New CP violation effect in charm decays

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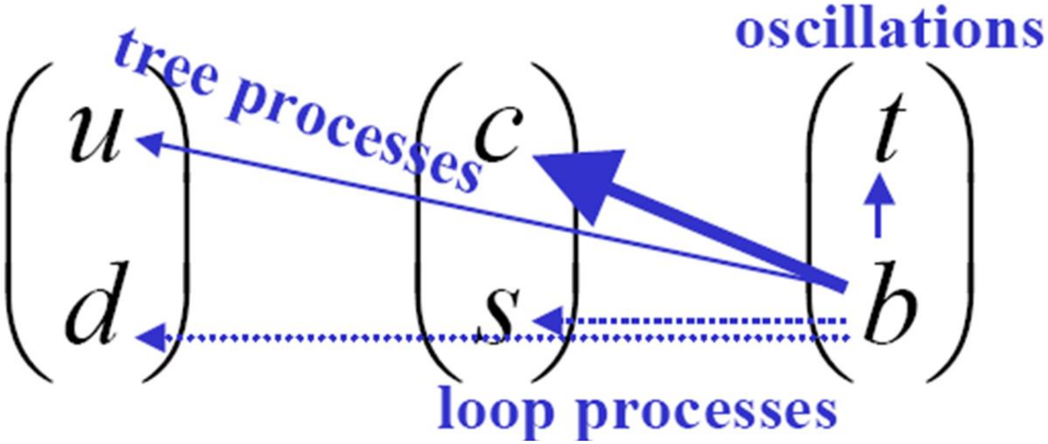
Direct CP violation

- Direct CP asymmetry established in kaon and bottom decays
- Not yet in charm decays, so its search is a top mission in particle physics
- Usually arises from interference between tree and penguin amplitudes
- Most precise measurement from LHCb

$$\Delta A_{CP} \equiv A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)$$
$$= (-1.0 \pm 0.8 \pm 0.3) \times 10^{-3},$$

Cabbibo-Kobayashi-Maskawa Matrix



(Wolfenstein parametrization)

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

Weak phase, ~~CP~~

$$; \begin{pmatrix} 0.97 & 0.23 & 0.004 \\ -0.23 & 0.97 & 0.04 \\ 0.004 & -0.04 & 1 \end{pmatrix}$$

(magnitudes only)

Tree-tree interference

- $D^0 \to K^+K^-$, $\pi^+\pi^-$ are singly Cabibbo suppressed modes

$T_{SCS} \propto V^*_{cd(s)} V_{ud(s)}$ $\qquad$ $P \propto V^*_{ci} V_{ui} \exp(i\delta)$

order λ $\qquad$ strong phase

- Direct CP asymmetry can also be induced by interference between Cabibbo favored and doubly Cabibbo suppressed tree amplitudes

$T_{CF} \propto V^*_{cs} V_{ud}$ $\qquad$ $T_{DCS} \propto V^*_{cd} V_{us} \exp(i\delta)$

order unity $\qquad$ order λ^2

Weak phase of DCS/CF

- Standard parametrization of CKM matrix

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{bmatrix}.$$

$$\phi \equiv Arg\left[-V_{cd}^{*}V_{us}/V_{cs}^{*}V_{ud}\right]$$

$$= (-6.2 \pm 0.4) \times 10^{-4}$$

Belle data

- Belle measurement with 3.2 sigma from zero

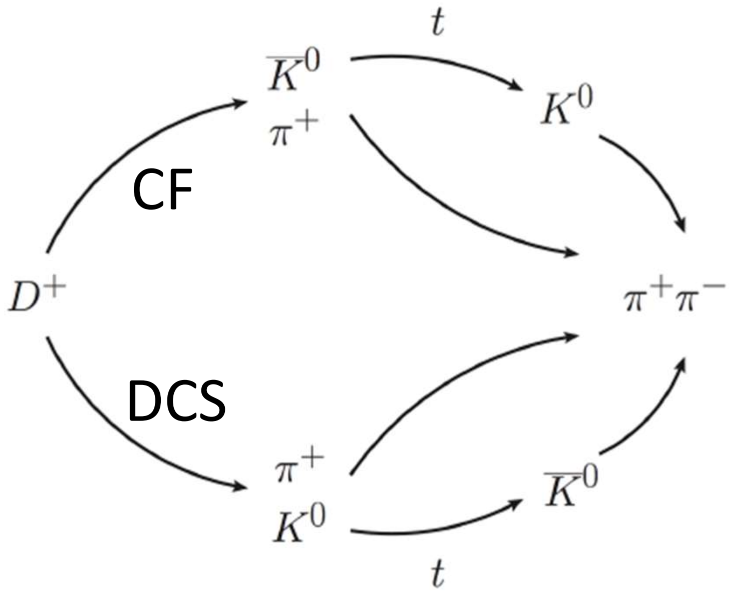
$$A_{CP}(D^+ \to \pi^+ K_S^0) = (-3.63 \pm 0.94 \pm 0.67) \times 10^{-3}$$

- Note that Ks is reconstructed via decay into two charged pions
- K_L also decays into two pions
- Data mainly due to kaon mixing of order 10^{-3}
- Postulated in literature: deducting kaon mixing, data reveal direct CP asymmetry in charm decays

Lipkin, Xing 1999
D'Ambrosio, Gao 2001
Bianco, Fabbri, Benson, Bigi 2003
Grossman, Nir 2012

Our observation

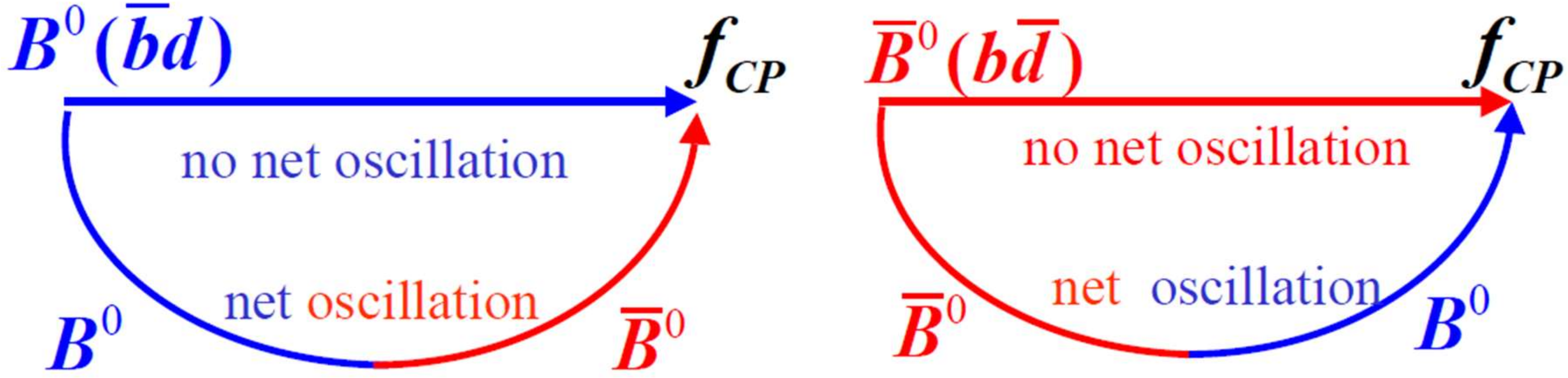
- This postulation is wrong
- Kaon mixing induces a new CP observable



- More complicated than ordinary mixing-induced CP asymmetry in, say, $B^0(t) \to \pi^+\pi^-$: both oscillation and decay occur in mother particle
- The new observable arises from interference between mother decay and daughter mixing

“Strong phase” from oscillation

- Ordinary mixing-induced CP violation



- $\exp(i\,\Delta m\,t)$ plays the role of “strong phase”
- Feature of CP violation from oscillation:
  as t -> 0, it vanishes

Time-dependent CP violation

- The rest is detail
- Consider

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

$$\Gamma_{\pi\pi}(t) \equiv \Gamma(D \to f K(t)(\to \pi^+\pi^-))$$

$$\overline{\Gamma}_{\pi\pi}(t) \equiv \Gamma(\overline{D} \to \overline{f} \underset{\substack{\uparrow \\ K^0(t) \text{ or } \overline{K}^0(t)}}{K(t)}(\to \pi^+\pi^-))$$

Relevant variables

- Kaon mixing $|K^0_{S,L}\rangle = p|K^0\rangle \mp q|\overline{K}^0\rangle$

indirect CP violation

$$q/p = (1-\epsilon)/(1+\epsilon)$$

$$|\epsilon| = (2.228 \pm 0.011) \times 10^{-3} \qquad \phi_\epsilon = 43.52 \pm 0.05^\circ$$

- averaged width $\Gamma = (\Gamma_S + \Gamma_L)/2$
- Width difference $\Delta\Gamma \equiv \Gamma_S - \Gamma_L$
- Mass difference $\Delta m \equiv m_L - m_S$
- Ratio of DCS/CF

$$\mathcal{A}(D \to f K^0)/\mathcal{A}(D \to f \overline{K}^0) = r_f\, e^{i(\phi+\delta_f)}$$

$$r_f \propto |V^*_{cd} V_{us} / V^*_{cs} V_{ud}| \sim \mathcal{O}(10^{-2})$$

3 CP observables

- Neglect direct CP asymmetry in $K \to \pi\pi$

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

- Known kaon mixing $\quad D(t) = e^{-\Gamma s t}(1-2r_f \cos\delta_f \cos\phi)$

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

- Direct CP asymmetry

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

- New observable

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

Global fits

- Adopt factorization-assisted topological-amplitude approach
- DCS/CF parameters for $D^+ \to \pi^+ K_S^0$ and $D_s^+ \to K^+ K_S^0$

maximize new CP observable

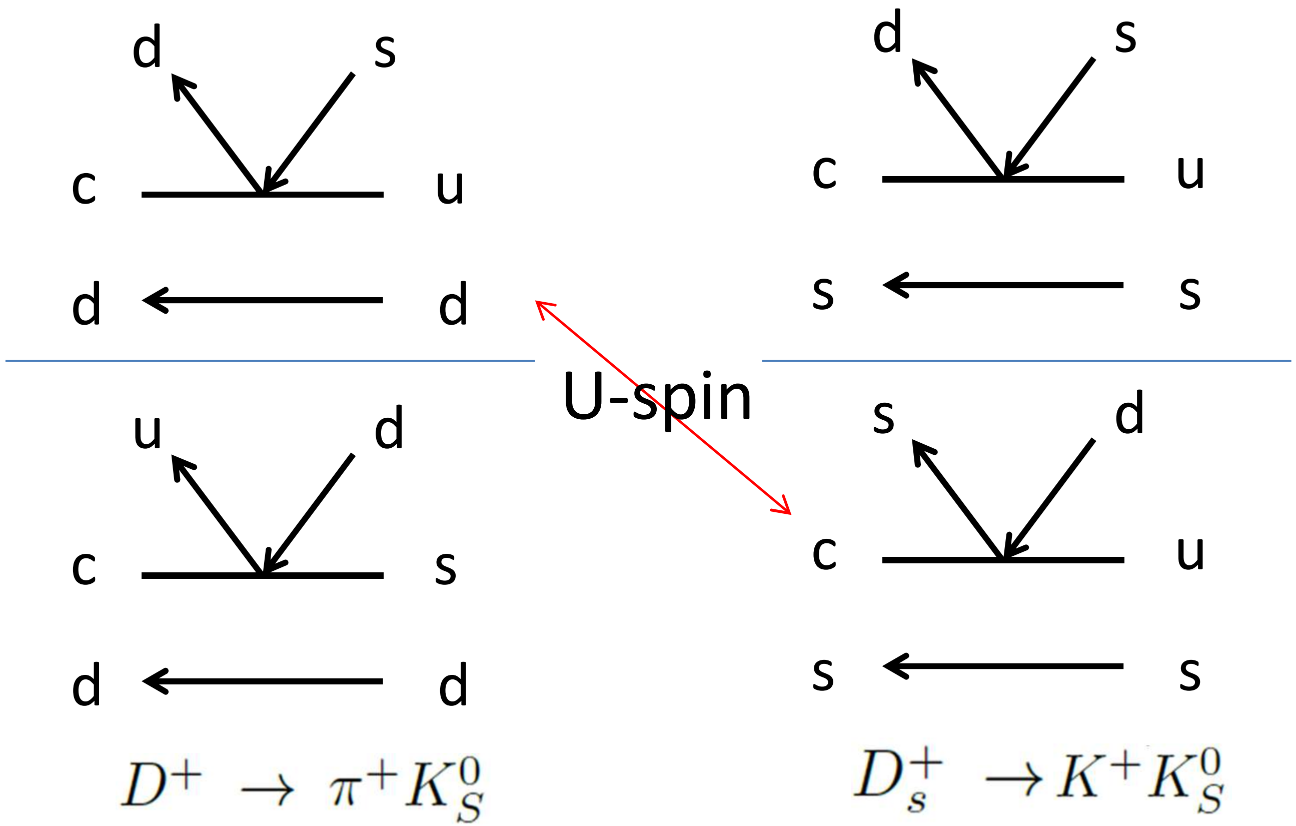
$$r_{\pi^+} = -0.073 \pm 0.004, \qquad \delta_{\pi^+} = -1.39 \pm 0.05,$$
$$r_{K^+} = -0.055 \pm 0.002, \qquad \delta_{K^+} = +1.45 \pm 0.05$$

- Direct CP asymmetry at t=0

$$A_{CP}^{\rm dir}(D^+ \to \pi^+ K_S^0) = (-8.6 \pm 0.4) \times 10^{-5}$$
$$A_{CP}^{\rm dir}(D_s^+ \to K^+ K_S^0) = (6.6 \pm 0.3) \times 10^{-5}.$$

U-spin symmetry

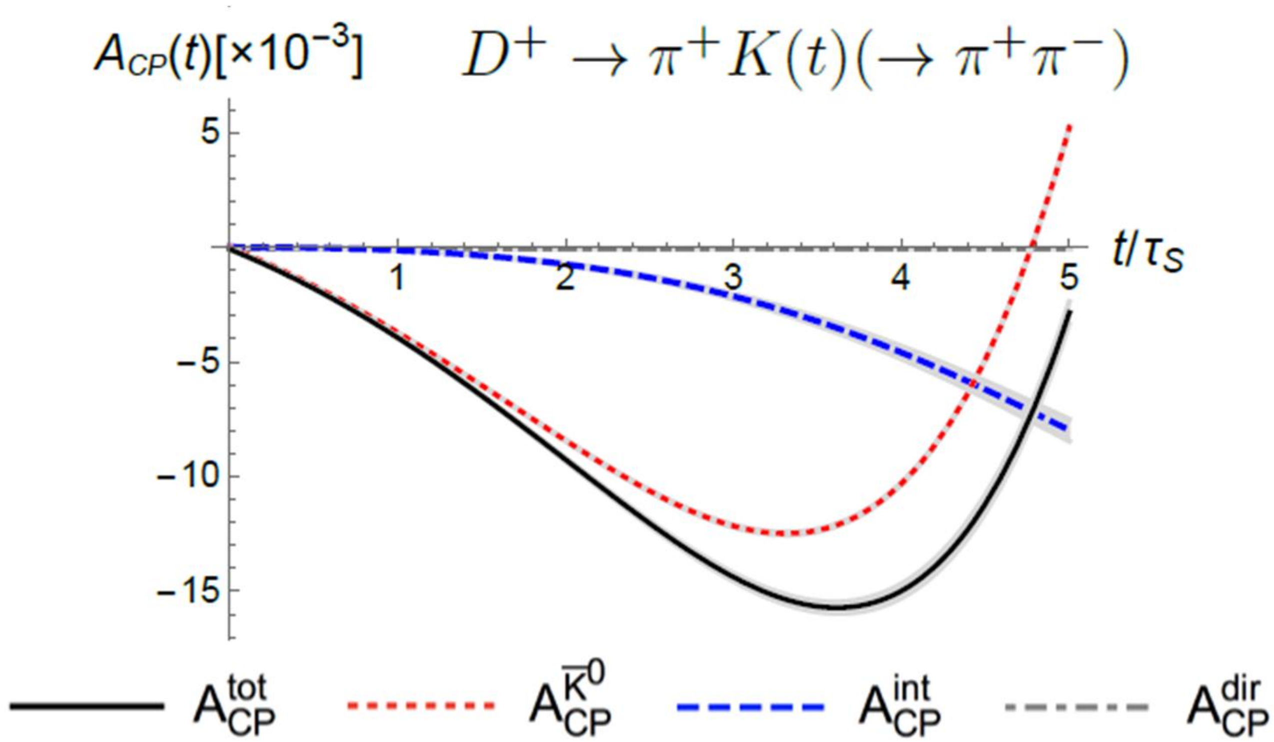
- Ratio of DCS/CF



- Reason why strong phase opposite in sign

Numerical results

- Direct CP asymmetry always negligible
- New observable becomes comparable to kaon mixing as t ~ few times of K short lifetime



Experimental verification

- To verify the new CP violation effect, measure

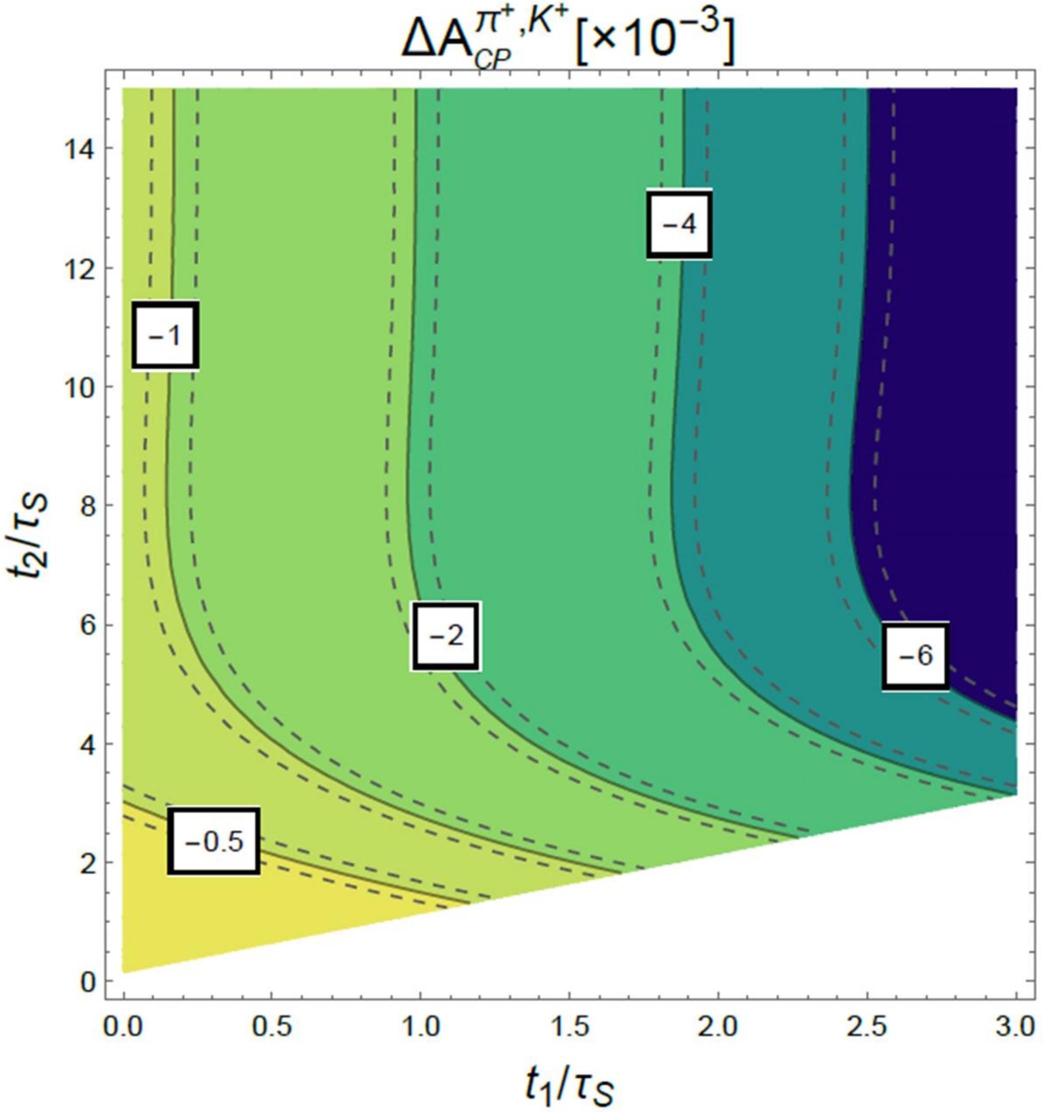
$$\Delta A_{CP}^{\pi^+,K^+} \equiv A_{CP}^{D^+\to\pi^+K_S^0}(t_1,t_2) - A_{CP}^{D_s^+\to K^+K_S^0}(t_1,t_2)$$
$$\simeq A_{CP}^{\mathrm{int},D^+\to\pi^+K_S^0}(t_1,t_2) - A_{CP}^{\mathrm{int},D_s^+\to K^+K_S^0}(t_1,t_2)$$

where time-integrated CP asymmetry

$$A_{CP}(t_1,t_2) = \frac{\int_{t_1}^{t_2}\left[A_{CP}^{\overline{K}^0}(t)+A_{CP}^{\mathrm{dir}}(t)+A_{CP}^{\mathrm{int}}(t)\right]dt}{\int_{t_1}^{t_2} D(t)dt}$$

- Kaon mixing cancels in the difference, and direct CP asymmetry is negligible

Theoretical prediction



Conclusion

- New effect, from interference between mother decay and daughter mixing, can be measured at Belle II and LHCb upgrade with precision of $\mathcal{O}(10^{-4})$
- If verified, need to be subtracted in order to extract direct CP asymmetry in charm decays
- Then direct CP asymmetry from DCS and CF interference, both being tree and better controlled by branching-ratio data, can be used to test new physics

Direct CPA in Belle data

- Recall Belle data

$$A_{CP}(D^+ \to \pi^+ K_S^0) = (-3.63 \pm 0.94 \pm 0.67) \times 10^{-3}$$

- Consider the integrated CP asymmetry in the limit

$$A_{CP}(t_1 \ll \tau_S \ll t_2 \ll \tau_L)$$
$$\simeq \frac{-2\mathcal{R}e(\epsilon) + 2r_f \sin\phi \sin\delta_f - 4\mathcal{I}m(\epsilon) r_f \cos\phi \sin\delta_f}{1 - 2r_f \cos\phi \cos\delta_f}$$

inputs

- Extract direct CP asymmetry from Belle data

$$(-0.06 \pm 1.15) \times 10^{-3}$$