Decay-Angular-Distribution correlated CP violation in heavy baryon decays

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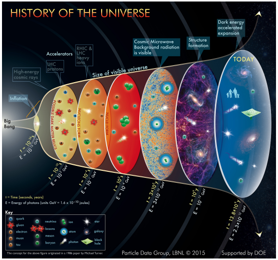
1. background and motivation

CPV and Matter-anti-Matter Asymmetry of the Universe

Sakharov's criteria

- B-violation;
- C, and CP violation;
- out of thermal equilibrium.



sphaleron transition:

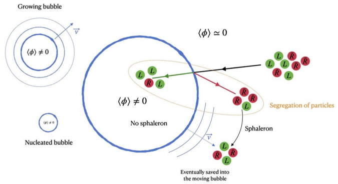
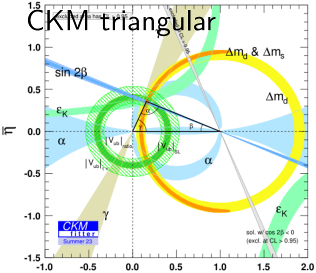


Figure 8. Sketch of electroweak baryogenesis based on nucleated bubbles and their growth. In this sketch, an equal amount of left-handed particles and right-handed antiparticles are considered (the right-handed particles and left-handed antiparticles are not participating in a sphaleron process). After particles are segregated—this is the chiral asymmetry—they are converted into a baryon

CKM triangular



- CPV has been observed in K, B, and D meson sectors
- CPV hasn't been observed in baryon decay processes

1964
Strange particles: *CP* violation in K meson decays
J. W. Cronin, V. L. Fitch *et al.*

1999, 2001
Strange particles: *CP* violation in decay
KTeV and NA48 collaborations

2001
Beauty particles: Time-dependent *CP* violation in B^0 meson decays
BaBar and Belle collaborations

2004
Beauty particles: Time-integrated *CP* violation in B^0 meson decays
BaBar and Belle collaborations

2012
Beauty particles: *CP* violation in B^+ meson decays
LHCb collaboration

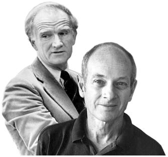
2013
Beauty-strange particles: Time-integrated *CP* violation in B_s^0 meson decays
LHCb collaboration

2019
Charm particles: *CP* violation in D^0 meson decays
LHCb collaboration

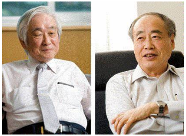
2020
Beauty-strange particles: Time-dependent *CP* violation in B_s^0 meson decays
LHCb collaboration

TODAY

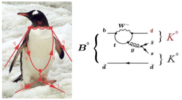
Cronin and Fitch

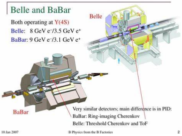


小林、益川

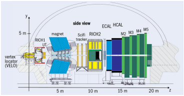


penguin diagram





LHCb



baryonic CPV in theory

CPV in hyperon

CPV corresponding to decay parameters: $\mathcal{O}(10^-5) - \mathcal{O}(10^-4)$

overall CPV in Λ_b

- Generalized factorization [Hsiao, Geng, 2015; Liu, Geng, 2021]:
  lost of non-factorizable contributions, such as W-exchange diagrams.
- QCDF [Zhu, Ke, Wei, 2016, 2018]:
  based on diquark picture, no W-exchange diagrams.
- PQCD [Lü, Wang, Zou, Ali, Kramer, 2009]:
  only considering leading twist baryon LCDAs.

	measurement	Generalized factorization	QCDF	PQCD
$Br(\Lambda_b \to p\pi^-) \times 10^{-6}$	4.5 ± 0.8	4.2 ± 0.7	$4.66^{+2.22}_{-1.81}$	$4.11 \sim 4.57$
$Br(\Lambda_b \to pK^-) \times 10^{-6}$	5.4 ± 1.0	4.8 ± 0.7	$1.82^{+0.97}_{-1.07}$	$1.70 \sim 3.15$
$A_{CP}(\Lambda_b \to p\pi^-)\%$	-2.5 ± 2.9	-3.9 ± 0.2	-32^{+49}_{-1}	$-3.74 \sim -3.08$
$A_{CP}(\Lambda_b \to pK^-)\%$	-2.5 ± 2.2	5.8 ± 0.2	-3^{+25}_{-4}	$8.1 \sim 11.4$

CPV in cascade decays of Λ_b

PRD108,L111901

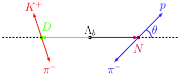


FIG. 1: Sketch of the full decay chain $\Lambda_b \to D(\to K^+\pi^-)N(\to p\pi^-)$.

2211.07332

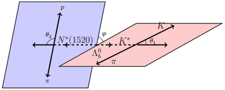
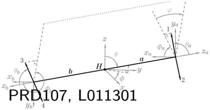


FIG. 1. The depicted figures of angular distributions of $\Lambda_b^0 \to N^*(1520)K^* \to p\pi K\pi$. The angle θ_1, θ_2 are defined in the rest frames of K^* and $N^*(1520)$, respectively. These angles also correspond to the definition of angular distribution (13).



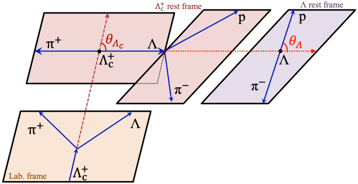
PRD107, L011301

FIG. 1. Illustration of the kinematic variables for the four-body decay $H \to a(\to 12)b(\to 34)$. The reference frames is defined according to the Jackson convention. Note that θ and ϕ are defined in the c. m. frame of H, while $\theta_{a(b)}$ and $\phi_{a(b)}$

CPV in baryon: exp. search

CPV search in hyperon BESIII, STCF (Jin-Lin Fu's talk) and Belle
CPV search in charmed baryon: See Pei-Rong Li's talk
CPV search in bottom baryon LHCb: See Ji-bo He and Jia-Jie Han's talk

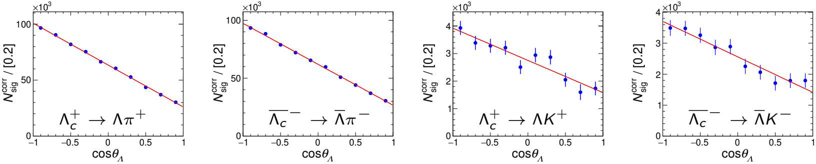
Belle: α-induced CPA (Sci.Bull. 68 (2023) 583), will seen in Sen Jia's talk



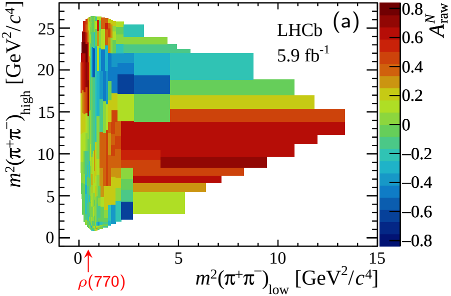
$$\frac{dN}{d\cos\theta_\Lambda} \propto 1 + \alpha_{\Lambda_c^+}\alpha_- \cos\theta_\Lambda$$

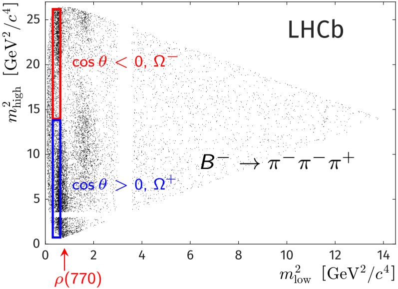
$$A_{CP}^{\alpha}(\Lambda \to p\pi) = \frac{\alpha_- + \alpha_+}{\alpha_- - \alpha_+} \approx \frac{\alpha_{\Lambda_c^+}\alpha_- - \alpha_{\Lambda_c^-}\alpha_+}{\alpha_{\Lambda_c^+}\alpha_- + \alpha_{\Lambda_c^-}\alpha_+}$$

$$A_{CP}^{\alpha}(\Lambda \to p\pi) = +0.013 \pm 0.007 \pm 0.011$$



what next?





Forward-Backward Asymmetry (FBA)

Interference of S- and P-wave, with a strong phase δ

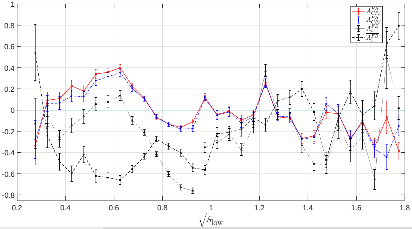
$$\mathcal{A} = a_S + e^{i\delta} a_P \cos\theta, \quad a_{S(P)} = a^{\rm tree}_{S(P)} + a^{\rm penguin}_{S(P)}$$

$$A^{FB}_{B^-} = \frac{N^{\Omega^+}_{B^-} - N^{\Omega^-}_{B^-}}{N^{\Omega^+}_{B^-} + N^{\Omega^-}_{B^-}} = \frac{\Re(\langle a_S^* a_P e^{i\delta}\rangle)}{|\langle a_P\rangle|^2/3 + |\langle a_S\rangle|^2}.$$

$$A^{FB}_{CP} = \frac{1}{2}(A^{FB}_{B^-} - A^{FB}_{B^+}).$$

(ZHZ, PLB820, 136537)

Y.-R. Wei, ZHZ, PRD 106(2022), 113002



strong phase between S and P waves

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

$$\mathcal{A} = a_S + e^{i\delta} a_P \cos\theta, \quad a_{S(P)} = a_{S(P)}^{\text{tree}} + a_{S(P)}^{\text{penguin}}$$

$$A_{B^-}^{FB} = \frac{N_{B^-}^{\Omega^+} - N_{B^-}^{\Omega^-}}{N_{B^-}^{\Omega^+} + N_{B^-}^{\Omega^-}} = \frac{\Re(\langle a_S^* a_P e^{i\delta} \rangle)}{|\langle a_P \rangle|^2/3 + |\langle a_S \rangle|^2}.$$

$$A_{CP}^{FB} = \frac{1}{2}(A_{B^-}^{FB} - A_{B^+}^{FB}).$$

$\Lambda_c^+ \to \Xi^0 K$

From Pei-Rong Li's slides

Strong phase shift: $-1.55 \pm 0.25 \pm 0.05$ or $1.59 \pm 0.25 \pm 0.05$ $\alpha \propto \cos \sim 0.02$

Very different from hyperon decays ➡ strong phase ~ 0

Only a few measurements

$\Lambda^0 \to p\pi^-$

$\alpha = +0.65 \pm 0.02$
$\beta = -0.10 \pm 0.07$
$\gamma = +0.75 \pm 0.02$
$\beta/\alpha = -0.16 \pm 0.10$
$\Delta = -\arctan(\beta/\alpha) = 9.0^\circ \pm 5.5^\circ$
$|p|/|s| = 0.38 \pm 0.01$

Phys. Rev. Lett. **19**, 391 (1967)

$\Xi^- \to \Lambda^0 \pi^-$

Parameter	This work
$\xi_P - \xi_S$	$(1.2 \pm 3.4 \pm 0.8) \times 10^{-2}$ rad
$\delta_P - \delta_S$	$(-4.0 \pm 3.3 \pm 1.7) \times 10^{-2}$ rad

Strong phase shift

Nature 606 (2022) 7912, 64-69

cascade decays $H \to h_1 R$ (weak), $R \to h_2 h_3$ (strong)

2. Decay angular distribtuion induced CPA in cascade decays

analysis of heavy hadron cascade decays

cascade decay in bottom and charmed hadrons

bottom or charmed hadrons are common to decay cascadely a two-body weak decay followed by a strong one

angular distribution of $\mathbb{B} \to \mathcal{B} M$ and CPV

Suppose $\mathcal{B}$ or M decays through strong interactions into two granddaughter hadrons (denoted as 1 and 2),

$$\overline{|\mathcal{M}^J|^2} = \sum_{\substack{0 \le j \le 2s_R \\ j \text{ even}}} w^{(j)} P_j \left(c_{\theta_1^*} \right),$$

$$w^{(j)} \sim \mathcal{W}^{(j)} = \sum_{\sigma} (-)^{\sigma - n_R} \langle s_R - \sigma s_R \sigma | s_R s_R j 0 \rangle \sum_{\lambda_3} \left| \mathcal{F}^J_{\sigma \lambda_3} \right|^2 .$$

$$\alpha^{(j)} = \frac{w^{(j)}}{w^{(0)}}, \qquad A_{CP}^{(j)} = \frac{1}{2}(\alpha^{(j)} - \overline{\alpha^{(j)}}).$$

Physical interpretation of $\alpha^{(j)}$: contain the polarization of R.

interference pattern: helicity form v.s. canonical form

$$\mathcal{W}^{(j)} = \sum_{ls,l's'} \rho^{j}_{ls,l's'} a^{J}_{ls} a^{J*}_{l's'},$$

$$\mathcal{F}^{J}_{\sigma\lambda_3} = \sum_{ls} \left(\frac{2l+1}{2J+1}\right)^{\frac{1}{2}} \langle l0s\sigma-\lambda_3|lsJ\sigma-\lambda_3\rangle\langle s_{R_i}\sigma s_3-\lambda_3|s_{R_i}s_3s\sigma{-}\lambda_3\rangle a^{J}_{ls},$$

$$\begin{aligned}\rho^{j}_{ls,l's'} &= \frac{\sqrt{(2l+1)(2l'+1)}}{2J+1}\sum_{\sigma\lambda_3}(-)^{\sigma-n_R}\langle s_R-\sigma s_R\sigma|s_Rs_Rj0\rangle \\ &\times \langle l0s\ \sigma{-}\lambda_3|lsJ\ \sigma{-}\lambda_3\rangle\langle s_R\sigma s_3\ {-}\lambda_3|s_Rs_3s\ \sigma{-}\lambda_3\rangle \\ &\times \langle l'0s'\ \sigma{-}\lambda_3|l's'J\ \sigma{-}\lambda_3\rangle\langle s_R\sigma s_3\ {-}\lambda_3|s_Rs_3s'\ \sigma{-}\lambda_3\rangle.\end{aligned}$$

Properties of ρ

1. *Nonzero elements satisfy the triangle inequality (necessary condition):*

$$|l - l'| \leq j \leq l + l',$$
$$|s - s'| \leq j \leq s + s'.$$

2. *Zero elements:*

$$\rho^j_{ls,l's'} = 0, \text{ if} \begin{cases} j \text{ is even, } l \text{ and } l' \text{ one is even, the other is odd;} \\ j \text{ is odd, both } l \text{ and } l' \text{ are even or odd.} \end{cases}$$

important!

interference between amplitudes with different parities are absent in the decay angular distributions!

total number of independent canonical amplitudes for $\mathbb{B} \to \mathcal{B}M$

$(2s_1 + 1)(2s_2 + 1) - \kappa(\kappa + 1), \quad \kappa = \min\{s_1 + s_2 - s_3, 0\}$.
half of which are parity even (odd).

analysis of heavy hadron cascade decays

Table: typical decay

weak mode	a_{ls} parity-even	a_{ls} parity-odd	strong mode
$\frac{1}{2}^+ \to \frac{1}{2}^+ + 1^-$	$a_{1\frac{1}{2}},\ a_{1\frac{3}{2}}$	$a_{0\frac{1}{2}},\ a_{2\frac{3}{2}}$	$\frac{1}{2}^+ \to \frac{1}{2}^+ + 0^-$ $1^- \to 0^- + 0^-$
$\frac{1}{2}^+ \to \frac{1}{2}^+ + 1^+$	$a_{0\frac{1}{2}},\ a_{2\frac{3}{2}}$	$a_{1\frac{1}{2}},\ a_{1\frac{3}{2}}$	$\frac{1}{2}^+ \to \frac{1}{2}^+ + 0^-$ $1^+ \to 0^- + 0^-$
$\frac{1}{2}^+ \to \frac{3}{2}^+ + 1^-$	$a_{1\frac{1}{2}},\ a_{1\frac{3}{2}}\ ,\ a_{3\frac{5}{2}}$	$a_{0\frac{1}{2}},\ a_{2\frac{3}{2}},\ a_{2\frac{5}{2}}$	$1^- \to 0^- + 0^-$ $\frac{3}{2}^+ \to \frac{1}{2}^+ + 0^-$ $\frac{3}{2}^+ \to \frac{1}{2}^+ + 1^-$
$\frac{1}{2}^+ \to \frac{3}{2}^+ + 2^+$	$a_{1\frac{1}{2}},\ a_{1\frac{3}{2}}\ ,\ a_{3\frac{5}{2}}$	$a_{0\frac{1}{2}},\ a_{2\frac{3}{2}},\ a_{2\frac{5}{2}}$	$\frac{3}{2}^+ \to \frac{1}{2}^+ + 0^-$ $2^+ \to 0^- + 0^-$

Typical example: $\frac{1}{2}^+ \to \frac{1}{2}^+ + 1^-(\to 0^- + 0^-)$

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta} = \frac{1}{2} + \frac{\alpha^{(2)}}{2}P_2(c_\theta) = \frac{1}{2} - \frac{\mathcal{W}^{(2)}}{2\sqrt{2}\mathcal{W}^{(0)}}P_2(c_\theta).$$

$$A_{CP}^{(2)} = \frac{1}{2}(\alpha^{(2)} - \overline{\alpha^{(2)}})$$

$$\begin{aligned}\mathcal{W}^{(0)} &= \frac{1}{\sqrt{3}}\left(|\mathcal{F}_{1\frac{1}{2}}|^2 + |\mathcal{F}_{-1-\frac{1}{2}}|^2 + |\mathcal{F}_{0\frac{1}{2}}|^2 + |\mathcal{F}_{0\ -\frac{1}{2}}|^2\right)\\ &= \frac{1}{2\sqrt{3}}\left(|a_{0\frac{1}{2}}|^2 + |a_{1\frac{1}{2}}|^2 + |a_{1\frac{3}{2}}|^2 + |a_{2\frac{3}{2}}|^2\right),\end{aligned}$$

$$\begin{aligned}\mathcal{W}^{(2)} &= \frac{1}{\sqrt{3}}\left[\frac{1}{\sqrt{2}}\left(|\mathcal{F}_{1\frac{1}{2}}|^2 + |\mathcal{F}_{-1-\frac{1}{2}}|^2\right) - \sqrt{2}\left(|\mathcal{F}_{0\frac{1}{2}}|^2 + |\mathcal{F}_{0\ -\frac{1}{2}}|^2\right)\right]\\ &= \frac{1}{2\sqrt{3}}\left[\frac{1}{2}\left(|a_{1\frac{3}{2}}|^2 + |a_{2\frac{3}{2}}|^2\right) - \frac{5\sqrt{2}}{3}\Re\left(a_{0\frac{1}{2}}a^*_{2\frac{3}{2}} + a_{1\frac{1}{2}}a^*_{1\frac{3}{2}}\right)\right].\end{aligned}$$

According to the analysis above, we propose to search for decay-distribution-correlated CPV in cascade decays of the types

- 1) $\mathbb{B} \to \mathcal{B}M$, $M \to M_1 M_2$, with the spin of M is nonzero;
  - $b \to d u \bar{u}$ transition: $\Lambda_b^0 \to p\rho(770)^+$, $\Lambda_b^0 \to N(1520)^* \rho(770)^+$;
  - $b \to s u \bar{u}$ transition: $\Lambda_b^0 \to \Lambda\rho(770)^0$, $\Lambda_b^0 \to pK^*(892)^-$, $\Lambda_b^0 \to N(1520)K^*$;
  - $c \to u d \bar{d}$ transitions: $\Lambda_c^+ \to p\rho(770)^0$, $\Xi_c^+ \to p\overline{K^*}(892)^0$;
  - $c \to u s \bar{s}$ transitions: $\Lambda_c^+ \to p\phi$, $\Lambda_c^+ \to \Sigma^+ K^*(892)^0$.
- 2) $\mathbb{B} \to \mathcal{B}M$, $\mathcal{B} \to \mathcal{B}' M'$, with the spin of the baryon resonance $\mathcal{B}$ is larger than $\frac{1}{2}$, and the spin of M is nonzero.
  - $c \to u d \bar{d}$ transitions: $\Lambda_c^+ \to N(1520)^* \rho(770)^0$, $\Xi_c^+ \to N(1520)^* \overline{K^*}(892)^0$;
  - $c \to u s \bar{s}$ transitions: $\Lambda_c^+ \to N(1520)^* \phi$, $\Lambda_c^+ \to \Sigma^+ K^*(892)^0$;
  - $b \to d u \bar{u}$ transition: $\Lambda_b^0 \to N(1520)^* \rho(770)^+$;
  - $b \to s u \bar{u}$ transition: $\Lambda_b^0 \to N(1520)K^*$.

Beyond Generalized Factorization

Only Strong Phase is not enough, we has to go beyond Generalized Factorization

$$a_{ls} = (\lambda^T_{CKM} a^T + \lambda^P_{CKM} a^P) K_{ls} e^{i\delta_{ls}}$$

$\alpha^{(2)}$ will be independent of CKM, hence No CPV corresponding to $\alpha^{(2)}$.
Go beyond GF:

$$a_{ls} = (\lambda^T_{CKM} a^T_{ls} + \lambda^P_{CKM} a^P_{ls}) K_{ls} e^{i\delta_{ls}}$$

3 Summary and Outlook

Summary and Outlook

- CPV hasn't observed in the baryon sector,
- interfer. of intermediate resonances plays important role for CP violation in three-body decays of bottom meson,
- decay-angular-distribution correlated CPV is also worth searching in bottom or charmed baryon decays,
- Outlook: More CPV observables in four-body decays.

Thank you for your attentions!