CP Violation in charm

Fu-Sheng Yu

Lanzhou University

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Outline

1. LHCb's measurement is understood in the SM

2. Implication for the next observation of charm CPV

3. New CPV effect in charm decays into neutral kaons

1. First observation of charm CPV

LHCb observes charm CPV

LHCb, PRL122, 211803 (2019)

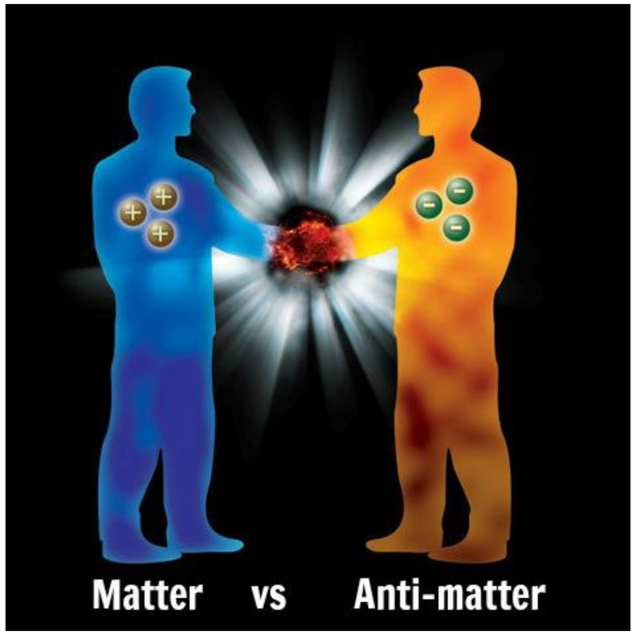
$$\Delta A_{CP} = A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)$$
$$= (-1.54 \pm 0.29) \times 10^{-3}$$

- $> 5\sigma$, **first observation of CPV in charm**

Milestone in particle physics

See Sun's and Cheng's talks

CP Violation



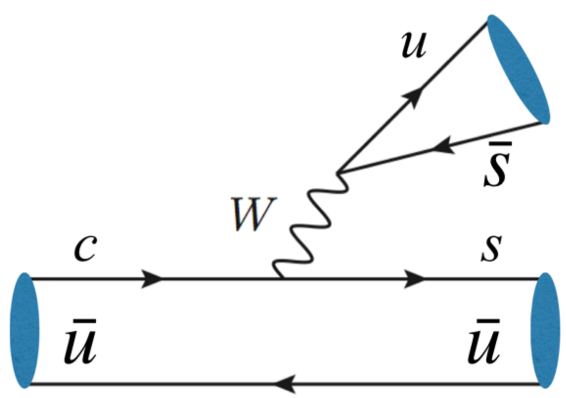
CP: Charge-Parity symmetry

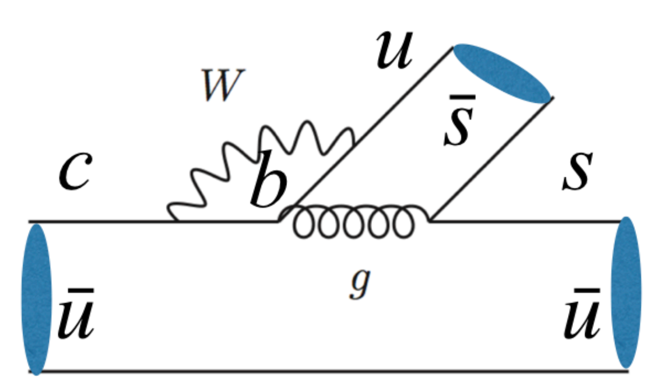
Particle-Antiparticle symmetry

- **Matter-Antimatter asymmetry of the Universe**
- **CP violation** is required by Sakharov conditions [Sakharov, 1967]
- CPV in the SM is not large enough, thus a **window to New Physics**

Direct CPV in charm

tree **v.s.** **penguin**





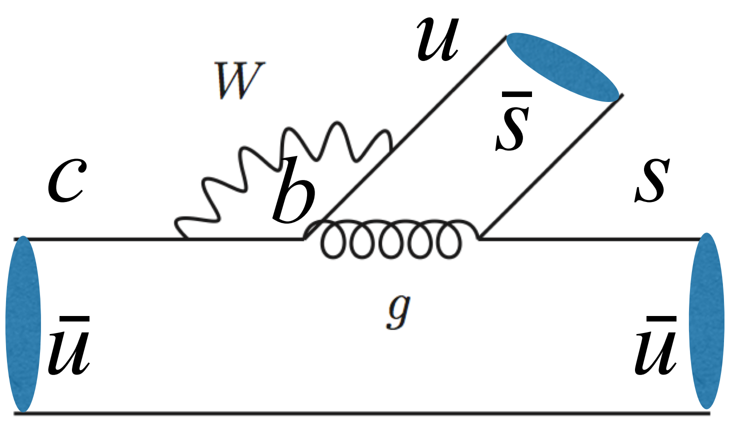
$V_{cd}V_{ud}/V_{cs}V_{us}$ $\quad$ $V_{cb}V_{ub}$

λ $\quad$ $\lambda^5 + i\lambda^5$

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

CPV in SCS decays: tree *v.s.* penguin

- **Ambiguity in penguins**
  - **heavy quark expansion $1/m_c$,** m_c=1.3GeV, **converges slowly** in exclusive decays



★ **$\Delta A_{CP}(K^+K^-, \pi^+\pi^-)$ predicted from 10^{-4} to 10^{-2}**

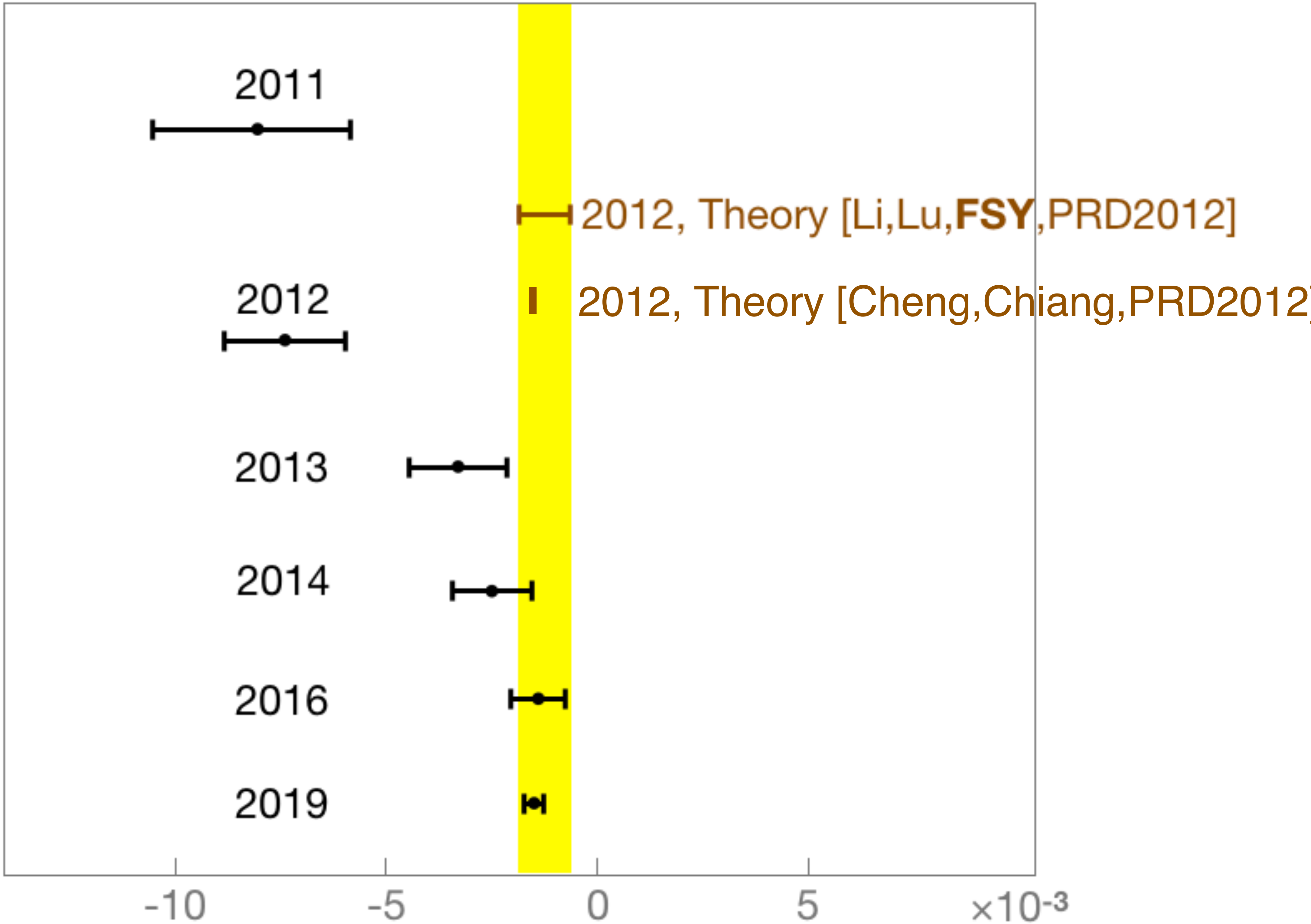
Grossman, Kagan, Nir, '07; Bigi, Paul, '11; Isidori, Kamenik, Ligeti, Perez, '11; Brod, Grossmann, Kagan, Zupan, '11, '12; Feldmann, Nandi, Soni, '12; Bhattarcharya, Gronau, Rosner, '12; Cheng, Chiang, '12; Li, Lu, **FSY**, '12; Franco, Mishima, Silvestrini, '12; Hiller, Jung, Schacht, '12. Khodjamirian,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

The only prediction of O(10^{-3})

Cheng,Chiang,'12 : $(-1.51 \pm 0.04) \times 10^{-3}$

Li, Lu, **FSY**,'12 : $(-0.6 \sim -1.9) \times 10^{-3}$

Exp Averages



Understanding charm CPV

$$\mathcal{A}(D^0 \to K^+K^-) = \lambda_s \mathcal{T}^{KK} + \lambda_b \mathcal{P}^{KK},$$

$$\mathcal{A}(D^0 \to \pi^+\pi^-) = \lambda_d \mathcal{T}^{\pi\pi} + \lambda_b \mathcal{P}^{\pi\pi},$$

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

$$r = |\lambda_b/\lambda_{d,s}|$$

$$2r\sin\gamma = 1.5 \times 10^{-3}$$

$$\Delta A_{CP} = (-1.54 \pm 0.29) \times 10^{-3}$$

→

$$\left(\frac{|\mathcal{P}^{KK}|}{|\mathcal{T}^{KK}|} \sin\delta^{KK} + \frac{|\mathcal{P}^{\pi\pi}|}{|\mathcal{T}^{\pi\pi}|} \sin\delta^{\pi\pi} \right) \approx 1$$

Li, Lu, **FSY**, PRD86,036012(2012); 1903.10638

$$\left(\frac{|\mathcal{P}^{KK}|}{|\mathcal{T}^{KK}|}\sin\delta^{KK} + \frac{|\mathcal{P}^{\pi\pi}|}{|\mathcal{T}^{\pi\pi}|}\sin\delta^{\pi\pi}\right) \approx 1 \quad \rightarrow \quad \boxed{\frac{|\mathcal{P}|}{|\mathcal{T}|}\sin\delta \sim 1/2}$$

topological approach

Li, Lu, **FSY**, '12

$$\frac{\mathcal{P}^{\pi\pi}}{\mathcal{T}^{\pi\pi}} = 0.66 e^{i134^\circ}, \quad \text{and} \quad \frac{\mathcal{P}^{KK}}{\mathcal{T}^{KK}} = 0.45 e^{i131^\circ}$$

$$A_{CP} \sim 10^{-3}$$

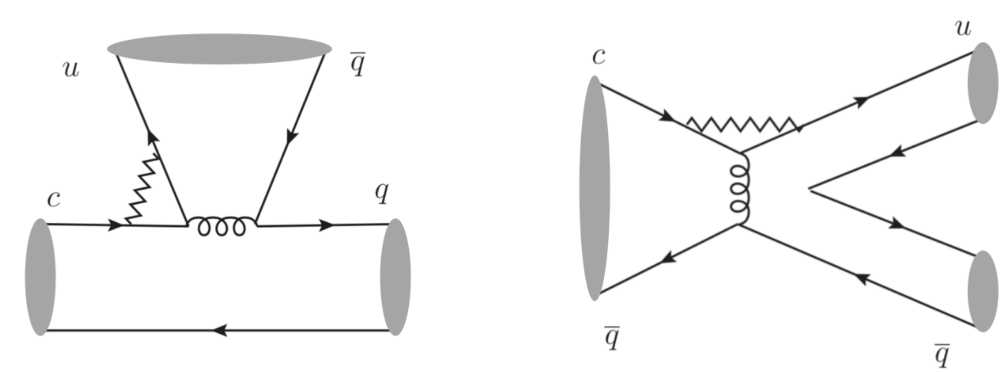
Perturbative QCD

Khodjamirian, Petrov, '17

$$\frac{|\mathcal{P}|}{|\mathcal{T}|} \sim \frac{\alpha_s}{\pi} \sim 0.1$$

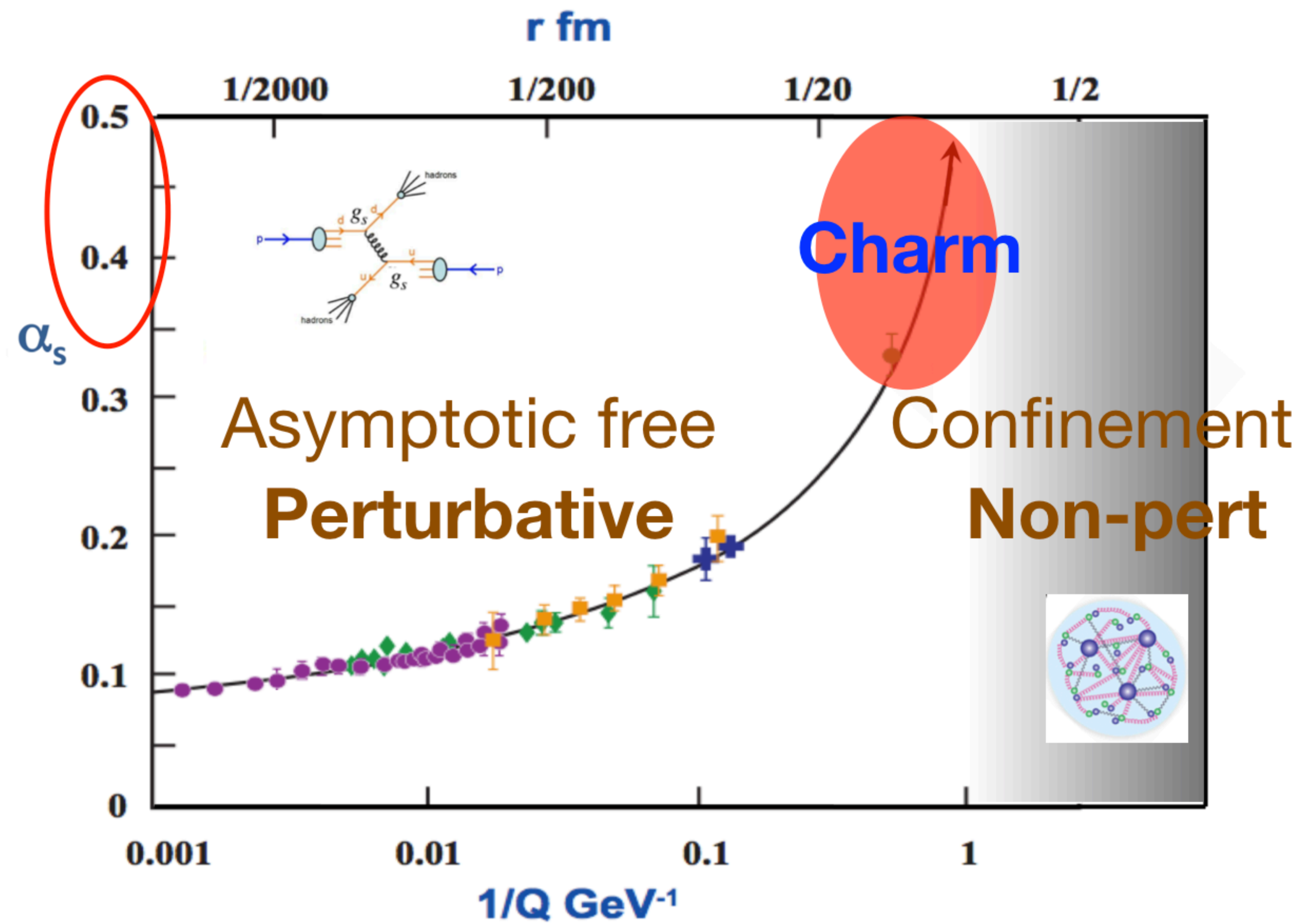
$$A_{CP} \lesssim 10^{-4}$$

Key: **Long-distance non-perturbative**



Understand: tree —> penguin; Branching ratio —> CPV

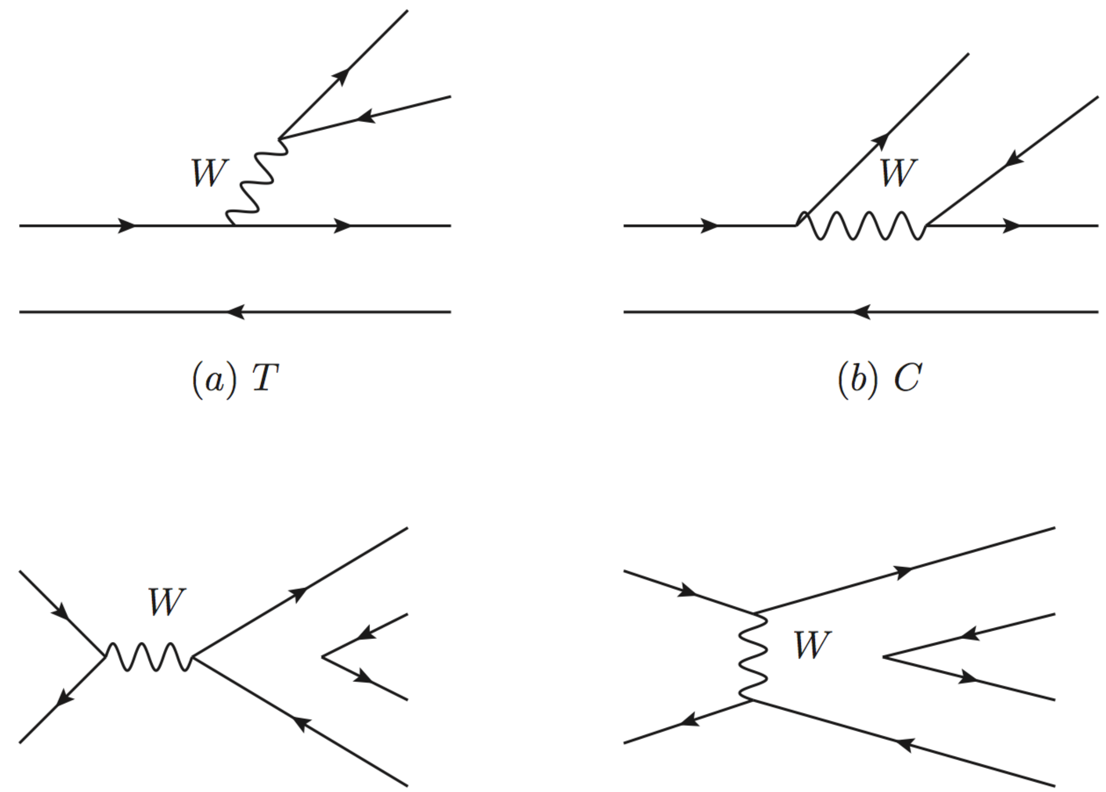
QCD



r fm
1/2000
1/200
1/20
1/2
0.5
0.4
0.3
0.2
0.1
0
α_s
hadrons
p
g_s
Charm
Asymptotic free
Perturbative
Confinement
Non-pert
0.001
0.01
0.1
1
1/Q GeV-1

Topological Amplitudes

- According to the **weak flavour flows**
- **Including all strong interaction effects**
- **Amplitudes extracted from data**

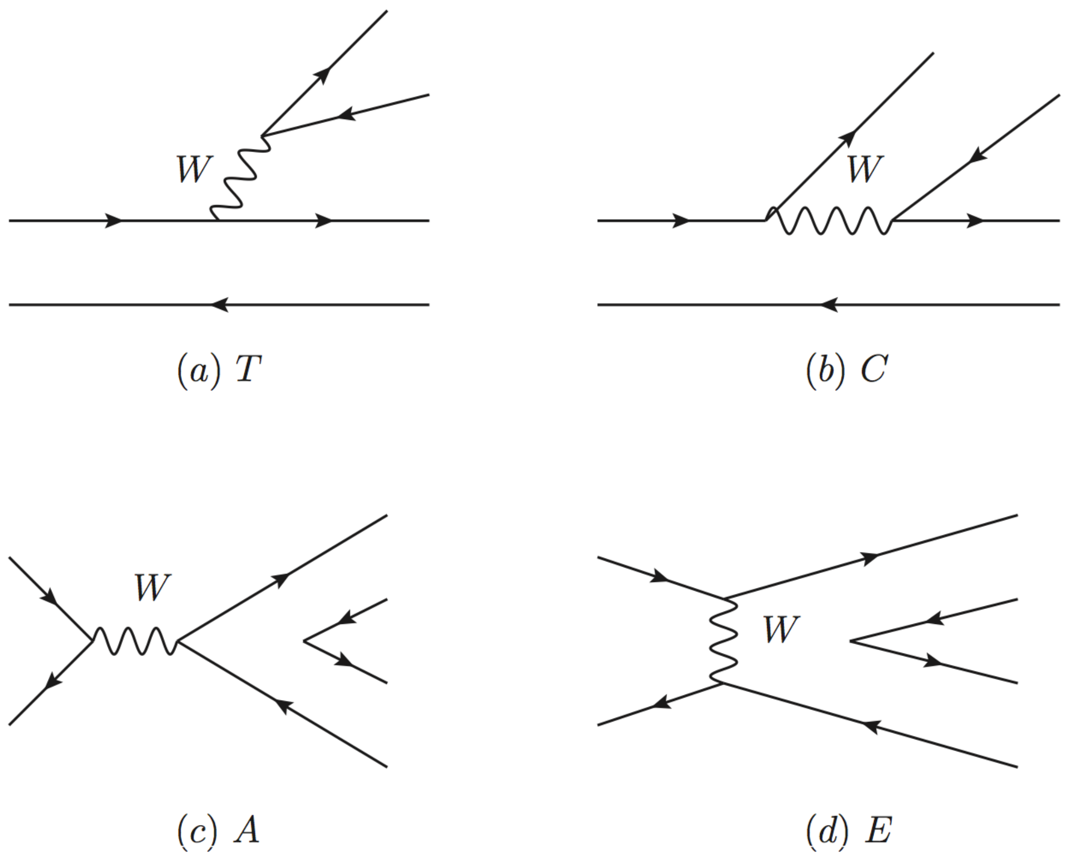


(a) T (b) C (c) A (d) E

Chau,86’; Chau,Cheng,87’; Bhattacharya, Rosner, 08’; Cheng, Chiang,10’

- Always in the flavour **SU(3) symmetry** limit, but **losing predictive power**

Factorization-Assisted Topological-Amplitude Approach (FAT)



- Dynamics In **factorization**:
  - **Short-distance**: Wilson coefficients
  - **Long-distance**: hadronic matrix elements

↓

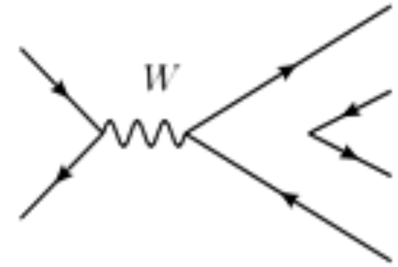
Non-perturbative quantities

↓

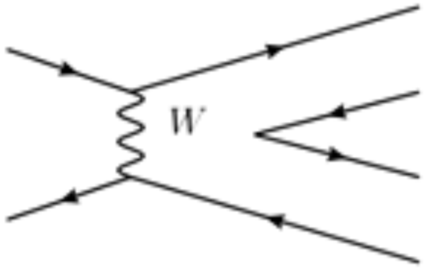
Extracted from data

Li, Lu, **FSY**, '12

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



(c) A



(d) E

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

Li, Lu, **FSY**, ’12

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

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

perturbative

nonperturbative

Modes	Br(exp)	Br(this work)	$A_{CP}^{SM} \times 10^{-3}$
$D^0 \to \pi^+\pi^-$	1.45 ± 0.05	1.43	0.58
$D^0 \to K^+K^-$	4.07 ± 0.10	4.19	−0.42
$D^0 \to K^0\bar{K}^0$	0.320 ± 0.038	0.36	1.38
$D^0 \to \pi^0\pi^0$	0.81 ± 0.05	0.57	0.05
$D^0 \to \pi^0\eta$	0.68 ± 0.07	0.94	−0.29
$D^0 \to \pi^0\eta'$	0.91 ± 0.13	0.65	1.53
$D^0 \to \eta\eta$	1.67 ± 0.18	1.48	0.18
$D^0 \to \eta\eta'$	1.05 ± 0.26	1.54	−0.94
$D^+ \to \pi^+\pi^0$	1.18 ± 0.07	0.89	0
$D^+ \to K^+\bar{K}^0$	6.12 ± 0.22	5.95	−0.93
$D^+ \to \pi^+\eta$	3.54 ± 0.21	3.39	−0.26
$D^+ \to \pi^+\eta'$	4.68 ± 0.29	4.58	1.18
$D_S^+ \to \pi^0K^+$	0.62 ± 0.23	0.67	0.39
$D_S^+ \to \pi^+K^0$	2.52 ± 0.27	2.21	0.84
$D_S^+ \to K^+\eta$	1.76 ± 0.36	1.00	0.70
$D_S^+ \to K^+\eta'$	1.8 ± 0.5	1.92	−1.60

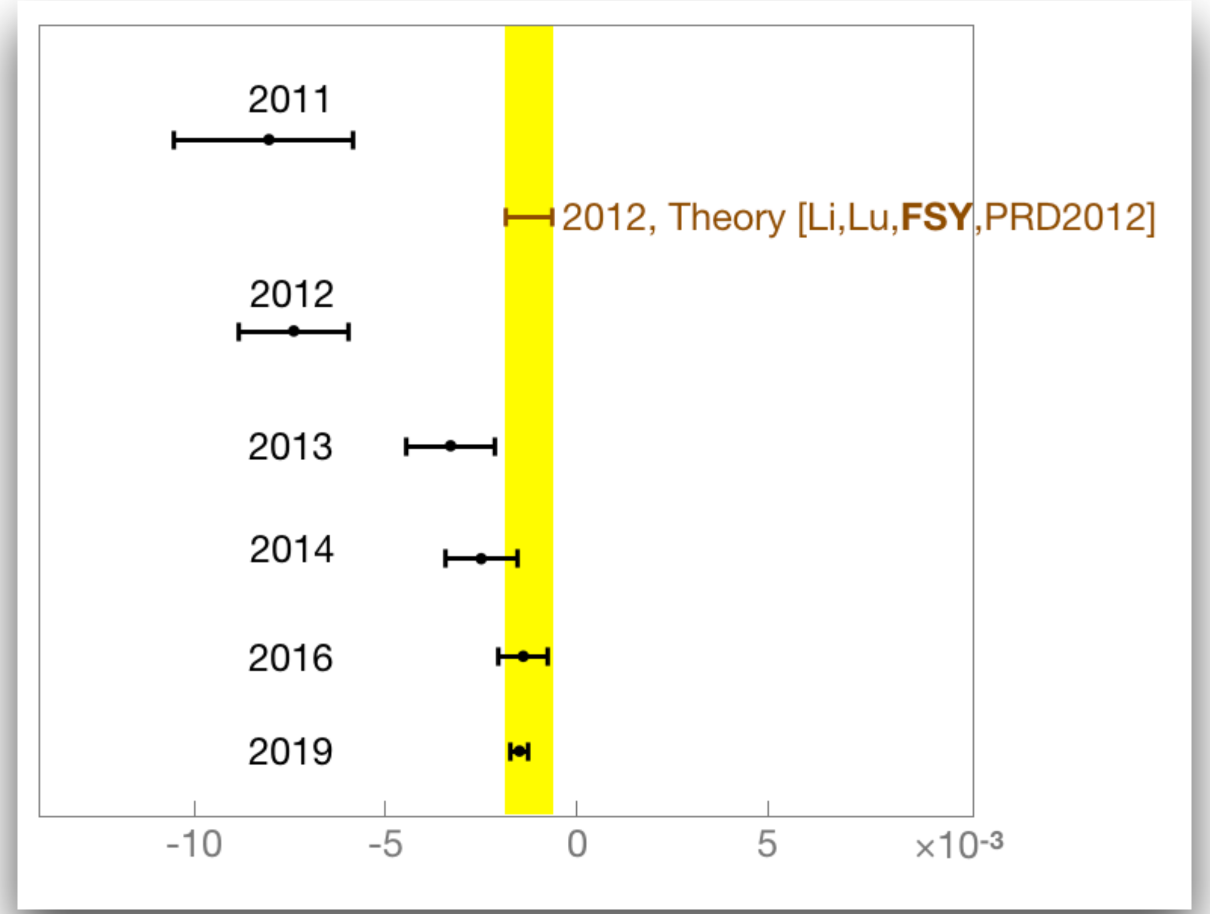
2. then predict charm CPV

1. Understand QCD dynamics @ 1GeV by Branching Ratios

Li, Lu, **FSY**, ’12

Modes	Br(exp)	Br(this work)	$A_{CP}^{SM} \times 10^{-3}$
$D^0 \to \pi^+\pi^-$	1.45 ± 0.05	1.43	0.58
$D^0 \to K^+K^-$	4.07 ± 0.10	4.19	-0.42

$$\Delta A_{CP}^{SM} = -1 \times 10^{-3}$$



1. Understand QCD dynamics @ 1GeV by Branching Ratios

2. Then predict charm CPV

Factorization-Assisted Topological (FAT) approach

Li, Lu, **FSY**, '12

2. Next potential mode of observation of charm CPV

Implications of LHCb2019

LHCb, PRL122, 211803 (2019)

$$\Delta A_{CP} = A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)$$

$$= (-1.54 \pm 0.29) \times 10^{-3}$$

1. Charm CPV of order 10^{-3}

2. Precision of order 10^{-4}

Implication: What next potential to observe charm CPV?

1. Charm CPV of order 10^{-3}	2. Precision of order 10^{-4}

1) Large branching fractions
2) Fully charged final particles @LHCb
3) Large production

$$Br(D^+ \to K^+K^-\pi^+) = 9.5 \times 10^{-3}$$

Compared to $Br(D^0 \to \pi^+\pi^-) = 1.4 \times 10^{-3}$

which dominates error of

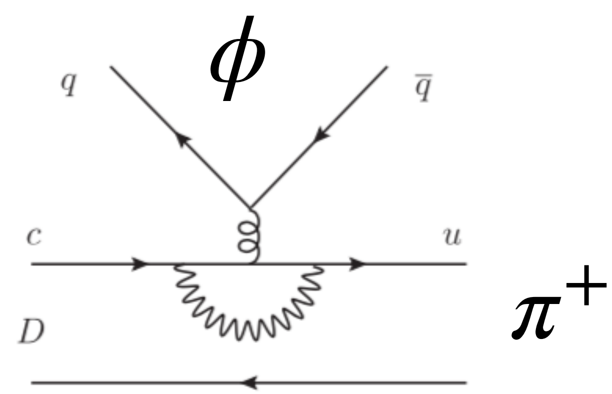
$$\Delta A_{CP} = (-1.54 \pm 0.29) \times 10^{-3}$$

Li, Lu, **FSY**, 1903.10638

What is the next potential mode to observe charm CPV?

$$Br(D^+ \to K^+K^-\pi^+) = 9.5 \times 10^{-3}$$

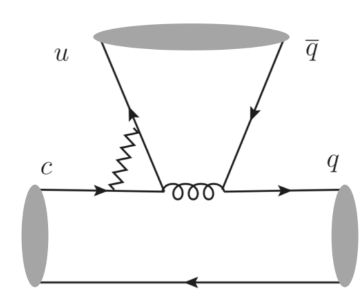
$$A_{CP}(D^+ \to \pi^+\phi) = 10^{-7}$$

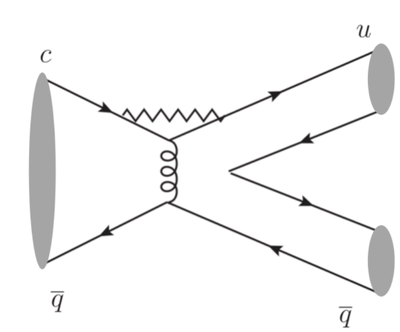


Qin, Li, Lu, **FSY**, '14

$$A_{CP}(D^+ \to K^+\overline{K}^{*0}) = 0.2 \times 10^{-3}$$

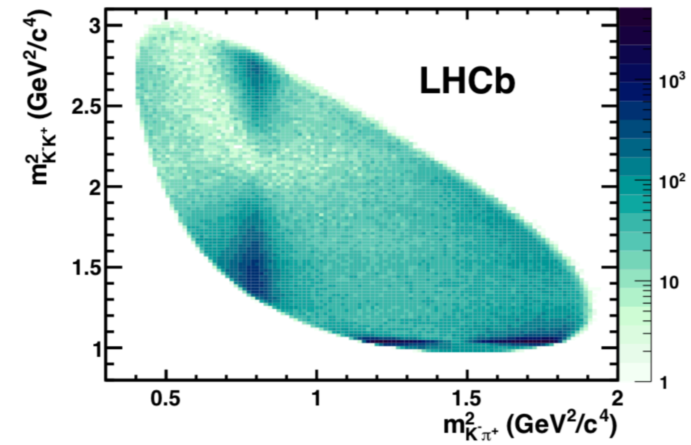
$$A_{CP}(D^+ \to K^+\overline{K}_0^{*0}(1430)) = -0.88 \times 10^{-3}$$





Li, Lu, **FSY**, 1903.10638

Searching Strategies



1. Binned $D^+ \to K^+K^-\pi^+$

	Branching Fractions	CP Violation
$D^+ \to \pi^+\phi$	2.6×10^{-3}	10^{-7} Benchmark
$D^+ \to K^+\overline{K}^{*0}$	2.4×10^{-3}	0.2×10^{-3}
$D^+ \to K^+\overline{K}_0^{*0}(1430)$	1.8×10^{-3}	-0.9×10^{-3}

Li, Lu, **FSY**, 1903.10638

Searching Strategies

2. Phase Space Integrated

Li, Lu, **FSY**, 1903.10638

(1) $A_{CP}(D^+ \to K^+K^-\pi^+) - A_{CP}(D^+ \to \pi^+\pi^-\pi^+)$

$= A_{CP}^{\text{raw}}(D^+ \to K^+K^-\pi^+) - A_{CP}^{\text{raw}}(D^+ \to \pi^+\pi^-\pi^+)$

Br=0.95% Br=0.3%

(2) $A_{CP}(D^+ \to K^+K^-\pi^+) - A_{CP}(D_s^+ \to K^+\pi^+\pi^-)$

$= \left[A_{CP}^{\text{raw}}(D^+ \to K^+K^-\pi^+) - A_{CP}^{\text{raw}}(D^+ \to K^-\pi^+\pi^+)\right]$

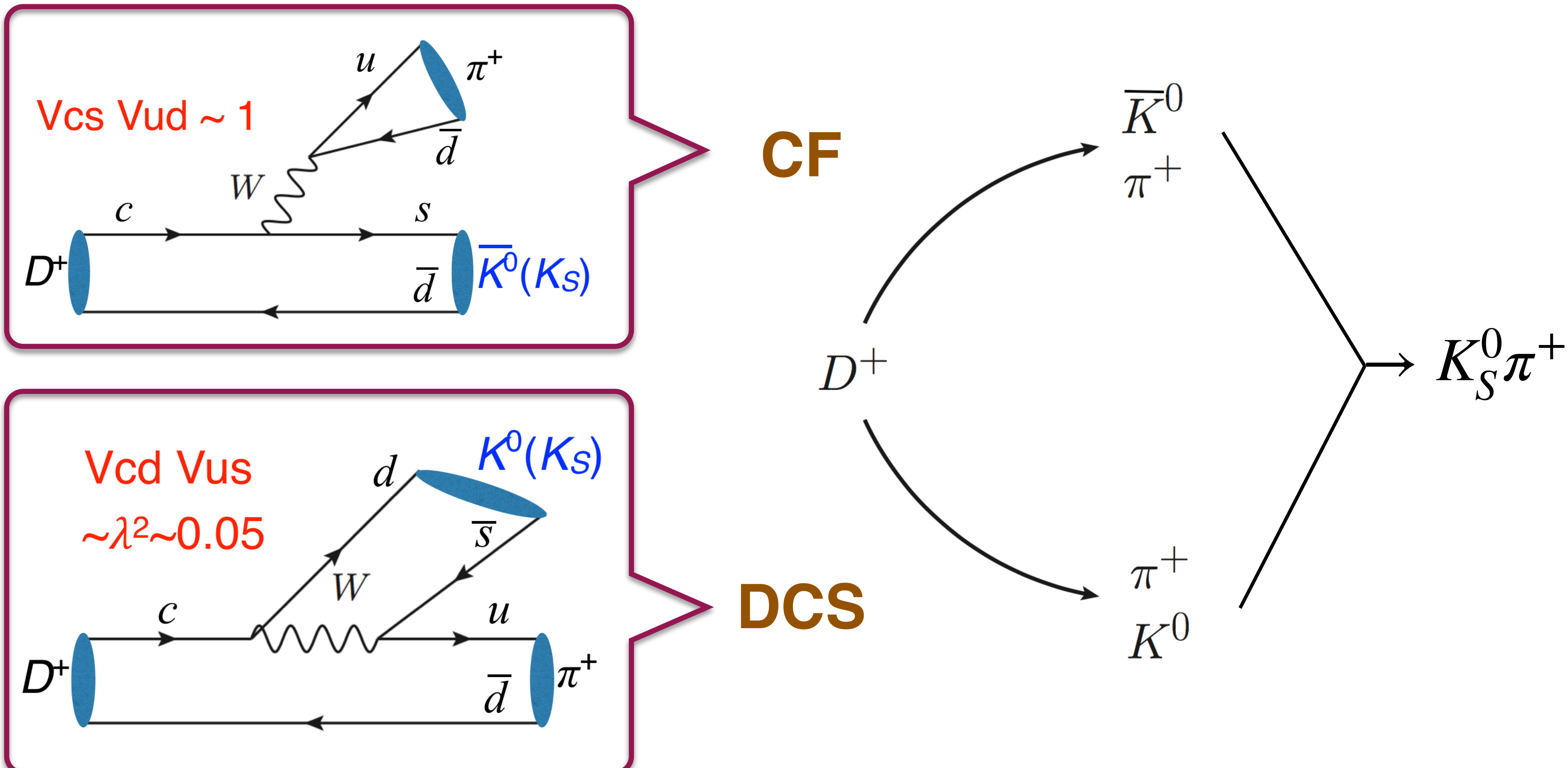
Br=0.95% Br=9%

$- \left[A_{CP}^{\text{raw}}(D_s^+ \to K^+\pi^+\pi^-) - A_{CP}^{\text{raw}}(D_s^+ \to K^+K^-\pi^+)\right]$

Br=0.66% Br=5.5%

3. New CPV effect

3. CPV in $D \to f\, K_S$



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

Postulated in literature:

deducting kaon mixing,

data reveal direct CPV in charm

$$A_{CP}^{D^+\to K^0_S\pi^+} \equiv \frac{\Gamma(D^+\to K^0_S\pi^+)-\Gamma(D^-\to K^0_S\pi^-)}{\Gamma(D^+\to K^0_S\pi^+)+\Gamma(D^-\to K^0_S\pi^-)}$$

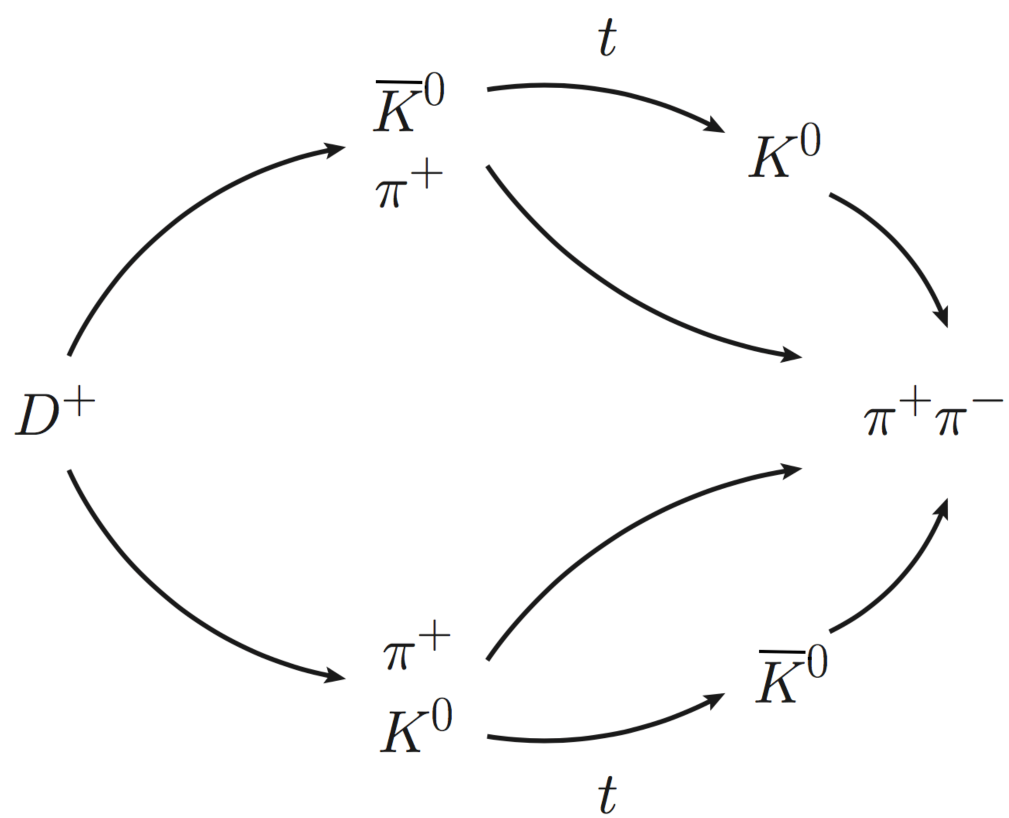
$$= A_{CP}^{\Delta C} + A_{CP}^{\bar{K}^0}$$

Lipkin, Xing, ’95; D’Ambrosio, Gao, ’01; Bianco, Fabbri, Benson, Bigi, ’03; Grossman, Nir, ’12; Belle, ’12

However…

Full decay chain

$$D^+ \to \pi^+ K(t)(\to \pi^+\pi^-)$$



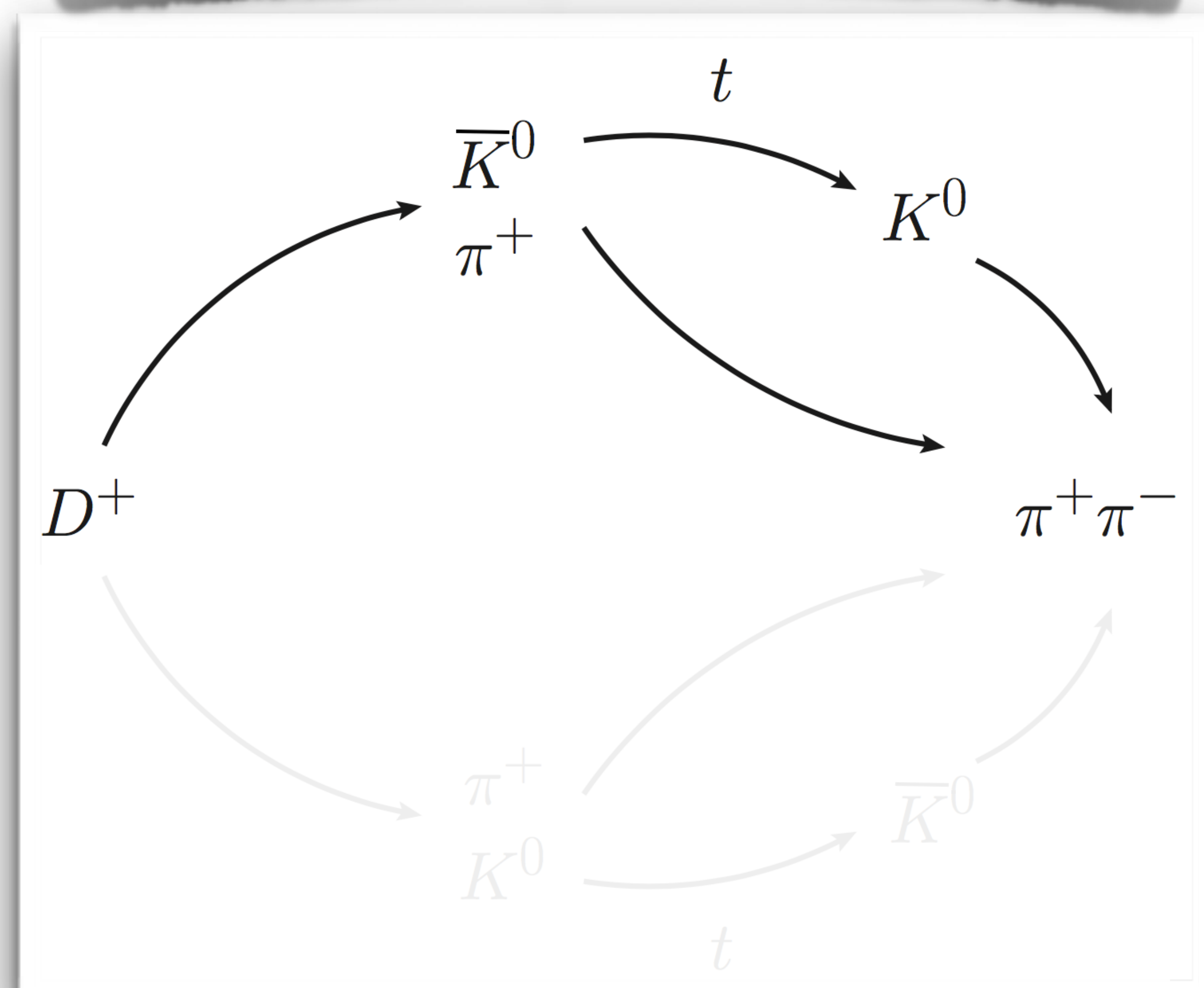
$$A_{CP}(t) = A_{CP}^{\overline{K}^0}(t) + A_{CP}^{\mathrm{dir}}(t)$$

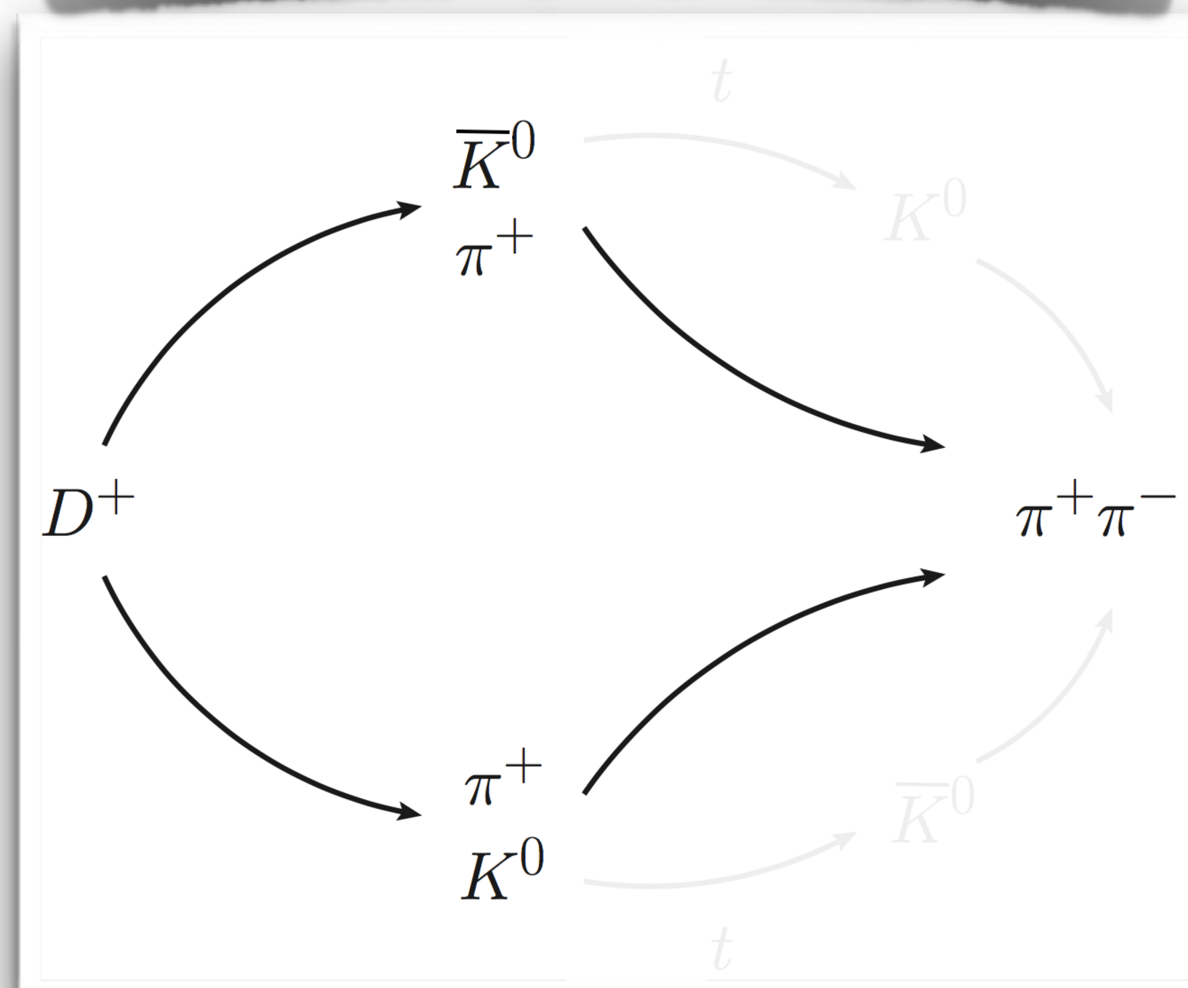
Indirect CPV in kaon mixing

$\mathrm{Re}(\epsilon)=10^{-3}$

Direct CPV in charm decays

$\mathrm{Im}(V_{cd}V_{us}/V_{cs}V_{ud})=\lambda^6=10^{-5}$





Z.z. Xing, '95; Grossman, Nir, '12

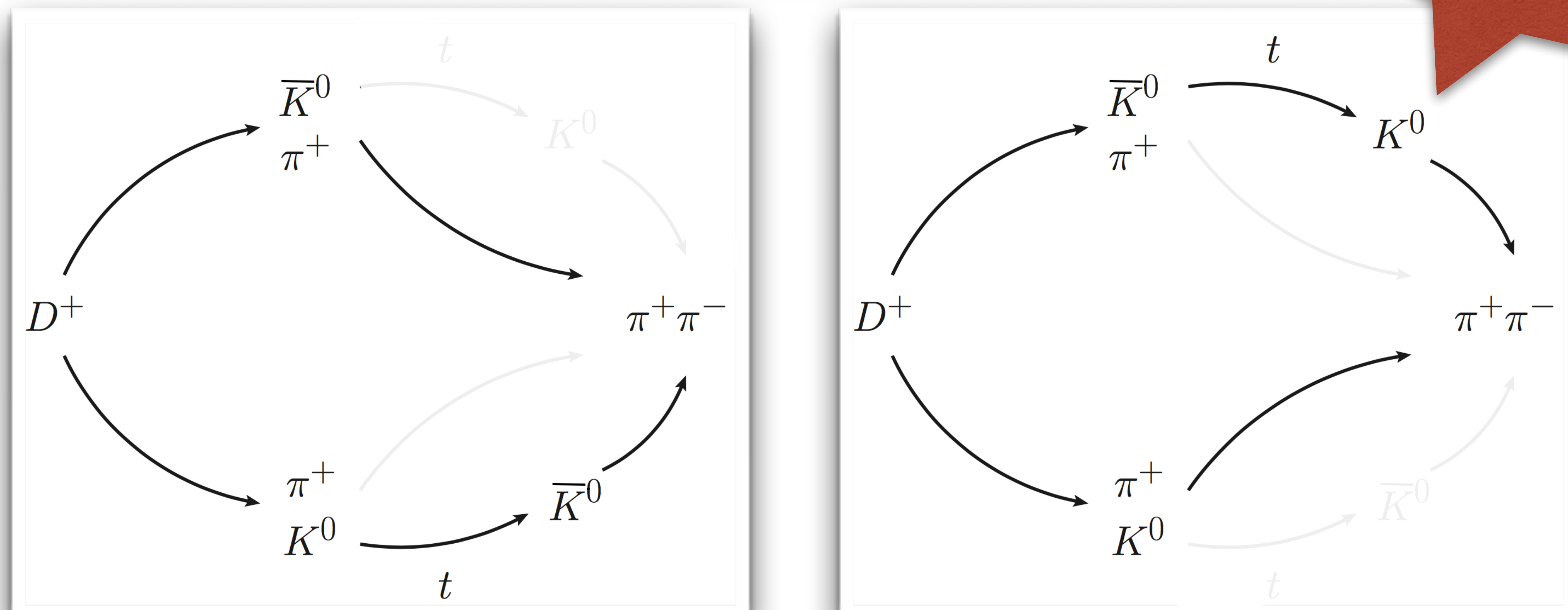
Bigi, Yamamoto, '95

$$A_{CP}(t) = A_{CP}^{\overline{K}^0}(t) + A_{CP}^{\rm dir}(t) + A_{CP}^{\rm int}(t)$$

CPV induced by mother decay and daughter mixing

Im(ϵ) Re($V_{cd}^{*}V_{us}/V_{cs}^{*}V_{ud}$)=$10^{-4\sim-3}$

NEW

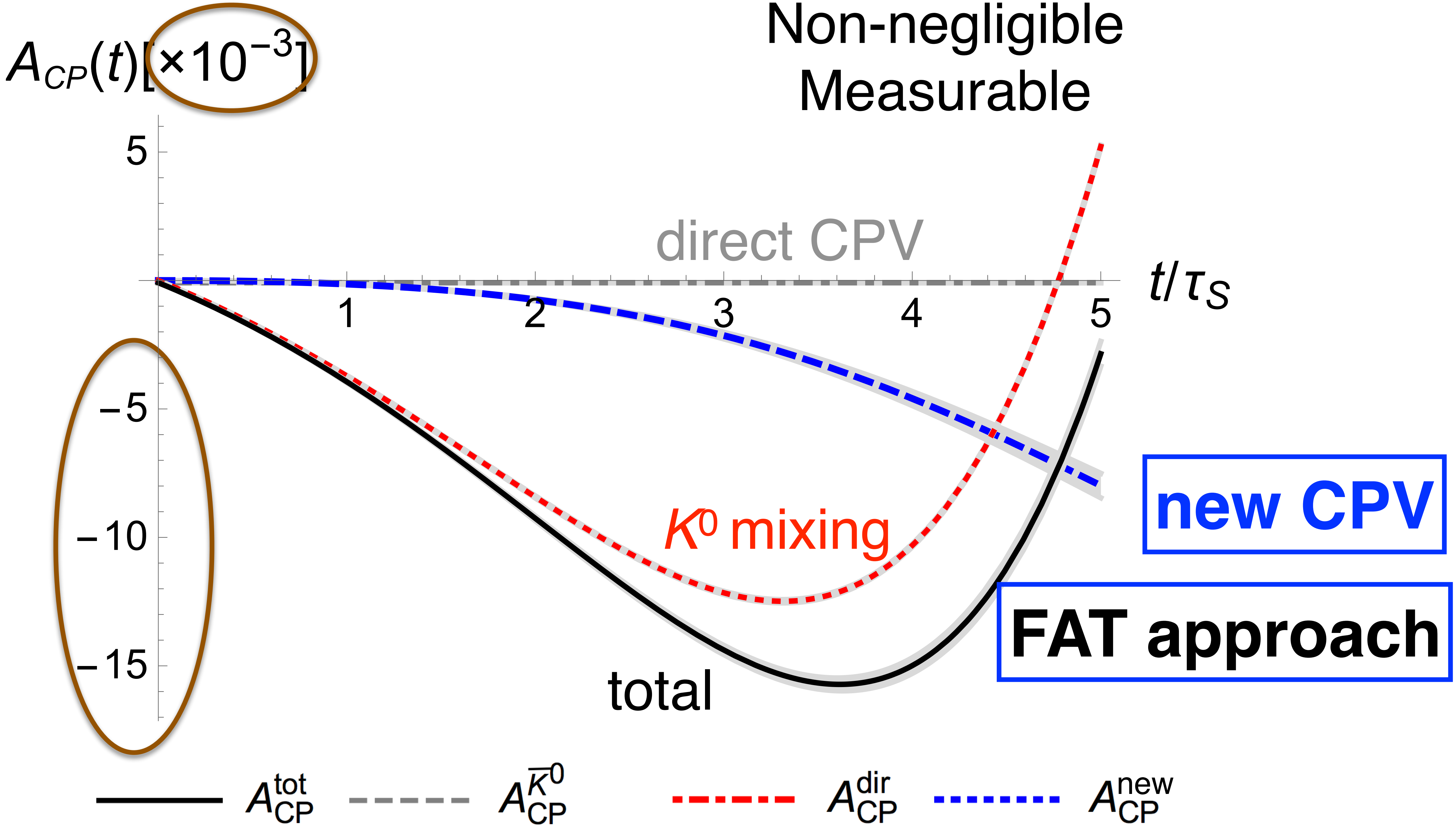


D.Wang, **FSY**, H.n.Li, Phys.Rev.Lett 119, 181802(2017)

$$A_{CP}^{\overline{K}^0}(t) \;>\; A_{CP}^{\rm int}(t) \;>\; A_{CP}^{\rm dir}(t)$$

$D^+ \to K_S^0 \pi^+$

Non-negligible
Measurable



Belle: Evidence for CP Violation in the Decay $D^+ \to K_S^0 \pi^+$

PRL109,021601(2012) [arXiv:1203.6409]

$$A_{CP}^{D^+\to K_S^0\pi^+} \equiv \frac{\Gamma(D^+ \to K_S^0\pi^+) - \Gamma(D^- \to K_S^0\pi^-)}{\Gamma(D^+ \to K_S^0\pi^+) + \Gamma(D^- \to K_S^0\pi^-)}$$

$$= A_{CP}^{\Delta C} + A_{CP}^{\bar{K}^0} + A_{CP}{}^{int}$$

$$A_{CP}^{D^+\to K_S^0\pi^+} = (-0.363 \pm 0.094 \pm 0.067)\%$$ Belle

$$A_{CP}^{\bar{K}^0} = (-0.339 \pm 0.007)\%$$

$$A_{CP}^{\Delta C} = (-0.024 \pm 0.115)\%$$

Belle

$$A^{\Delta C} = (-0.006 \pm 0.115)\%$$

[Wang, **FSY**, Li, ’17]

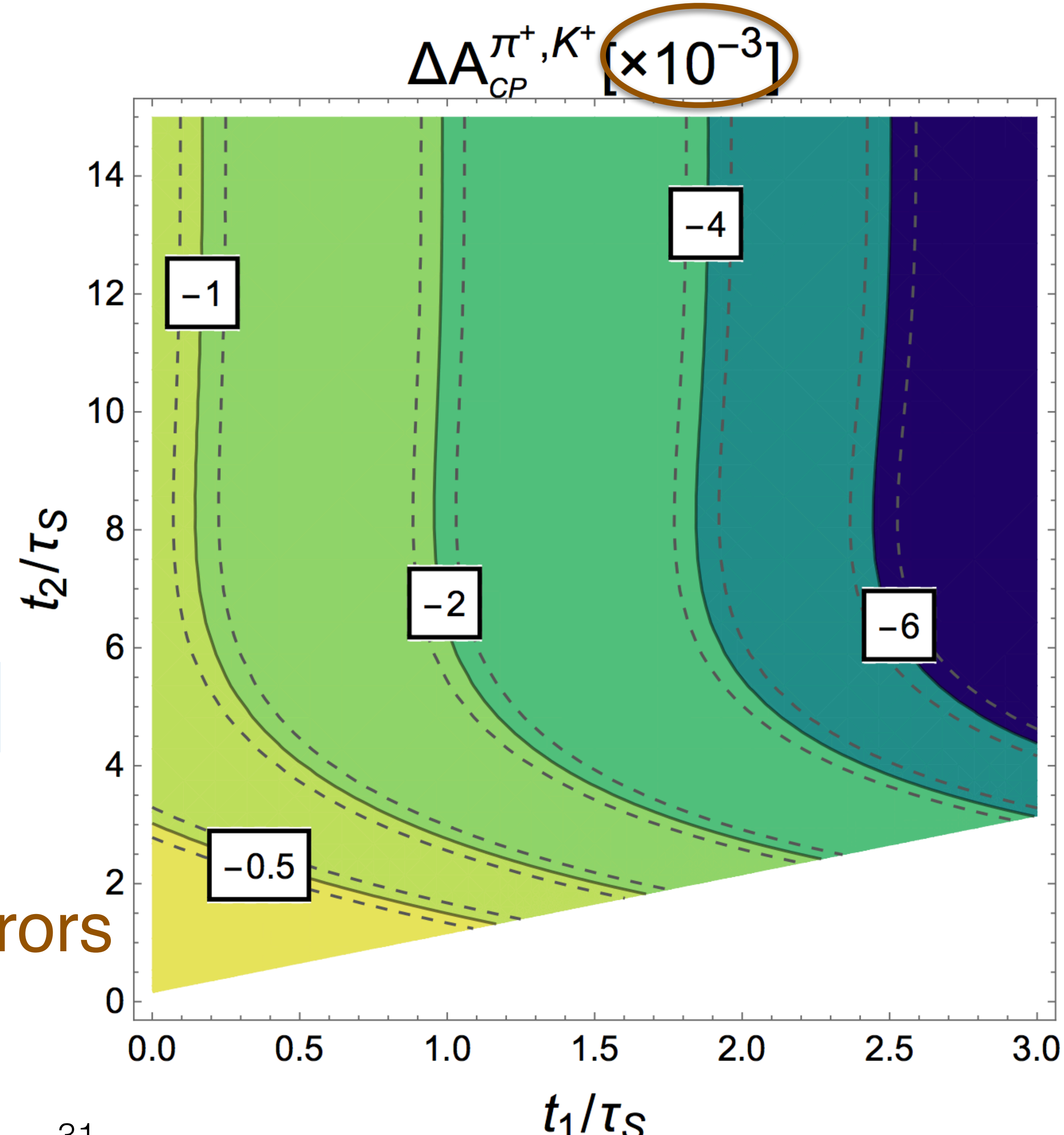
$$\Delta A_{CP} = A_{CP}(D^+ \to \pi^+ K_S^0) - A_{CP}(D_s^+ \to K^+ K_S^0)$$

New Observable

revealing

new CPV effect

$$A_{CP}(t) \simeq \left[A_{CP}^{\overline{K}^0}(t) + A_{CP}^{dir}(t) + A_{CP}^{int}(t) \right]$$

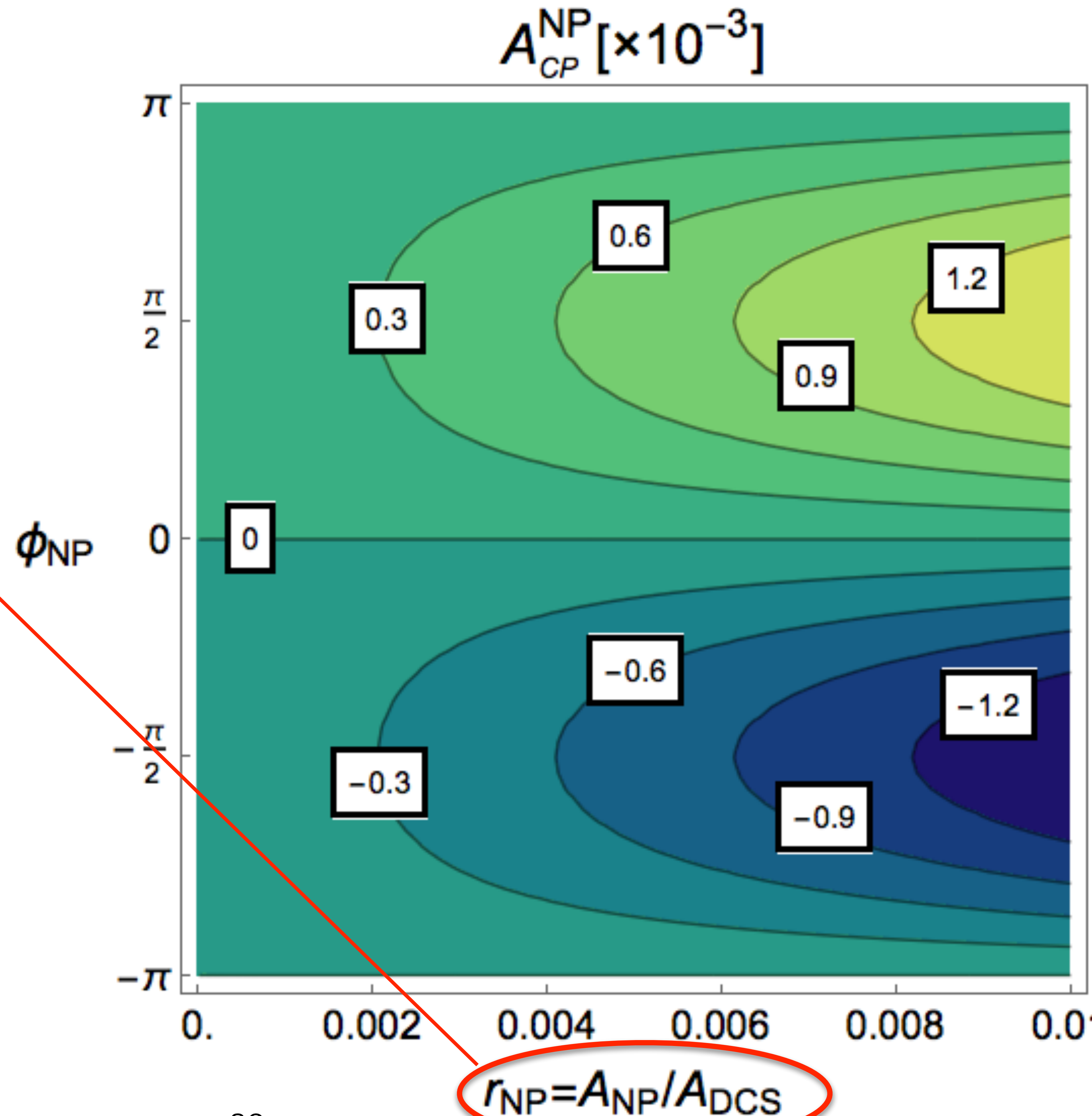


Cancel some systematic errors
@ LHCb & Belle-II

[Wang, **FSY**, Li, '17]

$$\mathcal{A}(D \to f K_S^0) = \mathcal{A}_{CF}^{\rm SM} + \mathcal{A}_{DCS}^{\rm SM}(1 + r^{\rm NP} e^{i\phi^{\rm NP}} e^{i\delta^{\rm NP}})$$

$$\frac{\mathcal{A}_{NP}}{\mathcal{A}_{SM}} = (0.1 \sim 1)\%$$



$$\mathcal{A}(D \to f K_S^0) = \mathcal{A}_{CF}^{\rm SM} + \mathcal{A}_{DCS}^{\rm SM}(1 + r^{\rm NP} e^{i\phi^{\rm NP}} e^{i\delta^{\rm NP}})$$

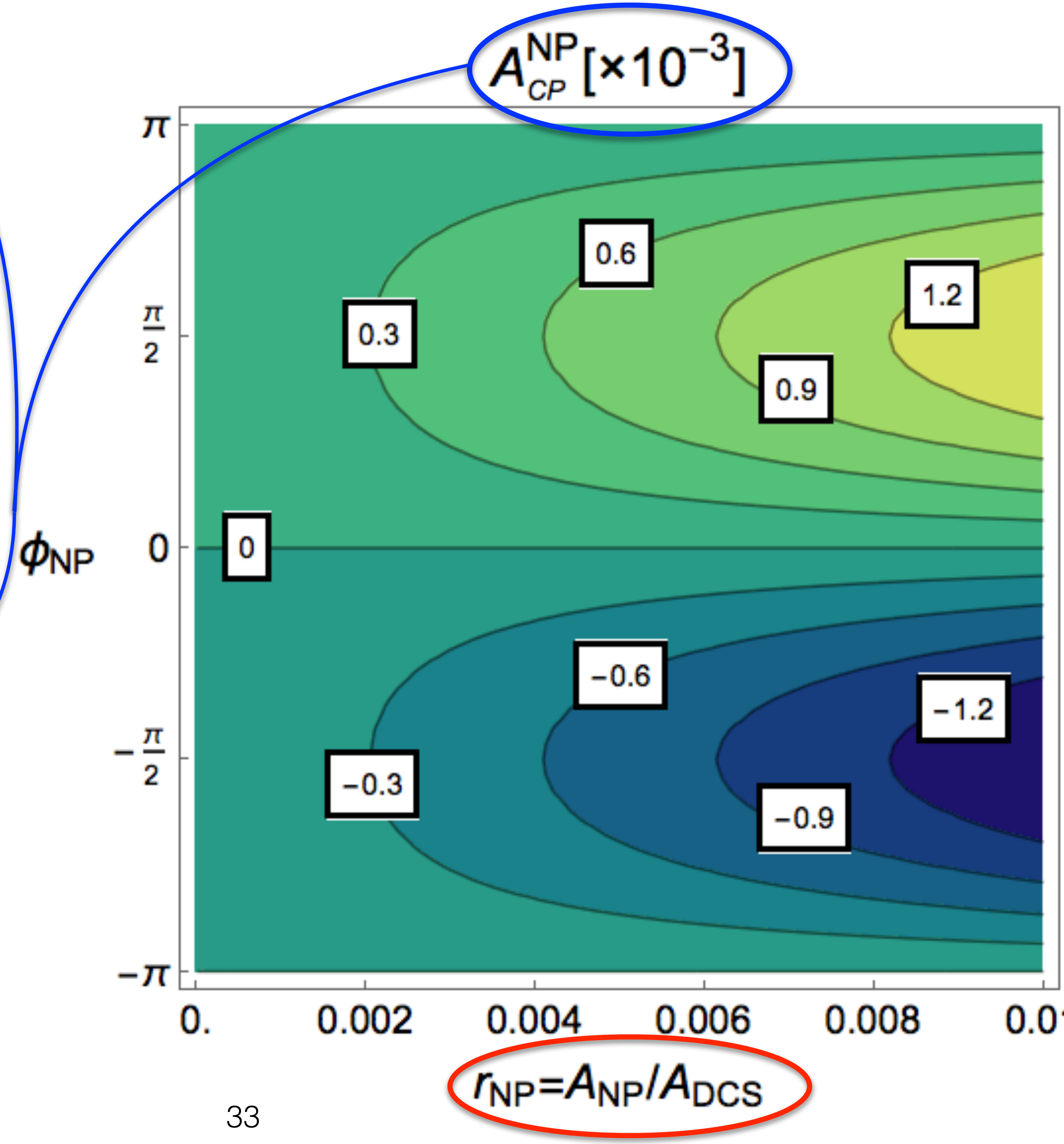
$$A_{\rm SM}^{dir} = \mathcal{O}(10^{-5})$$

Even if

$$\frac{\mathcal{A}_{NP}}{\mathcal{A}_{SM}} = (0.1 \sim 1)\%$$

$$\frac{A_{CP}^{NP}}{A_{CP}^{SM}} = \mathcal{O}(10)$$

Promising for new physics!



Summary

- CPV in D0->K+K- and pi+pi-
  - Understandable in the Standard Model
- Next potential observation in D+->K+K-pi+
- New CPV effect is found in CF $D \to K_S f$
  - mother decay and daughter mixing
- Charm CPV is becoming more charming with precision at order of 10^{-4}