CP Violation in charm

Fu-Sheng Yu

Lanzhou University

第十八届全国中高能核物理大会

21-25 June 2019 @ 湖南师范大学

LHCb observes charm CPV

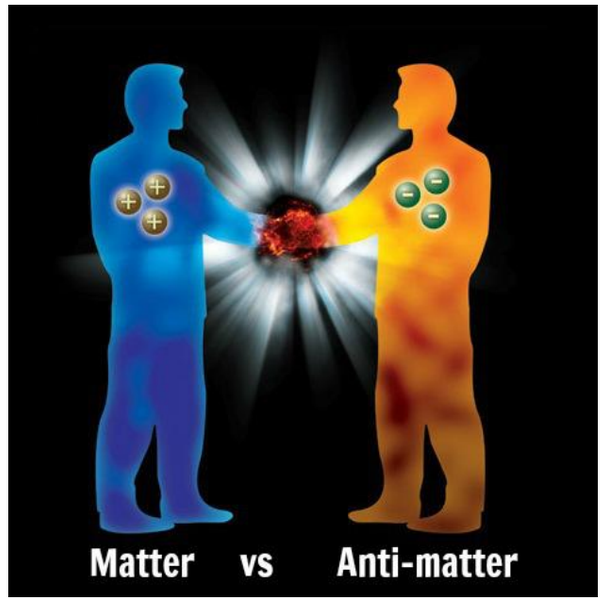
1903.08726

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

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

Big News !

CP Violation



CP: Charge-Parity symmetry

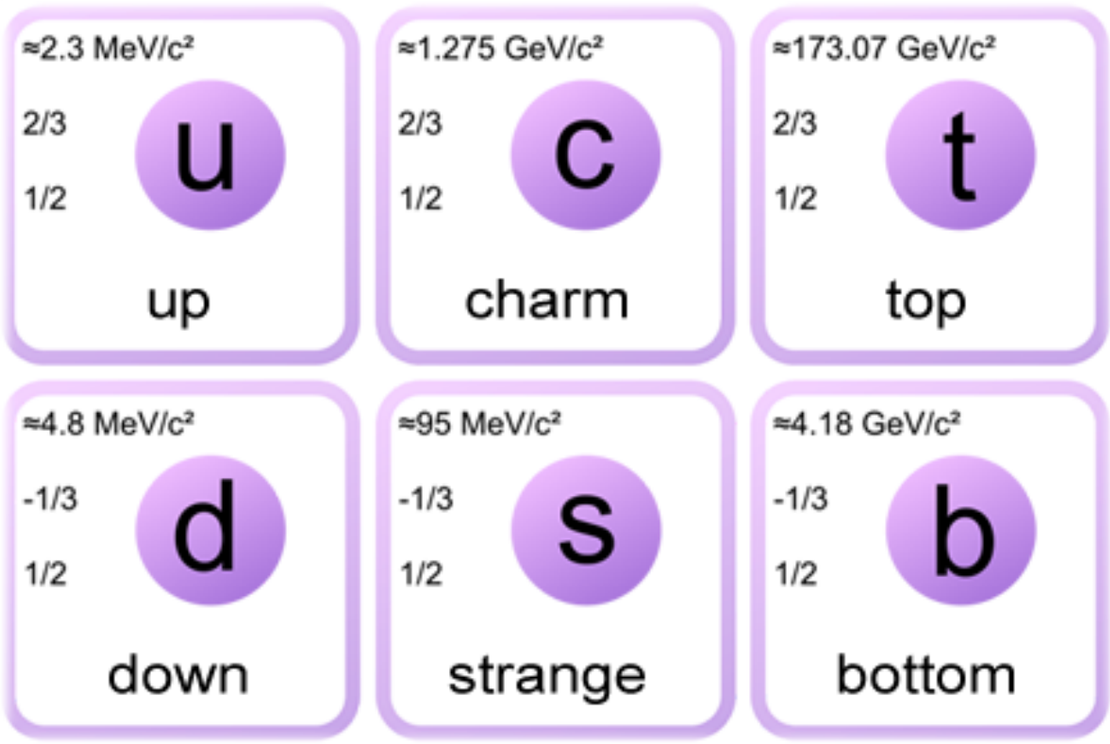
Particle-Antiparticle symmetry

- **Matter-Antimatter asymmetry of the Universe**

- **CP violation** is required by Sakharov conditions
  [Sakharov, 1967]

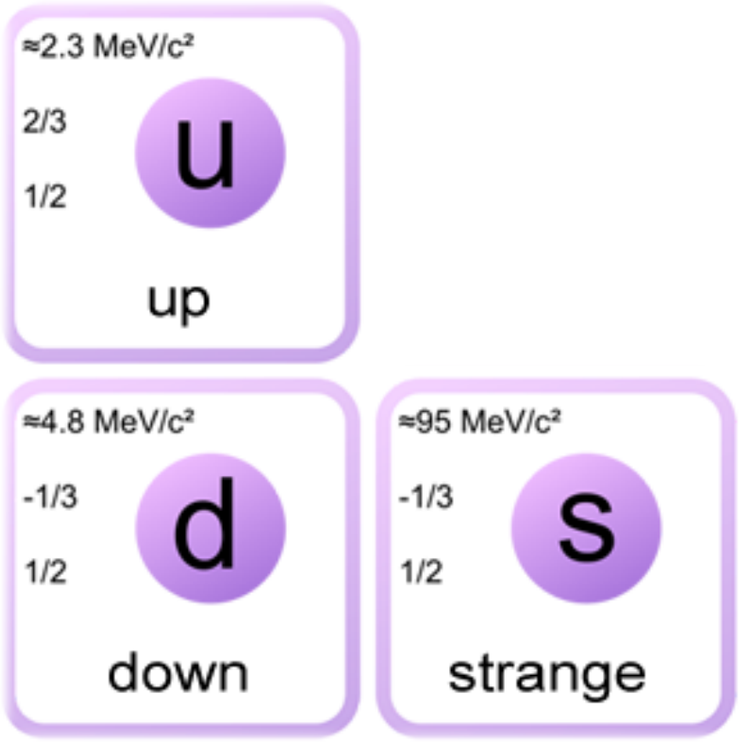
- CPV in the SM is not large enough, thus a **window to New Physics**

Milestone by observed charm CPV



SM: 3 families and 6 flavors of quarks

Milestone by observed charm CPV

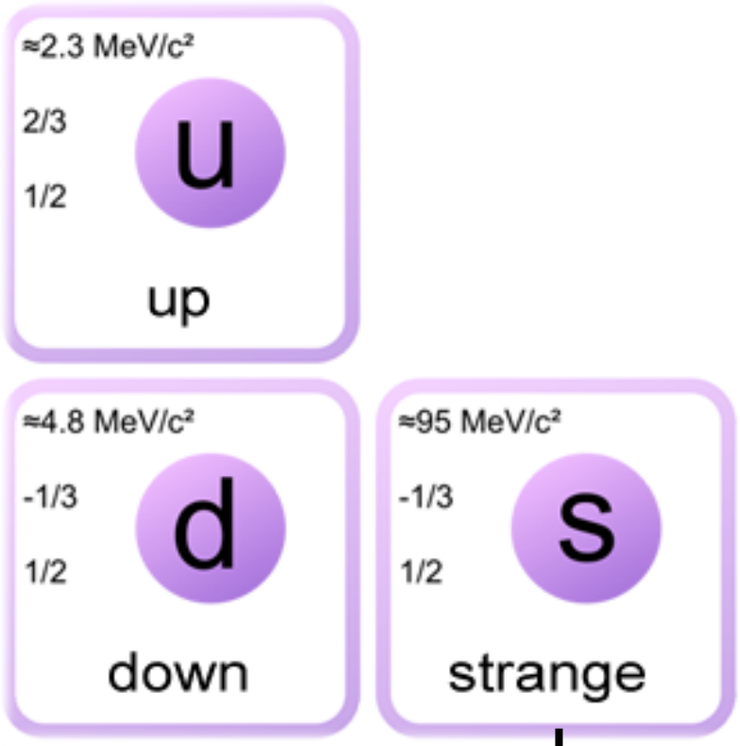


At the beginning, Gell-Mann: 3 quarks

Li, Yang: Parity violated

C and P violated, but CP conserved

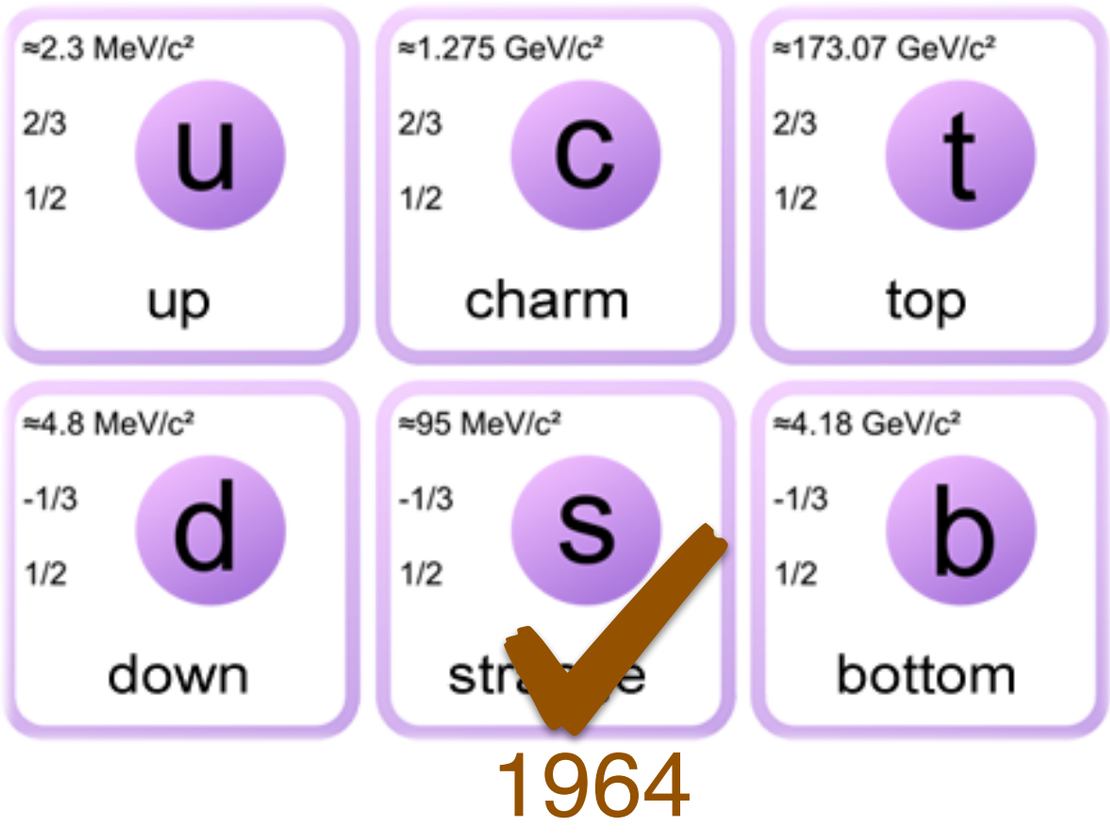
Milestone by observed charm CPV



~~CP conserved~~

first observation of
CP Violation in 1964

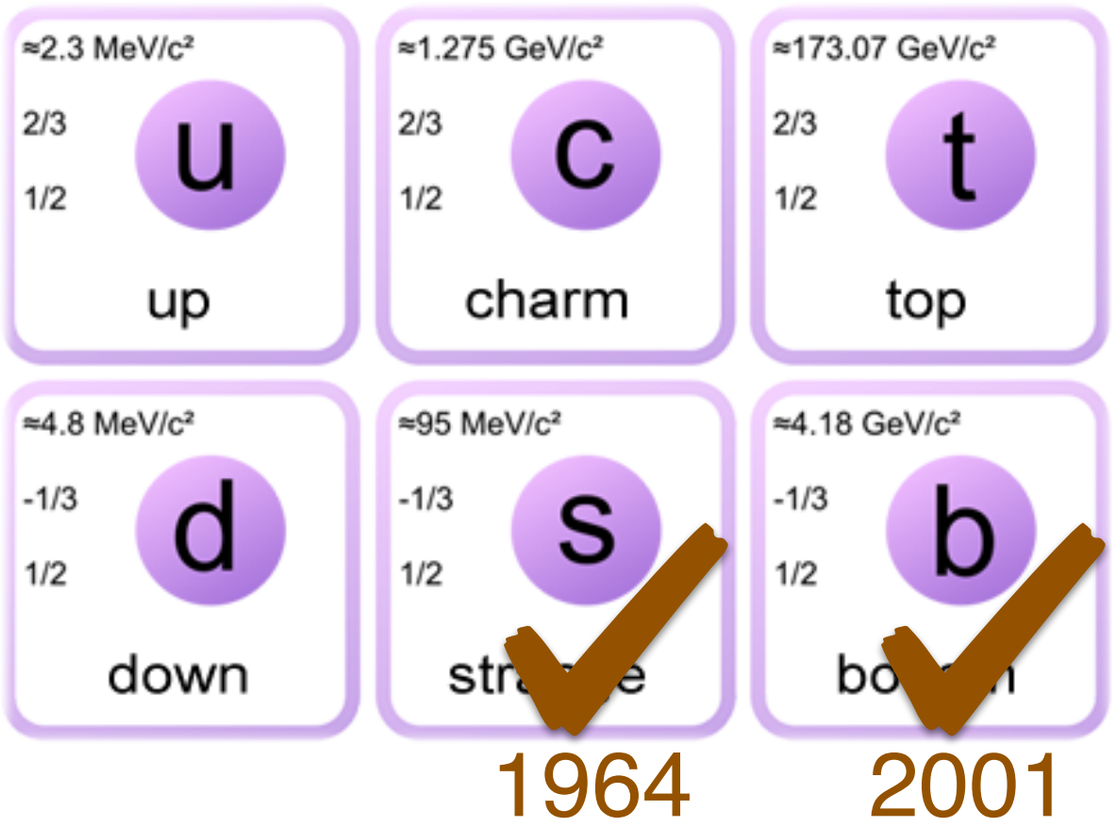
Milestone by observed charm CPV



1964

1973, KM: 3 families and 6 quarks —> CPV

Milestone by observed charm CPV

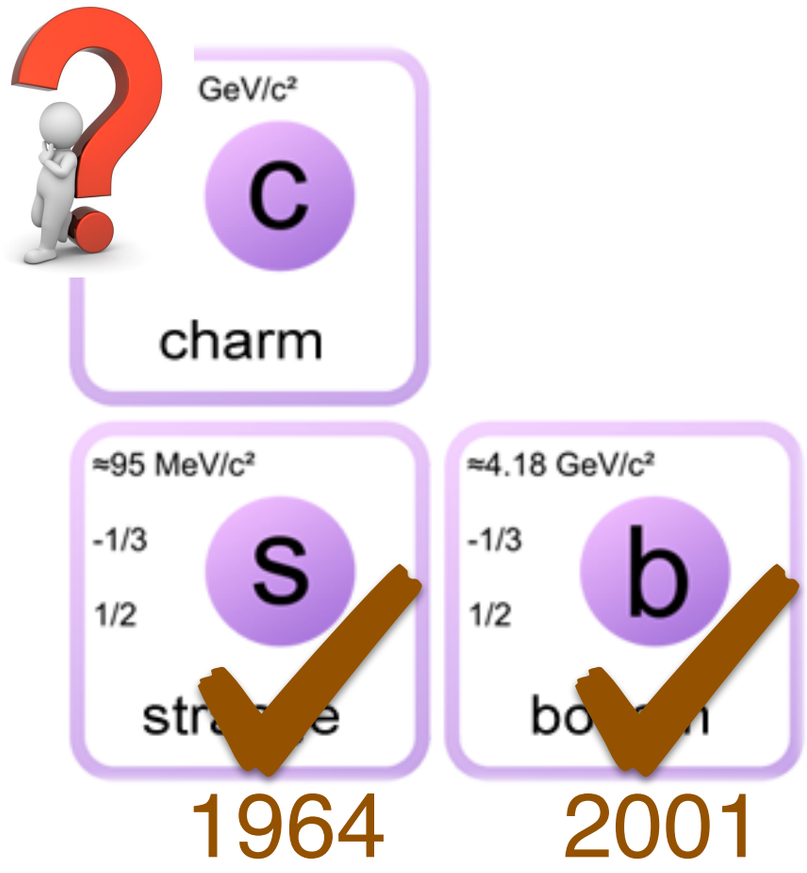


KM mechanism —> CPV

Milestone by observed charm CPV

Charm CPV

1. **Yes or No?**
2. **How large?**
3. **SM or NP?**



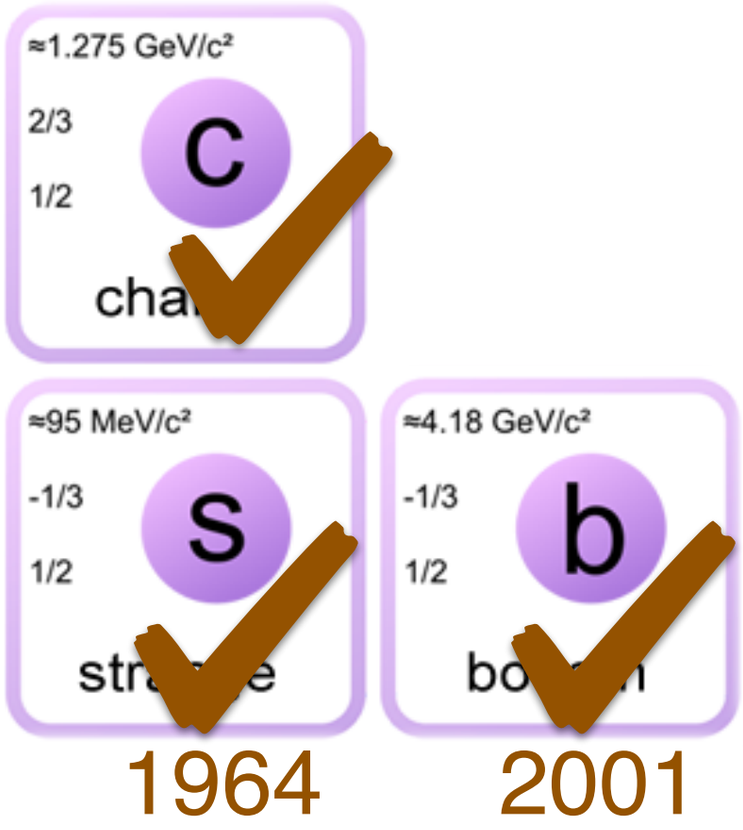
Milestone by observed charm CPV

Charm CPV

Observation

LHCb 2019 !!

Milestone !!



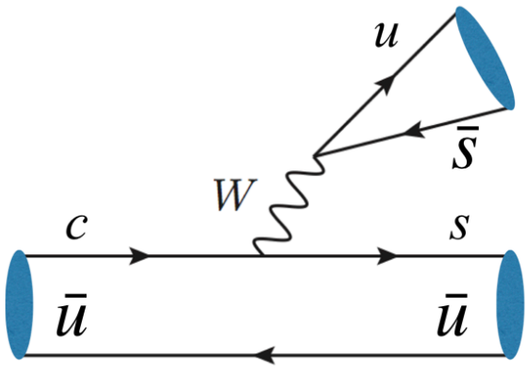
Milestone by observed charm CPV

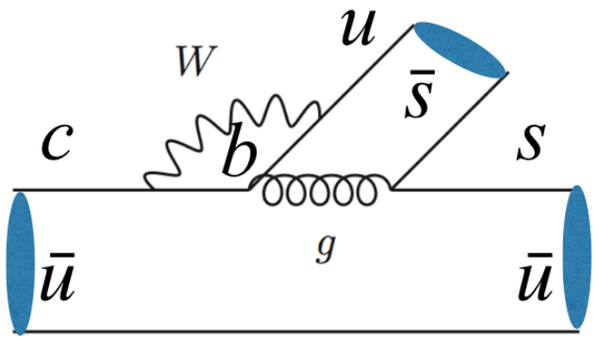
Charm CPV

1. **Yes or No?** **Yes!!**
2. **How large?** **10^{-3}**
3. **SM or NP?**

Direct CPV in charm

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





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

λ

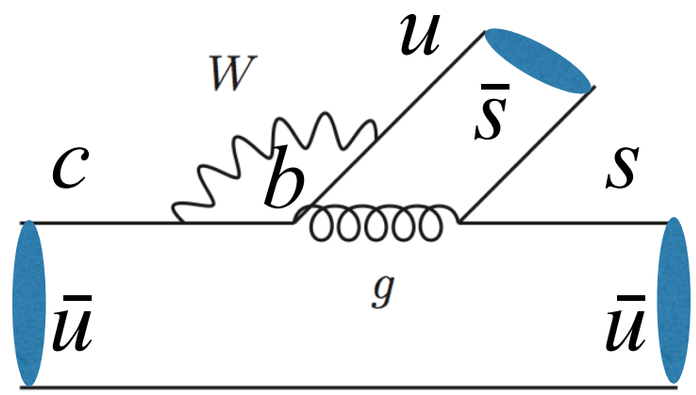
$V_{cb}V_{ub}$

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

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

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



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

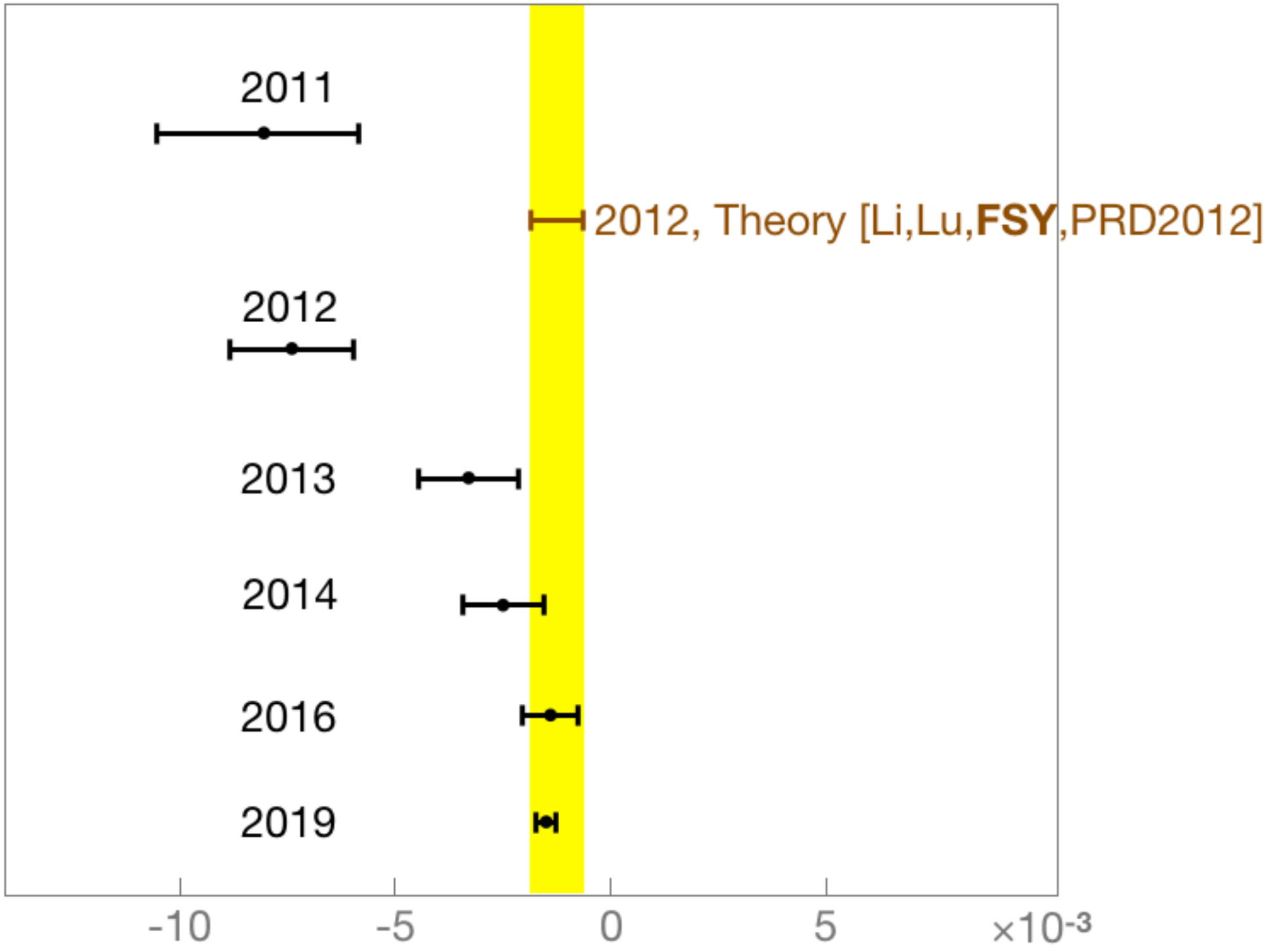
Grossman, Kagan, Nir, ’07; Bigi, Paul, ’11; Isidori, Kamenik, Ligeti, Perez, ’11; Brod, Grossmann, Kagan, Zupan, ’11, ’12; Feldmann, Nandi, Soni, ’12; Bhattarcharya, Gronau, Rosner, ’12; Cheng, Chiang, ’12; Li, Lu, **FSY**, ’12; Franco, Mishima, Silvestrini, ’12; Hiller, Jung, Schacht, ’12. Khodjamirian,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



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

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

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

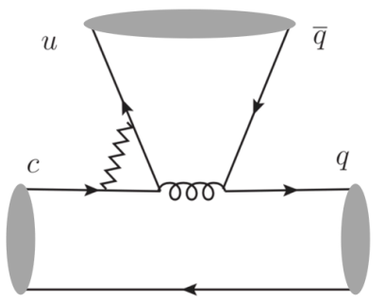
Perturbative QCD

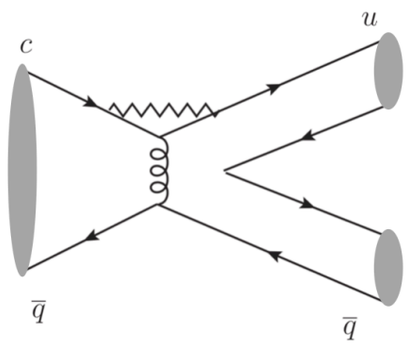
Khodjamirian, Petrov, ’17

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

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

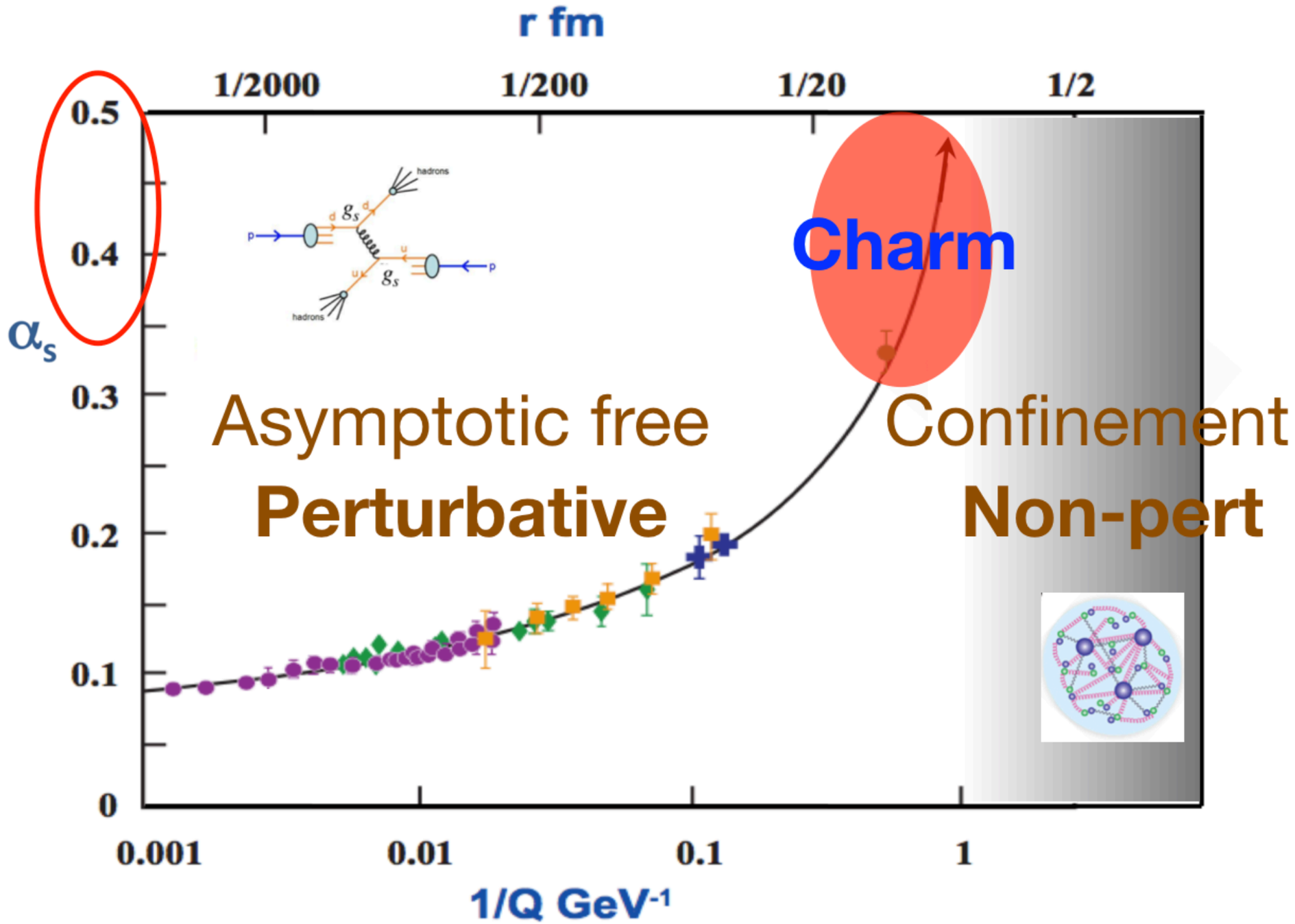
Key: **Long-distance non-perturbative**





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

QCD

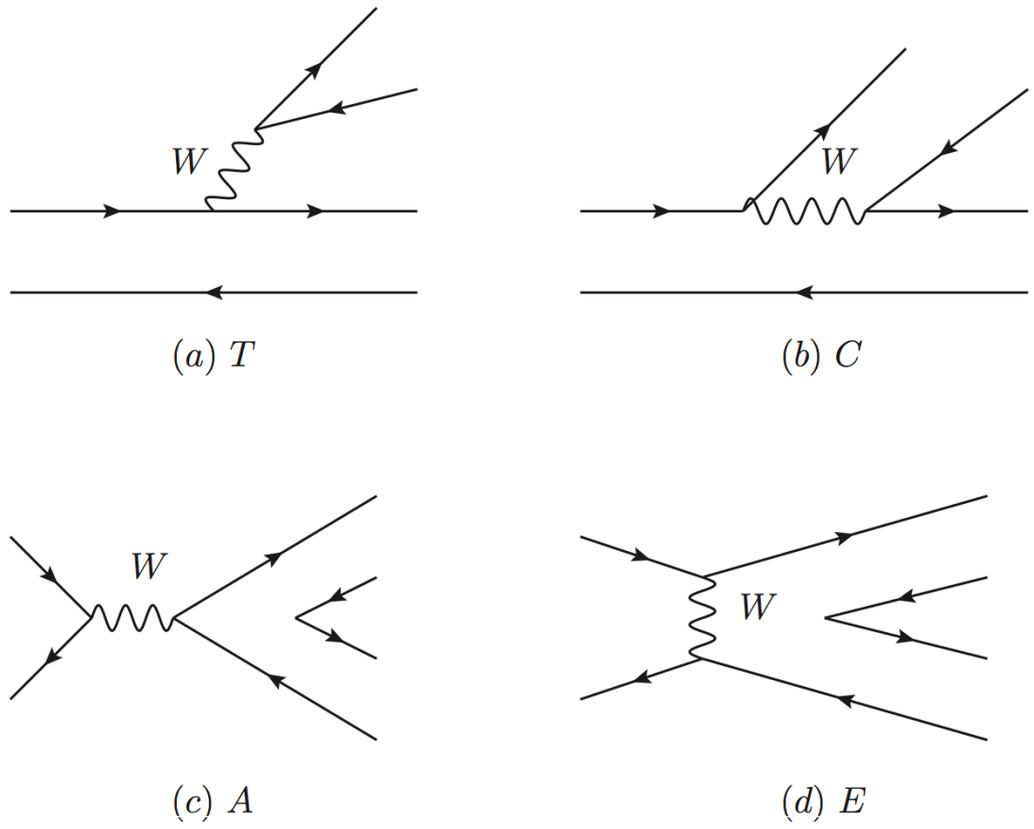

r fm
1/2000
1/200
1/20
1/2
0.5
0.4
0.3
0.2
0.1
0
α_s
0.001
0.01
0.1
1
1/Q GeV^{-1}
hadrons
p
d
g_s
u
Charm
Asymptotic free
Perturbative
Confinement
Non-pert

Topological Amplitudes

- According to the **weak flavour flows**

- **Including all strong interaction effects**

- **Amplitudes extracted from data**

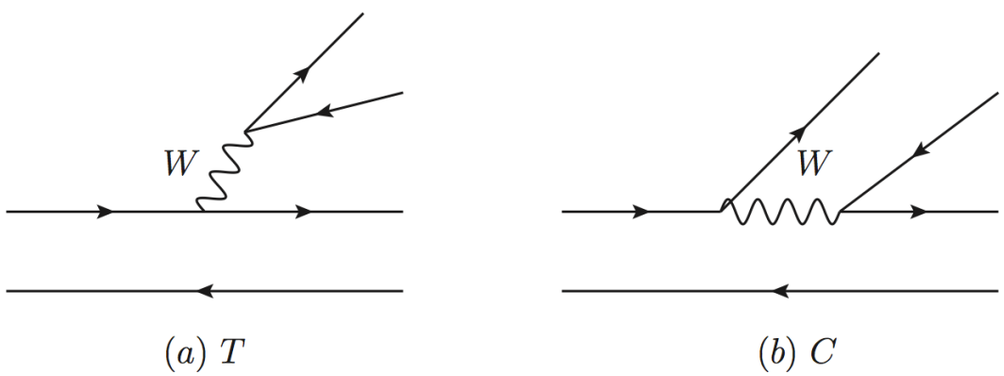


$(a)\ T$ $(b)\ C$ $(c)\ A$ $(d)\ E$

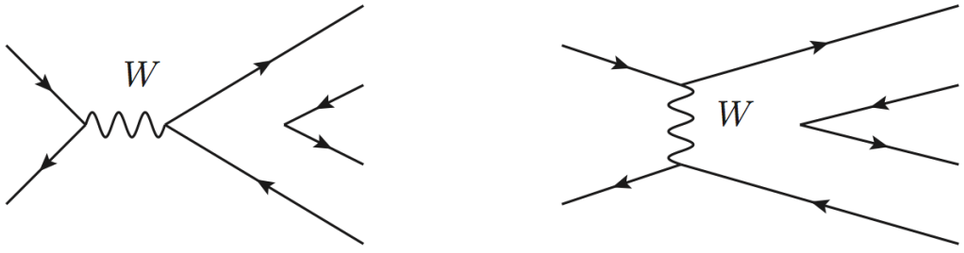
Chau,86'; Chau,Cheng,87'; Bhattacharya, Rosner, 08'; Cheng, Chiang,10'

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

Factorization-Assisted Topological-Amplitude Approach (FAT)



$(a)\ T$ $(b)\ C$



$(c)\ A$ $(d)\ E$

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

↓

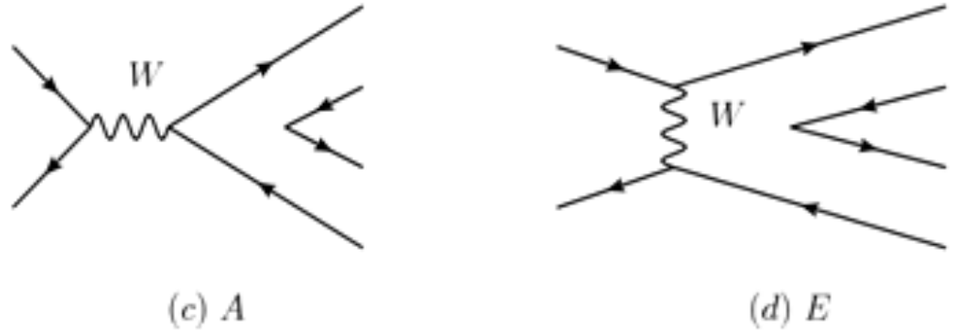
Non-perturbative quantities

↓

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)	$A_{CP}^{\rm SM} \times 10^{-3}$
$D^0 \to \pi^+\pi^-$	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

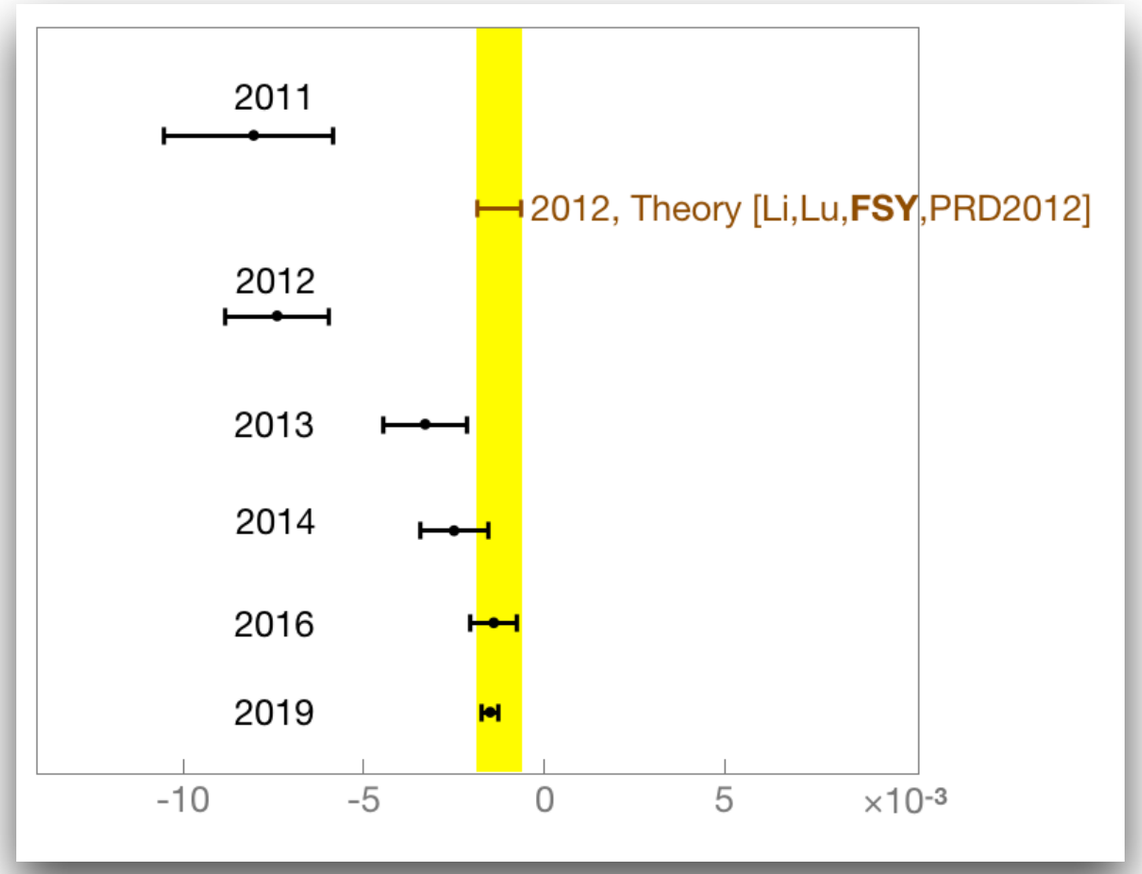
Li, Lu, **FSY**, ’12

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

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

1. Understand QCD dynamics @ 1GeV by Branching Ratios

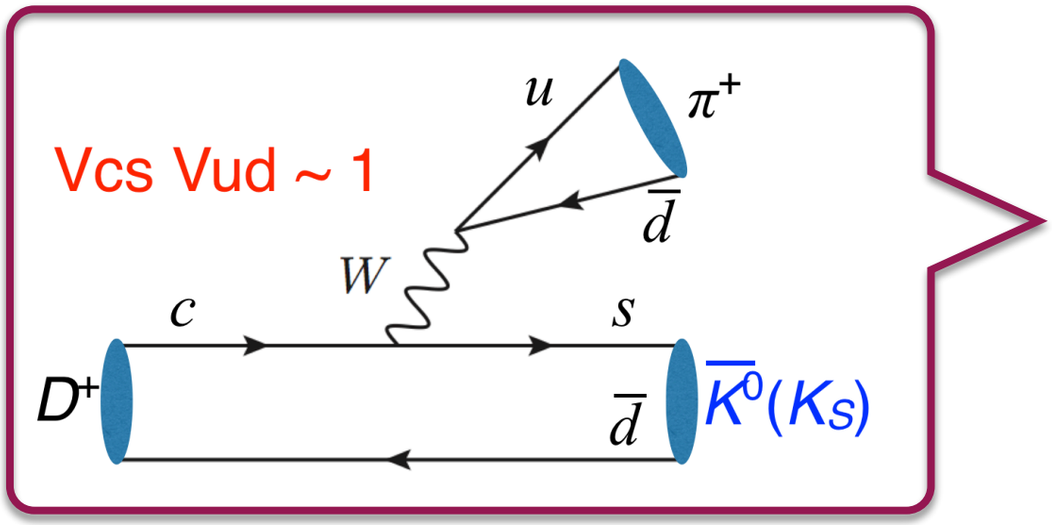
2. Then predict charm CPV



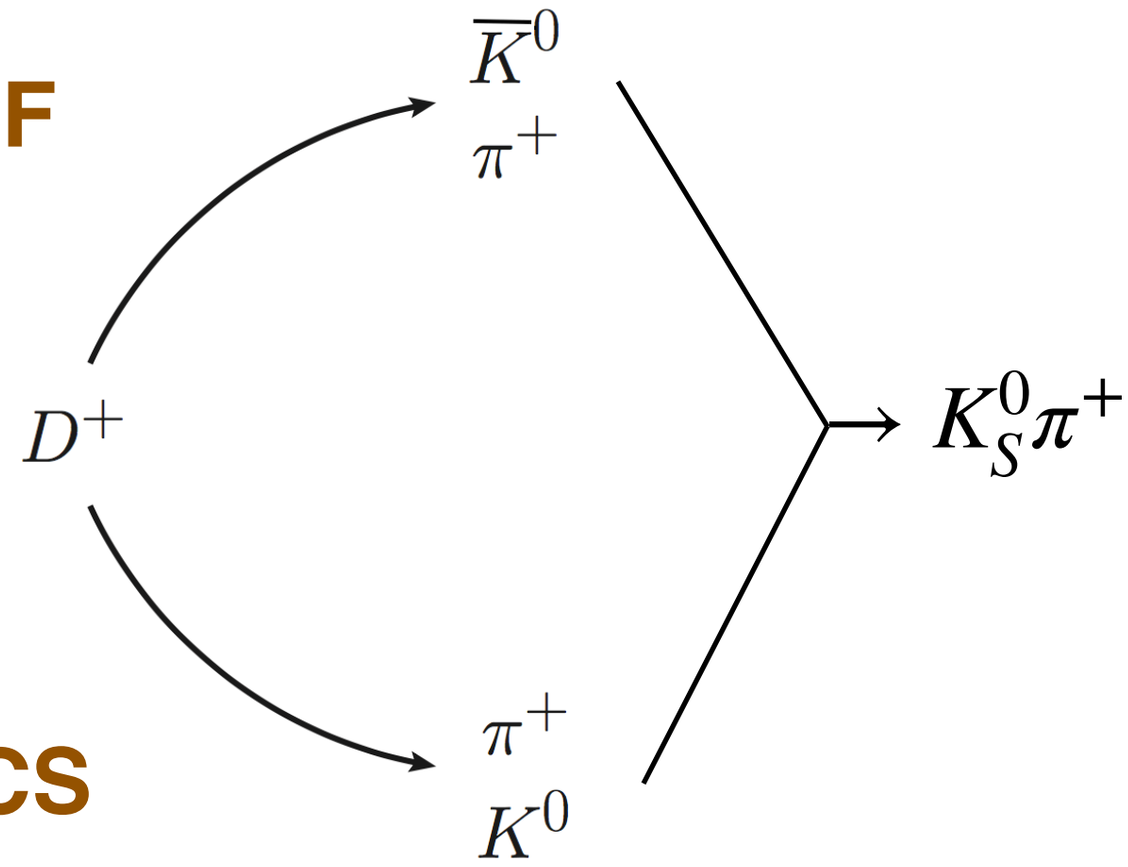
Factorization-Assisted Topological (FAT) approach

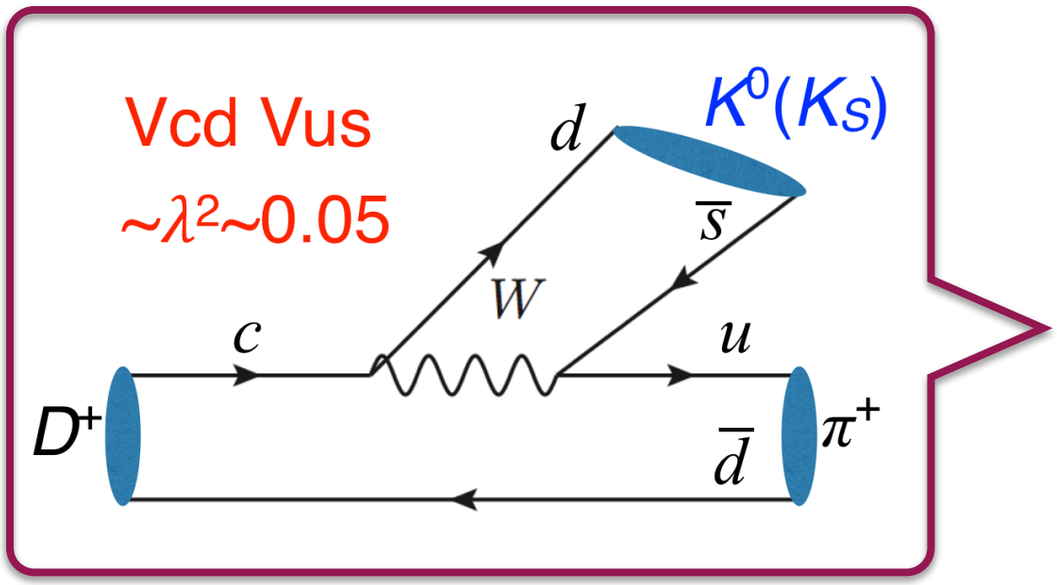
Li, Lu, **FSY**, ’12

2. CPV in $D \to f K_S$



CF





DCS

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

Postulated in literature:

deducting kaon mixing,
data reveal direct CPV in charm

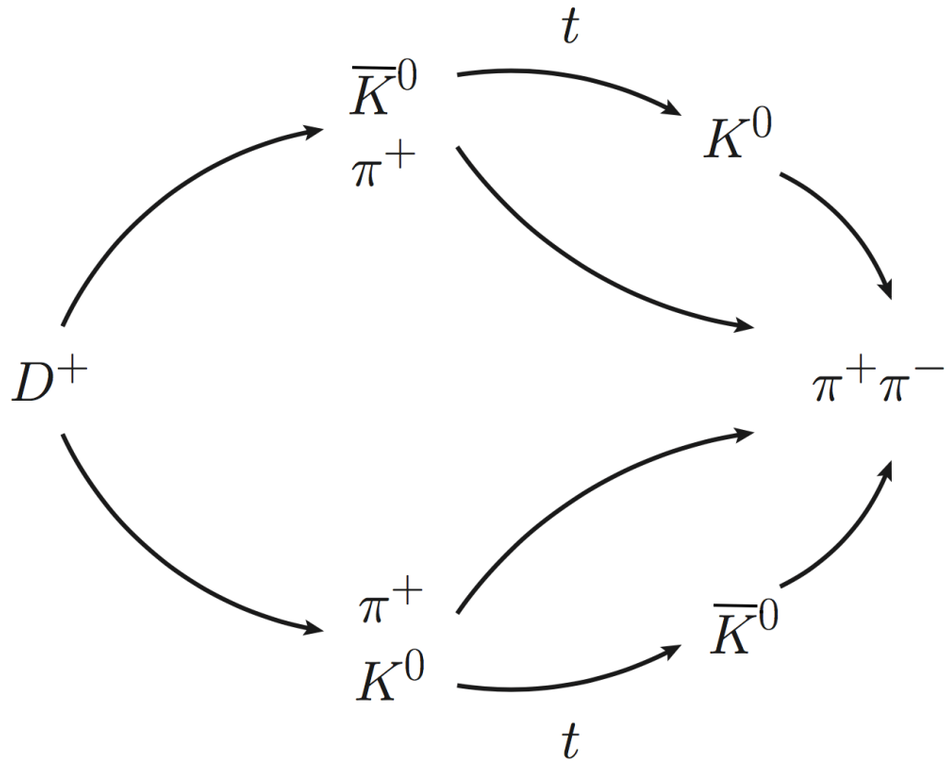
$$A_{CP}^{D^+\to K_S^0\pi^+} \equiv \frac{\Gamma(D^+\to K_S^0\pi^+)-\Gamma(D^-\to K_S^0\pi^-)}{\Gamma(D^+\to K_S^0\pi^+)+\Gamma(D^-\to K_S^0\pi^-)} = A_{CP}^{\Delta C} + A_{CP}^{\bar{K}^0}$$

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

However…

Full decay chain

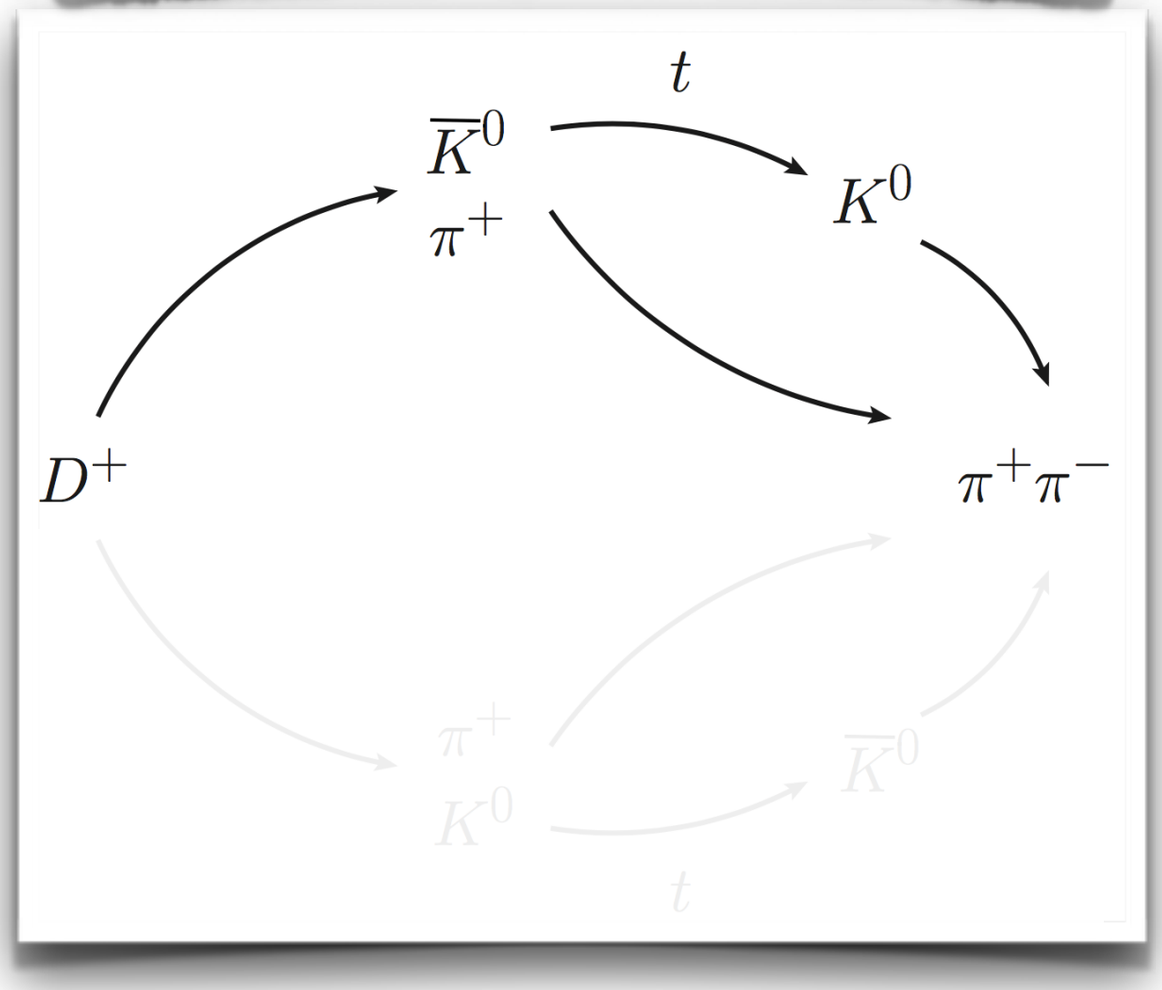
$$D^+ \to \pi^+ K(t)(\to \pi^+\pi^-)$$



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

Indirect CPV in kaon mixing

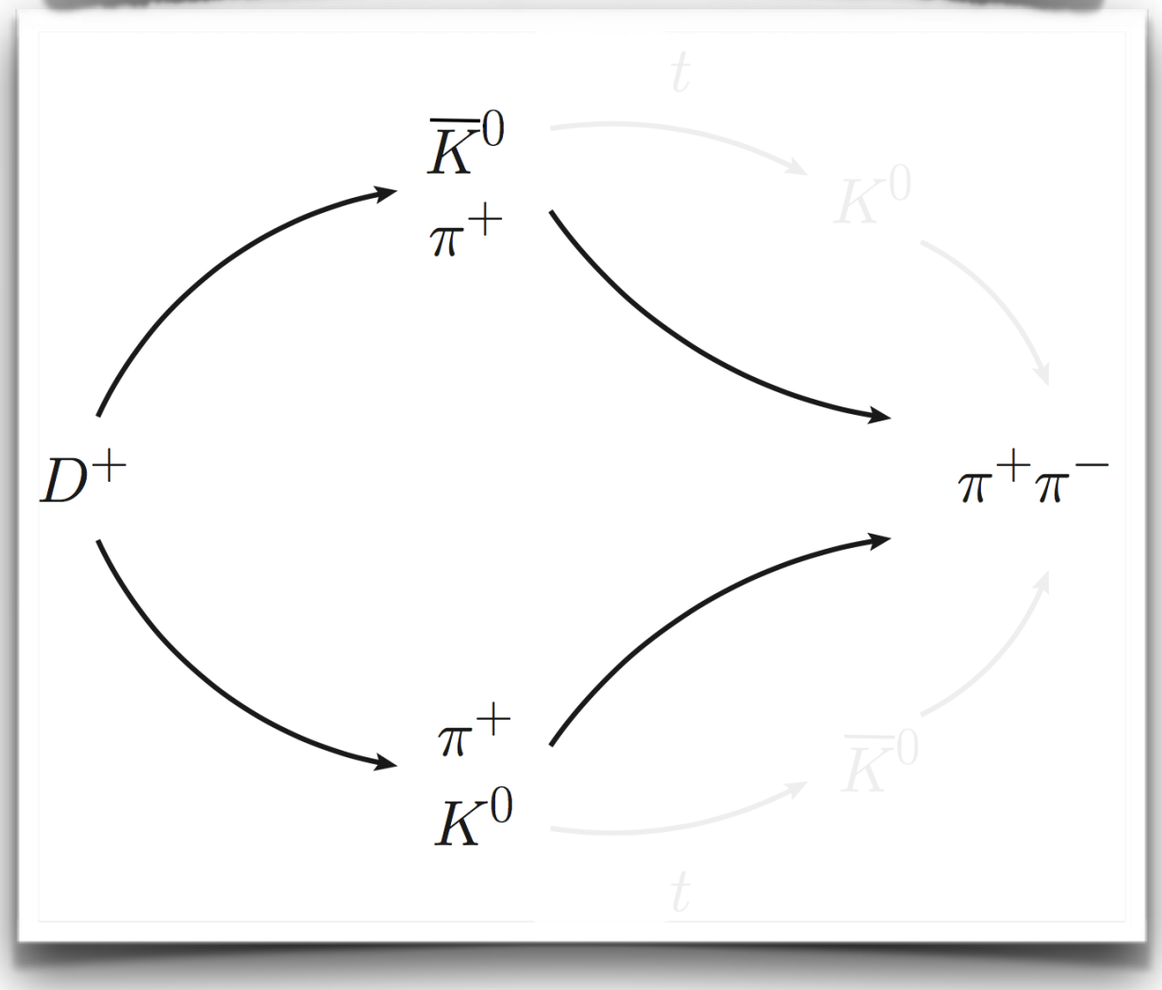
$\mathrm{Re}(\epsilon)=10^{-3}$



Z.z. Xing, ’95; Grossman, Nir, ’12

Direct CPV in charm decays

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



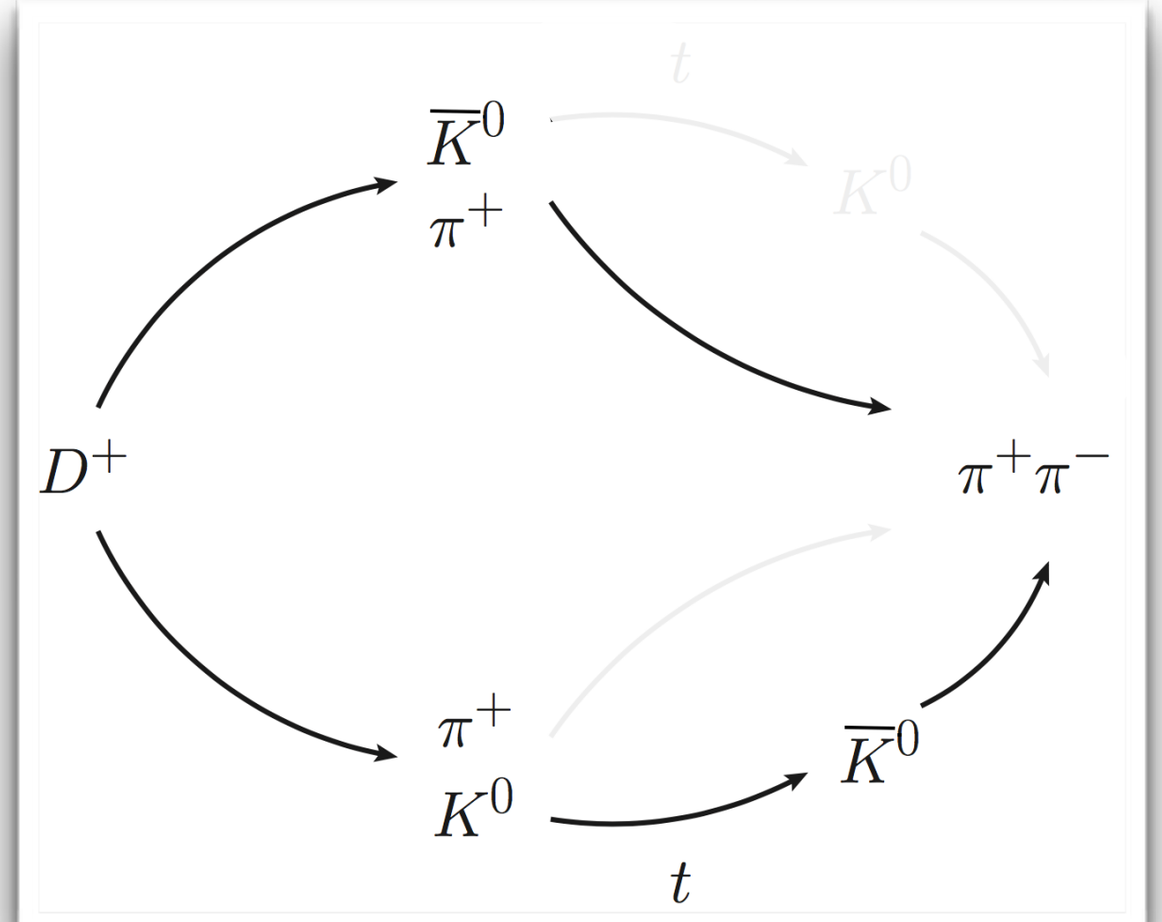
Bigi, Yamamoto, ’95

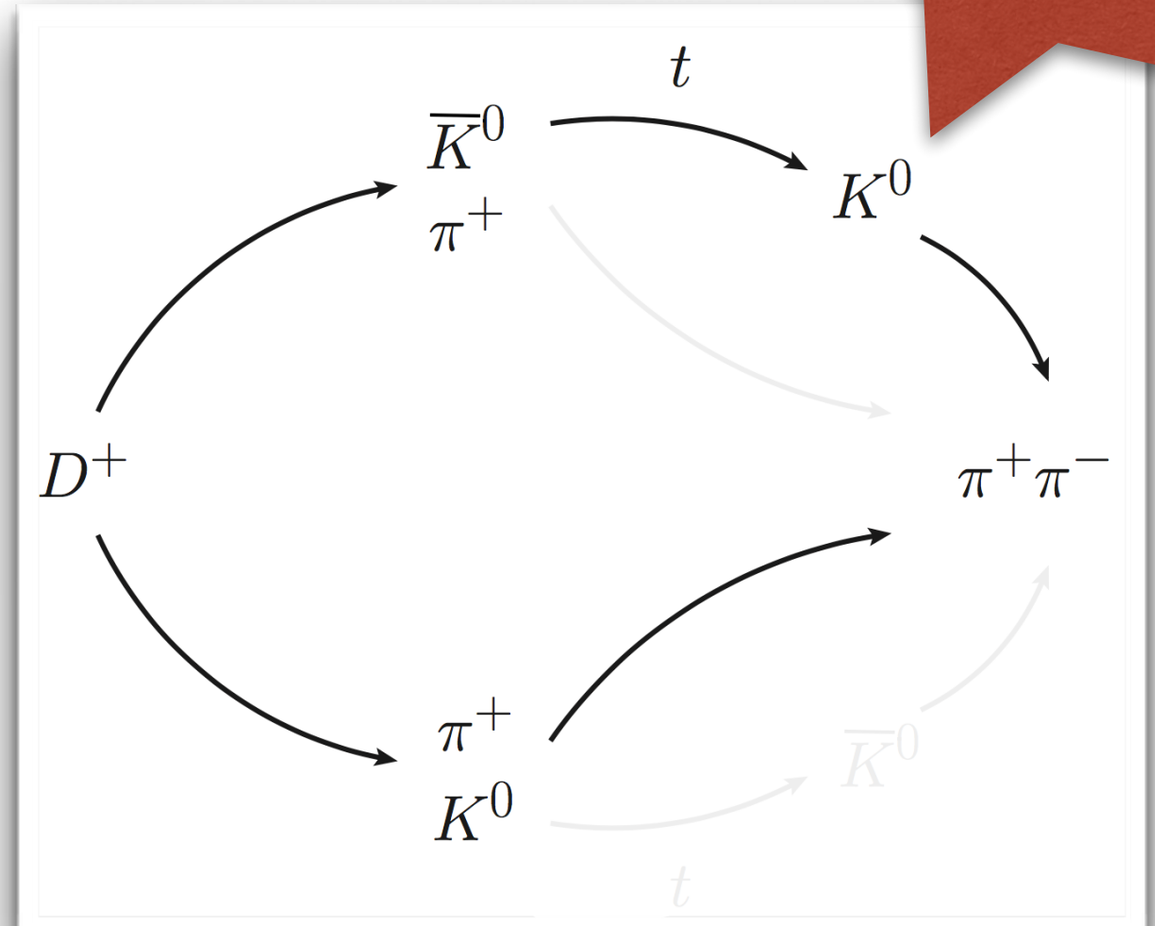
$$A_{CP}(t) = A_{CP}^{\overline{K}^0}(t) + A_{CP}^{\rm dir}(t) + A_{CP}^{\rm int}(t)$$

CPV induced by mother decay and daughter mixing

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

NEW





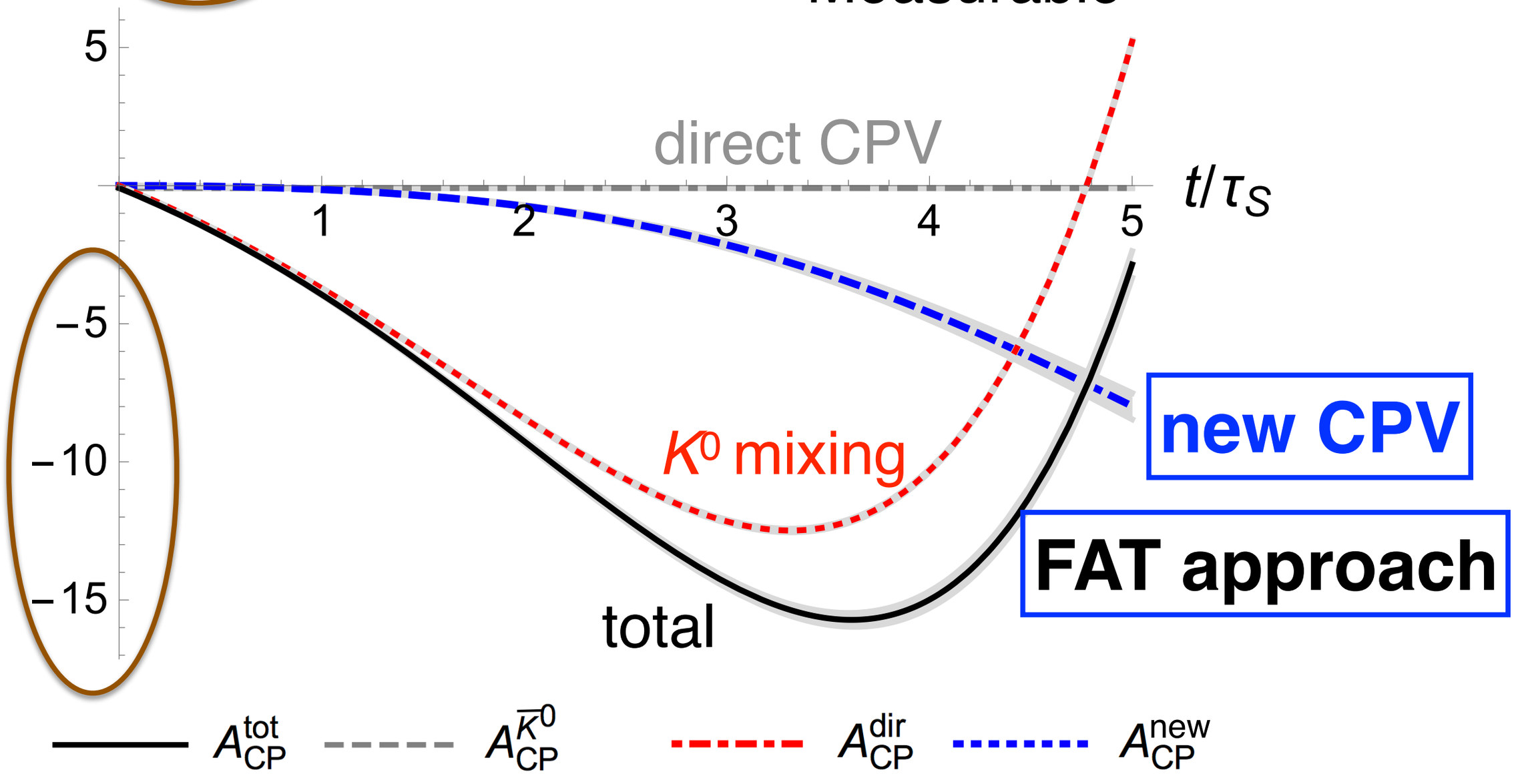
D.Wang, **FSY**, H.n.Li, Phys.Rev.Lett 119, 181802(2017)

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

Non-negligible
Measurable

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

$A_{CP}(t)[\times 10^{-3}]$



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

PRL109,021601(2012) [arXiv:1203.6409]

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

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

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

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

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

Belle

$A^{\Delta C}$=(-0.006±0.115)%

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

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

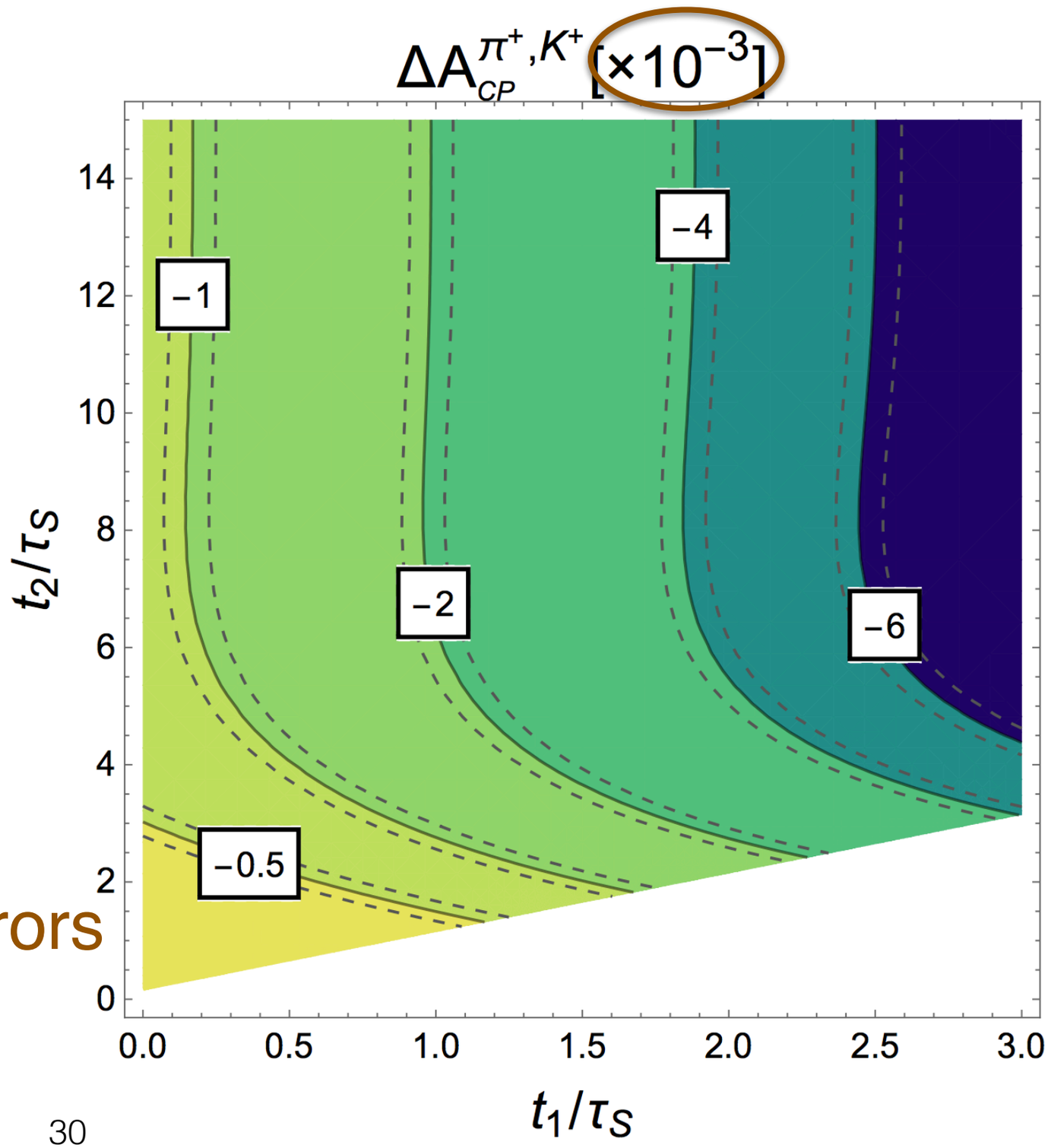
New Observable

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]



Summary

- CPV in D0->K+K- and pi+pi-
  - Understandable in the Standard Model
  - FAT approach works well in charm
- New CPV effect is found in CF $D \to K_S f$
  - mother decay and daughter mixing
  - To be subtracted to extract direct CPV
- Charm CPV is becoming more charming with precision at order of 10^{-4}