重子对产生过程 $B^0 \to p\bar{p}K^+\pi^-$ 的CP破坏

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based on 2504.19228

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吉林大学

1. background
2. CPV in the angular correlations in four-body decays of heavy hadrons
3. How LHCb missed the discovery of CPV in baryon-production process in 2022
4. summary and outlook

1. background

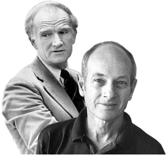
CPV in hadron decay

story incomplete, but more interesting

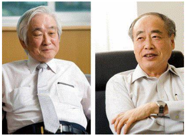
- pure mesonic processes: CPV has been observed in K, B, and D meson sectors
- baryonic decays: *small* CPV observed in $\Lambda_b \to pK^-\pi^+\pi^-$ ($A_{CP} = (2.45 \pm 0.46 \pm 0.10)\%$).
- baryon-anti-baryon ($\mathcal{B}\overline{\mathcal{B}'}$) production processes: No CPV was confirmed.

Towards M. Everest.

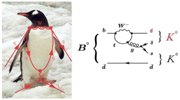
Cronin and Fitch

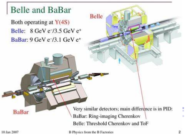


Kobayashi (小林)、Maskawa (益川)

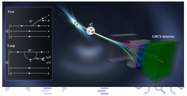


penguin diagram





LHCb



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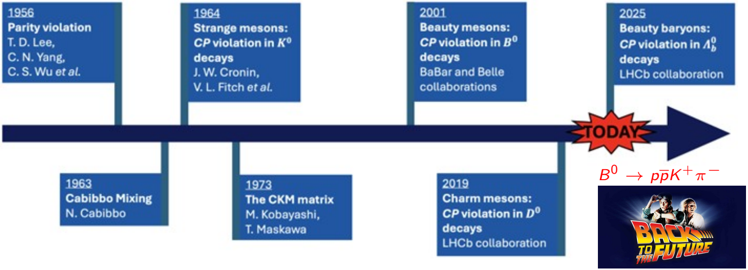
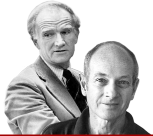


$B^0 \to p\bar{p}K^+\pi^-$

Cronin and Fitch



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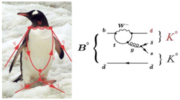

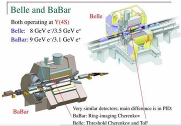

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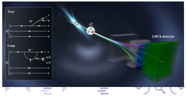


Motivations

In this talk we will show that

extremely strong evidence of CPV exists in baryon-anti-baryon ($\mathcal{B}\overline{\mathcal{B}'}$) pair production of bottom meson multi-body decay process: $B^0 \to p\bar{p}K^+\pi^-$.

Why $\mathcal{B}\overline{\mathcal{B}'}$ pair production of bottom meson multi-body decay processes

- unique config., make the story of CPV in hardon decay more complete
- $\mathcal{B}\overline{\mathcal{B}'}$-pair threshold enhancement in multi-body decays ($BR(\mathcal{B}\overline{\mathcal{B}'}X) > BR(\mathcal{B}\overline{\mathcal{B}'})$)
- four-body decays

Theor. and Exp.

Theoretical study

- N. Paver, Riazuddin, PLB 201(1988) 279
- M. Gronau, J,L, Rosner, Phys.Rev.D 37 (1988) 688
- W.S. Hou, A. Soni, PRL86 (2001) 4247
- H.Y. Cheng, K.C. Yang, Phys.Rev.D 66 (2002) 014020
- J.L. Rosner, PRD68 (2003) 014004
- B.S. Zou, H.C. Chiang, PRD 69 (2004) 034004
- M, Suzuki, J.Phys.G 34 (2007) 283
- C.Q. Geng, H.K. Hsiao, PRD 74 (2006) 094023

Exp. study

- Belle or Bell II, PRL 88(2002) 181803; PRL 91(2003) 022001; PRL 92(2004) 131801
- LHCb, PRL 113 (2014), 141801; PRD 108 (2023), 032007

2. CPV in the angular correlations in four-body decays of heavy hadrons

Kinematics

cascade decay $H_Q \to a_k(\to 12)b_m(\to 34)$

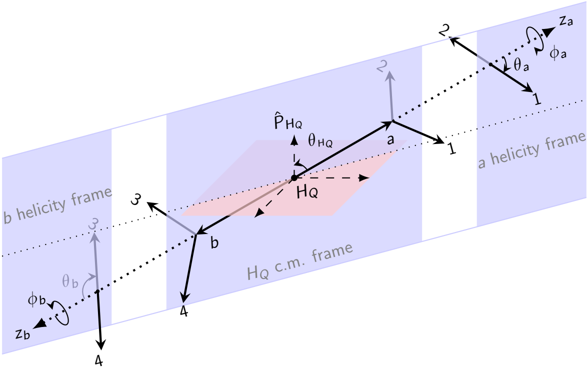


Figure: Illustration of the five angles defined in the main text for the decay $H_Q \to a(\to 12)b(\to 34)$.

Kinematics $\leftrightarrow$ Dynamics

cascade decay $H_Q \to a_k(\to 12)b_m(\to 34)$

Decay amplitude squared 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

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

Kinematics ↔ Dynamics

cascade decay $H_Q \to a_k(\to 12) b_m(\to 34)$

Quantum number entanglement for unpolarized H_Q

Entanglement between kinematical-angle correlated quantum numbers!

$$\sigma_a - \sigma_{a'} = \sigma_b - \sigma_{b'}$$

The kinematical factors merge into

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

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

Kinematics ↔ Dynamics

cascade decay $H_Q \to a_k(\to 12)b_m(\to 34)$

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

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

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	$\Psi_0^{20} = \frac{1}{2}(3c^2_{\theta_a} - 1)$	$\Psi_0^{21} = \frac{1}{2}(3c^2_{\theta_a} - 1) c_{\theta_b}$ $\Psi_1^{21} = s_{\theta_a} c_{\theta_a} s_{\theta_b} c_\varphi$ $\Phi_1^{21} = s_{\theta_a} c_{\theta_a} s_{\theta_b} s_\varphi$	$\Psi_0^{22} = \frac{1}{4}(3c^2_{\theta_a} - 1)(3c^2_{\theta_b} - 1)$ $\Psi_1^{22} = s_{\theta_a} c_{\theta_a} s_{\theta_b} c_{\theta_b} c_\varphi$ $\Phi_1^{22} = s_{\theta_a} c_{\theta_a} s_{\theta_b} c_{\theta_b} s_\varphi$ $\Psi_2^{22} = \frac{3}{8} s^2_{\theta_a} s^2_{\theta_b} c_{2\varphi}$ $\Phi_2^{22} = \frac{3}{8} s^2_{\theta_a} s^2_{\theta_b} s_{2\varphi}$

Kinematics $\leftrightarrow$ Dynamics

cascade decay $H_Q \to a_k(\to 12)b_m(\to 34)$

Constraints to j_a and j_b

- Triangular inequality

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

- 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.

Inversely, if possible j_a (and j_b) is seen from the data, we can infer what kind of resonances enters.

Kinematics $\leftrightarrow$ Dynamics (interference pattern)

Kinematics ↔ Dynamics

CPA inducde by Interference between intermediate resonances

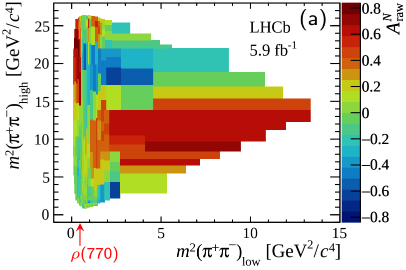
Resonance-Interference

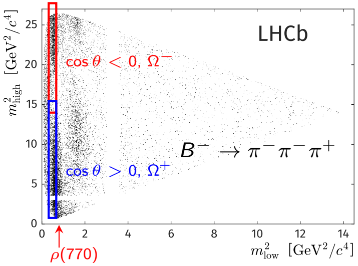
- I. CPAs in angular distributions
- II. complementary CPA observables

Kinematics ↔ Dynamics

Resonance-Interference: I. CPAs in angular distributions

Forward-Backward Asymmetry induced CPA (FB-CPA)



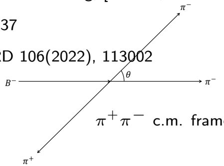


ZHZ, X.-H. Guo, and Y.-D. Yang, [PRD87, 076007 (2013)]

ZHZ, PLB820, 136537

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

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



$\pi^+\pi^-$ c.m. frame

Kinematics $\leftrightarrow$ Dynamics

Resonance-Interference: I. CPAs in angular distributions

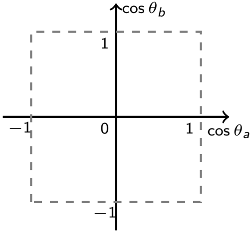
CPV in baryon-four-body decays: $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ $N(1440) - N(1520)$ and $f_0(500) - \rho(770)$, ZHZ, PRD107(2023),L011301

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

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

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

2 Dim Phase Space



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

TFFBA-CPA

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

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

Kinematics ↔ Dynamics

Resonance-Interference: I. CPAs in angular distributions

Partial-Wave CPAs

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

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

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

$$\mathcal{W}^{(j)}_{ii'} = \sum_{\sigma\lambda_3} (-)^{\sigma - s} \langle s_{R_i} - \sigma s_{R_{i'}} \sigma | s_{R_i} s_{R_{i'}} j0 \rangle \mathcal{F}^J_{R_i,\sigma\lambda_3} \mathcal{F}^{J*}_{R_{i'},\sigma\lambda_3},$$

$$\mathcal{S}^{(j)}_{ii'} = \sum_{\lambda_1'\lambda_2'} (-)^{s-\lambda'} \langle s_{R_i} - \lambda' s_{R_{i'}} \lambda' | s_{R_i} s_{R_{i'}} j0 \rangle \mathcal{F}^{R_i, s_{R_i}}_{\lambda_1'\lambda_2'} \mathcal{F}^{R_{i'}, s_{R_{i'}} *}_{\lambda_1'\lambda_2'}$$

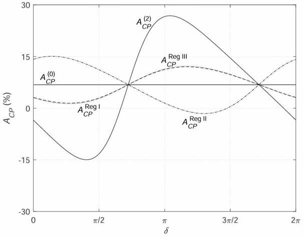


Figure 1. The PWCPA $A_{CP}^{(2)}$ (solid curvy line) for $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ near the resonance $\Delta^0(1232)$ as a function of the strong phase δ. The regional CP asymmetry $A_{CP}^{(0)}$ (solid straight line), $A_{CP}^{\mathrm{Reg\ I}}$ (dotted line), $A_{CP}^{\mathrm{Reg\ II}}$ (dash-dotted line), and $A_{CP}^{\mathrm{Reg\ III}}$ (dashed line) are also shown for comparison. The difference between $A_{CP}^{\mathrm{Reg\ I}}$ and $A_{CP}^{\mathrm{Reg\ III}}$ is very tiny. Other PWCPAs $A_{CP}^{(1)}$ 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 $(m_\Delta + \Gamma_\Delta)^2$.

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

Kinematics $\leftrightarrow$ Dynamics

Resonance-Interference: II. complementary CPA observables

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

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

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

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

Kinematics ↔ Dynamics

Resonance-Interference: II. complementary CPA observables

LHCb, PRD 101 (2020) 012006 [1909.05212]

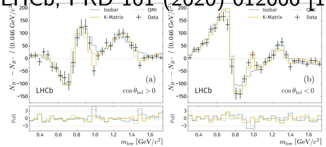
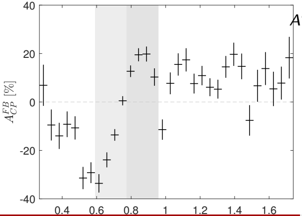


Figure 12: Raw difference in the number of B^- and B^+ candidates in the low $m_{\rm low}$ region, for (a) positive, and (b) negative cosine of the helicity angle. The pull distribution is shown below each fit projection.

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

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

PRD 110 (2024) L111301 [2407.20586]



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

Angular correlation CPV observables in four-body cascade decays

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

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

Decay angular correlation asymmetries

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

CPV observables

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

CPV observables $\leftrightarrow$ Kinematics $\leftrightarrow$ Dynamics (interference pattern)

3. How LHCb missed the discovery of CPV in baryon-production process in 2022

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

arXiv > hep-ex > arXiv:2205.08973

Search... Hel

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

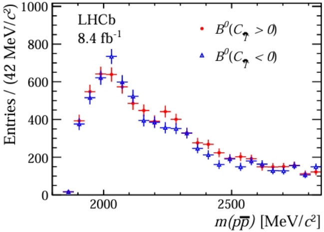
A search for CP and P violation in charmless four-body $B^0 \to p\bar{p}K^+\pi^-$ decays is performed using triple-product asymmetry observables. It is based on proton-proton collision data collected by the LHCb experiment at centre-of-mass energies of 7, 8 and 13 TeV, corresponding to a total integrated 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

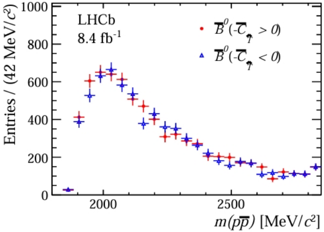
Comments:	All figures and tables, along with any supplementary material and additional information, are available at this https URL (LHCb public pages)
Subjects:	**High Energy Physics - Experiment (hep-ex)**
Report number:	LHCb-PAPER-2022-003, CERN-EP-2022-083
Cite as:	arXiv:2205.08973 **[hep-ex]**
	(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

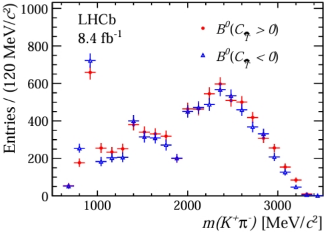
From: Matteo Bartolini [view email]
[v1] Wed, 18 May 2022 14:54:32 UTC (517 KB)
[v2] Wed, 16 Aug 2023 12:23:37 UTC (739 KB)

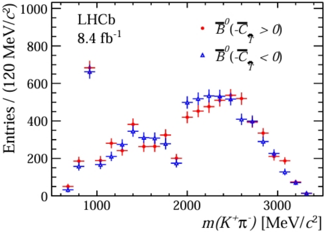
"No evidence of CPV (corresponding to T-odd correlation) in $B^0 \to p\bar{p}K^+\pi^-$."



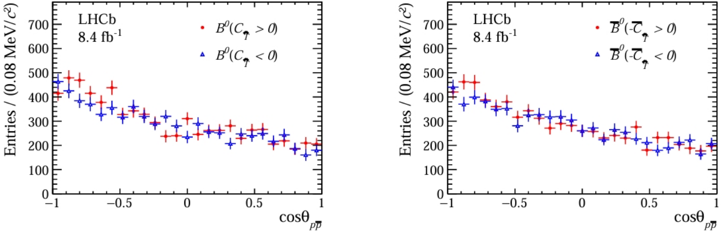


threshold enhancement

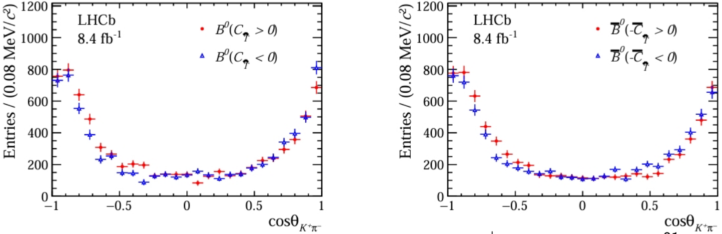




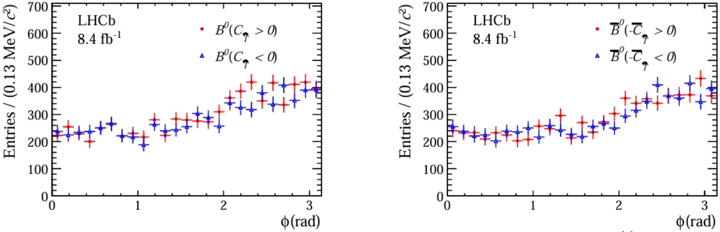
considerable contribution from $K^*(892)$



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}

focusing on phase space around $K^*(892)$ and the threshold region of $p\bar{p}$

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

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	$\Psi_0^{20} = \frac{1}{2}(3c_{\theta_a}^2 - 1)$	$\Psi_0^{21} = \frac{1}{2}(3c_{\theta_a}^2 - 1) c_{\theta_b}$ $\Psi_1^{21} = s_{\theta_a} c_{\theta_a} s_{\theta_b} c_\varphi$ $\Phi_1^{21} = s_{\theta_a} c_{\theta_a} s_{\theta_b} s_\varphi$	$\Psi_0^{22} = \frac{1}{4}(3c_{\theta_a}^2 - 1)(3c_{\theta_b}^2 - 1)$ $\Psi_1^{22} = s_{\theta_a} c_{\theta_a} s_{\theta_b} c_{\theta_b} c_\varphi$ $\Phi_1^{22} = s_{\theta_a} c_{\theta_a} s_{\theta_b} c_{\theta_b} s_\varphi$ $\Psi_2^{22} = \frac{3}{8} s_{\theta_a}^2 s_{\theta_b}^2 c_{2\varphi}$ $\Phi_2^{22} = \frac{3}{8} s_{\theta_a}^2 s_{\theta_b}^2 s_{2\varphi}$

Extracting the event yields from LHCb's paper

B^0	Scheme A				Scheme B					
sign of					$m^2_{K\pi} - m^2_{K*} < 0$			$m^2_{K\pi} - m^2_{K*} > 0$		
$c_{\theta_a} c_{\theta_b} c_\varphi$	reg.	$A_{\hat{T}}$	sign s_φ	yie.	reg.	$A_{\hat{T}}$	yie.	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.

Extracting the event yields from LHCb's paper

$\overline{B^0}$	Scheme A				Scheme B					
sign of $c_{\bar{\theta}_a} c_{\bar{\theta}_b} c_{\bar{\varphi}}$	reg.	$\bar{A}_{\hat{T}}$	sign $s_{\bar{\varphi}}$	yie.	$m^2_{K\pi} - m^2_{K*} < 0$			$m^2_{K\pi} - m^2_{K*} > 0$		
					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 $\overline{B^0} \to p\bar{p}K^-\pi^+$.

Accessible angular correlations based on the data in LHCb's paper

$j_a \backslash j_b$	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	$\Psi_0^{20} = \frac{1}{2}(3c_{\theta_a}^2 - 1)$ ×	$\Psi_0^{21} = \frac{1}{2}(3c_{\theta_a}^2 - 1)c_{\theta_b}$ × $\Psi_1^{21} = s_{\theta_a} c_{\theta_a} s_{\theta_b} c_{\varphi}$ $\Phi_1^{21} = s_{\theta_a} c_{\theta_a} s_{\theta_b} s_{\varphi}$	$\Psi_0^{22} = \frac{1}{4}(3c_{\theta_a}^2 - 1)(3c_{\theta_b}^2 - 1)$ × $\Psi_1^{22} = s_{\theta_a} c_{\theta_a} s_{\theta_b} c_{\theta_b} c_{\varphi}$ $\Phi_1^{22} = s_{\theta_a} c_{\theta_a} s_{\theta_b} c_{\theta_b} s_{\varphi}$ $\Psi_2^{22} = \frac{3}{8} s_{\theta_a}^2 s_{\theta_b}^2 c_{2\varphi}$ × $\Phi_2^{22} = \frac{3}{8} s_{\theta_a}^2 s_{\theta_b}^2 s_{2\varphi}$

Accessible angular correlations based on the data in LHCb's paper

$j_a \backslash j_b$	0	1	2
0		$\Psi_0^{01} c_{\theta_b}$	
1	$\Psi_0^{10} = c_{\theta_a}$	$\Psi_0^{11} = c_{\theta_a} c_{\theta_b}$ $\Psi_1^{11} = s_{\theta_a} s_{\theta_b} c_\varphi$ $\Phi_1^{11} = s_{\theta_a} s_{\theta_b} s_\varphi$	$\Psi_1^{12} = s_{\theta_a} s_{\theta_b} c_{\theta_b} c_\varphi$ $\Phi_1^{12} = s_{\theta_a} s_{\theta_b} c_{\theta_b} s_\varphi$
2		$\Psi_1^{21} = s_{\theta_a} c_{\theta_a} s_{\theta_b} c_\varphi$ $\Phi_1^{21} = s_{\theta_a} c_{\theta_a} s_{\theta_b} s_\varphi$	$\Psi_1^{22} = s_{\theta_a} c_{\theta_a} s_{\theta_b} c_{\theta_b} c_\varphi$ $\Phi_1^{22} = s_{\theta_a} c_{\theta_a} s_{\theta_b} c_{\theta_b} s_\varphi$ $\Phi_2^{22} = \frac{3}{8} s_{\theta_a}^2 s_{\theta_b}^2 s_{2\varphi}$

$\mathcal{Y}_\sigma^{j_aj_b}$	$A^{\mathcal{Y}_\sigma^{j_aj_b}}$	$\overline{A}^{\mathcal{Y}_\sigma^{j_aj_b}}$	$A_{CP}^{\mathcal{Y}_\sigma^{j_aj_b}}$	$\tilde{A}^{\mathcal{Y}_\sigma^{j_aj_b}}$	$\overline{\tilde{A}}^{\mathcal{Y}_\sigma^{j_aj_b}}$	$\tilde{A}_{CP}^{\mathcal{Y}_\sigma^{j_aj_b}}$
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.

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

interf. dynamics

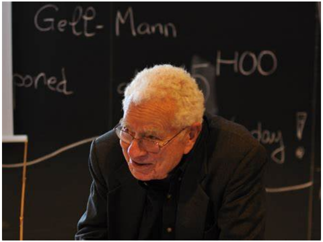
- $\boldsymbol{\Psi_0^{01}}$: FB-CPA, interf. $K^*(892)$ and a scalar.
- $\boldsymbol{\Psi_0^{11}}$: two-fold FB-CPA, interf. $K^*(892)$ and a scalar, meanwhile, $0^\pm$ and $1^\mp$.
- Ψ_1^{12}: Left-Right Asymmetry CPA,

4 summary and outlook

summary and outlook

- extremely strong evidence of CPV in $B^0 \to p\bar{p}K^+\pi^-$, CPA$\sim$ 10%
- LHCb could have observed CPV in baryon-production process in 2022;
- Full analysis of CPV corresponding to angular-correlations is a powerful tool, able to extract dynamics behind;
- opportunities for CPV investigation in charmed sectors and more.

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



Thank you for your attentions!