CP Asymmetries in Strange and Charm Baryon Decay

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Status and Motivation: history of CPV for K meson

- CP violation (CPV) in $K_L \to \pi^+\pi^-$ 1963, 1964
- Tiny *direct* CPV in $K_L \to \pi^+\pi^-$ vs. $K_L \to \pi^0\pi^0$ 1990, NA31/NA48 and KTeV experiments

- Particle Data Group 2016:

$$|\epsilon_K|_{\rm exp.} = (2.228 \pm 0.011) \cdot 10^{-3}\,,$$
$$\mathrm{Re}(\epsilon'/\epsilon_K)_{\rm exp.} = (1.66 \pm 0.23) \cdot 10^{-3}\,;$$

- Buras et al [*JHEP* 1511 (2015) 202] Standard Model: not produce the exp.data

$$\mathrm{Re}(\epsilon'/\epsilon_K)_{\text{“Buras”}} = (0.86 \pm 0.32) \cdot 10^{-3}\,.$$

- Lattice [N. Garron, *PoS CD* 15 (2016) 034, UKQCD]

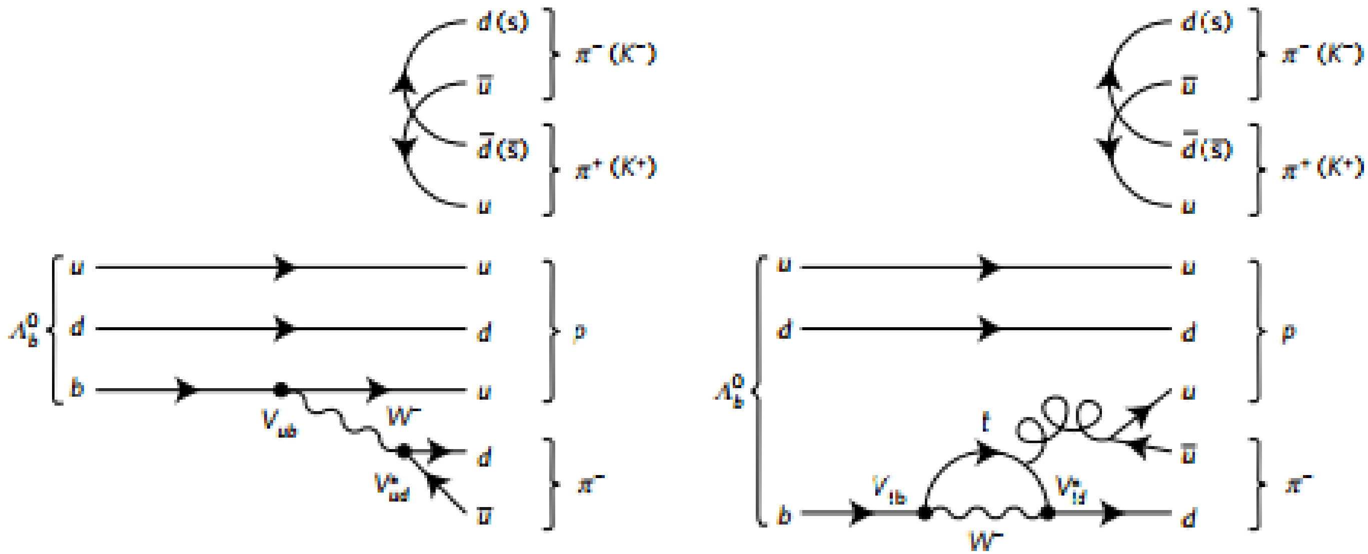
$$\mathrm{Re}(\epsilon'/\epsilon_K)_{\rm LQCD} = (0.138 \pm 0.515 \pm 0.443) \cdot 10^{-3}.$$

These data consistent with SM, or some possible hints of New Dynamics

Status and Motivation: how about baryon?

CPV established in decays of strange & beauty meson, but none for baryons --
except for the only evidence for Λ_b^0[*Nature Physics* **13**, 391–396 (2017)]

experiment at the Large Hadron Collider, we search for CP-violating asymmetries in the decay angle distributions of Λ_b^0 baryons decaying to $p\pi^-\pi^+\pi^-$ and $p\pi^-K^+K^-$ final states. These four-body hadronic decays are a promising place to search for sources of CP violation both within and beyond the standard model of particle physics. We find evidence for CP violation in Λ_b^0 to $p\pi^-\pi^+\pi^-$ decays with a statistical significance corresponding to 3.3 standard deviations including systematic uncertainties. This represents the first evidence for CP violation in the baryon sector.



d (s)
ū
d̄ (s̄)
u
π⁻ (K⁻)
π⁺ (K⁺)
Λb0
u
d
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W⁻
V*ud
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Table 2 | Measurements of *CP*- and *P*-violating observables.

	$a_P^{\hat{T}}$-odd [%]	$a_{CP}^{\hat{T}}$-odd [%]
Scheme A	$\Lambda_b^0 \to p\pi^-\pi^+\pi^-$	
1	21.64 ± 8.28 ± 0.60	−7.69 ± 8.28 ± 0.60
2	−2.04 ± 3.26 ± 0.60	−0.33 ± 3.26 ± 0.60
3	2.03 ± 6.12 ± 0.60	1.94 ± 6.12 ± 0.60
4	−2.45 ± 4.60 ± 0.60	−3.49 ± 4.60 ± 0.60
5	−10.04 ± 4.13 ± 0.60	10.29 ± 4.13 ± 0.60
6	−6.40 ± 5.23 ± 0.60	6.51 ± 5.23 ± 0.60
7	−11.91 ± 5.00 ± 0.60	8.40 ± 5.00 ± 0.60
8	0.94 ± 5.60 ± 0.60	−1.88 ± 5.60 ± 0.60
9	−5.38 ± 4.67 ± 0.60	7.20 ± 4.67 ± 0.60
10	−4.26 ± 4.98 ± 0.60	−11.24 ± 4.98 ± 0.60
11	13.94 ± 7.19 ± 0.60	−2.90 ± 7.19 ± 0.60
12	−7.64 ± 4.79 ± 0.60	−5.35 ± 4.79 ± 0.60
Scheme B		
1	−0.42 ± 4.92 ± 0.60	1.81 ± 4.92 ± 0.60
2	−1.63 ± 4.88 ± 0.60	2.86 ± 4.88 ± 0.60
3	−14.73 ± 5.13 ± 0.60	2.87 ± 5.13 ± 0.60
4	−0.32 ± 4.95 ± 0.60	19.79 ± 4.95 ± 0.60
5	−2.71 ± 5.16 ± 0.60	4.47 ± 5.16 ± 0.60
6	−3.85 ± 4.79 ± 0.60	−7.23 ± 4.79 ± 0.60
7	−14.40 ± 4.65 ± 0.60	−5.44 ± 4.65 ± 0.60
8	−3.75 ± 4.14 ± 0.60	0.76 ± 4.14 ± 0.60
9	−4.16 ± 4.01 ± 0.60	7.74 ± 4.01 ± 0.60
10	4.21 ± 3.84 ± 0.60	−9.16 ± 3.84 ± 0.60
Integrated	−3.71 ± 1.45 ± 0.32	1.15 ± 1.45 ± 0.32
Phase space bin	$\Lambda_b^0 \to p\pi^-K^+K^-$	
1	3.27 ± 6.07 ± 0.66	−4.68 ± 6.07 ± 0.66
2	4.43 ± 6.73 ± 0.66	4.73 ± 6.73 ± 0.66
Integrated	3.62 ± 4.54 ± 0.42	−0.93 ± 4.54 ± 0.42

phase space bins
&
dihedral angle phi bins

Experimental situation of CPV for Λ

based on SM: [Donoghue, Xiao-Gang He, Pakvasa PRD1986]

$$A_{\mathrm{CP}}(\Lambda \to p\pi^-) \sim (0.05 - 1.2) \cdot 10^{-4}$$
$$A_{\mathrm{CP}}(\Xi^- \to \Lambda\pi^-) \sim (0.2 - 3.5) \cdot 10^{-4}$$

combined [Tandeau and Valencia, PRD2003]

$$-0.5 \cdot 10^{-4} \le A_{\Lambda\Xi} \equiv \frac{\alpha_\Lambda \alpha_\Xi - \alpha_{\bar\Lambda} \alpha_{\bar\Xi}}{\alpha_\Lambda \alpha_\Xi + \alpha_{\bar\Lambda} \alpha_{\bar\Xi}} \le 0.5 \cdot 10^{-4}.$$

HyperCP measurement [2004, 2009]:

$$A_{\Lambda\Xi} = (0.0 \pm 5.1 \pm 4.4) \cdot 10^{-4}$$

- The decays of strange baryon are mostly two-body final states

① Rescattering effects are sizable

$$\mathrm{BR}(\Lambda \to p\pi^-) = 0.639 \pm 0.005$$
$$\mathrm{BR}(\Lambda \to n\pi^0) = 0.358 \pm 0.005$$

② The impact of rescattering is not obvious when one does not employ spin

$$\mathrm{BR}(\Sigma^- \to n\pi^-) = (99.848 \pm 0.005) \times 10^{-2}$$

③ Source of strange baryons

$$\mathrm{BR}(J/\psi \to \bar{\Lambda}\Lambda) = (1.61 \pm 0.15) \cdot 10^{-3}$$
$$\mathrm{BR}(J/\psi \to \Lambda\bar{\Lambda}\pi^+\pi^-) = (4.3 \pm 1.0) \cdot 10^{-3}$$
$$\mathrm{BR}(J/\psi \to \bar{p}p) = (2.120 \pm 0.029) \cdot 10^{-3}$$
$$\mathrm{BR}(J/\psi \to \bar{p}p\pi^+\pi^-) = (6.0 \pm 0.5) \cdot 10^{-3}$$

④ CPT invariance tells us

$$A_{\mathrm{CP}}(\Lambda \to p\pi^-) \simeq -A_{\mathrm{CP}}(\Lambda \to n\pi^0)$$
$$A_{\mathrm{CP}}(\Sigma^+ \to p\pi^0) \simeq -A_{\mathrm{CP}}(\Sigma^+ \to n\pi^+).$$

first concentrate on $\Lambda \to p\pi^-$

For a two-body decay, event number is the only observable without spins included. [**production asymmetries not problem for BES and ppbar collider, but do care for LHCb**]

1. A new important era starts with BESIII data and HIEPA, also trigger $J/\psi \to \Lambda\bar{\Lambda}$ studies in LHCb.

   1.3*10^9 Jpsi events has already been accumulated
   10^10 Jpsi events are planned by the end of 2018

2. Next we will point out different paths to find CP asymmetries.

Decay asymmetry parameter

- X,Y spin-1/2 baryon

$$J/\psi \to \bar{Y}Y \to [\bar{X}\bar{\pi}][X\pi]$$

$$\alpha_Y^{(X)} = \langle \vec{\sigma}_Y \cdot (\vec{\sigma}_X \times \vec{\pi}_X) \rangle \,,\; \alpha_{\bar{Y}}^{(\bar{X})} = \langle \vec{\sigma}_{\bar{Y}} \cdot (\vec{\sigma}_{\bar{X}} \times \vec{\pi}_{\bar{X}}) \rangle \,,$$

$$\langle A_{\rm CP}^{(X)} \rangle = \frac{\alpha_Y^{(X)} + \alpha_{\bar{Y}}^{(\bar{X})}}{\alpha_Y^{(X)} - \alpha_{\bar{Y}}^{(\bar{X})}}$$

- Jacob-Wick helicity formalism to make angular analysis, to extract decay parameter α

$$\alpha_{\bar{\Lambda}}^{(\bar{p})} = -0.755 \pm 0.083$$

$$\alpha_{\Lambda}^{(p)} = 0.642 \pm 0.013.$$

- Based on BES2010 data, 10% accuracy -->1% not trivial
- Now we are talking 0.1% sensitivity

T-odd triple-product term

$$C_T = (\vec{p}_X \times \vec{p}_\pi) \cdot \vec{p}_{\bar{X}} \qquad \bar{C}_T = (\vec{p}_{\bar{X}} \times \vec{p}_{\bar{\pi}}) \cdot \vec{p}_X$$

$$\langle A_T \rangle = \frac{N(C_T > 0) - N(C_T < 0)}{N(C_T > 0) + N(C_T < 0)}$$

$$\langle \bar{A}_T \rangle = \frac{N(\bar{C}_T > 0) - N(\bar{C}_T < 0)}{N(\bar{C}_T > 0) + N(\bar{C}_T < 0)} .$$

N is the event number

Thus

$$\mathcal{A}_T = \frac{1}{2}\left[\langle A_T \rangle + \langle \bar{A}_T \rangle\right] = \langle A_T \rangle \neq 0$$

← CPV observable

$$\mathcal{A}_T(d) = \frac{N(C_T > |d|) - N(C_T < -|d|)}{N(C_T > |d|) + N(C_T < -|d|)}$$

← Second step

1. Fake CP asymmetry due to final state interaction
2. The charge conjugate of this channel is itself, defferent for $D^0(\bar{D}^0) \to K\bar{K}\pi\pi/4\pi.$

Here it is untagged sample!

Sensitivity study

Channel	# of events	Sensitivity on $\mathcal{A}_T$
$J/\psi \to \Lambda\bar{\Lambda} \to [p\pi^-][\bar{p}\pi^+]$	2.6×10^6	0.06%
$J/\psi \to \Sigma^+\bar{\Sigma}^- \to [p\pi^0][\bar{p}\pi^0]$	2.5×10^6	0.06%
$J/\psi \to \Xi^0\bar{\Xi}^0 \to [\Lambda\pi^-][\bar{\Lambda}\pi^+]$	1.1×10^6	0.1%
$J/\psi \to \Xi^-\bar{\Xi}^+ \to [\Lambda\pi^0][\bar{\Lambda}\pi^0]$	1.6×10^6	0.08%

TABLE I. The numbers of reconstructed events after considering decay branching fractions, tracking, and particle identification. The sensitivity is estimated without considering possible background dilutions, which should be small at the BESIII experiment. Estimations are based on the 10^{10} J/ψ data which will be collected by the BESIII collaboration by the end of 2018 (and the branching fractions from PDG2016). Systematic uncertainties are expected to be of the same order as the statistical uncertainties shown in the table.

Subtleties

- If there is polarized baryon source, $\Xi^0 \to \Lambda\pi \to (p\pi)\pi$, one may construct more observables from helicity amplitudes, angular analysis [Kang, Li, Lu, A.Datta 2011]
- Quark-hadron duality, in particular, close to thresholds

$J/\psi \to \bar{\Sigma}^- \Sigma^+ \to [\bar{p}\pi^0][p\pi^0]$, $\Delta(1232)\bar{\Delta}(1232)$ as backgrounds,

$M(\Sigma^+) \cong 1189\ \mathrm{MeV}$ $M(\Delta(1232)) \cong 1232\ \mathrm{MeV}$ with width 117MeV,

BES backgounds small <= second vertex technique

- Another challenge $J/\psi \to \bar{\Xi}^+ \Xi^- \to \bar{\Lambda}\pi^+ \Lambda\pi^-$, the source of CPV come from: $\Xi \to \Lambda\pi$ or $\Lambda \to p\pi^-$ or their interference

"Accuracy" will improve a lot, also super tau-charm factory?

Charm baryon decay

$$\Lambda_c^+ \to pK^-\pi^+\pi^0 / \Lambda\pi^+\pi^+\pi^- / pK_S\pi^+\pi^-$$

$$\mathrm{BR}(\Lambda_c^+ \to pK^-\pi^+\pi^0) \simeq 4.4\,\% \;,\; \mathrm{BR}(\Lambda_c^+ \to \Lambda\pi^+\pi^+\pi^-) \simeq 3.6\,\% \;,\; \mathrm{BR}(\Lambda_c^+ \to pK_S\pi^+\pi^-) \simeq 1.6\,\%^{\dagger}$$

Not only two-body final state, but also three-body with Dalitz plot.

Crucial information are given there about fundamental dynamics, not as a "background" for two-body FS.

SM predicts CPV for the 3rd channel about 3.3×10^{-3} due to $K^0-\overline{K}^0$ oscillation

Cabibbo favoured?

CPV with decay asymmetry parameter:
FOCUS Colla. PLB 634, 165 (2006)
CLEO Colla. PRL 94, 191801 (2005)

A model calculation for singly Cabibbo-suppressed, see Cheng, Kang, Xu PRD2018

Absolute BR measurement, BES Colla. PRL 115, 221805 (2015)

Lessons

One has to be realistic: very likely we will not find CPV in these weak decays of Λ_c^+

Yet it is *not* a waste of time:

(a) It is not a miracle to find CPV in Cabibbo suppressed decays of Λ_c^+ yet it is crucial to calibrate such transitions with Cabibbo favored ones with more data & analyses about four-body FS.

(b) We can expect sizable PV in the weak decay of Λ_c^+.

(c) At least, one can get novel lessons about the impact of strong forces close to thresholds, namely about non-perturbative QCD.

Beam constrained mass distribution

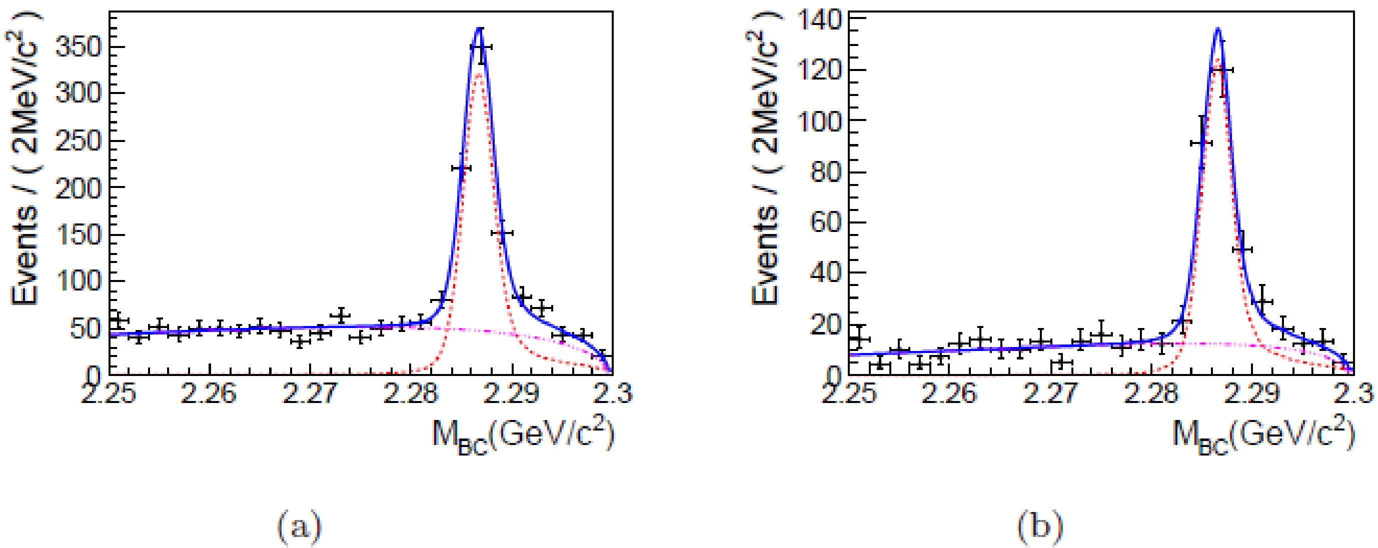

Fig. 1. M_{BC} distribution of (a) $\Lambda_c^+ \to pK^-\pi^+\pi^0$ and (b) $\Lambda_c^+ \to \Lambda\pi^+\pi^+\pi^-$, bar are MC simulation. The blue solid curves are the sum of fit funtions, wh represent the backgrounds (signals).

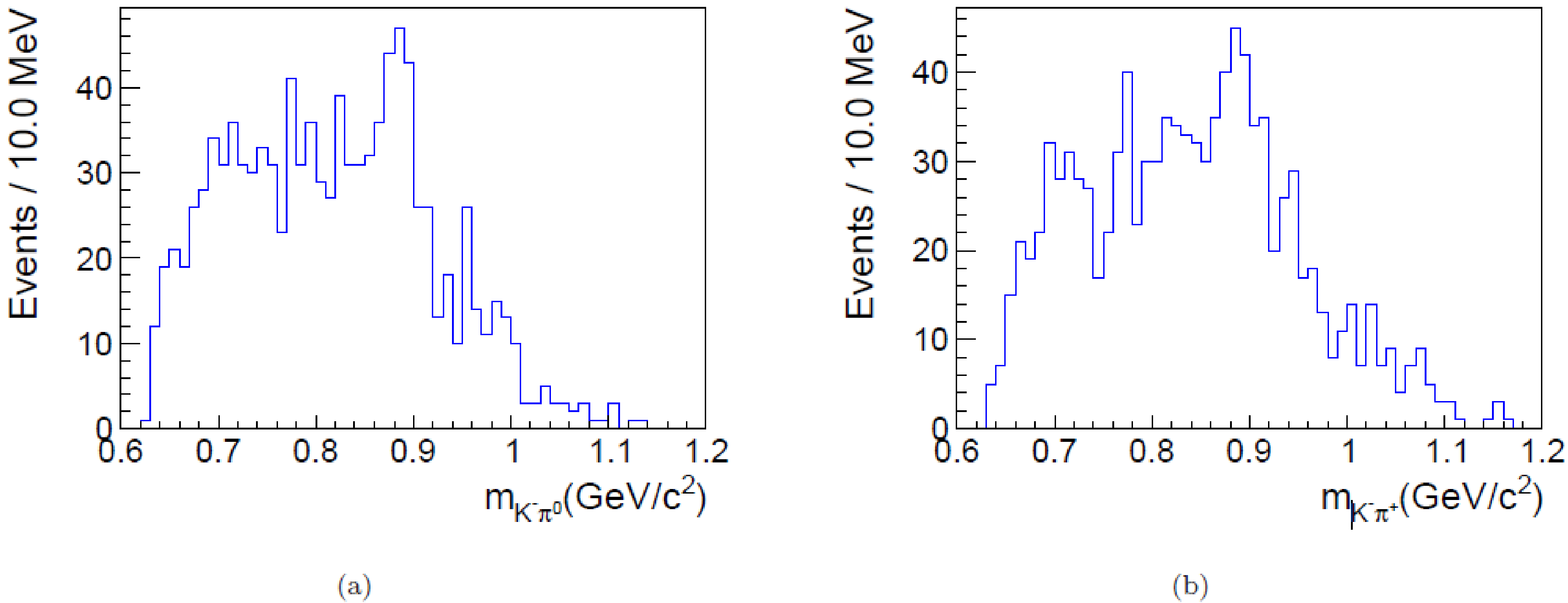

Fig. 2. The result of MC simulation for the invariant mass distribution of $K^-\pi^0$ (a) and $K^-\pi^+$ (b) for $\Lambda_c^+ \to pK^-\pi^+\pi^0$, where the impact of $K^*(892)$ is shown.

MC study

Direct CPV			
channel	1x	10x	1000x
$\Lambda_c^+ \to pK^-\pi^+\pi^0$	$\cdots \pm 0.227$	$\cdots \pm 0.072$	$\cdots \pm 0.0072$
$\Lambda_c^+ \to \Lambda\pi^+\pi^+\pi^-$	$\cdots \pm 0.479$	$\cdots \pm 0.143$	$\cdots \pm 0.0143$
$\Lambda_c^+ \to pK_S^0\pi^+\pi^-$	$\cdots \pm 0.251$	$\cdots \pm 0.076$	$\cdots \pm 0.0077$

$a_{\rm P}$ and δ_{CP}			
channel	1x	10x	1000x
$\Lambda_c^+ \to pK^-\pi^+\pi^0$	$\cdots \pm 0.231$	$\cdots \pm 0.073$	$\cdots \pm 0.0073$
$\Lambda_c^+ \to \Lambda\pi^+\pi^+\pi^-$	$\cdots \pm 0.459$	$\cdots \pm 0.142$	$\cdots \pm 0.0143$
$\Lambda_c^+ \to pK_S^0\pi^+\pi^-$	$\cdots \pm 0.253$	$\cdots \pm 0.077$	$\cdots \pm 0.0076$

$$a_{\rm P} \equiv \frac{1}{2}(A_{\rm T-odd} + \bar{A}_{\rm T-odd}) \neq 0$$

$$\delta_{\rm CP} \equiv \frac{1}{2}(A_{\rm T-odd} - \bar{A}_{\rm T-odd}) \neq 0$$

$a_{\rm P}$ and δ_{CP}			
	1x	10x	1000x
bin1	$\cdots \pm 0.529$	$\cdots \pm 0.160$	$\cdots \pm 0.0158$
bin2	$\cdots \pm 0.562$	$\cdots \pm 0.185$	$\cdots \pm 0.0185$
bin3	$\cdots \pm 0.294$	$\cdots \pm 0.095$	$\cdots \pm 0.0093$

1x: current data sample at BESIII
10x: finally planned
1000x: corresponding to HIEPA

Triple Product Asymmetry and direct CPV

Similarity

(1) comparing a signal in a given decay with the corresponding signal in the CP-transformed process

(2) needs "interference"

Difference

$$\mathcal{A}_{CP}^{dir} \propto \sin\phi \sin\delta \;,$$

ϕ Weak CP violating phase

$$\mathcal{A}_{T} \propto \sin\phi \cos\delta \;.$$

δ Strong CP-conserving phase

(1) a non-zero direct CP asymmetry only if there is a nonzero strong-phase difference between the two decay amplitudes

(2)TP asymmetries are maximal when the strong-phase difference vanishes

- Higgs boson, searching for 40 years
- *It is not trivial at all, but as usual, there is a price for the prize!*
- HIEPA provides huge data sample, thus huge opportunity