CP violation in charm

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Will emphasize comparison with Cheng-Chiang’s approach

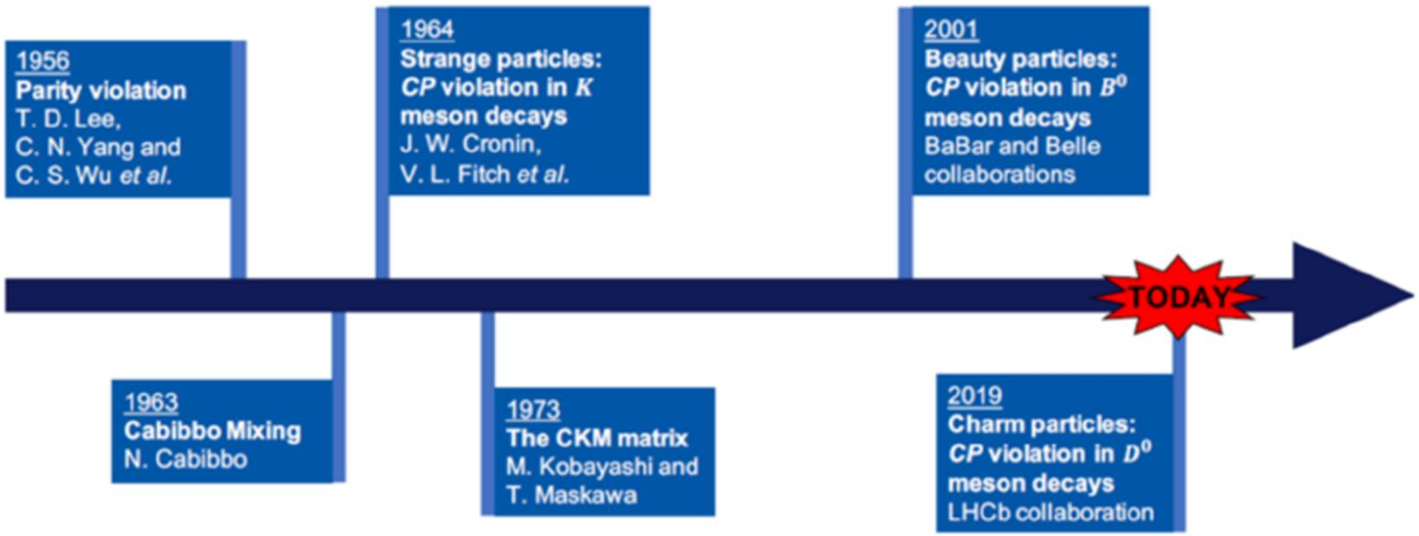
LHCb observes charm CPV

21 March 2019: Discovery of CP violation in charm particle decays.

An important milestone in the history of particle physics.

[$\Delta A_{CP} = (-0.154\pm0.029)\%$]

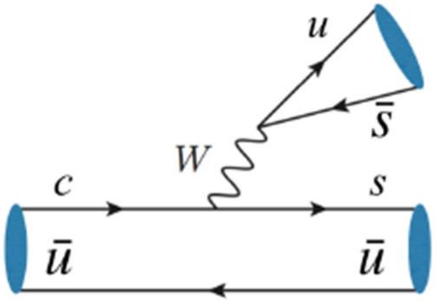
The LHCb collaboration has just presented at the Rencontres de Moriond EW and in a special CERN Seminar the first observation of CP violation in charm particle decays. Quarks can be split into two sectors: those with the same electrical charge as the up quark (up-type quarks, charge +2/3), and those with the same as the down quark (down-type quarks, charge -1/3). Differences in the properties of matter and antimatter, arising from the so-called phenomenon of CP violation, had been observed in the past using the decays of K and B mesons, i.e. of particles that contain strange or beauty quarks, which are both down-type quarks. By contrast, despite decades of experimental searches, CP violation in the decays of charmed particles, i.e. containing the charm quark, which is an up-type quark, escaped detection so far. The result announced today constitutes the first observation of CP violation in decays of a charmed particle.



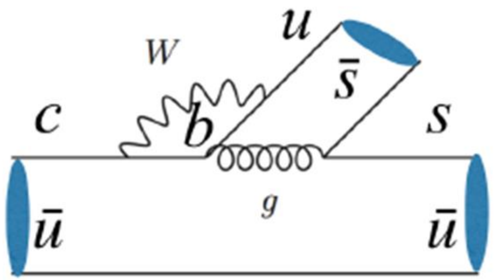
Direct CPV in charm

singly Cabbibo suppressed: SCS

tree v.s. **penguin**



need strong phase between them



$V_{cd}V_{ud}/V_{cs}V_{us}$

λ

$V_{cb}V_{ub}$

weak phase

$\lambda^5 + i\lambda^5$

$$\Delta A_{CP} \equiv A_{CP}(K^- K^+) - A_{CP}(\pi^- \pi^+)$$ ~ 0.01%

Data before 2012

- Large observed DCP ~ 1% signal new physics?

Experiment	$A_{CP}^{D^0 \to K^+K^-}$ (%)	$A_{CP}^{D^0 \to \pi^+\pi^-}$ (%)	ΔA_{CP} (%)
BaBar PRL 100, 061803 (2008)	0.00±0.34±0.13	-0.24±0.52±0.22	N.A.
LHCb PRL 108,111602 (2012)	N.A.	N.A.	-0.82±0.21±0.11
CDF	-0.24±0.22±0.09 PRD 85,012009 (2012) with 6.0 fb^{-1}	+0.22±0.24±0.11 PRD 85,012009 (2012) with 6.0 fb^{-1}	-0.62±0.21±0.10 CHARM (2012) with 9.6 fb^{-1}
Belle preliminary (2012)	-0.32±0.21±0.09	+0.55±0.36±0.09	-0.87±0.41±0.06

- Stimulated lots of theoretical studies!

Range of SM predictions

- Order of magnitude estimate in terms of CKM and Wilson coefficients (Bigi et al): 10E-4
- Topological amplitude with penguin ~ W exchange (Cheng, Chiang); factorization-assisted topological amplitude (Li, Lu, Yu): 10E-3
- Fit to LHCb data (Gronau et al.): 10E-2
- Allowing penguin > tree (Silvestrini et al.): wide

Grossman, Kagan, Nir, '07; Bigi, Paul, '11; Isidori, Kamenik, Ligeti, Perez, '11; Brod, Grossmann, Kagan, Zupan, '11, '12; Feldmann, Nandi, Soni, '12; Bhattarcharya, Gronau, Rosner, '12; Cheng, Chiang, '12; Li, Lu, **FSY**, '12; Franco, Mishima, Silvestrini, '12; Hiller, Jung, Schacht, '12. Khodjamirian, Petrov, 17.

Theoretical difficulty

- Charm quark mass m_C ~ 1.3 GeV not big enough to have small expansion parameters

  $\alpha_S(m_c) \sim 0.3, \quad \Lambda_{QCD}/m_c \sim 0.3$

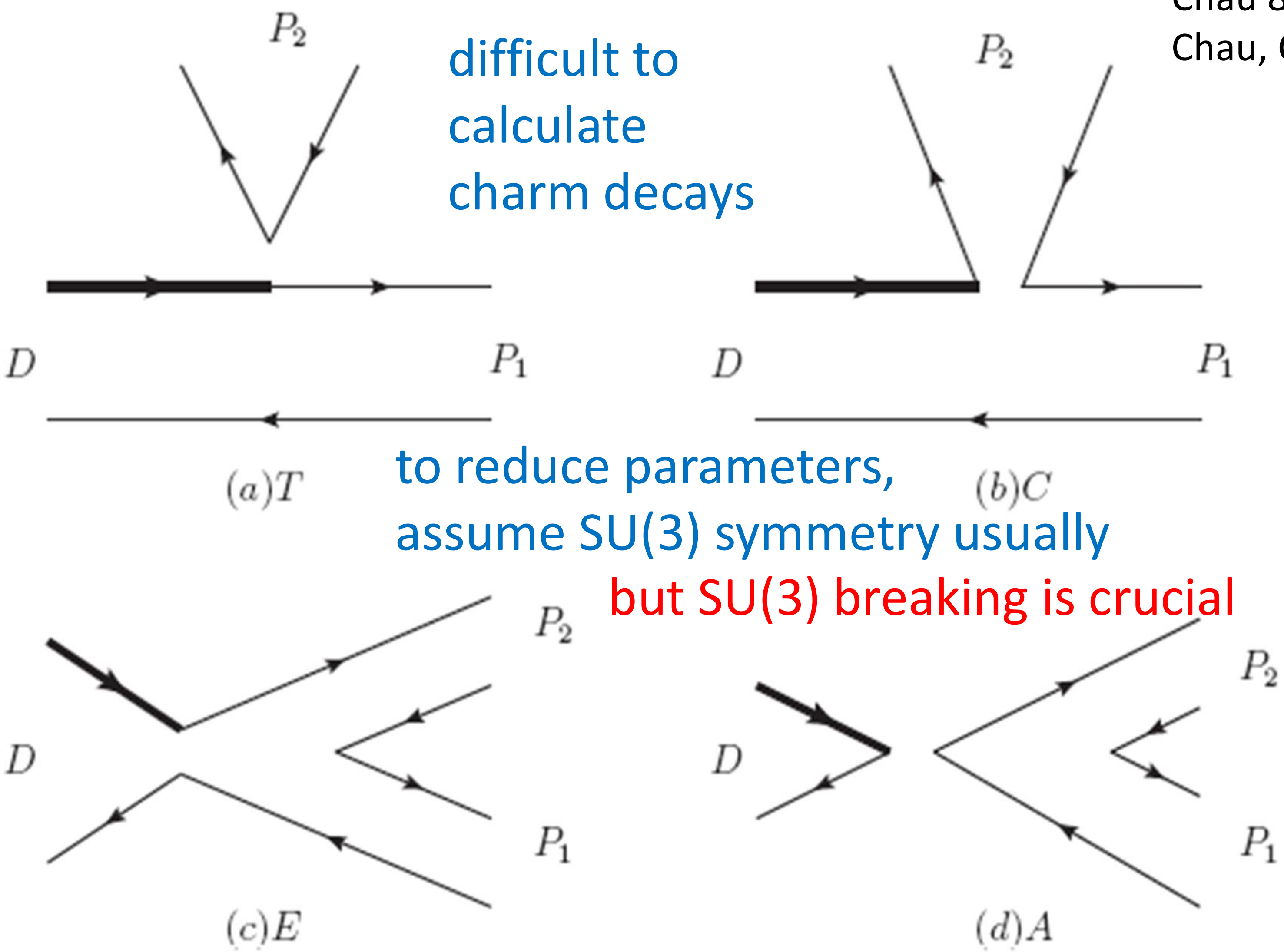
- Perturbation does not apply to D decays
- Soft gluon corrections could make 10-100 times difference (Tseng and Li, 98)
- m_C too heavy to apply chiral perturbation
- Charm decays sensitive to SU(3) symmetry breaking, difficult to estimate

	Br(exp)
$D^0 \to \pi^+\pi^-$	1.45±0.05
$D^0 \to K^+K^-$	4.07±0.10

The most difficult part is how to get penguin in charm decays

Topological diagrams

Chau 80
Chau, Cheng 86



difficult to calculate charm decays

to reduce parameters, assume SU(3) symmetry usually

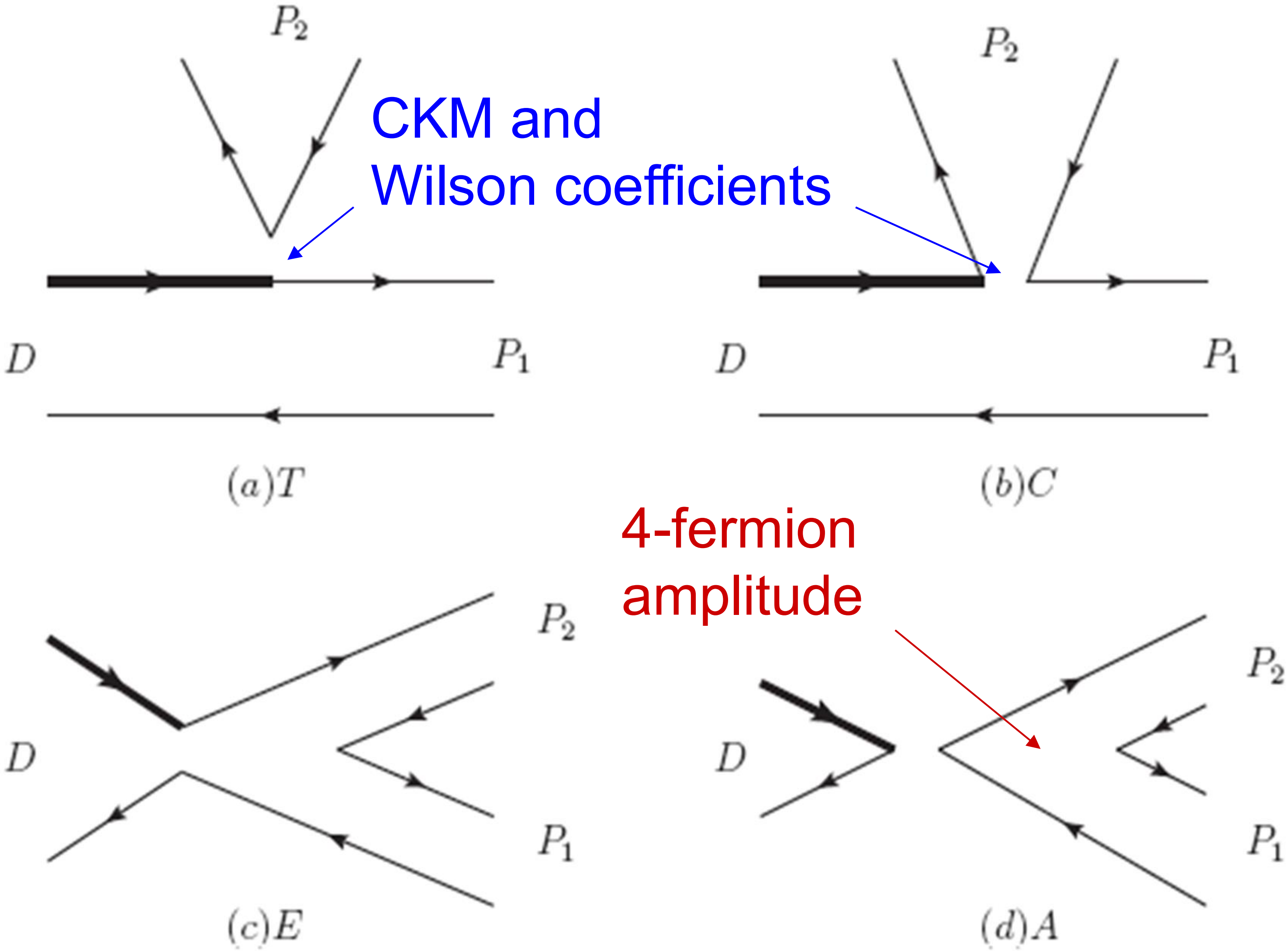
but SU(3) breaking is crucial

Factorization-assisted Topological amplitude

- Factorization of short- and long-distance dynamics into Wilson coefficients and matrix elements of 4-fermion operators
- SU(3) breaking included into matrix elements
- Use abundant data of branching ratios (dominated by trees) to fix parameters
- Penguin either related to tree via matrix elements, factorizable (constrained by other data), or helicity suppressed, if not related
- Predict CP asymmetries

Li, Lu, Yu 1203.3120

Tree topologies



Emission amplitudes

- Standard parameterization of color-favored and color-suppressed

$$\langle P_1 P_2 | \mathcal{H}_{eff} | D \rangle_{T,C}$$

$$= \frac{G_F}{\sqrt{2}} V_{CKM} a_{1,2}(\mu) f_{P_2} (m_D^2 - m_{P_1}^2) F_0^{DP_1}(m_{P_2}^2)$$

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

neglect nonfactorizable contribution due to large factorizable one

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

relative phase between T and C

↑

nonfactorizable contribution

W-exchange & W-annihilation

- For E and A, factorizable contribution helicity suppressed

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

for pi pi final state

differentiate quark pairs from vacuum

sources of SU(3) breaking

$$b^E_{q,s}(\mu) = C_2(\mu) \chi^E_{q,s} e^{i\phi^E_{q,s}}$$

$$b^A_{q,s}(\mu) = C_1(\mu) \chi^A_{q,s} e^{i\phi^A_{q,s}}$$

magnitudes, phases

Cabbibo-suppressed BRs

$\chi^2 = 7.3$ per d.o.f. compared to 87 (SU(3))

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

Penguin parameterization and direct CP asymmetries

Must explain BRs first

Otherwise, some important dynamics may be missed

Penguin operators

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

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

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

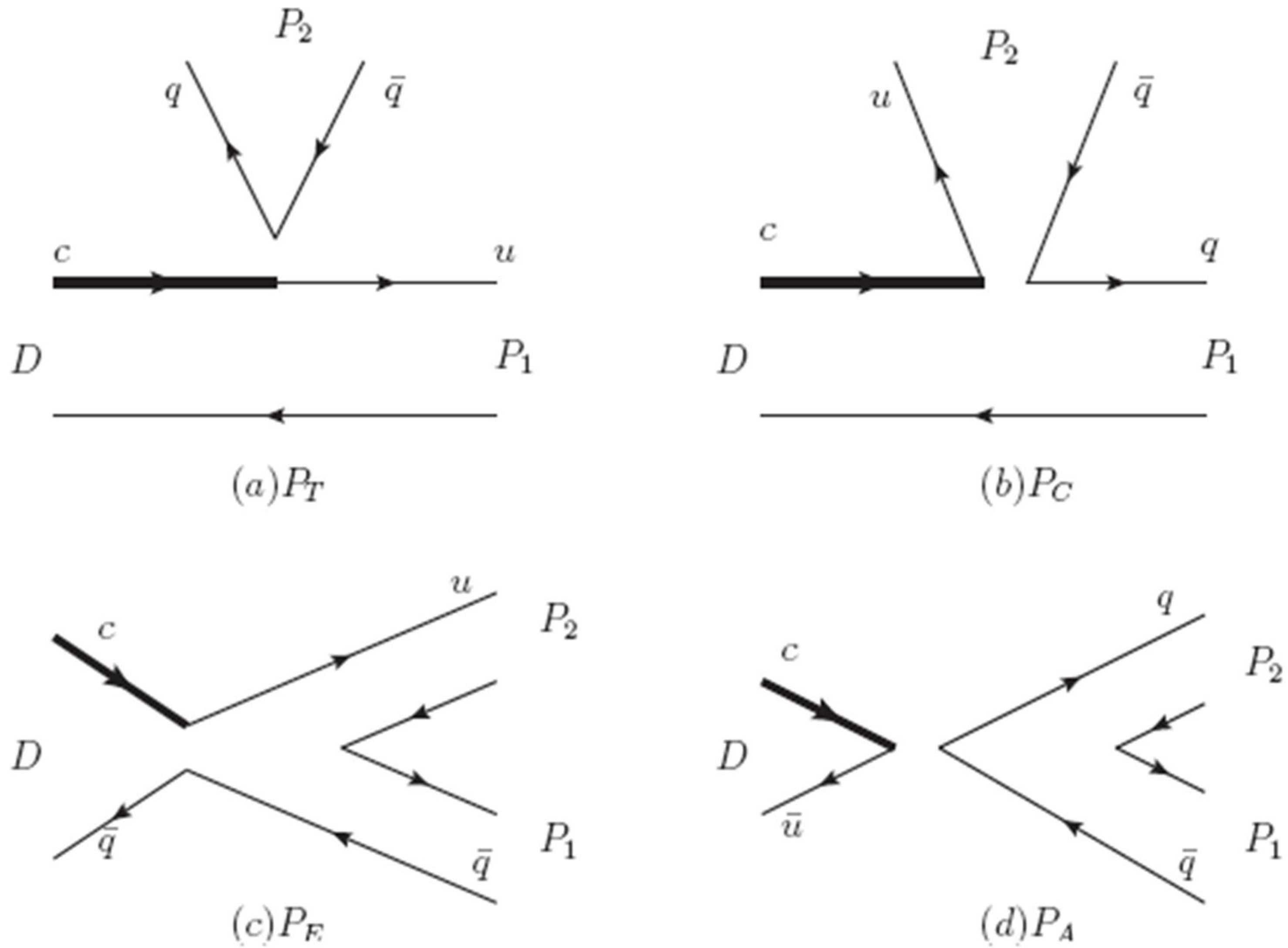
new operators

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

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

contribute to Wilson coefficients

Penguin topologies



Penguin color-favored emission

- Penguin color-favored emission is trivially related to T

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

matrix element same as T

$$a_3(\mu) = C_3(\mu) + \frac{C_4(\mu)}{N_c}$$

$$a_5(\mu) = C_5(\mu) + \frac{C_6(\mu)}{N_c}$$

Penguin annihilation

- O3,O5 negligible
- O4 and O6 contribute to penguin annihilation, and helicity suppression applies

$$\langle P_1(q\bar{q}')P_2(q'\bar{q})|(\bar{u}c)_{V-A}(\bar{q}'q')_{V+A}|D(c\bar{u})\rangle$$
$$= \langle P_1(q\bar{q}')P_2(q'\bar{q})|(\bar{u}c)_{V-A}(\bar{q}'q')_{V-A}|D(c\bar{u})\rangle$$

- Only nonfactorizable contribution, and related to W-annihilation trivially

matrix element same as A

- O4,O6 combined into

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

Penguin exchange

- O3, O5, O6 contribute to penguin exchange. Helicity suppression applies to O3, but not to O5, O6 (relation between PE and E nontrivial)
- New factorizable contribution from O5,O6 exists
- Factorization hypothesis holds

$$\langle P_1(q'\bar{q})P_2(u\bar{q}')|(\bar{u}c)_{V-A}(\bar{q}'q')_{V+A}|D(c\bar{q})\rangle$$

$$= -2\langle P_1(q'\bar{q})P_2(u\bar{q}')|(\bar{u}q')_{S+P}|0\rangle\langle 0|(\bar{q}'c)_{S-P}|D(c\bar{q})\rangle$$

Scalar penguin

- Other process help fix factorizable amplitude
- Assume dominance of scalar resonance

$$\langle P_1 P_2 | \bar{q}_1 q_2 | 0 \rangle = \langle P_1 P_2 | S \rangle \langle S | \bar{q}_1 q_2 | 0 \rangle = g_S B_S(q^2) m_S \bar{f}_S$$

$a_0(1450)$ for the $\pi\eta$, $\pi\eta'$, and $(KK)^{\pm}$ final states

$f_0(1370)$, $f_0(1500)$, and $f_0(1710)$

for the $\pi^0\pi^0$, $\pi^+\pi^-$, $K^0\bar{K}^0$, K^+K^-, and $\eta\eta^{(\prime)}$

$K_0^*(1430)$ for the $K\pi$ and $K\eta^{(\prime)}$ final states

- Formalism work for $\tau \to K\pi\nu_\tau$ decay rate

Parameterization of PE

- Combined with nonfactorizable contribution from O3

$$P_E = C_3(\mu)\chi^E_{q,s} e^{i\phi^E_{q,s}} f_D m_D^2 \left(\frac{f_{P_1} f_{P_2}}{f_\pi^2}\right)$$
$$+ 2\left[C_6(\mu) + \frac{C_5(\mu)}{N_c}\right] g_S B_S(m_D^2) m_S \bar{f}_S f_D \frac{m_D^2}{m_c}$$

Breit-Wigner of scalar resonance

Predictions

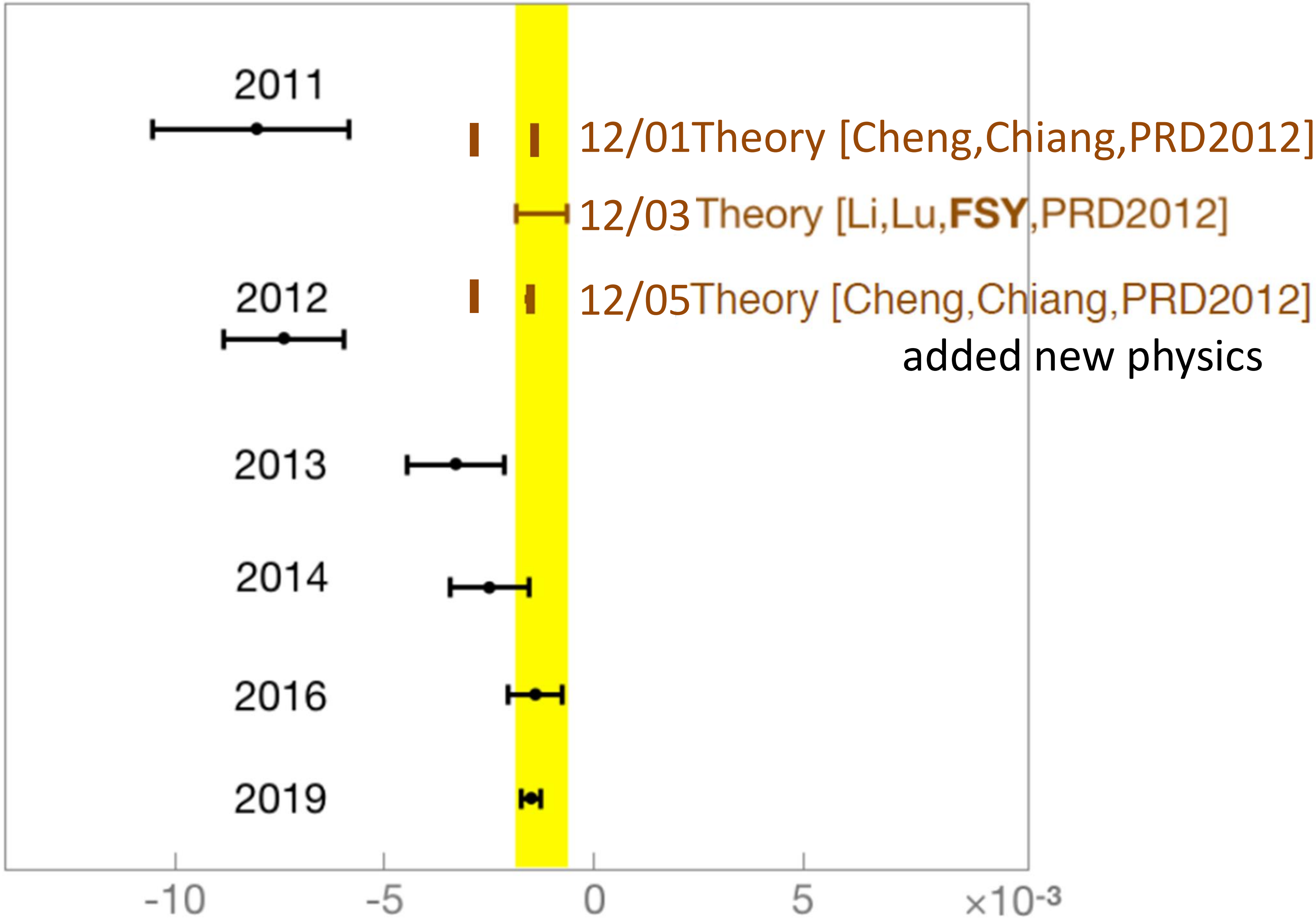
- formulate penguin contributions without introducing additional free parameters
- Penguin matrix elements are either related to tree matrix elements, or factorizable, helicity suppressed, if not related
- If factorizable, scalar resonances dominate and fixed by tau decay
- Unambiguous prediction: $\Delta A_{\rm CP} = -1.00 \times 10^{-3}$
- next mode to measure Acp: $D^+ \to K^+ K^- \pi^+$

Li, Lu, Yu 1903.10638

Direct CP asymmetries

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
$D^0 \to K^0\overline{K}^0$	−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
$D^+ \to K^+\overline{K}^0$	−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

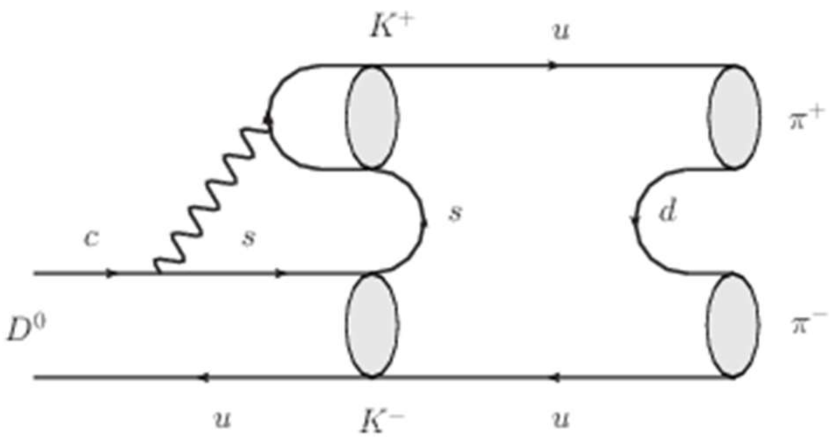
Exp Averages



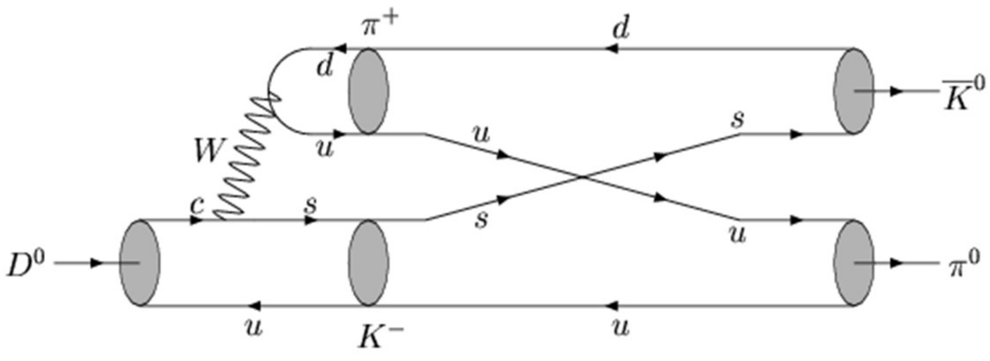
Cheng-Chiang's approach

- Adopt topological amplitudes, so tree and penguin are independent
- Use Cabibbo allowed BRs to determine topological amplitudes T, C, E, A
- Use semileptonic data to determine T(KK), T(pipi) via relevant form factors
- Use singly Cabibbo suppressed BRs of K^+K^-, $\pi^+\pi^-$, $\pi^0\pi^0$ and $K^0\overline{K}^0$ to determine Ed, Es
- Assume major penguin PE=E, get CPV of SCS D decays from T(KK), T(pipi), Ed, Es, PE

Large LD contribution to PE can arise from $D^0 \to K^+K^-$ followed by a resonant like FSI



PE



E

My comment: this is a strong assumption

PE from T(KK), E from T, they differ;
PE not from quark exchange, but E is;
involve different resonances;
difficult to estimate theoretical uncertainty;

tiny error from E ↓

$$\Delta A_{CP} =$$
$$-(0.139 \pm 0.004)\%$$
$$-(0.151 \pm 0.004)\%$$

1205.0589

Long-distance penguin 1909.03063

- Set PE=E, and vary the central values by 20% for magnitude and 30% for phase

small SD from QCDF

$$\left(\frac{P_s + PE_s^{\rm LD}}{T + E + \Delta P}\right)_{\pi\pi} = 0.77\, e^{i114^\circ}, \qquad \left(\frac{P_d + PE_d^{\rm LD}}{T + E - \Delta P}\right)_{KK} = \begin{cases} 0.45\, e^{i137^\circ} \\ 0.45\, e^{i120^\circ} \end{cases}$$

$$a_{CP}^{\rm dir}(\pi^+\pi^-) = (0.80 \pm 0.22) \times 10^{-3},$$

$$a_{CP}^{\rm dir}(K^+K^-) = \begin{cases} (-0.33 \pm 0.14) \times 10^{-3} & \text{Solution I}, \\ (-0.44 \pm 0.12) \times 10^{-3} & \text{Solution II} \end{cases}$$

$$\Delta a_{CP}^{\rm dir} = \begin{cases} (-1.14 \pm 0.26) \times 10^{-3} & \text{Solution I}, \\ (-1.25 \pm 0.25) \times 10^{-3} & \text{Solution II} \end{cases}$$

closer to LLY

Detailed comparison

CC: For Cabibbo-allowed D→PP decays (in units of 10^{-6} GeV)

T = 3.113 ± 0.011 (taken to be real)

CC: 1909.03063

C = (2.767 ± 0.029) exp[i(-151.3±0.3)°]

E = (1.48 ± 0.04) exp[i(120.9±0.4)°]

A= (0.55 ± 0.03) exp[i(23^{+7}_{-10})°]

$$|T_{KK}/T| = 1.269$$

$$|T_{\pi\pi}/T| = 0.964$$

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

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

$$(PE)^{\rm LD} \approx (1.48 \pm 0.30)\, e^{i(120.9\pm 30.0)^\circ}$$

LLY:

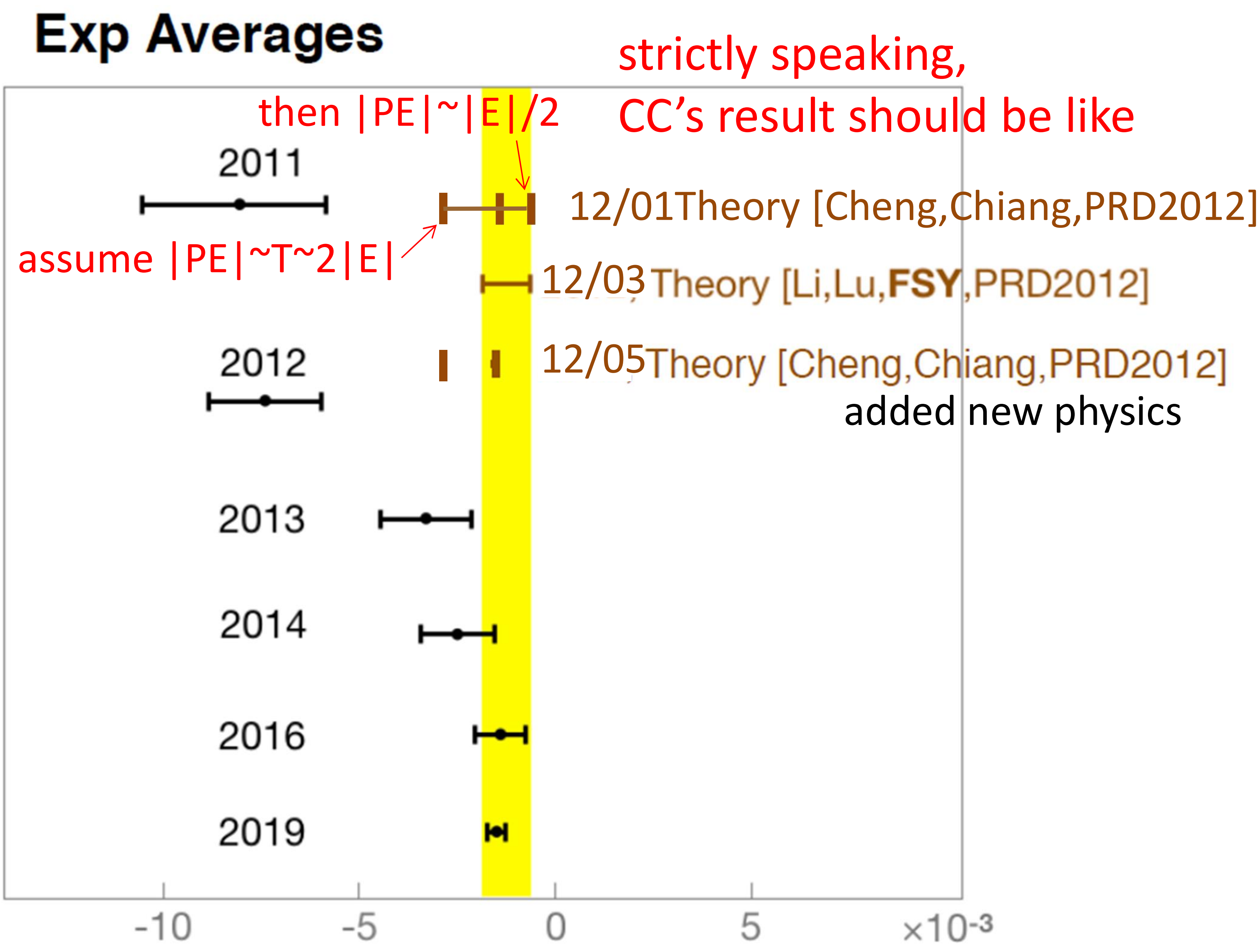
$$T^{\pi\pi} = 2.73, \quad E^{\pi\pi} = 0.82 e^{-i142^\circ},$$

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

Pc more important

$$P_C^{\pi\pi} = 0.87 e^{i134^\circ}, \quad P_E^{\pi\pi} = 0.81 e^{i111^\circ}, \quad P_A^{\pi\pi} = 0.25 e^{-i43^\circ},$$

$$P_C^{KK} = 1.21 e^{i135^\circ}, \quad P_E^{KK} = 0.87 e^{i111^\circ}, \quad P_A^{KK} = 0.45 e^{-i5^\circ},$$


Exp Averages
strictly speaking,
CC's result should be like
then |PE|~|E|/2
2011
12/01Theory [Cheng,Chiang,PRD2012]
assume |PE|~T~2|E|
12/03 Theory [Li,Lu,FSY,PRD2012]
2012
12/05Theory [Cheng,Chiang,PRD2012]
added new physics
2013
2014
2016
2019
-10
-5
0
5
×10-3

Summary

- Factorization provides platform, on which SU(3) breaking can be introduced; and prescription, through which penguin can be related to tree
- Use abundant data of branching ratios to fix hadronic parameters and then predict penguins
- Not just analysis of D->PP, but proposal of framework for general two-body hadronic D decays with predictive power
- Different from Cheng and Chiang's phenomenological approach, but results turn out to be similar

Back-up slides

Penguin color-suppressed emission

- Penguin color-suppressed emission is similar

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

$$a_4(\mu) = C_4(\mu) + C_3(\mu)\left[\frac{1}{N_c} + \chi_{nf}e^{i\phi}\right]$$
$$a_6(\mu) = C_6(\mu) + C_5(\mu)\left[\frac{1}{N_c} + \chi_{nf}e^{i\phi}\right]$$
$$r_\chi = \frac{2m_{P_2}^2}{m_c(m_u + m_q)}$$

- PQCD formula for (S-P)(S+P) nonfactorizable contribution reveals similarity to (V-A)(V-A)