
$D^0 \to \pi^+\pi^-$	0.02 ± 0.01	0.86	0	0.58
$D^0 \to K^+K^-$	0.13 ± 0.8	−0.48	0	−0.42
$D^0 \to \pi^0\pi^0$	-0.54 ± 0.31	0.85	0	0.05
$D^0 \to K^0\bar{K}^0$	-0.28 ± 0.16	0	1.11	1.38
$D^0 \to \pi^0\eta$	1.43 ± 0.83	−0.16	−0.33	−0.29
$D^0 \to \pi^0\eta'$	-0.98 ± 0.47	−0.01	0.53	1.53
$D^0 \to \eta\eta$	0.50 ± 0.29	−0.71	0.29	0.18
$D^0 \to \eta\eta'$	0.28 ± 0.16	0.25	−0.30	−0.94
$D^+ \to \pi^+\pi^0$		0	0	0
$D^+ \to K^+\bar{K}^0$	-0.51 ± 0.30	−0.38	−0.13	−0.93
$D^+ \to \pi^+\eta$		−0.65	−0.54	−0.26
$D^+ \to \pi^+\eta'$		0.41	0.38	1.18
$D_S^+ \to \pi^0K^+$		0.88	0.32	0.39
$D_S^+ \to \pi^+K^0$		0.52	0.13	0.84
$D_S^+ \to K^+\eta$		−0.19	0.80	0.70
$D_S^+ \to K^+\eta'$		−0.41	−0.45	−1.60

Result of CP asymmetries

- The prediction of difference of CPV in D->KK and D-> pipi in the SM

$$\Delta A_{CP}^{SM} = -1.00 \times 10^{-3}$$

  - Enhanced from naively expectation in SM 10^{-4}
  - The same sign as, but one order of magnitude smaller than experiment $\Delta A_{CP}^{\exp} = (-0.74 \pm 0.15)\%$
- Uncertainty mainly from *<(S+P)(S-P)>* in P_E

$$\Delta A_{CP} = (-0.57 \sim -1.87) \times 10^{-3}$$

- If CPV remains the current central value (~1 %), may be a signal of new physics

Summary (I)

- Propose a theoretical framework for *D->PP* decays based on **factorization**
- Explain branching ratios at tree level
- Unambiguous predictions of direct CP asymmetries in *D->PP* in the SM

$$\Delta A_{CP} = -1.00 \times 10^{-3}$$

- Much smaller than current measurements

Summary (II)

- Our framework is of predictive power
  - Factorization
  - Wilson coefficients and hadronic matrix elements
- In progress, *D->PV, VV*
- New-physics effects on *ΔAcp*
  - combining NP Wilson coefficients
  - with hadronic matrix elements determined in this work.

THANK YOU!

Back-ups

Parameters by global fit

$$\Lambda = 0.56\ \text{GeV}, \quad \chi_{nf} = -0.59, \quad \chi_q^E = 0.11,$$
$$\chi_s^E = 0.18, \quad \chi_q^A = 0.12, \quad \chi_s^A = 0.17,$$
$$S_\pi = -0.50, \quad \phi = -0.62, \quad \phi_q^E = 4.80,$$
$$\phi_s^E = 4.23, \quad \phi_q^A = 4.06, \quad \phi_s^A = 3.48,$$

Numerical results (I)

$$a_1(\pi\pi) = 1.09, \qquad a_2(\pi\pi) = 0.81e^{i147.8^\circ},$$
$$a_1(KK) = 1.10, \qquad a_2(KK) = 0.83e^{i148.2^\circ},$$

$$C_2(\pi\pi) = 1.26, \qquad C_2(KK) = 1.27,$$

$$a_1(\pi\eta') = 1.12 \text{ and } a_2(\pi\eta') = 0.89e^{i149.6^\circ}$$

$$C_2(\pi\eta') = 1.32$$

Numerical Results (II)

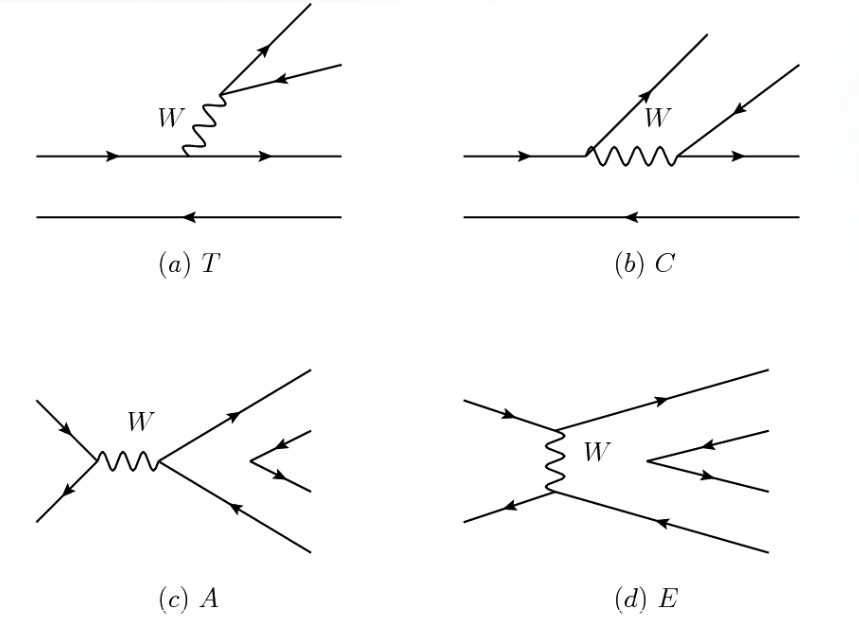
$$T^{\pi\pi} = 2.73, \qquad E^{\pi\pi} = 0.82e^{-i142^\circ},$$
$$T^{KK} = 3.65, \qquad E^{KK} = 1.2e^{-i85^\circ},$$

$$P_C^{\pi\pi} = 0.87e^{i134^\circ}, \qquad P_E^{\pi\pi} = 0.81e^{i111^\circ},$$
$$P_A^{\pi\pi} = 0.25e^{-i43^\circ}, \qquad P_C^{KK} = 1.21e^{i135^\circ},$$
$$P_E^{KK} = 0.87e^{i111^\circ}, \qquad P_A^{KK} = 0.45e^{-i5^\circ},$$

$$\mathcal{T}^{\pi\pi} = 2.14e^{-i14^\circ}, \qquad \mathcal{P}^{\pi\pi} = 1.40e^{i121^\circ},$$
$$\frac{\mathcal{P}^{\pi\pi}}{\mathcal{T}^{\pi\pi}} = 0.66e^{i134^\circ}, \qquad \mathcal{T}^{KK} = 3.94e^{-i18^\circ},$$
$$\mathcal{P}^{KK} = 1.79e^{i114^\circ}, \qquad \frac{\mathcal{P}^{KK}}{\mathcal{T}^{KK}} = 0.45e^{i131^\circ}.$$

Topological diagrams for BRs

- According to weak interactions and flavor flows
- Include all strong interaction effects, involving FSI
- This is a complete set
- Topological diagrammatic approach was studied in the flavor SU(3) symmetry limit



[Cheng & Chiang, 2010]

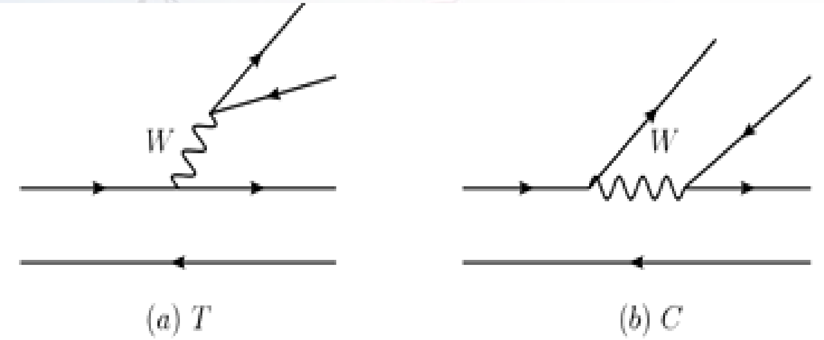
➢ How SU(3) breaking ??

Nambu-Goldstone bosons

- Pion : massless Goldstone boson, and $q\bar{q}$ bound state?
  - **Massless** boson => huge spacetime
    => large separation between qqbar
    => **high mass** due to confinement => contradiction!
  - Reconciliation : Tight bound qqbar, but multi-parton => soft cloud (Lepage, Brodsky 79; Nussinov, Shrock 08; Duraisamy, Kagan 08)
  - **Glauber phase** corresponds to soft cloud [H.n Li, S. Mishima, 09]
  - Pion is unique
  - **SU(3) breaking** effects: distinguish **pions** from other final states

Emission Amplitudes

- Color-favored Tree (T)
- Color-suppressed (C)



$$\langle P_1 P_2 | \mathcal{H}_{eff} | D \rangle_{T,C} = \frac{G_F}{\sqrt{2}} V_{CKM} a_{1,2}(\mu) f_{P_2} (m_D^2 - m_{P_1}^2) F_0^{DP_1}(m_{P_2}^2)$$

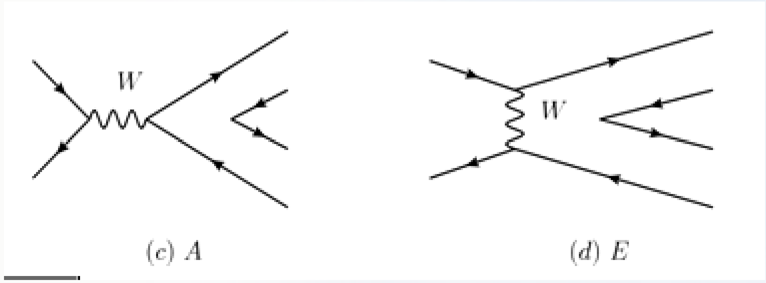
$$a_1(\mu) = C_2(\mu) + \frac{C_1(\mu)}{N_c},$$

$$a_2(\mu) = C_1(\mu) + C_2(\mu)\left[\frac{1}{N_c} + \chi_{nf} e^{i\phi}\right],$$

Non-factorizable contribution

Relative phase by FSI

$$\mu = \sqrt{\Lambda m_D (1 - r_2^2)}, \quad r_2 = m_{P_2}^2 / m_D^2$$



W-annihilation (A)
W-exchange (E)

$$\langle P_1 P_2 | \mathcal{H}_{\rm eff} | D \rangle_{E,A} = \frac{G_F}{\sqrt{2}} V_{\rm CKM} b_{q,s}^{E,A}(\mu) f_D m_D^2 \left(\frac{f_{P_1} f_{P_2}}{f_\pi^2} \right)$$

Dominated by **non-factorizable** contribution

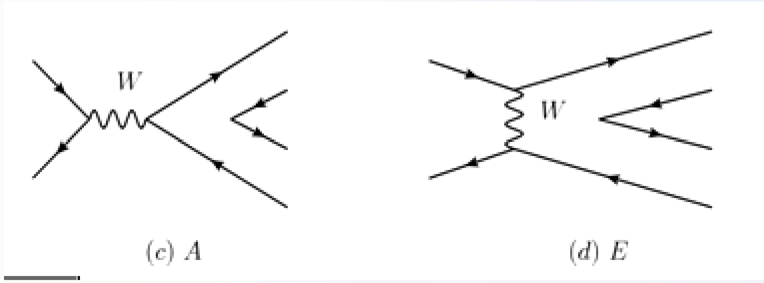
$$b_{q,s}^{A}(\mu) = C_1(\mu) \chi_{q,s}^{A} e^{i\phi_{q,s}^{A}}$$
$$b_{q,s}^{E}(\mu) = C_2(\mu) \chi_{q,s}^{E} e^{i\phi_{q,s}^{E}}$$

E>A

Quark pair from vaccum

$$\chi^A \sim \chi^E$$

- Factorizable contribution neglected by helicity suppression



W-annihilation (A)
W-exchange (E)

$$\langle P_1 P_2 | \mathcal{H}_{\rm eff} | D \rangle_{E,A} = \frac{G_F}{\sqrt{2}} V_{\rm CKM} b_{q,s}^{E,A}(\mu) f_D m_D^2 \left(\frac{f_{P_1} f_{P_2}}{f_\pi^2} \right)$$

Dominated by **non-factorizable** contribution

$$b_{q,s}^A(\mu) = C_1(\mu) \chi_{q,s}^A e^{i\phi_{q,s}^A}$$
$$b_{q,s}^E(\mu) = C_2(\mu) \chi_{q,s}^E e^{i\phi_{q,s}^E}$$

SU(3) breaking effects

large $Br(D^0 \to K^0 \overline{K^0})$

$$\mu = \sqrt{\Lambda m_D (1 - r_1^2)(1 - r_2^2)},$$

$$r_{1,2} = m_{P_1,P_2}/m_D$$

$$\chi_q \neq \chi_s$$

Emission penguins

$$P_T = a_3(\mu)\langle P_2|(\bar{q}q)_{V-A}|0\rangle\langle P_1|(\bar{u}c)_{V-A}|D\rangle$$
$$+ a_5(\mu)\langle P_2|(\bar{q}q)_{V+A}|0\rangle\langle P_1|(\bar{u}c)_{V-A}|D\rangle,$$
$$= [a_3(\mu) - a_5(\mu)]f_{P_2}(m_D^2 - m_{P_1}^2)F_0^{DP_1}(m_{P_2}^2),$$

$$a_3(\mu) = C_3(\mu) + \frac{C_4(\mu)}{N_c}, \qquad a_5(\mu) = C_5(\mu) + \frac{C_6(\mu)}{N_c},$$

$$P_C = a_4(\mu)\langle P_2|(\bar{u}q)_{V-A}|0\rangle\langle P_1|(\bar{q}c)_{V-A}|D\rangle$$
$$- 2a_6(\mu)\langle P_2|(\bar{u}q)_{S+P}|0\rangle\langle P_1|(\bar{q}c)_{S-P}|D\rangle$$
$$= [a_4(\mu) + a_6(\mu)r_\chi]f_{P_2}(m_D^2 - m_{P_1}^2)F_0^{DP_1}(m_{P_2}^2),$$

$$r_\chi = \frac{2m_{P_2}^2}{m_c(m_u + m_q)},$$

$$a_4(\mu) = C_4(\mu) + C_3(\mu)\left[\frac{1}{N_c} + \chi_{nf}e^{i\phi}\right],$$
$$a_6(\mu) = C_6(\mu) + C_5(\mu)\left[\frac{1}{N_c} + \chi_{nf}e^{i\phi}\right].$$

Annihilation Penguins

$$P_A = [C_4(\mu) + C_6(\mu)]\chi^A_{q,s} e^{i\phi^A_{q,s}} f_D m_D^2 \left(\frac{f_{P_1} f_{P_2}}{f_\pi^2}\right).$$

Non-factorizable

$$P_E = C_3(\mu)\chi^E_{q,s} e^{i\phi^E_{q,s}} f_D m_D^2 \left(\frac{f_{P_1} f_{P_2}}{f_\pi^2}\right)$$

$$+ 2\left[C_6(\mu) + \frac{C_5(\mu)}{N_c}\right] g_S B_S(m_D^2) m_S \bar{f}_S f_D \frac{m_D^2}{m_c},$$

← Non-factorizable

← •(S+P)(S-P) •Factorizable

Resonances dominated

$$B_S(q^2) = \frac{1}{q^2 - m_S^2 + i m_S \Gamma_S(q^2)}.$$

- Quark loops

$$C_{3,5}(\mu) \to C_{3,5}(\mu) - \frac{\alpha_s(\mu)}{8\pi N_c} \sum_{q=d,s} \frac{\lambda_q}{\lambda_b} C^{(q)}(\mu, \langle l^2 \rangle),$$

$$C_{4,6}(\mu) \to C_{4,6}(\mu) + \frac{\alpha_s(\mu)}{8\pi} \sum_{q=d,s} \frac{\lambda_q}{\lambda_b} C^{(q)}(\mu, \langle l^2 \rangle),$$

$$C^{(q)}(\mu, \langle l^2 \rangle) = \left[G^{(q)}(\mu, \langle l^2 \rangle) - \frac{2}{3} \right] C_2(\mu),$$

$$G^{(q)}(\mu, \langle l^2 \rangle) = -4 \int_0^1 dx x(1-x) \ln \frac{m_q^2 - x(1-x)\langle l^2 \rangle}{\mu^2}.$$

- Magnetic penguins

$$C_{3,5}(\mu) \to C_{3,5}(\mu) + \frac{\alpha_s(\mu)}{8\pi N_c} \frac{2m_c^2}{\langle l^2 \rangle} C_{8g}^{\text{eff}}(\mu),$$

$$C_{4,6}(\mu) \to C_{4,6}(\mu) - \frac{\alpha_s(\mu)}{8\pi} \frac{2m_c^2}{\langle l^2 \rangle} C_{8g}^{\text{eff}}(\mu),$$

Cabibbo-favored BRs
well consistent with data

Modes	Br(FSI)	Br(diagram)	Br(pole)	Br(exp)	Br(this work)
$D^0 \to \pi^0 \bar{K}^0$	1.35	2.36 ± 0.08	2.4 ± 0.7	2.38 ± 0.09	2.41
$D^0 \to \pi^+ K^-$	4.03	3.91 ± 0.17	3.9 ± 1.0	3.891 ± 0.077	3.70
$D^0 \to \bar{K}^0 \eta$	0.80	0.98 ± 0.05	0.8 ± 0.2	0.96 ± 0.06	1.00
$D^0 \to \bar{K}^0 \eta'$	1.51	1.91 ± 0.09	1.9 ± 0.3	1.90 ± 0.11	1.73
$D^+ \to \pi^+ \bar{K}^0$	2.51	3.08 ± 0.36	3.1 ± 2.0	3.074 ± 0.096	3.22
$D_S^+ \to K^+ \bar{K}^0$	4.79	2.97 ± 0.32	3.0 ± 0.9	2.98 ± 0.08	3.00
$D_S^+ \to \pi^+ \eta$	1.33	1.82 ± 0.32	1.9 ± 0.5	1.84 ± 0.15	1.65
$D_S^+ \to \pi^+ \eta'$	5.89	3.82 ± 0.36	4.6 ± 0.6	3.95 ± 0.34	3.44
$D_S^+ \to \pi^+ \pi^0$		0	0	<0.06	0

Doubly Cabibbo-Suppressed BRs

Modes	Br(diagram)	Br(pole)	Br(exp)	Br(this work)
$D^0 \to \pi^0 K^0$	0.67 ± 0.02	0.6 ± 0.2		0.69
$D^0 \to \pi^- K^+$	1.12 ± 0.05	1.6 ± 0.4	1.48 ± 0.07	1.67
$D^0 \to K^0 \eta$	0.28 ± 0.02	0.22 ± 0.05		0.29
$D^0 \to K^0 \eta'$	0.55 ± 0.03	0.5 ± 0.1		0.50
$D^+ \to \pi^+ K^0$	1.98 ± 0.22	1.7 ± 0.5		2.38
$D^+ \to \pi^0 K^+$	1.59 ± 0.15	2.2 ± 0.4	1.72 ± 0.19	1.97
$D^+ \to K^+ \eta$	0.98 ± 0.04	1.2 ± 0.2	1.08 ± 0.17[a]	0.66
$D^+ \to K^+ \eta'$	0.91 ± 0.17	1.0 ± 0.1	1.76 ± 0.22[b]	1.14
$D_S^+ \to K^+ K^0$	0.38 ± 0.04	0.7 ± 0.4		0.63