# CP ASYMMETRIES IN CHARM

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# STATUS AND MOTIVATION

- 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:

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

- 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]

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

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

- CP violation (CPV) established in decays of strange & beauty meson, but how for charm meson, strange and charm baryon?

*"It is not trivial at all; as usual there is a price for a prize"*

---- from I.I. Bigi

LHCb $\Lambda_b^{+} \rightarrow p\pi^{-}\pi^{+}\pi^{-}$ Nature Physics 13, 391 (2017)

Standard Model of particle physics. We find evidence for *CP* violation in $\Lambda_b^0$ 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.

Triple product asymmetry, local CPV

# OUTLINE

- CP violation in D->VV

  Xian-Wei Kang and Hai-Bo Li, Phys.Lett.B 2010

- CP violation in strange baryon

  I.I.Bigi, Xian-Wei Kang, Hai-Bo Li  Chin.Phys.C 2018

- CP violation in $\Lambda_c^+$ decay

  Xian-Wei Kang, Hai-Bo Li, Gong-Ru Lu and A. Datta,  Int.J.Mod.A 2011

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# TRIPLE PRODUCT (TP)

$$\vec{v}_1 \cdot (\vec{v}_2 \times \vec{v}_3)$$

$\vec{v}$ can be a three-momentum or spin vector

$\vec{v}$ changes sign under time-reversal (T) operation

Existence of such term indicate a CP violating signal assuming CPT invariance?

*Not yet, one should compare to CP-conjugate channel to eliminate the fake CP asymmetry*

# $D(p) \to V_1(k,\varepsilon_1)V_2(q,\varepsilon_2)$

Momentum p, k, q, and polarization tensor $\varepsilon$

$$\begin{aligned}\mathcal{M} &\equiv as + bd + icp \\ &= a\epsilon_1^* \cdot \epsilon_2^* + \frac{b}{m_1 m_2}(p\cdot\epsilon_1^*)(p\cdot\epsilon_2^*) \\ &\quad + i\frac{c}{m_1 m_2}\epsilon^{\alpha\beta\gamma\delta}\epsilon_{1\alpha}^*\epsilon_{2\beta}^* k_\gamma p_\delta\,,\end{aligned}$$

$$\begin{aligned}a &= \sum_j a_j e^{i\delta_{sj}} e^{i\phi_{sj}}\,, \\ b &= \sum_j b_j e^{i\delta_{dj}} e^{i\phi_{dj}}\,, \\ c &= \sum_j c_j e^{i\delta_{pj}} e^{i\phi_{pj}}\,,\end{aligned}$$

$\phi$ Weak CP violating phase

$\delta$ Strong CP-conserving phase

$$\begin{aligned}|\mathcal{M}|^2 &= |a|^2|\epsilon_1^*\cdot\epsilon_2^*|^2 + \frac{|b|^2}{m_1^2 m_2^2}|(k\cdot\epsilon_2^*)(q\cdot\epsilon_1^*)|^2 + \frac{|c|^2}{m_1^2 m_2^2}|\epsilon^{\alpha\beta\gamma\delta}\epsilon_{1\alpha}^*\epsilon_{2\beta}^* k_\gamma p_\delta|^2 + 2\frac{Re(ab^*)}{m_1 m_2}(\epsilon_1^*\cdot\epsilon_2^*)(k\cdot\epsilon_2^*)(q\cdot\epsilon_1^*) \\ &\quad + 2\frac{Im(ac^*)}{m_1 m_2}(\epsilon_1^*\cdot\epsilon_2^*)\epsilon^{\alpha\beta\gamma\delta}\epsilon_{1\alpha}^*\epsilon_{2\beta}^* k_\gamma p_\delta + 2\frac{Im(bc^*)}{m_1^2 m_2^2}(k\cdot\epsilon_2^*)(q\cdot\epsilon_1^*)\epsilon^{\alpha\beta\gamma\delta}\epsilon_{1\alpha}^*\epsilon_{2\beta}^* k_\gamma p_\delta\,.\end{aligned}$$

In rest frame $\varepsilon^{\alpha\beta\gamma\delta}\varepsilon^{*}_{1\alpha}\varepsilon^{*}_{2\beta}k_{\gamma}p_{\delta} \rightarrow (\vec{\varepsilon}_1^{\,*} \times \vec{\varepsilon}_2^{\,*}) \cdot \vec{k}$
just triple product term

$$A_T \propto Im(ac^*) = \sum_{i,j} a_i c_j \sin[(\phi_{si} - \phi_{pj}) + (\delta_{si} - \delta_{pj})]$$

fake CP asymmetry due to the strong phase $\delta$ , i.e., nonzero $A_T$ even for vanishing weak phase $\phi$

$$\bar{a} = \sum_j a_j e^{i\delta_{sj}} e^{-i\phi_{sj}} ,$$

$$\bar{b} = \sum_j b_j e^{i\delta_{dj}} e^{-i\phi_{dj}} ,$$

$$\bar{c} = \sum_j c_j e^{i\delta_{pj}} e^{-i\phi_{pj}} .$$

Conjugate channel, weak phase changes sign

$$\frac{1}{2}(A_T + \bar{A}_T) \propto \frac{1}{2}[Im(ac^*) - Im(\bar{a}\bar{c}^*)] = \sum_{i,j} a_i c_j \sin(\phi_{si} - \phi_{pj}) \cos(\delta_{si} - \delta_{pj}) ,$$

$\phi = 0 \Rightarrow A_T + \overline{A}_T = 0$

A true CP-violating observable !

# 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

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

$$\mathcal{A}_T \propto \sin\phi \cos\delta \ .$$

(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

# OBSERVABLE

$$\mathrm{Im}(ac^*) \sim \mathrm{Im}(A_\perp A_0^*) \Rightarrow$$

$$\mathcal{A} = \frac{1}{2}(\mathcal{A}_T{}^0 + \bar{\mathcal{A}}_T{}^0) \tag{18}$$

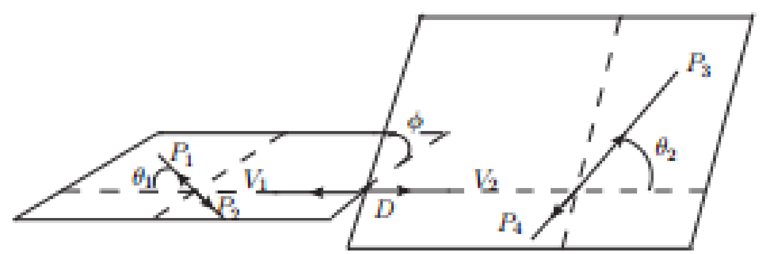
$$= \frac{1}{2}\left(\frac{Im(A_\perp A_0^*)}{|A_0|^2 + |A_\perp|^2 + |A_{||}|^2} + \frac{Im(\bar{A}_\perp \bar{A}_0^*)}{|\bar{A}_0|^2 + |\bar{A}_\perp|^2 + |\bar{A}_{||}|^2}\right),$$

These quantities can be accessed by a full angular analysis ---- based on the helicity formalism

Cornerstone ref. Jacob and Wick, Annals Phys.281,774(2000)

Amplitude for A->BC

$$\mathcal{M} = D^{J_A}_{M_A,\lambda_B-\lambda_C}(\varphi,\vartheta,-\varphi)A_{\lambda_B,\lambda_C}$$




$$\frac{d\Gamma}{d\cos\theta_1 d\cos\theta_2 d\phi} \propto \frac{1}{2}\sin^2\theta_1\sin^2\theta_2\cos^2\phi|A_{||}|^2 + \frac{1}{2}\sin^2\theta_1\sin^2\theta_2\sin^2\phi|A_\perp|^2 + \cos^2\theta_1\cos^2\theta_2|A_0|^2$$

$$-\frac{1}{2}\sin^2\theta_1\sin^2\theta_2\sin 2\phi Im(A_\perp A_{||}^*) - \frac{\sqrt{2}}{4}\sin 2\theta_1\sin 2\theta_2\cos\phi Re(A_{||}A_0^*) + \frac{\sqrt{2}}{4}\sin 2\theta_1\sin 2\theta_2\sin\phi Im(A_\perp A_0^*)$$

# EXPECTED SENSITIVITY

| $VV$ | Br (%) | Eff. ($\epsilon$) | Expected errors |
|---|---|---|---|
| $\rho^0\rho^0 \to (\pi^+\pi^-)(\pi^+\pi^-)$ | 0.18 | 0.74 | 0.004 |
| $\bar{K}^{*0}\rho^0 \to (K^-\pi^+)(\pi^+\pi^-)$ | 1.08 | 0.68 | 0.002 |
| $\rho^0\phi \to (\pi^+\pi^-)(K^+K^-)$ | 0.14 | 0.26 | 0.006 |
| $\rho^+\rho^- \to (\pi^+\pi^0)(\pi^-\pi^0)$ | 0.6* | 0.55 | 0.002 |
| $K^{*+}K^{*-} \to (K^+\pi^0)(K^-\pi^0)$ | 0.08* | 0.55 | 0.006 |
| $K^{*0}\bar{K}^{*0} \to (K^+\pi^-)(K^-\pi^+)$ | 0.048 | 0.62 | 0.002 |
| $\bar{K}^{*0}\rho^+ \to (K^-\pi^+)(\pi^+\pi^0)$ | 1.33 | 0.59 | 0.001 |

20 $\mathrm{fb}^{-1}$ data at $\psi(3770)$ peak at BESIII

Only statistical error. Assuming the systematic error is of the same order, reaching the accuracy of 0.01

Cited by BaBar collaboration.

# AVAILABLE MEASUREMENT: FOCUS 2005

Phys.Lett.B 622 (2005) 239

$$C_T \equiv \vec{p}_{K^+} \cdot (\vec{p}_{\pi^+} \times \vec{p}_{\pi^-}) \qquad \overline{C_T} \equiv \vec{p}_{K^-} \cdot (\vec{p}_{\pi^-} \times \vec{p}_{\pi^+}).$$

$$A_T = \frac{\Gamma(C_T > 0) - \Gamma(C_T < 0)}{\Gamma(C_T > 0) + \Gamma(C_T < 0)} \qquad \overline{A_T} = \frac{\Gamma(-\overline{C_T} > 0) - \Gamma(-\overline{C_T} < 0)}{\Gamma(-\overline{C_T} > 0) + \Gamma(-\overline{C_T} < 0)}.$$

$$A_{\text{Tviol}} = \frac{1}{2}(A_T - \overline{A_T}) =$$

| Decay mode | $A(\%)$ |
|---|---|
| $D^0 \to K^+K^-\pi^+\pi^-$ | $1.0 \pm 5.7 \pm 3.7$ |
| $D^+ \to K_S K^+\pi^+\pi^-$ | $2.3 \pm 6.2 \pm 2.2$ |
| $D_S^+ \to K_S K^+\pi^+\pi^-$ | $-3.6 \pm 6.7 \pm 2.3$ |

1. An example, there may be update or measurements of other channels
2. Measure the asymmetry by counting event numbers. Our proposals certainly go beyond it: accessing the angular information
3. The sensitivities for BESIII are improved a lot, level of 0.001-0.1

# CP MEASUREMENT IN STRANGE BARYON

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

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

combined [Tandeau and Valencia, PRD2003]

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

HyperCP measurement [2004, 2009]:

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

A new important era starts with BESIII data by the end of 2018, also trigger $J/\psi \to \Lambda\bar{\Lambda}$ studies in LHCb.

$1.3\times10^9\ J/\psi$ events has already been accumulated

$10^{10}\ J/\psi$ events are planned by the end of 2018

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

- 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 $p\bar{p}$ collider, but do care for LHCb]

# DECAY PARAMETER ASYMMETRY

- X,Y are spin-1/2 baryons $J/\psi \to \bar{Y}Y \to [\bar{X}\bar{\pi}][X\pi]$

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

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

- Jacob-Wick helicity formalism to make angular analysis, to extract decay parameter $\alpha$

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

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

- Based on BES2010 data, 10% accuracy -->1% not trivial
- Now we are talking 0.1% sensitivity by the end of 2018
- Higgs boson, searching for 40 years

# T-ODD TRIPLE-PRODUCT TERM

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

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

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

N is the event number

Thus

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

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, different for $D^0(\overline{D}^0) \to K\overline{K}\pi\pi / 4\pi$ *Here it is untagged sample!*

# SENSITIVITY STUDY

| Channel | # of events | Sensitivity on $\mathcal{A}_T$ |
|---|---|---|
| $J/\psi \to \Lambda\bar{\Lambda} \to [p\pi^-][\bar{p}\pi^+]$ | $2.6 \times 10^6$ | 0.06% |
| $J/\psi \to \Sigma^+\bar{\Sigma}^- \to [p\pi^0][\bar{p}\pi^0]$ | $2.5 \times 10^6$ | 0.06% |
| $J/\psi \to \Xi^0\bar{\Xi}^0 \to [\Lambda\pi^-][\bar{\Lambda}\pi^+]$ | $1.1 \times 10^6$ | 0.1% |
| $J/\psi \to \Xi^-\bar{\Xi}^+ \to [\Lambda\pi^0][\bar{\Lambda}\pi^0]$ | $1.6 \times 10^6$ | 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 $10^{10}$ $J/\psi$ 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 $J/\psi \to \overline{\Sigma}^- \Sigma^+ \to [\overline{p}\pi^0][p\pi^0]$, $\Delta(1232)\overline{\Delta}(1232)$ as backgrounds.

  $M(\Sigma^+) \simeq 1189\,MeV \quad M(\Delta(1232)) \simeq 1232\,MeV$ and width 117MeV,

  *BES backgrounds small <= second vertex technique*
- Another challenge for $J/\psi \to \Xi^+\Xi^- \to [\overline{\Lambda}\pi^+][\Lambda\pi^-]$

  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?

# CHARMED BARYON $\Lambda_c^+ \to BP$ and $\Lambda_c^+ \to BV$

B: Spin-1/2 baryon, P: pseudoscalar, V: Vector $\Lambda_c^+ \to \Lambda\pi^+, \Lambda_c^+ \to \Lambda\rho^+$

1. The strong scattering phases between $\Lambda$ and $\pi$ are small, measuring TP asymmetry is favored

S-wave $\delta_0 \leq -3.4^\circ$, P-wave $\delta_1 \simeq -0.05^\circ$

2 $\mathcal{M}_P \equiv A(\Lambda_c^+ \to BP) = \bar{u}_B(a + b\gamma_5)u_{\Lambda_c},$

In the amplitude squared $-2Im(ab^*)\epsilon_{\mu\nu\rho\sigma}p_B^\mu s_B^\nu p_{\Lambda_c}^\rho s_{\Lambda_c}^\sigma$

$\mathrm{Im}(ab^*) \sim \mathrm{Im}(A_{1/2,0}A^*_{-1/2,0})$ Angular analysis

Caveat: measurement of spin, challenge to BES

3. As a first step, following LHCb paper, measuring local CPV for a four-body decay phase space bins and dihedral angle phi bins

- New Physics (NP) can predict large CPV, do not always be so pessimistic

Using a two-Higgs doublet model (2HDM)

$$H_{eff}^{NP} = \frac{G_F}{\sqrt{2}} \frac{y_s y_d}{g^2} \frac{2M_W^2}{m_{H_+}^2} \bar{s}(1-\gamma_5) c \bar{u}(1+\gamma_5) d,$$

$$A(\Lambda_c^+ \to \Lambda\pi) = \bar{u}_\Lambda \left[ a_{SM}(1+r_a) + b_{SM}(1+r_b)\gamma_5 \right] u_{\Lambda_c}$$

$$r_b = -r_a = r$$

$$r = e^{i\phi} \frac{|y_s y_d|}{a_1 V_{cs} V_{ud} g^2} \frac{2M_W^2}{m_{H_+}^2} \frac{m_\pi^2}{(m_u + m_d) m_c},$$

r signifies the deviation from Standard Model $r \approx 0.14 e^{i\tilde{\phi}}$

$\tilde{\phi}$ is the NP CP-violating phase

$$\text{TP asymmetry} \sim 0.14 \sin\tilde{\phi}$$

# SUMMARY

- Two points

(1) The advantage of triple product asymmetry in the case of vanishing strong phase

(2) One need to compare to the CP conjugate process to get a true CP violating observable

- Three channels

$$D \to VV$$
$$J/\psi \to \Lambda\overline{\Lambda} \to [p\pi^-][\overline{p}\pi^+]$$
$$\Lambda_c^+ \to \Lambda\pi^+, \Lambda\rho^+$$

For the 3rd channel, one needs the information of spin, challenge
As a first step, again, triple product involving three momenta for a four-body decay

*Note added*: we also propose to use $\psi(3770) \to \mathrm{D}\overline{\mathrm{D}} \to (\mathrm{VV})(\mathrm{VV})$ to measure new CPV observables; $\psi(3770) \to \mathrm{D}\overline{\mathrm{D}} \to (\mathrm{VV})(\mathrm{K}\pi)$ to measure strong K pi phase

[Ref: Charles, Descotes-Genon, Xian-Wei Kang, Hai-Bo Li, and Gong-Ru Lu, PRD2010]