CP violation in charmless three-body $B^{\pm}$ decays at LHCb

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On behalf of the LHCb collaboration

March 10, 2023
LISHEP conference

Generalities on *CP* violation

- Process involving weak interactions violate the ***CP* symmetry**
- 1973: Cabibbo-Kobayashi-Maskawa matrix describes the probability of flavour transition

Wolfenstein parametrization

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \simeq \begin{pmatrix} 1-\lambda^2/2 & \lambda & \lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ \lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

Phys. Rev. Lett. 51 (1983) 1945

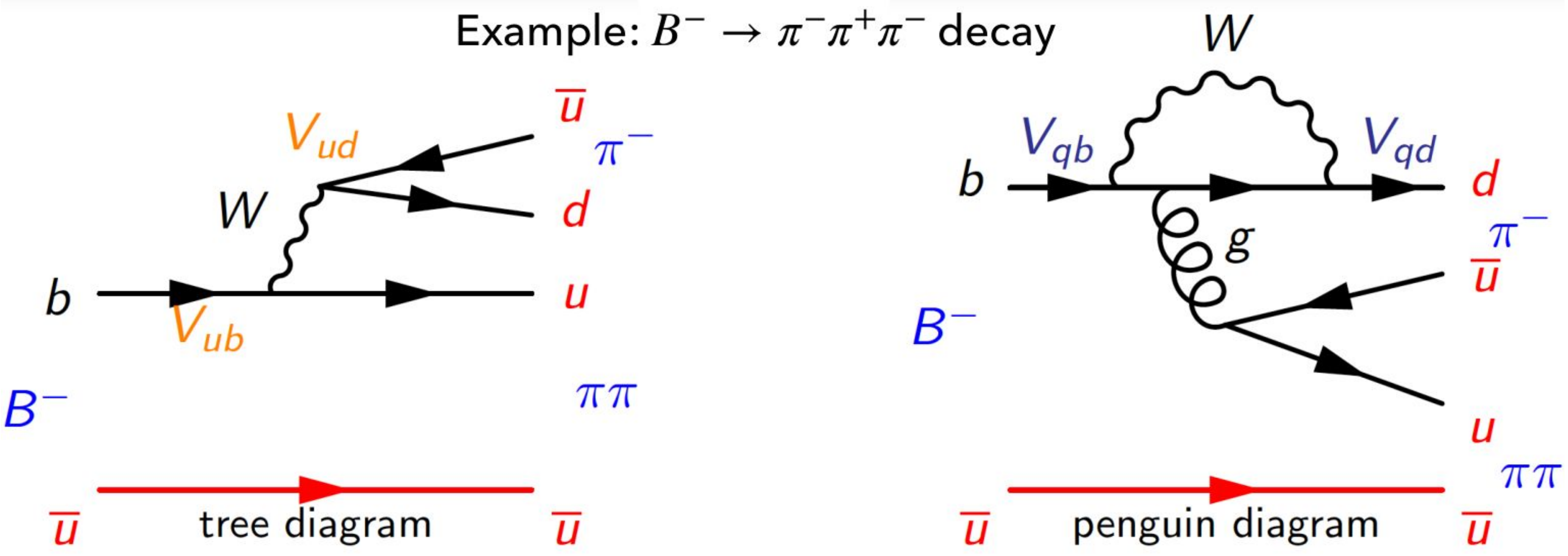
$\lambda \simeq 0.23$

$$A_{CP} = \frac{|A(B \to f)|^2 - |A(\bar{B} \to \bar{f})|^2}{|A(B \to f)|^2 + |A(\bar{B} \to \bar{f})|^2} = \frac{2|A_2/A_1|\sin(\delta_1 - \delta_2)\sin(\phi_1 - \phi_2)}{1 + |A_2/A_1|^2 + |A_2/A_1|\cos(\delta_1 - \delta_2)\cos(\phi_1 - \phi_2)}$$

- **Weak phases**: CKM matrix elements
- **Strong phases**: short distance penguin contributions, final-state interactions (FSI)

Prog. Part. Nucl. Phys. 114 (2020) 103808

Generalities on *CP* violation



Introduction

- Analysis motivated by large asymmetries observed in $B^{\pm} \to h^{\pm}h^{+}h^{-}$ decays through the phase space

  → Measurements of CP violation with run I data Phys. Rev. D90 (2014) 112004

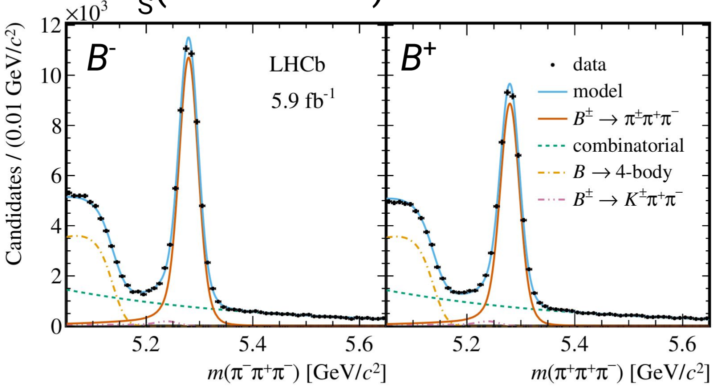
  → Amplitude analysis of $B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ and $B^{\pm} \to \pi^{\pm}K^{+}K^{-}$ decays Phys. Rev. Lett. 124 (2020) 031801 Phys. Rev. Lett. 123 (2019) 231802

- **Run II data used**, integrated luminosity: 5.9 fb^{-1}
- Decays studied: $B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$, $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$, $B^{\pm} \to \pi^{\pm}K^{+}K^{-}$ and $B^{\pm} \to K^{\pm}K^{+}K^{-}$
- Selection based on MVA, PID and charm vetoes
- Efficiency obtained from simulation samples

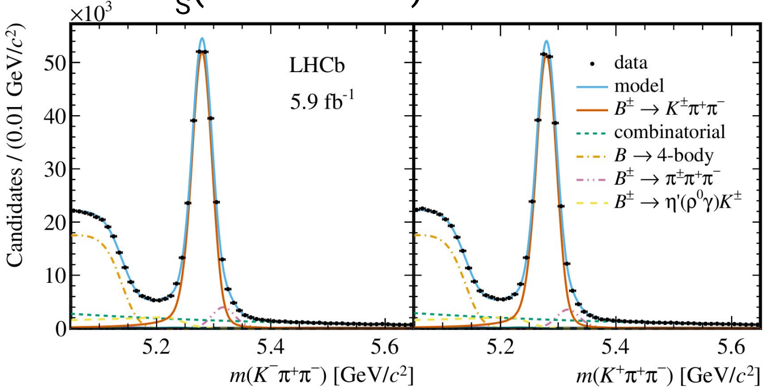
Mass fit results

arXiv:2206.07622
Accepted by PRD

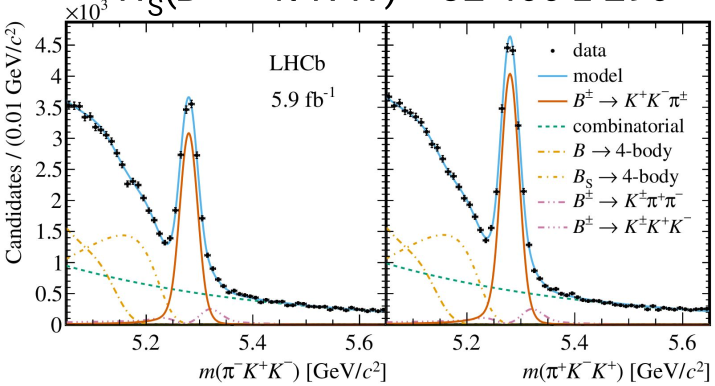
$N_S(B^\pm \to \pi^\pm\pi^+\pi^-) = 100\,999 \pm 527$



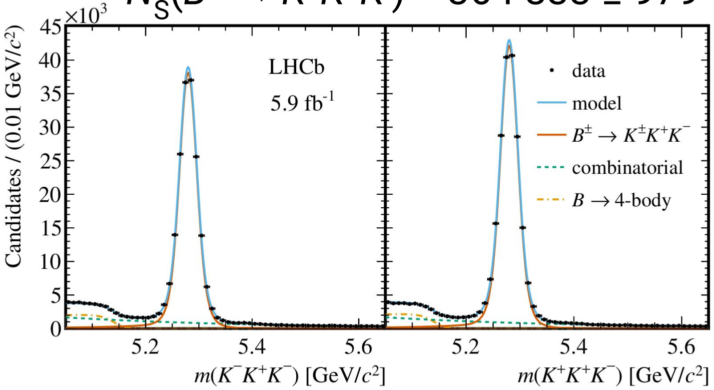
$N_S(B^\pm \to K^\pm\pi^+\pi^-) = 499\,211 \pm 861$



$N_S(B^\pm \to \pi^\pm K^+K^-) = 32\,466 \pm 296$



$N_S(B^\pm \to K^\pm K^+K^-) = 364\,833 \pm 979$



Phase space integrated asymmetries

arXiv:2206.07622
Accepted by PRD

(stat) (syst) $(J/\psi K^{\pm})$

$$A_{CP}(B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}) = +0.011 \pm 0.002 \pm 0.003 \pm 0.003 \ (2.4\sigma)$$

$$A_{CP}(B^{\pm} \to K^{\pm}K^{+}K^{-}) = -0.037 \pm 0.002 \pm 0.002 \pm 0.003 \ (8.5\sigma)$$

$$A_{CP}(B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}) = +0.080 \pm 0.004 \pm 0.003 \pm 0.003 \ (14.1\sigma)$$

$$A_{CP}(B^{\pm} \to \pi^{\pm}K^{+}K^{-}) = -0.114 \pm 0.007 \pm 0.003 \pm 0.003 \ (13.6\sigma)$$

First observation of CPV in $B^{\pm} \to K^{\pm}K^{+}K^{-}$ and $B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$, $B^{\pm} \to \pi^{\pm}K^{+}K^{-}$ confirmed

Comparison with run1 results

Phys. Rev. D90 (2014) 112004

(stat) (syst) $(J/\psi K^{\pm})$

$$A_{CP}(B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}) = +0.025 \pm 0.004 \pm 0.007 \pm 0.007$$

$$A_{CP}(B^{\pm} \to K^{\pm}K^{+}K^{-}) = -0.036 \pm 0.004 \pm 0.002 \pm 0.007$$

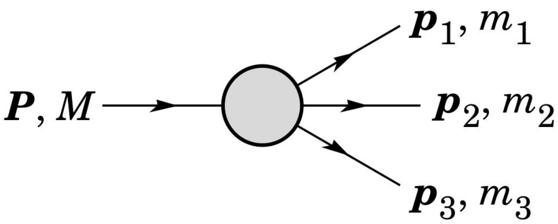
$$A_{CP}(B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}) = +0.058 \pm 0.008 \pm 0.009 \pm 0.007$$

$$A_{CP}(B^{\pm} \to \pi^{\pm}K^{+}K^{-}) = -0.123 \pm 0.017 \pm 0.012 \pm 0.007$$

Three-body decays in the phase space

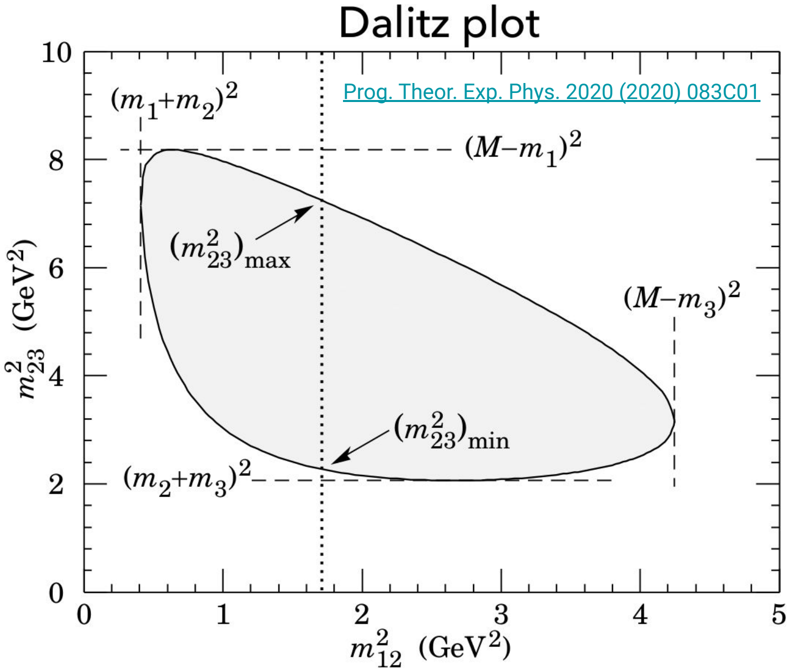
The phase space distribution of events allows us to understand of the physical mechanisms giving rise to the integrated asymmetries

Density distribution in a three-body decay

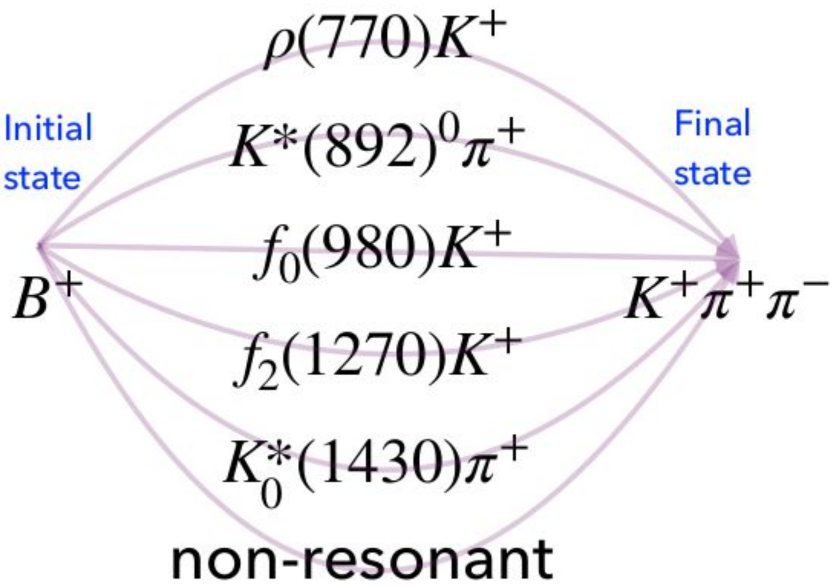


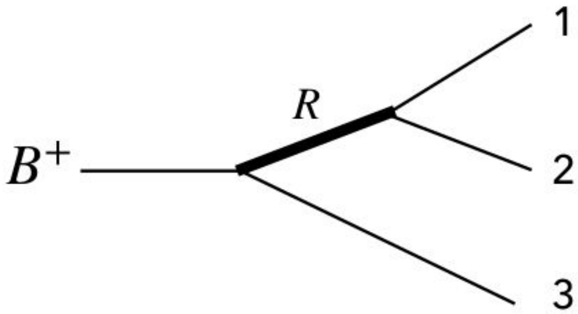
$$d\Gamma = \frac{1}{(2\pi)^3}\frac{1}{32M^3}\,|\mathscr{M}|^2\,\mathrm{d}m_{ij}^2\,\mathrm{d}m_{jk}^2$$

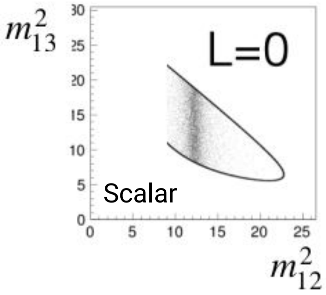
$$m_{ij}^2 = (E_i + E_j)^2 - (p_i + p_j)^2$$

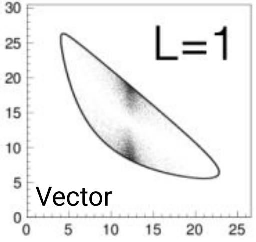


Three-body decays in the phase space

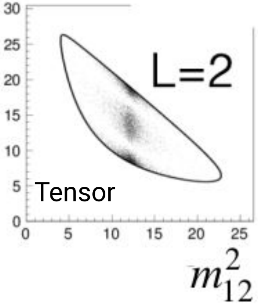








L = total angular momentum

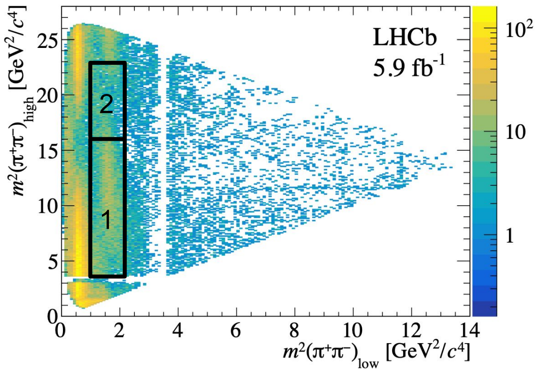


CP asymmetry in the phase space

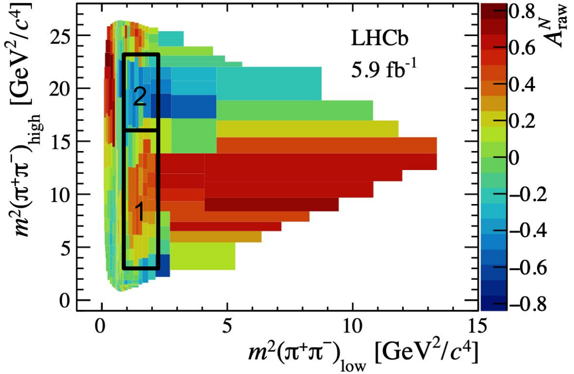
arXiv:2206.07622
Accepted by PRD

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

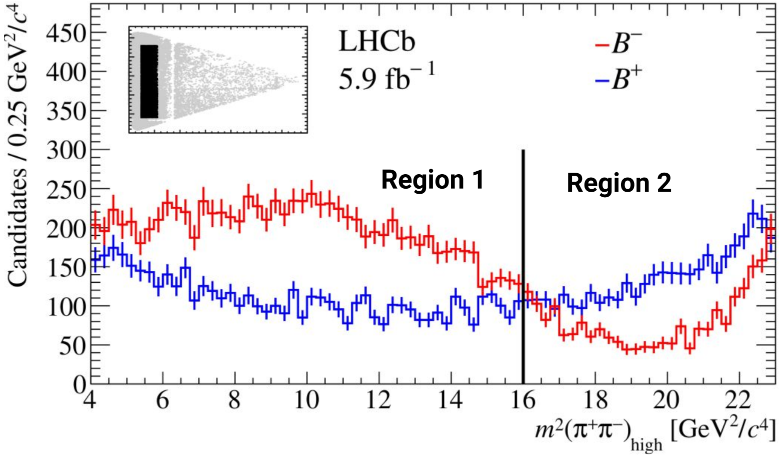
Phase space distribution of events



Asymmetry in bins of phase space



Selected region: $1 < m^2(\pi^+\pi^-)_{low} < 2.25$
$4 < m^2(\pi^+\pi^-)_{high} < 23$



Region 1

$A_{CP} = (+30.3 \pm 0.9_{stat} \pm 0.4_{syst} \pm 0.3_{J/\psi K})\,\%$

Region 2

$A_{CP} = (-28.4 \pm 1.7_{stat} \pm 0.7_{syst} \pm 0.3_{J/\psi K})\,\%$

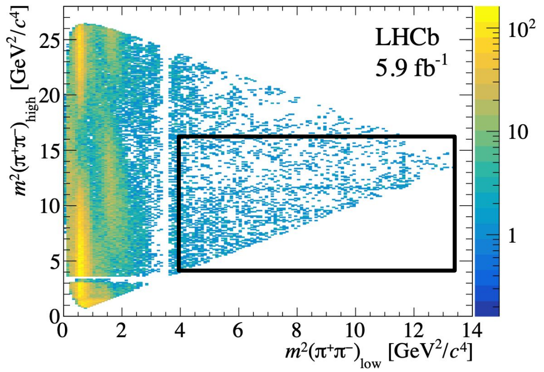
→ **Asymmetry sign changing caused by strong phases**

CP asymmetry in the phase space

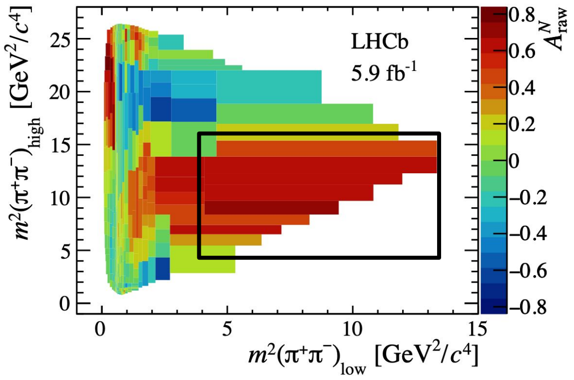
arXiv:2206.07622
Accepted by PRD

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

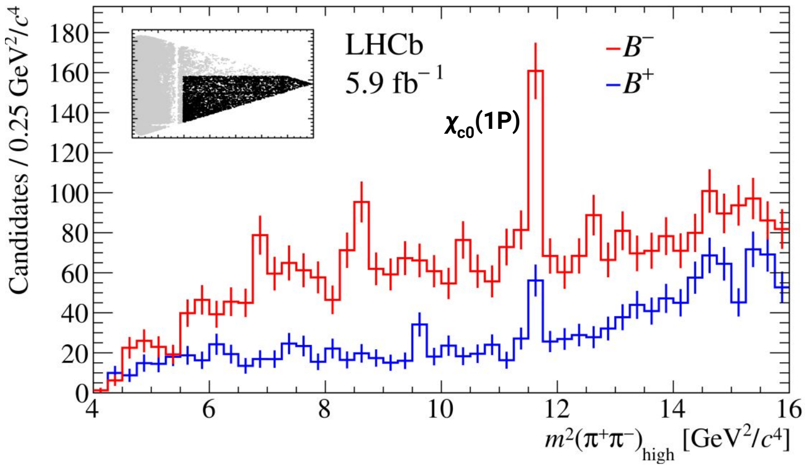
Phase space distribution of events



Asymmetry in bins of phase space



Selected region: $4 < m^2(\pi^+\pi^-)_{low} < 15$
$4 < m^2(\pi^+\pi^-)_{high} < 16$



$$A_{CP} = (+74.5 \pm 2.7_{\text{stat}} \pm 1.8_{\text{syst}} \pm 0.3_{J/\psi K})\ \%$$

Huge observed asymmetry

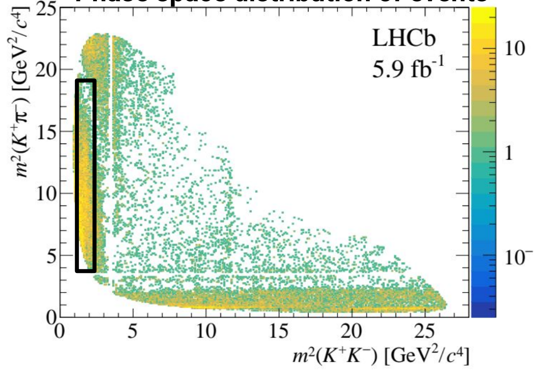
- **No direct CPV expected in χ_{c0}(1P) in SM**
  → Interference with a non-resonant decay amplitude
  → Double-charm rescattering

Phys. Rev. Lett. 74 (1995) 4984
Phys. Lett. B806 (2020) 135409

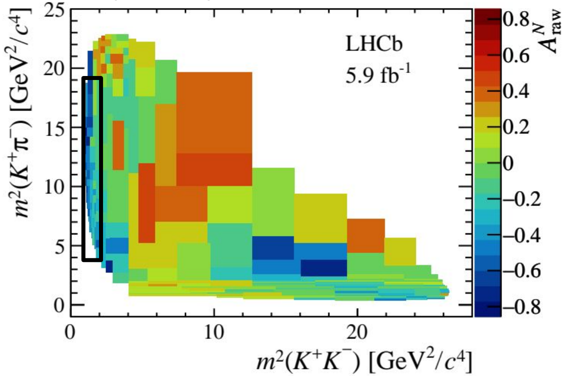
CP asymmetry in the phase space

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

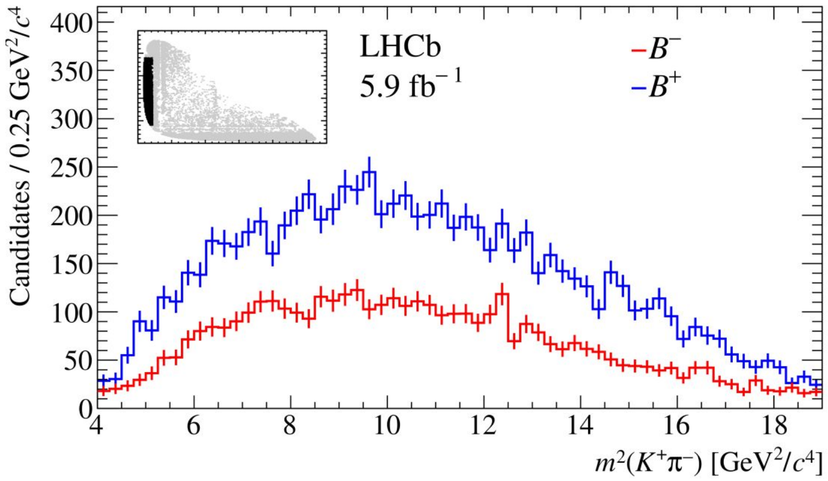
Phase space distribution of events



Asymmetry in bins of phase space



Selected region: $1 < m^2(K^+K^-) < 2.25$
$4 < m^2(K^+\pi^-) < 19$



$$A_{CP} = (-35.8 \pm 1.0_{\text{stat}} \pm 1.4_{\text{syst}} \pm 0.3_{J/\psi K})\,\%$$

- **Amplitude analysis with run I:** Phys. Rev. Lett. 123 (2019) 231802
  → A_{cp}(rescattering) = (-66.4 ± 3.8 ± 1.9)%
  → Relative size contribution = (16.4 ± 0.8 ± 1.0)%

$B^{\pm} \rightarrow PV$ decays

- Few $B^{\pm} \rightarrow h^{\pm}(V \rightarrow h^{+}h^{-})$ measurements in the literature and huge theoretical interest
- Total amplitudes for B^{+} and B^{-}

$$\mathcal{M}_{\pm} = a_{\pm}^{V} e^{i\delta_{\pm}^{V}} F_{V}^{\mathrm{BW}} \cos\theta(s_{\perp}, s_{\|}) + a_{\pm}^{S} e^{i\delta_{\pm}^{S}} F_{S}^{\mathrm{BW}}$$

$$S_{\|} \equiv (p_{h^{+}} + p_{h^{-}})^{2}$$
$$S_{\perp} \equiv (p_{h_{b}} + p_{h^{\pm}})^{2}$$
$\theta \equiv$ helicity angle

- Asymmetry ∝ square modulus of amplitude difference

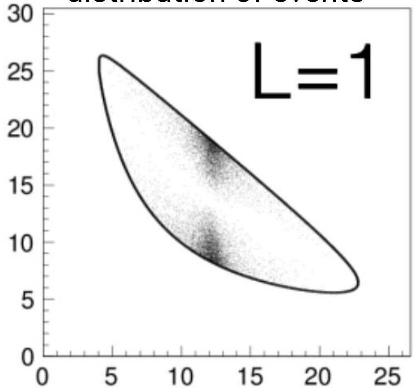
Direct scalar A_{cp} — Scalar and vector interference — Direct vector A_{cp}

$$|\mathcal{M}_{\pm}|^{2} = f(\cos\theta(m_{V}^{2}, s_{\perp})) = p_{0}^{\pm} + p_{1}^{\pm}\cos\theta(m_{V}^{2}, s_{\perp}) + p_{2}^{\pm}\cos^{2}\theta(m_{V}^{2}, s_{\perp})$$

- Quadratic function to get amplitude parameters
$\rightarrow f(x) = p_{0} + p_{1}x + p_{2}x^{2}$

$$A_{CP}^{V} = \frac{|\mathcal{M}_{-}|^{2} - |\mathcal{M}_{+}|^{2}}{|M_{-}|^{2} + |\mathcal{M}_{+}|^{2}} = \frac{p_{2}^{-} - p_{2}^{+}}{p_{2}^{-} + p_{2}^{+}}$$

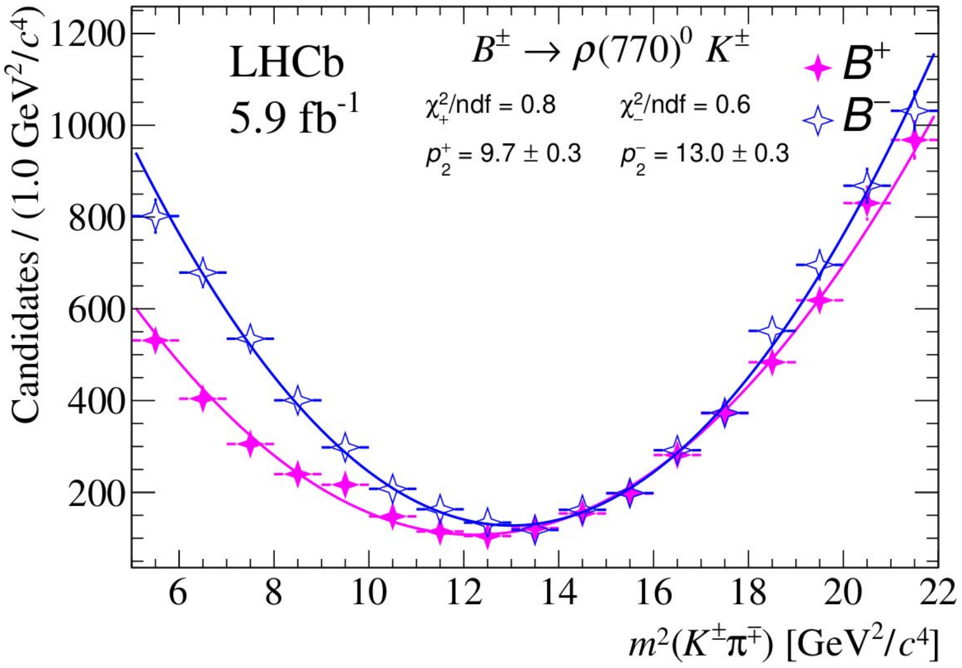
Vector resonance distribution of events



$B^\pm \to PV$ decays

arXiv:2206.02038
Accepted by PRD

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



- Phase space selected region:
  $0.49 < m^2(\pi^+\pi^-) < 0.72$
  $5 < m^2(K^+\pi^-) < 22$

- **Asymmetry** in the region dominated by $B^\pm \to \rho(770)K^\pm$ decays **for the first time observed**

$$A_{CP} = (15.0 \pm 1.9_{\text{stat}} \pm 1.1_{\text{syst}} \pm 0.3_{J/\psi K^\pm})\,\%$$

$$A_{CP} = (44 \pm 10 \pm 4^{+5}_{-13})\%$$

BaBar Phys. Rev. D78 (2008) 012004

$$A_{CP} = (30 \pm 11 \pm 2^{+11}_{-4})\%$$

Belle Phys. Rev. Lett. 96 (2006) 251803

$B^\pm \to PV$ decays

arXiv:2206.02038
Accepted by PRD

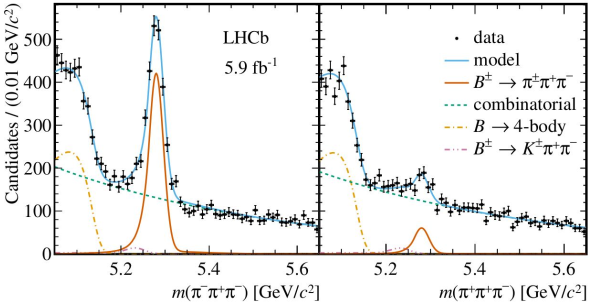
Final results, full run II data

Decay channel	Vector Resonance	$A_{CP}^V \pm\sigma_{\text{stat}} \pm \sigma_{\text{syst}}$
$B^\pm \to \pi^\pm\pi^+\pi^-$	$\rho(770)^0 \to \pi^+\pi^-$	-0.004 $\pm$ 0.017 $\pm$ 0.009
$B^\pm \to K^\pm\pi^+\pi^-$	$\rho(770)^0 \to \pi^+\pi^-$	+0.150 $\pm$ 0.019 $\pm$ 0.011 (6.8σ)
	$K^*(892)^0 \to K^\pm\pi^\mp$	-0.015 $\pm$ 0.021 $\pm$ 0.012
$B^\pm \to \pi^\pm K^+K^-$	$K^*(892)^0 \to K^\pm\pi^\mp$	+0.007 $\pm$ 0.054 $\pm$ 0.032
$B^\pm \to K^\pm K^+K^-$	$\phi(1020) \to K^+K^-$	+0.004 $\pm$ 0.010 $\pm$ 0.007

Conclusion

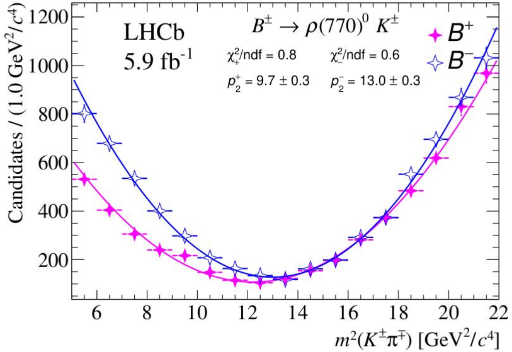
$B^{\pm} \to h^{\pm}h^{+}h^{-}$

- ❑ Non-uniform asymmetries observed in the phase space
- ❑ Significant CPV in the $\pi\pi \leftrightarrow KK$ rescattering region
- ❑ Indication of CPV in the region of the $\chi_{c0}(1P)$ resonance



$B^{\pm} \to PV$

- ❑ Observation for the first time of CPV in the region dominated by the $B^{\pm} \to \rho(770)K^{\pm}$ decays
- ❑ Significant improvement compared to Belle and BaBar

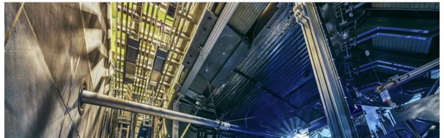


CERN news, 18/03/2022

Largest matter-antimatter asymmetry observed

New results from the LHCb experiment on CP asymmetry in charmless three-body charged B meson decays include the largest CP asymmetry ever observed

18 MARCH, 2022 | By Piotr Traczyk



FOLHA DE SÃO PAULO, 17/03/2022

Assimetria em acelerador de partículas pode apontar por que Universo é feito de matéria

Estudo realizado pelo Centro Europeu de Física de Partículas tem forte participação brasileira

17.mar.2022 às 21h54

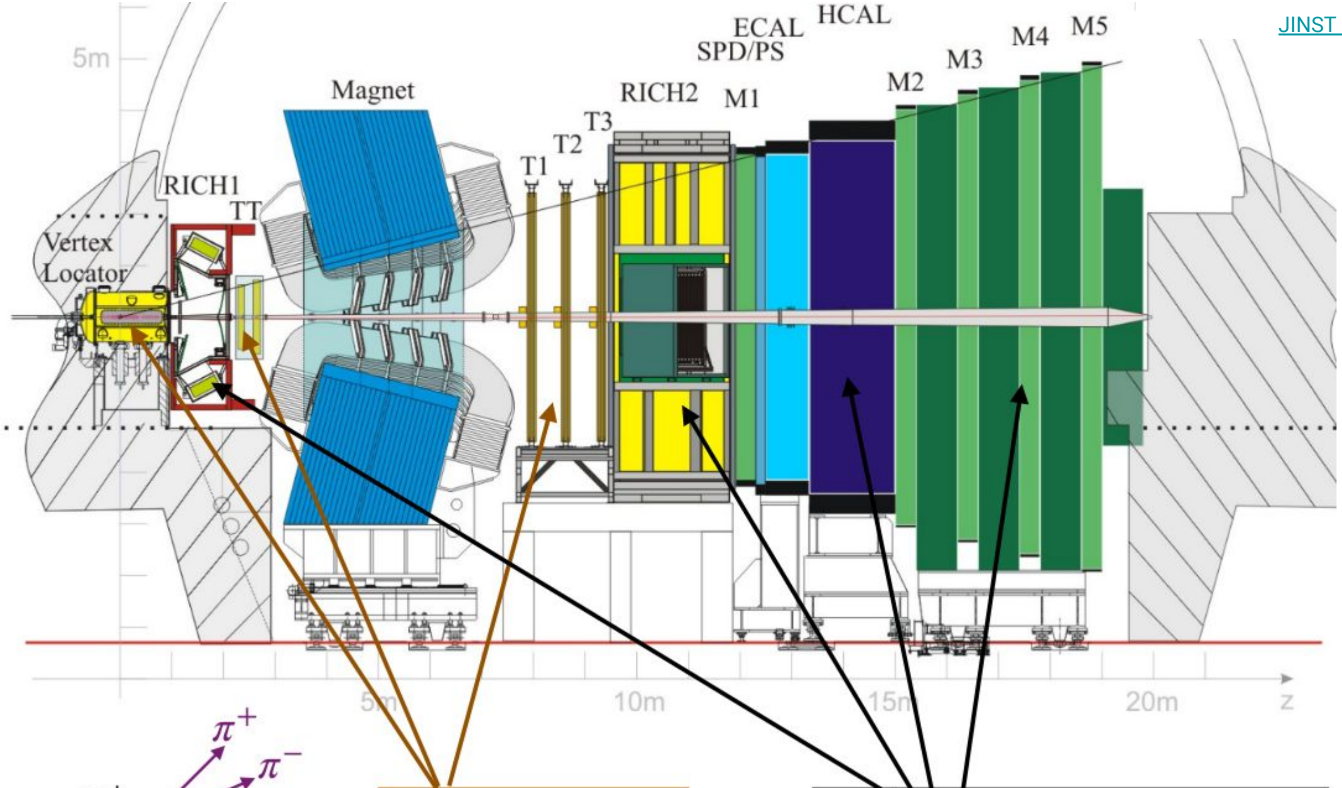
https://home.cern/news/news/physics/largest-matter-antimatter-asymmetry-observed

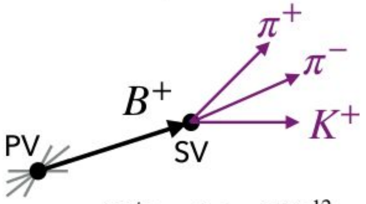
https://www1.folha.uol.com.br/ciencia/2022/03/assimetria-em-acelerador-de-particulas-pode-apontar-por-que-universo-e-feito-de-materia.shtml

BACKUP

The LHCb detector

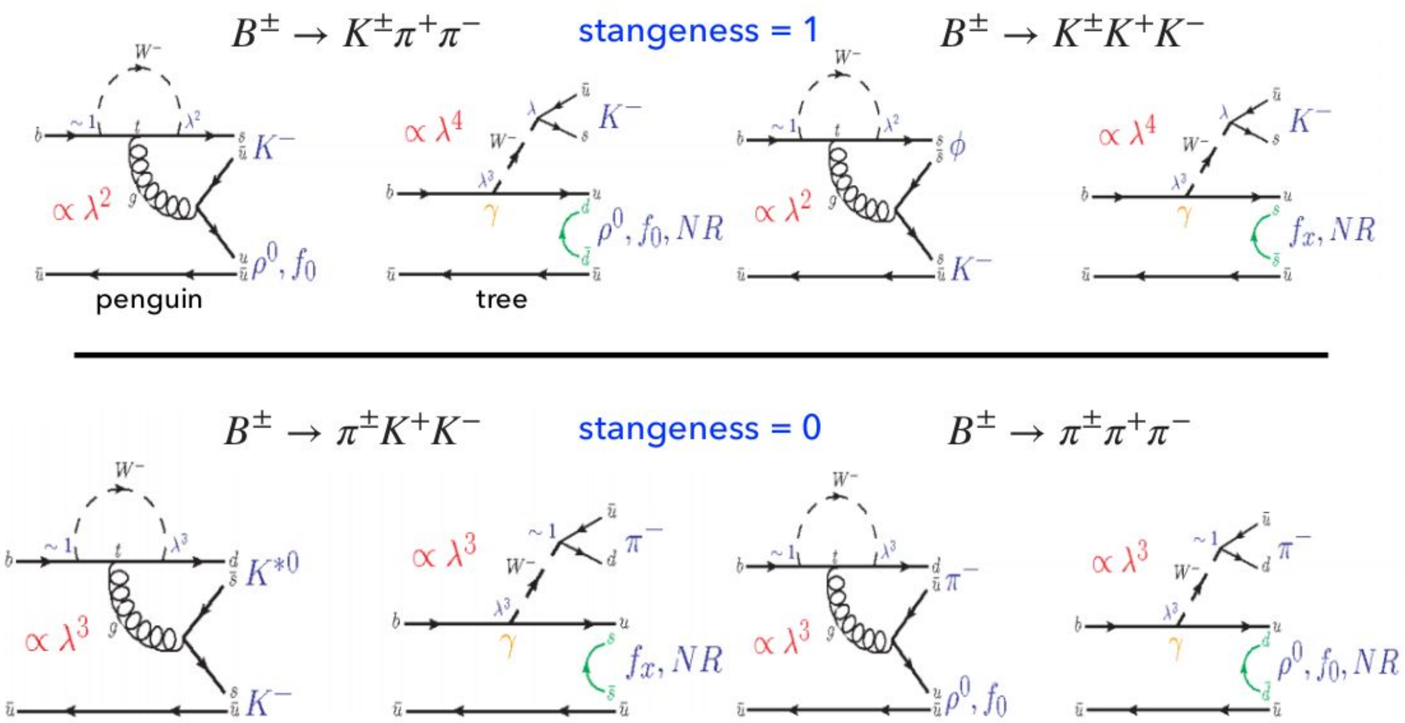
[JINST 3 (2008) S08005]





$\tau(B^{\pm}) = 1.6 \times 10^{-12}$s

Relevant diagrams



CP violation from interferences between:

- penguin and tree diagrams
- resonances in the phase space

CPT contraints on *CP* violation

- *CP* violation: $\Gamma(P \to f) - \Gamma(\bar{P} \to \bar{f}) \neq 0$
- CPT symmetry: total decay widths of P and $\bar{P}$ are the same

$$\Gamma(P \to f_1) + \ldots + \Gamma(P \to f_n) = \Gamma(\bar{P} \to \bar{f}_1) + \ldots + \Gamma(\bar{P} \to \bar{f}_n)$$

→ requires communication between the different decay modes having the same quantum numbers

- Final-state hadronic interactions:

→ provide the strong phases for *CP* violation to be observed

→ is a key ingredient to preserve CPT symmetry

Prog. Part. Nucl. Phys. 114 (2020) 103808

Efficiency correction

- From simulated samples (2015 + 2016 + 2017)
- Square Dalitz plot coordinates $\{m_{12}, \theta_{12}\}$
- Separately by polarity, trigger and year

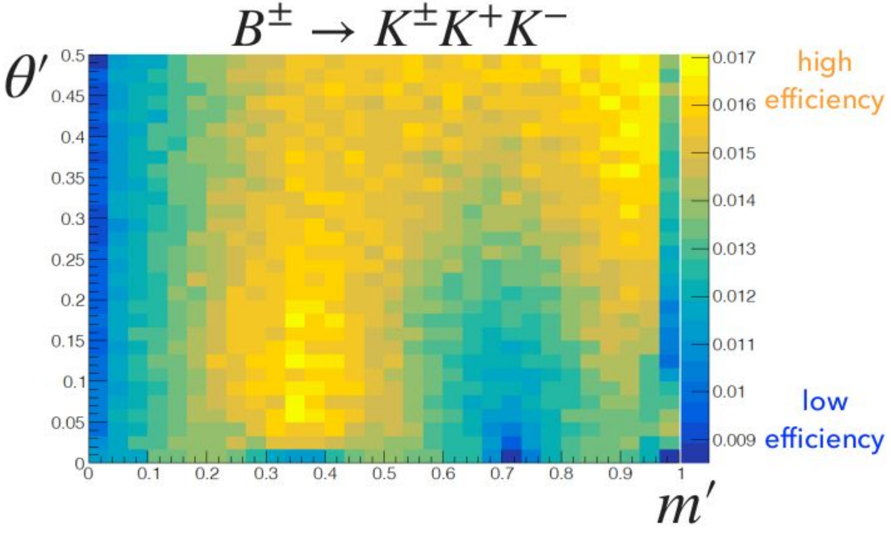
  → Maps are combined by using weights from data

Efficiency map

B+ and B- separately

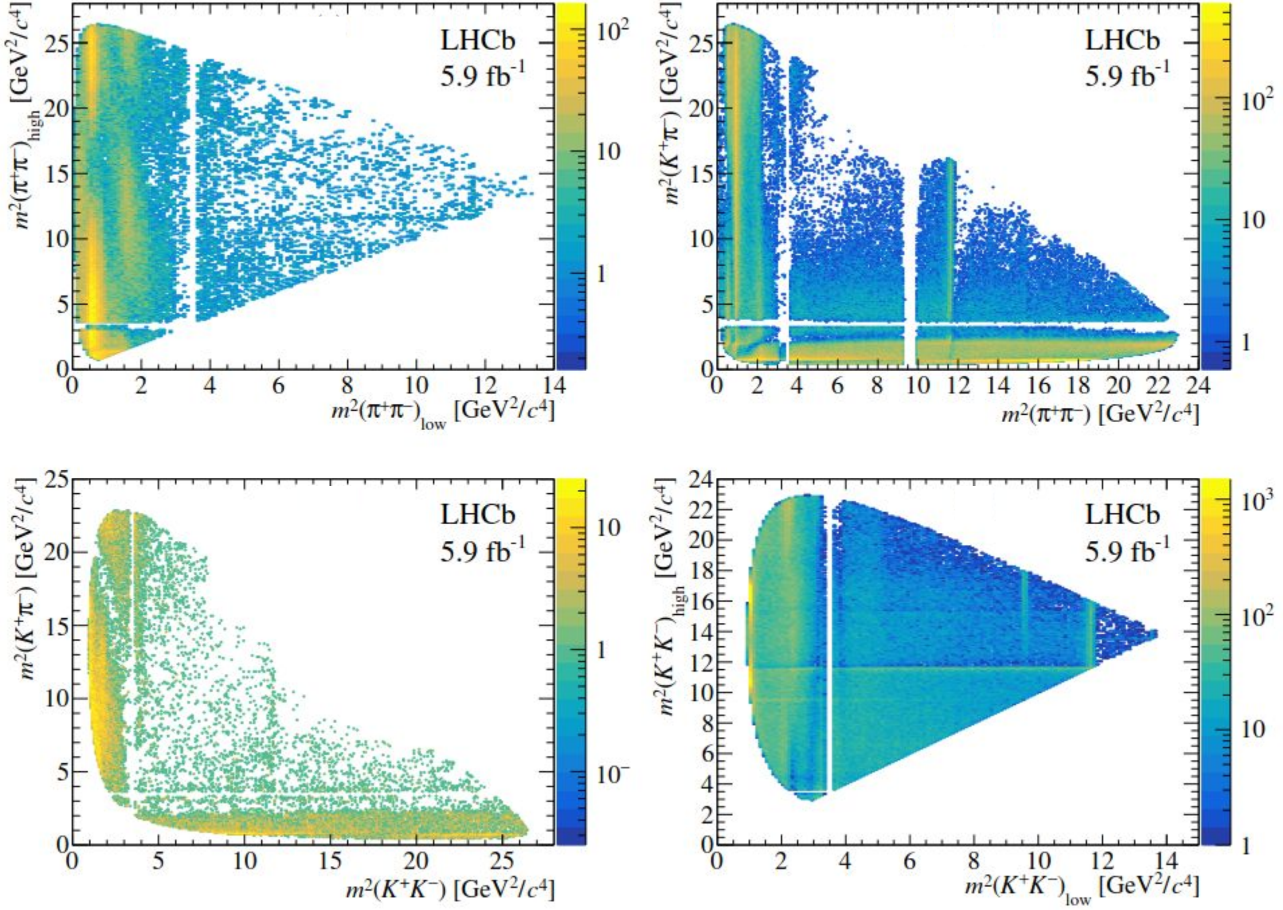
$$\varepsilon_{B^\pm} = \frac{Histo^{final}_{B^\pm}}{Histo^{Gen}_{B^\pm}}$$

- Selection cuts
- Detection asymmetry
- PID efficiency from PIDcalib
- Trigger correction



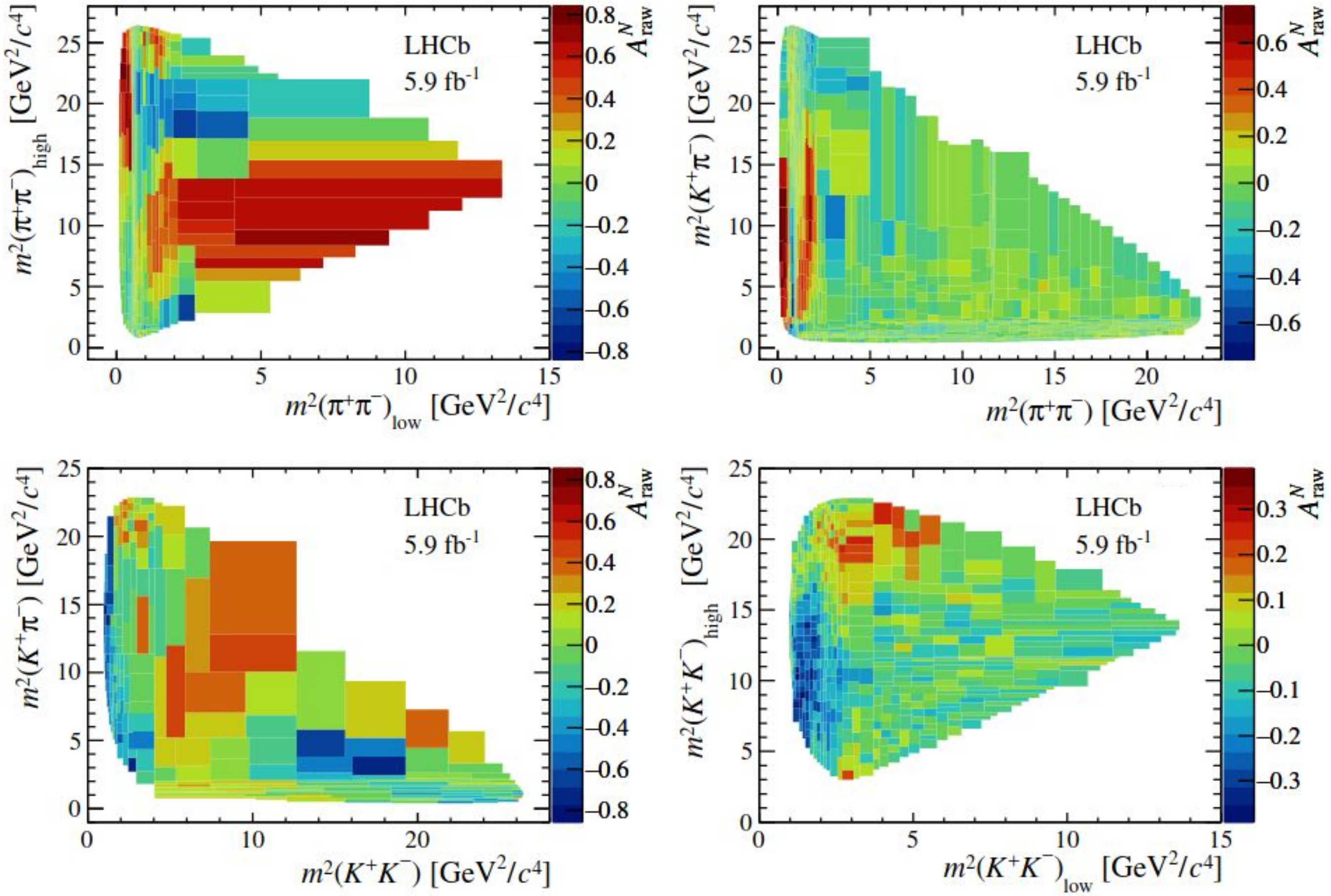
Dalitz plots

arXiv:2206.07622
Accepted by PRD



Asymmetry in bins of phase space

arXiv:2206.07622
Accepted by PRD



arXiv:2206.07622
Accepted by PRD

Regions of the phase space

	N_{sig}	A_{raw}	A_{CP}	
$B^\pm \to \pi^\pm\pi^+\pi^-$				
Region 1	$14\,330 \pm 150$	$+0.309 \pm 0.009$	$+0.303 \pm 0.009 \pm 0.004 \pm 0.003$	(29.9σ)
Region 2	$4\,850 \pm 130$	-0.287 ± 0.017	$-0.284 \pm 0.017 \pm 0.007 \pm 0.003$	(15.2σ)
Region 3	$2\,270 \pm 60$	$+0.747 \pm 0.027$	$+0.745 \pm 0.027 \pm 0.018 \pm 0.003$	(23.0σ)
$B^\pm \to K^\pm\pi^+\pi^-$				
Region 1	$41\,980 \pm 280$	$+0.201 \pm 0.005$	$+0.217 \pm 0.005 \pm 0.005 \pm 0.003$	(27.3σ)
Region 2	$27\,040 \pm 250$	-0.149 ± 0.007	$-0.145 \pm 0.007 \pm 0.006 \pm 0.003$	(15.0σ)
$B^\pm \to \pi^\pm K^+K^-$				
Region 1	$11\,430 \pm 170$	-0.363 ± 0.010	$-0.358 \pm 0.010 \pm 0.014 \pm 0.003$	(20.2σ)
Region 2	$2\,600 \pm 120$	$+0.075 \pm 0.031$	$+0.097 \pm 0.031 \pm 0.005 \pm 0.003$	(3.1σ)
$B^\pm \to K^\pm K^+K^-$				
Region 1	$76\,020 \pm 350$	-0.189 ± 0.004	$-0.178 \pm 0.004 \pm 0.004 \pm 0.003$	(28.3σ)
Region 2	$37\,440 \pm 320$	$+0.030 \pm 0.005$	$+0.043 \pm 0.005 \pm 0.004 \pm 0.003$	(6.3σ)