CP Violation in charm

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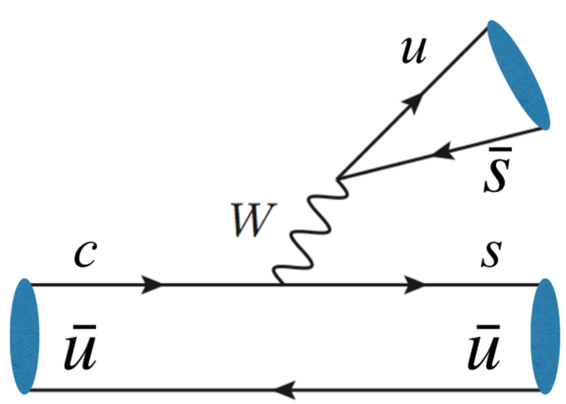
Thank Wenbiao for invitation !

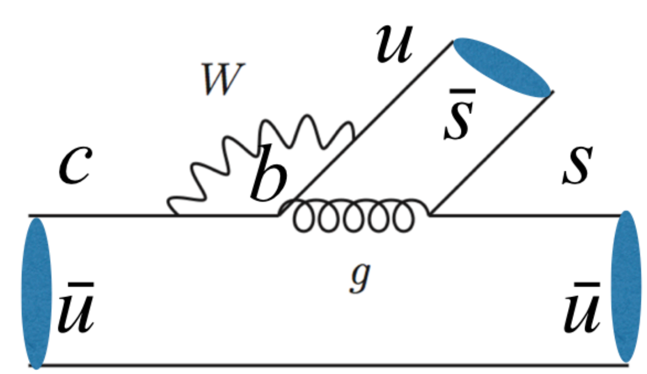
LHCb observes charm CPV

1903.08726

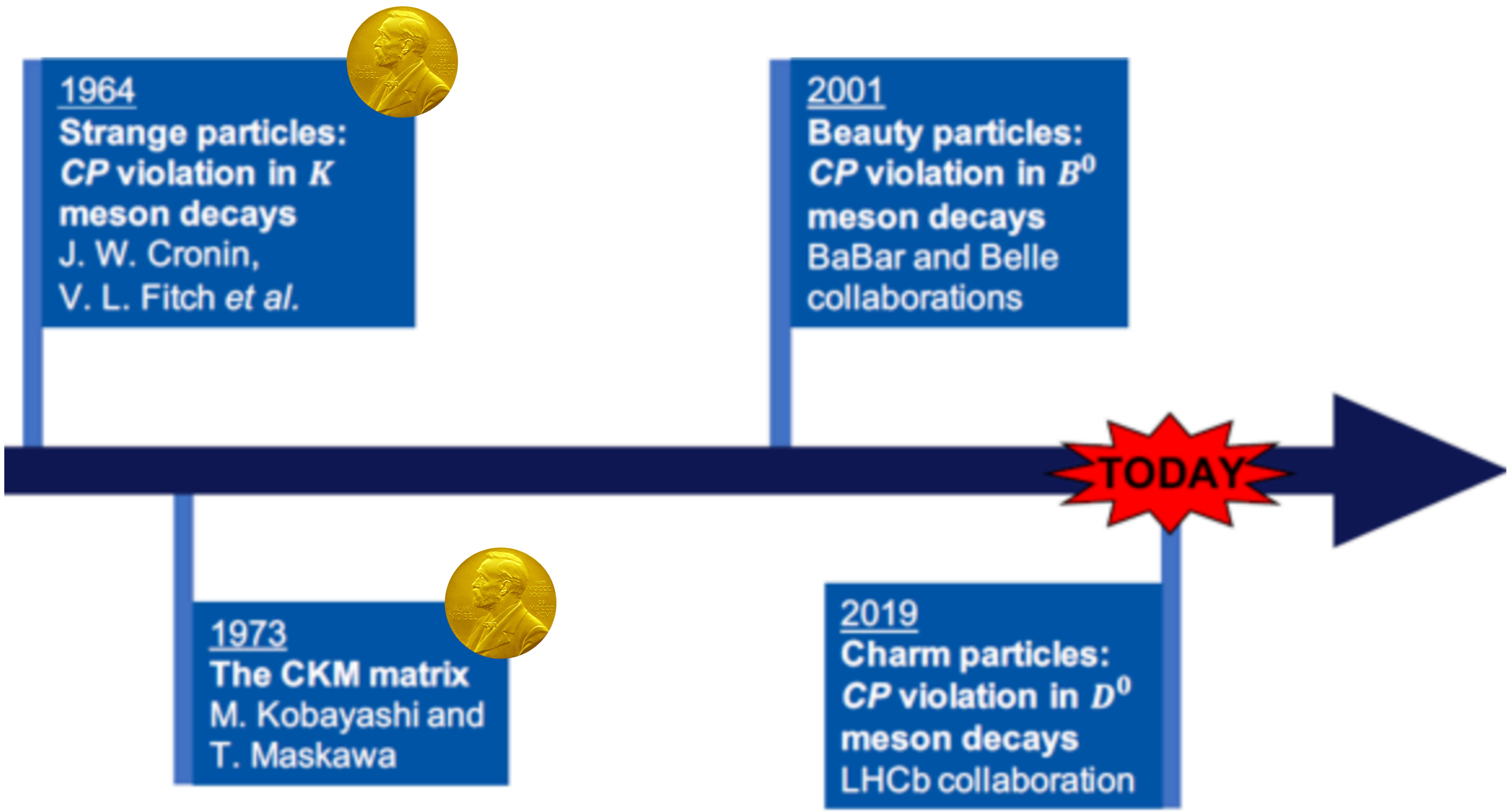
$$\Delta A_{CP} = A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)$$
$$= (-1.54 \pm 0.29) \times 10^{-3}$$

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

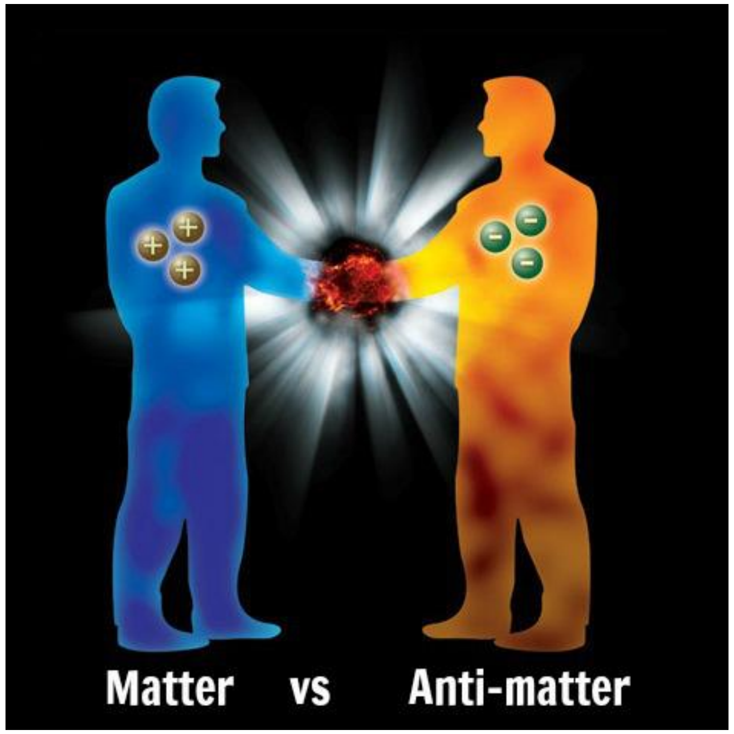




LHCb observes charm CPV



An important milestone in particle physics



- Matter-Antimatter asymmetry of the Universe
- Sakharov conditions: [Sakharov, 1967]

  1) C and **CP violation**

  2) Baryon number violation

  3) Out-of-equilibrium dynamics

CP violation

- Asymmetry between particle and anti-particle

$$A_{CP}(f;\, t) \equiv \frac{\Gamma(D^0(t) \to f) - \Gamma(\overline{D}^0(t) \to f)}{\Gamma(D^0(t) \to f) + \Gamma(\overline{D}^0(t) \to f)}$$

- Non-vanishing Acp requires two terms of amplitudes, with different weak phases and strong phases

$$A = A_1 e^{i\phi_1} e^{i\delta_1} + A_2 e^{i\phi_2} e^{i\delta_2}$$

$$A_{CP} \approx 2r \sin(\delta_1 - \delta_2) \sin(\phi_1 - \phi_2)$$

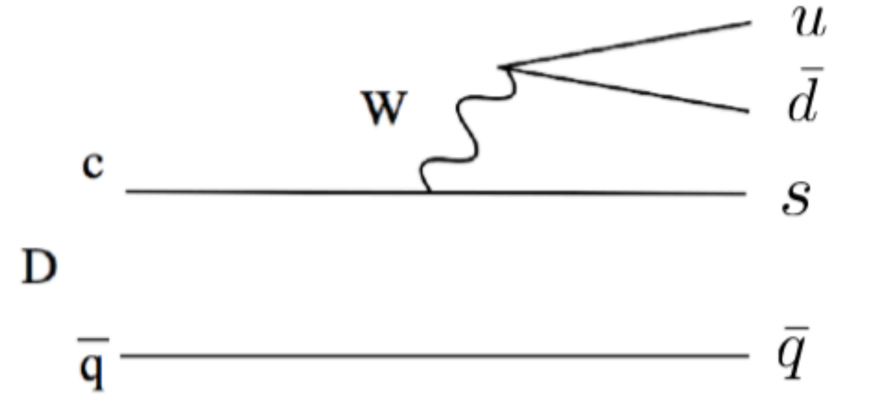
$$r = \frac{|A_2|}{|A_1|} \ll 1$$

★ Can be classified by SM CKM suppression

★ Cabibbo-favored (CF) decay
- originates from $c \to s\, u\bar{d}$
- examples: $D^0 \to K^-\pi^+$

$V_{cs}V^*_{ud}$

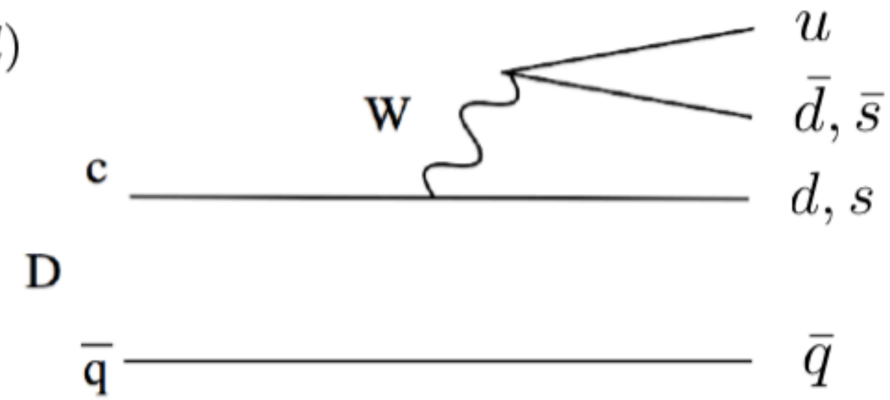
~ 1



★ Singly Cabibbo-suppressed (SCS) decay
- originates from $c \to q\, u\bar{q}$
- examples: $D^0 \to \pi\pi$ and $D^0 \to KK$

$V_{cs(d)}V^*_{us(d)}$

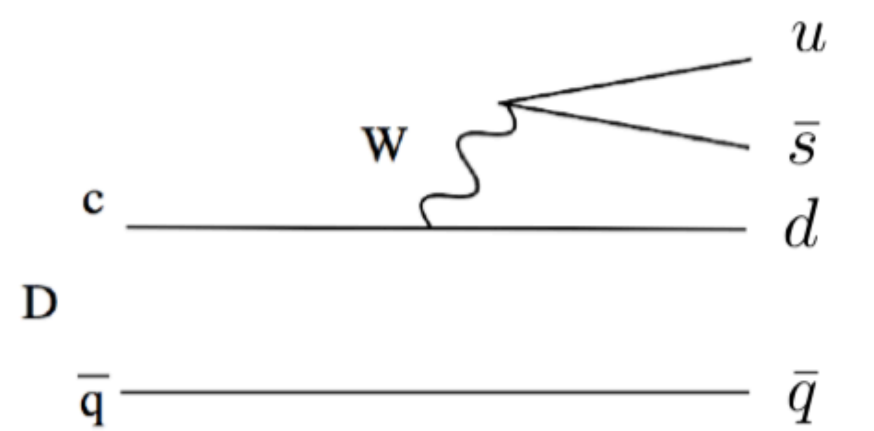
$\sim \lambda$



★ Doubly Cabibbo-suppressed (DCS) decay
- originates from $c \to d\, u\bar{s}$
- examples: $D^0 \to K^+\pi^-$

$V_{cd}V^*_{us}$

$\sim \lambda^2$



$$\lambda = 0.225$$

Outline

1. CPV in Cabibbo-suppressed processes
    - $\Delta A_{CP} = A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)$

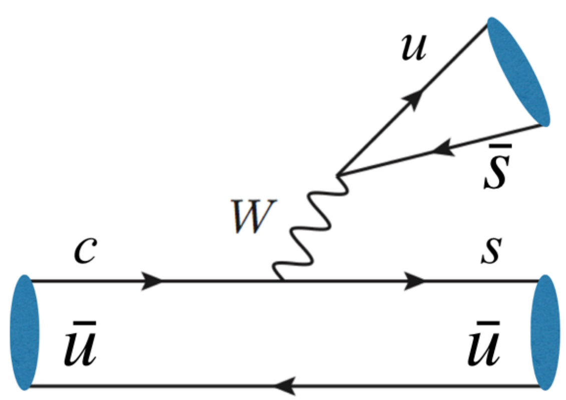
2. CPV in Cabibbo-favored D to neutral Kaons

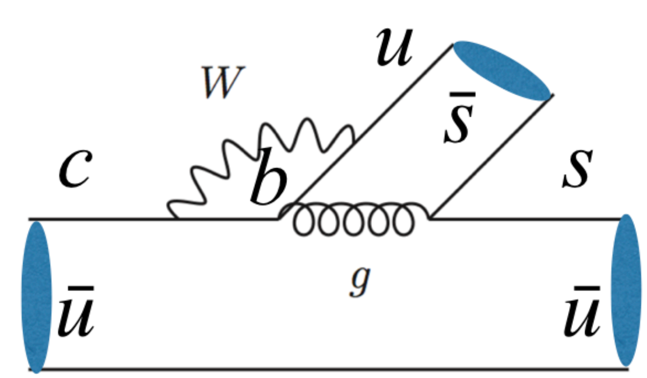
1. CPV in Singly Cabibbo-Suppressed (SCS) modes

Direct CPV in charm

Scenario 1 :   SCS

tree v.s. **penguin**





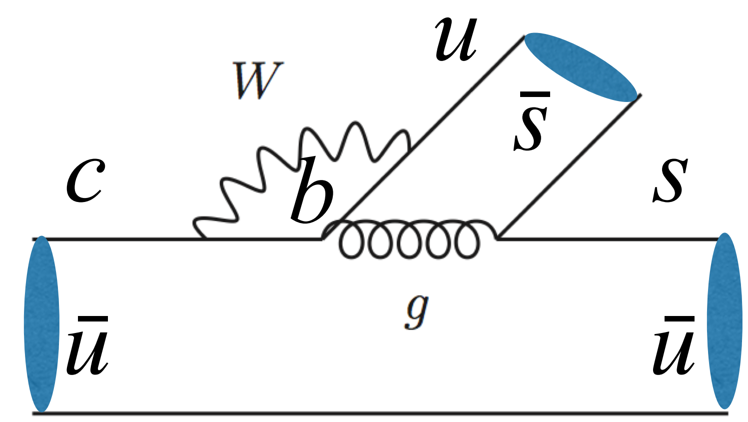
$V_{cd}V_{ud}/V_{cs}V_{us}$ $V_{cb}V_{ub}$

λ $\lambda^5 + i\lambda^5$

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

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.

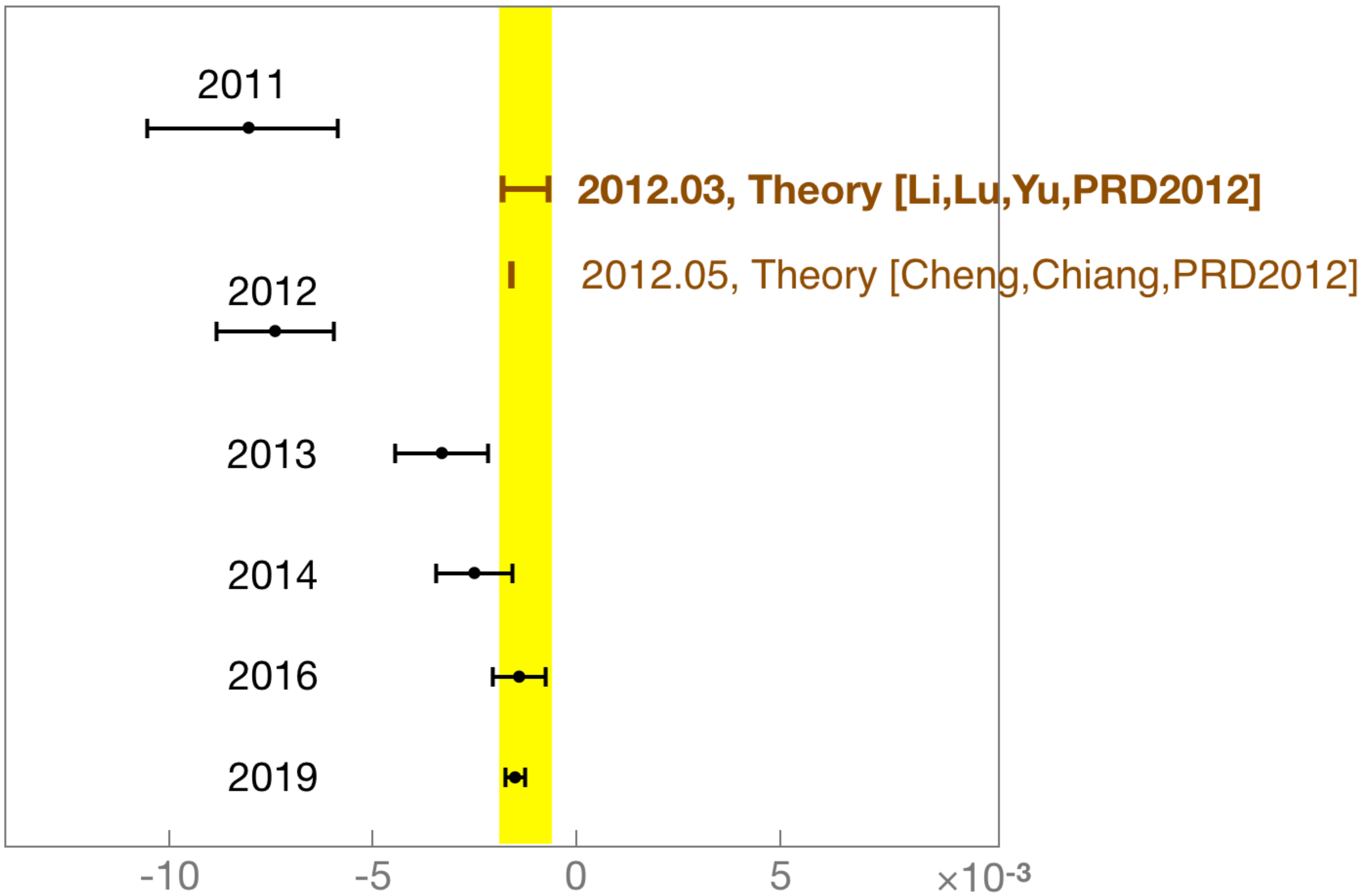
Cheng,Chiang,'12 : $(-1.51 \pm 0.04) \times 10^{-3}$

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

Measurements of ΔA_{CP}

Measurements	ΔA_{CP}	Publication	World Average
2011LHCb (D*)	(-0.82±0.24)%	PRL108,111602	(-0.74±0.15)%
2012 CDF	(-0.62±0.23)%	PRL109,111801	
2012 Belle	(-0.87±0.41)%	1212.1975	
2013LHCb (D*)	(-0.34±0.18)%	LHCb-CONF-2013-03	(-0.33±0.12)%
2013LHCb (B)	(+0.49±0.33)%	PLB723(2013)33	
2014LHCb (B)	(+0.14±0.18)%	JHEP07(2014)041	(-0.25±0.10)%
2016LHCb (D*)	(-0.10±0.09)%	PRL116,191601	(-0.14±0.07)%
2019LHCb(all)	(-0.15±0.03)%	1903.08726	(-0.16±0.03)%

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

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

→

$$\frac{|\mathcal{P}|}{|\mathcal{T}|}\sin\delta \sim 1/2$$

topological approach

Li, Lu, **FSY**, '12; Cheng, Chiang, '12

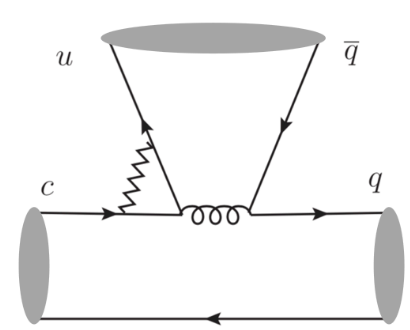
$$\frac{\mathcal{P}^{\pi\pi}}{\mathcal{T}^{\pi\pi}} = 0.66 e^{i134^\circ}, \quad \text{and} \quad \frac{\mathcal{P}^{KK}}{\mathcal{T}^{KK}} = 0.45 e^{i131^\circ}$$

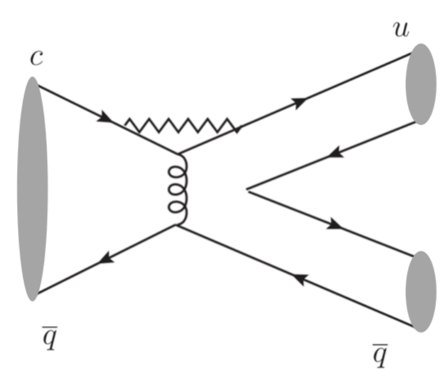
$\Delta U = 0$ over $\Delta U = 1$

Grossman, Schacht, '19

$$|\tilde{p}_0|\sin(\delta_{\rm strong}) = 0.65 \pm 0.11$$

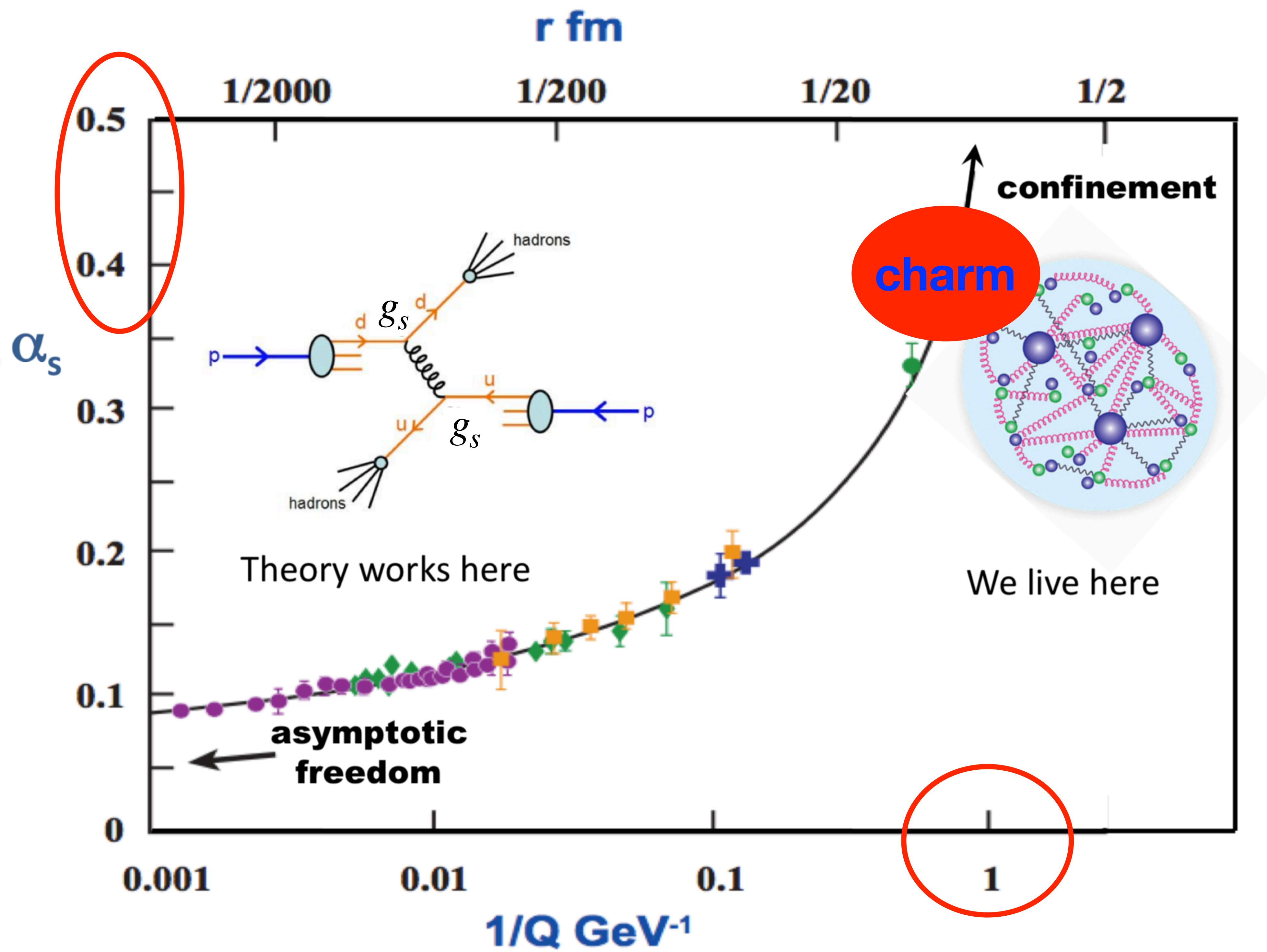
Key: **Long-distance non-perturbative**





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

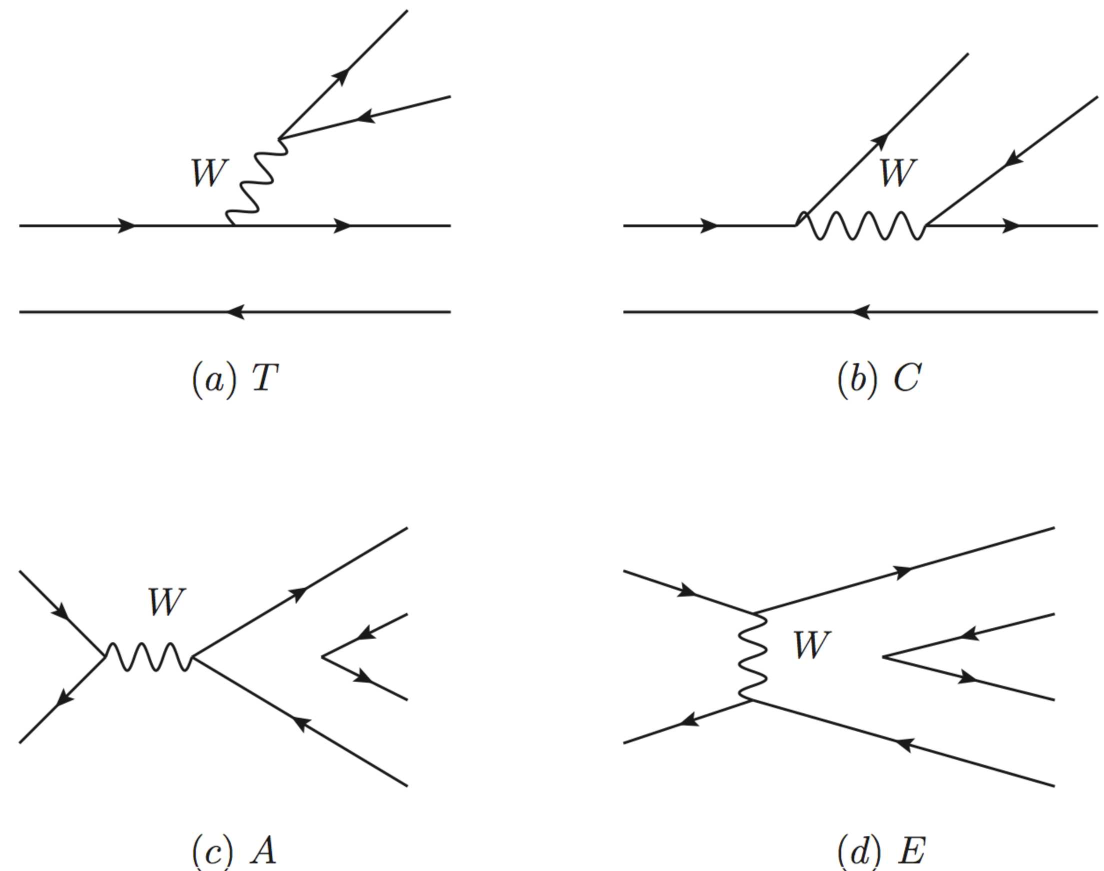
The QCD “dilemma”



[S.Olsen’s talk @ HIEPA2018]

Topological Amplitudes

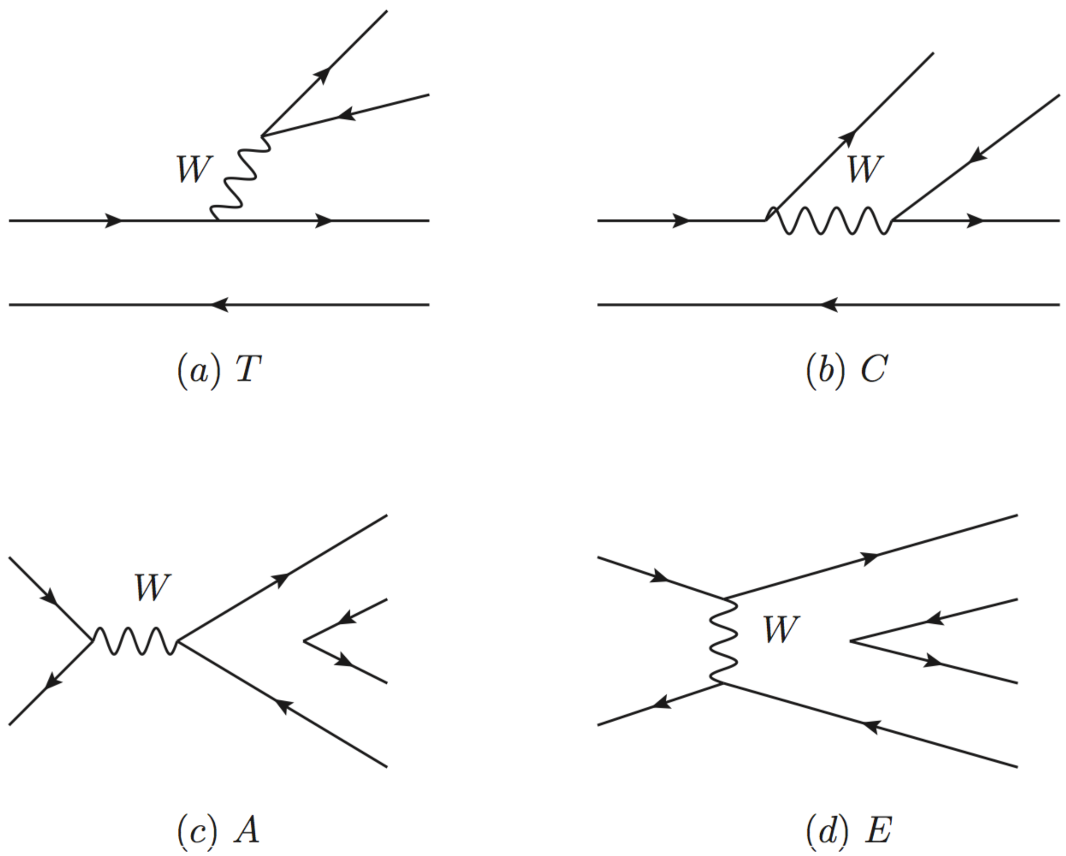
- According to the **weak flavour flows**
- **Including all strong interaction effects**
- **Amplitudes extracted from data**



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

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

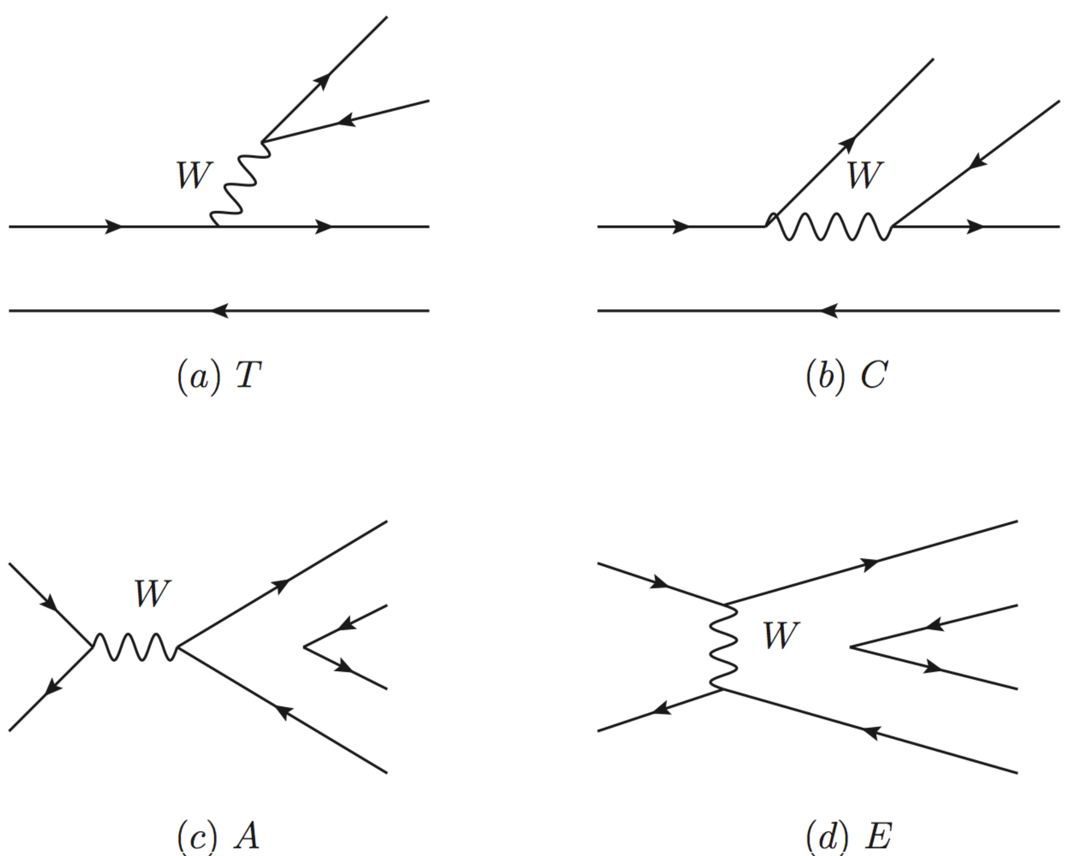
Factorization-Assisted Topological-Amplitude Approach (FAT)



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

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

Factorization-Assisted Topological-Amplitude Approach (FAT)



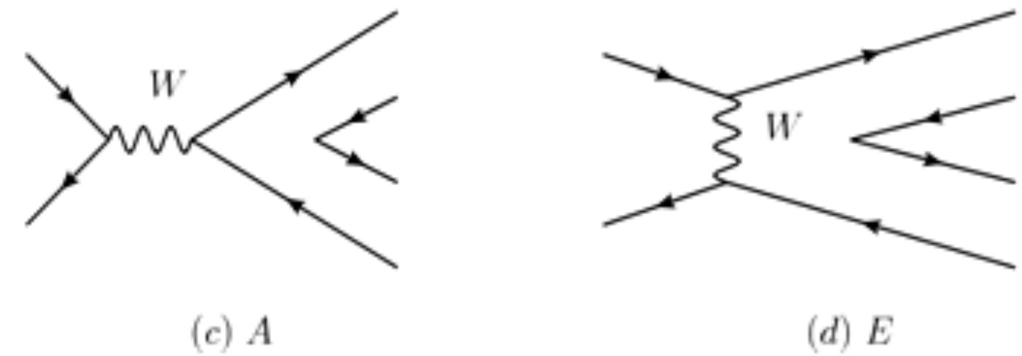
- Dynamics In **factorization**:
  - **Short-distance**: Wilson coefficients
  - **Long-distance**: hadronic matrix elements

Non-perturbative quantities

Extracted from data

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

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



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

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

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

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

SU(3) breaking effects

nonperturbative contributions

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

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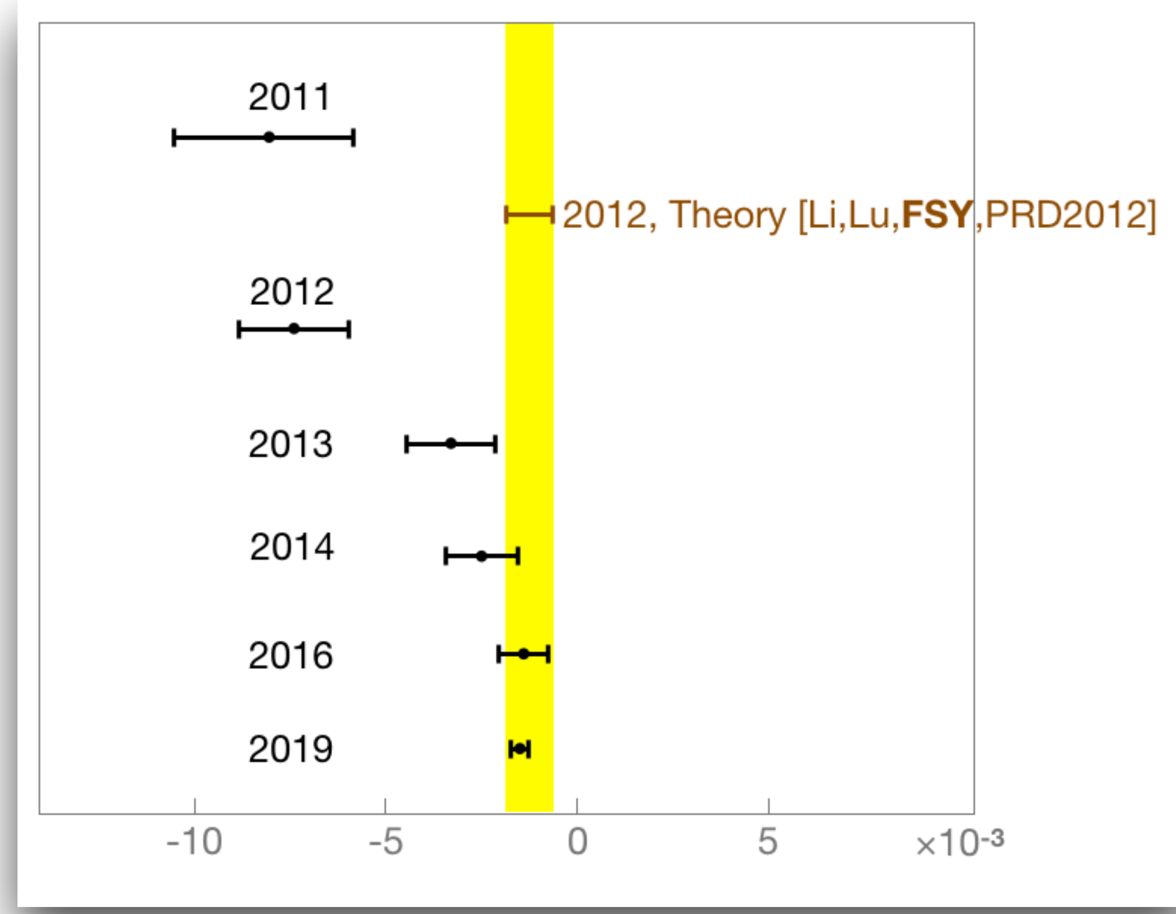
$$\Delta A_{CP}^{SM} = -1 \times 10^{-3}$$



1. **Understand QCD dynamics @ 1GeV by Branching Ratios**

2. **Then predict charm CPV**

Factorization-Assisted Topological approach

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

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Factorization-Assisted Topological approach

Li, Lu, **FSY**, ’12

Implications of LHCb2019

1903.08726

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

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

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

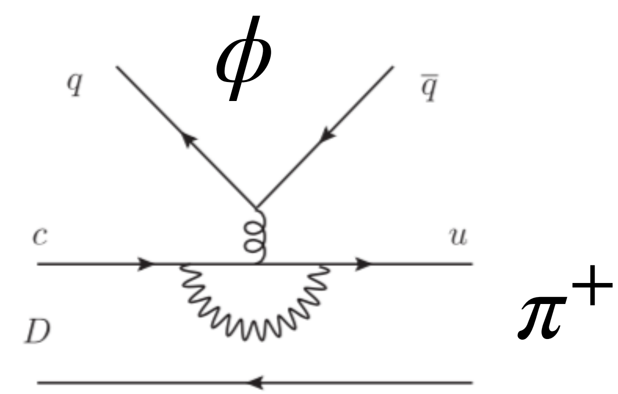
$$\Delta A_{CP} = (-1.54 \pm 0.29) \times 10^{-3}$$

Li, Lu, **FSY**, 1903.10638

What is the next potential mode to observe charm CPV?

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

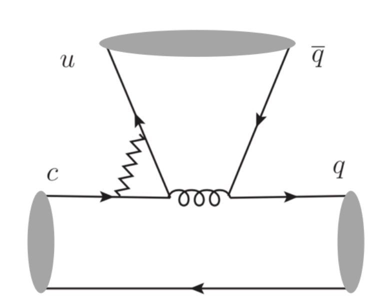
$$A_{CP}(D^+ \to \pi^+\phi) = 10^{-7}$$

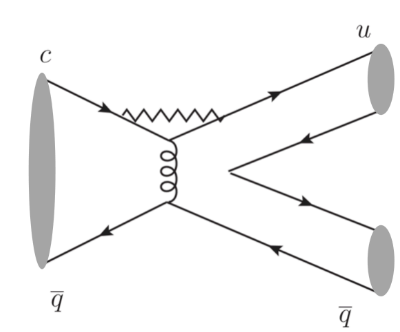


Qin, Li, Lu, **FSY**, '14

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

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



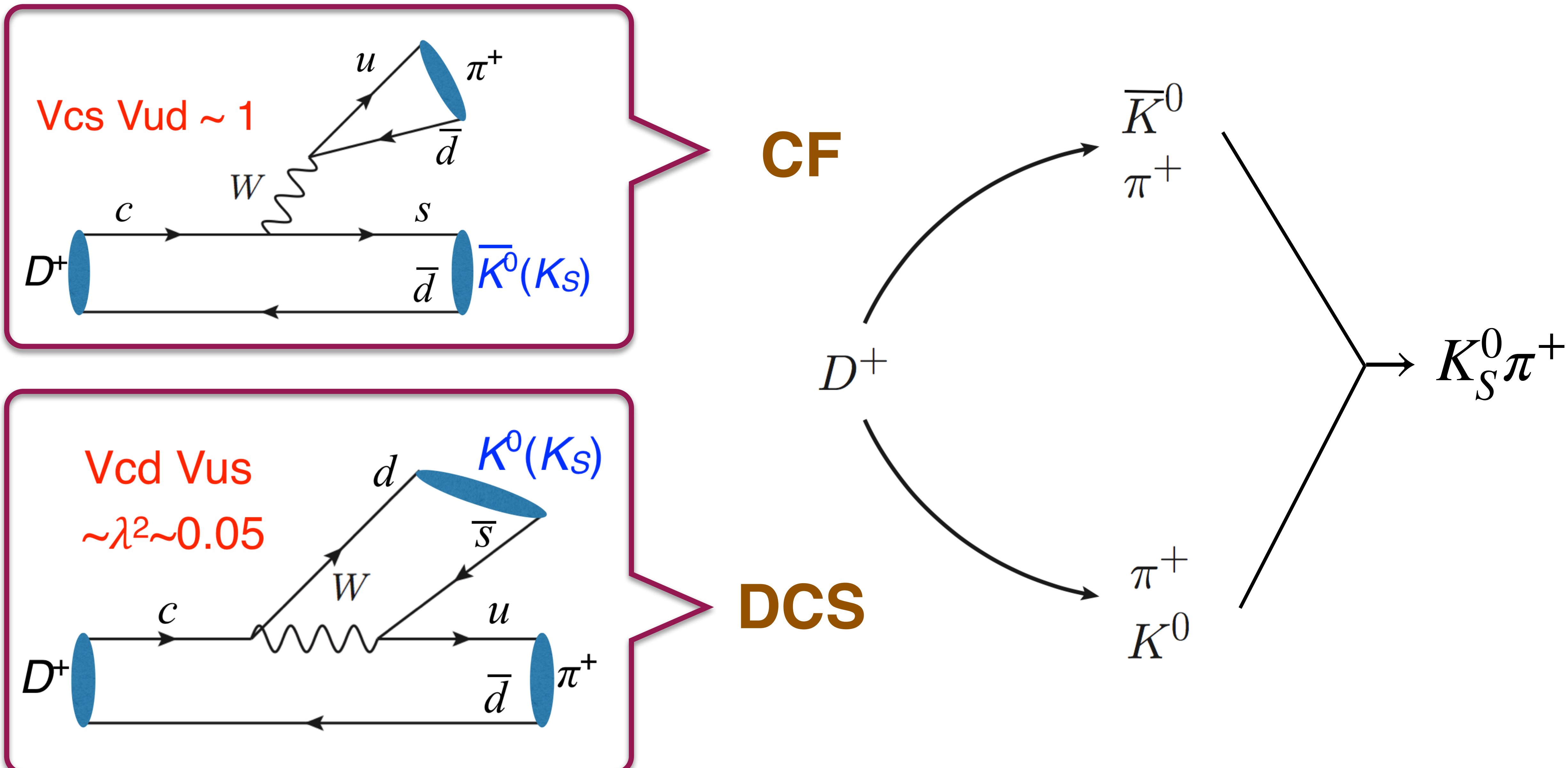


Li, Lu, **FSY**, 1903.10638

2. CPV in Cabibbo-Favored (CF) and Doubly Cabibbo-Suppressed (DCS) modes

Precision —> 10^{-4} ?

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



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

New Physics in $D \to f\, K_S^0$

$$A_{CP}^{dir} \sim 2 r_f \sin\phi \sin\delta_f$$

SM: $\phi = O(10^{-4})$

NP: $\phi = O(1)$

Search for new physics at tree-level

Postulated in literature:

deducting kaon mixing,

data reveal direct CPV in charm

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

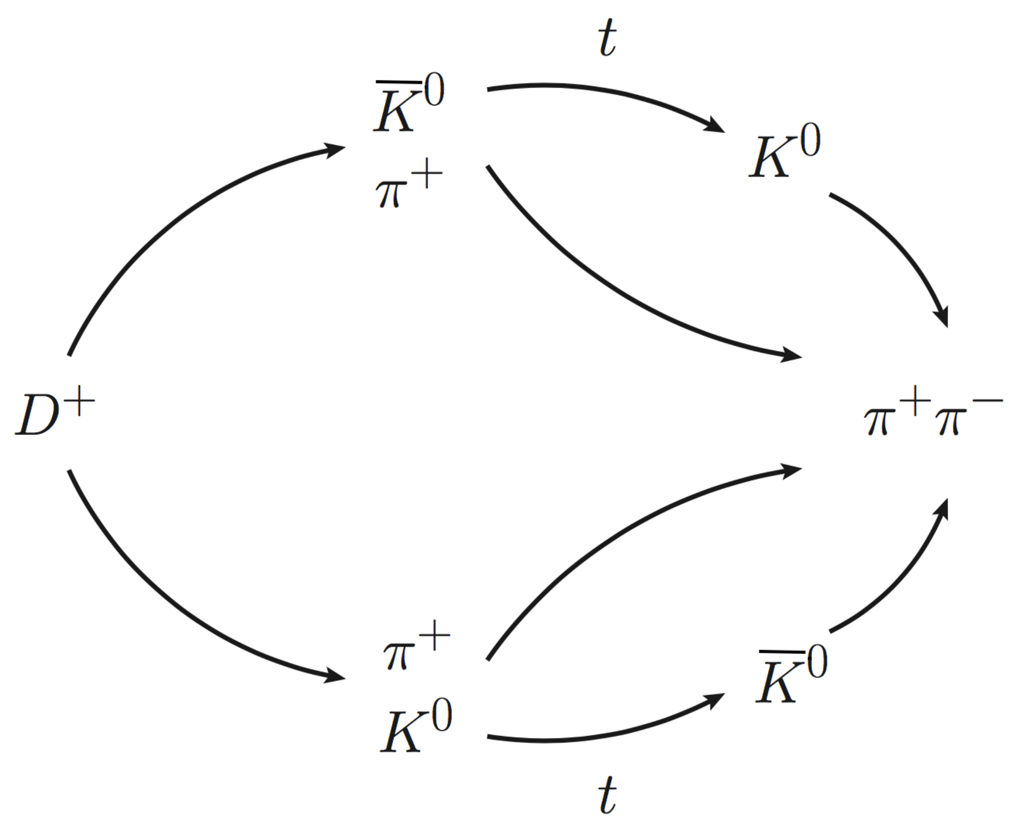
$$= A_{CP}^{\Delta C} + A_{CP}^{\bar{K}^0}$$

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

However…

Full decay chain

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



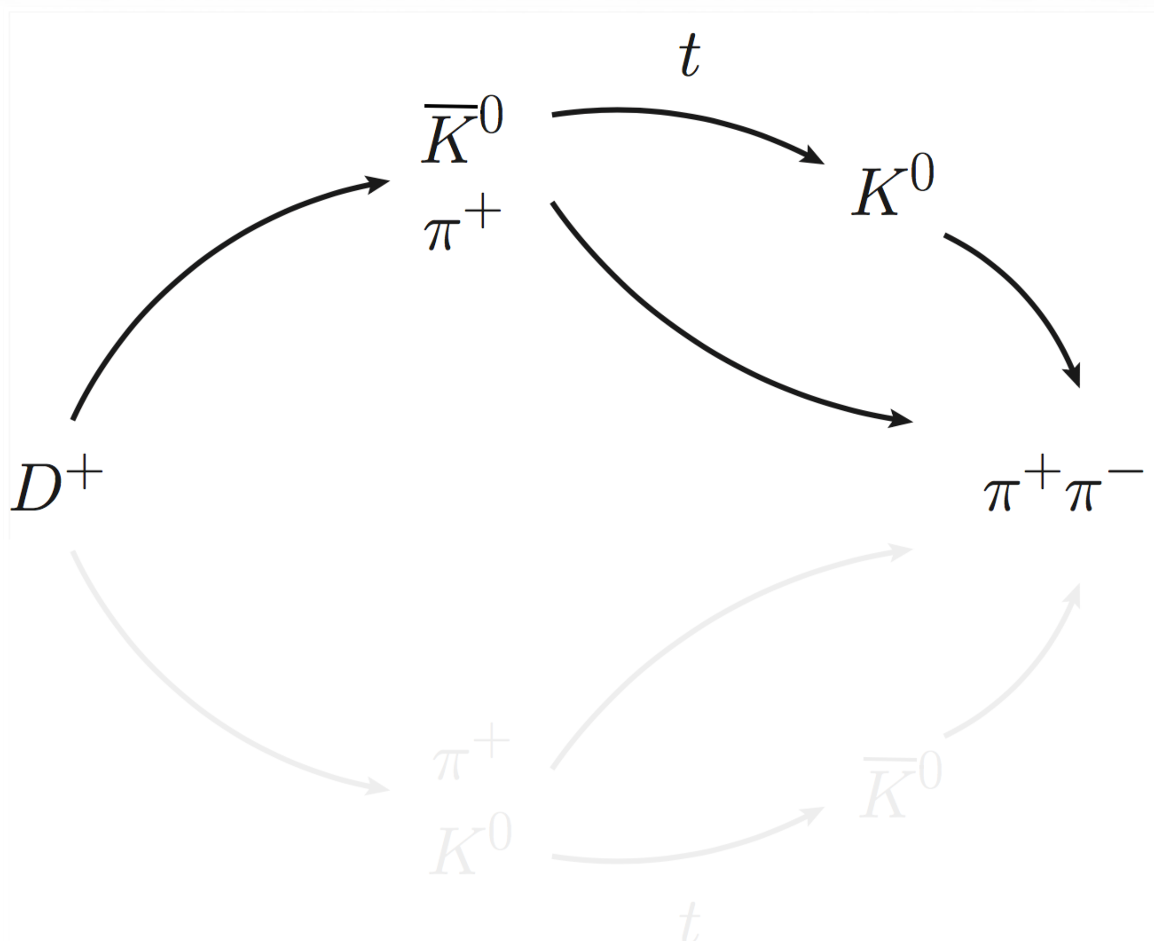
$$A_{CP}(t) = A_{CP}^{\overline{K}^0}(t) + A_{CP}^{\mathrm{dir}}(t)$$

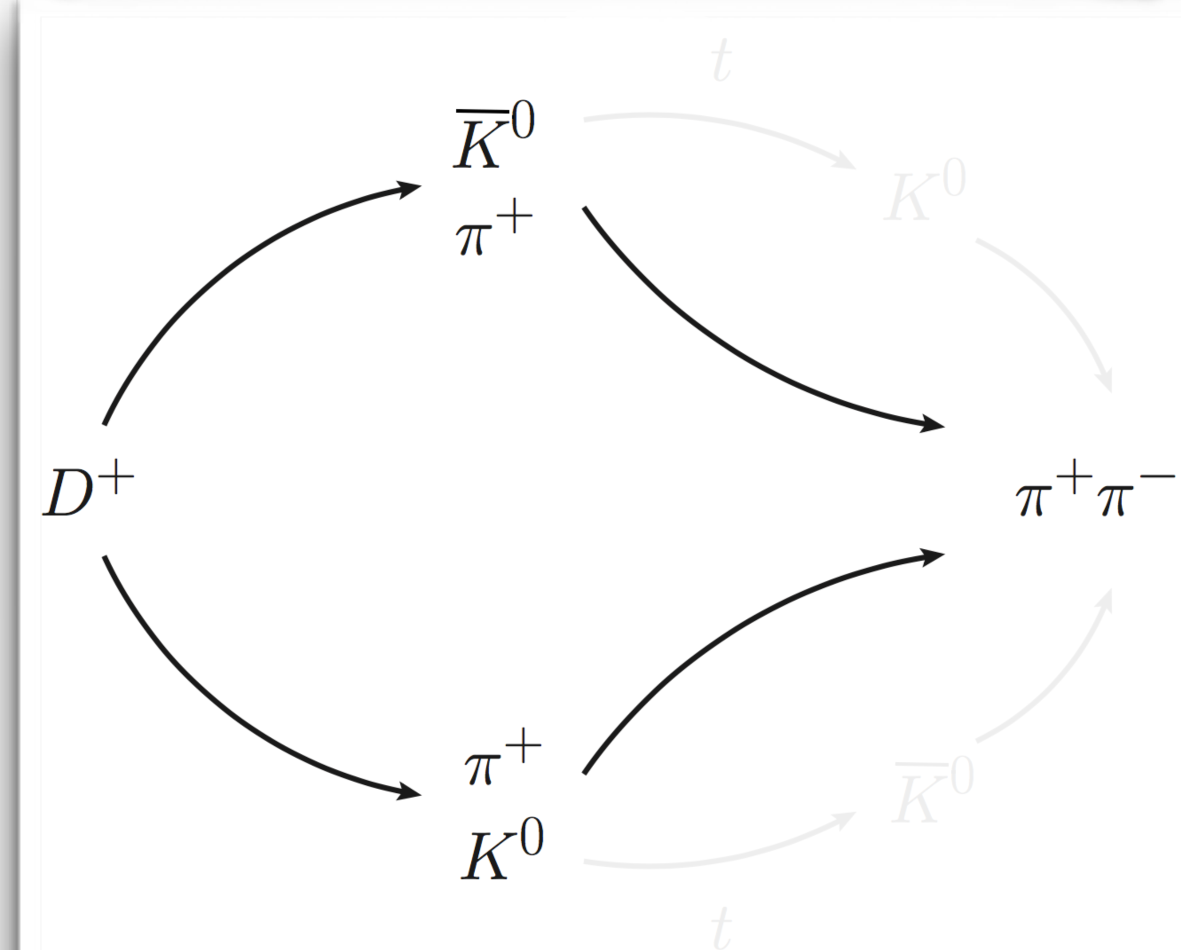
Indirect CPV in kaon mixing

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

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

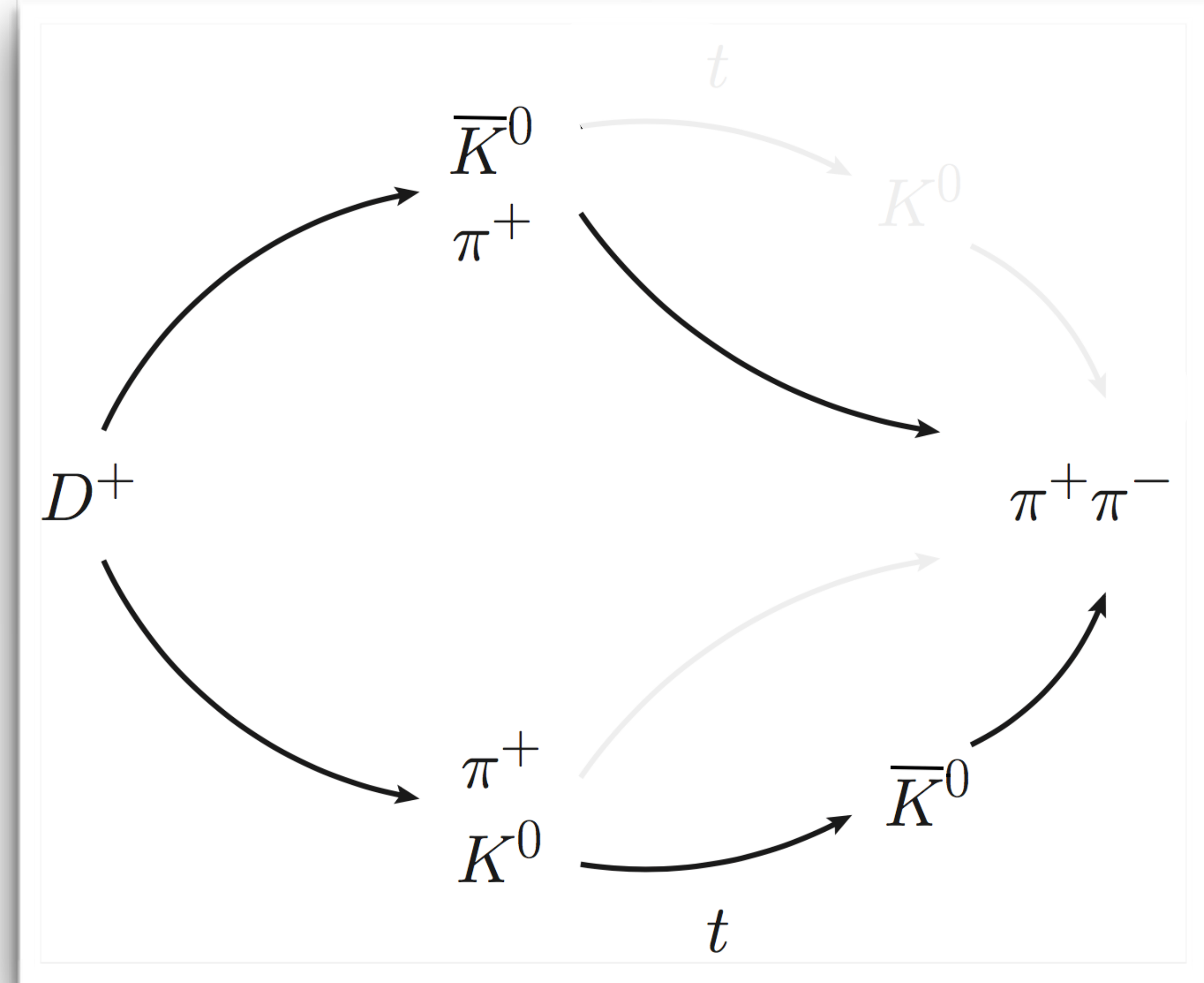
Bigi, Yamamoto, '95

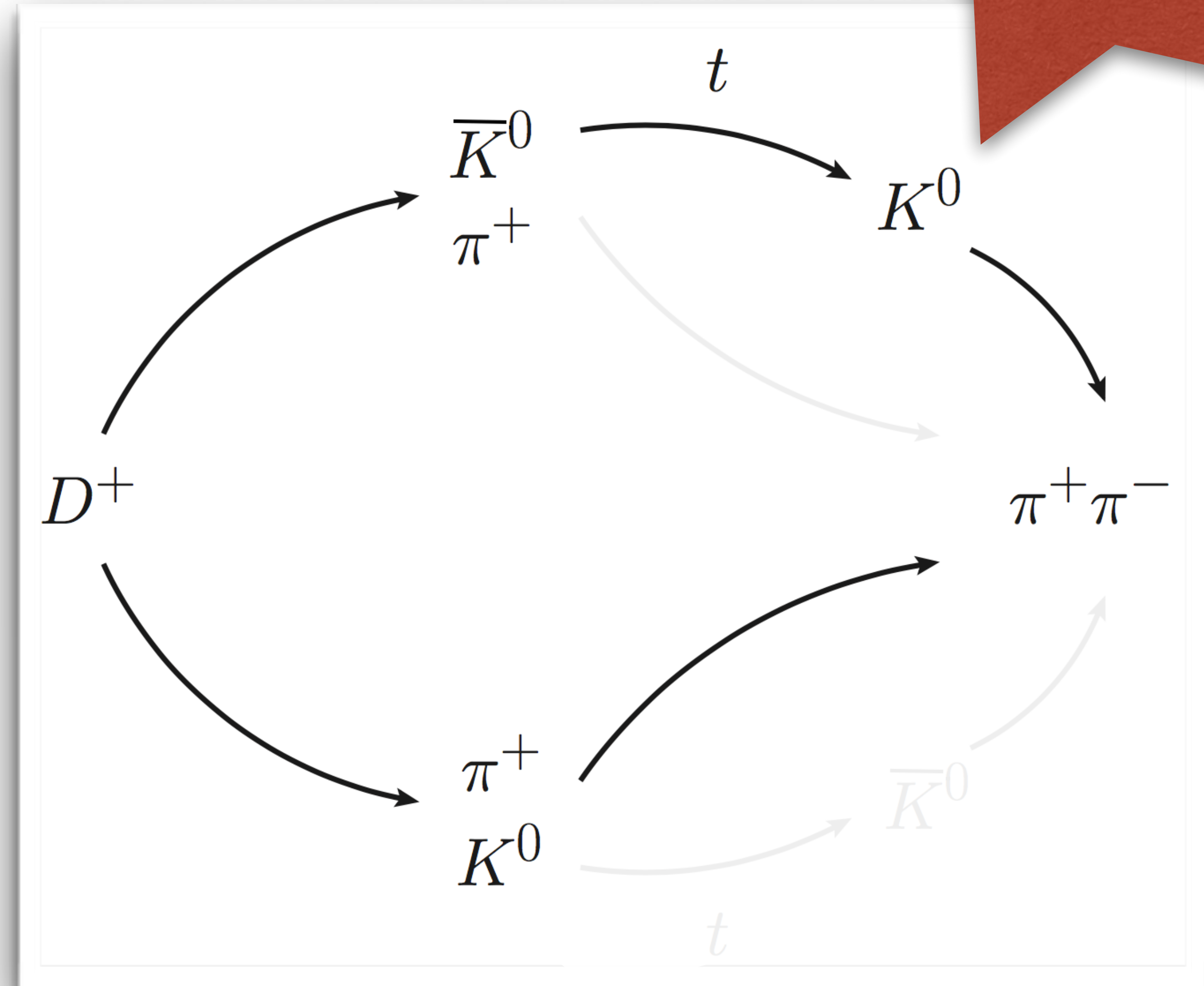
$$A_{CP}(t) = A_{CP}^{\overline{K}^0}(t) + A_{CP}^{\mathrm{dir}}(t) + A_{CP}^{\mathrm{int}}(t)$$

CPV induced by mother decay and daughter mixing

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

NEW

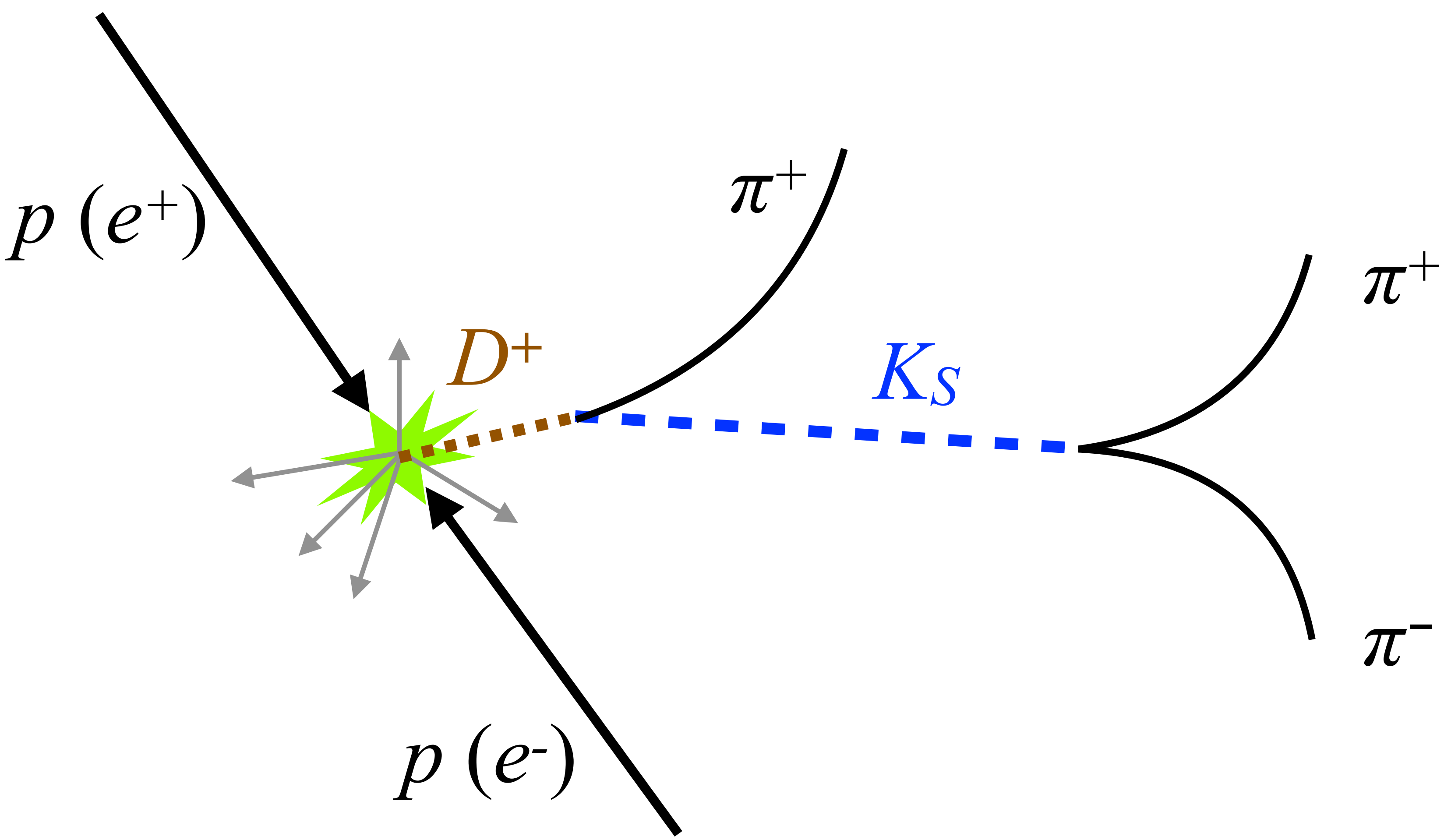




D.Wang, **FSY**, H.n.Li, Phys.Rev.Lett 119, 181802(2017)

Time-dependent & Time integrated CPV

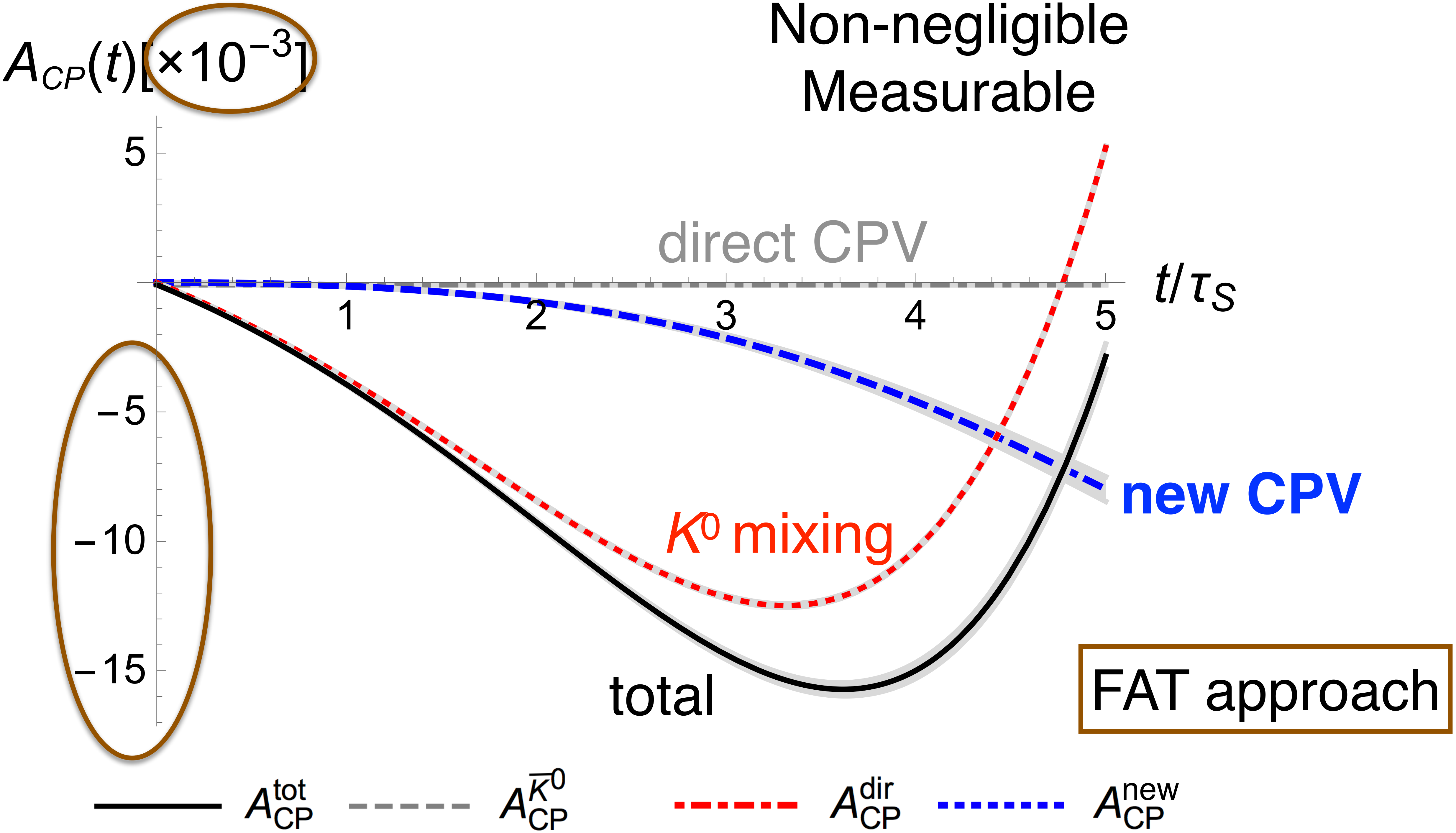
time of K_S flying



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

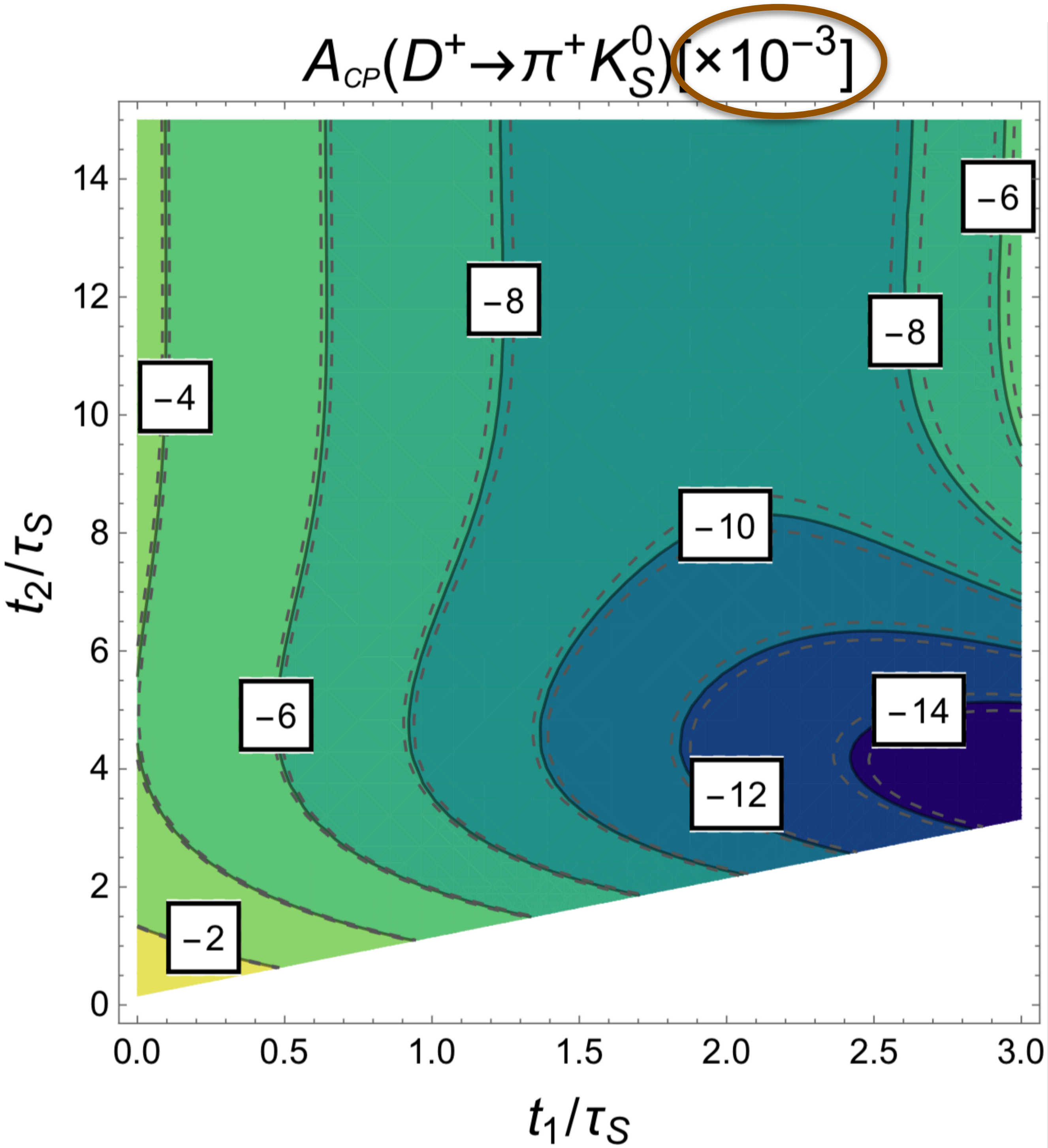
Non-negligible
Measurable

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

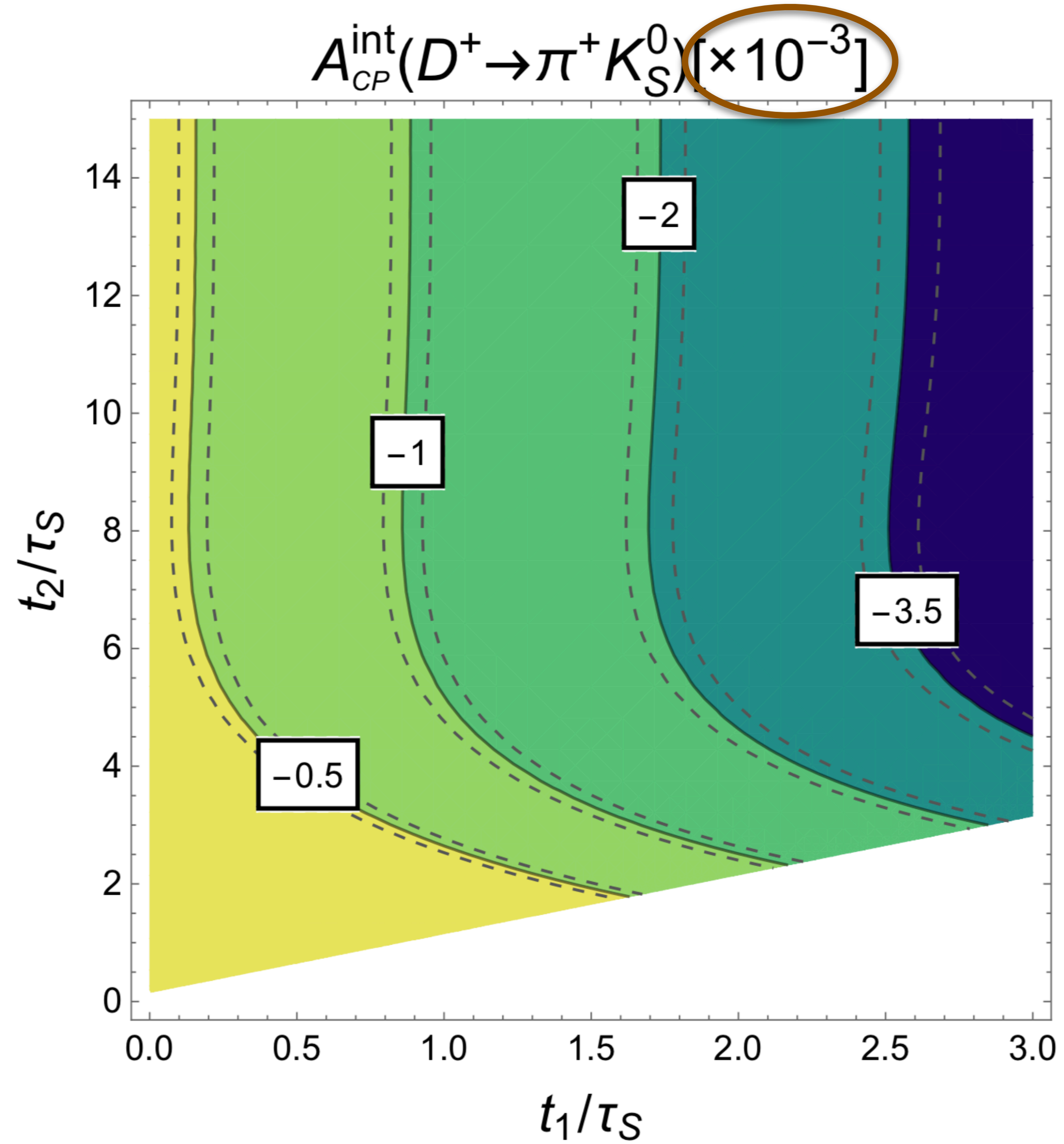


Time-Integrated CPV

total



Interference



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

PRL109,021601(2012) [arXiv:1203.6409]

$$A_{CP}^{D^+\to K_S^0\pi^+} \equiv \frac{\Gamma(D^+ \to K_S^0\pi^+) - \Gamma(D^- \to K_S^0\pi^-)}{\Gamma(D^+ \to K_S^0\pi^+) + \Gamma(D^- \to K_S^0\pi^-)} = A_{CP}^{\Delta C} + A_{CP}^{\bar{K}^0}, \quad (1)$$

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

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

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

Belle

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

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

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

Belle

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

[Wang, **FSY**, Li, ’17]

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

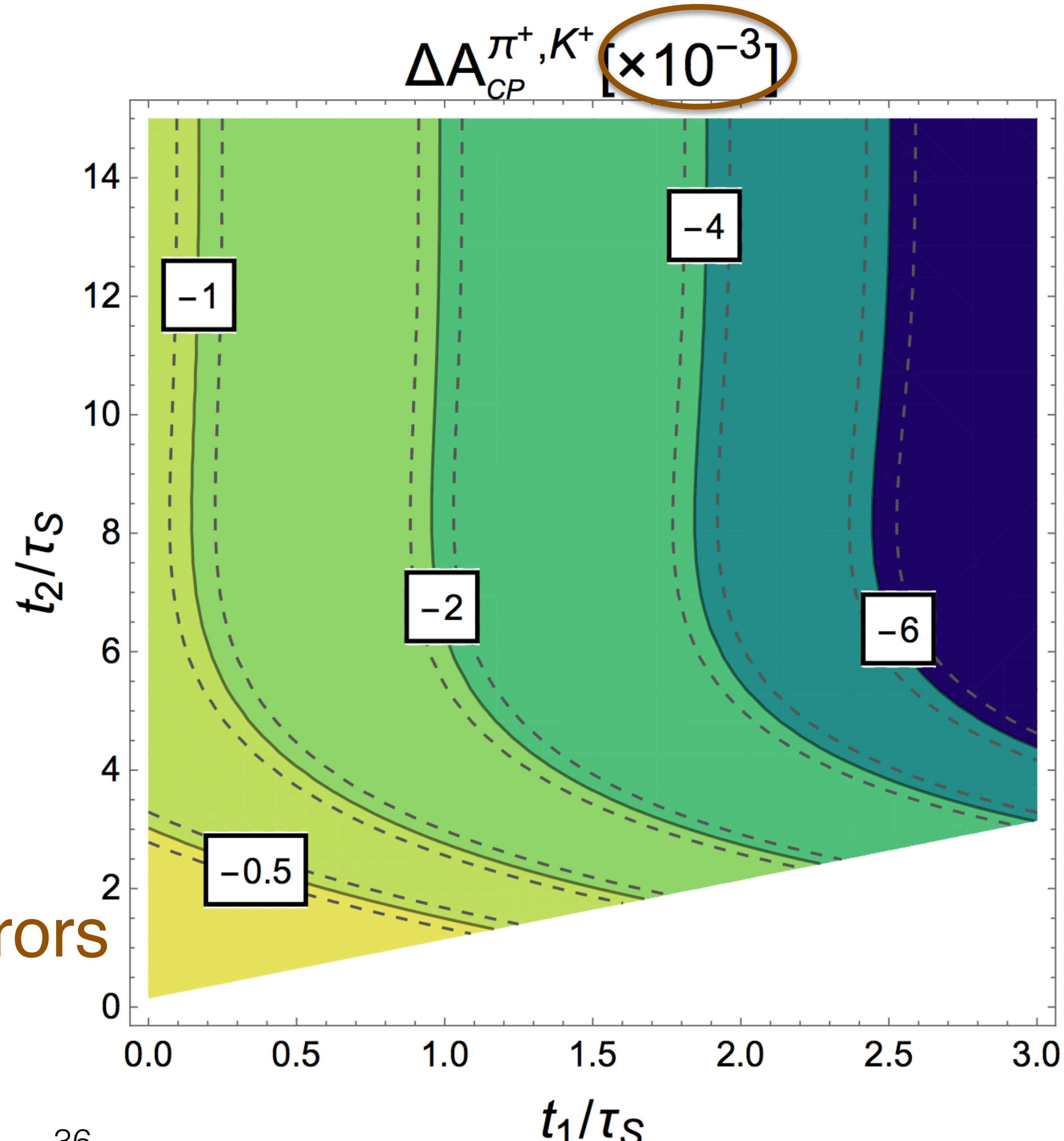
New Observable

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]



New CPV @ Ultimate Precision

LHCb: $\Delta a_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$ @ 9 fb^{-1}

CF mode	Yield
$D^+ \to K_S \pi^+$	4.8×10^6
$D_s^+ \to K_S K^+$	1.5×10^6

SCS mode	Yield
$D^0 \to K^+ K^-$	7.7×10^6
$D^0 \to \pi^+ \pi^-$	2.5×10^6

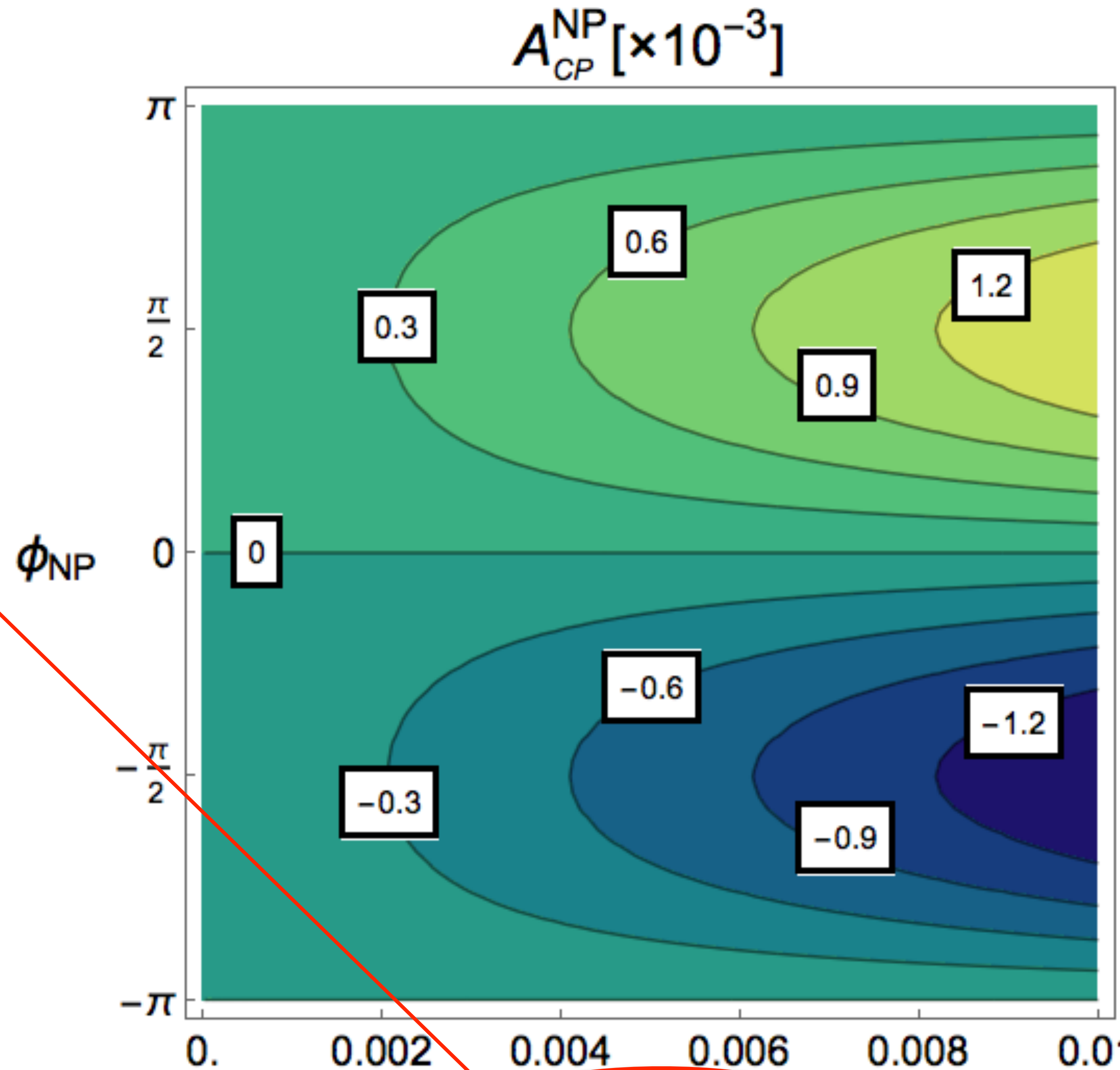
[1406.2624] LHCb @ 3 fb^{-1} [1602.03160]

mode	$\mathcal{L}$ (fb^{-1})	A_{CP} (%)	Belle II at 50 ab^{-1}
$D^+ \to K_s^0 \pi^+$	977	$-0.36 \pm 0.09 \pm 0.07$	± 0.03

Belle II book, 1808.10567

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

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



$r_{NP} = A_{NP}/A_{DCS}$

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

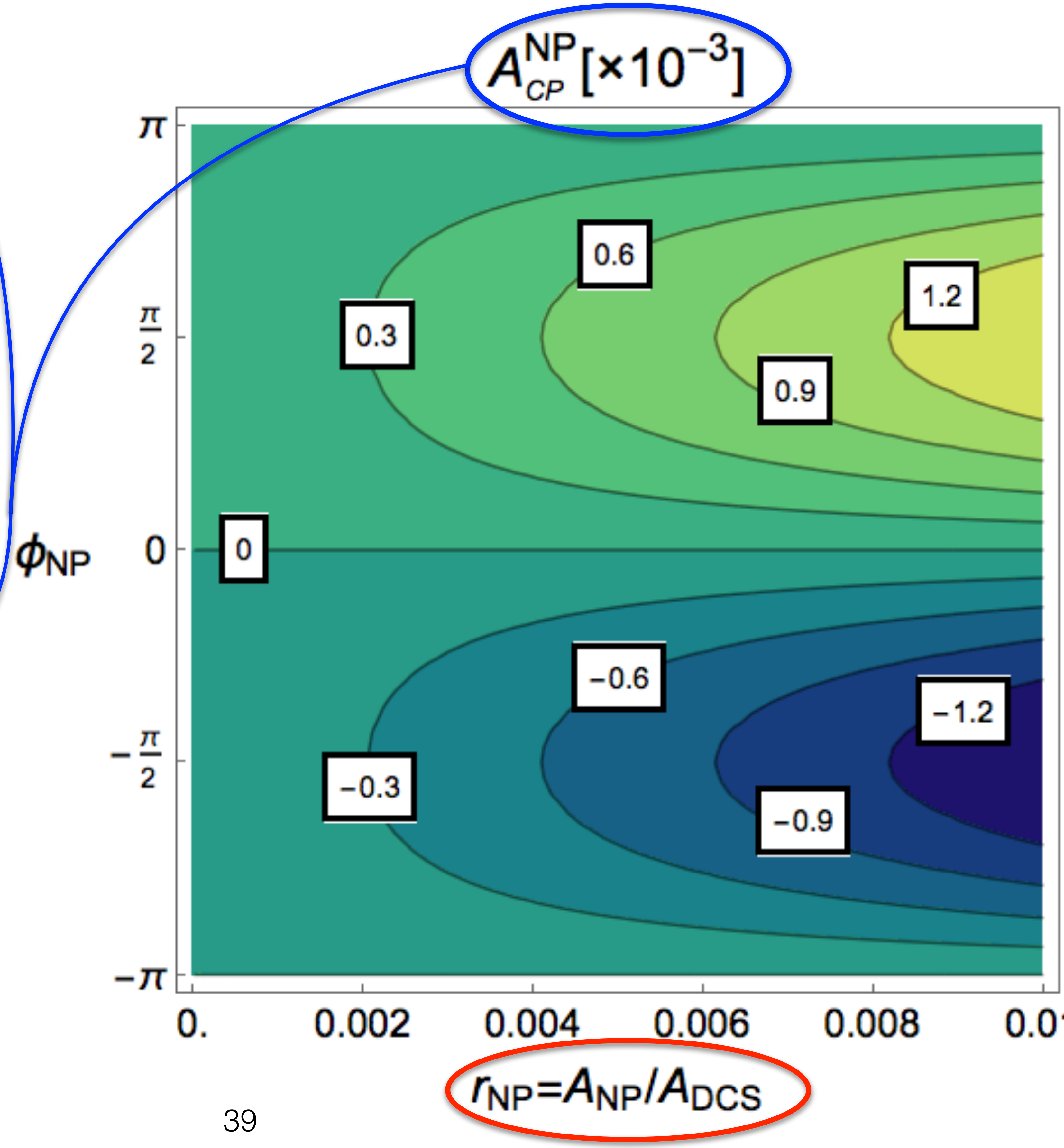
$A_{\rm SM}^{dir} = \mathcal{O}(10^{-5})$

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!

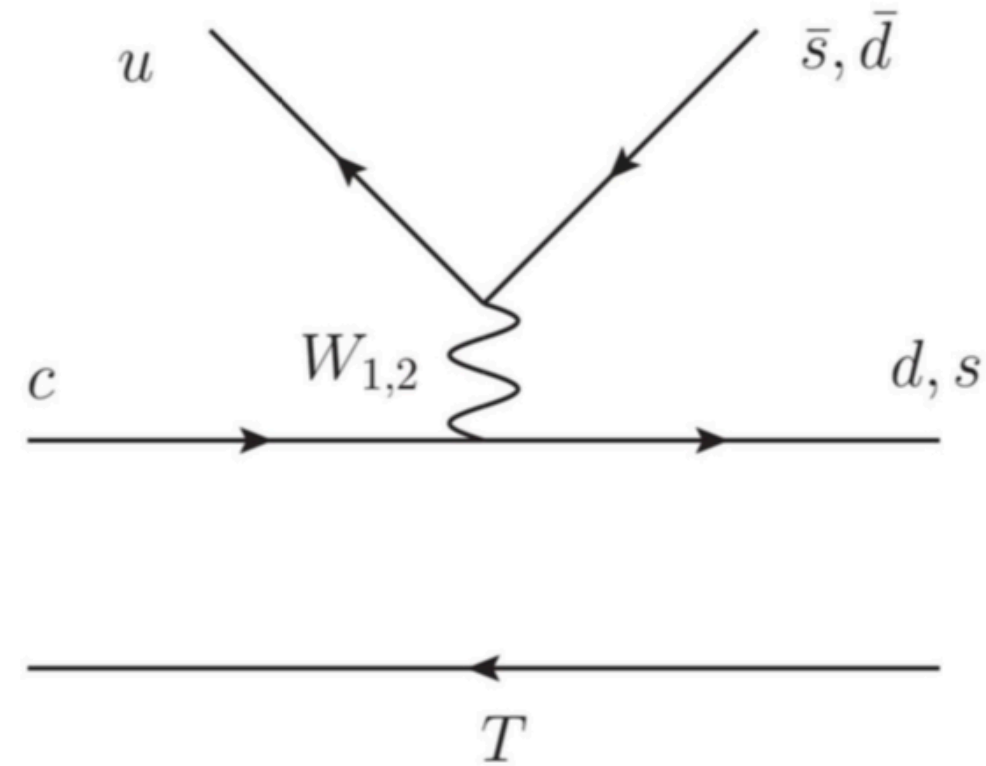


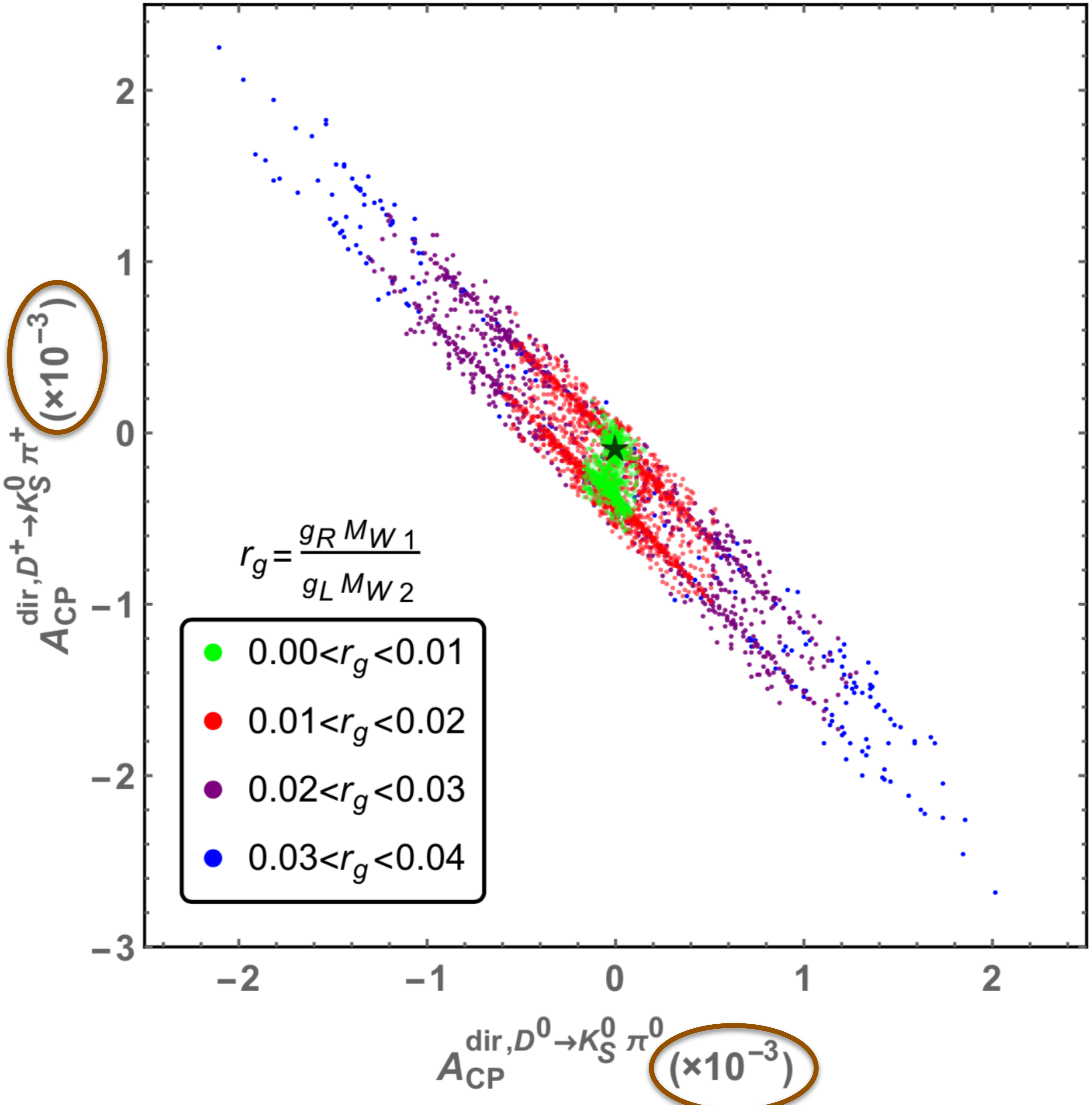
Left-Right Symmetric Model

$$SU(2)_L \times SU(2)_R \times U(1)_{B-L} \to SU(2)_L \times U(1)_Y$$

$$\begin{pmatrix} W_L^- \\ W_R^- \end{pmatrix} = \begin{pmatrix} \cos\zeta & -\sin\zeta e^{iw} \\ \sin\zeta e^{-iw} & \cos\zeta \end{pmatrix} \begin{pmatrix} W_1^- \\ W_2^- \end{pmatrix}$$

$$V_{CKM}^R = \begin{pmatrix} 0 & e^{i\phi_0} & 0 \\ \cos\theta e^{i\phi_1} & 0 & -\sin\theta e^{i(\phi_1-\phi_3)} \\ \sin\theta e^{i\phi_2} & 0 & \cos\theta e^{i(\phi_2-\phi_3)} \end{pmatrix}$$





constrained by ΔM_K, ΔM_{B_d}, ΔM_{B_s}, $|\epsilon|$, $S_{J/\Psi K_S^0}$ and $\phi_{B_s}^{c\bar{c}s}$

Advantages — $A_{CP}(D\to K_S f)$

1. **Less ambiguities. Only tree diagrams,** easily established in theory, extracted from Br's. **Compared to SCS processes with penguins.** FAT approach works well.

2. **More clear to signal NP.** NP may have large CP phase

3. **Large branching fractions to measure.** CF processes.

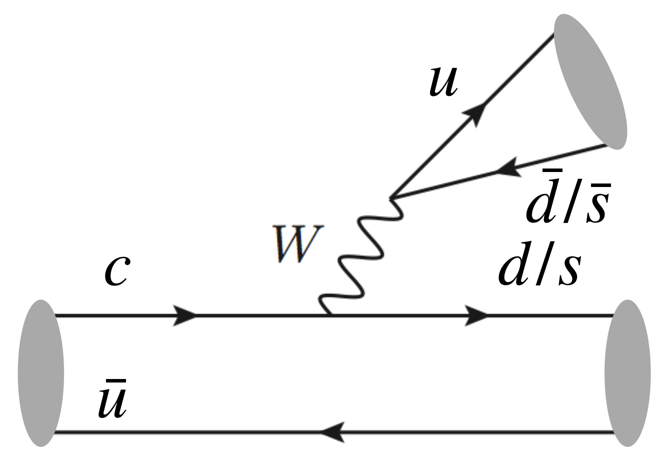
Summary

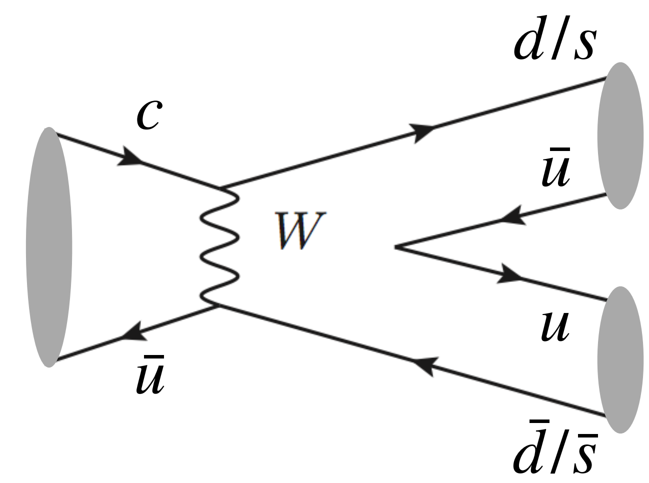
- CPV in D0->K+K- and pi+pi-
  - Understandable in the Standard Model
  - Next potential is D+ ->K+K-pi+
- New CPV effect is found in CF $D \to K_S f$
  - mother decay and daughter mixing
  - To be subtracted to extract direct CPV
- Charm CPV is becoming more charming with precision at order of 10^{-4}

Thank you for your attention!

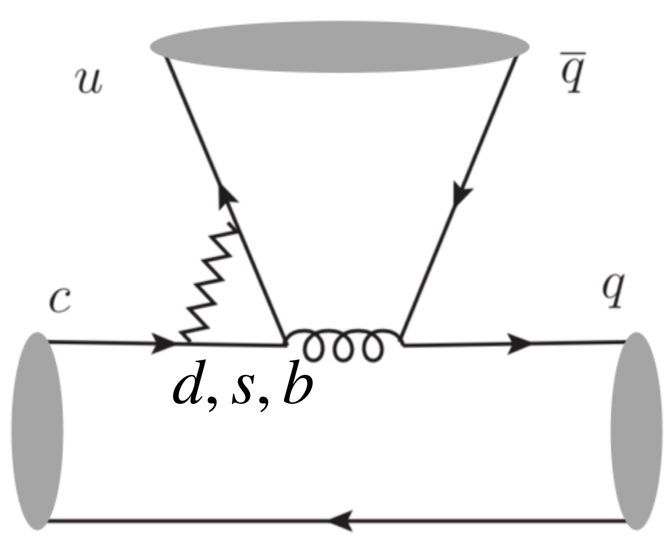
Backups

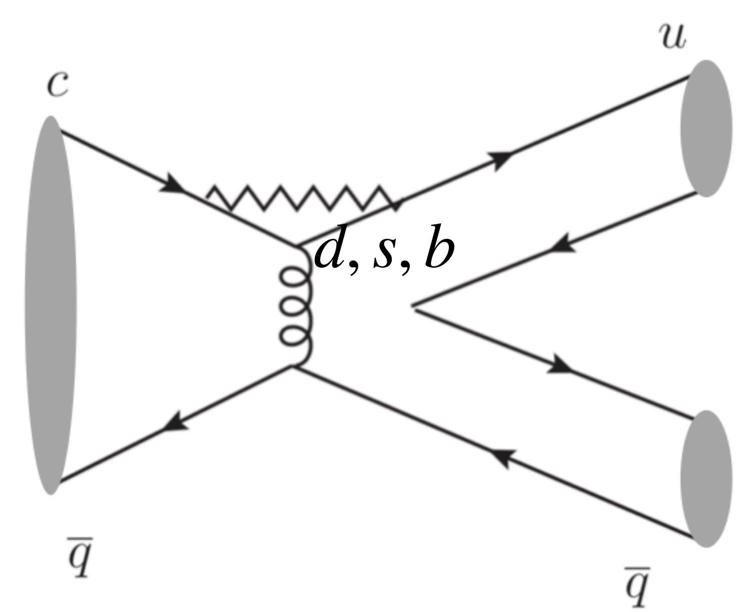
Tree





Penguin



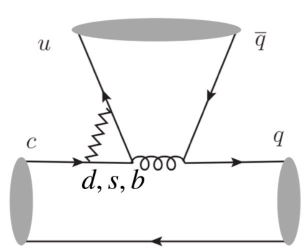


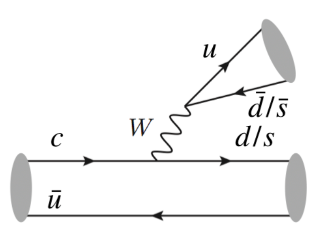
$$\left(\frac{|\mathcal{P}^{KK}|}{|\mathcal{T}^{KK}|}\sin\delta^{KK}+\frac{|\mathcal{P}^{\pi\pi}|}{|\mathcal{T}^{\pi\pi}|}\sin\delta^{\pi\pi}\right)\approx 1$$

$$\frac{|\mathcal{P}|}{|\mathcal{T}|}\sin\delta\sim 1/2 \quad \text{or } \mathrm{Im}[\mathcal{P}/\mathcal{T}]\sim 1/2$$

FAT2012

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





$$= \quad \frac{P}{T}=\frac{a_4+a_6 r_\chi}{a_1}=0.36e^{-i108^\circ}$$

$$r_\chi=2m_0^2/m_c=2.8, \text{ where } m_0^\pi=m_\pi^2/(m_u+m_d)$$

$$a_4=-0.036-i0.098,\ a_6=-0.031-i0.098$$

$$C_{3,5}(\mu)\to C_{3,5}-\frac{\alpha_s(\mu)}{8\pi N_c}\sum_{q=d,s}\frac{\lambda_q}{\lambda_b}C^q(\mu,\langle l^2\rangle)+\frac{1}{N_c}\frac{\alpha_s(\mu)}{4\pi}\frac{m_c^2}{\langle l^2\rangle}[C_{8g}(\mu)+C_5(\mu)],$$

$$C_{4,6}(\mu)\to C_{4,6}+\frac{\alpha_s(\mu)}{8\pi}\sum_{q=d,s}\frac{\lambda_q}{\lambda_b}C^q(\mu,\langle l^2\rangle)-\frac{\alpha_s(\mu)}{4\pi}\frac{m_c^2}{\langle l^2\rangle}[C_{8g}(\mu)+C_5(\mu)],$$

$$D \to f K_S^0 (\to \pi^+ \pi^-)$$

$$A_{CP}(t) \equiv \frac{\Gamma_{\pi\pi}(t) - \overline{\Gamma}_{\pi\pi}(t)}{\Gamma_{\pi\pi}(t) + \overline{\Gamma}_{\pi\pi}(t)}$$

Define: $$\frac{A_{DCS}}{A_{CF}} = \frac{\mathcal{A}(D \to K^0 f)}{\mathcal{A}(D \to \overline{K}^0 f)} = r\, e^{i(\phi+\delta)}$$

strong phase

weak phase

r ~λ^2~0.05

Tree amplitudes !!!

Can be extracted from data of branching fractions

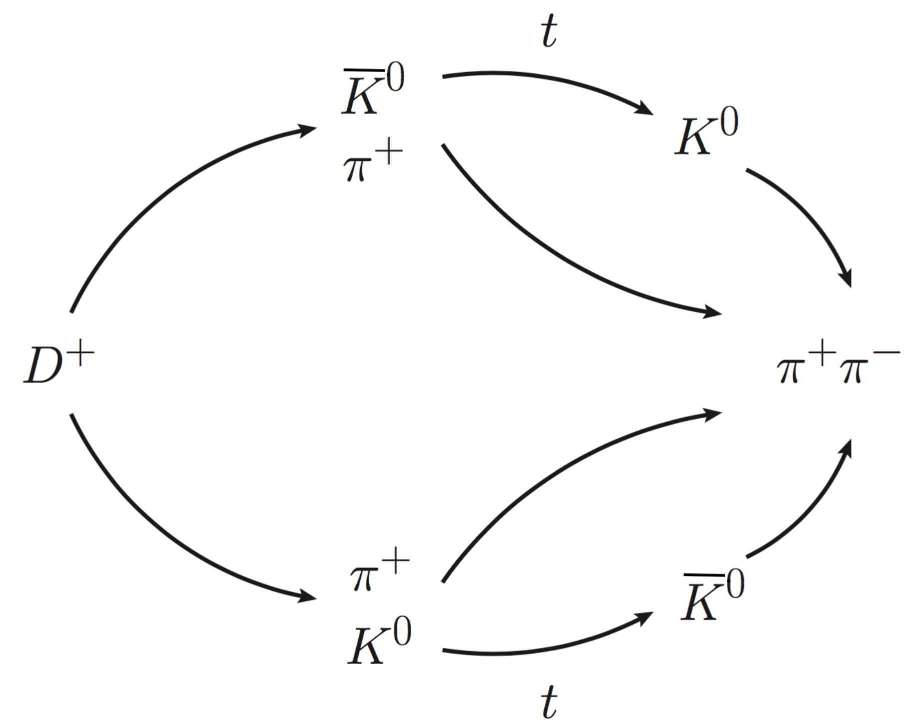
$$A_{CP}(t) = A_{CP}^{\overline{K}^0}(t) + A_{CP}^{\text{dir}}(t) + A_{CP}^{\text{int}}(t)$$

$$A_{CP}^{\overline{K}^0}(t) = 2e^{-\Gamma_S t}\mathcal{R}e(\epsilon) - 2e^{-\Gamma t}\Big[\mathcal{R}e(\epsilon)\cos(\Delta m t) + \mathcal{I}m(\epsilon)\sin(\Delta m t)\Big],$$

$$A_{CP}^{\text{dir}}(t) = e^{-\Gamma_S t}\, 2r_f \sin\delta_f \sin\phi$$

SM: $\phi \equiv Arg\left[-V_{cd}^* V_{us}/V_{cs}^* V_{ud}\right] = (-6.2 \pm 0.4) \times 10^{-4}$

$$A_{CP}^{\text{int}}(t) = -4r_f \cos\phi \sin\delta_f \Big[e^{-\Gamma_S t}\mathcal{I}m(\epsilon) - e^{-\Gamma t}\Big(\mathcal{I}m(\epsilon)\cos(\Delta m t) - \mathcal{R}e(\epsilon)\sin(\Delta m t)\Big)\Big]$$



Mother decay, daughter mixing

$$\phi \equiv Arg\left[-V_{cd}^{*}V_{us}/V_{cs}^{*}V_{ud}\right] = (-6.2\pm0.4)\times 10^{-4}$$

$$A_{CP}(t_1 \ll \tau_S \ll t_2 \ll \tau_L)$$

$$\simeq \frac{-2\mathcal{R}e(\epsilon) + 2r_f \sin\phi \sin\delta_f - 4\mathcal{I}m(\epsilon) r_f \cos\phi \sin\delta_f}{1 - 2r_f \cos\phi \cos\delta_f}$$

CPV in kaon mixing (10^{-3})

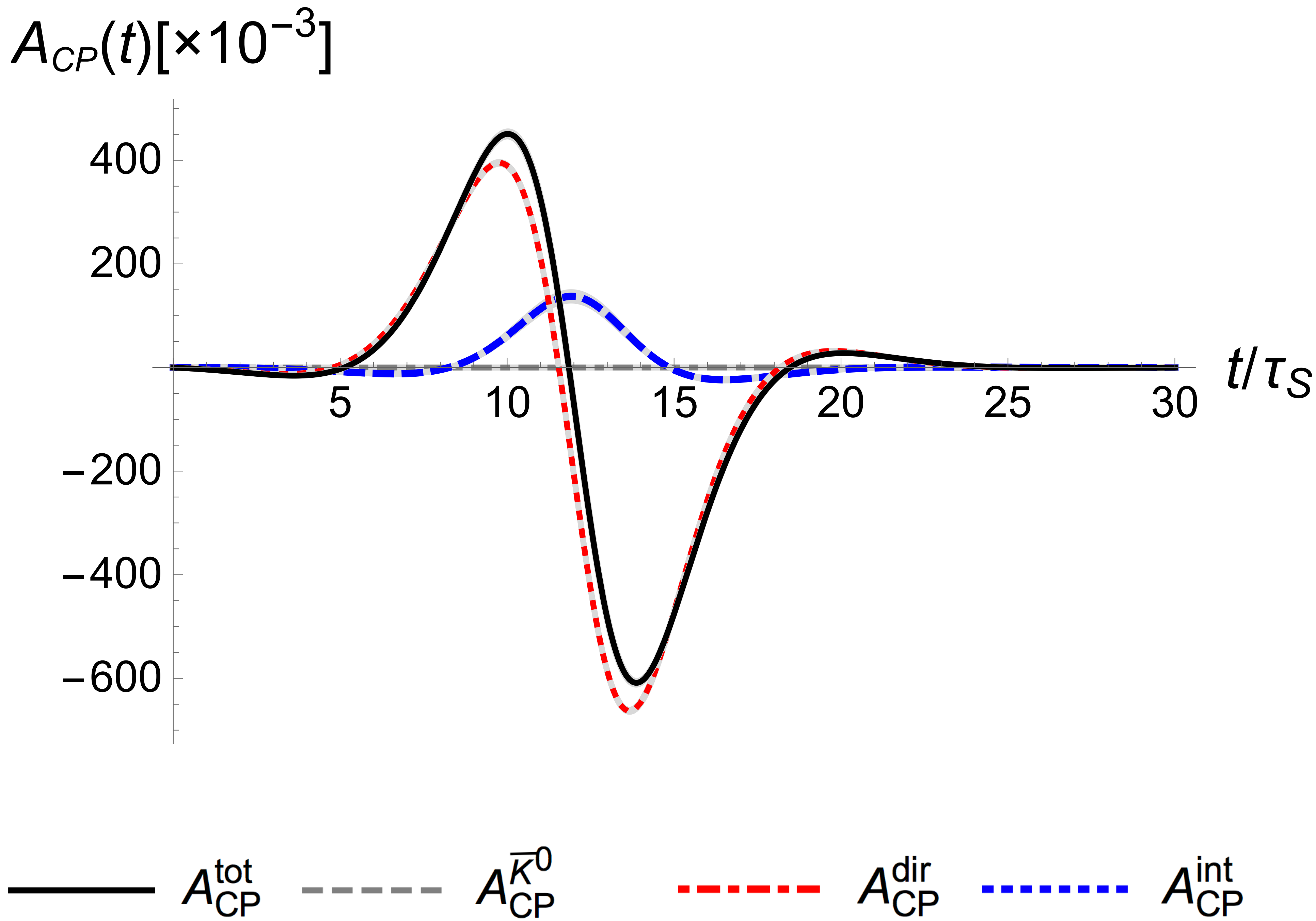
direct CPV (10^{-5})

New CPV effect $(10^{-4\sim-3})$

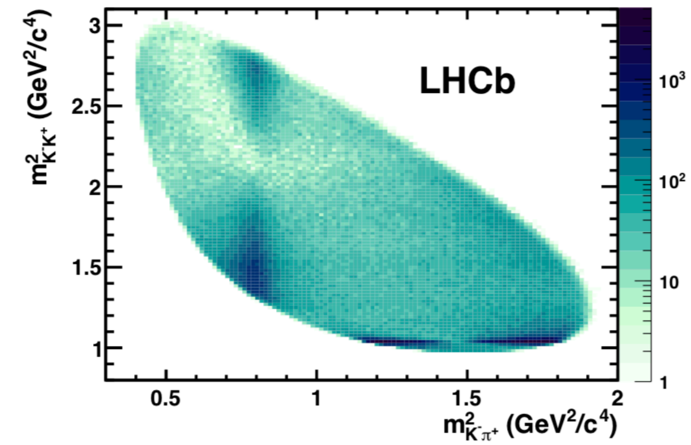
Sensitive to New Physics CP phase

Time-dependent CPV

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



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

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

Br=0.95% Br=0.3%

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

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

Br=0.95% Br=9%

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

Br=0.66% Br=5.5%