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FBA induced CP asymmetry in $\overline{B}^0 \to K^-\pi^+\pi^0$ in phase space around the resonances $\overline{K}^*(892)^0$ and $\overline{K}_0^*(700)$

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第五届强子与重味物理理论与实验联合研讨会

河北师范大学，石家庄

Motivation & Overview

Motivation

- In multi-body decays, interference among resonances induces significant CP asymmetry.

Target Channel

- **Decay Process:** $\overline{B}^0 \to K^- \pi^+ \pi^0$
- **Dominant Resonances:** $K^*(892)^0$ and $K_0^*(700)$

What We Did

- **Key Observables:** Investigated Forward-Backward Asymmetry (FBA) and FB-CPA to study the interference effects.
- **Main Results:** Analyzed the non-trivial correlation between FBA and FB-CPA.

  FB-CPAs can be found around $K^*(892)^0$.

Helicity Angle and FBA

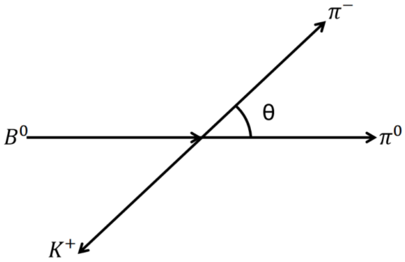


Figure 1: Definition of θ in the $\overline{B}^0 \to K^-\pi^+\pi^0$ decay channel

- **FBA Definition:** The event yield difference of π^0 flying forward ($\cos\theta > 0$) versus backward ($\cos\theta < 0$) in the $K^+\pi^-$ C.O.M. frame:

$$A^{FB} = \frac{\int_0^1 \langle|\mathcal{M}|^2\rangle \, d\cos\theta - \int_{-1}^0 \langle|\mathcal{M}|^2\rangle \, d\cos\theta}{\int_{-1}^1 \langle|\mathcal{M}|^2\rangle \, d\cos\theta}$$

Derivation of FBA Formula

- **Total Amplitude (S & P waves):** $\mathcal{M} = \mathcal{A}_S + \mathcal{A}_P \cos\theta$ (Resonances: $S = \overline{K}_0^*(700)$, $P = \overline{K}^*(892)^0$)

$\Downarrow$ *Modulus squared*

$$\langle|\mathcal{M}|^2\rangle = \langle|\mathcal{A}_S|^2\rangle + \langle|\mathcal{A}_P|^2\rangle \cos^2\theta + \underbrace{2\Re(\langle\mathcal{A}_P\mathcal{A}_S^*\rangle)\cos\theta}_{\text{Interference Term}}$$

$\Downarrow$ *Integrate over* $\cos\theta$

- **Denominator** $\left(\int_{-1}^{1}\right) \Rightarrow 2\langle|\mathcal{A}_S|^2\rangle + \frac{2}{3}\langle|\mathcal{A}_P|^2\rangle + \mathbf{0}$ (*Odd interference term vanishes*)
- **Numerator** $\left(\int_0^1 - \int_{-1}^0\right) \Rightarrow \mathbf{0} + \mathbf{0} + 2\Re(\langle\mathcal{A}_P\mathcal{A}_S^*\rangle)$ (*Even terms cancel out*)

$\Downarrow$ *Substitute back & simplify*

$$A^{FB} = \frac{\Re(\langle\mathcal{A}_P\mathcal{A}_S^*\rangle)}{\langle|\mathcal{A}_S|^2\rangle + \langle|\mathcal{A}_P|^2\rangle/3}$$

Interference Observables and CP Asymmetries

- The FBA precisely isolates the real part of the S-P wave interference:

$$A^{FB} = \frac{\Re(\langle \mathcal{A}_P \mathcal{A}_S^* \rangle)}{\langle |\mathcal{A}_S|^2 \rangle + \langle |\mathcal{A}_P|^2 \rangle / 3}$$

- **CP-Averaged FBA** (Describes the overall interference effect):

$$A_{ave}^{FB} = \frac{1}{2} \left(A^{FB} + \overline{A^{FB}} \right)$$

- **FB-CPA** (Extracts the pure CP-violating asymmetry):

$$A_{CP}^{FB} = \frac{1}{2} \left(A^{FB} - \overline{A^{FB}} \right)$$

Amplitude Parameterization

- In the resonance region, the decay is dominated by $\overline{B}^0 \to \overline{K}_0^*(700)(\to K^-\pi^+)\pi^0$ and $\overline{B}^0 \to \overline{K}^*(892)^0(\to K^-\pi^+)\pi^0$ cascade processes, allowing the amplitude to be parameterized as:

$$\mathcal{M}_{\overline{B}^0\to K^-\pi^+\pi^0} = \mathcal{A}_S + \mathcal{A}_P e^{i\delta} \cos\theta$$

- where δ is the relative phase between them. We can further isolate the Breit-Wigner factor,

$$\mathcal{A}_X = \frac{\tilde{\mathcal{A}}_X}{s - m_X^2 + i m_X \Gamma_X}$$

- for $X = S$ and P,

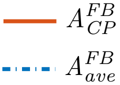
$$\tilde{\mathcal{A}}_P = \sqrt{2} m_{K^{*0}} g_{K^{*0}K\pi} \left(\frac{s_{\pi^0\pi^-,\max} - s_{\pi^0\pi^-,\min}}{2} \right) \cdot \Bigg\{ V_{ub} V_{us}^* a_2 f_\pi A_0^{B\to K^{*0}} + V_{tb} V_{ts}^* \left[\left(a_4 - \frac{1}{2} a_{10} \right) f_{K^*(892)^0} F_1^{B\to\pi} + \frac{3}{2}(a_7 - a_9) f_\pi A_0^{B\to K^{*0}} \right] \Bigg\}$$

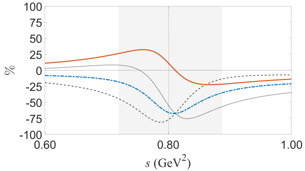
$$\tilde{\mathcal{A}}_S = \sqrt{2} g_{K_0^* K\pi} \cdot \Bigg(- V_{ub} V_{us}^* a_2 (m_B^2 - m_{K_0^*}^2) f_\pi F_0^{B\to K_0^*} + V_{tb} V_{ts}^* \Bigg\{ \left[a_4 - \frac{1}{2} a_{10} - \frac{2 m_{K_0^*}^2}{m_b m_s} \left(a_6 - \frac{1}{2} a_8 \right) \right] (m_B^2 - m_\pi^2) f_{K_0^*} F_0^{B\to\pi} - \frac{3}{2}(a_7 - a_9)(m_B^2 - m_{K_0^*}^2) f_\pi F_0^{B\to K_0^*} \Bigg\} \Bigg)$$

1. Introduction
2. Theoretical Framework
3. Results and Analysis
4. Summary

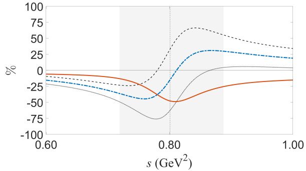
Numerical Results: s-dependence for $N_c^{eff} = 1$

$a_i = c_i + c_{i+1}/N_c^{eff}$ for odd i and $a_i = c_i + c_{i-1}/N_c^{eff}$ for even i



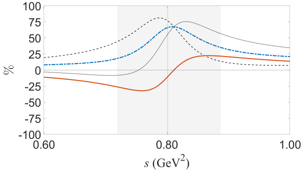


(a) $\delta = 0$

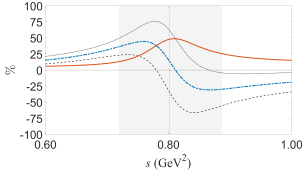


(b) $\delta = \pi/2$

The sign behaviors of A_{ave}^{FB} and A_{CP}^{FB} are correlated !



(c) $\delta = \pi$



(d) $\delta = 3\pi/2$

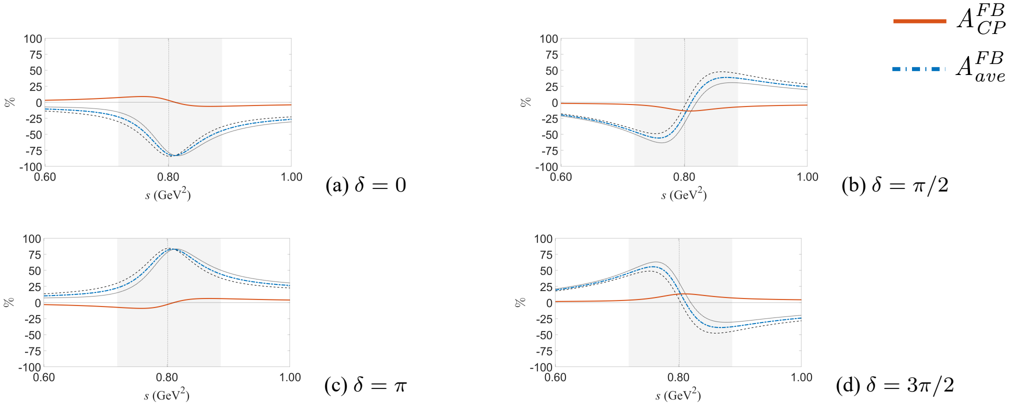
$\delta \sim 0, \pi \implies A_{CP}^{FB}$ changes sign

$\delta \sim 0, \pi \implies A_{ave}^{FB}$ NO sign change

$\delta \sim \pi/2, 3\pi/2 \implies A_{CP}^{FB}$ NO sign change

$\delta \sim \pi/2, 3\pi/2 \implies A_{ave}^{FB}$ changes sign

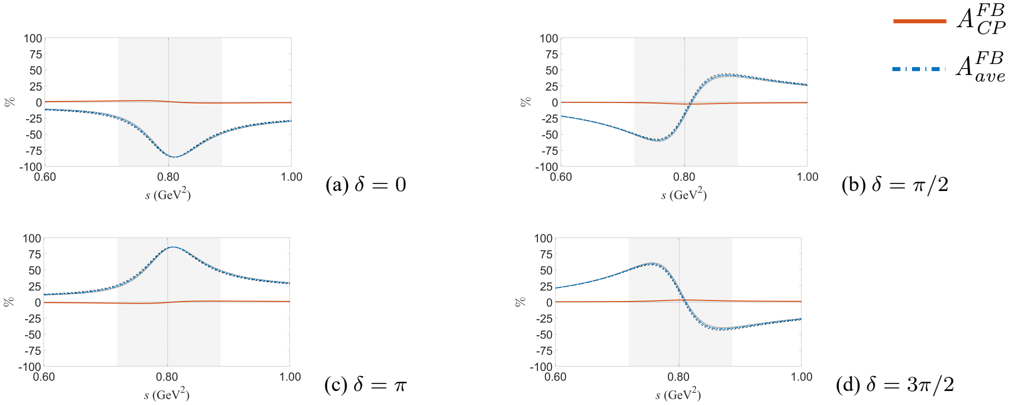
Numerical Results: s-dependence for $N_c^{eff} = 2$



(a) $\delta = 0$ (b) $\delta = \pi/2$ (c) $\delta = \pi$ (d) $\delta = 3\pi/2$

- The CP violation observables FB-CPAs are much more sensitive to the values of N_c^{eff}
- A non-zero FB-CPAs lies in the regions of $\overline{K}^*(892)^0$ and $\overline{K}_0^*(700)$ for $N_c^{eff} = 1$ and 2

Numerical Results: s-dependence for $N_c^{eff} = 3$



(a) $\delta = 0$ (b) $\delta = \pi/2$ (c) $\delta = \pi$ (d) $\delta = 3\pi/2$

- The FB-CPAs is negligibly small for $N_c^{eff} = 3$
- A_{CP}^{FB} strongly depends on non-factorizable effects

Key Points from Numerical Results

The numerical results highlight two critical phenomena:

- **Sign-Change mechanism:** The underlying dynamics that drive A_{CP}^{FB} to change sign (or remain unchanged) when s passes through the resonance peak m_P^2.
- **Observational correlation:** The physical origin of the approximately correlated behavior between the two observables.
  (A_{ave}^{FB} changes sign $\Longleftrightarrow$ A_{CP}^{FB} remains unchanged, and vice versa)

Underlying Mechanism

Analysis

By isolating the Breit-Wigner factors, the interference term in FBA can be expressed as

$$\Re(\mathcal{A}_S^*\mathcal{A}_P e^{i\delta}) = \lambda\left\{\left[1+\frac{(s-m_P^2)(s-m_S^2)}{m_P\Gamma_P m_S\Gamma_S}\right]\Re(\tilde{\mathcal{A}}_S^*\tilde{\mathcal{A}}_P e^{i\delta}) + \left[-\frac{s-m_P^2}{m_P\Gamma_P}+\frac{s-m_S^2}{m_S\Gamma_S}\right]\Im(\tilde{\mathcal{A}}_S^*\tilde{\mathcal{A}}_P e^{i\delta})\right\}$$

The normalization factor:

$$\lambda = \frac{m_P\Gamma_P m_S\Gamma_S}{\left[\left(s-m_P^2\right)^2+(m_P\Gamma_P)^2\right]\left[\left(s-m_S^2\right)^2+(m_S\Gamma_S)^2\right]}$$

Γ_S is considerably larger than Γ_P.

Since we focus mainly on the region when s is around the mass-squared of S and P, we have $\Gamma_s \gg \sqrt{|s-m_S^2|}$ and $\Gamma_s \gg \sqrt{|s-m_P^2|}$.

Analysis

After the approximation:

$$\Re(\mathcal{A}_S^*\mathcal{A}_P e^{i\delta}) = \lambda\left[\Re(\tilde{\mathcal{A}}_S^*\tilde{\mathcal{A}}_P e^{i\delta}) - \frac{s-m_P^2}{m_P\Gamma_P}\Im(\tilde{\mathcal{A}}_S^*\tilde{\mathcal{A}}_P e^{i\delta}) + \mathcal{O}(\epsilon)\right]$$

$$(\frac{\Gamma_P}{\Gamma_S}, \quad \frac{\sqrt{|s-m_S^2|}}{\Gamma_S}, \quad \frac{\sqrt{|s-m_P^2|}}{\Gamma_S} \sim \mathcal{O}(\epsilon) \ll 1)$$

Up to the order $\mathcal{O}(\epsilon)$, the interference term can be strictly splitted into two parts:

$$\Re(\mathcal{A}_S^*\mathcal{A}_P e^{i\delta}) = \lambda\,(\Delta + \Sigma)$$

Where

$$\Delta = \left(-\sin\delta - \frac{s-m_P^2}{m_P\Gamma_P}\cos\delta\right)\Im(\tilde{\mathcal{A}}_S^*\tilde{\mathcal{A}}_P)$$

$$\Sigma = \left(-\frac{s-m_P^2}{m_P\Gamma_P}\sin\delta + \cos\delta\right)\Re(\tilde{\mathcal{A}}_S^*\tilde{\mathcal{A}}_P)$$

Answer

- CP-Conjugation Properties (If δ is the dominant strong phase):

$$\Re(\tilde{\mathcal{A}}_S^* \tilde{\mathcal{A}}_P) \approx \Re(\tilde{\mathcal{A}}_S^{CP*} \tilde{\mathcal{A}}_P^{CP}),\ \Im(\tilde{\mathcal{A}}_S^* \tilde{\mathcal{A}}_P) \approx -\Im(\tilde{\mathcal{A}}_S^{CP*} \tilde{\mathcal{A}}_P^{CP}) \implies \Delta \approx -\Delta^{CP},\ \Sigma \approx \Sigma^{CP}$$

- Simplification:

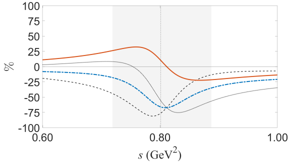
$$A_{CP}^{FB} \sim \Re(\mathcal{A}_S^* \mathcal{A}_P e^{i\delta}) - \Re(\mathcal{A}_S^{CP*} \mathcal{A}_P^{CP} e^{i\delta}) \sim (\Delta + \Sigma) - (\Delta^{CP} + \Sigma^{CP}) \approx \Delta - \Delta^{CP} \approx 2\Delta$$

$$A_{ave}^{FB} \sim \Re(\mathcal{A}_S^* \mathcal{A}_P e^{i\delta}) + \Re(\mathcal{A}_S^{CP*} \mathcal{A}_P^{CP} e^{i\delta}) \sim (\Delta + \Sigma) + (\Delta^{CP} + \Sigma^{CP}) \approx \Sigma + \Sigma^{CP} \approx 2\Sigma$$

- Where

$$\Delta = \left(-\sin\delta - \frac{s - m_P^2}{m_P \Gamma_P} \cos\delta \right) \Im(\tilde{\mathcal{A}}_S^* \tilde{\mathcal{A}}_P)$$

$$\Sigma = \left(-\frac{s - m_P^2}{m_P \Gamma_P} \sin\delta + \cos\delta \right) \Re(\tilde{\mathcal{A}}_S^* \tilde{\mathcal{A}}_P)$$



$\delta = 0\,,\, N_c^{eff} = 1$

Correlation: Strong Phase and Sign-Change Behavior

The behaviors of the two observables across the resonance mass are correlated:

	Sign Change Across Resonance?	
Strong Phase (δ)	A^{FB}_{ave} ($\sim 2\Sigma$)	A^{FB}_{CP} ($\sim 2\Delta$)
$\delta \sim 0, \pi$	No	**Yes**
$\delta \sim \pi/2, 3\pi/2$	**Yes**	No

- Exactly one observable experiences a sign change, driven by the dominance of either the Δ or Σ term.
- **Universality:** Crucially, this correlated sign-change behavior is **model-independent** and **channel-independent**.

Potential FB-CPA Values & Experimental Viability

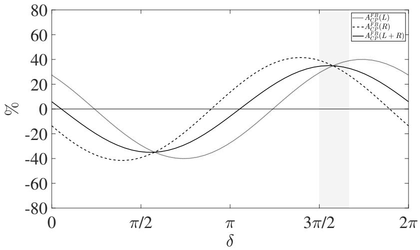


Figure 2: FB-CPAs vs. strong phase δ

Model Predictions:

- Dalitz analysis by BaBar [arXiv:0711.4417] favors: $\delta \in [3\pi/2, 5\pi/3]$.
- Assuming effective color $N_c^{eff} = 1$:
  - FB-CPA around $\overline{K}^*(892)^0$ reaches $\sim$ **35%**.
  - Likely accessible for **Belle-II**.

Connection to LHCb's $A_{CP|S}$:

- LHCb searches for CPV in $D \to KK\pi$ near $\phi(1020)$ using the $A_{CP|S}$ observable [arXiv:2409.01414]. Our Sign Change Rule provides the physical mechanism for this: it maps phase-space sign flips, dictating exactly how to prevent CP asymmetry cancellation.

Summary

Theoretical Mechanism

- **Interference Extraction:** FBA precisely isolates the S-P wave interference.
- **Non-trivial Correlation:** The sign behaviors of A_{ave}^{FB} and A_{CP}^{FB} are correlated .
  (1)Model-independent (2)Channel-independent
- **Underlying Mechanism:** Driven by the different behaviors of the Σ and Δ terms depending on the strong phase δ.

Experimental Impacts

- **Potential Signal:** Obtained a CP asymmetry up to $\sim \mathbf{35\%}$.
- **Future Prospect:** Potentially accessible by **Belle-II** collaborations.

Thanks for your attention !