(New) CPV in charm decays into neutral kaons

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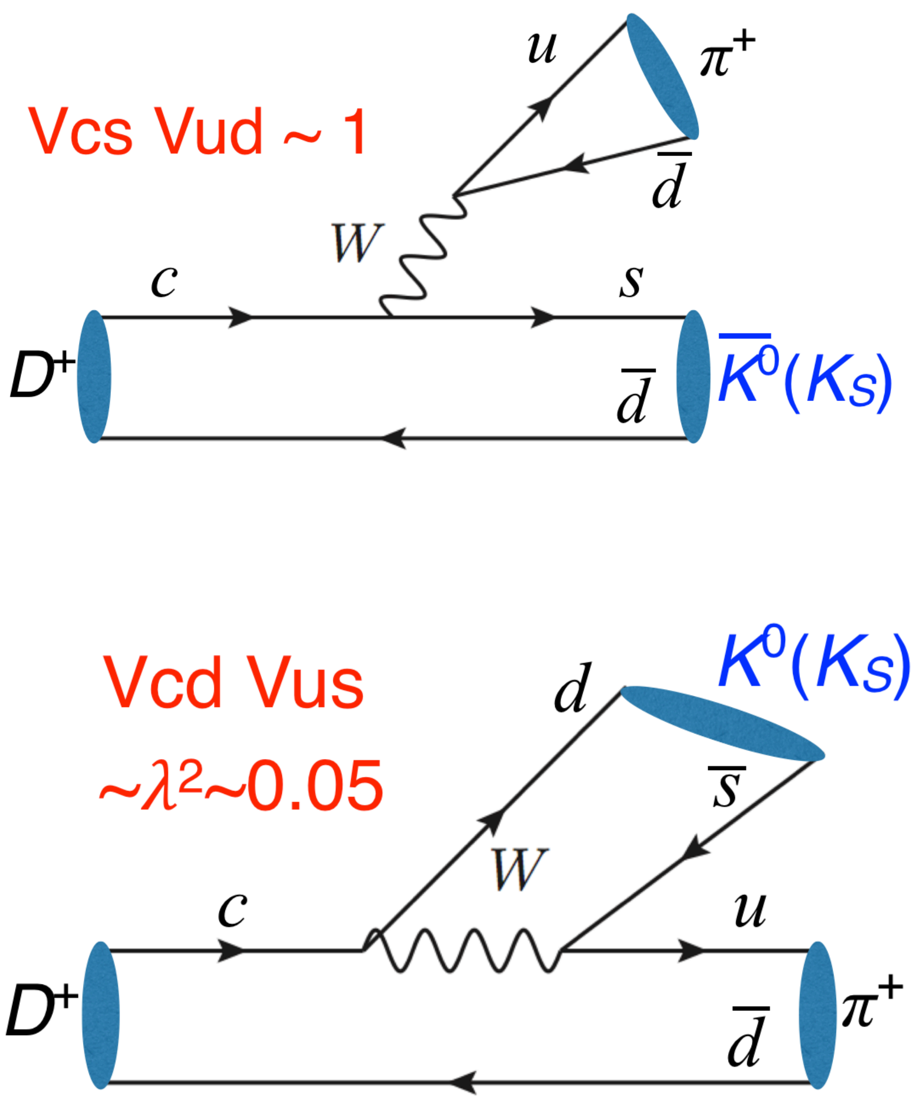
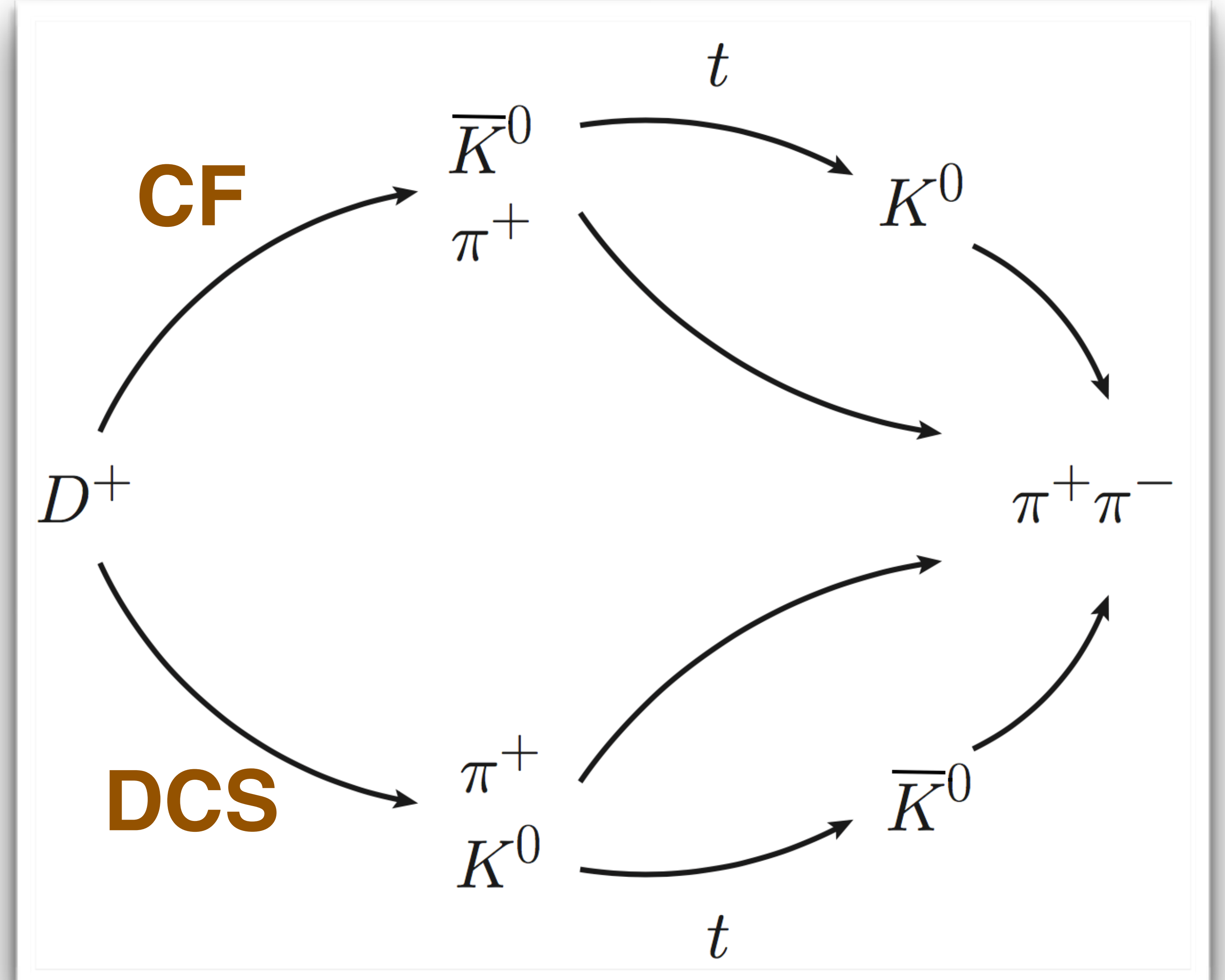
[D.Wang, **FSY**, H.n.Li, PRL119, 181802(2017); in ready]

CP Violation can occur in $D \to f\, K_S$





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

[PRL 109, 021601 (2012)]

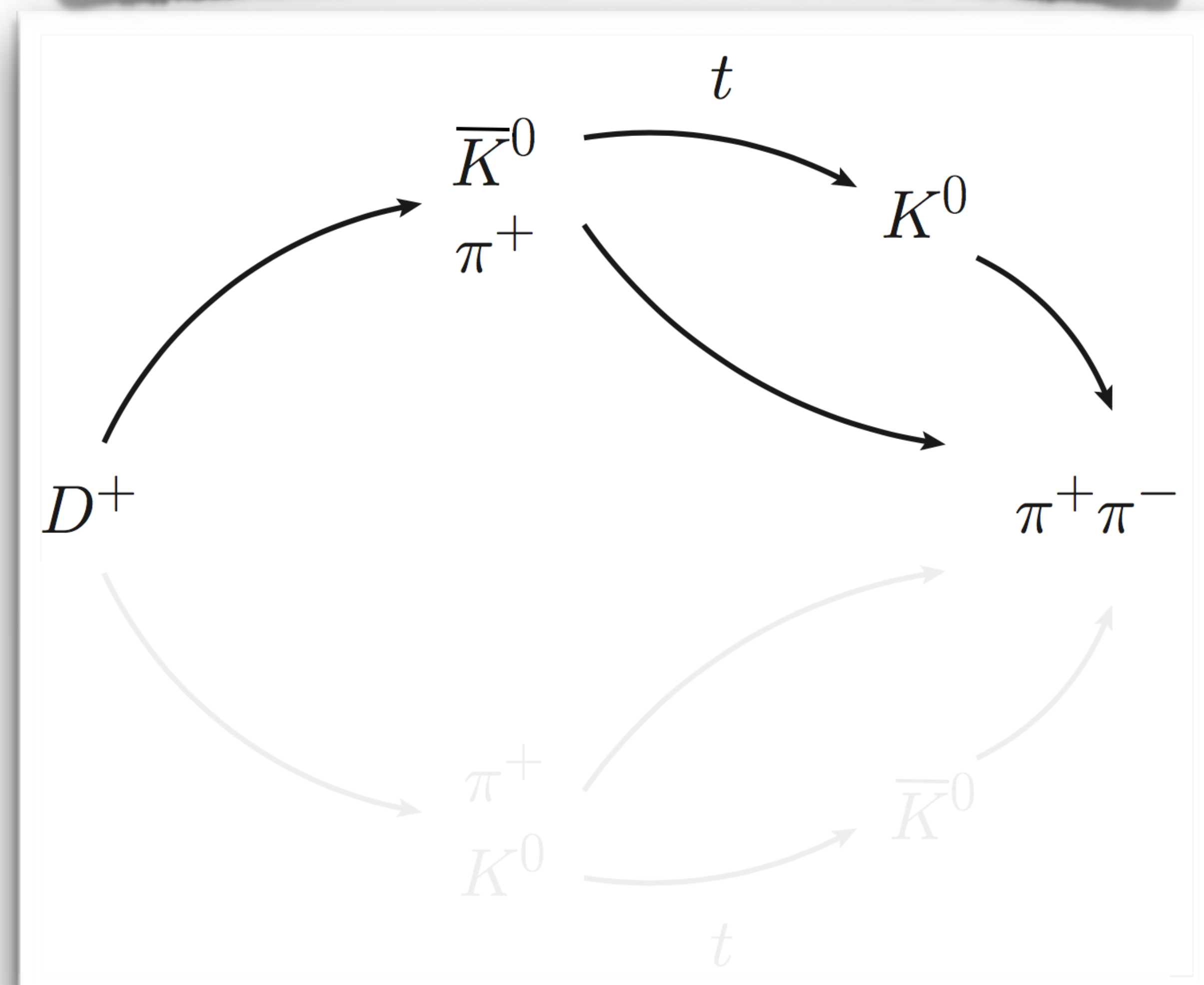
$$A_{CP}(t) \simeq \left[A^{\overline{K}^0}_{CP}(t) + A^{dir}_{CP}(t) \qquad\qquad \right] / D(t)$$

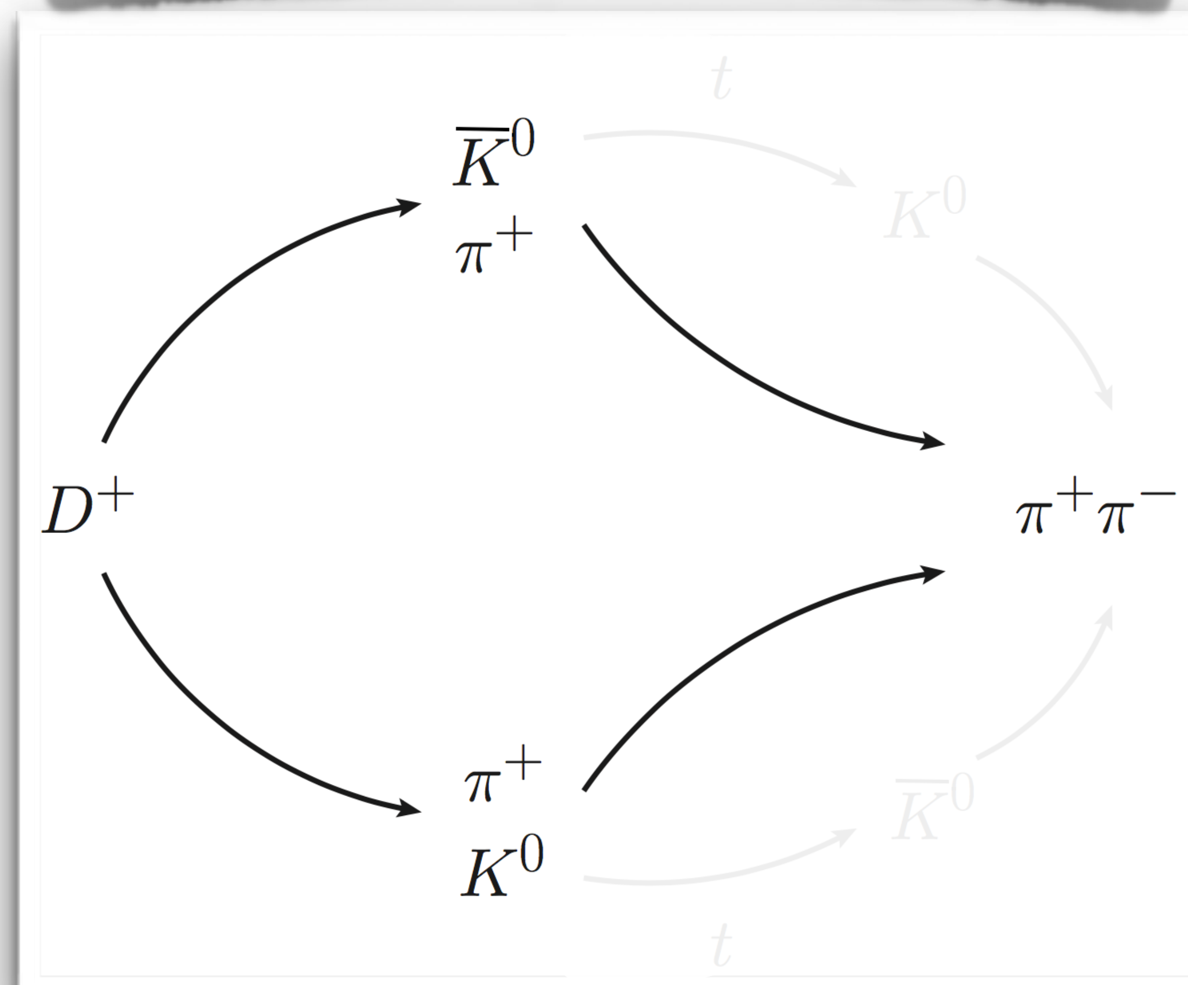
Indirect CPV in kaon mixing

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

Direct CPV in charm decays

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





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

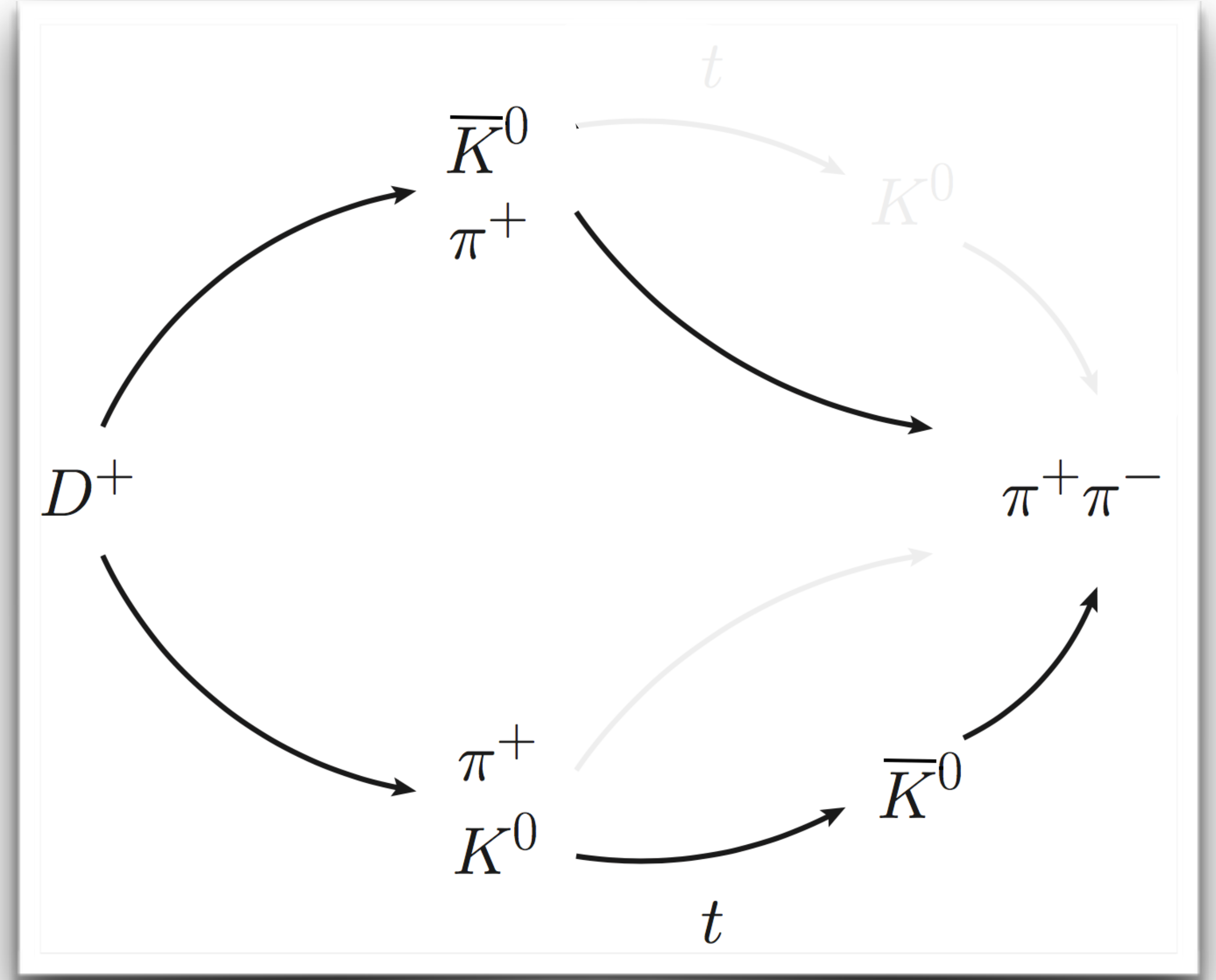
[Bigi, Yamamoto,PLB 349,363(1995)]

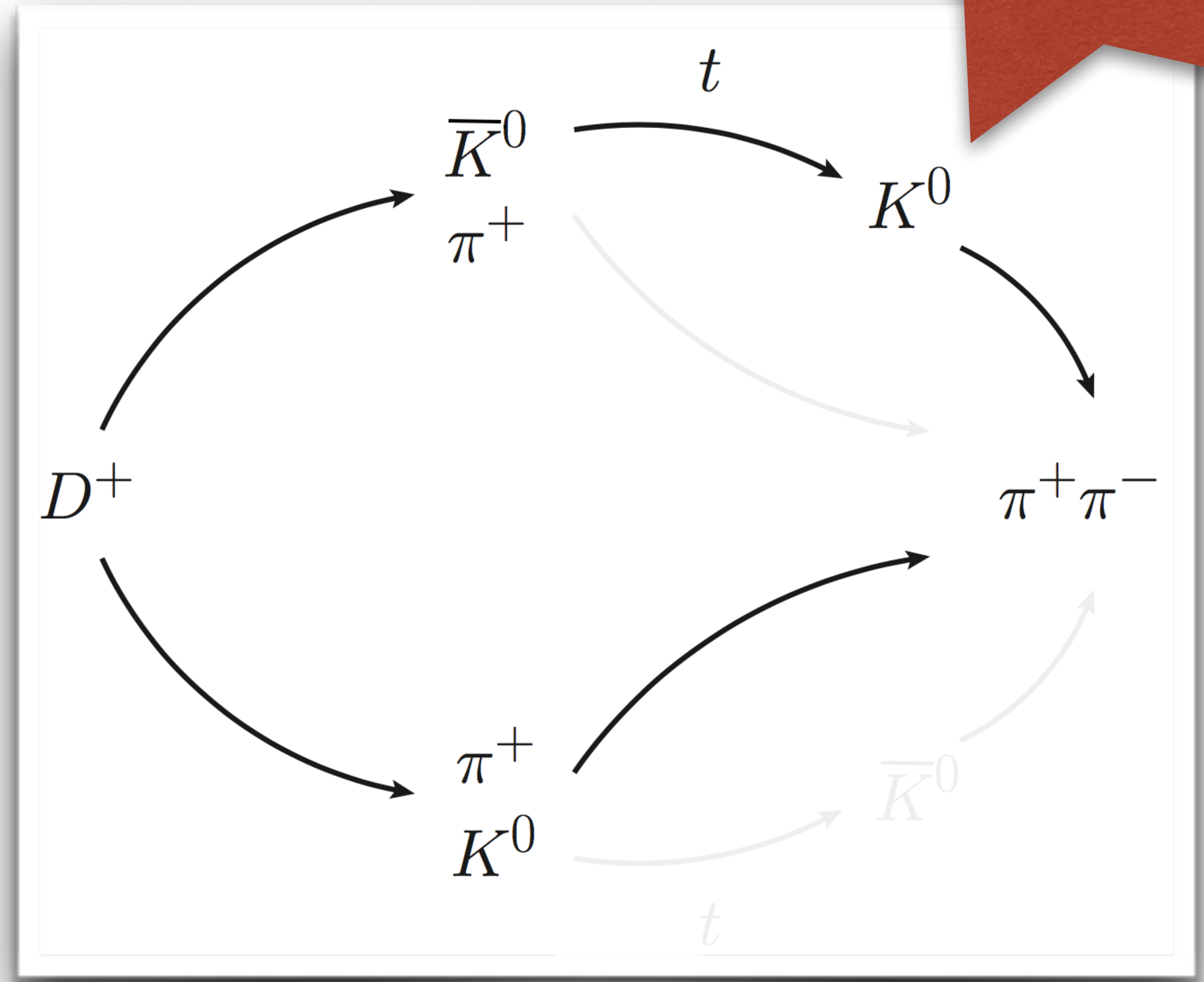
$$A_{CP}(t) \simeq \left[A_{CP}^{\overline{K}^0}(t) + A_{CP}^{dir}(t) + \boxed{A_{CP}^{int}(t)} \right] / D(t)$$

CPV in interference between kaon mixing and charm decays

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

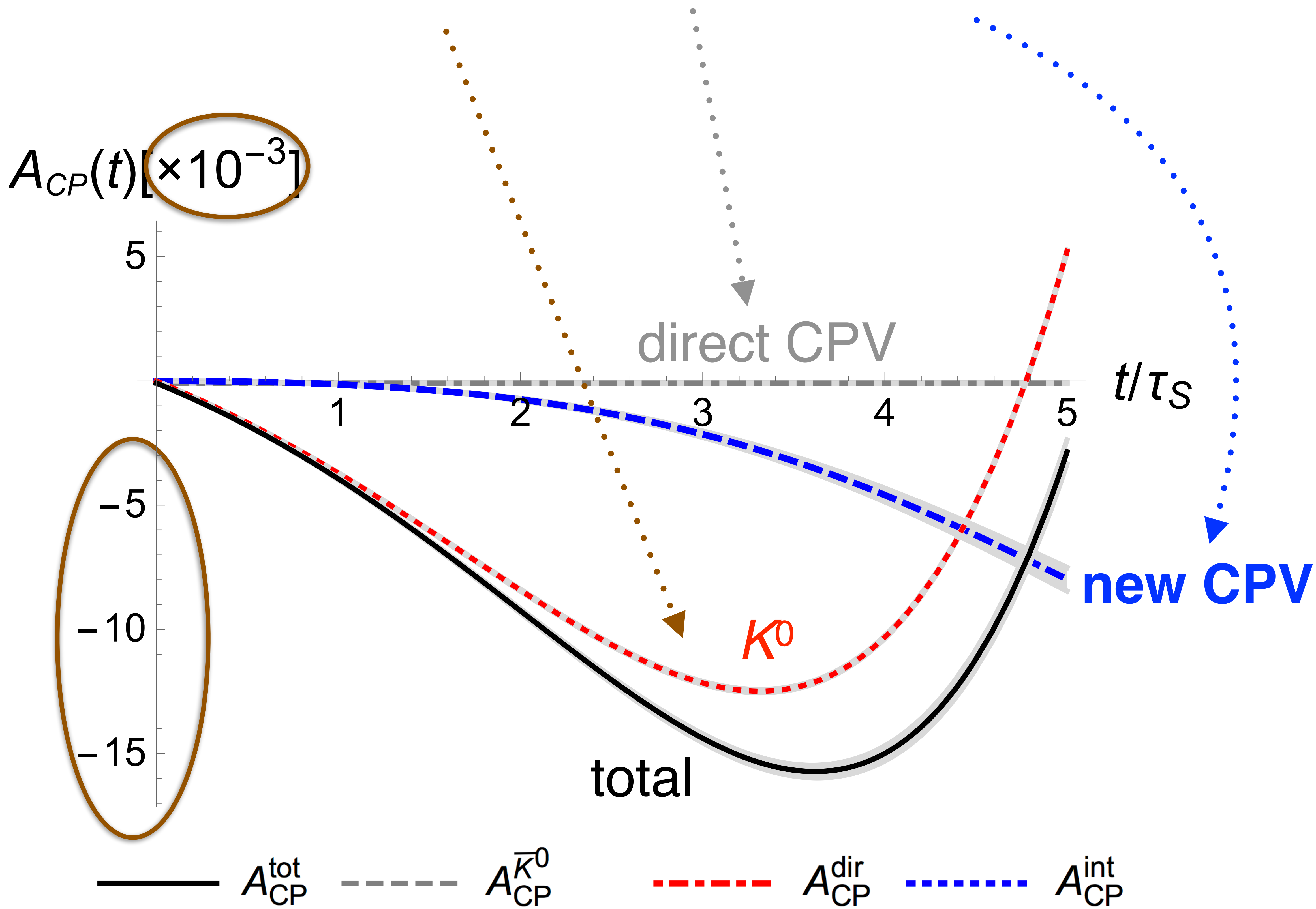
NEW





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

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



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

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

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

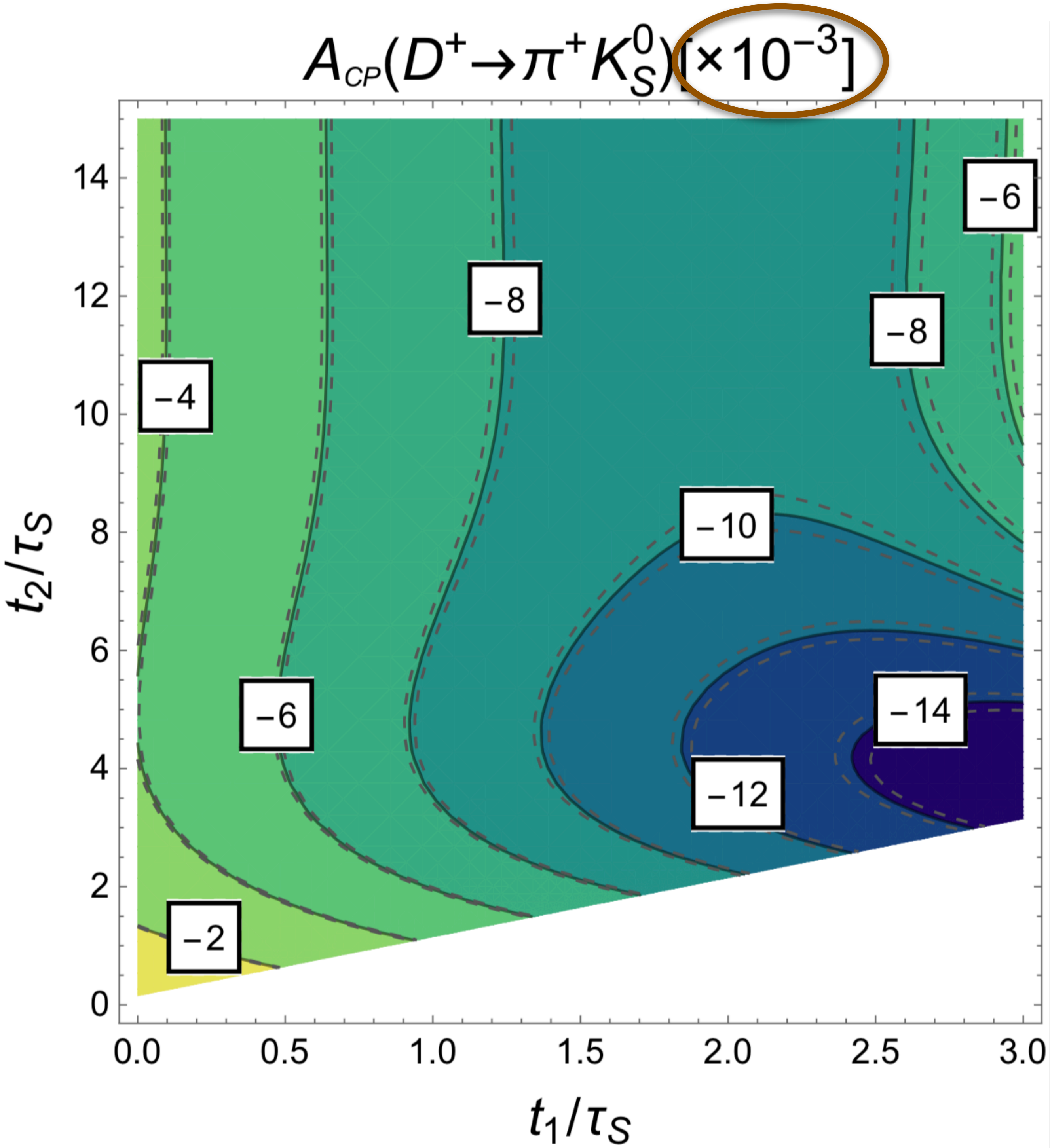
[1406.2624] LHCb @ 3 fb^{-1} [1602.03160]

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

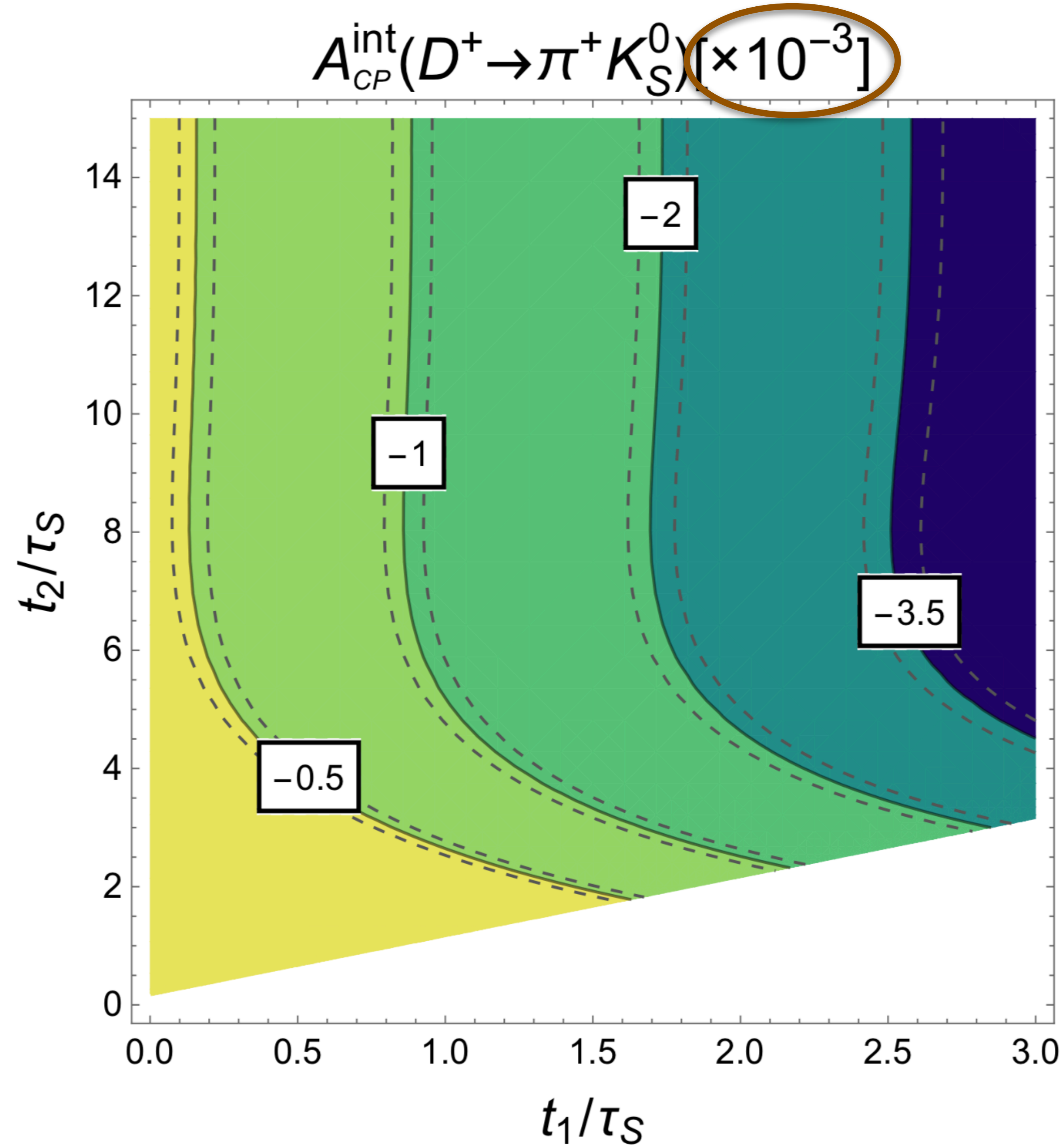
[Schwartz, arXiv:1701.07159]

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]

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

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

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

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

Belle, ‘12

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

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

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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

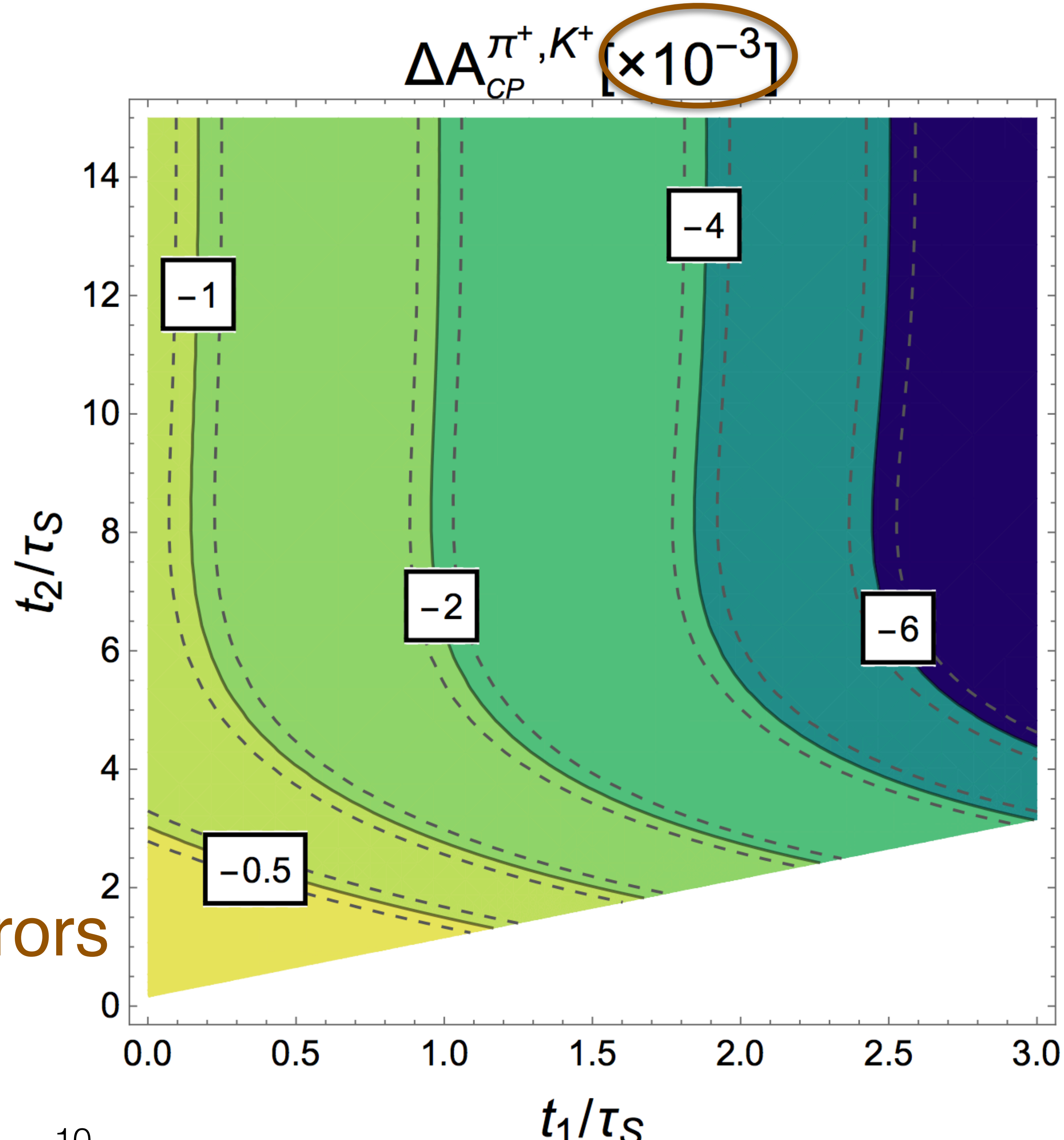
$$\boxed{\Delta A_{CP} = A_{CP}(D^+ \to \pi^+ K_S^0) - A_{CP}(D_s^+ \to K^+ K_S^0)}$$

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 $D \to f\, K_S^0$

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

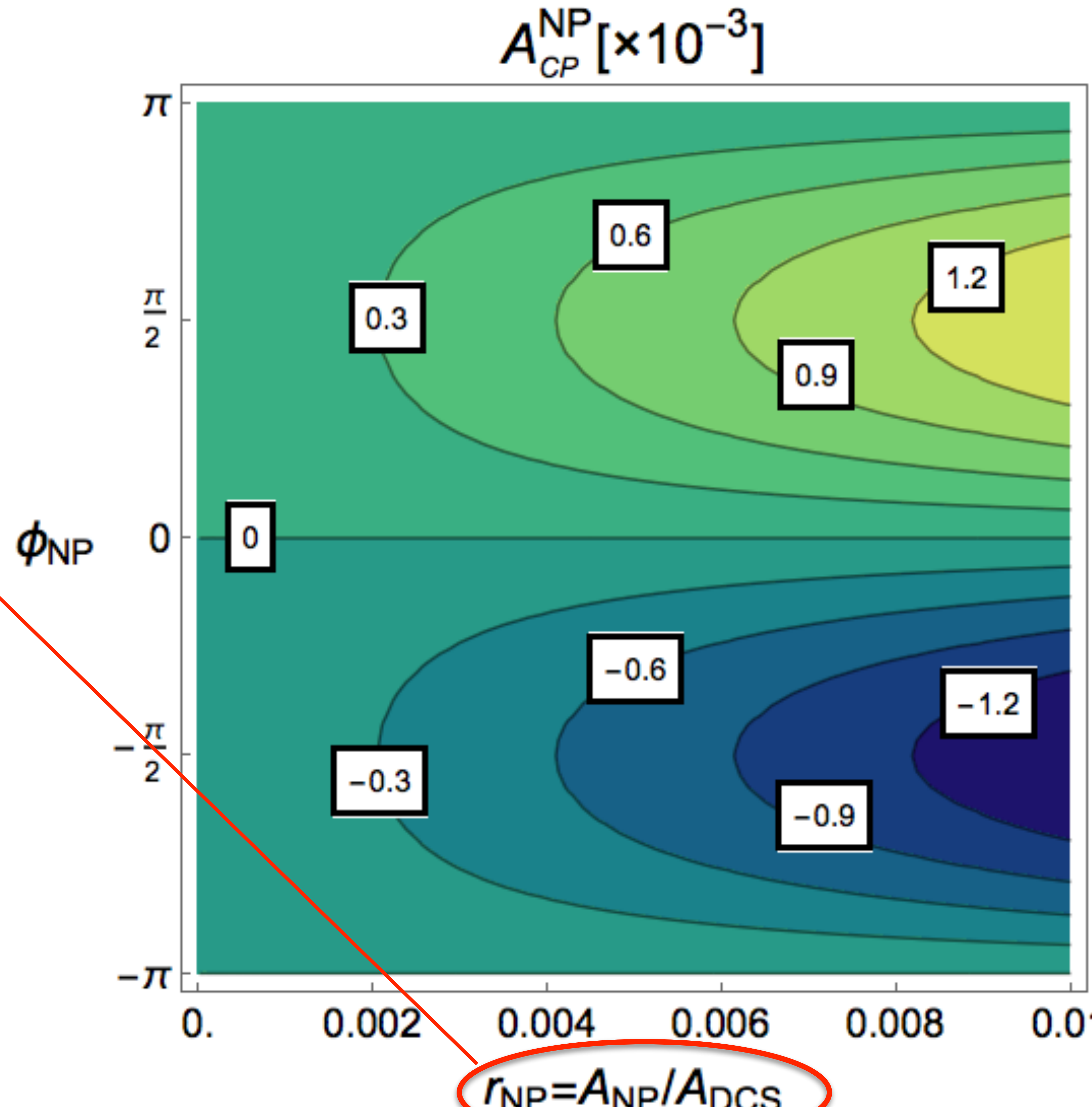
SM: $\phi \equiv Arg\left[-V_{cd}^* V_{us} / V_{cs}^* V_{ud}\right] = (-6.2 \pm 0.4) \times 10^{-4}$

NP: $\phi = O(1)$

Search for new physics at tree-level

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

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



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

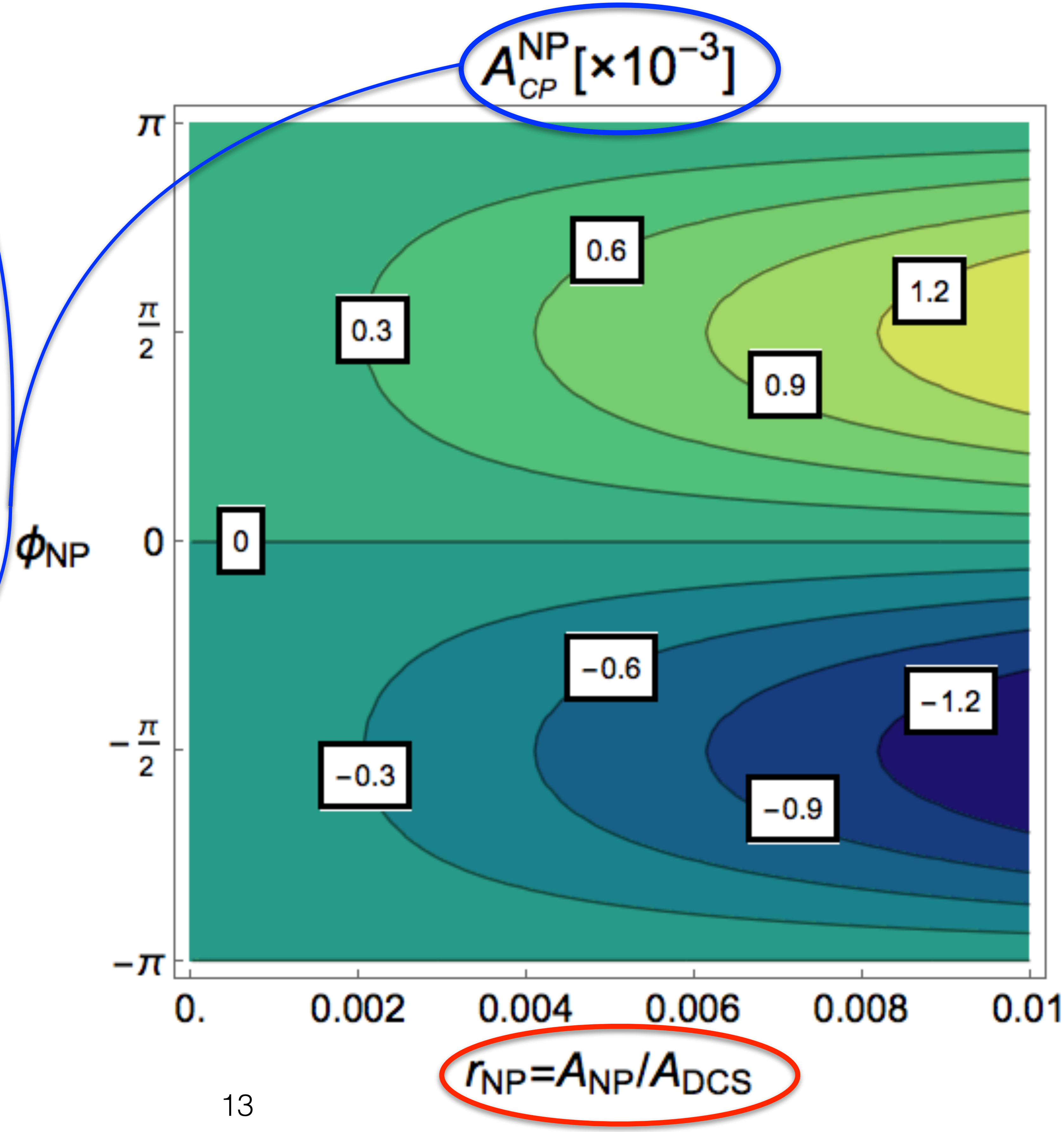
$A_{\rm SM}^{dir} = \mathcal{O}(10^{-5})$

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!



Ambiguities in penguins

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

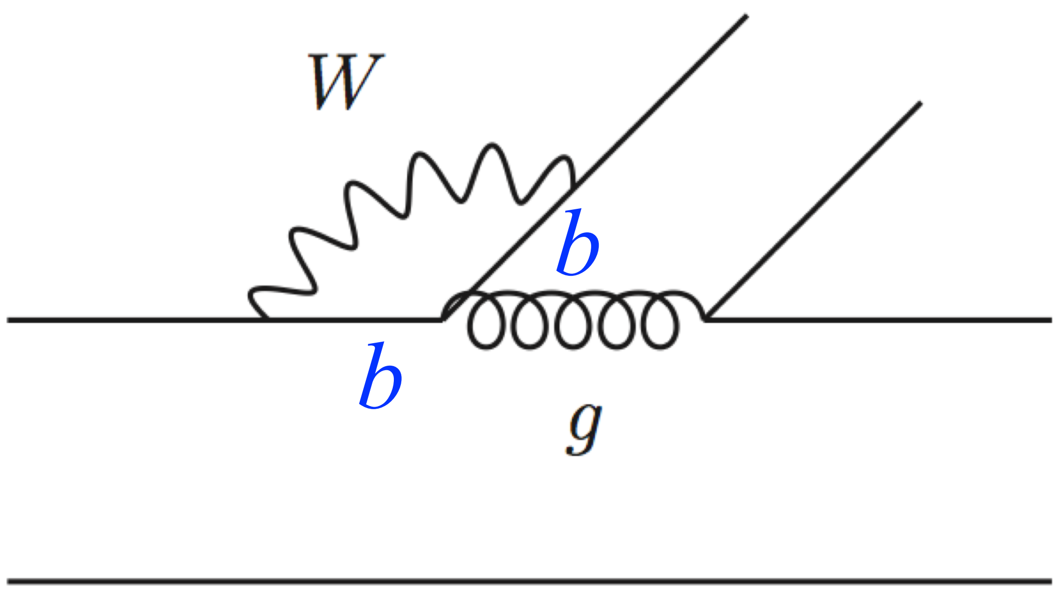
range from 10^{-5} to 10^{-2} in literature

[many papers…]

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

  ΔAcp(KK,ππ)$_{exp}$ <~ $\mathcal{O}(10^{-3})$

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



If CPV observed, cannot tell SM or NP

Summary

- **New CPV effect** is found in $D \to K_{S,L} f$
- 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

Newest LHCb measurement, arXiv:1602.03160, PRL

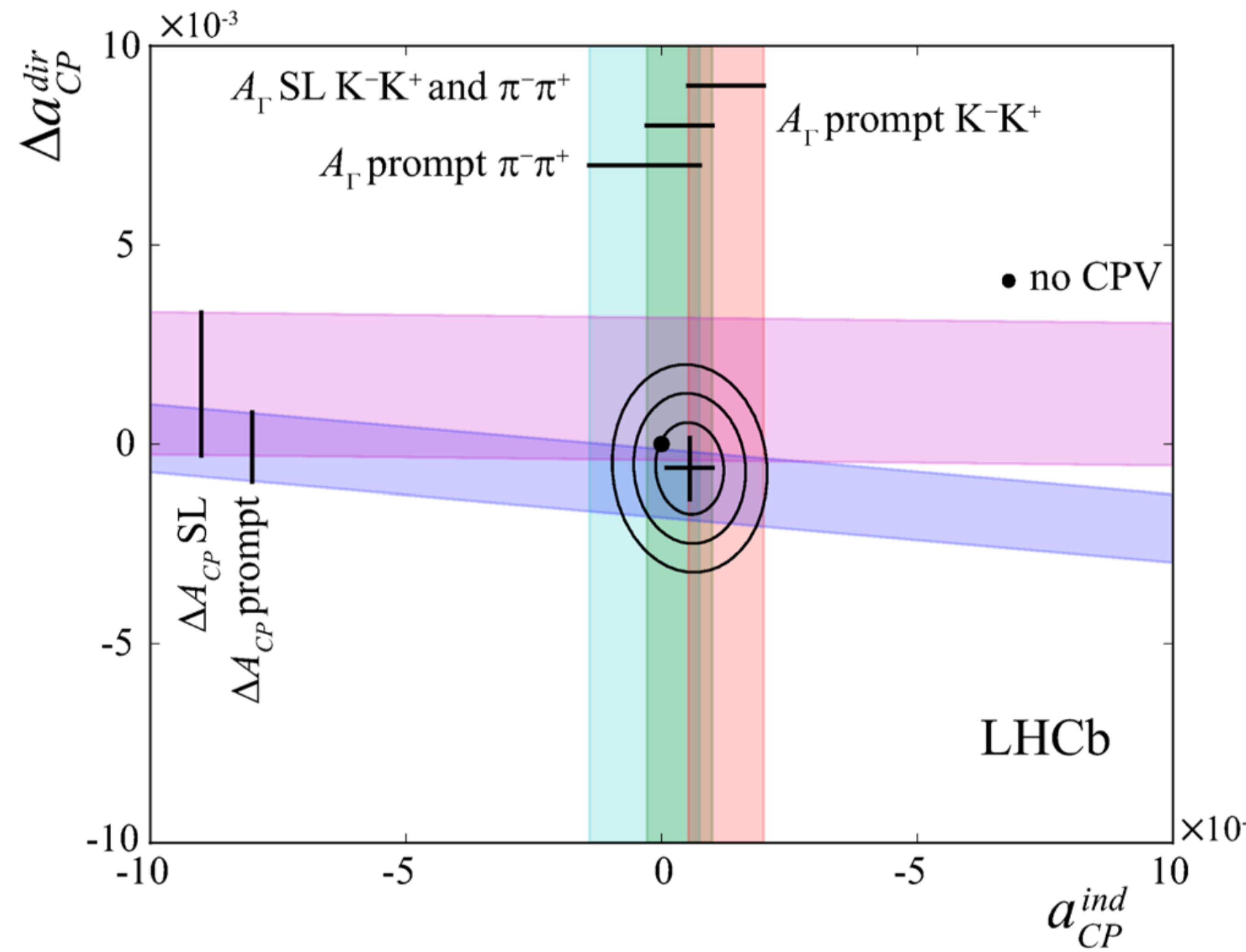
$$\Delta A_{CP} \equiv A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+)$$
$$\approx \Delta a_{CP}^{\rm dir}\left(1 + \frac{\overline{\langle t\rangle}}{\tau} y_{CP}\right) + \frac{\Delta\langle t\rangle}{\tau} a_{CP}^{\rm ind}$$
$$\Delta A_{CP} = [-0.10 \pm 0.08({\rm stat}) \pm 0.03({\rm syst})]\%$$

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

$$a_{CP}^{\rm ind} = (0.058 \pm 0.044)\%$$

$$\overline{\langle t\rangle}/\tau(D^0) = 2.0949 \pm 0.0004({\rm stat}) \pm 0.0159({\rm syst})$$

$$\Delta\langle t\rangle/\tau(D^0) = 0.1153 \pm 0.0007({\rm stat}) \pm 0.0018({\rm syst})$$



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

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

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

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

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

strong phase

weak phase

~λ^2~0.05

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

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

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

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

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

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

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

$$D^+ \to K_S^0\pi^+ \qquad \underbrace{(1+\bar{\varepsilon}^*)V_{cd}^*V_{us}\boxed{(C+A)}}_{\text{DCS}} - \underbrace{(1-\bar{\varepsilon}^*)V_{cs}^*V_{ud}\boxed{(T+C)}}_{\text{CF}}$$

$$D_s^+ \to K_S^0K^+ \qquad \underbrace{(1+\bar{\varepsilon}^*)V_{cd}^*V_{us}\boxed{(T+C)}}_{\text{DCS}} - \underbrace{(1-\bar{\varepsilon}^*)V_{cs}^*V_{ud}\boxed{(C+A)}}_{\text{CF}}$$

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

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

Interesting modes in experiments

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

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

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

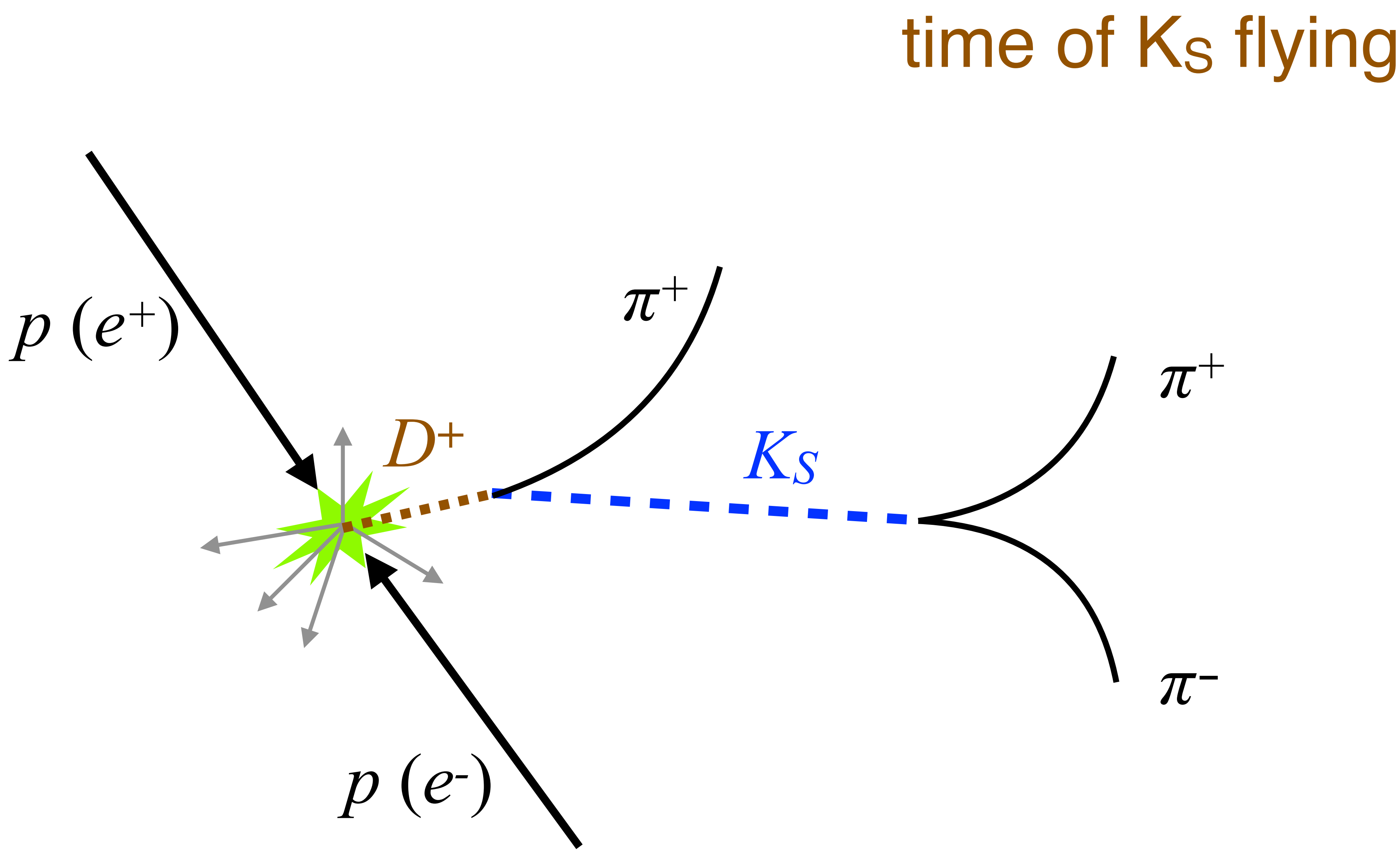
Br=5%

and

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

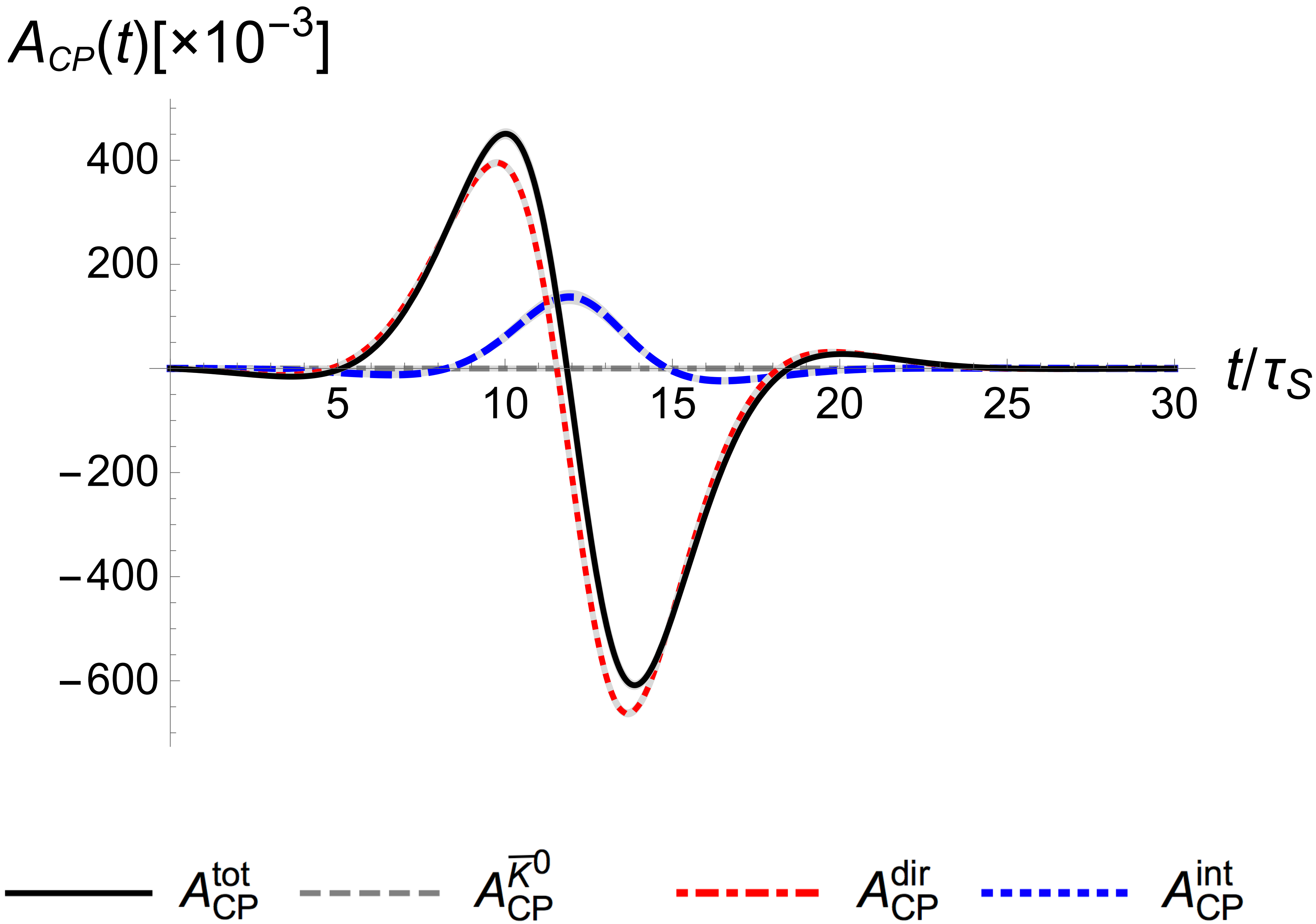
$$= [A_{raw}^{\Lambda_c^+ \to pK}(t_1, t_2) - A_{raw}^{\Lambda_c^+ \to pK^-\pi^+}]$$
$$- [A_{raw}^{D^+ \to K\pi^+}(t_1, t_2) - A_{raw}^{D^+ \to K^-\pi^+\pi^+}]$$

Time-dependent & Time integrated CPV



Time-dependent CPV

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



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}

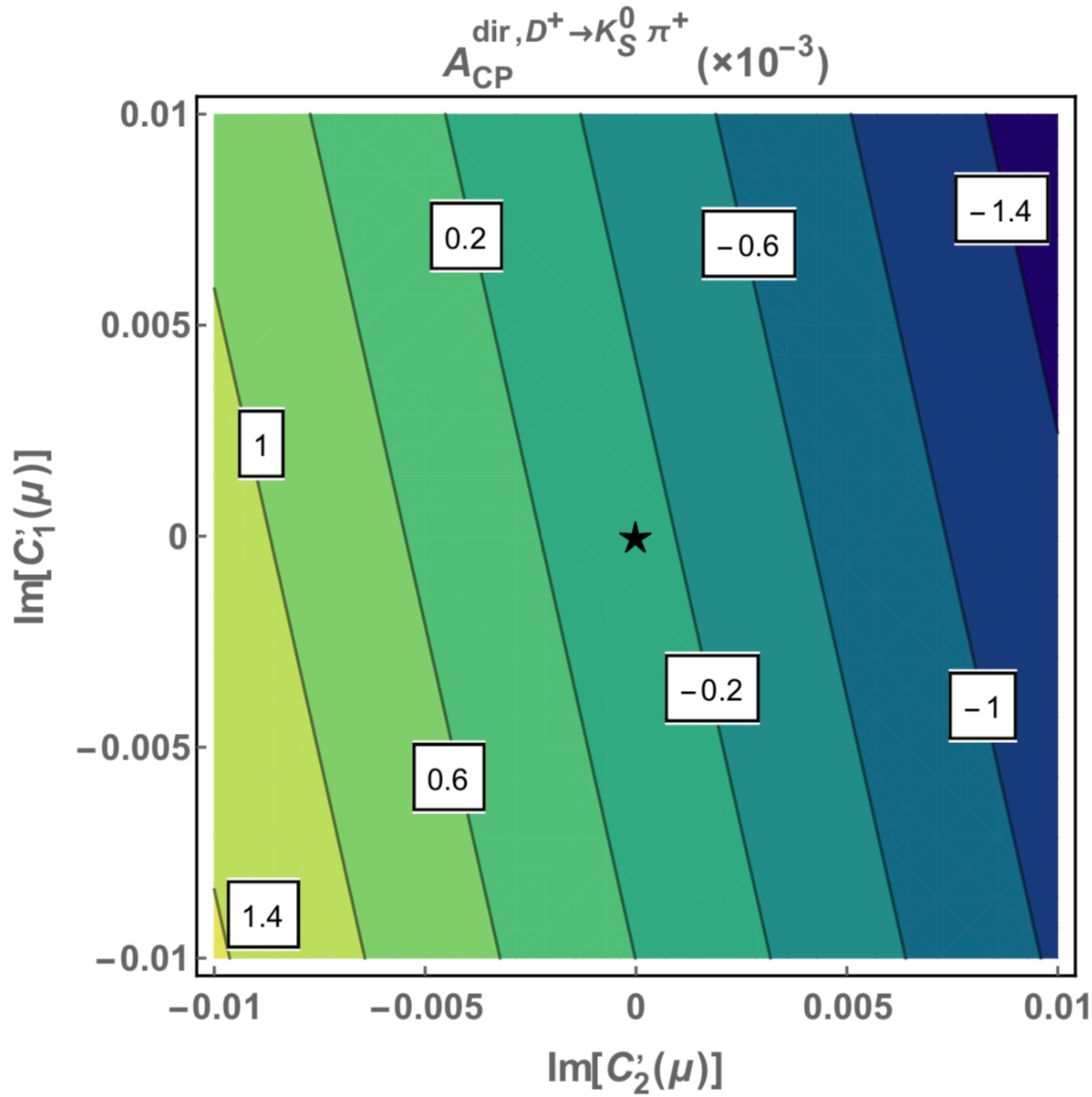
3. **Signal CPV in charm. $A_{CP}(K^0)$ cancelled**

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

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

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

7. **Some systematic uncertainties cancelled**

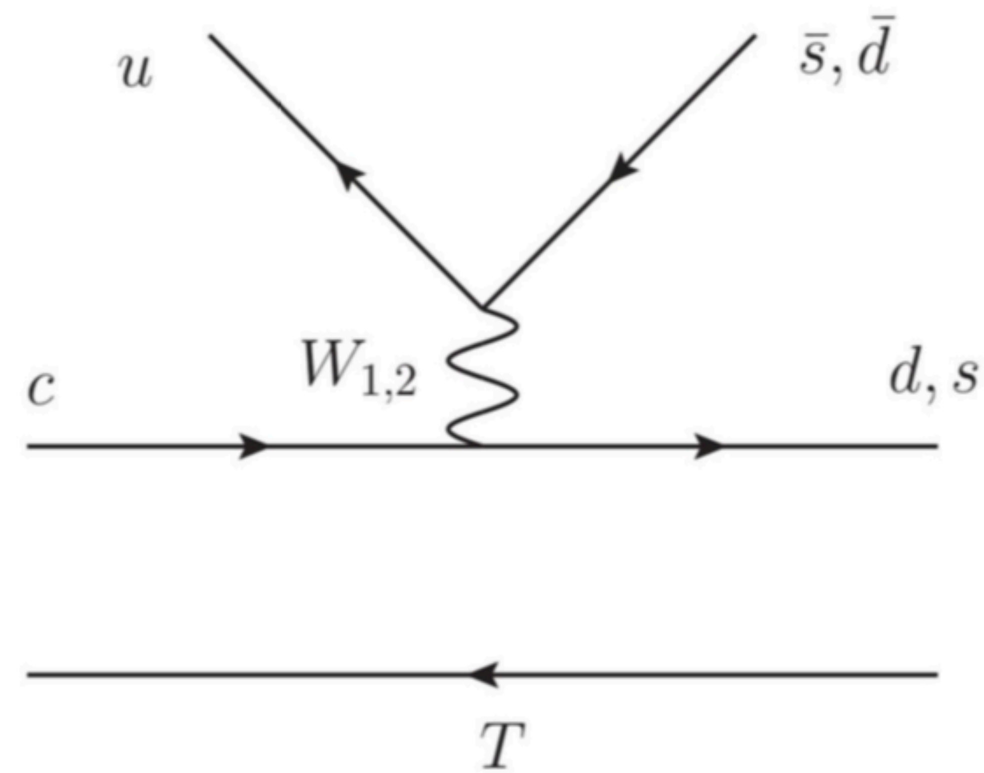

$A_{CP}^{dir, D^+ \to K_S^0 \pi^+}$ ($\times 10^{-3}$)
0.2
−0.6
−1.4
1
−0.2
−1
0.6
1.4
0.01
0.005
0
−0.005
−0.01
$\mathrm{Im}[C_1'(\mu)]$
−0.01
−0.005
0
0.005
0.01
$\mathrm{Im}[C_2'(\mu)]$

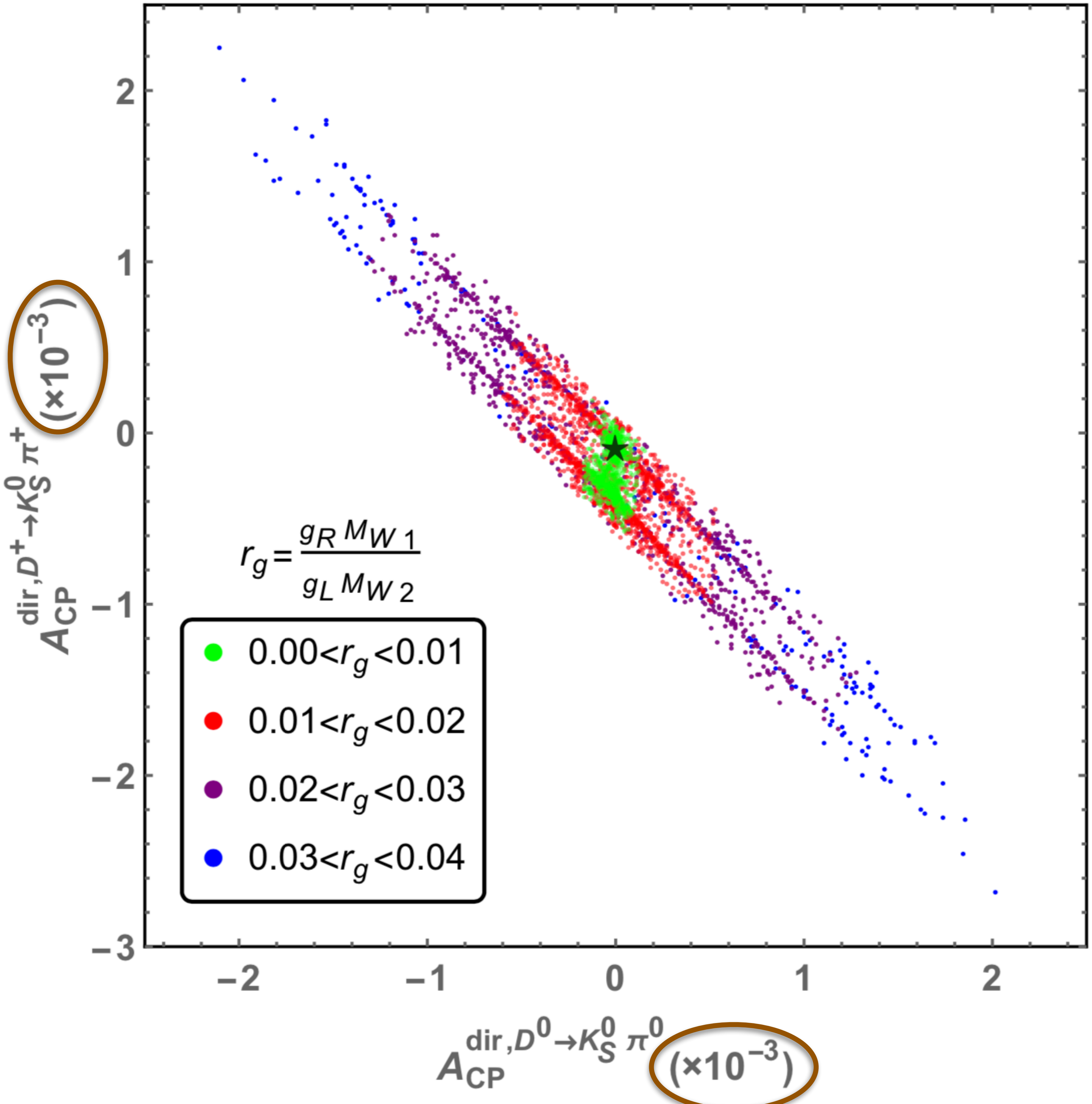
Left-Right Symmetric Model

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

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

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





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