(New) CPV in charm decays into neutral kaons

Fu-Sheng Yu

Lanzhou University

ICHEP 2018, Seoul

[D.Wang, **FSY**, H.n.Li, PRL119, 181802(2017); in ready]

Outline

1. Introduction
   - ambiguities of CPV in singly Caibbo-suppressed modes
2. CPV in Cabibbo-favored D->f Ks
   - new CPV effects
   - promising to search for new physics
   - advantages
3. Summary

1. Introduction

- **CPV** **in charm** decays plays an important role in searching for new physics (NP)
  - **SM** predictions are always **very small**
  - Search for **NP** with **special up sector,** complimentary to B and K systems.
- **Searching for CPV is one of the most important topics in charm physics.**

Direct CPV in charm

SCS

tree + **penguin**

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

λ $\lambda^5 + i\lambda^5$

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

$$\Delta a_{CP}^{\text{dir}} = (-0.061 \pm 0.076)\%$$

LHCb, '16

CF with $K_S{}^0$

CF + **DCS**

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

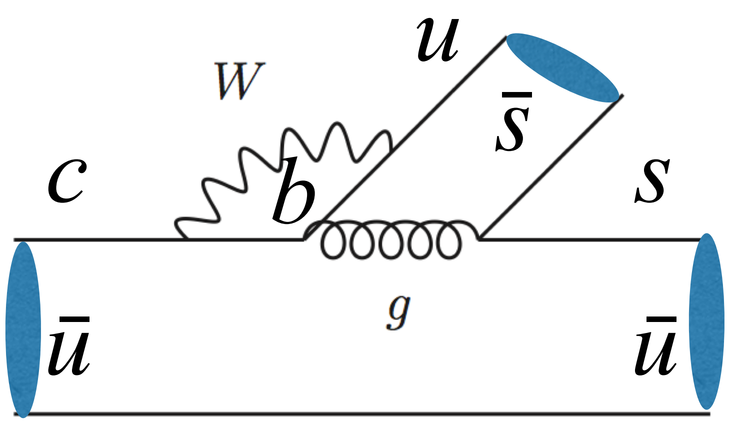
1 $\lambda^2 + i\lambda^6$

$$A_{CP}^{D^+\to K_S^0\pi^+} = (-0.363\pm0.094\pm0.067)\%$$

Belle, '12

CPV in Singly Cabibbo-Suppressed decays

- **Ambiguity in penguins**
  - **heavy quark expansion $1/m_c$,** m_c=1.3GeV, **does not work** in exclusive processes



★ **$\Delta A_{CP}(K^+K^-, \pi^+\pi^-)$ predicted from 10^{-5} to 10^{-2}**

Grossman, Kagan, Nir, '07; Bigi, Paul, '11; Isidori, Kamenik, Ligeti, Perez, '11; Brod, Grossmann, Kagan, Zupan, '11, '12; Bhattarcharya, Gronau, Rosner, '12; Feldmann, Nandi, Soni, '12; Cheng, Chiang, '12; Li, Lu, **FSY**, '12;

★ **Even if CPV observed at 10^{-3}, not distinguishable for New Physics or SM**

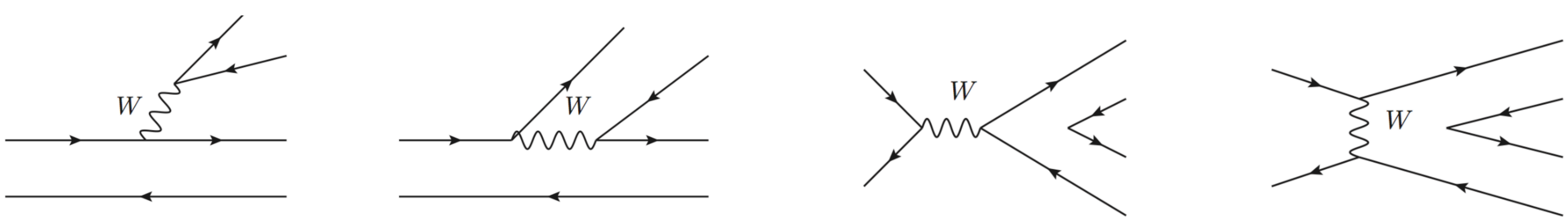
Tree amplitudes

- **Better understood, from data of BRs**
  - Topological diagrams in flavor SU(3) symmetry

    Cheng, Chiang, '10; Bhattarcharya, Rosner, '09
  - Topological diagrams in SU(3) breaking

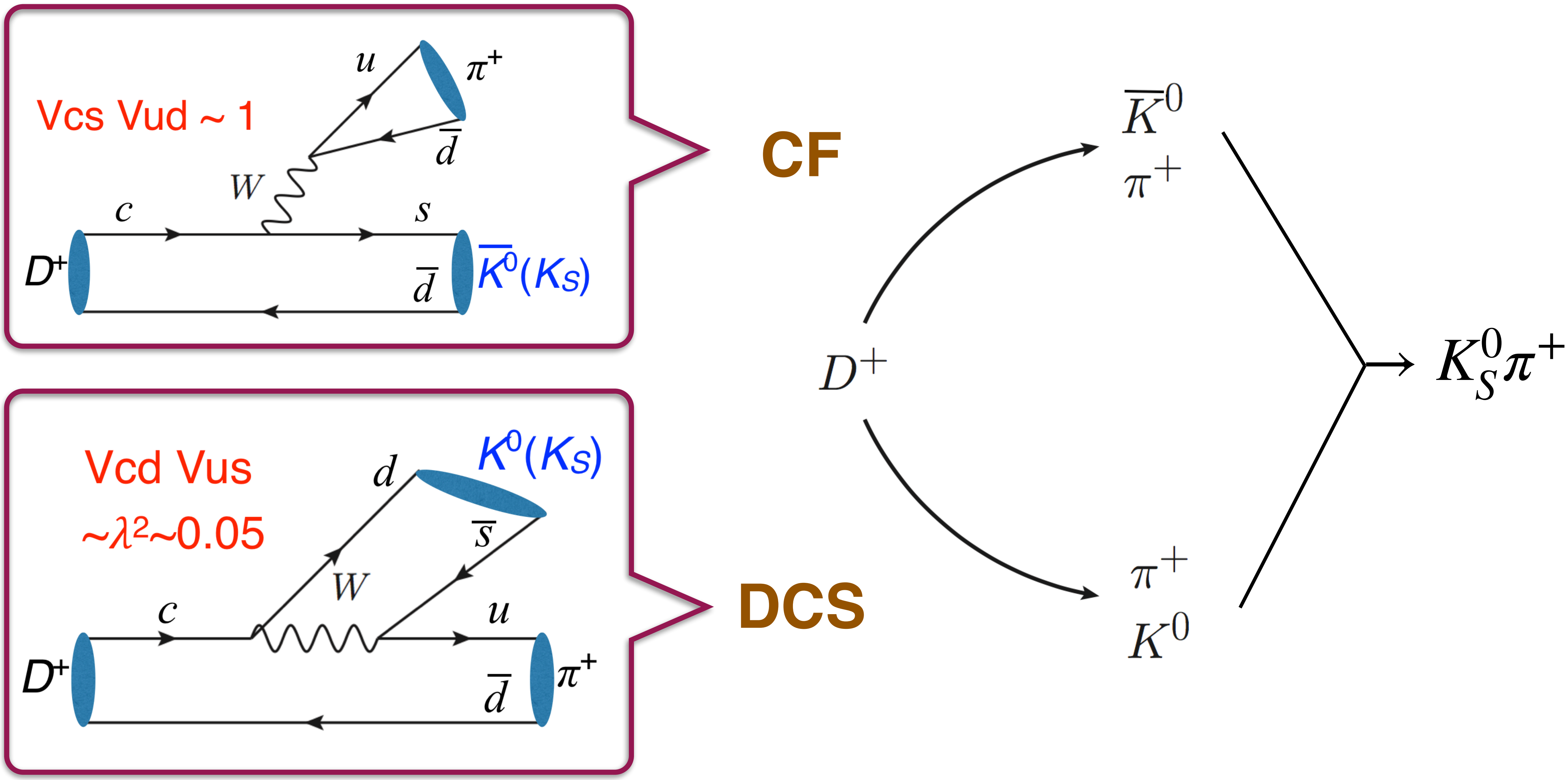
    Muller, Nierste, Schacht, '15
  - Topological diagrams in factorization

    Li, Lu, Qin, **FSY**, '12, '14



CPV in tree, would be better understood

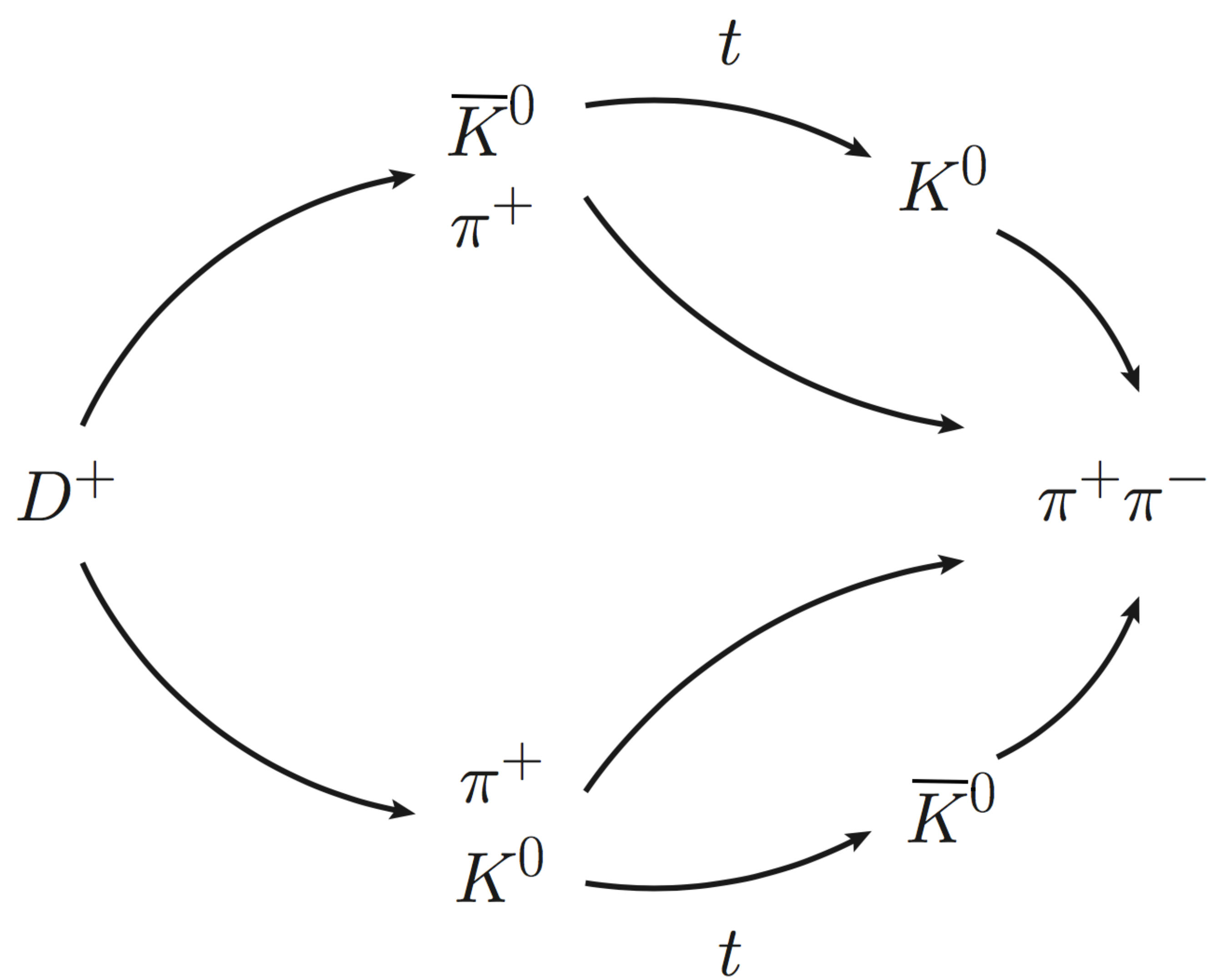
2. CP Violation in $D \to f\, K_S$



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

Full decay chain

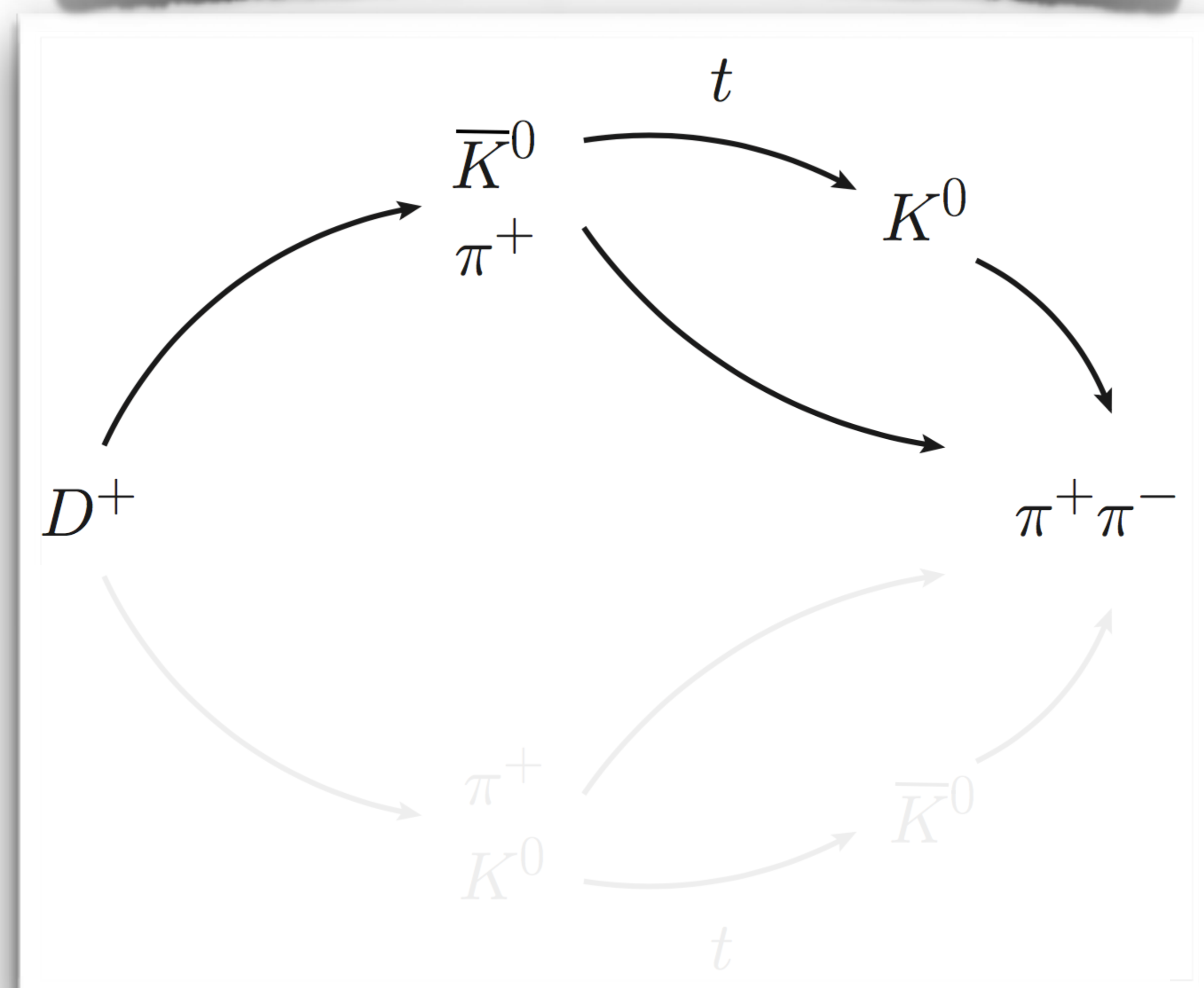
$$D^+ \to \pi^+ K(t)(\to \pi^+\pi^-)$$



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

Indirect CPV in kaon mixing

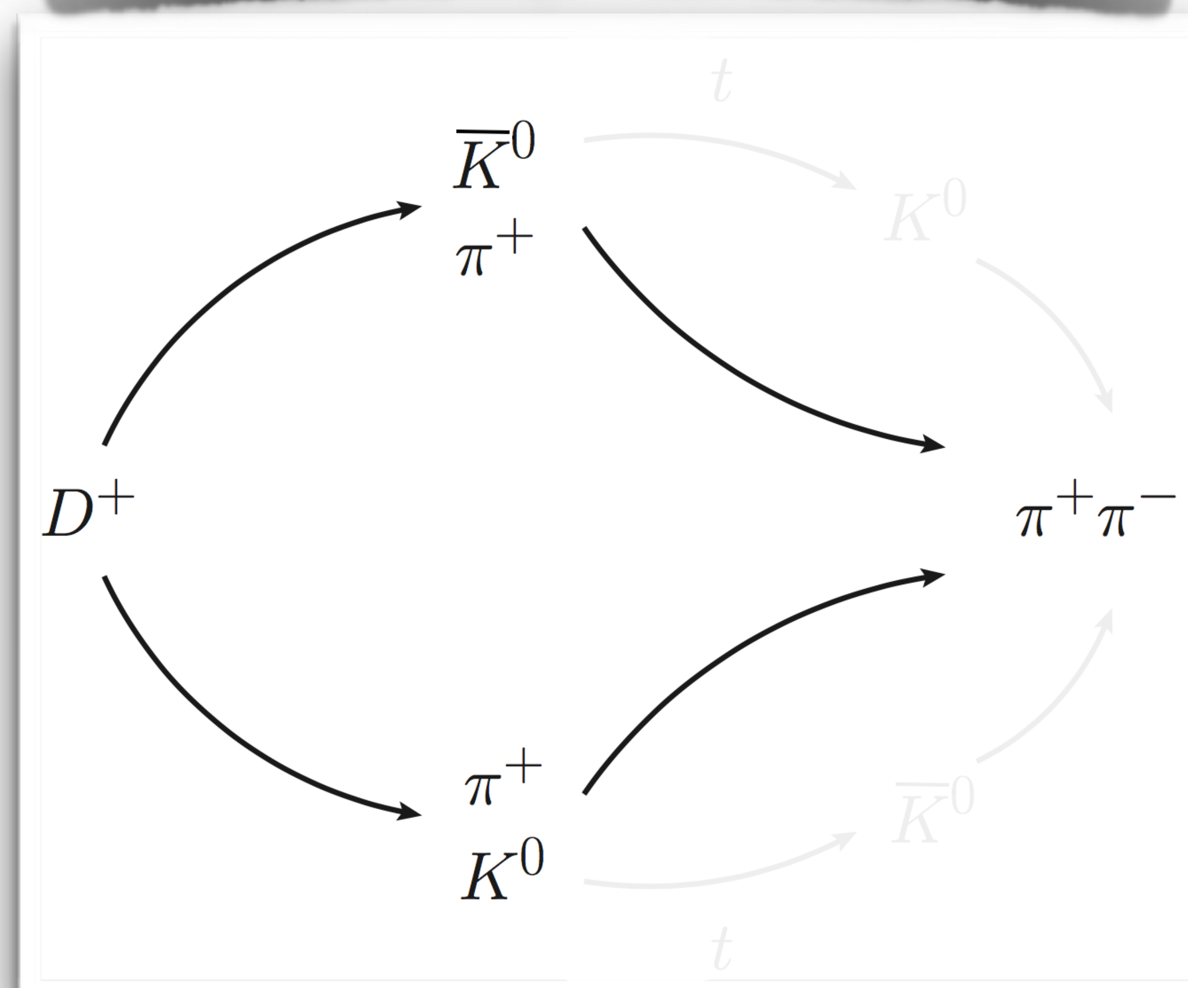
Re(ϵ)=10^{-3}



[Zhi-Zhong Xing,PLB 353,313(1995)]

Direct CPV in charm decays

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



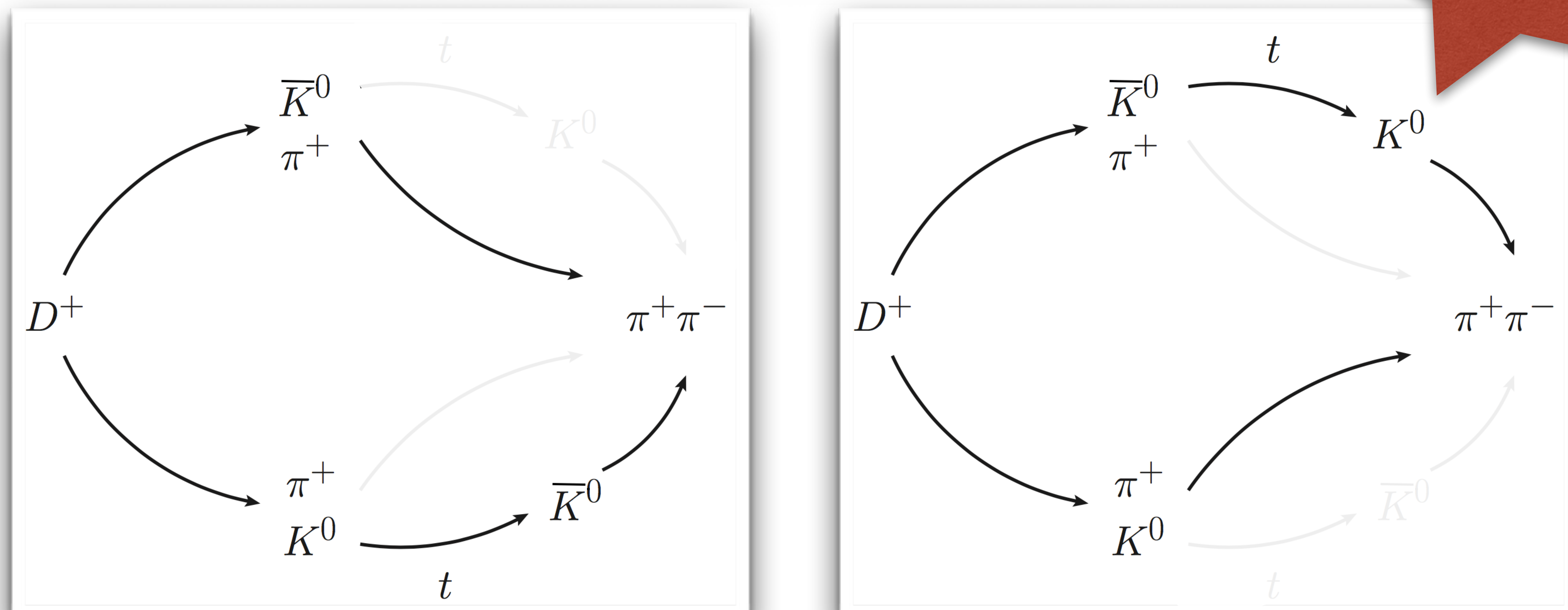
[Bigi, Yamamoto,PLB 349,363(1995)]

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

CPV in interference between kaon mixing and charm decays

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

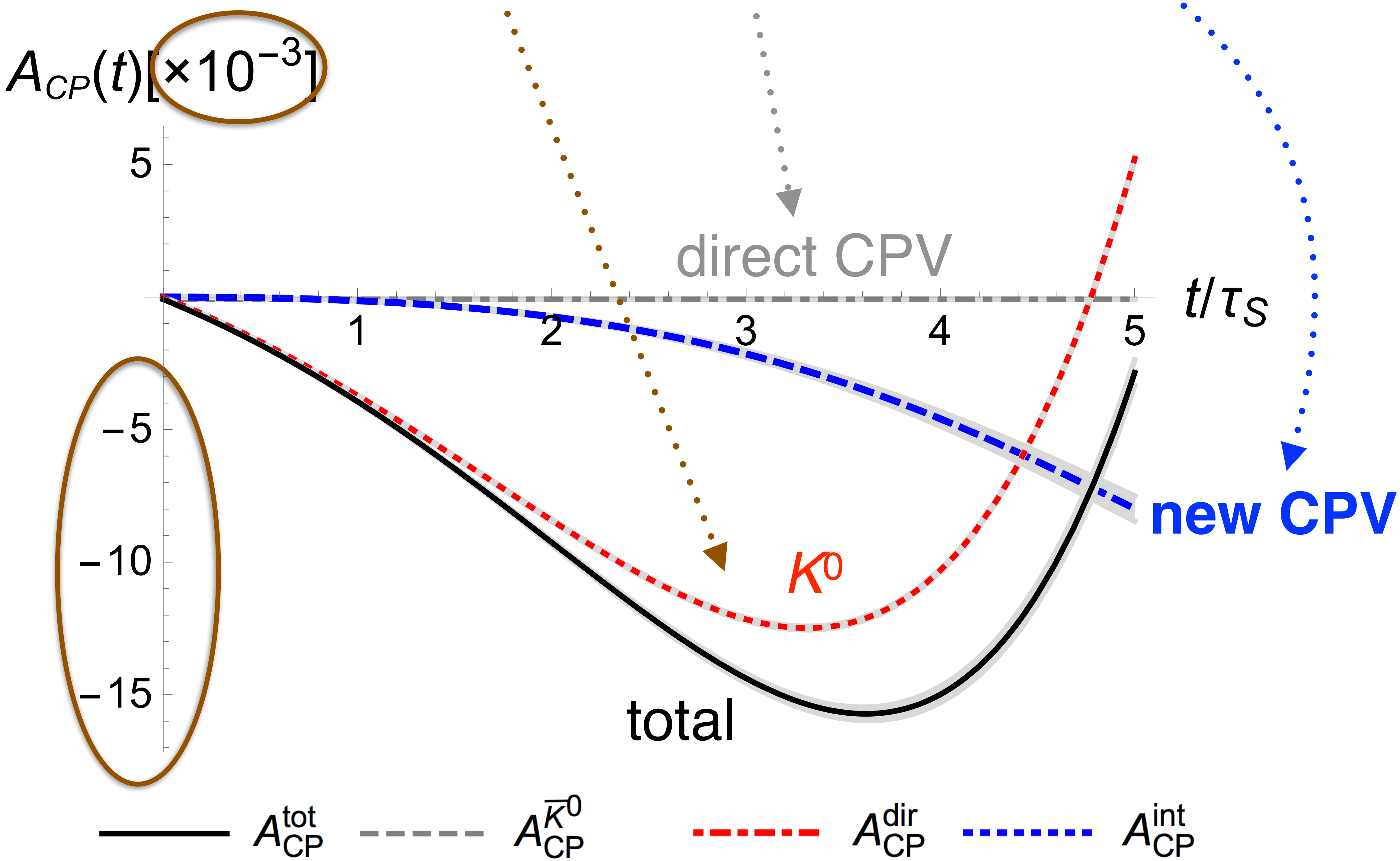
NEW



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

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

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



Precision in exp: $\mathcal{O}(10^{-4})$

LHCb: $\Delta a_{CP}^{\mathrm{dir}} = (-0.061 \pm 0.076)\%$ @ 3 fb^{-1}

$\to$ **1.2×10^{-4}** @ 50 fb^{-1}

[LHCb, EPJC73,2373(2013)]

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

[1701.07159]

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, ‘12

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, ‘12

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

[Wang, **FSY**, Li, ’17]

LHCb:

Search for CP violation in $D^+ \to \phi\pi^+$ and $D_s^+ \to K_S^0\pi^+$ decays

JHEP 1306 (2013) 112, [arXiv:1303.4906]

$$A_{CP}(D^+ \to \phi\pi^+) = A_{\rm raw}(D^+ \to \phi\pi^+) - \boxed{A_{\rm raw}(D^+ \to K_S^0\pi^+)} + A_{CP}(K^0/\overline{K}^0)$$

SCS CF as a control mode

Direct CPV in $D^+ \to K_S^0\pi^+$ decay is assumed to be negligible.

BUT, $A_{CP}(D^+ \to \phi\pi^+) \le \mathcal{O}(10^{-4})$ is expected

$A_{CP}^{\rm int}(D^+ \to K_S^0\pi^+) \sim -0.4 \times 10^{-3}$ is comparable

New CPV effect is non-negligible!!!

Be careful when using D->pi KS as control mode, both at LHCb and Belle II

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

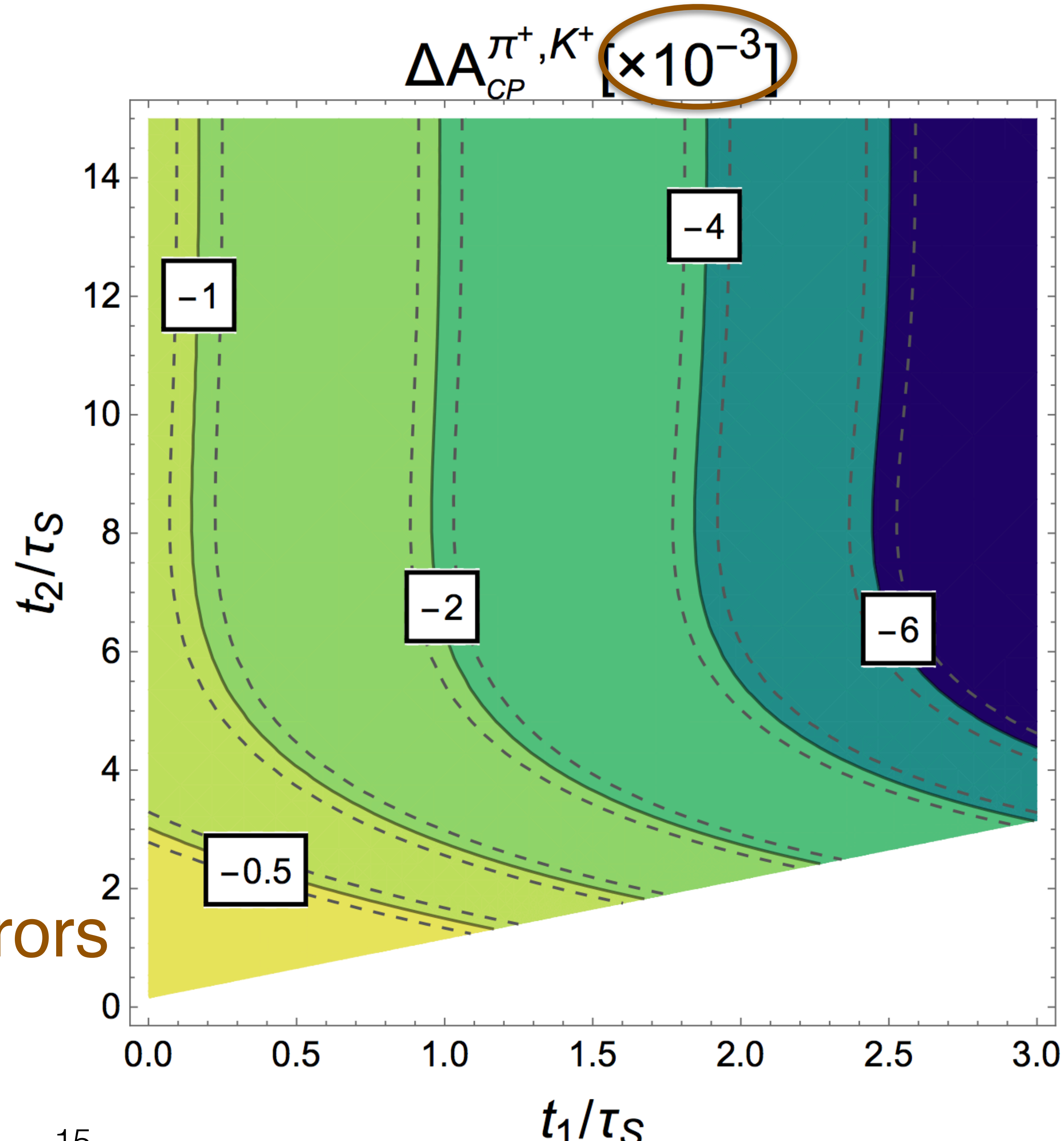
New Observable

revealing

new CPV effect

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

Cancel some systematic errors @ LHCb & Belle-II



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

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

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

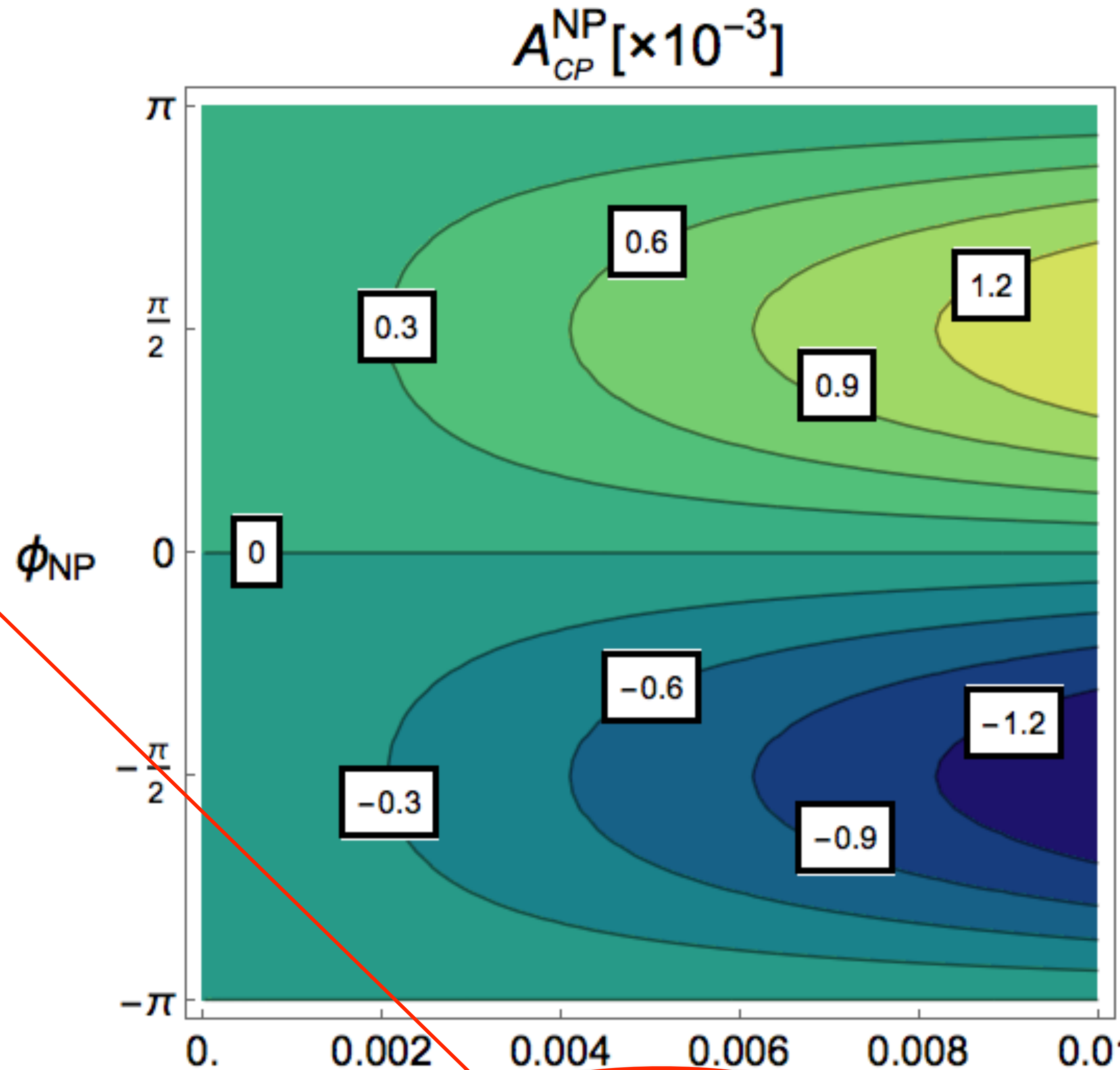
SM: $\phi \equiv Arg\,[-V_{cd}^* V_{us}/V_{cs}^* V_{ud}] = (-6.2 \pm 0.4) \times 10^{-4}$

NP: ϕ=O(1)

Search for new physics at tree-level

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

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



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

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

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

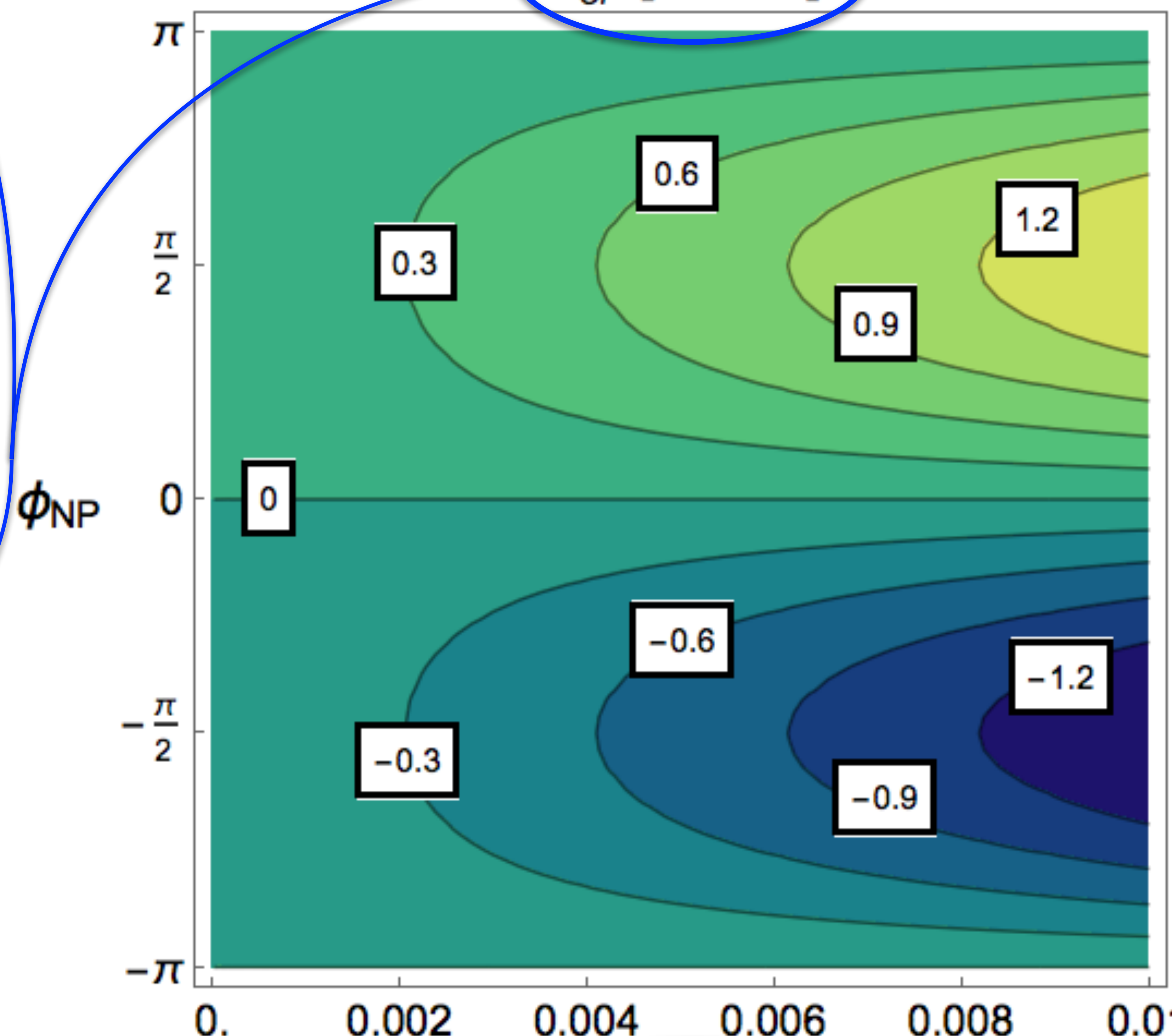
Even if

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

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

Promising for new physics!

$A_{CP}^{\rm NP}[\times 10^{-3}]$



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

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.

- In the SM, we don't know how large Acp is in SCS, but we do know it in CF and DCS.

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

Advantages — ΔA_{CP}

3. **Order of 10^{-3} in SM, accessible by experiments in the near future**

4. **CPV is doubled in ΔA_{CP}, compared to individual A_{CP}**

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

6. **Some systematic uncertainties cancelled**

Summary

- **New CPV effect** is found in $D \to K_S f$
- It is **accessible at Belle II and LHCb**, and can not be neglected
- dCPV is promising to **search for New Physics at tree level**, compared to penguins in charm!!

Thank you for your attention!

Backups

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

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

$$\Gamma_{\pi\pi}(t) \equiv \Gamma(D \to f K_S^0(t) \to f[\pi\pi]_K)$$

$$\overline{\Gamma}_{\pi\pi}(t) \equiv \Gamma(\overline{D} \to \overline{f} K_S^0(t) \to \overline{f}[\pi\pi]_K)$$

$$\frac{\text{DCS}}{\text{CF}} \qquad \frac{\mathcal{A}(D \to K^0 f)}{\mathcal{A}(D \to \overline{K}^0 f)} = \underbrace{r}_{\sim\lambda^2\sim 0.05}\, e^{i(\phi+\delta)}$$

ϕ: weak phase

δ: strong phase

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

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

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

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

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

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

CPV in kaon mixing | direct CPV | New CPV effect

(10^{-3}) | (10^{-5}) | $(10^{-4 \sim -3})$

Sensitive to New Physics CP phase

$$\boxed{\Delta A_{CP}(D^+, D_s^+) \equiv A_{CP}^{D^+\to\pi^+K_S^0}(t_1,t_2) - A_{CP}^{D_s^+\to K^+K_S^0}(t_1,t_2)}$$

$A_{CP}^{\overline{K}^0}$ is mode-independent and cancelled

In the limit of SU(3) symmetry

Topologies

$D^+ \to K_S^0\pi^+$ $\quad (1+\bar{\varepsilon}^*)V_{cd}^*V_{us}\boxed{(C+A)} - (1-\bar{\varepsilon}^*)V_{cs}^*V_{ud}\boxed{(T+C)}$

DCS CF

$D_s^+ \to K_S^0K^+$ $\quad (1+\bar{\varepsilon}^*)V_{cd}^*V_{us}\boxed{(T+C)} - (1-\bar{\varepsilon}^*)V_{cs}^*V_{ud}\boxed{(C+A)}$

DCS CF

Opposite sign of strong phases in the SU(3) symmetry

Constructive in $\Delta A_{CP}(D^+, D_s^+)$

Interesting modes in experiments

LHCb: $A_{CP}(D^+ \to K_S \pi^+) - A_{CP}(D_s^+ \to K_S K^+)$ $\sim 10^{-3}$

$$= \left[A_{\mathrm{raw}}(D^+ \to K_S \pi^+) - A_{\mathrm{raw}}(D^+ \to K^-\pi^+\pi^+)\right]_{Br=9\%}$$

$$- \left[A_{\mathrm{raw}}(D_s^+ \to K_S K^+) - A_{\mathrm{raw}}(D_s^+ \to K^-\pi^+K^+)\right]_{Br=5\%}$$

and

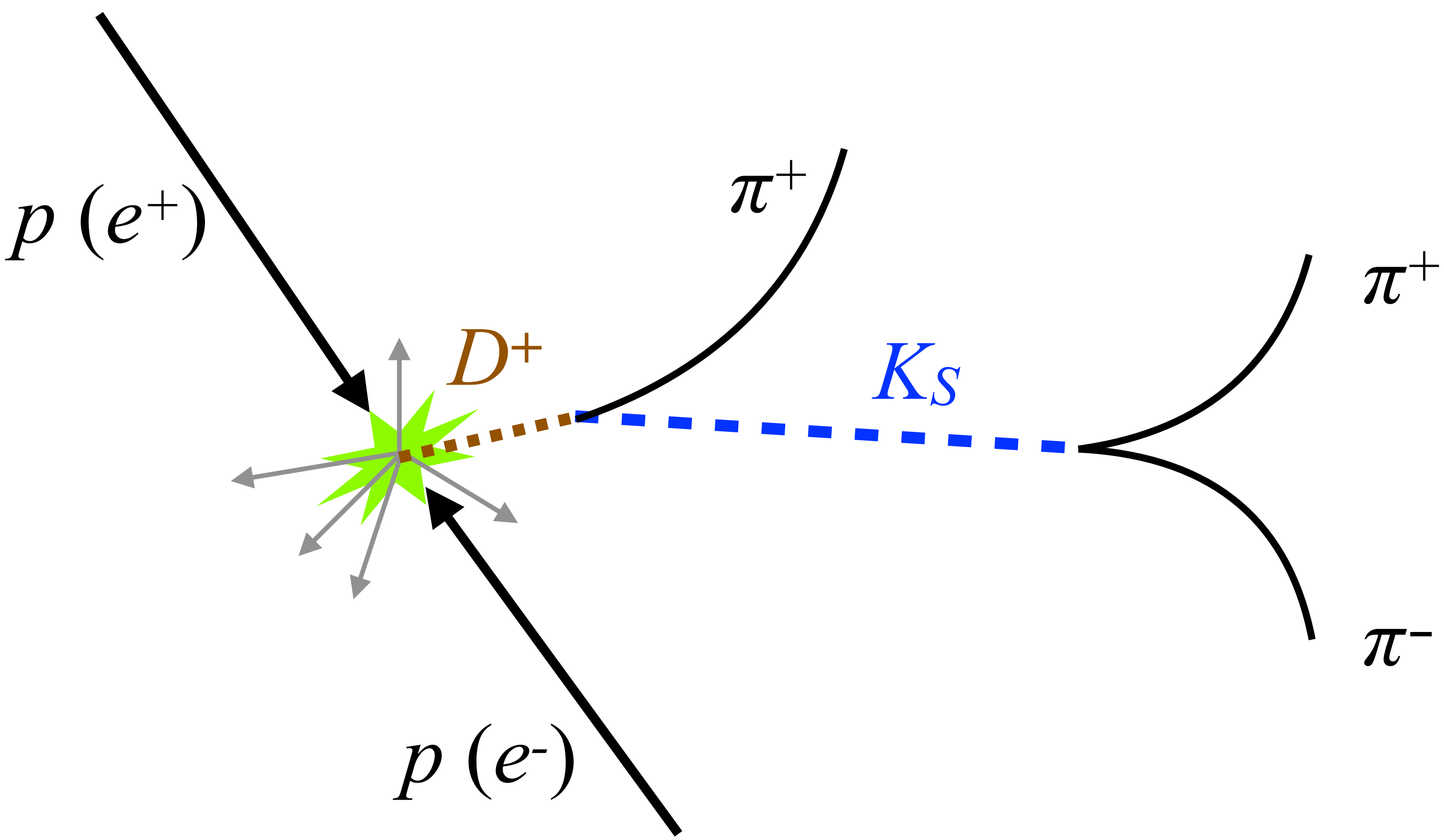
$$A_{CP}^{\Lambda_c^+ \to pK}(t_1, t_2) - A_{CP}^{D^+ \to K\pi^+}(t_1, t_2)$$

$$= [A_{raw}^{\Lambda_c^+ \to pK}(t_1, t_2) - A_{raw}^{\Lambda_c^+ \to pK^-\pi^+}]$$

$$- [A_{raw}^{D^+ \to K\pi^+}(t_1, t_2) - A_{raw}^{D^+ \to K^-\pi^+\pi^+}]$$

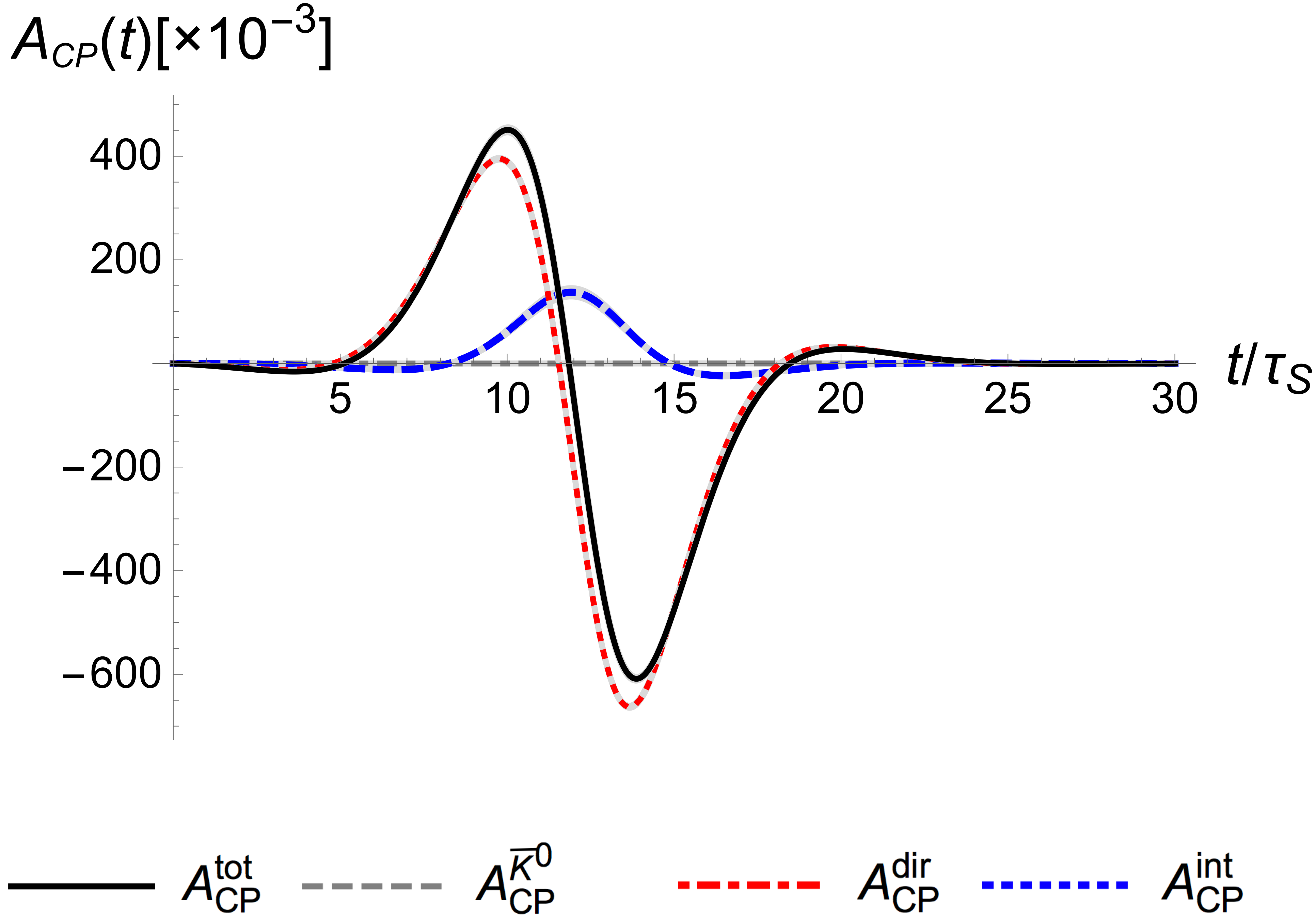
Time-dependent & Time integrated CPV

time of K_S flying



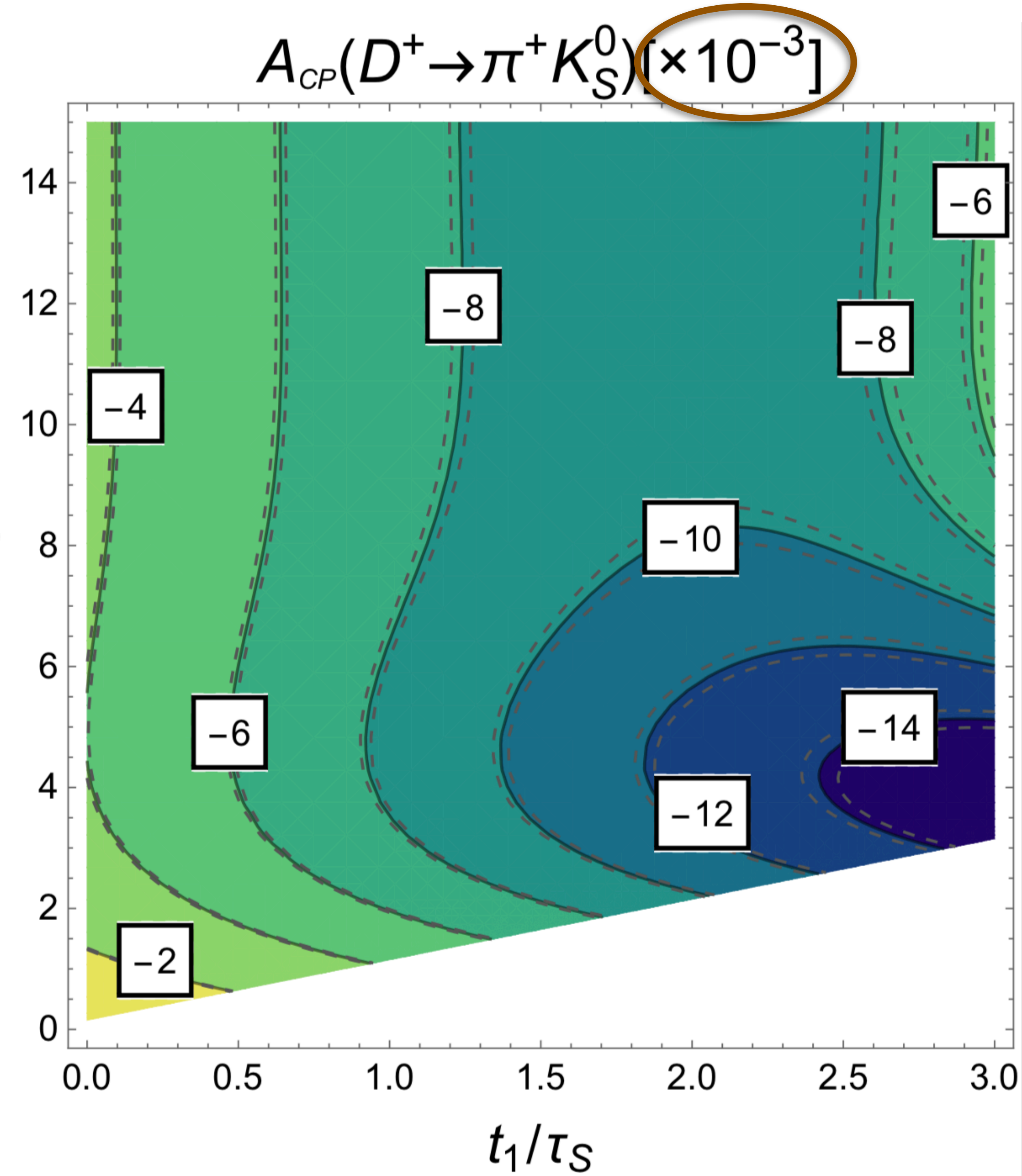
Time-dependent CPV

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

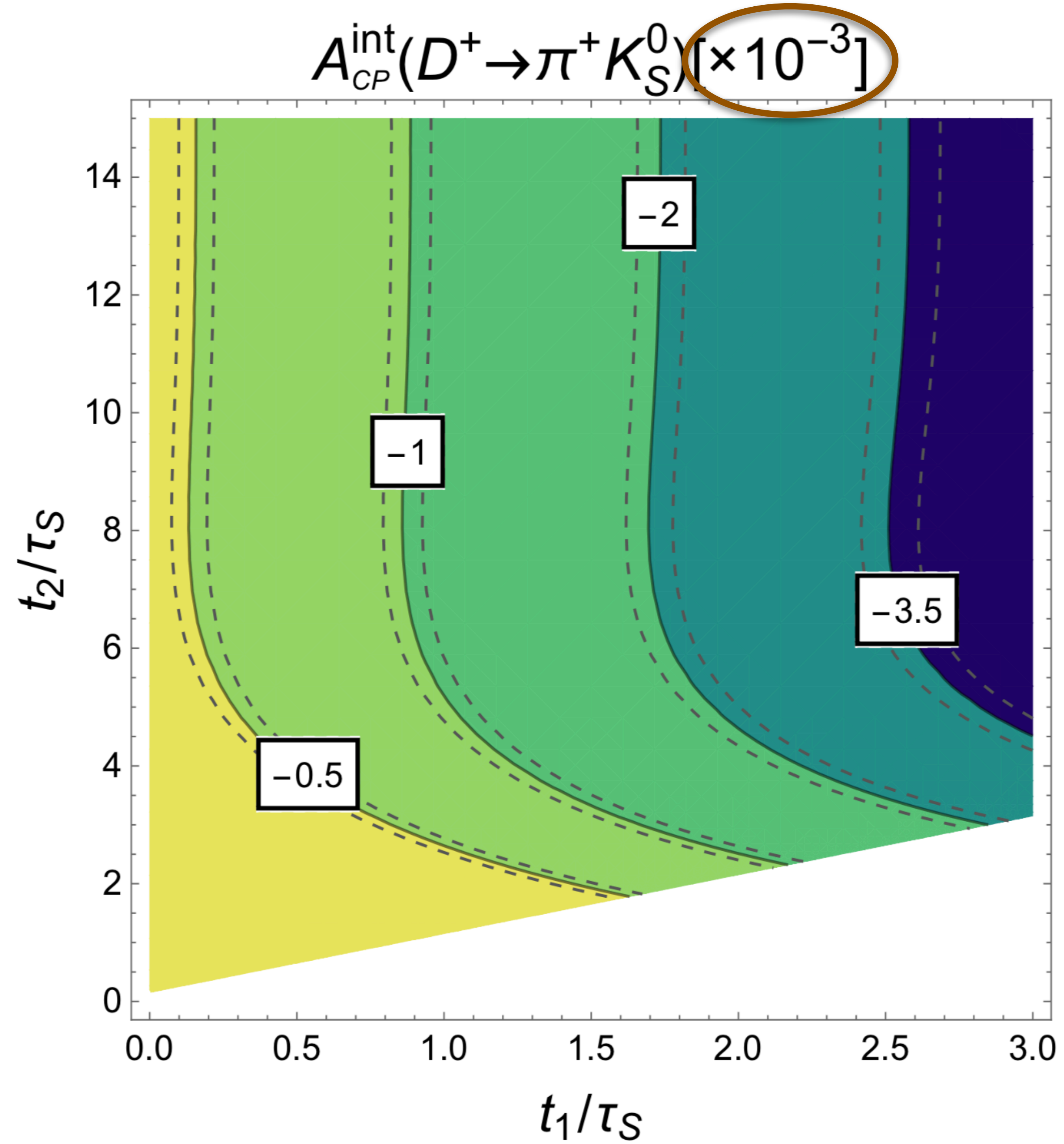


Time-Integrated CPV

total



Interference



Ambiguities in penguins

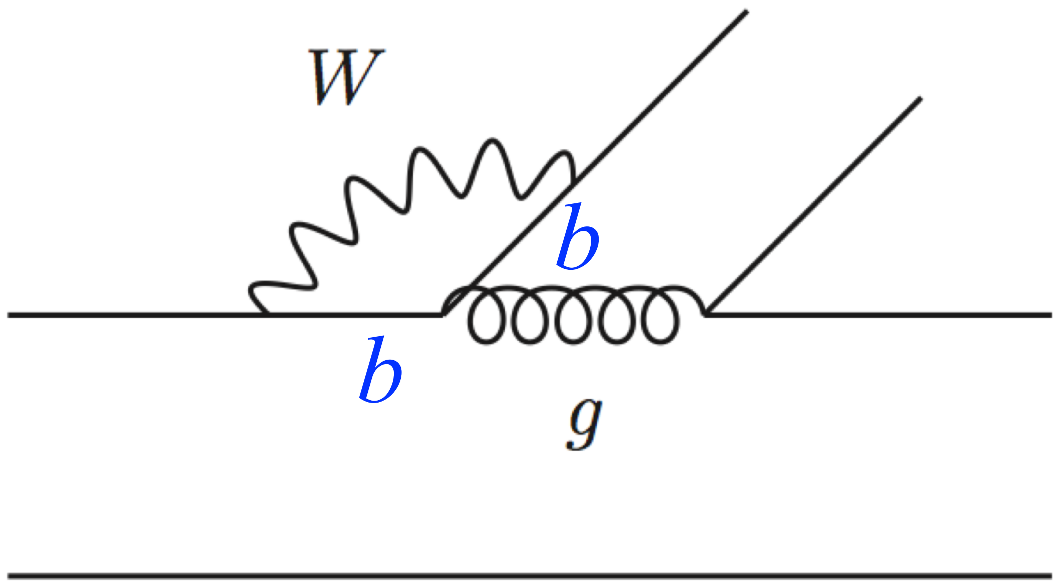
$\Delta A_{CP}(K^+K^-, \pi^+\pi^-)$

range from 10^{-5} to 10^{-2} in literature

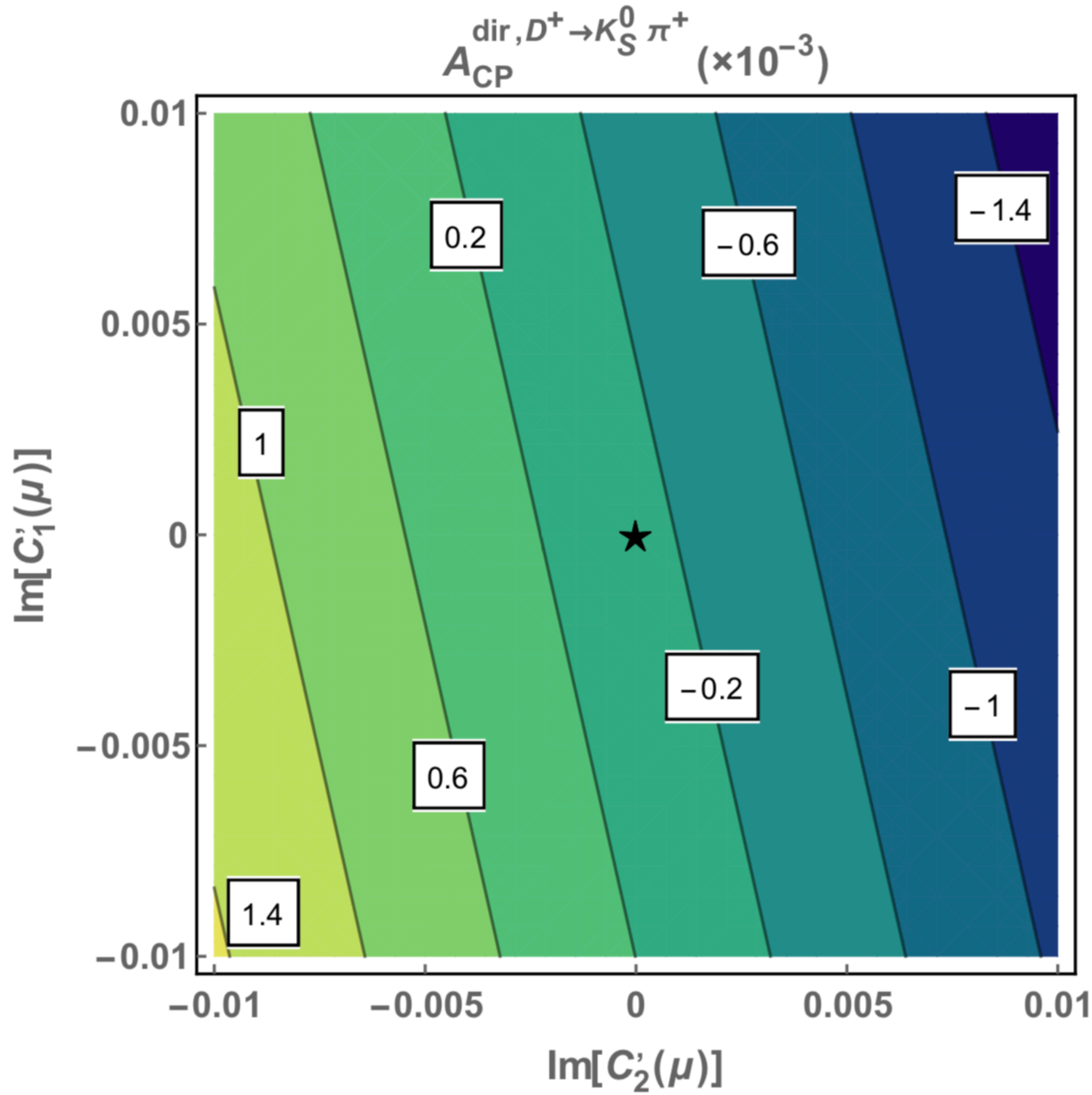
- $@m_c \sim 1.5$GeV, perturbation theories do not work
- Tree diagrams extracted from branching fractions (Br)
- Penguin neglected in Br's

  $\Delta A_{cp}(KK,\pi\pi)_{exp} <\sim \mathcal{O}(10^{-3})$

  uncertainties of Br's $\sim \mathcal{O}(\%)$



If CPV observed, cannot tell SM or NP



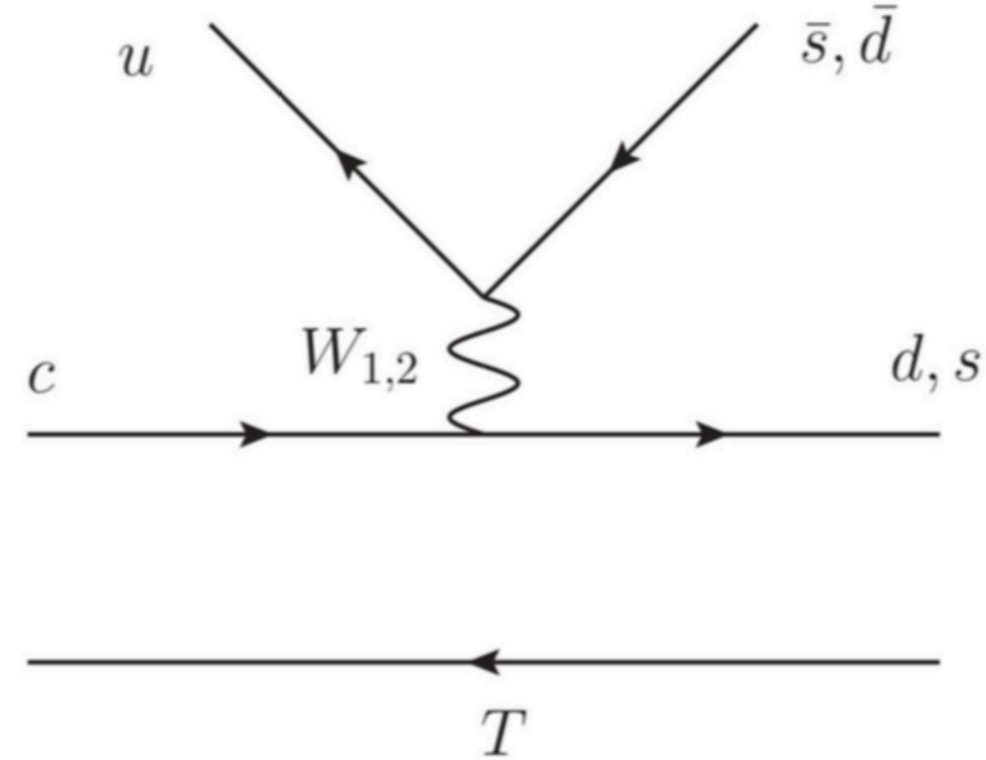
$A_{CP}^{\mathrm{dir},D^+\to K_S^0\pi^+}$ ($\times 10^{-3}$)
0.01
0.005
0
−0.005
−0.01
−0.01
−0.005
0
0.005
0.01
Im[$C_1'(\mu)$]
Im[$C_2'(\mu)$]
0.2
−0.6
−1.4
1
−0.2
−1
0.6
1.4

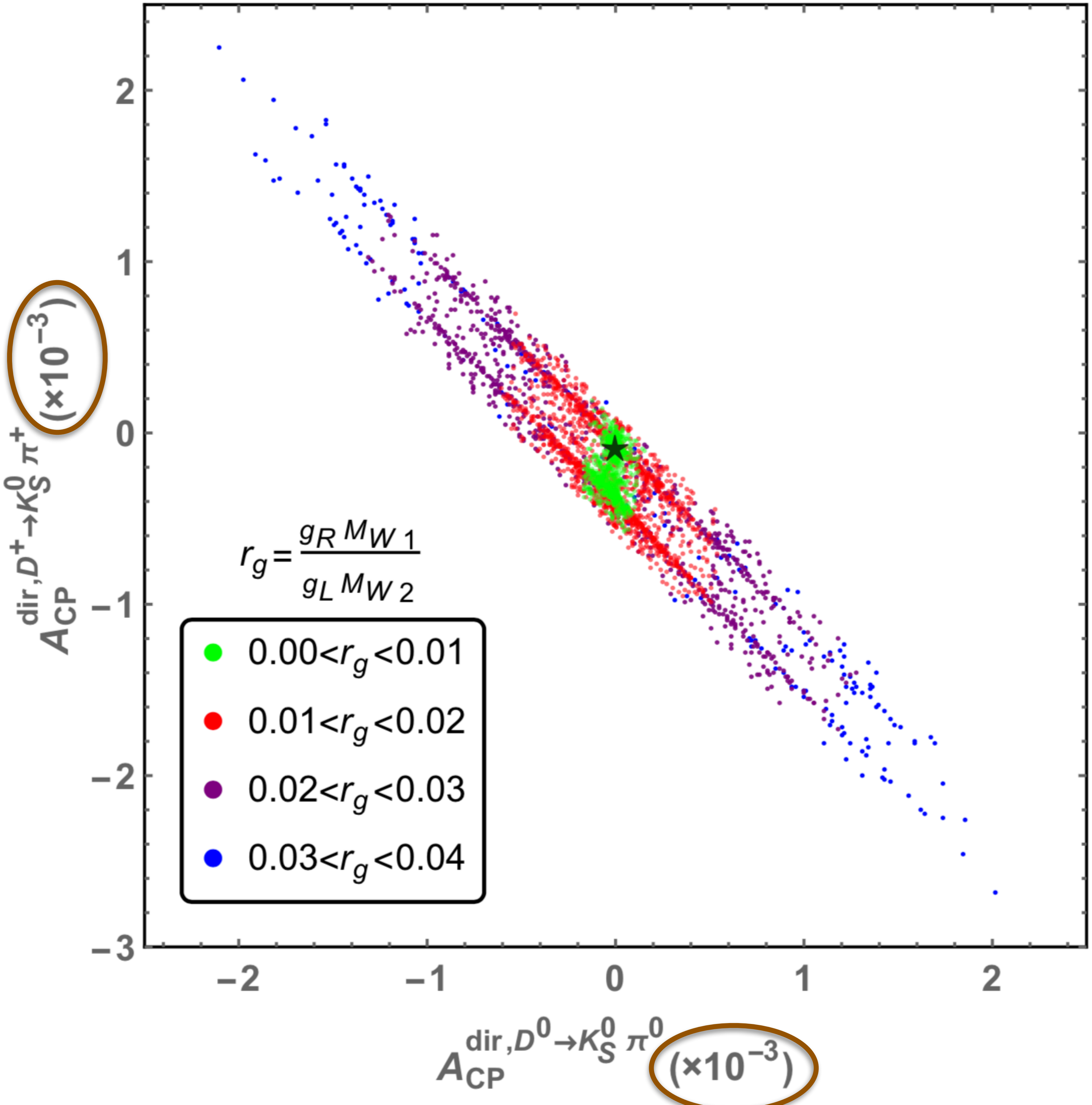
Left-Right Symmetric Model

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

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

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





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