Regional *CP* violation in three-body decays of heavy hadrons

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   - Regional *CP* asymmetry for $\Lambda_b^0 \to p\pi^0\pi^-$
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CPV in SM

Typical form of CP asymmetry in a decay process $i \to f$

$$A_{CP} \equiv \frac{|\mathscr{M}_{i\to f}|^2 - |\mathscr{M}_{\bar{i}\to\bar{f}}|^2}{|\mathscr{M}_{i\to f}|^2 + |\mathscr{M}_{\bar{i}\to\bar{f}}|^2} \sim sin\phi sin\delta$$

$$\mathscr{M}_{i\to f} = \langle f|H_{tree}|i\rangle + \langle f|H_{pen.}|i\rangle \doteq |\langle f|H_{tree}|i\rangle| + |\langle f|H_{pen.}|i\rangle|\, e^{i\phi} e^{i\phi}$$

- ϕ, weak phase in CKM matrix
- δ strong phase from strong interaction
  - perturbative, loop diagram of QCD (large scacle), QED,..., small
  - nonperturbative, QCD ($\sim \Lambda_{QCD}$), large

$$\mathscr{M}_{i\to f} = \langle f|H_{tree}|i\rangle + \langle f|H_{pen.}|i\rangle \doteq |\langle f|H_{tree}|i\rangle| + |\langle f|H_{pen.}|i\rangle|\, e^{i\phi} e^{i\phi}$$

- "Local" *CP* asymmetry in phase space for some 3-body decays of *B*-meson is available.
- Large *CP*v which does not clearly correspond to any resonances
- Needs theoretical explanations

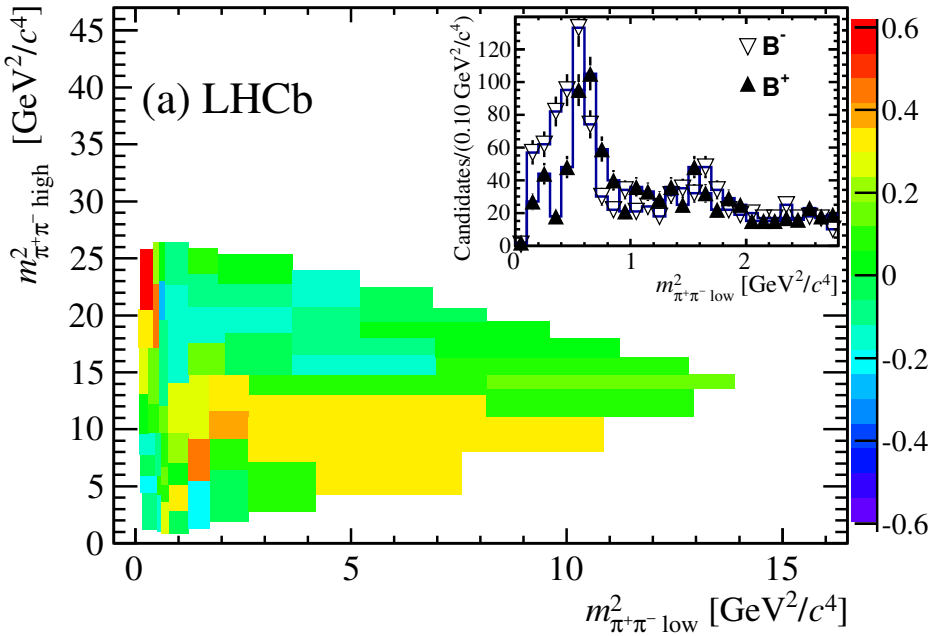
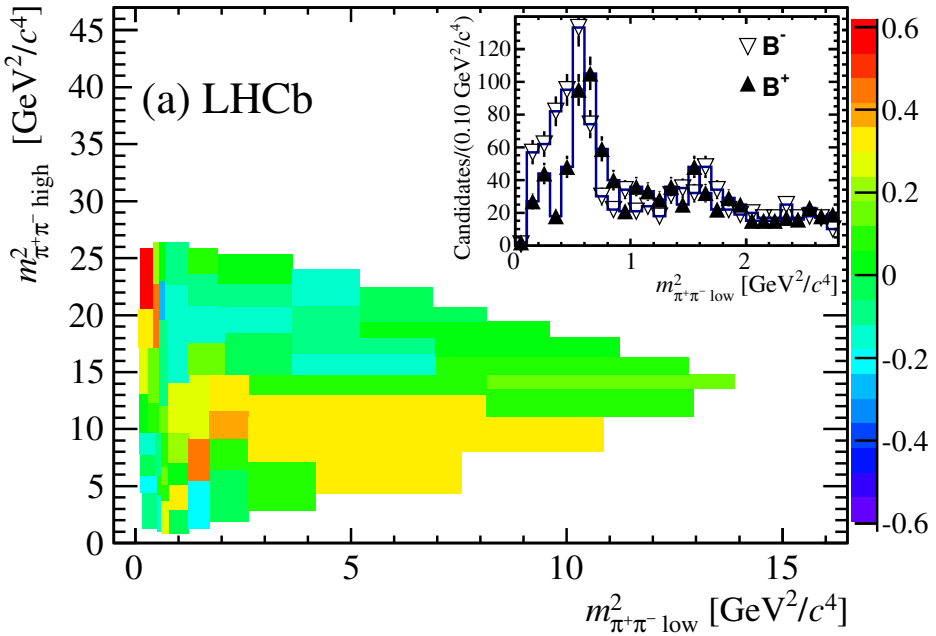


Figure: CP asymmetry for $B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ by LHCb. (PRL112, 011801)

$B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$

simple picture: interference of amplitudes corresponding to $\rho^0(770)$ and $f_0(500)$ [1303.3676, ZZ, Guo, Yang]

$$\mathscr{M}_{B^+\to\pi^+\pi^+\pi^-}$$
$$= \mathscr{M}_{B^+\to\pi^+\rho(\to\pi^+\pi^-)} + \mathscr{M}_{B^+\to\pi^+ f(\to\pi^+\pi^-)}$$



$$\mathscr{M}_{B^+\to\pi^+\rho^0(\to\pi^+\pi^-)} =$$
$$[BW]_{\rho^0} \times (c^T_{\rho^0} V_{ub} V^*_{ud} - c^P_{\rho^0} V_{tb} V_{td}) \times P_1(g)$$

$$\mathscr{M}_{B^+\to\pi^+\rho^0(\to\pi^+\pi^-)} =$$
$$[BW]_{f_0} \times (c^T_{f_0} V_{ub} V^*_{ud} - c^P_{f_0} V_{tb} V_{td}) \times P_0(g)$$

$B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$

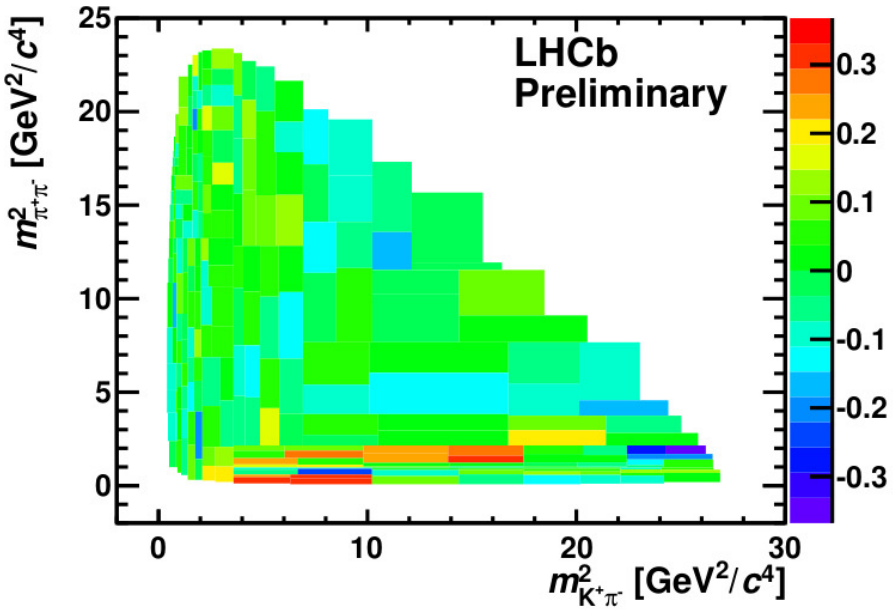


Figure: CP asymmetry for $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$ by LHCb. [1301.0283]

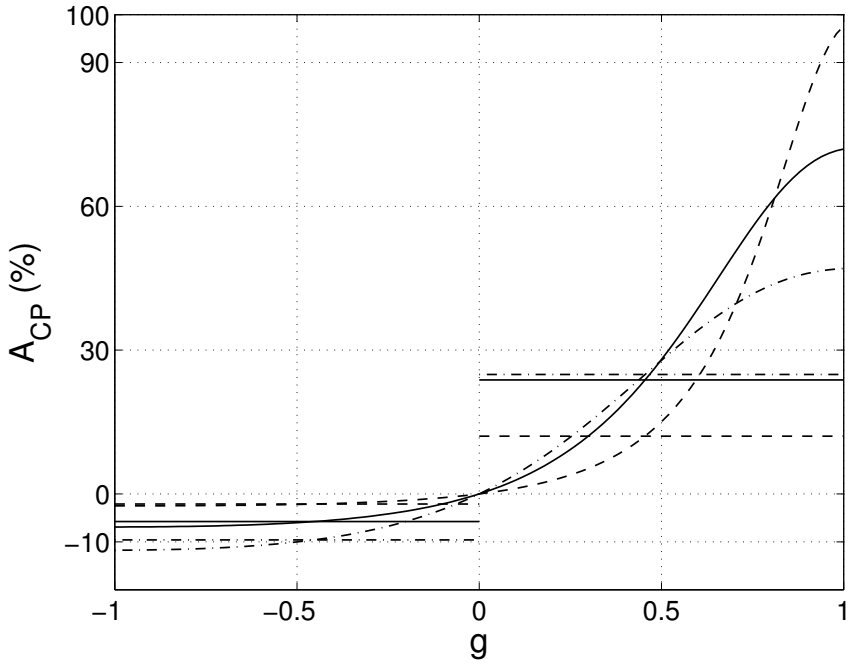


Figure: CP asymmetry for $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$ around the vic. of $\rho(770)$ by the interfer. of amp. corrsponding to $\rho^0(770)$ and $f_0(500)$. [1308.5242, ZZ, Guo, Yang]

Q: Could similar interference behaviour happen in b-baryon decay?

(No CPV is established in baryon sector except an evidence [$\Lambda_b^0 \to pK^-$, PRL106,181802].)

- interference of two intermediate baryons H_A and H_B [I]

$$\mathscr{M}_{\Lambda_b \to M_1 M_2 H_3} = \mathscr{M}_{\Lambda_b \to M_1 H_A(\to M_2 H_3)} + \mathscr{M}_{\Lambda_b \to M_1 H_B(\to M_2 H_3)} \quad (1)$$

- interference of two intermediate baryons H_A and H_B [II]

$$\mathscr{M}_{\Lambda_b \to M_1 M_2 H_3} = \mathscr{M}_{\Lambda_b \to M_2 H_A(\to M_1 H_3)} + \mathscr{M}_{\Lambda_b \to M_1 H_B(\to M_2 H_3)} \quad (2)$$

- interference of a baryon resonance H with a meson resonance M

$$\mathscr{M}_{\Lambda_b \to M_1 M_2 H_3} = \mathscr{M}_{\Lambda_b \to M_1 H(\to M_2 H_3)} + \mathscr{M}_{\Lambda_b \to HM(\to M_1 M_2)} \quad (3)$$

Diff Decay Amplitude and Diff CPv

In the overlap region of ρ^0 and N^+, the decay amplitude can be expressed as

$$\mathscr{M} = \frac{\langle p\pi^0|\hat{\mathscr{H}_1}|N^+\rangle\langle\pi^- N^+|\hat{\mathscr{H}}_{\rm eff}|\Lambda_b^0\rangle}{s_0 - m_N^2 + im_N\Gamma_N} + \frac{\langle\pi^0\pi^-|\hat{\mathscr{H}_2}|\rho^-\rangle\langle p\rho^-|\hat{\mathscr{H}}_{\rm eff}|\Lambda_b^0\rangle}{s - m_\rho^2 + im_\rho\Gamma_\rho}.$$

- $\hat{\mathscr{H}}_{\rm eff}$: weak Hamiltonian
- $\hat{\mathscr{H}_1}$ strong, Yukawa type; $\hat{\mathscr{H}_2}$ strong, scalarQED type

The differential CP asymmetry is then defined as

$$A_{CP} = \frac{\overline{|\mathscr{M}|^2} - \overline{|\bar{\mathscr{M}}|^2}}{\overline{|\mathscr{M}|^2} + \overline{|\bar{\mathscr{M}}|^2}}. \tag{4}$$

- factorization approach for matrix elements $\langle \pi^- N^+(p\rho)|\hat{\mathscr{H}}_{\rm eff}|\Lambda_b^0\rangle$,
- determine coupling constants of $\hat{\mathscr{H}_1}$ and $\hat{\mathscr{H}_2}$ from exp.data
- the relative strong phase of $\mathscr{H}_1$ and $\mathscr{H}_2$, δ, is treated as a free parameter
- The form factors for $\Lambda_b \to N^+$ are not available – rough estimation

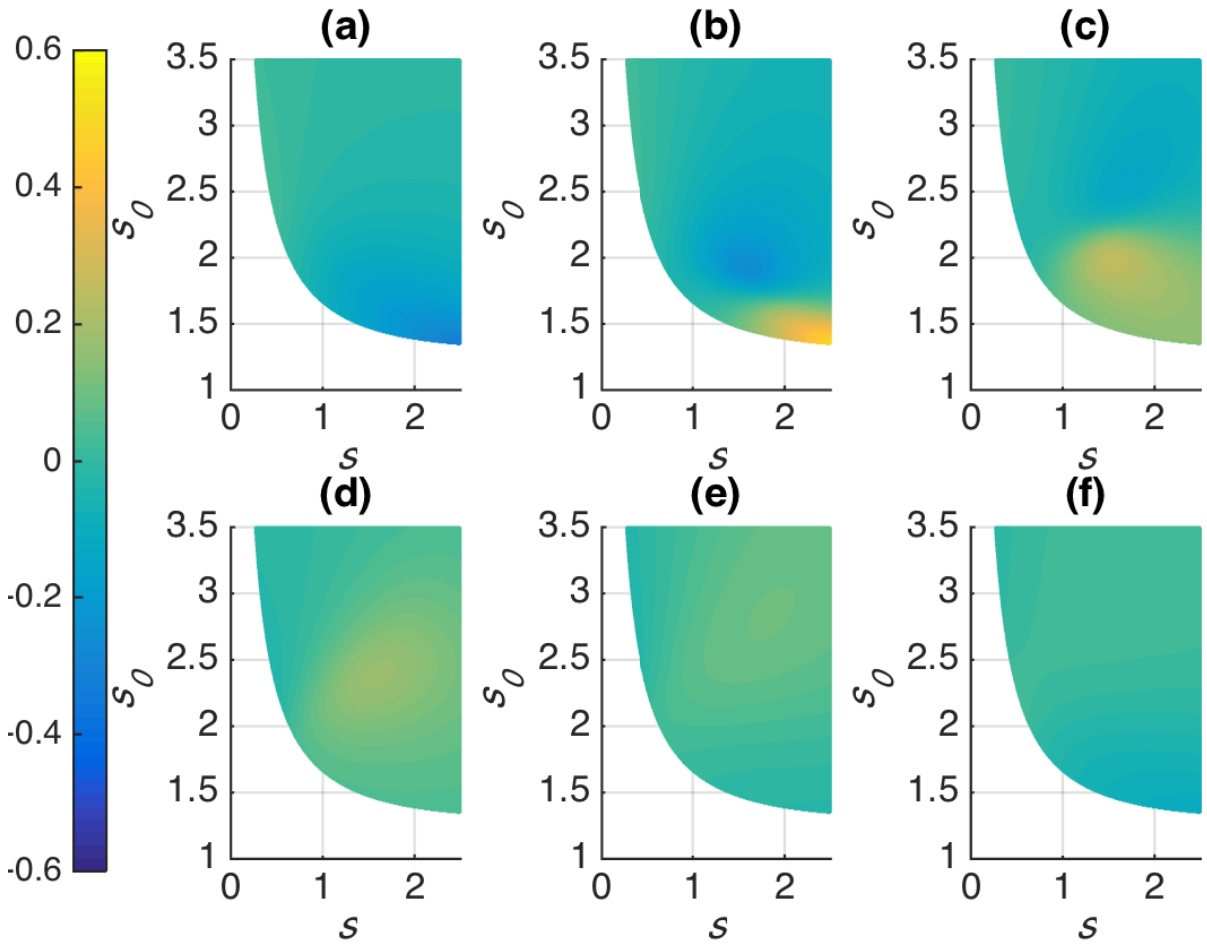


Figure: Differential CP asymmetries (in unit of %) distributions in the overlap region of the phase space for various values of δ. The six diagrams (a) to (f) correspond to δ taking values form 0 to $5\pi/3$ for every $\pi/3$. The invariant mass squares s and s_0 are in units of GeV^2. [1507.04459, ZZ, Wang, Guo]

The regional CP asymmetry

$$A_{CP}^{\Omega} = \frac{\Gamma^{\Omega} - \bar{\Gamma}^{\Omega}}{\Gamma^{\Omega} + \bar{\Gamma}^{\Omega}}, \tag{5}$$

where Ω is some region of the phase space, Γ^{Ω} and $\bar{\Gamma}^{\Omega}$ are the regional decay width for $\Lambda_b^0 \to p\pi^0\pi^-$ and $\overline{\Lambda}_b^0 \to \overline{p}\pi^0\pi^+$, respectively, with the former one taking the form

$$\Gamma^{\Omega} = \frac{1}{256\pi^3 m_{\Lambda_b}^3} \int_{\Omega} ds ds_0 \overline{|\mathscr{M}|^2}. \tag{6}$$

We will focus on $\Omega_{\rm OL}$:

$$m_\rho + \Gamma_\rho < \sqrt{s} < m_\rho + 2\Gamma_\rho,\ \ m_N - \frac{\Gamma_N}{2} < \sqrt{s_0} < m_N + \frac{\Gamma_N}{2}. \qquad (7)$$

The reason for this choice:

- Exclude the pollution of other resonances.
- Amplitude corresponding to resonances $\rho^-(770)$ is larger than that of $N^+(1440)$.

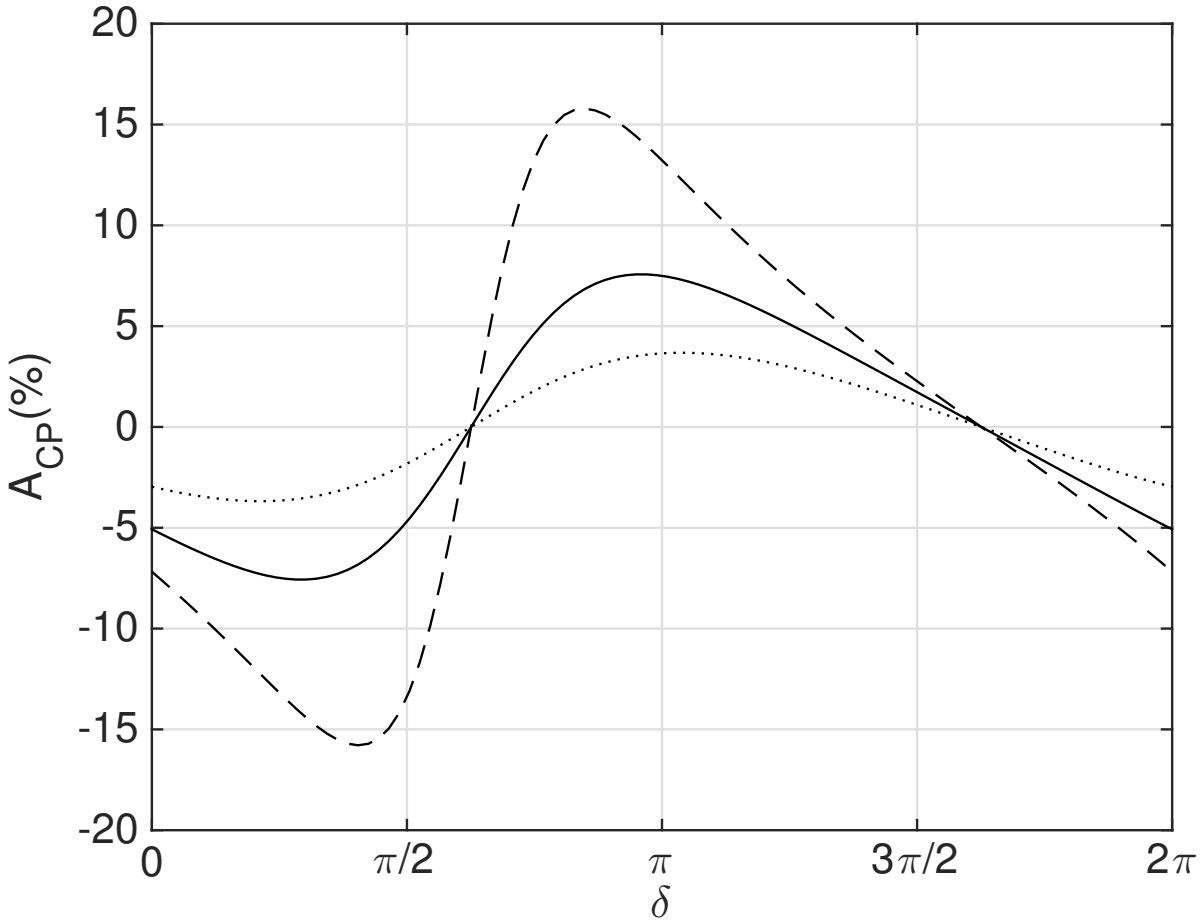


Figure: CP asymmetries in Region $\Omega_{\rm OL}$ as a function of the strong phase δ. The dashed, solid, and dotted curves are for $F^{\Lambda_b\to p}/F^{\Lambda_b\to N^+} = 0.5$, 1, and 2. [1507.04459, ZZ, Wang, Guo]

Conclusion

- The observed large CP asymmetry in 3-body decay of B meson can be understood as interference of amplitudes corresponding to intermediate resonances
- Interference of resonances in Λ_b decays can result in differential and regional CPV in phase space.

Thanks!