*CP*As corresponding to the imaginary parts of the interference terms in cascade decays of heavy hadrons

张振华
南华大学
email: zhenhua_zhang@163.com
Based on 2407.20586
In collaboration with 祁敬娟 杨建宇

第二十一届全国重味物理和CP破坏研讨会
2024.10.25-10.29 湖南 衡阳

1. background and motivation

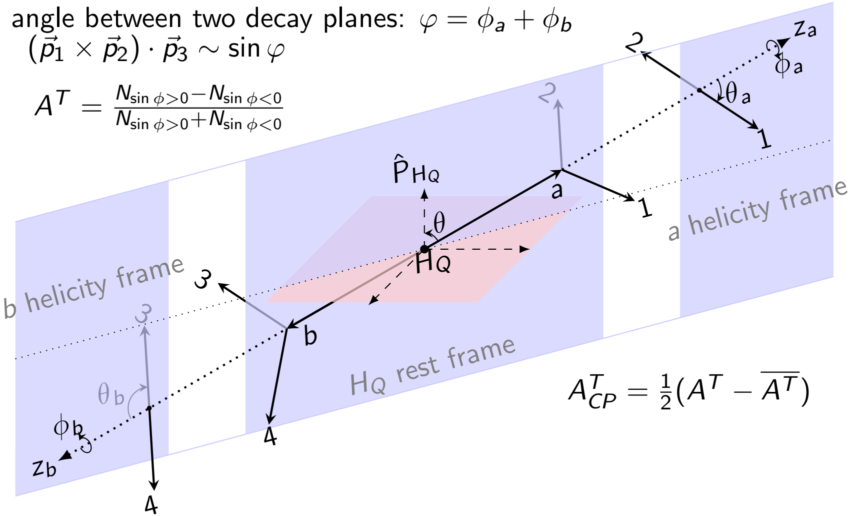
CPV induced by TPA in four-body decays

Triple-Product Asymmetry A^T (see Long-Ke Li's talk)

angle between two decay planes: $\varphi = \phi_a + \phi_b$

$(\vec{p}_1 \times \vec{p}_2) \cdot \vec{p}_3 \sim \sin\varphi$

$$A^T = \frac{N_{\sin\phi>0} - N_{\sin\phi<0}}{N_{\sin\phi>0} + N_{\sin\phi<0}}$$



$$A^T_{CP} = \frac{1}{2}(A^T - \overline{A^T})$$

CPV induced by TPA in four-body decays

TPA induced CP asymmetries

TP-CPA is proportional to the cosine of a strong phase δ:

$$\Im(ab^*) - \Im(\overline{a}\overline{b}^*) \sim \sin\phi_{\text{weak}}\cos\delta,$$

Why?

$$\mathcal{A} = \sum_k A_k$$

$$|\mathcal{A}|^2 \sim \Re(A_k A_{k'}^*)$$

$$A_{CP} \sim \Re(A_k A_{k'}^*) - \Re(\overline{A_k}\ \overline{A_{k'}}^*) \sim \sin\phi_{\text{weak}}\sin\delta$$

$$\mathcal{A} = \sum_m A_m e^{im\varphi}$$

$$|\mathcal{A}|^2 \sim \Re(A_m A_{m'}^* e^{i(m-m')\varphi}) \sim \Re(A_m A_{m'}^*)\cos[(m-m')\varphi] + \Im(A_m A_{m'}^*)\sin[(m-m')\varphi]$$

CPV induced by TPA in four-body decays

TP-CPA searching

- $D^0 \to K^+K^-\pi^+\pi^-$, $D^+ \to K^+K^-\pi^+\pi^0$, $D^+_{(s)} \to K^+K^-\pi^+\pi^0$, $D^+_{(s)} \to K^+\pi^-\pi^+\pi^0$, $D^0 \to K^0_S K^0_S \pi^+\pi^-$, $\Lambda^0_b \to pK^-\pi^+\pi^-$, $\Lambda^0_b \to pK^-K^+K^-$, $\Xi^0_b \to pK^-K^-\pi^+$
- $\Lambda^0_b \to p\pi^-\pi^+\pi^-$: $a_P^{\hat{T}-\text{odd}} = (-4.0 \pm 0.7 \pm 0.2)\%$.
- TPA induces CP asymmetry (TP-CPA) has never been observed yet.

general consideration

$$\mathcal{A} = \sum_m A_m e^{im\varphi} \qquad\qquad \mathcal{A} = \sum_k a_k b_k$$

$$\begin{aligned} |\mathcal{A}|^2 &\sim \Re(A_m A_{m'}^* e^{i(m-m')\varphi}) \\ &\sim \Re(A_m A_{m'}^*)\cos[(m-m')\varphi] \\ &\quad +\Im(A_m A_{m'}^*)\sin[(m-m')\varphi] \end{aligned}$$

$$\begin{aligned} |\mathcal{A}|^2 &\sim \Re[(a_k b_k)(a_{k'}^* b_{k'}^*)] \\ &\sim \Re(a_k a_{k'}^*)\Re(b_k b_{k'}^*) \\ &\quad +\Im(a_k a_{k'}^*)\Im(b_k b_{k'}^*) \end{aligned}$$

non-zero $\Im(b_k b_{k'}^*)$ provides opportunities for CPA corresponding to $\Im(a_k a_{k'}^*)$.

2 interference of resonances in cascade decays

three-body cascade decay $\mathbb{H} \to rc$, $r \to ab$

$$\mathcal{M} = \sum_r \frac{\mathcal{A}_r}{s_r}, \qquad s_r = s - m_r^2 + \mathrm{i} m_r \Gamma_r$$

decay amplitude squared

$$\overline{|\mathcal{M}|^2} \approx \frac{|\mathcal{A}_1|^2}{|s_1|^2} + \frac{|\mathcal{A}_2|^2}{|s_2|^2} + 2\Re\left(\frac{\mathcal{A}_1 \mathcal{A}_2^*}{s_1 s_2^*}\right),$$

The interfering term

$$\Re\left(\frac{\mathcal{A}_1 \mathcal{A}_2^*}{s_1 s_2^*}\right) = \frac{\Re\left(\mathcal{A}_1 \mathcal{A}_2^*\right) \Re\left(s_1 s_2^*\right) + \Im\left(\mathcal{A}_1 \mathcal{A}_2^*\right) \Im\left(s_1 s_2^*\right)}{|s_1 s_2|^2}.$$

The interfering term

$$\Re\left(\frac{\mathcal{A}_1\mathcal{A}_2^*}{s_1 s_2^*}\right) = \frac{\Re\left(\mathcal{A}_1\mathcal{A}_2^*\right)\Re\left(s_1 s_2^*\right) + \Im\left(\mathcal{A}_1\mathcal{A}_2^*\right)\Im\left(s_1 s_2^*\right)}{\left|s_1 s_2\right|^2}.$$

$$\Re\left(s_1 s_2^*\right) = m_1\Gamma_1 m_2\Gamma_2 + \left(s - m_1^2\right)\left(s - m_2^2\right)$$

$$\begin{aligned}\Im\left(s_1 s_2^*\right) &= \left(s - m_2^2\right) m_1\Gamma_1 - \left(s - m_1^2\right) m_2\Gamma_2 \\ &= m_1\Gamma_1\left(1 - \frac{m_2\Gamma_2}{m_1\Gamma_1}\right)\left(s - {m_2'}^2\right)\end{aligned}$$

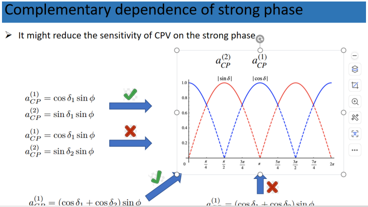
where $m_2' = m_2\sqrt{(1 - \frac{m_1\Gamma_2}{m_2\Gamma_1})/(1 - \frac{m_2\Gamma_2}{m_1\Gamma_1})}$.
Now the difference between the behaviour of $\Re\left(s_1 s_2^*\right)$ and $\Im\left(s_1 s_2^*\right)$ is obvious: while the latter tends to change sign as s passes through ${m_2'}^2$, the former does not.

a pair of CPV observables

$$A_{CP} \equiv \frac{\int_{m_2'^2-\Delta_-}^{m_2'^2+\Delta_+}\left(\overline{|\mathcal{M}|^2}-\overline{|\overline{\mathcal{M}}|^2}\right)ds}{\int_{m_2'^2-\Delta_-}^{m_2'^2+\Delta_+}\left(\overline{|\mathcal{M}|^2}+\overline{|\overline{\mathcal{M}}|^2}\right)ds} \sim \sin\delta \quad \text{contribution mainly from } \Re\left(\mathcal{A}_1\mathcal{A}_2^*\right)$$

$$A_{CP}^{\Im} \equiv \frac{\int_{m_2'^2-\Delta_-}^{m_2'^2+\Delta_+}\left(\overline{|\mathcal{M}|^2}-\overline{|\overline{\mathcal{M}}|^2}\right)\ \mathrm{sgn}\left(s-m_2'^2\right)ds}{\int_{m_2'^2-\Delta_-}^{m_2'^2+\Delta_+}\left(\overline{|\mathcal{M}|^2}+\overline{|\overline{\mathcal{M}}|^2}\right)ds} \sim \cos\delta \quad \text{mainly } \Im\left(\mathcal{A}_1\mathcal{A}_2^*\right)$$

From Jian-Peng Wang's slides in 2023

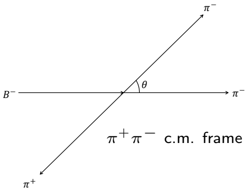


$$\mathrm{sgn}(x) = \begin{cases} +1, & x > 0; \\ -1, & x < 0. \end{cases}$$

3 Forward-Bacward Asymmetry induced CPA in $B^{\pm} \to \pi^{+}\pi^{-}\pi^{\pm}$

Forward-Bacward Asymmetry induced CPA in $B^{\pm} \to \pi^+\pi^-\pi^{\pm}$

Interfering of $\rho^(770)$ and $f_0(500)$ results in FBA.



$$A_{CP}^{FB} \equiv \frac{\int_{m_2'^2-\Delta_-}^{m_2'^2+\Delta_+} \int_{-1}^{+1} \left(\overline{|\mathcal{M}|^2} - \overline{|\overline{\mathcal{M}}|^2}\right) \ \mathrm{sgn}(c_\theta)\, dc_\theta ds}{\int_{m_2'^2-\Delta_-}^{m_2'^2+\Delta_+} \int_{-1}^{+1} \left(\overline{|\mathcal{M}|^2} + \overline{|\overline{\mathcal{M}}|^2}\right) dc_\theta ds}$$

$$A_{CP}^{FB,\Im} \equiv \frac{\int_{m_2'^2-\Delta_-}^{m_2'^2+\Delta_+} \int_{-1}^{+1} \left(\overline{|\mathcal{M}|^2} - \overline{|\overline{\mathcal{M}}|^2}\right) \ \mathrm{sign}(c_\theta) \ \mathrm{sgn}\left(s - m_2'^2\right) dc_\theta ds}{\int_{m_2'^2-\Delta_-}^{m_2'^2+\Delta_+} \int_{-1}^{+1} \left(\overline{|\mathcal{M}|^2} + \overline{|\overline{\mathcal{M}}|^2}\right) dc_\theta ds}$$

LHCb, PRD 101 (2020) 012006 [1909.05212]

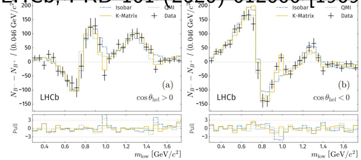
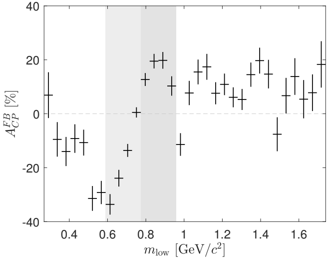


Figure 12: Raw difference in the number of B^- and B^+ candidates in the low $m_{\rm low}$ region, for (a) positive, and (b) negative cosine of the helicity angle. The pull distribution is shown below each fit projection.



$$A_{CP,k}^{FB} = \frac{(N_{B^-} - N_{B^+})_{\cos\theta_{\rm hel}>0,k} - (N_{B^-} - N_{B^+})_{\cos\theta_{\rm hel}<0,k}}{(N_{B^-} + N_{B^+})_{\cos\theta_{\rm hel}>0,k} + (N_{B^-} + N_{B^+})_{\cos\theta_{\rm hel}<0,k}}$$

$$A_{CP}^{FB,\rm ave} = \frac{\sum_{k=8}^{15}[(N_{B^-} - N_{B^+})_{\cos\theta_{\rm hel}>0,k} - (N_{B^-} - N_{B^+})_{\cos\theta_{\rm hel}<0,k}]}{\sum_{k=8}^{15}[(N_{B^-} + N_{B^+})_{\cos\theta_{\rm hel}>0,k} + (N_{B^-} + N_{B^+})_{\cos\theta_{\rm hel}<0,k}]} = (0.8 \pm 1.0)\%$$

$$A_{CP}^{FB,\Im} = \frac{\left(\sum_{k=12}^{15} - \sum_{k=8}^{11}\right)\left[(N_{B^-} - N_{B^+})_{\cos\theta_{\rm hel}>0,k} - (N_{B^-} - N_{B^+})_{\rm co}\right.}{\sum_{k=8}^{15}\left[(N_{B^-} + N_{B^+})_{\cos\theta_{\rm hel}>0,k} + (N_{B^-} + N_{B^+})_{\cos\theta_{\rm hel}<}\right.} = (13.2 \pm 1.0)\%$$

4 Summary and Outlook

Summary and Outlook

- pair(s) of complementary CPA observables may provide us opportunities of discoveries CPV in charmed hadron multi-body decays, in heavy baryon decays.

Thank you for your attentions!

欢迎各位老师推荐优秀毕业生加入南华大学！