DIRECT CP ASYMMETRIES IN HADRONIC D DECAYS

Fu-Sheng Yu

Co-tutors: Prof. Cai-Dian Lu (IHEP, Beijing)
Dr. Emi Kou (LAL, Orsay)

5th FCPPL workshop

arXiv:1203.3120[hep-ph]

Outline

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

Evidence of CPV

- First evidence of CP violation in charmed meson decays by LHCb, with 3.5 σ [PRL. 108 (2012) 111602]

$$\Delta A_{CP}^{exp} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)$$
$$= [-0.82 \pm 0.21(\text{stat}) \pm 0.11(\text{syst})]\%$$

- Confirmed by CDF , with 2.7 σ [CDF note 10784]

$$\Delta A_{CP} = [-0.62 \pm 0.21(\text{stat}) \pm 0.10(\text{syst})]\%$$

- Naively expected much smaller in the SM

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

- Necessary to predict more precisely in the SM.

Dynamics of D decays

- To predict CPV, we have to well understand the important decay mechanism.
- At first, branching ratios should be well explained

➢ ***A long-standing puzzle:***

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

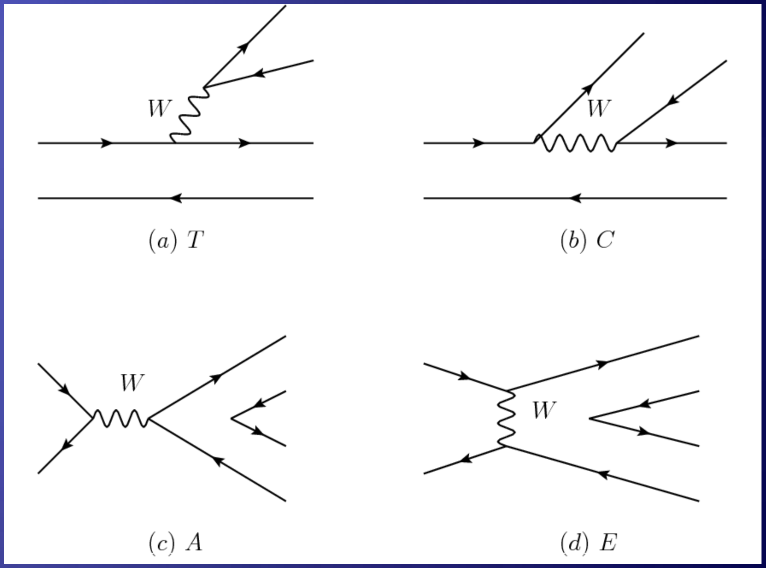
- *R=1* in the SU(3) flavor symmetry limit
- Imply large **SU(3) breaking** effects

Guidelines

- Framework: topological amplitudes in **factorization** hypothesis:
  - Short-distance dynamics: Wilson coefficients
  - Long-distance dynamics: hadronic matrix elements
- Introduce **non-perturbative** parameters in hadronic matrix elements
  - Charm mass $m_c \approx 1.3$ GeV , not reliable for perturbation in coupling constant and $1/m_c$
- Include large **SU(3) breaking effects**.

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 ??

Mode-dependent dynamics

SU(3) breaking effects

- **Evolution of Wilson coefficients** depending on masses of decay products
  - Difference of mass ratios $\frac{m_\pi}{m_D}$ vs $\frac{m_K}{m_D}$ 　mK~0.5 GeV　mD~1.8 GeV
  - Especially for the modes with η′ involved 　Mη′~1 GeV
- **Glauber strong phase** associated with **pion** in nonfactorizable amplitudes [H.n Li, S. Mishima, 2009]
  - Pion: as a massless Goldstone boson, and as a $q\bar{q}$ bound state ?

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

Branching ratios

Include important dynamics

For SU(3) breaking effects

Cabibbo-favored BRs
well consistent with data

Modes	Br(FSI)	Br(diagram)	Br(pole)	Br(exp)	Br(this work)
$D^0 \to \pi^0 \overline{K}^0$	1.35	2.36±0.08	2.4 ± 0.7	2.38±0.09	2.37
$D^0 \to \pi^+ K^-$	4.03	3.91±0.17	3.9 ± 1.0	3.891±0.077	3.71
$D^0 \to \overline{K}^0 \eta$	0.80	0.98±0.05	0.8 ± 0.2	0.96±0.06	1.00
$D^0 \to \overline{K}^0 \eta'$	1.51	1.91±0.09	1.9 ± 0.3	1.90±0.11	1.68
$D^+ \to \pi^+ \overline{K}^0$	2.51	3.08±0.36	3.1 ± 2.0	3.074±0.096	3.17
$D_S^+ \to K^+ \overline{K}^0$	4.79	2.97±0.32	3.0 ± 0.9	2.98±0.08	2.99
$D_S^+ \to \pi^+ \eta$	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

Cabibbo-suppressed BRs our advantage

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	1.44 ⟵
$D^0 \to K^+K^-$	4.56	1.92±0.08	3.0 ± 0.8	4.07±0.10	4.19 ⟵
$D^0 \to K^0\overline{K}^0$	0.93	0	0.3 ± 0.1	0.320±0.038	0.35
$D^0 \to \pi^0\pi^0$	1.16	1.35±0.05	0.8 ± 0.2	0.81±0.05	0.55
$D^0 \to \pi^0\eta$	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	0.64
$D^0 \to \eta\eta$	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	1.52
$D^+ \to \pi^+\pi^0$	1.7	0.88±0.10	1.0 ± 0.5	1.18±0.07	0.88
$D^+ \to K^+\overline{K}^0$	8.6	5.46±0.53	8.4 ± 1.6	6.12±0.22	5.97
$D^+ \to \pi^+\eta$	3.6	1.48±0.26	1.6 ± 1.0	3.54±0.21	3.37 ⟵
$D^+ \to \pi^+\eta'$	7.9	3.70±0.37	5.5 ± 0.8	4.68±0.29	4.54 ⟵
$D_S^+ \to \pi^0K^+$	1.6	0.86±0.09	0.5 ± 0.2	0.62±0.23	0.65
$D_S^+ \to \pi^+K^0$	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

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

- 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	1.44
$D^0 \to K^+K^-$	4.56	1.92±0.08	3.0 ± 0.8	4.07±0.10	4.19

- Large SU(3) breaking effects
  - Glauber phase associated with pions
    - dominate source of the difference between these two modes

Must Explain BRs well

otherwise, some important dynamics may be missed

↓

penguin parameterization and predict direct CP asymmetries

Direct CP asymmetry

- Definition:

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

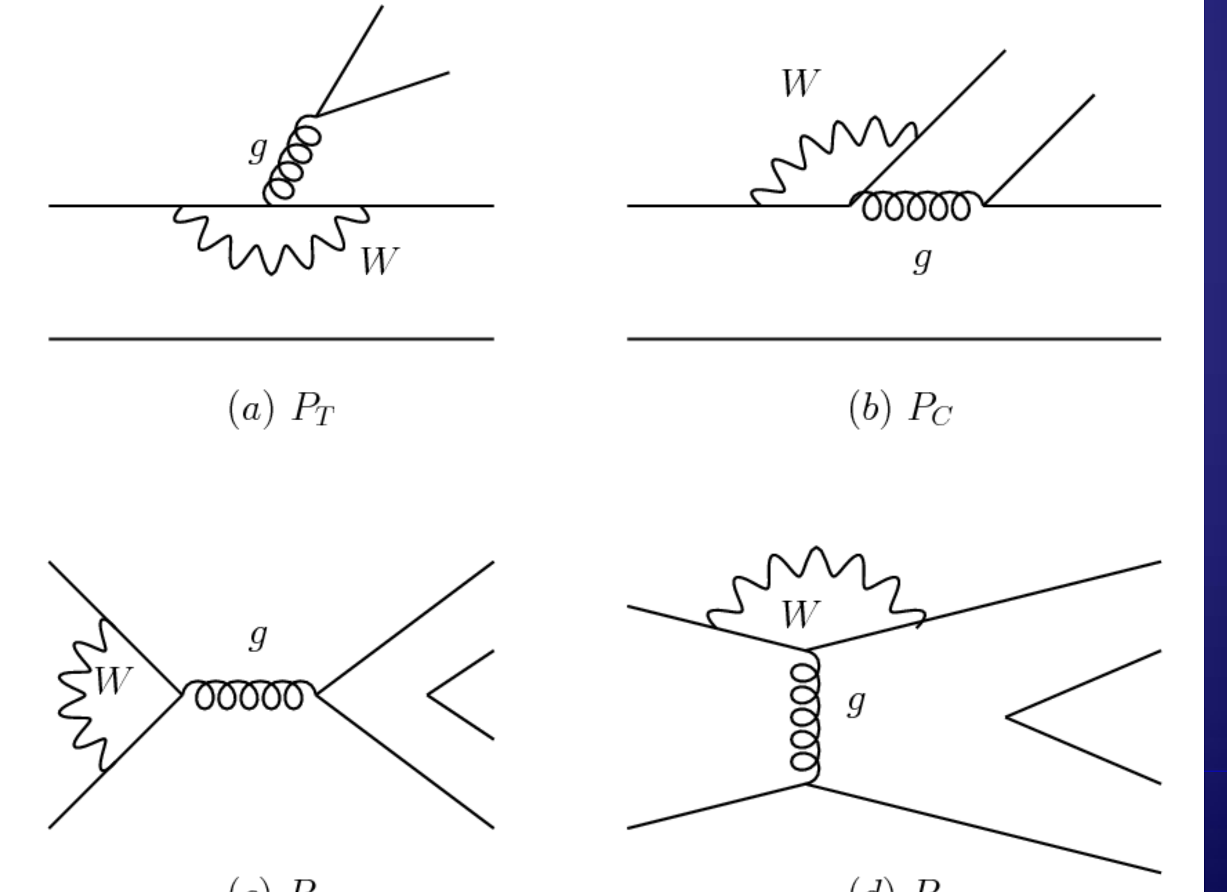
- Occurs only in singly Cabibbo-suppressed decays
- Interference of Tree and Penguin contributions

$$A(D \to f) = V_{cd}^{*} V_{ud} T - V_{cb}^{*} V_{ub} P$$

$$V_{CKM} = \begin{pmatrix} 1-\lambda^2/2-\lambda^4/8 & \lambda & A\lambda^3(\bar\rho - i\bar\eta) + A\lambda^5(\bar\rho - i\bar\eta)/2 \\ -\lambda + A^2\lambda^5[1-2(\bar\rho + i\bar\eta)]/2 & 1-\lambda^2/2-\lambda^4(1+4A^2)/8 & A\lambda^2 \\ A\lambda^3(1-\bar\rho - i\bar\eta) & -A\lambda^2 + A\lambda^4[1-2(\bar\rho + i\bar\eta)]/2 & 1-A^2\lambda^4/2 \end{pmatrix}$$

Penguin topologies

- All topological penguin diagrams for D->PP



$(a)\ P_T$ $(b)\ P_C$ $(c)\ P_A$ $(d)\ P_E$

Penguin parameterization

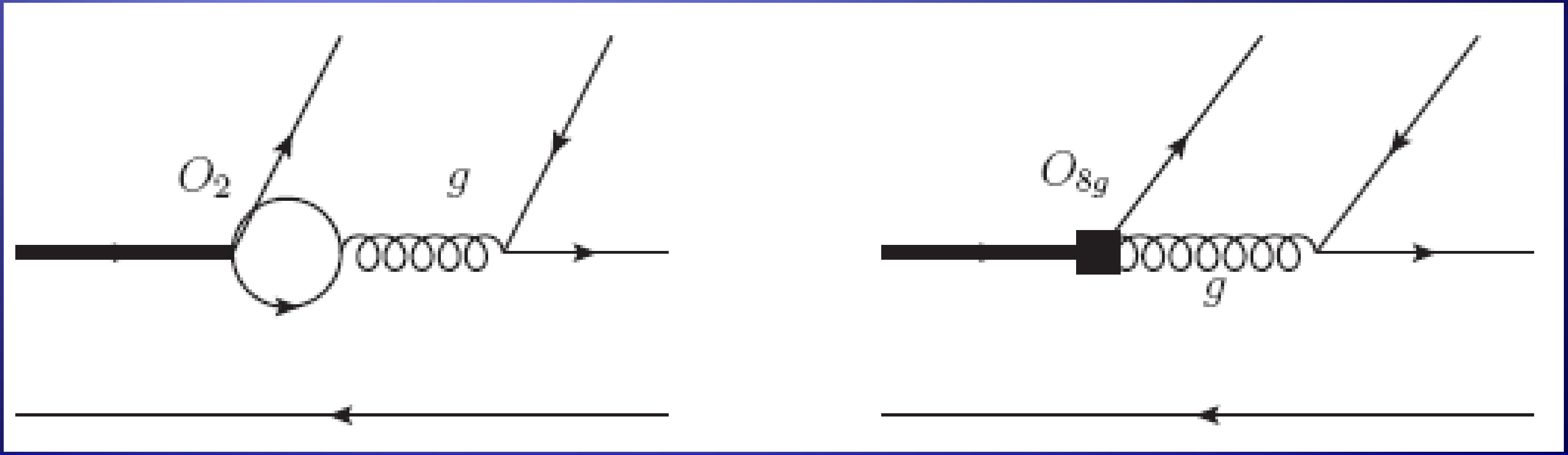
- Long-distance hadronic parameters, related to tree level, fixed by the data of branching ratios
- Combine the short-distance dynamics associated with penguin operators
- Then predict direct CP asymmetries

Strategy: relate penguin to tree

- At tree level, operators are all *(V-A)(V-A)*
- For penguins, the hadronic matrix elements with *(V-A)(V-A)* operators are the same as tree level
- *(V-A)(V+A)* can be related to tree by a sign, since either *V* or *A* contribute to D->PP
- *(S-P)(S+P)* are different and subtle
- Related to tree parameters by chiral enhancement, or neglected by power suppression

Quark loops & Magnetic penguin

- quark loops and magnetic penguin are absorbed into short-distance Wilson coefficients



Predictions

- Penguin matrix elements are either related to tree matrix elements (fixed by BRs),

  or factorizable and calculable, or power suppressed, if not able to be related
- formulate penguin contribution without introducing additional free parameters
- **Unambiguous** predictions of direct CP asymmetries

Predictions of Direct CP asymmetries

Modes	a_{CP}(FSI)	a_{CP}(diagram)	a_{CP}^{tree}	$a_{CP}^{tot}(\times 10^{-3})$
$D^0 \to \pi^+\pi^-$	0.02 ± 0.01	0.86	0	0.74 ⬅
$D^0 \to K^+K^-$	0.13 ± 0.8	-0.48	0	-0.54 ⬅
$D^0 \to \pi^0\pi^0$	-0.54 ± 0.31	0.85	0	0.26
$D^0 \to K^0\overline{K}^0$	-0.28 ± 0.16	0	0.69	0.90
$D^0 \to \pi^0\eta$	1.43 ± 0.83	-0.16	-0.29	-0.61
$D^0 \to \pi^0\eta'$	-0.98 ± 0.47	-0.01	0.43	1.67
$D^0 \to \eta\eta$	0.50 ± 0.29	-0.71	0.29	0.18
$D^0 \to \eta\eta'$	0.28 ± 0.16	0.25	-0.30	0.97
$D^+ \to \pi^+\pi^0$		0	0	-0.23
$D^+ \to K^+\overline{K}^0$	-0.51 ± 0.30	-0.38	-0.08	-0.93
$D^+ \to \pi^+\eta$		-0.65	-0.46	0.63
$D^+ \to \pi^+\eta'$		0.41	0.30	1.28
$D_S^+ \to \pi^0K^+$		0.88	0.17	0.76
$D_S^+ \to \pi^+K^0$		0.52	-0.01	0.87
$D_S^+ \to K^+\eta$		-0.19	0.75	0.76
$D_S^+ \to K^+\eta'$		-0.41	-0.48	1.83

Difference of CP asymmetries

- The prediction in the SM

$$\Delta A_{CP}^{SM} \equiv A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = -0.13\%$$

- Enhanced from naively expectation in SM 10^{-4}

- LHCb $\Delta A_{CP} = [-0.82 \pm 0.24]\%$
- CDF $\Delta A_{CP} = [-0.62 \pm 0.23]\%$

- The prediction is still smaller than experimental measurements
- If CPV remains the current central value (~1 %), may be a signal of new physics

Summary

- Explain branching ratios at tree level
- Parameterize penguin contributions, related to tree amplitudes under factorization hypothesis
  - Fix hadronic parameters using data of branching ratios
  - Combine short-distance dynamics associated with penguin operators
- Unambiguous predictions of direct CP asymmetries in D->PP in the SM
- Especially $\Delta A_{CP}^{SM} = -0.13\%$
- Much smaller than LHCb and CDF measurements

THANK YOU!

Improvement of BRs involving η′

- Benefited from the scale-dependent Wilson coefficients, predictions with all the η′ involved modes are improved, compared to the pole model and diagrammatic approach

Modes	Br(FSI)	Br(diagrammatic)	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	1.84
$D_S^+ \to \pi^+ \eta'$	5.89	3.82±0.36	4.6 ± 0.6	3.95±0.34	3.25
$D^0 \to \pi^0 \eta'$	1.7	0.74±0.02	0.6 ± 0.2	0.91±0.13	0.70
$D^0 \to \eta \eta'$	2.2	1.19±0.07	1.1 ± 0.1	1.05±0.26	1.58
$D^+ \to \pi^+ \eta'$	7.9	3.70±0.37	5.5 ± 0.8	4.68±0.29	4.78 ⬅
$D_S^+ \to K^+ \eta'$	5.2	1.07±0.17	1.4 ± 0.4	1.8±0.5	1.67
$D^+ \to K^+ \eta'$		0.91±0.17	1.0 ± 0.1	1.76±0.22	1.07

Penguin operators

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

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

(V-A)(V-A)

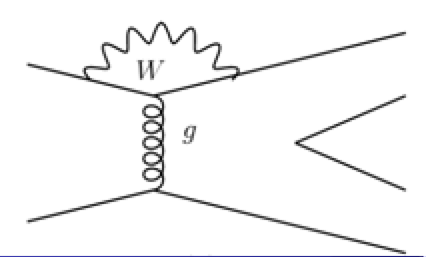
$$O_5 = \sum_{q'=u,d,s} (\bar{u}_\alpha c_\alpha)_{V-A}(\bar{q}'_\beta q'_\beta)_{V+A},$$

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

(V-A)(V+A)

(S+P)(S-P)

Penguin exchange annihilation amplitude



- The hadronic matrix elements with the operators of (S-P)(S+P) are absent in tree level
- No helicity suppression for (S-P)(S+P), so their contributions can not be neglected
- Can not use the hadronic parameters at tree level
- Assumed to be dominated by scalar resonances