Charmed baryons at LHCb

XIV International conference on beauty, charm and hyperon hadrons

Jakub Ryżka on behalf of the LHCb collaboration

AGH, University of Science and Technology

10th June 2022

Outline

Introduction

- Why are we interested in (charmed) baryons?

CP violation in charmed baryons

- Difference between $\Lambda_c^+ \to pK^-K^+$ and $p\pi^-\pi^+$ decays
- In Ξ_c^+ decays using binned and unbinned methods

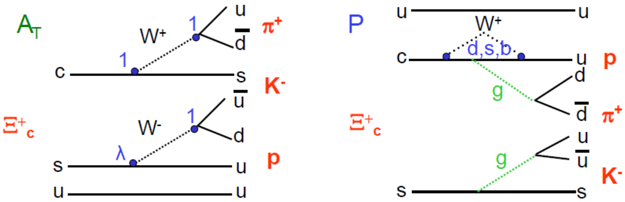
Decays and properties of charmed baryons

- The lifetimes of Ω_c^0 and Ξ_c^0
- Excited Ω_c^0 in $\Omega_b^- \to \Xi_c^+ K^- \pi^-$ decays
- Doubly charmed $\Xi_{cc}^{++} \to \Xi_c^{\prime +}\pi^+$ states
- Doubly charmed Ξ_{cc}^+ in $\Xi_c^+\pi^-\pi^+$

Summary

Why are we interested in c-baryons?

- The SM does not fully explain matter-antimatter asymmetry,
- Violation of CP symmetry is one of the conditions for baryogenesis,
- **So far, CP violation is not observed in ANY baryon decays,**
- In charm sector, CP violation is predicted to be $\sim 10^{-3}$ or less,



- **Searches for CP violation can be interpreted as searches for effects beyond the SM**.

Why are we interested in c-baryons?

- Charmed baryons properties are used to test the Standard Model (lifetimes, branching ratios),
- Observations of new baryons (i. e. exotic) are additional tests.

- Mixing and indirect CPV in charm mesons at LHCb, **Edward's talk**,
- Direct CPV in charm mesons at LHCb, **Artur's talk**,
- Today: Charmed baryons.

CP asymmetry difference between $\Lambda_c^+ \to pK^-K^+$ and $p\pi^-\pi^+$ decays

JHEP03 (2018) 182

- $\sqrt{s} = 7$ and 8 TeV, 2011 & 2012, $L_{int} = 3\ fb^{-1}$,
- The Λ_c^+ candidates reconstructed from $\Lambda_b^0 \to \Lambda_c^+ \mu^- X$ decay.

$$A_{CP} = \frac{\Gamma(f) - \Gamma(\bar{f})}{\Gamma(f) + \Gamma(\bar{f})}, \quad A_{raw} = \frac{N(f\mu^-) - N(\bar{f}\mu^+)}{N(f\mu^-) + N(\bar{f}\mu^+)}$$

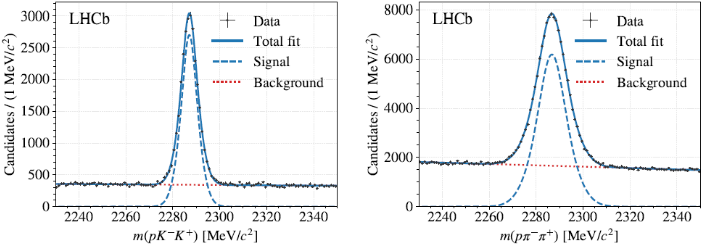
$$A_{raw}(f) = A_{CP}(f) + A_P^{\Lambda_b^0}(f\mu) + A_D^{\mu}(\mu) + A_D^{f}(f)$$

- Kinematics of the pK^-K^+ and $p\pi^-\pi^+$ are not equal - latter data are weighted.

$$\Delta A_{CP}^{wgt} = A_{CP}(pK^-K^+) - A_{CP}^{wgt}(p\pi^-\pi^+) \approx A_{raw}(pK^-K^+) - A_{raw}^{wgt}(p\pi^-\pi^+)$$

CP asymmetry difference between $\Lambda_c^+ \to pK^-K^+$ and $p\pi^-\pi^+$ decays

JHEP03 (2018) 182



$\sqrt{s}$	Polarity	Int. lumi. [pb^{-1}]	pK^-K^+ yield	$p\pi^-\pi^+$ yield
7 TeV	Up	422 ± 7	2880 ± 70	$18\,450 \pm 190$
7 TeV	Down	563 ± 9	3940 ± 80	$25\,130 \pm 230$
8 TeV	Up	1000 ± 11	9040 ± 120	$57\,730 \pm 350$
8 TeV	Down	992 ± 11	9330 ± 120	$60\,080 \pm 360$

Total yields: $\sim 25\text{k}$ (pK^-K^+), $\sim 187\text{k}$ ($p\pi^-\pi^+$) candidates

CP asymmetry difference between $\Lambda_c^+ \to pK^-K^+$ and $p\pi^-\pi^+$ decays

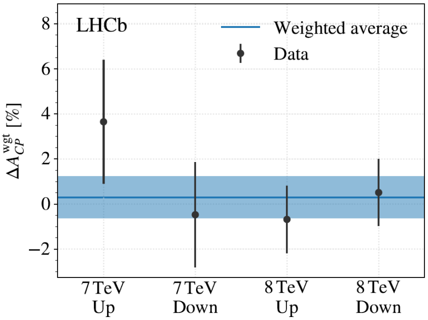
$$A_{raw}(pK^-K^+) = (3.72 \pm 0.78)\%$$

$$A_{raw}^{wgt}(p\pi^-\pi^+) = (3.42 \pm 0.47)\%$$

$$\mathbf{\Delta A_{CP}^{wgt} = (0.30 \pm 0.91 \pm 0.61)\%}$$

- **The first measurement of the *CP* violation parameter in Λ_c^+ decays,**
- **Central value is measured to be consistent with zero.**

JHEP03 (2018) 182



The first CPV search in $\Xi_c^+ \to pK^-\pi^+$

S_{CP}

The significance of a difference between number of the particles and antiparticles:

$$S_{CP}^i = \frac{N_+^i - \alpha N_-^i}{\sqrt{\alpha(N_+^i + N_-^i)}}$$

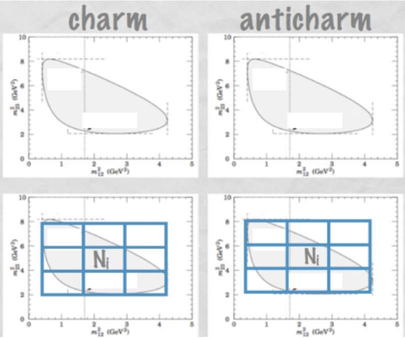
$\alpha = N_+/N_-$

$\chi^2/ndf = \sum_i S_{CP}^i/(nbins - 1)$

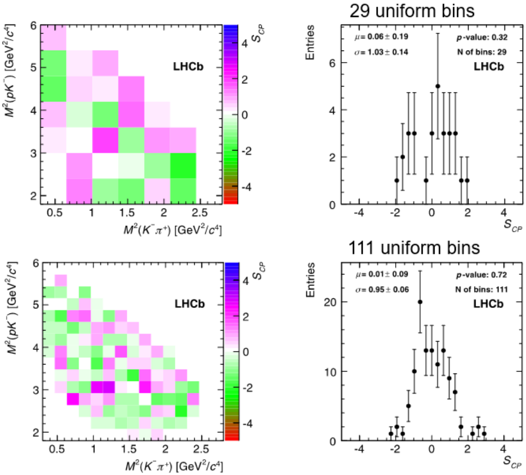
No CPV: $S_{CP} \sim N(0,1)$

CPV: p-value « 1 ($5\sigma \sim 6 \cdot 10^{-7}$)

Phys. Rev. D 80, 096006



The first CPV search in $\Xi_c^+ \to pK^-\pi^+$ - S_{CP} method



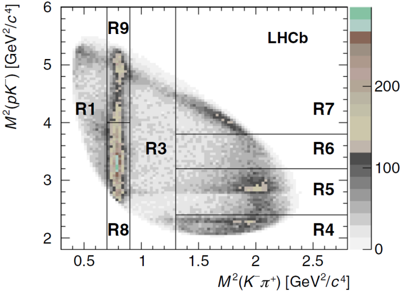
Eur. Phys. J. C80 (2020) 986

- $\sqrt{s} = 7$ TeV and 8 TeV, $L_{int} = 3\ fb^{-1}$
- p - values $> 32\%$,
- S_{CP} distributions agree with $N(0,1)$,
- **Results are consistent with *CP* symmetry.**

The first *CPV* search in $\Xi_c^+ \to pK^-\pi^+$

- The unbinned methods can be more sensitive than the binned ones,
- To increase sensitivity the method is performed in regions.

Eur. Phys. J. C80 (2020) 986



k-nearest neighbours

The kNN tests whether baryons and antibaryons share the same parent distribution function

$$T = \frac{1}{n_k(n_+ + n_-)} \sum_{i=1}^{n_+ + n_-} \sum_{k=1}^{n_k} I(i,k)$$

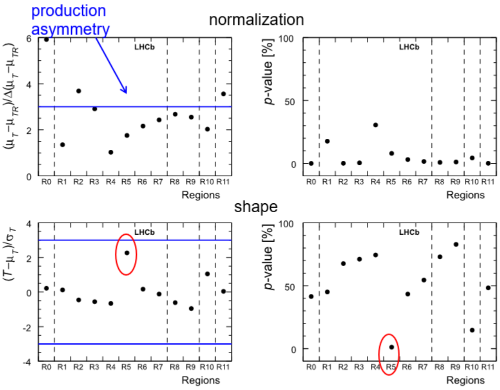
Under the null hypothesis $T \sim N(\mu_T, \sigma_T)$

$$\mu_T = \frac{n_+(n_+ - 1) + n_-(n_- - 1)}{n(n-1)}$$

$$\lim_{n, n_k, D \to \infty} \sigma_T^2 = \frac{1}{nn_k}\left(\frac{n_+ n_-}{n^2} + 4\frac{n_+^2 n_-^2}{n^4}\right)$$

J. Am. Stat. Assoc. 81, 799 (1986)

The first CPV search in $\Xi_c^+ \to pK^-\pi^+$ - kNN method



Eur. Phys. J. C80 (2020) 986

- Nonzero asymmetry in normalisation as an effect of the production asymmetry,
- **Results are consistent with *CP* symmetry,**
- Local effect in one region (red circle) corresponds to 2.7σ (to be continued...).

The next CPV search in $\Xi_c^+ \to pK^-\pi^+$

- The other model independent methods:
  - Energy test (LHCb: Phys. Lett. B740 (2015) 158, Phys. Lett. B769 (2017) 345, Phys. Rev. D102 (2020), 051101)

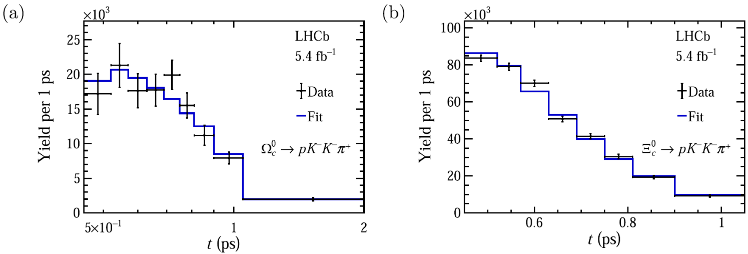
$$T = \frac{1}{n(n-1)} \sum_{i,j>i}^{n} K(|\vec{x}_i - \vec{x}_j|) + \frac{1}{m(m-1)} \sum_{i,j>i}^{n} K(|\vec{x}'_i - \vec{x}'_j|) - \sum_{i=1}^{n} \sum_{j=1}^{m} K(|\vec{x}_i - \vec{x}'_j|)$$

  - Kernel Density Estimation (never used in CPV searches, Szumlak T., Performance of the LHCb Vertex locator and the measurement of the forward-backward asymmetry in $B_d^0 \to K^{*0}(892)\mu^+\mu^-$ decay channel as a probe of New Physics", Krakow (2013)) a non parametric way to estimate the pdf of a random variable.
- We look forward for data in Run 3.

The lifetimes of Ω_c^0 and Ξ_c^0

Sci. Bull. 67 (2022) 479

- $\sqrt{s} = 13$ TeV, $L_{int} = 5.4\ fb^{-1}$,
- The Ω_c^0 and Ξ_c^0 baryons are produced directly from pp interactions and reconstructed in the $pK^-K^-\pi^+$ final state.

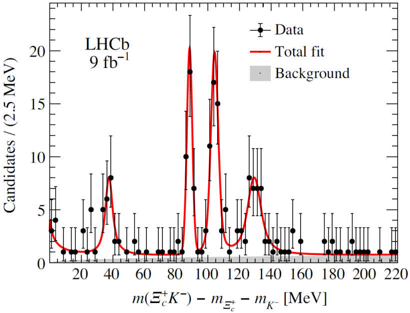


$$\boldsymbol{\tau_{\Omega_c^0} = 274.5 \pm 12.4\ fs, \quad \tau_{\Xi_c^0} = 152.0 \pm 2.0\ fs}$$

Excited Ω_c^0 in $\Omega_b^- \to \Xi_c^+ K^- \pi^-$ decays

Phys. Rev. D 104 L091102 (2021)

- $\sqrt{s} = 7, 8$ and 13 TeV, $L_{int} = 9\ fb^{-1}$,
- **The first observation of the $\Omega_b^- \to \Xi_c^+ K^- \pi^-$ decay,**
- **Four excited Ω_c^0 baryons are observed with the significance of each exceeding five standard deviations.**



$$\mathrm{m}(\Omega_b^-) = 6\,044.3 \pm 1.2 \pm 1.1^{+0.19}_{-0.22}\ \mathrm{MeV}$$

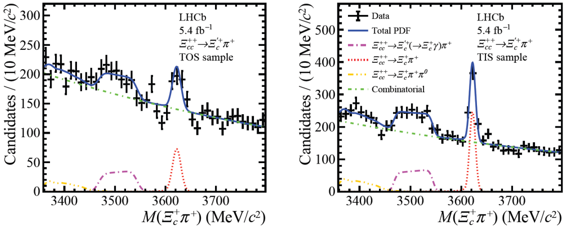
Doubly charmed $\Xi_{cc}^{++} \to \Xi_c'^{+} \pi^{+}$ decay

JHEP 2205 (2022) 038

- $\sqrt{s} = 13$ TeV, $L_{int} = 5.4\ fb^{-1}$,

$$\frac{B(\Xi_{cc} \to \Xi_c'^{+} \pi^{+})}{B(\Xi_{cc} \to \Xi_c^{+} \pi^{+})} = \frac{N_{\Xi_c'^{+}}}{N_{\Xi_c^{+}}} \times \frac{\epsilon_{\Xi_c^{+}}}{\epsilon_{\Xi_c'^{+}}} = 1.41 \pm 0.17 \pm 0.10$$

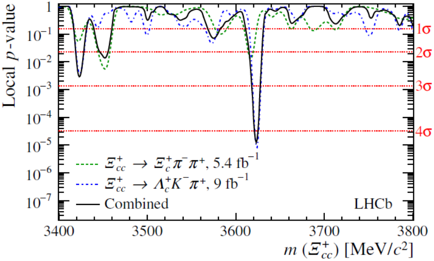
- The first observation of $\Xi_{cc}^{++} \to \Lambda_c^{+} K^{-} \pi^{-} \pi^{+}$ in 2017,
- Ξ_{cc}^{++} properties: lifetime (2018), mass (2020), cross-section (2020),
- New decay mode of the doubly charmed baryon $\Xi_{cc}^{++} \to \Xi_c'^{+} \pi^{+}$.



Doubly charmed Ξ_{cc}^{+} in $\Xi_c^{+}\pi^{-}\pi^{+}$

JHEP 12 2021, 107

- $\sqrt{s} = 13$ TeV, $L_{int} = 5.4\ fb^{-1}$,
- The test statistics $q_{\pm}$ was used,
- p-value of 0.0108 (0.0024) at mass of 3 617 (3 452) MeV/c^2 corresponding to 2.3 σ (2.8 σ)
- **No significant signal is observed yet**



Summary

- The first measurement of a CPV parameter in Λ_c decays:

$$\Delta A_{CP}^{wgt} = (0.30 \pm 0.91 \pm 0.61)\%$$

- The first CPV search $\Xi_c^+ \to pK^-\pi^+$ consistent with CP symmetry
- The measurement of Ω_c^0 and Ξ_c^0 lifetimes:

$$\tau_{\Omega_c^0} = 274.5 \pm 12.4\ fs, \quad \tau_{\Xi_c^0} = 152.0 \pm 2.0\ fs$$

- The first observation of the $\Omega_b^- \to \Xi_c^+ K^- \pi^-$ decay and precise measurement of the Ω_b^- mass:

$$m(\Omega_b^-) = 6044.3 \pm 1.2 \pm 1.1^{+0.19}_{-0.22}\ MeV$$

- Four excited Ω_c^0 baryons were observed with significance $> 5\sigma$,
- New decay mode of doubly charmed baryon $\Xi_{cc}^{++} \to \Xi_c'^{+}\pi^+$,

$$\frac{B(\Xi_{cc} \to \Xi_c'^{+}\pi^+)}{B(\Xi_{cc} \to \Xi_c^{+}\pi^+)} = 1.41 \pm 0.17 \pm 0.10$$

- Searches for CPV in charmed baryons are continuing...(Run 3 ...)

Back-up

Energy test

Defined as the analogue of the potential energy of the field of charges

$$T = \frac{1}{2}\int\int (f_p(\vec{x}) - f_a(\vec{x}))(f_p(\vec{x}') - f_a(\vec{x}'))K(\vec{x}, \vec{x}')d\vec{x}d\vec{x}'$$

$$K(\vec{x}, \vec{x}') = exp(-\frac{(\vec{x} - \vec{x}')^2}{2\delta})$$

ET can be estimated without the need for any knowledge about the f_p or f_a:

$$T = \frac{1}{n(n-1)}\sum_{i,j>i}^{n} K(|\vec{x}_i - \vec{x}_j|) + \frac{1}{m(m-1)}\sum_{i,j>i}^{n} K(|\vec{x}'_i - \vec{x}'_j|) - \sum_{i=1}^{n}\sum_{j=1}^{m} K(|\vec{x}_i - \vec{x}'_j|)$$

Distribution for $H_0 : f_p = f_a$ is unknown - how to find p-value **p**?

- T for overall samples - **nominal T**.
- Set of T calculated for samples with random sign - **permuted T**

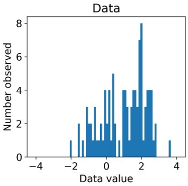
$$\boxed{p = \frac{\text{number of permuted } T \text{ values greater than nominal } T}{\text{total number of permuted } T \text{ values}}}$$

Kernel Density Estimation technique

KDE is a non parametric way to estimate the pdf of a random variable.

$$\hat{f}(x) = \frac{1}{n}\sum_{i=1}^{n}\omega(x - x_i, h)$$

- $\omega = \frac{1}{h}K(\frac{t}{h})$ - weighting function
- K - kernel, $K(\frac{t}{h}) = (1 - |t|/h)$, $|t| < h$
- h - bandwidth parameter
- $h^i_{opt} = \frac{k\hat{S}N^{-0.2}}{\sqrt{f(x_i)}}$, $k = 1.06$, $\hat{S}$ - std of the sample, N - sample size



→