Parttial Wave CP Asymmetry: a novel strategy for hunting for CPV in baryon sector

based on ZHZ and X.-H. Guo, 2103.11335

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   - CPV in B meson multi-body decay
   - current status of CPV in baryon decays

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CPV in decays, a very short review

CPV in decays

For a decay which the amplitudes is a sum of several ones, $\mathcal{A} = \sum_j \mathcal{A}_j$:

$$A_{CP} \sim \sum_{ij} a_{ij} \sin\phi_{ij} \sin\delta_{ij}$$

- ϕ_{ij}: weak phase difference of A_i and A_j (from CKM in SM).
- δ_{ij}: unitary phase, or strong phase difference of A_i and A_j.

example: $B^{\pm} \to \rho^0\pi^{\pm}$

$$\mathcal{A}_{B^+\to\rho^0\pi^+} = \lambda_u \mathcal{A}^{\mathrm{tree}} - \lambda_t \mathcal{A}^{\mathrm{penguin}}$$

$$\mathcal{A}_{B^-\to\rho^0\pi^-} = \lambda_u^* \mathcal{A}^{\mathrm{tree}} - \lambda_t^* \mathcal{A}^{\mathrm{penguin}}$$

$$A_{CP} \sim \sin[\arg(\lambda_u/\lambda_t)] \sin\delta$$

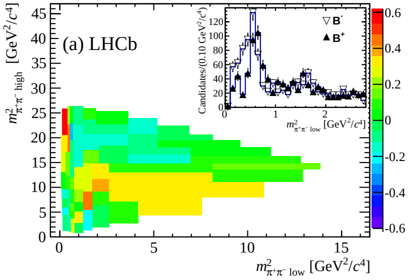
current exp. status of CPV in decays

- B meson: $\surd\surd\cdots$
- D meson: $\surd$
- baryon decay: $\times$

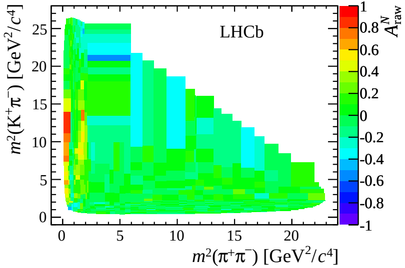
CPV in B meson multi-body decay

Large regional CPA in phase space: interference of resonances in phase space

$B^\pm \to \pi^\pm\pi^+\pi^-$ (LHCb, PRL,112 (2014),011801)



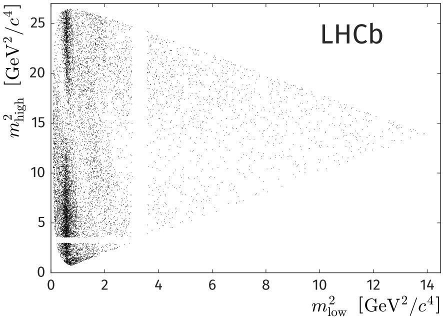
$B^\pm \to K^\pm\pi^+\pi^-$ (LHCb, PRD90(2014),112004)



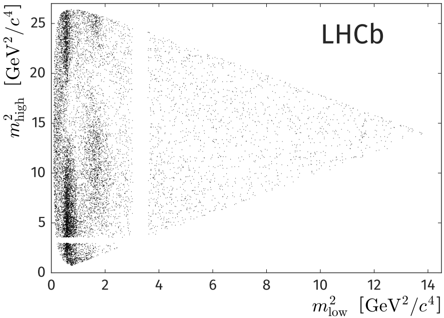
Events distributed in phase space

PRL 124 (2020) 031801 [1909.05211]

$B^+ \to \pi^+\pi^+\pi^-$



$B^- \to \pi^-\pi^+\pi^-$



- Interference of $\rho^0(770)$ and $f_0(500)$ results in large regional CPA. ZHZ X.-H. Guo, and Y.-D. Yang, PRD87,076007.
- Forward-Backward Asymmstry induced CP Asymmetry (FBI-CPA). (ZHZ [2002.12263])

Lessons from CPV studies of B meson multi-body decays

- large regional CPAs
- rich resonances structures
- interference of near-by resonances: non-perturbative strong phase δ.

current status of CPV in baryon decays

- CPA as large as 20% are expected in some channels of Λ_b^0 (Y.K. Hsiao, C.Q. Geng, PRD91,116007).
- no confirmation for exp. side.
    - 2-body and multi-body decays of heavy baryons
    - low statistics
    - regional and integrated CPA
    - Triple Product Asymmetry induced CPAs (with evidence)

no evidence of $\mathrm{CPV}_{\mathrm{baryon}}$ currently + Lessons from $\mathrm{CPV}_{B\ \mathrm{meson}}$=??

resonances interference in multi-body decays of heavy baryons

2 *CP*V study in the baryon sector

- Partial Wave *CP* Asymmetry (PWCPA)
- Applications to baryon decays

Interference of $X \to h_1 h_2$ and $Y \to h_1 h_2$ in decay $H \to h_1 h_2 h_3 \cdots h_n$

$$\overline{|\mathcal{M}|^2} = \sum_j P_j(c_{\theta_1^*}) w^{(j)}.$$

- θ_1^* the angle between $\vec{p}^*_{h_1}$ and $\sum_{k=3}^n \vec{p}^*_k$ in rest frame of $h_1 h_2$.
- $c_{\theta_1^*}$ is a function of s_{12}.

example for $\mathcal{M}$: three body cascade decay, in helicity formalism

$$\mathcal{M}^{Jm_z,s}_{\lambda_1\lambda_2\lambda_3} = \frac{1}{s_{12} - m_B^2 + i m_B \Gamma_B} \sum_\sigma \tilde{\mathcal{M}}^{s\sigma}_{\lambda_1\lambda_2} \mathcal{M}^{Jm_z}_{\sigma\lambda_3},$$

$$\mathcal{M}^{Jm_z}_{\sigma\lambda_3} = \mathcal{F}^J_{\sigma\lambda_3} D^{J*}_{m_z,\sigma-\lambda_3}(\phi_B, \theta_B, 0),$$

$$\tilde{\mathcal{M}}^{s\sigma}_{\lambda_1\lambda_2} = \mathcal{M}^{s\sigma}_{\lambda_1'\lambda_2'} D^{j_1*}_{\lambda_1'\lambda_1}(\phi_{W1}, \theta_{W1}, 0) D^{j_2*}_{\lambda_2'\lambda_2}(\phi_{W2}, \theta_{W2}, 0),$$

$$\mathcal{M}^{s\sigma}_{\lambda_1'\lambda_2'} = \mathcal{F}^s_{\lambda_1'\lambda_2'} D^{s*}_{\sigma,\lambda_1'-\lambda_2'}(\phi_1', \theta_1', 0).$$

dynamical/physical content of $w^{(j)}$

$w^{(j)}$ can be divided into three terms:

$$w^{(j)} = w_X^{(j)} + w_Y^{(j)} + w_{XY}^{(j)}.$$

$$w_R^{(j)} = \sum_{m_z,\sigma,\lambda_k^{(\prime)}} \xi_{\sigma\lambda'}^{j_R j_R j} \frac{\left|\mathcal{G}_{\lambda_1'\lambda_2'}^{j_R} \mathcal{A}_{\sigma\lambda_3\cdots}^{m_z,R}\right|^2}{|s_R|^2}\Bigg|_{\lambda'=\lambda_1'-\lambda_2'},$$

$$w_{XY}^{(j)} = 2\sum_{m_z,\sigma,\lambda_k^{(\prime)}} \xi_{\sigma\lambda'}^{j_X j_Y j} \Re\left(\frac{\mathcal{G}_{\lambda_1'\lambda_2'}^{j_Y *} \mathcal{G}_{\lambda_1'\lambda_2'}^{j_X} \mathcal{A}_{\sigma\lambda_3\cdots}^{m_z,X} \mathcal{A}_{\sigma\lambda_3\cdots}^{m_z,Y*}}{s_X s_Y^*}\right)\Bigg|_{\lambda'=\lambda_1'-\lambda_2'}.$$

$$\xi_{\sigma\lambda}^{j_a j_b j} = (-)^{\sigma-\lambda'} \left(\begin{array}{cc|c} j_a & j_b & j \\ -\sigma & \sigma & 0 \end{array}\right) \left(\begin{array}{cc|c} j_a & j_b & j \\ -\lambda & \lambda & 0 \end{array}\right).$$

Selection rules

- The interference terms show up only when
  - $j = |j_X - j_Y|, \cdots, j_X + j_Y$.
  - $(-)^j P_X P_Y = +1$.
- The non-interference terms show up only for even j satisfying $j = 0, \cdots, 2j_{X/Y}$.

derived from

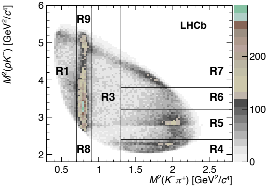
- rotational symmetry (properties of C-G)
- parity symmetry of strong processes $X/Y \to h_1 h_2$.

PWCPA (ZHZ and X.-H. Guo, 2103.11335)

The differential decay amplitude for $H \to h_1 h_2 h_3 \cdots h_n$:

$$\langle d\Gamma \rangle \propto \int_{s_{12,\mathrm{low}}}^{s_{12,\mathrm{high}}} \overline{|\mathcal{M}|^2} \cdots ds_{12} d\tau \propto \sum_j P_j(c_{\theta^*_{13}}) \left\langle w^{(j)} \right\rangle dc_{\theta^*_1}.$$

$\Xi_c \to pK^-\pi^+$



PW*CP*As for the *j*th-wave:

$$A_{CP}^{(j)} \equiv \frac{\langle w^{(j)} \rangle - \langle \bar{w}^{(j)} \rangle}{\langle w^{(j)} \rangle + \langle \bar{w}^{(j)} \rangle}.$$

$$A_{CP}^{(j)} \equiv \frac{\sum_{a,b=X,Y} \left\langle \frac{1}{s_a s_b^*} \right\rangle \sum_\sigma (-)^{j_a+j_b-\sigma} \left(\begin{matrix} j_a & j_b \\ -\sigma & \sigma \end{matrix} \middle| \begin{matrix} j \\ 0 \end{matrix} \right) \sum_{m_z,\lambda_3,\cdots} \left[\mathcal{A}^{m_z,a}_{\sigma\lambda_3\cdots} \mathcal{A}^{m_z,b*}_{\sigma\lambda_3\cdots} - \overline{\mathcal{A}}^{m_z,a}_{\sigma\lambda_3\cdots} \overline{\mathcal{A}}^{m_z,b*}_{\sigma\lambda_3\cdots} \right]}{\sum_{a,b=X,Y} \left\langle \frac{1}{s_a s_b^*} \right\rangle \sum_\sigma (-)^{j_a+j_b-\sigma} \left(\begin{matrix} j_a & j_b \\ -\sigma & \sigma \end{matrix} \middle| \begin{matrix} j \\ 0 \end{matrix} \right) \sum_{m_z,\lambda_3,\cdots} \left[\mathcal{A}^{m_z,a}_{\sigma\lambda_3\cdots} \mathcal{A}^{m_z,b*}_{\sigma\lambda_3\cdots} + \overline{\mathcal{A}}^{m_z,a}_{\sigma\lambda_3\cdots} \overline{\mathcal{A}}^{m_z,b*}_{\sigma\lambda_3\cdots} \right]}.$$

PW*CP*A

- applicable to decays of heavy mesons and baryons
- can be used in CPV hunting in the baryon decays
- model independent comparing with Amplitude Analysis Technic
- potentially solved the statistic problem

Applications to baryon decays

$\Lambda_b^0 \to p\pi^-\pi^+\pi^-$

- The dominate of $\Delta^{++} \to p\pi^+$ implies the dominate of $\Delta^0 \to p\pi^-$.
- The large width of $N^0(1440)$ implies a potential subleading contribution $N^0(1440) \to p\pi^-$.

Table: Some low-lying baryon resonances which decay to $N\pi$ substantially.

Baryons	J^P	m (MeV)	Γ (MeV)	$BR(N\pi)$ (%)
$\Delta(1232)$	$\frac{3}{2}^+$	1232	117	99.4
$N(1440)$	$\frac{1}{2}^+$	1440	350	55-75
$N(1520)$	$\frac{3}{2}^-$	1515	110	55-65
$N(1535)$	$\frac{1}{2}^-$	1530	110	35-52
$N(1650)$	$\frac{1}{2}^-$	1650	125	50-70

$\Lambda_b^0 \to p\pi^-\pi^0$: an illustration

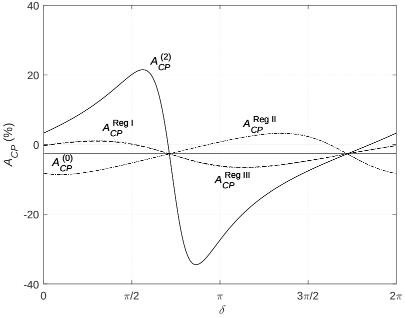
The interference of $\Delta^0(1232)$ and $N^0(1440)$:

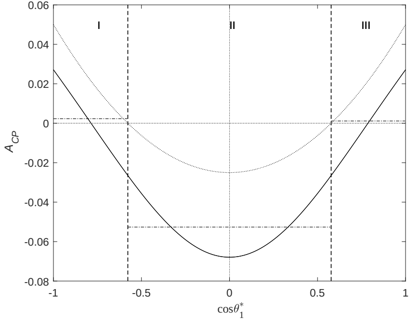
$$\mathcal{M} = \sum_{X=N,\Delta} \frac{\mathcal{A}_{X\to p\pi^-}\mathcal{A}_{\Lambda_b^0\to X\pi^0}e^{i\delta_X}}{s_{p\pi^-} - m_X^2 + im_X\Gamma_X}.$$

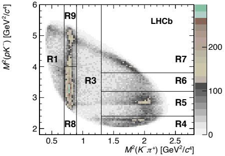
- δ_X: the strong phases corresponding to X.
- CPV corresponding to the interference of Δ^0 and N^0: $\propto \sin\delta$, $(\delta = \delta_\Delta - \Delta_N)$.
- selection rules: interference only shows up for $j = 2$.

PWCPAs in $\Lambda_b^0 \to p\pi^-\pi^0$

dependence on strong phase δ $\qquad\qquad$ $\delta = \pi/2$







The measurement method for $A_{CP}^{(j)}$.

P_j-weighted event yields:

$$\mathcal{N}_{j-\text{weighted}} \equiv \sum_k P_j(c_{\theta^*_{1,k}}).$$

The experimental values of the PWCPAs:

$$A_{CP}^{(j)} = \frac{\mathcal{N}_{j-\text{weighted}} - \bar{\mathcal{N}}_{j-\text{weighted}}}{\mathcal{N}_{j-\text{weighted}} + \bar{\mathcal{N}}_{j-\text{weighted}}}.$$

3 Summary and Outlook

Summary and Outlook

- intoducing PWCPA in multi-body decays of heavy hadron
- PWCPA can be measured in decays with any spin configuration and with any numbers of particles in the final state
- CPV in baryon decays could be hunt through measurements of PWCPA

Thanks for your attention!