回到未来2022

LHCb是如何与重子产生过程的CP破坏失之交臂的

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In collaboration with 郭新恒 杨健宇

LHCb Physics 2025
2025.04.25-28 湖北 武汉

1. 背景
2. 通过完全角关联的分析研究四体级联衰变中的CPA
3. LHCb是如何与重子对产生过程的CP破坏失之交臂的
4. 总结展望

1. 背景

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

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Based on 2403.05011
In collaboration with Yu-Jie Zhao and Xin-Heng Guo

University of South China (南华大学)

第三届强子与重味物理理论与实验联合研讨会
04/05/2024-04/09/2024 武汉

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

email: zher
Based
In collaboration with

University of

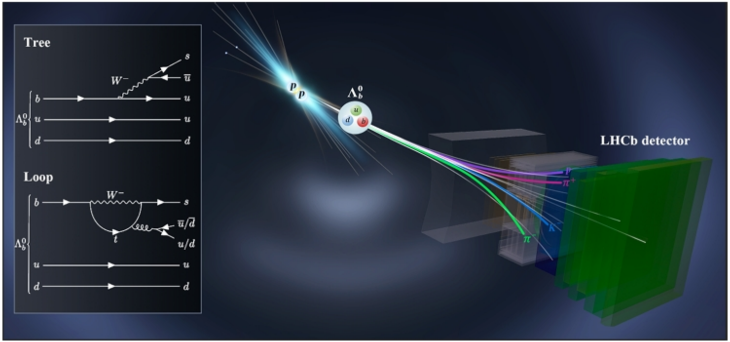
第三届强子与重味
04/05/202

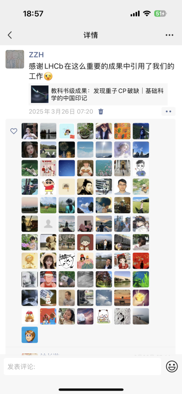
Summary and Outlook

- 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!

CP 破坏在底重子4体衰变中被LHCb发现



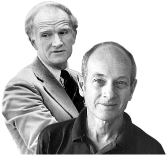


$$A_{CP}(pK^-\pi^+\pi^-) = (2.45 \pm 0.46 \pm 0.10)\%$$
$$A_{CP}(R(p\pi^+\pi^-)K^-) = (5.4 \pm 0.9 \pm 0.1)\%$$
$$A_{CP}(R(pK^-)R(\pi^+\pi^-)) = (5.3 \pm 1.3 \pm 0.2)\%$$

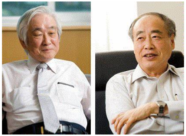
CPV history

- pure mesonic processes: CPV has been observed in K, B, and D meson sectors
- baryonic decays: CPV observed in $\Lambda_b \to pK^-\pi^+\pi^-$.
- baryon-anti-baryon production processes: No CPV was confirmed.

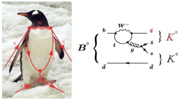
Cronin and Fitch

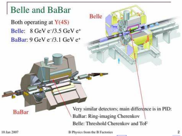


小林、益川

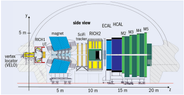


penguin diagram





LHCb



CPV history

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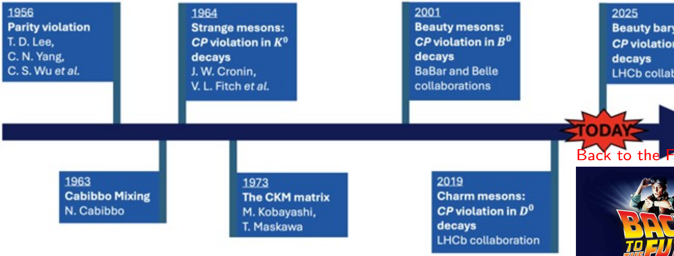
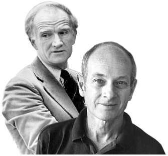
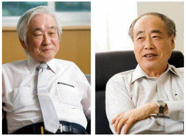


Back to the Future 2022

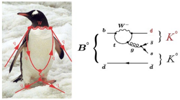
Cronin and Fitch

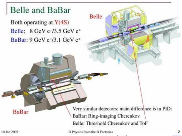


小林、益川

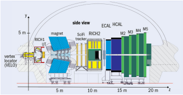


penguin diagram





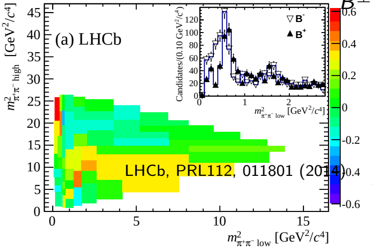
LHCb



- I. regional CPA (localized CPA)
- II. CPAs corresponding in decay angular correlations
- III. complementary CPA observables in resonances interferences

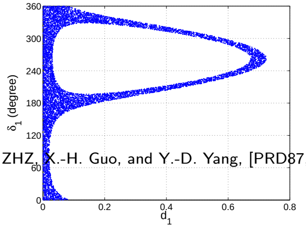
I. regional CPA (localized CPA)

Interference of $\rho^0(770)$ and $f_0(500)$: non-trivial dependence of CPA on $m^2_{\pi\pi,\text{high}}$ or $m^2_{K^+\pi^-}$



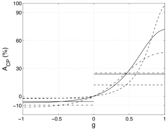
LHCb, PRL112, 011801 (2014)

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



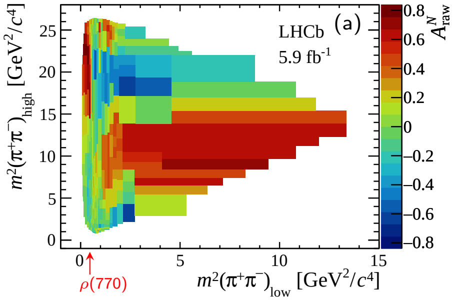
ZHZ, X.-H. Guo, and Y.-D. Yang, [PRD87, 076007 (2013)]

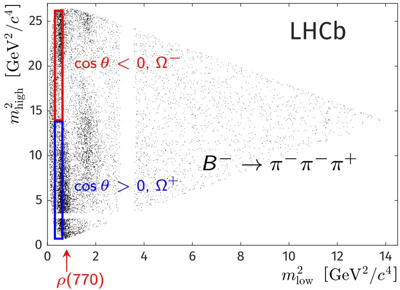
$$
\begin{aligned}
\mathcal{A} &= a_S + a_P c_\theta \\
a_{S(P)} &= a^{\text{tree}}_{S(P)} + a^{\text{penguin}}_{S(P)} \\
A_{CP} &\propto \frac{1}{3} A^P_{CP} \cos^2\theta + \frac{|\langle a_S\rangle|^2 + |\langle \bar{a}_S\rangle|^2}{|\langle a_P\rangle|^2 + |\langle \bar{a}_P\rangle|^2} A^S_{CP} + \frac{\Re(\langle a_P a^*_S\rangle - \langle \bar{a}_P \bar{a}^*_S\rangle)}{|\langle a_P\rangle|^2 + |\langle \bar{a}_P\rangle|^2} \cos\theta,
\end{aligned}
$$



II. CPAs corresponding in decay angular correlations

Forward-Backward Asymmetry (FBA) induced CPA (FB-CPA)

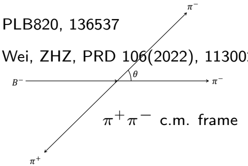




$$A^{FB}_{B^-} = \frac{N^{\Omega^+}_{B^-} - N^{\Omega^-}_{B^-}}{N^{\Omega^+}_{B^-} + N^{\Omega^-}_{B^-}} = \frac{\Re(\langle a_S^* a_P e^{i\delta}\rangle)}{|\langle a_P\rangle|^2/3 + |\langle a_S\rangle|^2}.$$

ZHZ, PLB820, 136537

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



2-fold FB-CPA in 4-body decay

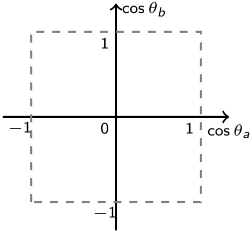
Applications to $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$: $N(1440) - N(1520)$ and $f_0(500) - \rho(770)$

$\Lambda_b^0 \to N(\to p\pi^-) f/\rho(\to \pi^+\pi^-)$: c_{θ_a} and c_{θ_b} are correlated.

$$
(\Gamma_{jl}) \sim \begin{pmatrix} \text{Non-int} & (N_{1440}N_{1520})|f|^2,\ (N_{1440}N_{1520})|\rho|^2 & \text{Non-int} \\ (f\rho)|N_{1440}|^2,\ (f\rho)|N_{1520}|^2 & (N_{1440}N_{1520}f\rho)_{GI} & (f\rho)|N_{1520}|^2 \\ \text{Non-int} & (N_{1440}N_{1520})|\rho|^2 & \text{Non-int} \end{pmatrix}.
$$

GI term corresponding to $\cos\theta_a \cos\theta_b$

2 Dim Phase Space



two-fold FBA (TFFBA): $j = 1 = l$

$$\tilde{A}^{11} = \frac{(N_I - N_{II} + N_{III} - N_{IV})}{N}$$

TFFBA-CPA

$$A_{CP}^{11} = \frac{1}{2}(\tilde{A}^{11} - \overline{\tilde{A}^{11}})$$

II. CPAs corresponding in decay angular correlations

Partial-Wave CPAs

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

$$w^{(j)} = \sum_{ii'} \left\langle \frac{\mathcal{S}_{ii'}^{(j)} \mathcal{W}_{ii'}^{(j)}}{\mathcal{I}_{R_i} \mathcal{I}_{R_{i'}}} \right\rangle,$$

$$\mathcal{W}_{ii'}^{(j)} = \sum_{\sigma \lambda_3} (-)^{\sigma - s} \langle s_{R_i} - \sigma s_{R_{i'}} \sigma | s_{R_i} s_{R_{i'}} j 0 \rangle \mathcal{F}^J_{R_i, \sigma \lambda_3} \mathcal{F}^{J*}_{R_{i'}, \sigma \lambda_3},$$

$$\mathcal{S}_{ii'}^{(j)} = \sum_{\lambda_1' \lambda_2'} (-)^{s-\lambda'} \langle s_{R_i} - \lambda' s_{R_{i'}} \lambda' | s_{R_i} s_{R_{i'}} j 0 \rangle \mathcal{F}^{R_i, s_{R_i}}_{\lambda_1' \lambda_2'} \mathcal{F}^{R_{i'}, s_{R_{i'}} *}_{\lambda_1' \lambda_2'}$$

$$A^j_{CP} = \frac{w^j - \overline{w}^j}{w^j + \overline{w}^j}$$

ZHZ, X.-H. Guo, JHEP07(2021)177

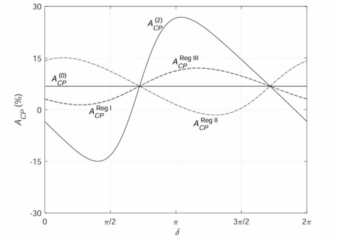


Figure 1. The PW*CP*A $A_{CP}^{(2)}$ (solid curvy line) for $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ near the resonance $\Delta^0(1232)$ as a function of the strong phase δ. The regional *CP* asymmetry $A_{CP}^{(0)}$ (solid straight line), $A_{CP}^{\text{Reg I}}$ (dotted line), $A_{CP}^{\text{Reg II}}$ (dash-dotted line), and $A_{CP}^{\text{Reg III}}$ (dashed line) are also shown for comparison. The difference between $A_{CP}^{\text{Reg I}}$ and $A_{CP}^{\text{Reg III}}$ is very tiny. Other PW*CP*As $A_{CP}^{(1)}$ and $A_{CP}^{(3)}$ are not shown due to the reason explained in the text. The invariant mass squared $s_{p\pi}$ is integrated from $(m_\Delta - \Gamma_\Delta)^2$ to $(m_\Delta + \Gamma_\Delta)^2$.

III. complementary CPA observables in resonance-interf.

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

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

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

$$A_{CP}^2 + \tilde{A}_{CP}^2 \sim \sin^2\phi$$

III. complementary CPA observables in resonance-interf.

LHCb, PRD 101 (2020) 012006 [1909.05212]

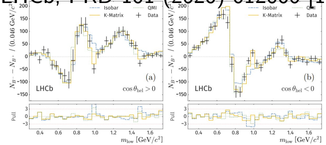
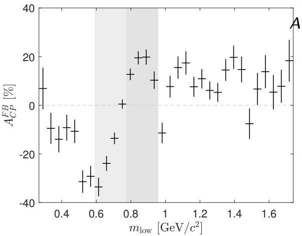


Figure 12: Raw difference in the number of B^- and B^+ candidates in the low $m_{\rm low}$ region, for (a) positive, and (b) negative cosine of the helicity angle. The pull distribution is shown below each fit projection.

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

$$A_{CP}^{FB,{\rm ave}} = \frac{\sum_{k=8}^{15}[(N_{B-} - N_{B+})_{\cos\theta_{\rm hel}>0,k} - (N_{B-} - N_{B+})_{\cos\theta_{\rm hel}<0,k}]}{\sum_{k=8}^{15}[(N_{B-} + N_{B+})_{\cos\theta_{\rm hel}>0,k} + (N_{B-} + N_{B+})_{\cos\theta_{\rm hel}<0,k}]} = (0.8 \pm 1.0)\%$$

PRD 110 (2024) L111301 [2407.20586]



$$A_{CP}^{FB,\Im} = \frac{\left(\sum_{k=12}^{15} - \sum_{k=8}^{11}\right)\left[(N_{B-} - N_{B+})_{\cos\theta_{\rm hel}>0,k} - (N_{B-} - N_{B+})_{\cos\theta_{\rm hel}<0,k}\right]}{\sum_{k=8}^{15}\left[(N_{B-} + N_{B+})_{\cos\theta_{\rm hel}>0,k} + (N_{B-} + N_{B+})_{\cos\theta_{\rm hel}<0,k}\right]} = (13.2 \pm 1.0)\%$$

2 通过完全角关联的分析研究四体级联衰变中的CPA

4体级联衰变运动学

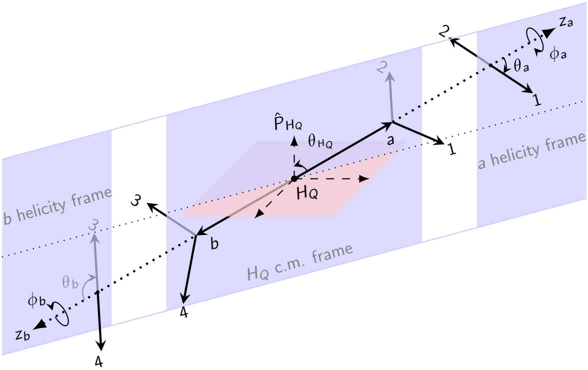


Figure: Illustration of the five angles defined in the main text for the decay $H_Q \to a(\to 12)b(\to 34)$.

4体级联衰变的振幅模方

The decay amplitude squared (DAS) for $H_Q \to a_k(\to 12)b_m(\to 34)$

$$\overline{|\mathcal{A}|^2} \propto \sum_{\sigma_a\sigma_{a'}\sigma_b\sigma_{b'}} \sum_{j_a} \sum_{j_b} \gamma^{j_a j_b}_{\sigma_a\sigma_b\sigma_{a'}\sigma_{b'}} \Omega^{j_a j_b}_{\sigma_a\sigma_b\sigma_{a'}\sigma_{b'}},$$

The kinematical factors

$$\Omega^{j_a j_b}_{\sigma_a\sigma_b\sigma_{a'}\sigma_{b'}} \equiv P_{\sigma_{ab},\sigma_{a'b'}}(\theta_{H_Q}) d^{j_a}_{\sigma_{a'a},0}(\theta_a) d^{j_b}_{\sigma_{b'b},0}(\theta_b) e^{i(\bar{\sigma}\varphi+\hat{\sigma}\phi)},$$

j_a 和 j_b 的限制条件

The first one is the triangular inequality

$$|s_{a_k} - s_{a_{k'}}| \leqslant j_a \leqslant s_{a_k} + s_{a_{k'}}.$$

that j_a must satisfied for a given pair of a_k and $a_{k'}$.
Parity symmetry in the strong decay $a \to 12$

$$(-)^{j_a} = \Pi_{a_k} \Pi_{a_{k'}},$$

If let a_k and $a_{k'}$ run over all the allowed possibilities, we obtain all the allowed values of j_a.

非极化H_Q的角关联

For unpolarized H_Q

$$\overline{|\mathcal{A}|^2} \propto \sum_{j_a,j_b,\sigma} \left[\Re(\gamma_\sigma^{j_a j_b})\Psi_\sigma^{j_a j_b} - \Im(\gamma_\sigma^{j_a j_b})\Phi_\sigma^{j_a j_b}\right],$$

The kinematical factors merge into

$$\Omega_\sigma^{j_a j_b} = d^{j_a}_{\sigma,0}(\theta_a) d^{j_b}_{\sigma,0}(\theta_b) e^{i\sigma\varphi}.$$

Entanglement between kinematical angles!

Denote the kinematic factors as

$$\Phi_{\sigma}^{j_a j_b} = d^{j_a}_{\sigma,0}(\theta_a) d^{j_b}_{\sigma,0}(\theta_b) \sin\sigma\varphi,$$

$$\Psi_{\sigma}^{j_a j_b} = d^{j_a}_{\sigma,0}(\theta_a) d^{j_b}_{\sigma,0}(\theta_b) \cos\sigma\varphi,$$

j_a \ j_b	0	1	2
0	$\Psi_0^{00} = 1$ trivial	$\Psi_0^{01} c_{\theta_b}$	$\Psi_0^{02} = \frac{1}{2}(c^2_{\theta_b} - 1)$
1	$\Psi_0^{10} = c_{\theta_a}$	$\Psi_0^{11} = c_{\theta_a} c_{\theta_b}$ $\Psi_1^{11} = s_{\theta_a} s_{\theta_b} c_{\varphi}$ $\Phi_1^{11} = s_{\theta_a} s_{\theta_b} s_{\varphi}$	$\Psi_0^{12} = \frac{1}{2} c_{\theta_a}(3c^2_{\theta_b} - 1)$ $\Psi_1^{12} = s_{\theta_a} s_{\theta_b} c_{\theta_b} c_{\varphi}$ $\Phi_1^{12} = s_{\theta_a} s_{\theta_b} c_{\theta_b} s_{\varphi}$
2	$\Psi_0^{20} = \frac{1}{2}(3c^2_{\theta_a} - 1)$	$\Psi_0^{21} = \frac{1}{2}(3c^2_{\theta_a} - 1) c_{\theta_b}$ $\Psi_1^{21} = s_{\theta_a} c_{\theta_a} s_{\theta_b} c_{\varphi}$ $\Phi_1^{21} = s_{\theta_a} c_{\theta_a} s_{\theta_b} s_{\varphi}$	$\Psi_0^{22} = \frac{1}{4}(3c^2_{\theta_a} - 1)(3c^2_{\theta_b} - 1)$ $\Psi_1^{22} = s_{\theta_a} c_{\theta_a} s_{\theta_b} c_{\theta_b} c_{\varphi}$ $\Phi_1^{22} = s_{\theta_a} c_{\theta_a} s_{\theta_b} c_{\theta_b} s_{\varphi}$ $\Psi_2^{22} = \frac{3}{8} s^2_{\theta_a} s^2_{\theta_b} c_{2\varphi}$ $\Phi_2^{22} = \frac{3}{8} s^2_{\theta_a} s^2_{\theta_b} s_{2\varphi}$

Table: The first few angular correlations.

CPV observables

$$A_{CP}^{\mathcal{Y}_\sigma^{j_a j_b}} \equiv \frac{1}{2}\left(A^{\mathcal{Y}_\sigma^{j_a j_b}} - \overline{A}^{\mathcal{Y}_\sigma^{j_a j_b}}\right),$$

Decay angular correlation asymmetries

$$A^{\mathcal{Y}_\sigma^{j_a j_b}} \equiv \frac{1}{N}\left(N_{\mathcal{Y}_\sigma^{j_a j_b}>0} - N_{\mathcal{Y}_\sigma^{j_a j_b}<0}\right),$$

$$\overline{A}^{\mathcal{Y}_\sigma^{j_a j_b}} \equiv \frac{1}{\overline{N}}\left(\overline{N}_{\overline{\mathcal{Y}}_\sigma^{j_a j_b}>0} - \overline{N}_{\overline{\mathcal{Y}}_\sigma^{j_a j_b}<0}\right)$$

CPV observables

$$\tilde{A}_{CP}^{\mathcal{Y}_\sigma^{j_a j_b}} \equiv \frac{1}{2}\left(A^{\mathcal{Y}_\sigma^{j_a j_b}} - \overline{A}^{\mathcal{Y}_\sigma^{j_a j_b}}\right),$$

Decay angular correlation asymmetries

$$\tilde{A}^{\mathcal{Y}_\sigma^{j_a j_b}} \equiv \frac{1}{N}\left(N_{\mathrm{sgn}\cdot\mathcal{Y}_\sigma^{j_a j_b}>0} - N_{\mathrm{sgn}\cdot\mathcal{Y}_\sigma^{j_a j_b}<0}\right),$$

$$\overline{\tilde{A}}^{\mathcal{Y}_\sigma^{j_a j_b}} \equiv \frac{1}{\overline{N}}\left(\overline{N}_{\mathrm{sgn}\cdot\overline{\mathcal{Y}}_\sigma^{j_a j_b}>0} - \overline{N}_{\mathrm{sgn}\cdot\overline{\mathcal{Y}}_\sigma^{j_a j_b}<0}\right)$$

3 LHCb是如何与重子对产生过程的CP破坏失之交臂的

A type of decay involving baryon $B^0 \to p\bar{p}K^+\pi^-$

arXiv > hep-ex > arXiv:2205.08973

Search...

He

High Energy Physics - Experiment

[Submitted on 18 May 2022 (v1), last revised 16 Aug 2023 (this version, v2)]

Search for CP violation using $\hat{T}$-odd correlations in $B^0 \to p\bar{p}K^+\pi^-$ decays

LHCb collaboration

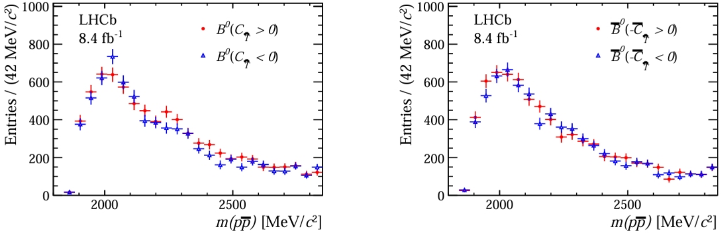
A search for CP and P violation in charmless four-body $B^0 \to p\bar{p}K^+\pi^-$ decays is performed using triple-product asymmetry observables. It is based on proton-proton collision data collected by the LHCb experiment at centre-of-mass energies of 7, 8 and 13 TeV, corresponding to a total integrated luminosity of 8.4 fb^{-1}. The CP- and P-violating asymmetries are measured both in the integrated phase space and in specific regions. No evidence is seen for CP violation. P-parity violation is observed at a significance of 5.8 standard deviations

Comments: All figures and tables, along with any supplementary material and additional information, are available at this https URL (LHCb public pages)
Subjects: **High Energy Physics - Experiment (hep-ex)**
Report number: LHCb-PAPER-2022-003, CERN-EP-2022-083
Cite as: arXiv:2205.08973 **[hep-ex]**
(or arXiv:2205.08973v2 **[hep-ex]** for this version)
https://doi.org/10.48550/arXiv.2205.08973
Journal reference: Phys. Rev. D108 (2023) 032007
Related DOI: https://doi.org/10.1103/PhysRevD.108.032007

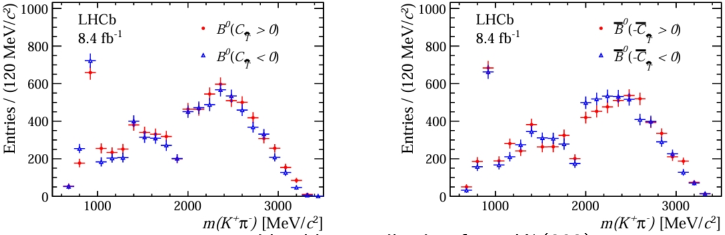
Submission history

From: Matteo Bartolini [view email]
[v1] Wed, 18 May 2022 14:54:32 UTC (517 KB)
[v2] Wed, 16 Aug 2023 12:23:37 UTC (739 KB)

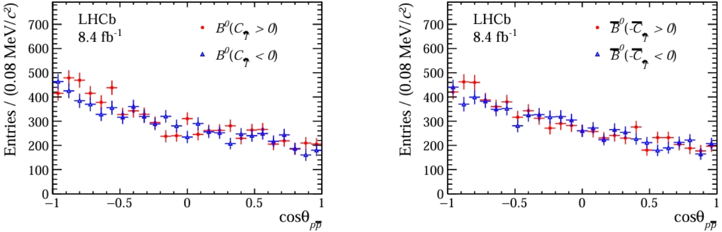
No evidence of CPV (corresponding to T-odd correlation) in $B^0 \to p\bar{p}K^+\pi^-$.
CP破坏就在那里！在其它角关联里！



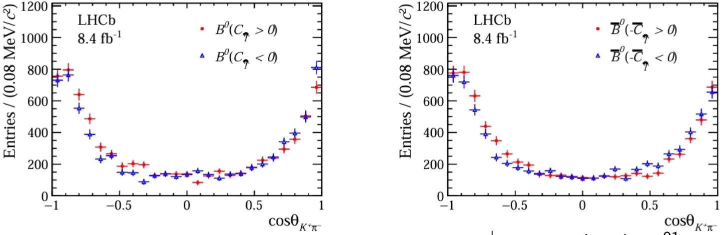
threshold enhancement



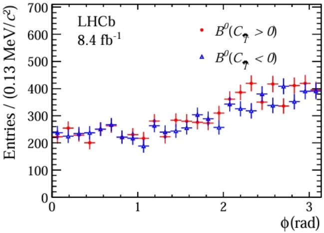
considerable contribution from $K^*(892)$

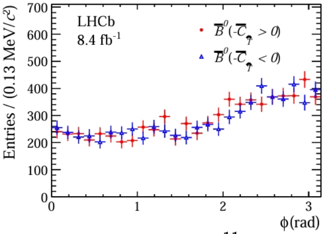


interference of $0^{\pm}$ and $1^{\mp}$, Ψ_0^{10}



slight FBA, interference of $0^{\pm}$ and $K^*(892)$, Ψ_0^{01}





no TPA but clearly left-right asymmetry (LRA), Φ_1^{11}

$$\Psi_0^{01}, \Psi_0^{10}, \Phi_1^{11} \Rightarrow j_a, j_b = 0, 1 \Rightarrow 0^{\pm}\&1^{\mp},\ K^*(892)\&0^+ \Rightarrow j_a, j_b = 0, 1, 2.$$

angular correlations

j_a \ j_b	0	1	2
0	$\Psi_0^{00} = 1$ trivial	$\Psi_0^{01} c_{\theta_b}$	$\Psi_0^{02} = \frac{1}{2}(c_{\theta_b}^2 - 1)$
1	$\Psi_0^{10} = c_{\theta_a}$	$\Psi_0^{11} = c_{\theta_a} c_{\theta_b}$ $\Psi_1^{11} = s_{\theta_a} s_{\theta_b} c_\varphi$ $\Phi_1^{11} = s_{\theta_a} s_{\theta_b} s_\varphi$	$\Psi_0^{12} = \frac{1}{2} c_{\theta_a}(3c_{\theta_b}^2 - 1)$ $\Psi_1^{12} = s_{\theta_a} s_{\theta_b} c_{\theta_b} c_\varphi$ $\Phi_1^{12} = s_{\theta_a} s_{\theta_b} c_{\theta_b} s_\varphi$
2	$\Psi_0^{20} = \frac{1}{2}(3c_{\theta_a}^2 - 1)$	$\Psi_0^{21} = \frac{1}{2}(3c_{\theta_a}^2 - 1) c_{\theta_b}$ $\Psi_1^{21} = s_{\theta_a} c_{\theta_a} s_{\theta_b} c_\varphi$ $\Phi_1^{21} = s_{\theta_a} c_{\theta_a} s_{\theta_b} s_\varphi$	$\Psi_0^{22} = \frac{1}{4}(3c_{\theta_a}^2 - 1)(3c_{\theta_b}^2 - 1)$ $\Psi_1^{22} = s_{\theta_a} c_{\theta_a} s_{\theta_b} c_{\theta_b} c_\varphi$ $\Phi_1^{22} = s_{\theta_a} c_{\theta_a} s_{\theta_b} c_{\theta_b} s_\varphi$ $\Psi_2^{22} = \frac{3}{8} s_{\theta_a}^2 s_{\theta_b}^2 c_{2\varphi}$ $\Phi_2^{22} = \frac{3}{8} s_{\theta_a}^2 s_{\theta_b}^2 s_{2\varphi}$

B^0 sign of $c_{\theta_a} c_{\theta_b} c_\varphi$	Scheme A reg.	Scheme A $A_{\hat{T}}$	Scheme A sign s_φ	Scheme A yie.	Scheme B $m^2_{K\pi} - m^2_{K*} < 0$ reg.	$A_{\hat{T}}$	yie.	Scheme B $m^2_{K\pi} - m^2_{K*} > 0$ reg.	$A_{\hat{T}}$	yie.
$- - +$	0	-16.5 ± 10.1	$+$	41	0	-26.7 ± 17.8	12	8	-5.1 ± 12.8	29
			$-$	57			20			32
$- - -$	1	6.1 ± 9.2	$+$	63	1	5.4 ± 15.8	21	9	6.6 ± 11.6	40
			$-$	55			19			35
$- + +$	2	-1.2 ± 7.0	$+$	101	2	-7.3 ± 11.1	38	10	0.7 ± 9.0	62
			$-$	103			44			61
$- + -$	3	25.3 ± 7.2	$+$	121	3	15.4 ± 12.8	35	11	30.9 ± 8.7	86
			$-$	72			26			46
$+ - +$	4	7.8 ± 11.1	$+$	44	4	-21.9 ± 13.9	20	12	38.4 ± 16.8	25
			$-$	37			32			11
$+ - -$	5	2.9 ± 8.3	$+$	75	5	-13.4 ± 13.9	22	13	11.6 ± 10.2	54
			$-$	70			29			42
$+ + +$	6	-22.8 ± 7.4	$+$	70	6	-19.3 ± 10.4	37	14	-24.1 ± 10.5	34
			$-$	112			55			56
$+ + -$	7	-10.4 ± 6.8	$+$	97	7	0.7 ± 10.9	42	15	-18.8 ± 8.6	55
			$-$	119			42			80

Table: The TPAs in different regions from the data of LHCb, and the corresponding event yields extracted from the TPAs data for $B^0 \to p\bar{p}K^+\pi^-$. In the table, c_{θ_a}, c_{θ_b}, c_φ and s_φ are abbreviations for $\cos\theta_a$, $\cos\theta_b$, $\cos\varphi$, and $\sin\varphi$, respectively.

$\overline{B^0}$	Scheme A				Scheme B					
sign of					$m^2_{K\pi} - m^2_{K*} < 0$			$m^2_{K\pi} - m^2_{K*} > 0$		
$c_{\bar{\theta}_a} c_{\bar{\theta}_b} c_{\bar{\varphi}}$	reg.	$\bar{A}_{\hat{T}}$	sign $s_{\bar{\varphi}}$	yie.	reg.	$\bar{A}_{\hat{T}}$	yie.	reg.	$\bar{A}_{\hat{T}}$	yie.
$- - +$	0	-13.2 ± 9.5	$-$	48	0	-21.9 ± 12.9	23	8	-8.0 ± 13.2	26
			$+$	63			37			31
$- - -$	1	3.2 ± 9.8	$-$	54	1	-1.6 ± 20.7	11	9	4.0 ± 11.2	41
			$+$	50			12			38
$- + +$	2	23.9 ± 10.0	$-$	62	2	18.9 ± 17.4	20	10	30.2 ± 12.2	44
			$+$	38			13			23
$- + -$	3	3.2 ± 7.8	$-$	85	3	5.0 ± 13.7	28	11	0.2 ± 9.4	57
			$+$	80			25			56
$+ - +$	4	24.3 ± 9.0	$-$	77	4	26.1 ± 16.3	24	12	22.7 ± 10.7	54
			$+$	47			14			34
$+ - -$	5	14.9 ± 8.6	$-$	78	5	21.9 ± 22.3	12	13	14.2 ± 8.8	74
			$+$	58			8			55
$+ + +$	6	-4.9 ± 8.6	$-$	64	6	-15.3 ± 11.4	33	14	6.4 ± 13.2	23
			$+$	71			44			20
$+ + -$	7	6.8 ± 6.6	$-$	123	7	2.8 ± 8.4	73	15	10.2 ± 9.5	61
			$+$	107			69			50

Table: The same as last TABLE but for $\overline{B^0} \to p\bar{p}K^-\pi^+$.

j_a \ j_b	0	1	2
0	$\Psi_0^{00} = 1$ trivial	$\Psi_0^{01} c_{\theta_b}$	$\Psi_0^{02} = \frac{1}{2}(c_{\theta_b}^2 - 1)$ ×
1	$\Psi_0^{10} = c_{\theta_a}$	$\Psi_0^{11} = c_{\theta_a} c_{\theta_b}$ $\Psi_1^{11} = s_{\theta_a} s_{\theta_b} c_\varphi$ $\Phi_1^{11} = s_{\theta_a} s_{\theta_b} s_\varphi$	$\Psi_0^{12} = \frac{1}{2} c_{\theta_a}(3c_{\theta_b}^2 - 1)$ × $\Psi_1^{12} = s_{\theta_a} s_{\theta_b} c_{\theta_b} c_\varphi$ $\Phi_1^{12} = s_{\theta_a} s_{\theta_b} c_{\theta_b} s_\varphi$
2	$\Psi_0^{20} = \frac{1}{2}(3c_{\theta_a}^2 - 1)$ ×	$\Psi_0^{21} = \frac{1}{2}(3c_{\theta_a}^2 - 1) c_{\theta_b}$ × $\Psi_1^{21} = s_{\theta_a} c_{\theta_a} s_{\theta_b} c_\varphi$ $\Phi_1^{21} = s_{\theta_a} c_{\theta_a} s_{\theta_b} s_\varphi$	$\Psi_0^{22} = \frac{1}{4}(3c_{\theta_a}^2 - 1)(3c_{\theta_b}^2 - 1)$ × $\Psi_1^{22} = s_{\theta_a} c_{\theta_a} s_{\theta_b} c_{\theta_b} c_\varphi$ $\Phi_1^{22} = s_{\theta_a} c_{\theta_a} s_{\theta_b} c_{\theta_b} s_\varphi$ $\Psi_2^{22} = \frac{3}{8} s_{\theta_a}^2 s_{\theta_b}^2 c_{2\varphi}$ × $\Phi_2^{22} = \frac{3}{8} s_{\theta_a}^2 s_{\theta_b}^2 s_{2\varphi}$

Table: The first few angular correlations.

$\mathcal{Y}_\sigma^{j_aj_b}$	$A^{\mathcal{Y}_\sigma^{j_aj_b}}$	$\overline{A}^{\mathcal{Y}_\sigma^{j_aj_b}}$	$A_{CP}^{\mathcal{Y}_\sigma^{j_aj_b}}$	$\tilde{A}^{\mathcal{Y}_\sigma^{j_aj_b}}$	$\tilde{\overline{A}}^{\mathcal{Y}_\sigma^{j_aj_b}}$	$\tilde{A}_{CP}^{\mathcal{Y}_\sigma^{j_aj_b}}$
Ψ_0^{01}	28.5	14.0	7.3	5.5	-16.2	**10.8**
Ψ_0^{10}	0.9	13.1	-6.1	/	/	/
Ψ_0^{11}	-0.7	5.0	-2.9	-2.3	-23.4	**10.6**
Ψ_1^{11}	-8.6	-14.9	-3.1	-12.1	-12.9	0.4
Φ_1^{11}	-1.0	7.0	-4.0	5.0	6.3	-0.6
Ψ_1^{12}	4.9	-14.0	**9.5**	/	/	/
Φ_1^{12}	-1.7	-0.1	-0.8	/	/	/
Ψ_1^{21}	-7.2	-4.4	-1.4	-6.3	2.0	-4.2
Φ_1^{21}	-7.4	3.7	-5.5	-2.4	1.9	-2.1
Ψ_1^{22}	-0.1	-1.0	0.5	/	/	/
Ψ_1^{22}	-10.6	-7.3	-1.6	/	/	/
Φ_2^{22}	-7.5	-1.2	-3.2	/	/	/
stat. err.	2.84	3.01	2.07	2.84	3.00	2.05

Table: Angular correlation asymmetries and CPAs extracted from the data in LHCb.

j_a \ j_b	0	1	2
0	$\Psi_0^{00} = 1$ trivial	$\Psi_0^{01} = c_{\theta_b}$	$\Psi_0^{02} = \frac{1}{2}(c_{\theta_b}^2 - 1)$ ×
1	$\Psi_0^{10} = c_{\theta_a}$	$\Psi_0^{11} = c_{\theta_a} c_{\theta_b}$ $\Psi_1^{11} = s_{\theta_a} s_{\theta_b} c_{\varphi}$ $\Phi_1^{11} = s_{\theta_a} s_{\theta_b} s_{\varphi}$	$\Psi_0^{12} = \frac{1}{2} c_{\theta_a}(3c_{\theta_b}^2 - 1)$ × $\Psi_1^{12} = s_{\theta_a} s_{\theta_b} c_{\theta_b} c_{\varphi}$ $\Phi_1^{12} = s_{\theta_a} s_{\theta_b} c_{\theta_b} s_{\varphi}$
2	$\Psi_0^{20} = \frac{1}{2}(3c_{\theta_a}^2 - 1)$ ×	$\Psi_0^{21} = \frac{1}{2}(3c_{\theta_a}^2 - 1)c_{\theta_b}$ × $\Psi_1^{21} = s_{\theta_a} c_{\theta_a} s_{\theta_b} c_{\varphi}$ $\Phi_1^{21} = s_{\theta_a} c_{\theta_a} s_{\theta_b} s_{\varphi}$	$\Psi_0^{22} = \frac{1}{4}(3c_{\theta_a}^2 - 1)(3c_{\theta_b}^2 - 1)$ × $\Psi_1^{22} = s_{\theta_a} c_{\theta_a} s_{\theta_b} c_{\theta_b} c_{\varphi}$ $\Phi_1^{22} = s_{\theta_a} c_{\theta_a} s_{\theta_b} c_{\theta_b} s_{\varphi}$ $\Psi_2^{22} = \frac{3}{8} s_{\theta_a}^2 s_{\theta_b}^2 c_{2\varphi}$ × $\Phi_2^{22} = \frac{3}{8} s_{\theta_a}^2 s_{\theta_b}^2 s_{2\varphi}$

- Ψ_0^{01}: FB-CPA, interf. $K^*(892)$ and a scalar.
- Ψ_0^{11}: two-fold FB-CPA, interf. $K^*(892)$ and a scalar, meanwhile, $0^{\pm}$ and $1^{\mp}$.
- Ψ_1^{12}: Left-Right Asymmetry CPA,

$\mathcal{Y}^{j_a j_b}_{\sigma}$	$\mathcal{F}$	$\mathcal{F}^*$	$\mathcal{Y}^{j_a j_b}_{\sigma}$	$\mathcal{F}$	$\mathcal{F}^*$
Ψ^{01}_{0}	$\mathcal{F}^{(0^\pm,0^+)}_{0,0}$	$\mathcal{F}^{(0^\pm,1^-)}_{0,0}$	Ψ^{02}_{0}	$\mathcal{F}^{(0^\pm,1^-)}_{0,0}$	$\mathcal{F}^{(0^\pm,1^-)}_{0,0}$
	$\mathcal{F}^{(1^\mp,0^+)}_{0,0}$	$\mathcal{F}^{(1^\mp,1^-)}_{0,0}$		$\mathcal{F}^{(1^\mp,1^-)}_{-1,-1}$	$\mathcal{F}^{(1^\mp,1^-)}_{-1,-1}$
Ψ^{10}_{0}	$\mathcal{F}^{(0^\pm,0^+)}_{0,0}$	$\mathcal{F}^{(1^\mp,0^+)}_{0,0}$		$\mathcal{F}^{(1^\mp,1^-)}_{0,0}$	$\mathcal{F}^{(1^\mp,1^-)}_{0,0}$
	$\mathcal{F}^{(0^\pm,1^-)}_{0,0}$	$\mathcal{F}^{(1^\mp,1^-)}_{0,0}$		$\mathcal{F}^{(1^\mp,1^-)}_{+1,+1}$	$\mathcal{F}^{(1^\mp,1^-)}_{+1,+1}$
Ψ^{11}_{0}	$\mathcal{F}^{(0^\pm,0^+)}_{0,0}$	$\mathcal{F}^{(1^\mp,1^-)}_{0,0}$	Ψ^{20}_{0}	$\mathcal{F}^{(1^\mp,0^+)}_{0,0}$	$\mathcal{F}^{(1^\mp,0^+)}_{0,0}$
	$\mathcal{F}^{(0^\pm,1^-)}_{0,0}$	$\mathcal{F}^{(1^\mp,0^+)}_{0,0}$		$\mathcal{F}^{(1^\mp,1^-)}_{-1,-1}$	$\mathcal{F}^{(1^\mp,1^-)}_{-1,-1}$
Ψ^{11}_{1}, Φ^{11}_{1}	$\mathcal{F}^{(0^\pm,0^+)}_{0,0}$	$\mathcal{F}^{(1^\mp,1^-)}_{+1,+1}$		$\mathcal{F}^{(1^\mp,1^-)}_{0,0}$	$\mathcal{F}^{(1^\mp,1^-)}_{0,0}$
	$\mathcal{F}^{(1^\mp,1^-)}_{-1,-1}$	$\mathcal{F}^{(0^\pm,0^+)}_{0,0}$		$\mathcal{F}^{(1^\mp,1^-)}_{+1,+1}$	$\mathcal{F}^{(1^\mp,1^-)}_{+1,+1}$
Ψ^{12}_{1}, Φ^{12}_{1}	$\mathcal{F}^{(0^\pm,1^-)}_{0,0}$	$\mathcal{F}^{(1^\mp,1^-)}_{+1,+1}$	Ψ^{12}_{0}	$\mathcal{F}^{(0^\pm,1^-)}_{0,0}$	$\mathcal{F}^{(1^\mp,1^-)}_{0,0}$
	$\mathcal{F}^{(1^\mp,1^-)}_{-1,-1}$	$\mathcal{F}^{(0^\pm,1^-)}_{0,0}$	Ψ^{21}_{0}	$\mathcal{F}^{(1^\mp,0^+)}_{0,0}$	$\mathcal{F}^{(1^\mp,1^-)}_{0,0}$
Ψ^{21}_{1}, Φ^{21}_{1}	$\mathcal{F}^{(1^\mp,0^+)}_{0,0}$	$\mathcal{F}^{(1^\mp,1^-)}_{+1,+1}$	Ψ^{22}_{0}	$\mathcal{F}^{(1^\mp,1^-)}_{-1,-1}$	$\mathcal{F}^{(1^\mp,1^-)}_{-1,-1}$
	$\mathcal{F}^{(1^\mp,1^-)}_{-1,-1}$	$\mathcal{F}^{(1^\mp,0^+)}_{0,0}$		$\mathcal{F}^{(1^\mp,1^-)}_{0,0}$	$\mathcal{F}^{(1^\mp,1^-)}_{0,0}$
Ψ^{22}_{1}, Ψ^{22}_{1}	$\mathcal{F}^{(1^\mp,1^-)}_{0,0}$	$\mathcal{F}^{(1^\mp,1^-)}_{+1,+1}$		$\mathcal{F}^{(1^\mp,1^-)}_{+1,+1}$	$\mathcal{F}^{(1^\mp,1^-)}_{+1,+1}$
	$\mathcal{F}^{(1^\mp,1^-)}_{-1,-1}$	$\mathcal{F}^{(1^\mp,1^-)}_{0,0}$	Ψ^{22}_{2}, Φ^{22}_{2}	$\mathcal{F}^{(1^\mp,1^-)}_{-1,-1}$	$\mathcal{F}^{(1^\mp,1^-)}_{+1,+1}$

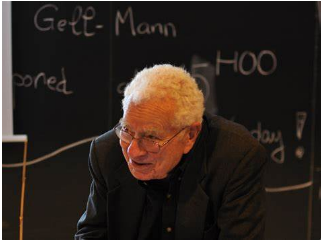
4 总结展望

总结

- LHCb本在2022年就有机会发现与重子相关的CP破坏的（非中国组）。
- 多体衰变过程角分布相关的CP破坏的实验分析对理解CP破坏的动力学非常重要。

展望

In the 1950s, if you discovered a new particle you got a Nobel Prize; in the 1960s, they fined you; by the 1970s, they should have put you in jail!—M. Gell-Mann



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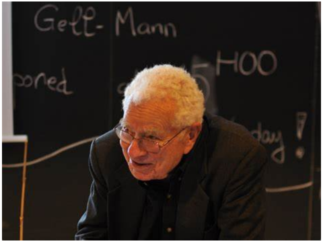

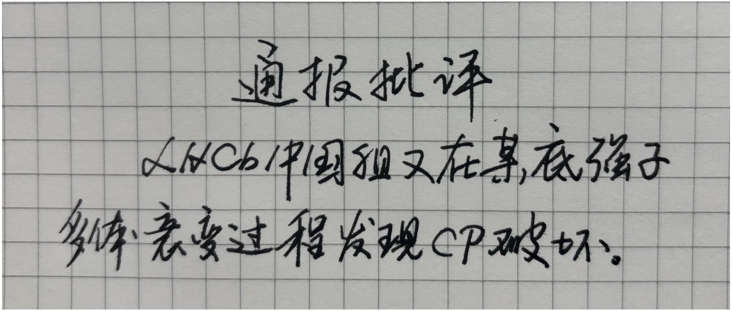

展望

- 祝贺LHCb中国组在重子相关过程中发现CP破坏现象。
- 预祝LHCb中国组取得越来越多的重要物理成果

Thank you for your attentions!