$K_S^0 - K_L^0$ asymmetries in charm hadron decays

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PRD 95, 073007 (2017)

& arXiv:1709.09873

Contents

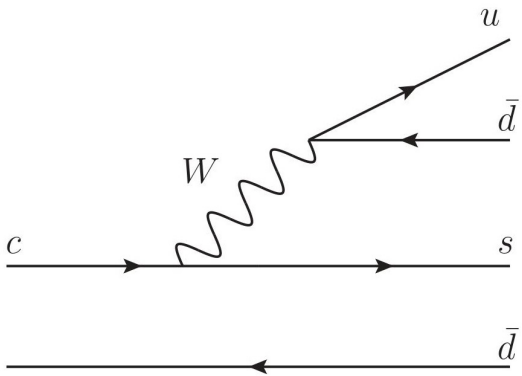
Motivation

- The two-body nonleptonic decays of charm hadrons can be classified into three types:
  - Cabibbo-favored (CF) processes
  - singly Cabibbo-suppressed (SCS) processes
  - doubly Cabibbo-suppressed (DCS) processes
- Only a few DCS modes are well measured due to the relatively small branching fractions
- Because of the relative smallness in the SM, the DCS processes can be significantly affected by new physics
- Charm decays into neutral kaons

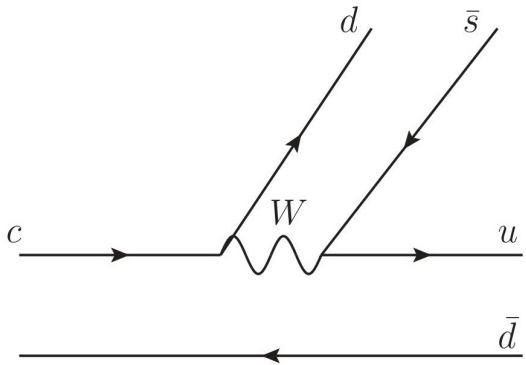
$$|K^0_{S,L}\rangle = \frac{1}{\sqrt{2(1+|\epsilon|^2)}}\left[(1+\epsilon)|K^0\rangle \pm (1-\epsilon)|\overline{K}^0\rangle\right]$$

Motivation

- Cabibbo-favored (CF) and doubly Cabibbo-suppressed (DCS) transitions



$V_{cs}V_{ud}$



$V_{cd}V_{us}$

- Interference between CF and DCS amplitudes $\Rightarrow$ $K_S^0 - K_L^0$ asymmetry

$K_S^0 - K_L^0$ asymmetry

- The definition of $K_S^0 - K_L^0$ asymmetry:

$$R(f) \equiv \frac{\Gamma(D \to K_S^0 f) - \Gamma(D \to K_L^0 f)}{\Gamma(D \to K_S^0 f) + \Gamma(D \to K_L^0 f)}.$$

  - I. I. Y. Bigi and H. Yamamoto, Phys. Lett. B **349**, 363 (1995).

- If we appoint

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

$$R(f) = -2\, r_f \frac{\cos(\phi+\delta_f)(1-|\epsilon|^2) + 2\sin(\phi+\delta_f)\mathcal{I}m(\epsilon)}{|1-\epsilon^*|^2 + |1+\epsilon^*|^2\, r_f^2}$$
$$\approx -2r_f(1+2\mathcal{R}e(\epsilon))(\cos(\phi+\delta_f) + 2\mathcal{I}m(\epsilon)\sin(\phi+\delta_f)).$$

  - ☞ In the SM, ϵ and ϕ are small $\Rightarrow$ $R(f) \simeq -2r_f \cos\delta_f$.
  - D. Wang, F. S. Yu, P. F. Guo and H. Y. Jiang, Phys. Rev. D **95**, no. 7, 073007 (2017).

$D^0 - \overline{D}^0$ mixing effect

- $D^0 - \overline{D}^0$ mixing:

$$|D_{H,L}\rangle = p|D^0\rangle \mp q|\overline{D}^0\rangle, \quad \frac{q}{p} = |\frac{q}{p}|e^{i\phi_D},$$

$$\mathcal{A}_{K_S^0} \equiv \mathcal{A}(D^0 \to K_S^0 f_{CP}^0), \quad \overline{\mathcal{A}}_{K_S^0} \equiv \mathcal{A}(\overline{D}^0 \to K_S^0 f_{CP}^0),$$

$$\lambda_{K_S^0} \equiv \frac{q}{p}\frac{\overline{\mathcal{A}}_{K_S^0}}{\mathcal{A}_{K_S^0}}, \quad x_D = \frac{\Delta m_D}{\Gamma_D}, \quad y_D = \frac{\Delta\Gamma_D}{2\Gamma_D}.$$

- The time-integrated decay rates of $D^0 \to K_S^0 f_{CP}^0$ decays:

$$\Gamma(D^0 \to K_S^0 f_{CP}^0) = \int_0^\infty \Gamma(D^0(t) \to K_S^0 f_{CP}^0)dt = |\mathcal{A}_{K_S^0}|^2\Big[1 + \frac{1+|\lambda_{K_S^0}|^2}{2}\frac{y^2}{1-y^2} - \frac{1-|\lambda_{K_S^0}|^2}{2}\frac{x^2}{1+x^2} + Re(\lambda_{K_S^0})\frac{y}{1-y^2} - Im(\lambda_{K_S^0})\frac{x}{1+x^2}\Big],$$

☞ $R(f_{CP}^0) \simeq -2r_{f_{CP}^0}\cos\delta_{f_{CP}^0} + y_D.$ $\qquad y_D \sim \mathcal{O}(10^{-3})$

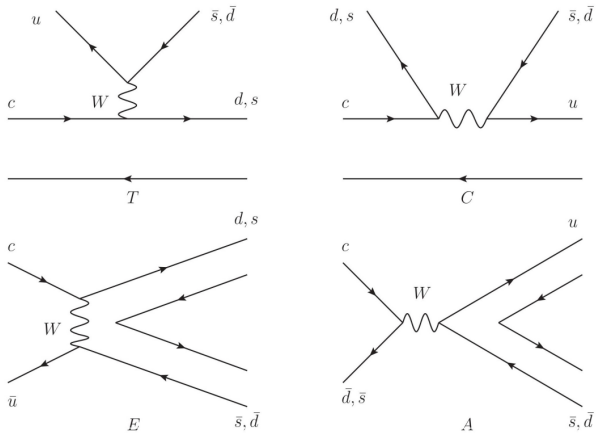
D. Wang, F. S. Yu, P. F. Guo and H. Y. Jiang, Phys. Rev. D **95**, no. 7, 073007 (2017).

The factorization-assisted topological-amplitude approach

- Topological Diagrams:

  T: color-favored tree amplitude
  C: color-suppressed tree amplitude
  E: W-exchange amplitude
  A: W-annihilation amplitude

  Hsiang-nan Li, Cai-Dian Lu, and Fu-Sheng Yu, Phys.Rev D 86, 036012(2012)



- Factorization($D \to PP$ as example):

$$T[C] = \frac{G_f}{\sqrt{2}} V_{CKM} a_1(\mu)[a_2(\mu)] f_{p_2}(m_D^2 - m_{P_1}^2) F_0^{D\to P_1}(m_{P_2}^2),$$

$$E[A] = \frac{G_f}{\sqrt{2}} V_{CKM} b_{q,s}^E(\mu)[b_{q,s}^A(\mu)] f_D m_D^2 (\frac{f_{P_1} f_{P_2}}{f_\pi^2}).$$

$$a_1(\mu) = C_2(\mu) + C_1(\mu)/N_c, \qquad a_2(\mu) = C_1(\mu) + C_2(\mu)[1/N_c + \chi_{nf} e^{i\phi}],$$

$$b_{q,s}^E(\mu) = C_2(\mu)\chi_{q,s}^E e^{i\phi_{q,s}^E}, \qquad b_{q,s}^A(\mu) = C_1(\mu)\chi_{q,s}^A e^{i\phi_{q,s}^A}.$$

Numerical results

- D^0 decays:

$$\frac{\mathcal{A}(D^0 \to K^0 f)}{\mathcal{A}(D^0 \to \overline{K}^0 f)} = \frac{C_{K^0} + E_{K^0}}{C_{\overline{K}^0} + E_{\overline{K}^0}} = \frac{V_{cd}^* V_{us}}{V_{cs}^* V_{ud}}$$

  - ☞ $R(D^0 \to K_{S,L}\pi^0) = R(D^0 \to K_{S,L}\eta^{(\prime)}) = R(D^0 \to K_{S,L}\rho^0) = R(D^0 \to K_{S,L}\omega) = R(D^0 \to K_{S,L}\phi) = 0.113 \pm 0.001.$
  - ☞ $y_D = (0.61 \pm 0.07) \times 10^{-2}$

Y. Amhis *et al.* [Heavy Flavor Averaging Group (HFAG) Collaboration], arXiv:1412.7515 [hep-ex].

- D^+ and D_s^+ decays:

$$R(D^+ \to K_{S,L}^0 \pi^+) = 0.025 \pm 0,008, \quad R(D_s^+ \to K_{S,L}^0 K^+) = 0.012 \pm 0.006,$$
$$R(D^+ \to K_{S,L}^0 \rho^+) = -0.037 \pm 0.011, \quad R(D_s^+ \to K_{S,L}^0 K^{*+}) = -0.070 \pm 0.032.$$

D. Wang, F. S. Yu, P. F. Guo and H. Y. Jiang, Phys. Rev. D **95**, no. 7, 073007 (2017).

Numerical results

Table 1: Numerical results of $K_S^0 - K_L^0$ asymmetries in $D^0 \to K_{S,L}^0 \pi^0$, $D^+ \to K_{S,L}^0 \pi^+$ and $D_s^+ \to K_{S,L}^0 K^+$.

	$R(D^0 \to K_{S,L}^0 \pi^0)$	$R(D^+ \to K_{S,L}^0 \pi^+)$	$R(D_s^+ \to K_{S,L}^0 K^+)$
R(diagram[1])	0.107	-0.005 ± 0.013	-0.002 ± 0.009
R(diagram[2])	0.107	-0.019 ± 0.016	-0.008 ± 0.007
R(QCDF[3])	0.106	-0.010 ± 0.026	-0.008 ± 0.007
$R(SU(3)_F$[4])	$0.09^{+0.04}_{-0.02}$		$0.11^{+0.04}_{-0.14}$
R(exp[5])	$0.108 \pm 0.025 \pm 0.024$	$0.022 \pm 0.016 \pm 0.018$	
R(FAT[6])	0.113 ± 0.001	0.025 ± 0.008	0.012 ± 0.006

- [1]B. Bhattacharya and J. L. Rosner, Phys. Rev. D 81, 014026 (2010).
- [2]H. Y. Cheng and C. W. Chiang, Phys. Rev. D 81, 074021 (2010).
- [3]D. N. Gao, Phys. Rev. D 91, no. 1, 014019 (2015).
- [4]S. Mller, U. Nierste and S. Schacht, Phys. Rev. D 92, no. 1, 014004 (2015).
- [5]Q. He et al. [CLEO Collaboration], Phys. Rev. Lett. 100, 091801 (2008).
- [6]D. Wang, F. S. Yu, P. F. Guo and H. Y. Jiang, Phys. Rev. D **95**, no. 7, 073007 (2017).

Charm baryon decays

- $K_S^0 - K_L^0$ asymmetry in charm baryon decays

$$R(B_c \to BK_{S,L}^0) \equiv \frac{\Gamma(B_c \to BK_S^0) - \Gamma(B_c \to BK_L^0)}{\Gamma(B_c \to BK_S^0) + \Gamma(B_c \to BK_L^0)}$$

  - ☞ $K_S^0 - K_L^0$ asymmetries are proportional to parameter r_f. If there is no DCS amplitudes in some decay modes, $r_f = 0$, $K_S^0 - K_L^0$ asymmetry will be zero.

- We suggest to measure $R(\Lambda_c^+ \to pK_{S,L}^0)$ to search for $\Lambda_c^+ \to pK^0$

  - D. Wang, P. F. Guo, W. H. Long and F. S. Yu, arXiv:1709.09873 [hep-ph].

  - ☞ The branching fraction of $\Lambda_c^+ \to pK_S^0$ has been measured:

$$\mathcal{B}(\Lambda_c^+ \to pK_S^0)_{\text{BESIII}} = (1.52 \pm 0.08 \pm 0.03)\%.$$

  - M. Ablikim *et al.* [BESIII Collaboration], Phys. Rev. Lett. **116**, no. 5, 052001 (2016)

Charm baryon decays

- $R(\Lambda_c^+ \to pK_{S,L}^0)$ is a promising observable to search for the two-body DCS amplitude of charmed baryon decays
  - $\Lambda_c^+ \to$ baryon octet $+$ pseudoscalar meson

$$\Lambda_c^+ \to pK^0, \qquad \Lambda_c^+ \to nK^+$$

  - $\Lambda_c^+ \to$ baryon octet $+$ vector meson

$$\Lambda_c^+ \to pK^{*0}(\to K^+\pi^-), \qquad \Lambda_c^+ \to nK^{*+}(\to K^+\pi^0)$$

  - $\Lambda_c^+ \to$ baryon decuplet $+$ pseudoscalar meson

$$\Lambda_c^+ \to K^0\Delta^+(\to p\pi^0), \qquad \Lambda_c^+ \to K^+\Delta^0(\to p\pi^-)$$

D. Wang, P. F. Guo, W. H. Long and F. S. Yu, arXiv:1709.09873 [hep-ph].

Relation between $K_S^0 - K_L^0$ asymmetry and CP violation

- $K_S^0 - K_L^0$ asymmetry $\quad R(f) \simeq -2r_f \cos\delta_f$
- CP violation in charm decays into neutral kaons ($t_1 \ll \tau_S \ll t_2 \ll \tau_L$)

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

  - F. S. Yu, D. Wang and H. n. Li, arXiv:1707.09297 [hep-ph].

- $D^+ \to \pi^+ K_S^0$ and $D_s^+ \to K^+ K_S^0$ decays

$$\frac{\mathcal{A}(D^+ \to \pi^+ K^0)}{\mathcal{A}(D^+ \to \pi^+ \overline{K}^0)} = \frac{C_{K^0} + A_{K^0}}{T_{\overline{K}^0} + C_{\overline{K}^0}} = r_\pi\, e^{i(\phi+\delta_\pi)}$$

$$\frac{\mathcal{A}(D_s^+ \to K^+ K^0)}{\mathcal{A}(D_s^+ \to K^+ \overline{K}^0)} = \frac{T_{K^0} + C_{K^0}}{C_{\overline{K}^0} + A_{\overline{K}^0}} = r_K\, e^{i(\phi+\delta_K)}$$

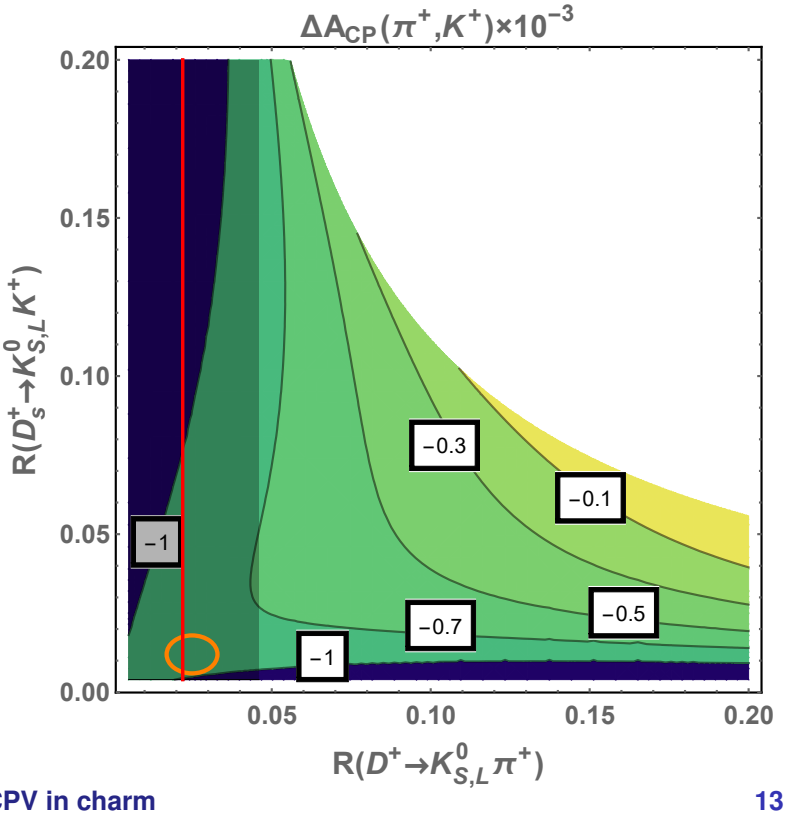
$$\Rightarrow \quad r_K = 1/r_\pi, \quad \delta_K = -\delta_\pi$$

☞ $K_S^0 - K_L^0$ asymmetries and CP violations in D^+ and D_s^+ decays are determined by two parameters under $SU(3)$ symmetry.

Relation between $K_S^0 - K_L^0$ asymmetry and CP violation

- small $K_S^0 - K_L^0$ asymmetry $\Rightarrow$ large strong phase δ_f $\Rightarrow$ large CP violation

  - $\delta_\pi = -1.39 \pm 0.05$, $\delta_K = 1.45 \pm 0.05$
  - $\Delta A_{CP}(\pi^+, K^+) \equiv A_{CP}^{D^+\to K_S^0\pi^+} - A_{CP}^{D_s^+\to K_S^0 K^+} \simeq A_{CP}^{\mathrm{int},D^+\to K_S^0\pi^+} - A_{CP}^{\mathrm{int},D_s^+\to K_S^0 K^+}$
  - $R(\pi^+) \times R(K^+) < 4\tan^4\theta_C$



Summary

- $K_S^0 - K_L^0$ asymmetries in D^0 decays are affected by $D^0 - \overline{D}^0$ mixing
- $K_S^0 - K_L^0$ asymmetry could be used to search for DCS decays of charm baryons.
- The measurement of $K_S^0 - K_L^0$ asymmetry will help us to estimate the CP violation in neutral kaon modes

Summary

- $K_S^0 - K_L^0$ asymmetries in D^0 decays are affected by $D^0 - \overline{D}^0$ mixing
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Thanks for your attention !