*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 PRD 110, L111301 [2407.20586] In collaboration with 祁敬娟 杨建宇

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2 interference of resonances in cascade decays

(3) Forward-Bacward Asymmetry induced CPA in $B^\pm o \pi^+\pi^-\pi^\pm$





background and motivation

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- Evidence of CPV in $\Lambda_b \to \Lambda K^+ K^-$ is found by LHCb to be enhanced in N^* region.
- While large regional CPA is found in some multi-body decays of bottom mesons, the overall CPA is smaller, hence cancellations occur.
- plenty CPV observables in multi-body decays
 T-odd observables, regional CPAs, partial-wave CP asymmetries,



CPV observables usually originates from the real parts if the interfering terms, and is proportional to $\sin\delta\sin\phi$

$$\mathcal{A} = \mathcal{A}_1 + \mathcal{A}_2$$
$$\mathcal{A}_{CP} \equiv |\mathcal{A}|^2 - |\overline{\mathcal{A}}|^2 \sim \Re(\mathcal{A}_1 \mathcal{A}_2^*) - \Re(\overline{\mathcal{A}_1 \mathcal{A}_2}^*) \sim \sin \delta \sin \phi$$

How about constructing an observable originates from the imaginary parts of the interfering terms:

$$\Im(A_1A_2^*) - \Im(\overline{A_1A_2}^*) \sim \cos\delta\sin\phi$$

example: CPV induced by TPA in four-body decays

Triple-Product Asymmetry A^{T}



TPA induced CP asymmetries

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

$$\Im(A_1A2^*) - \Im(\overline{A_1A_2}^*) \sim \sin \phi_{\mathsf{weak}} \cos \delta,$$

Why?

$$\mathcal{A} = \sum_{m} \mathcal{A}_{m} e^{im\varphi}$$

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

If $m - m' \neq 0$ (suppose m - m' = 1), one can construct CPA observables such as TPA induced CPA.

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TP-CPA searching

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

Inspiration from TPA induced CPA

$$\mathcal{A} = \sum_{m} A_{m} e^{im\varphi} \qquad \qquad \mathcal{A} = \sum_{k} \mathcal{A}_{k} = \sum_{k} a_{k} b_{k}$$

$$\sim \Re(A_{m}A_{m'}^{*}e^{i(m-m')\varphi}) \qquad \qquad |\mathcal{A}|^{2} \sim \Re[(a_{k}b_{k})(a_{k'}^{*}b_{k'}^{*})]$$

$$\sim \Re(A_{m}A_{m'}^{*})\cos[(m-m')\varphi] \qquad \qquad \sim \Re(a_{k}a_{k'}^{*})\Re(b_{k}b_{k'}^{*})$$

$$+ \Im(A_{m}A_{m'}^{*})\sin[(m-m')\varphi] \qquad \qquad + \Im(a_{k}a_{k'}^{*})\Im(b_{k}b_{k'}^{*})$$

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

 $|\mathcal{A}|^2$

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2 interference of resonances in cascade decays

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Image: A matrix

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example 1: three-body decay with a resonance plus a smooth background term

decay amplitude:

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

decay amplitude squared

$$\overline{\left|\mathcal{M}
ight|^2} pprox rac{\left|\mathcal{A}_r
ight|^2}{\left|s_r
ight|^2} + \left|\mathcal{B}_2
ight|^2 + 2\Re\left(rac{\mathcal{A}_1\mathcal{B}_2^*}{s_r}
ight),$$

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The interfering term

$$\Re\left(\frac{\mathcal{A}_{r}\mathcal{B}^{*}}{s_{r}}\right) = \frac{\Re\left(\mathcal{A}_{r}\mathcal{B}^{*}\right)\left(s-m_{r}^{2}\right)+\Im\left(\mathcal{A}_{r}\mathcal{B}^{*}\right)m_{r}\Gamma_{r}}{\left|s_{r}\right|^{2}}.$$

a pair of complementary CPV observables

$$A_{CP} \equiv \frac{\int_{m_r^2 - \Delta_-}^{m_r^2 + \Delta_+} \left(\overline{|\mathcal{M}|^2} - \overline{|\overline{\mathcal{M}}|^2} \right) ds}{\int_{m_r^2 - \Delta_-}^{m_r^2 + \Delta_+} \left(\overline{|\mathcal{M}|^2} + \overline{|\overline{\mathcal{M}}|^2} \right) ds} \sim \sin \delta \sin \phi \quad \text{mainly from } \Im \left(\mathcal{A}_r \mathcal{B}^* \right)$$

$$c_P \equiv \frac{\int_{m_r^2 - \Delta_-}^{m_r^2 + \Delta_+} \left(\overline{|\mathcal{M}|^2} - \overline{|\overline{\mathcal{M}}|^2} \right) \operatorname{sgn} \left(s - m_2'^2 \right) ds}{\int_{m_r^2 - \Delta_-}^{m_r^2 + \Delta_+} \left(\overline{|\mathcal{M}|^2} + \overline{|\overline{\mathcal{M}}|^2} \right) ds} \sim \cos \delta \sin \phi \quad \text{mainly } \Re \left(\mathcal{A}_r \mathcal{B}^* \right)$$

$$A_{CP} = \frac{A_{CP}^{m_r^2 + \Delta_+} \left(\overline{|\mathcal{M}|^2} + \overline{|\overline{\mathcal{M}}|^2} \right) ds}{\int_{m_r^2 - \Delta_-}^{m_r^2 + \Delta_+} \left(\overline{|\mathcal{M}|^2} + \overline{|\overline{\mathcal{M}}|^2} \right) ds} \sim \cos \delta \sin \phi \quad \text{mainly } \Re \left(\mathcal{A}_r \mathcal{B}^* \right)$$

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example 2: three-body decay with two nearby resonance

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

$$\mathcal{M} = rac{\mathcal{A}_1}{s_1} + rac{\mathcal{A}_2}{s_2}, \quad s_r = s - m_r^2 + \mathrm{i} m_r \Gamma_r$$

decay amplitude squared

$$\overline{\left|\mathcal{M}
ight|^2} pprox rac{\left|\mathcal{A}_1
ight|^2}{\left|s_1
ight|^2} + rac{\left|\mathcal{A}_2
ight|^2}{\left|s_2
ight|^2} + 2\Re\left(rac{\mathcal{A}_1\mathcal{A}_2^*}{s_1s_2^*}
ight),$$

The interfering term

$$\Re\left(\frac{\mathcal{A}_{1}\mathcal{A}_{2}^{*}}{s_{1}s_{2}^{*}}\right) = \frac{\Re\left(\mathcal{A}_{1}\mathcal{A}_{2}^{*}\right)\Re\left(s_{1}s_{2}^{*}\right) + \Im\left(\mathcal{A}_{1}\mathcal{A}_{2}^{*}\right)\Im\left(s_{1}s_{2}^{*}\right)}{\left|s_{1}s_{2}\right|^{2}}.$$

The interfering term

$$\Re\left(\frac{\mathcal{A}_{1}\mathcal{A}_{2}^{*}}{s_{1}s_{2}^{*}}\right) = \frac{\Re\left(\mathcal{A}_{1}\mathcal{A}_{2}^{*}\right)\Re\left(s_{1}s_{2}^{*}\right) + \Im\left(\mathcal{A}_{1}\mathcal{A}_{2}^{*}\right)\Im\left(s_{1}s_{2}^{*}\right)}{\left|s_{1}s_{2}\right|^{2}}$$

$$\Re(s_1s_2^*) = m_1\Gamma_1m_2\Gamma_2 + (s - m_1^2)(s - m_2^2)$$

$$\Im (s_1 s_2^*) = (s - m_2^2) m_1 \Gamma_1 - (s - m_1^2) m_2 \Gamma_2$$

= $m_1 \Gamma_1 (1 - \frac{m_2 \Gamma_2}{m_1 \Gamma_1}) (s - {m_2'}^2)$

where $m'_2 = m_2 \sqrt{\left(1 - \frac{m_1\Gamma_2}{m_2\Gamma_1}\right)/\left(1 - \frac{m_2\Gamma_2}{m_1\Gamma_1}\right)}$. Now the difference between the behaviour of $\Re\left(s_1s_2^*\right)$ and $\Im\left(s_1s_2^*\right)$ is obvious: while the latter tends to change sign as *s* passes through ${m'_2}^2$, the former does not.

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a pair of CPV observables

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

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

From Jian-Peng Wang's slides in 2023

Complementary dependence of strong phase



$$A_{CP}^2 + (A_{CP}^{\Im})^2 \sim \sin^2 \phi$$

CPA corresponding to the Im parts of interf.

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

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

Interfering of $\rho^0(770)$ with a S-wave results in FBA.



FBA induced CPA (FB-CPA):

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

Complementary CPV observable to FB-CPA:

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



(a) positive, and (b) negative cosine of the helicity angle. The pull distribution is shown below

each fit projection.

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



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Summary and Outlook

pair(s) of complementary CPA observables in multi-body decays

- overcome the cancellation problem of CPA
- more complete understanding of CPV induced by the interference of intermediate resonances
- provide us a more comprehensive method of study CPV in multi-body decays of heavy hadrons.

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Thank you for your attentions!

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