Charmless b-meson and b-baryon decays at LHCb

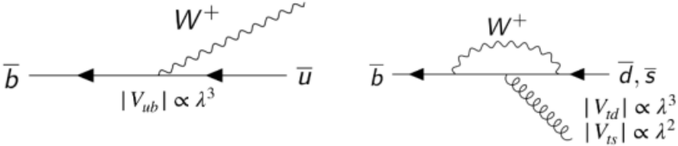
Laís Soares Lavra on behalf of the LHCb collaboration

Université Clermont Auvergne, LPC-Clermont, IN2P3/CNRS

European Physical Society Conference on High Energy Physics
Online Conference, 26th July 2021

Charmless b-meson decays

- Involve both **Tree** $b \to u$ and **Penguin** $b \to s, d$ transitions



- Dominant tree-level and penguin diagrams contribute in the same order of magnitude
- Sensitive to CP violation studies
- Multi-body decays possess rich resonant structures
  - Large CP violation signatures found in regions of the phase space
- Interesting to search for new sources of CP violation

Outline

- **Measurement of the relative branching fractions of $B^+ \to h^+ h'^+ h'^-$ decays**
  - Published as Phys. Rev. D102(2020) 112010 (arXiv:2010.11802)
- **Search for CP and observation of P violation in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$**
  - Published as Phys. Rev. D102(2020) 051101 (arXiv:1912.10741)
- **Search for CP violation in $\Xi_b^- \to pK^-K^-$**
  - Submitted to Phys. Rev. D (arXiv:2104.15074)

Measurement of the relative branching fractions of $B^+ \to h^+ h'^+ h'^-$ decays ($B^+ \to K^+ K^+ K^-$, $B^+ \to \pi^+ K^+ K^-$, $B^+ \to K^+ \pi^+ \pi^-$, $B^+ \to \pi^+ \pi^+ \pi^-$)

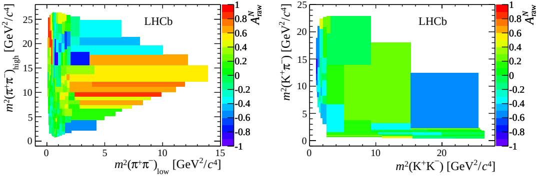
Phys. Rev. D102(2020) 112010
(arXiv:2010.11802)

Motivation

- Large integrated CP asymmetries and CP signatures in localized regions of the phase space
- Confirmed with recent amplitude analyses:
  - $B^+ \to \pi^+\pi^+\pi^-$ (PRL 124(2020)031801) (PRD 101(2020)012006)
  - $B^+ \to \pi^+K^+K^-$ (PRL 123(2019)231802)
- Fit fractions from amplitude analysis are converted into quasi-two-body branching fractions
  - Precise knowledge of three-body branching fraction is needed
  - Current knowledge of branching fraction not suficient given the sensitivity of the Dalitz plot analyses

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

(PRD 90(2014)112004)



Current knowledge BF $B^+ \to h^+h'^+h'^-$(PDG)

Decay	PDG average (10^{-6})
$B^+ \to K^+K^+K^-$	34.0 ± 1.4
$B^+ \to \pi^+K^+K^-$	5.2 ± 0.4
$B^+ \to K^+\pi^+\pi^-$	51.0 ± 2.9
$B^+ \to \pi^+\pi^+\pi^-$	15.2 ± 1.4

Measurement of the relative branching fractions of $B^+ \to h^+ h'^+ h'^-$

- Performed with Run 1 dataset: 3fb^{-1} from 2011+12
- Relative branching fraction ratios determined by

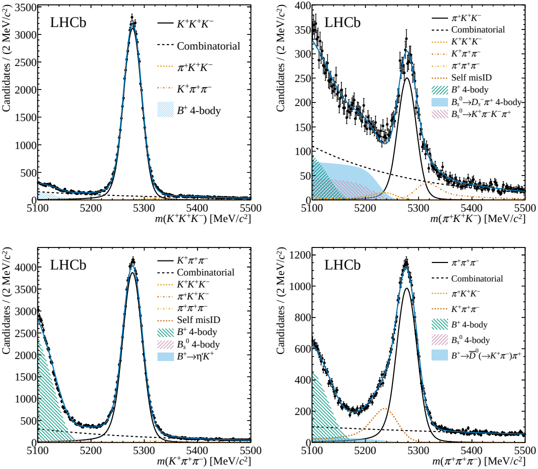
$$\frac{\mathcal{B}(B^+ \to h^+ h'^+ h'^-)}{\mathcal{B}(B^+ \to K^+ K^+ K^-)} = \frac{\mathcal{N}^{corr}_{hh'h'}}{\mathcal{N}^{corr}_{KKK}}$$

$\mathcal{N}^{corr} \to$ signal yield efficiency corrected

- Obtained as a function of Dalitz plot position

Signal Yields

Extraction of the signal and background yields from a simultaneous fit to all channels



Mass fit results:

Decay	Fit yield
$B^+ \to K^+K^+K^-$	$69\,310 \pm 280$
$B^+ \to \pi^+K^+K^-$	$5\,760 \pm 140$
$B^+ \to K^+\pi^+\pi^-$	$94\,950 \pm 430$
$B^+ \to \pi^+\pi^+\pi^-$	$25\,480 \pm 200$

Signal Yield correction:

$$\mathcal{N}^{corr} \propto \sum_{bins} \frac{w_{bin}}{\epsilon_{bin}}$$

$w_{bin} \to$ signal data background subtracted, $\epsilon_{bin} \to$ efficiency

Results

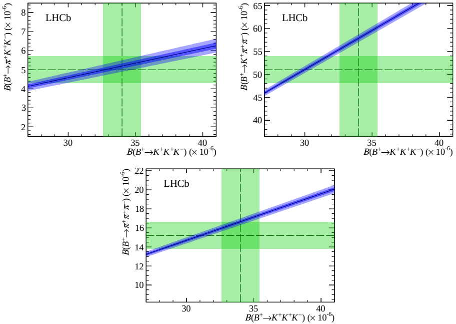
Measured relative branching fractions

$\mathcal{B}$ ratio	Value
$\mathcal{B}(B^+ \to \pi^+ K^+ K^-)/\mathcal{B}(B^+ \to K^+ K^+ K^-)$	$0.151 \pm 0.004 \pm 0.008$
$\mathcal{B}(B^+ \to K^+ \pi^+ \pi^-)/\mathcal{B}(B^+ \to K^+ K^+ K^-)$	$1.703 \pm 0.011 \pm 0.022$
$\mathcal{B}(B^+ \to \pi^+ \pi^+ \pi^-)/\mathcal{B}(B^+ \to K^+ K^+ K^-)$	$0.488 \pm 0.005 \pm 0.009$
$\mathcal{B}(B^+ \to K^+ K^+ K^-)/\mathcal{B}(B^+ \to \pi^+ K^+ K^-)$	$6.61 \pm 0.17 \pm 0.33$
$\mathcal{B}(B^+ \to K^+ \pi^+ \pi^-)/\mathcal{B}(B^+ \to \pi^+ K^+ K^-)$	$11.27 \pm 0.29 \pm 0.54$
$\mathcal{B}(B^+ \to \pi^+ \pi^+ \pi^-)/\mathcal{B}(B^+ \to \pi^+ K^+ K^-)$	$3.23 \pm 0.09 \pm 0.19$
$\mathcal{B}(B^+ \to K^+ K^+ K^-)/\mathcal{B}(B^+ \to K^+ \pi^+ \pi^-)$	$0.587 \pm 0.004 \pm 0.008$
$\mathcal{B}(B^+ \to \pi^+ K^+ K^-)/\mathcal{B}(B^+ \to K^+ \pi^+ \pi^-)$	$0.0888 \pm 0.0023 \pm 0.0047$
$\mathcal{B}(B^+ \to \pi^+ \pi^+ \pi^-)/\mathcal{B}(B^+ \to K^+ \pi^+ \pi^-)$	$0.2867 \pm 0.0029 \pm 0.0045$
$\mathcal{B}(B^+ \to K^+ K^+ K^-)/\mathcal{B}(B^+ \to \pi^+ \pi^+ \pi^-)$	$2.048 \pm 0.020 \pm 0.040$
$\mathcal{B}(B^+ \to \pi^+ K^+ K^-)/\mathcal{B}(B^+ \to \pi^+ \pi^+ \pi^-)$	$0.310 \pm 0.008 \pm 0.020$
$\mathcal{B}(B^+ \to K^+ \pi^+ \pi^-)/\mathcal{B}(B^+ \to \pi^+ \pi^+ \pi^-)$	$3.488 \pm 0.035 \pm 0.053$

- Large systematic uncertainties:
    - Dominant source from background modelling

Results

Comparison with the current world averages



Branching fractions ratios obtained (violet) compared to the PDG (green)

Results applied to quasi-two-body BFs from $B^{\pm} \to \pi^{+}\pi^{+}\pi^{-}$ amplitude analysis

$\mathcal{B}(B^{\pm} \to \rho^{0}(770)\pi^{+})$ improves relative error from 16% to 6%

Current world average (arXiv:1612.07233):

- $\mathcal{B}(B^{\pm} \to \rho^{0}(770)\pi^{+}) = (8.3^{+1.2}_{-1.3})\times 10^{-6}$

Improved measurement:

- $\mathcal{B}(B^{\pm} \to \rho^{0}(770)\pi^{+}) = (9.5 \pm 0.6)\times 10^{-6}$

- All measurements in good agreement
- Significant improvement in the precision of all measured ratios

Charmless b-baryon decays

Introduction

- Theory predicts large CP violation asymmetries in some charmless b-baryon decays (Phys. Rev. D91,116007(2015))

Theory prediction

- $A_{CP}(\Lambda_b \to pK^-) = (5.8 \pm 0.2)\%$
- $A_{CP}(\Lambda_b \to p\pi^-) = (-3.9 \pm 0.2)\%$
- $A_{CP}(\Lambda_b \to pK^{*-}) = (19.6 \pm 1.3)\%$
- $A_{CP}(\Lambda_b \to p\rho^-) = (-3.7 \pm 0.3)\%$

- CP violation not yet observed in any b-baryon decay
- Abundant production of b-baryons in *pp* collisions at the LHC

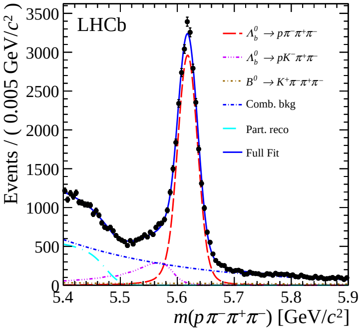
Search for CP and observation of P violation in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ decays

Phys. Rev. D102(2020) 051101 (arXiv:1912.10741)

Search for CP and P violation in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ decays

- $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ has contributions of many resonances
  - Possibility of CP asymmetries in regions of the phase space
- First evidence of CPV in baryons found in this decay with 3.3σ using Run 1 data (Nature Phys. 13 (2017) 391)
- Updated result using 6.6 fb^{-1} from Run 1+Run 2 (2011+12+15+16+17)
- Search for CPV with 2 methods:
  - Triple Product Asymmetries (TPA)
  - Unbinned energy test
- Published as PRD 102(2020)051101

Run 1+Run 2 (PRD 102(2020)051101)



- $N^{Run1+Run2}_{\Lambda_b^0 \to p\pi^-\pi^+\pi^-}$ =27600±200

Triple Product Asymmetries and Energy Test method

Triple Product Asymmetries $A_{\hat{T}}$

Based on scalar triple products $C_{\hat{T}} \equiv \vec{p}_p \cdot (\vec{p}_{\pi_{fast}} \times \vec{p}_{\pi_+})$

CP and P violating asymmetries observables:

$$a_{CP}^{\hat{T}-odd} = \frac{1}{2}(A_{\hat{T}} - \bar{A}_{\hat{T}}) \qquad a_{P}^{\hat{T}-odd} = \frac{1}{2}(A_{\hat{T}} + \bar{A}_{\hat{T}})$$

Measurements in bins and integrated over the phase space

Energy Test

- Sensitive to local asymmetries
- Relies on a test statistic to calculate the differences between two samples

Measurements in regions of the phase space

Results

Integrated measurements (TPA)

$a_{CP}^{\hat{T}-odd}$ = (-0.7±0.7±0.2)%

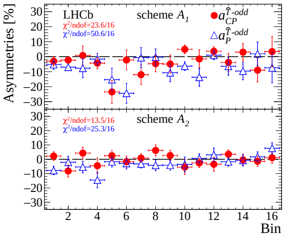
No evidence for CPV

$a_{P}^{\hat{T}-odd}$ = (-4.0±0.7±0.2)%

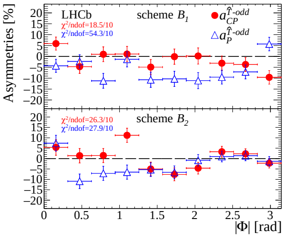
P violation observed with 5.5σ

Phase space bins measurements (TPA)

16 bins on helicity angles



10 bins on $|\Phi|$ angle



- **No evidence for CPV in regions of the phase space**
- **Local P violation at 5.1σ**

Energy Test

- **No evidence for local CPV**
- **Confirms local P violation observed at 5.3σ**

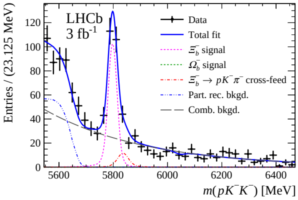
Search for CP violation in $\Xi_b^- \to pK^-K^-$

Submitted to Phys. Rev. D (arXiv:2104.15074)

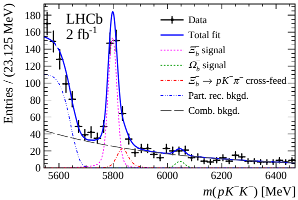
Search for CP violation in $\Xi_b^- \to pK^-K^-$

- Large local CPV observed in $B^\pm \to 3h$. Can similar behaviour be observed in baryonic modes?
- $\Xi_b^- \to pK^-K^-$ was first observed by LHCb in 3 fb^{-1} from 2011+12 (PRL 118(2017)112004)
- First amplitude analysis of $\Xi_b^- \to pK^-K^-$
  - Run 1: 3 fb^{-1} from 2011+12
  - Run 2: 2 fb^{-1} from 2015+16
  - First amplitude analysis of any baryon decay accounting for CP violation
- Search for $\Omega_b^- \to pK^-K^-$ decays
  - New upper limit set on $\mathcal{R} = \frac{f_{\Omega_b}}{f_{\Xi_b}} \times \frac{BF(\Omega_b^- \to pK^-K^-)}{BF(\Xi_b^- \to pK^-K^-)}$

Run 1 $N^{\Xi_b^-}$ =193±21

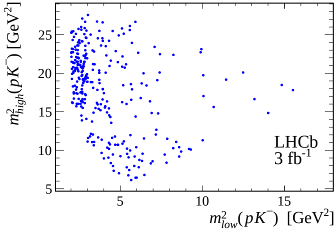


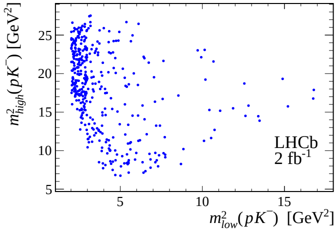
Run 2 $N^{\Xi_b^-}$ =297±23



Amplitude Analysis of $\Xi_b^- \to pK^-K^-$

- Model-dependent amplitude analysis
- Signal region: m(Ξ_b^-)±40 MeV
  - Signal purity: 63%(Run 1) 70%(Run 2)
- Phase space of $\Xi_b^- \to pK^-K^-$ has 5 degrees of freedom
  - Assumption: Ξ_b produced unpolarised, decay characterised by 2 variables
- Resonant structures observed in $m^2_{low}(pK)$
  - Λ^* and Σ^* resonances expected





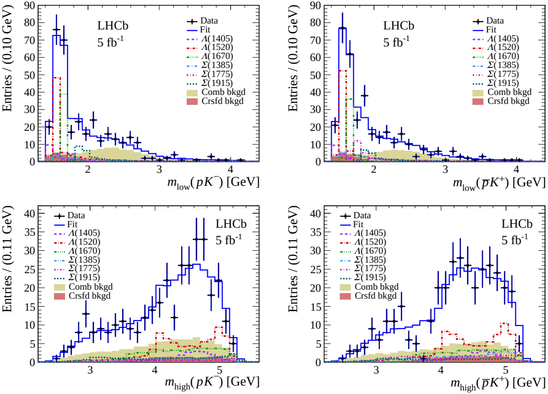
Fit to data

Baseline model:

- Contributions from Λ^* and Σ^*
  - $\Lambda(1520)$ used as reference
  - modelled as Breit-Wigner
- Nonresonant components
  - modelled as exponential

Fit to data:

- Simultaneous fit to Run1 & Run2
- No significant difference between Ξ_b^- and Ξ_b^+



Results: Ratio $\mathcal{R}$ of Ω_b^- and Ξ_b^- branching fractions

Combined Run1+Run2 results

Branching Fraction Limit

$$\mathcal{R} \equiv \frac{f_{\Omega_b^-}}{f_{\Xi_b^-}} \times \frac{\mathcal{B}(\Omega_b^- \to pK^-K^-)}{\mathcal{B}(\Xi_b^- \to pK^-K^-)} = (24 \pm 21(stat) \pm 14(sys)) \times 10^{-3}$$

Consistent and more precise than the previous LHCb measurement performed on Run 1 data (PRL 118(2017) 071801)

No observation of $\Omega_b^- \to pK^-K^-$ decay mode

Upper limit on the ratio of fragmentation and branching fractions:

$$\mathcal{R} \equiv \frac{f_{\Omega_b^-}}{f_{\Xi_b^-}} \times \frac{\mathcal{B}(\Omega_b^- \to pK^-K^-)}{\mathcal{B}(\Xi_b^- \to pK^-K^-)} < 62(71) \times 10^{-3}$$

Results: Amplitude Analysis

CP-asymmetry

Component	A^{CP} (10^{-2})
$\Sigma(1385)$	-27 ± 34 (stat) ± 73 (syst)
$\Lambda(1405)$	-1 ± 24 (stat) ± 32 (syst)
$\Lambda(1520)$	-5 ± 9 (stat) ± 8 (syst)
$\Lambda(1670)$	3 ± 14 (stat) ± 10 (syst)
$\Sigma(1775)$	-47 ± 26 (stat) ± 14 (syst)
$\Sigma(1915)$	11 ± 26 (stat) ± 22 (syst)

No significant A^{CP} is observed

Quasi 2-body Branching Fraction

$$\mathcal{B}\left(\Xi_b^- \to \Sigma(1385)K^-\right) = (0.26 \pm 0.11 \pm 0.17 \pm 0.10) \times 10^{-6},$$
$$\mathcal{B}\left(\Xi_b^- \to \Lambda(1405)K^-\right) = (0.19 \pm 0.06 \pm 0.07 \pm 0.07) \times 10^{-6},$$
$$\mathcal{B}\left(\Xi_b^- \to \Lambda(1520)K^-\right) = (0.76 \pm 0.09 \pm 0.08 \pm 0.30) \times 10^{-6},$$
$$\mathcal{B}\left(\Xi_b^- \to \Lambda(1670)K^-\right) = (0.45 \pm 0.07 \pm 0.13 \pm 0.18) \times 10^{-6},$$
$$\mathcal{B}\left(\Xi_b^- \to \Sigma(1775)K^-\right) = (0.22 \pm 0.08 \pm 0.09 \pm 0.09) \times 10^{-6},$$
$$\mathcal{B}\left(\Xi_b^- \to \Sigma(1915)K^-\right) = (0.26 \pm 0.09 \pm 0.21 \pm 0.10) \times 10^{-6},$$

$$\mathcal{B}(\Xi_b^- \to R^-) = \mathcal{B}(\Xi_b^- \to pK^-K^-) \times \mathcal{F}_i$$

$$\mathcal{B}(\Xi_b^- \to pK^-K^-) = (2.3 \pm 0.9) \times 10^{-6}$$

- Uncertainties
  - statistical
  - systematic
  - knowledge of $\mathcal{B}(\Xi_b^- \to pK^-K^-)$

Summary

Summary

$B^+ \to h^+ h'^+ h'^-$

- Measurements of all combinations of $B^+ \to h^+ h'^+ h'^-$ relative branching fractions
- All measurements in good agreement with their world-average results
- Significant improvement in the precision

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

- Two different methods to search for CP and P violation: TPA and Energy Test
- No evidence of CP violation
- Observation of P violation over 5σ locally and integrated over all phase space.

$\Xi_b^- \to pK^-K^-$

- First amplitude analysis of a baryon accounting for CP violation
- No evidence of CP violation
- Meausurement of six quasi two-body branching fraction of $\Xi_b^- \to pK^-K^-$
- No significant signal of $\Omega_b^- \to pK^-K^-$
- Set a new upper limit on the ratio of fragmentation and branching fraction of $\Xi_b^- \to pK^-K^-$ and $\Omega_b^- \to pK^-K^-$

Thank you for your attention

Backup slides

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

$\Lambda_b^0 \to p\pi^-\pi^+\pi^-$: Triple Product Asymmetries

Triple products are $\hat{T}$-odd[1] observables built combining the momentum $\vec{p}$ of three final states particles in the Λ_b^0 frame:

$$C_{\hat{T}} \equiv \vec{p}_p \cdot (\vec{p}_{\pi_{fast}} \times \vec{p}_{\pi_+})$$

Triple product asymmetries (TPA):

$$A_{\hat{T}} = \frac{N(C_{\hat{T}} > 0) - N(C_{\hat{T}} < 0)}{N(C_{\hat{T}} > 0) + N(C_{\hat{T}} < 0)} \qquad \bar{A}_{\hat{T}} = \frac{\bar{N}(\bar{C}_{\hat{T}} > 0) - \bar{N}(\bar{C}_{\hat{T}} < 0)}{\bar{N}(\bar{C}_{\hat{T}} > 0) + \bar{N}(\bar{C}_{\hat{T}} < 0)}$$

$N, \bar{N} \to$ number of Λ_b^0, $\bar{\Lambda}_b^0$ decays

Clean CP and P violating asymmetries observables are defined as:

$$a_{CP}^{\hat{T}-odd} = \frac{1}{2}(A_{\hat{T}} - \bar{A}_{\hat{T}}) \qquad a_{P}^{\hat{T}-odd} = \frac{1}{2}(A_{\hat{T}} + \bar{A}_{\hat{T}})$$

Measurements in bins and integrated over the phase space

[1] $\hat{T}$ is an operator called motion-reversal that reverts momentum and helicities.

$\Lambda_b^0 \to p\pi^-\pi^+\pi^-$: Triple Product Asymmetries

Phase space bins measurements:

- Scheme A: asymmetries measured as function of the polar and azimuthal angles of $p(\Delta^{++})$ in the $\Delta^{++}(N^{*+})$ rest frame
- Scheme B: asymmetries measured as a function of the angle $|\Phi|$, between the decays planes $p\pi^-_{fast}$ and $\pi^+\pi^-_{slow}$
- $A_1, B_1 \to m(p\pi^+\pi^-_{slow}) > 2.8$ GeV$/c^2$ dominated by a_1 resonance
- $A_2, B_2 \to m(p\pi^+\pi^-_{slow}) < 2.8$ GeV$/c^2$ dominated by N^{*+} decay

$\Lambda_b^0 \to p\pi^-\pi^+\pi^-$: Energy Test

- Model independent unbinned test sensitive to local asymmetries
- Statistical test T used to calculate the differences between two samples:

$$T \equiv \frac{1}{2n(n-1)} \sum_{i \neq j}^{n} \psi_{ij} + \frac{1}{2\bar{n}(\bar{n}-1)} \sum_{i \neq j}^{\bar{n}} \psi_{ij} - \frac{1}{n\bar{n}} \sum_{i=1}^{n} \sum_{j=1}^{\bar{n}} \psi_{ij}$$

$n(\bar{n}) \to$ number of $\Lambda_b^0(\bar{\Lambda}_b^0)$ candidates and $\psi_{ij} = e^{-d_{ij}^2/2\delta^2} \to d_{ij}$ is the distance in phase space of each pair of candidates ij and δ is the distance scale (free parameter)

- 4 subsamples defined $\to$ 3 tests performed (2 for CPV + 1 for P violation)

p-value results obtained for each test in 3 different δ

Distance scale δ	1.6 GeV^2/c^4	2.7 GeV^2/c^4	13 GeV^2/c^4
p-value (CP conservation, P even)	3.1×10^{-2}	2.7×10^{-3}	1.3×10^{-2}
p-value (CP conservation, P odd)	1.5×10^{-1}	6.9×10^{-2}	6.5×10^{-2}
p-value (P conservation)	1.3×10^{-7}	4.0×10^{-7}	1.6×10^{-1}

$$\Xi_b^- \to pK^-K^-$$

$\Xi_b^- \to pK^-K^-$: Total PDF of the phase space

$$\mathcal{P}^Q_{tot}(\Omega) = \frac{1}{N_{tot}}\left[N_{sig}\, P^Q_{sig}(\Omega) + N_{comb}\frac{(1 - QA_{comb})}{2} P_{comb}(\Omega) + \frac{N_{cf}}{2}\mathcal{P}_{cf}(\Omega)\right]$$

$\Omega \to$ Phase space in terms of DP variables

Signal PDF

$$\mathcal{P}^Q_{sig}(\Omega) = \frac{\epsilon^Q(\Omega)}{\Gamma}\frac{d\Gamma^Q}{d\Omega}$$

- $\frac{d\Gamma}{d\Omega}$ (differential decay density)
  Helicity formalism to parametrise the decay dynamics and isobar formalism to coherently sum all intermediate states
- $\epsilon(\Omega)$: signal efficiency

Combinatorial Background PDF

- Modelled using neural networks
- Training in the right sideband region
- PDF is predicted by extrapolating the model at Ξ_b mass

Cross-Feed PDF

- $\Xi_b^- \to pK^-\pi^-$ simulated samples weighted according to a model consisting of Λ and N resonances

$\Xi_b^- \to pK^-K^-$: Outputs of the amplitude analysis

Decay density defined using helicity and isobar formalism:

$$\frac{d\Gamma^Q}{d\Omega} = \frac{1}{(8\pi m_{\Xi_b})^3} \sum_{M_{\Xi_b},\lambda_p} \left| \sum_R A^Q_{R,M_{\Xi_b},\lambda_p} \right|^2$$

- $A \to$ symmetrised decay amplitude

Dalitz Plot fit output:

Fit Fractions

$$\mathcal{F}_i = \frac{\int_\Omega (d\Gamma_i^+/d\Omega + d\Gamma_i^-/d\Omega) d\Omega}{\int_\Omega (d\Gamma^+/d\Omega + d\Gamma^-/d\Omega) d\Omega}$$

Interference Fit Fractions

$$\mathcal{I}_{ij} = \frac{\int_\Omega (d\Gamma_{i,j}^+/d\Omega + d\Gamma_{i,j}^-/d\Omega) d\Omega}{\int_\Omega (d\Gamma^+/d\Omega + d\Gamma^-/d\Omega) d\Omega}$$

CP violation

$$A_i^{CP} = = \frac{\int_\Omega (d\Gamma_i^+/d\Omega - d\Gamma_i^-/d\Omega) d\Omega}{\int_\Omega (d\Gamma^+/d\Omega + d\Gamma^-/d\Omega) d\Omega}$$