Studies of Ξ_c baryons at LHCb

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Aleksei Chubykin [1]
on behalf of the LHCb Collaboration

[1] Petersburg Nuclear Physics Institute, NRC KI

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Outline

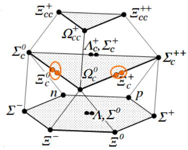
1. The LHCb detector
2. Observation of the doubly Cabibbo-suppressed decay $\Xi_c^+ \to p\phi$

   JHEP 04 (2019) 084
3. Observation of new Ξ_c^0 baryons decaying to $\Lambda_c^+ K^-$

   Phys. Rev. Lett. 124 (2020) 222001
4. First branching fraction measurement for the suppressed decay $\Xi_c^0 \to \Lambda_c^+\pi^-$

   Phys. Rev. D102 (2020) 071101(R)
5. Search for CP violation in $\Xi_c^+ \to pK^-\pi^+$ using model-independent techniques

   Eur. Phys. J. C80 (2020) 986
6. Conclusions



Multiplets of charmed baryons with highlights of baryons contained both c ans s quarks.[1]

Charmed baryons overview

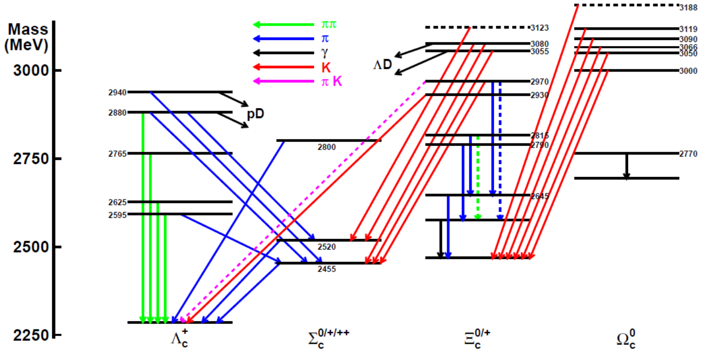


Figure 1.1: Charmed baryon spectrum as in Ref. [2] (provided by Heavy Flavor Averaging Group).

Charmed baryons overview

The LHCb detector

Observation of $\Xi_c^+ \to p\phi$
Diagram.
Spectra and fit.
Efficiencies calibration and systematics

New exited Ξ_c^0 baryons
General
Result

Measurement for $\Xi_c^0 \to \Lambda_c^+\pi^-$
Intro
Fits
Uncertainties and result

Search for CPV $\Xi_c^+ \to pK^-\pi^+$

Conclusions

The LHCb detector

The LHCb [3] detector is located at LHC in CERN

- a single-arm forward spectrometer
- the design is targeted to physics of b and c quarks
- high precision vertex detector
- unique ability of particle identification

- RUN I (2011-2012) RUN II (2015-2018)
- The integral luminosity corresponds to: 9.1 fb $^{-1}$

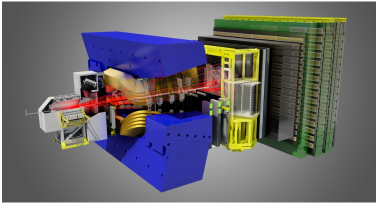


Figure 2.1: The LHCb detector

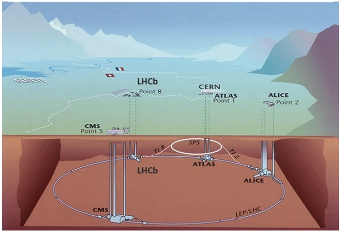


Figure 2.2: Overall view of the LHC experiments

pseudorapidity:	$2 < \eta < 5$
polar angle:	$10 < \theta < 250$ mrad
resolution :	$\Delta p/p = 0.5\%$ (low p)
	$\Delta p/p = 1.0\%$ (200 GeV/c)
ECAL resolution:	1% + 10% / $\sqrt{E}$ [GeV]
trigger efficiency:	90 % for dimuon decays
	30 % for multi-body hadronic
tracking efficiency:	96% for long tracks
Kaon ID:	95% for 5 % $\pi \to K$ mis-id
Muon ID:	97% for 1-3 % $\pi \to \mu$ mis-id

Table 1: Detector performance

Observation of the doubly Cabibbo-suppressed decay $\Xi_c^+ \to p\phi$

Observation of the doubly Cabibbo-suppressed decay $\Xi_c^+ \to p\phi$, JHEP 04 (2019) 084

- The LHCb is perfect tool for investigation of rare and suppressed decays.
- The research uses the pp collision data, integrated luminosity of 2 fb $^{-1}$, $\sqrt{s} = 8$ TeV

- Tree-level decays with both $u \to s$ and $c \to d$ transitions are known as doubly Cabibbo-suppressed (DCS)
- The CKM matrix elements $|V_{us}| \approx |V_{cd}| \ll |V_{ud}| \approx |V_{cs}|$
- The DCS decay branching fractions are smaller with respect to Cabibbo-favoured (CF) and singly Cabibbo-suppressed (SCS).

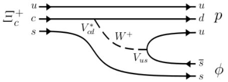


Figure 3.1: $\Xi_c^+ \to p\phi$ diagram

The DCS decays can keep important information:

- The role of a non-spectator quark, and in particular Pauli interference
- The lifetime hierarchy of charm baryons. Recent measurement of the Λ_c^+, Ξ_c^+ and Ξ_c^0 charm baryons lifetimes at LHCb [4]

The SCS $\Xi_c^+ \to pK^-\pi^+$ is used as a normalization decay channel:

$$R_{p\phi} = \frac{\mathcal{B}(\Xi_c^+ \to p\phi)}{\mathcal{B}(\Xi_c^+ \to pK^-\pi^+)}$$

Observation of the doubly Cabibbo-suppressed decay $\Xi_c^+ \to p\phi$

Observation of the doubly Cabibbo-suppressed decay $\Xi_c^+ \to p\phi$*, JHEP 04 (2019) 084*

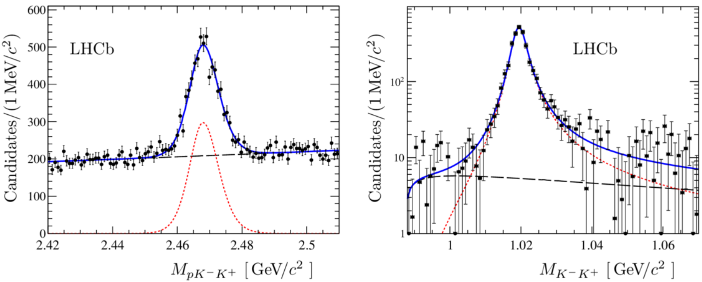


Figure 3.2: **Left:** Fit results for the $\Xi_c^+ \to pK^-K^+$ decay (ϕ region: $M_{K^-K^+} < 1.07\mathrm{GeV}/c^2$)
Right: Background subtracted K^-K^+ mass distribution for the $\Xi_c^+ \to pK^-K^+$ decay

- Extraction of K^-K^+ component from $M(pK^-K^+)$ mass-spectrum is done using unfolding $sPlot$-technique [5]

Observation of the doubly Cabibbo-suppressed decay $\Xi_c^+ \to p\phi$

Observation of the doubly Cabibbo-suppressed decay $\Xi_c^+ \to p\phi$, JHEP 04 (2019) 084

Uncertainty studies include following steps:

- Evaluation of the trigger-related uncertainties with the Λ_c^+ samples and MC studies
- Using the alternative calibration sample for PID-correction procedure
- Variation of signal and background models
- Variation of (p_t, y)-binning scheme
- Variation of the interpolation procedure for efficiency maps
- Pseudo-experiments for $sPlot$ technique validation

Source	Uncertainty (%)
Signal fit model	0.5
Background fit model	0.5
sPlot-related uncertainty	1.0
Trigger efficiency	3.0
PID efficiency	2.2
Tracking	1.0
(p_{T},y) binning	1.3
Size of simulation sample	0.7
Selection requirements	0.8
Total	4.4

Table 2: Systematic uncertainties relative to the central value of the ratio $R_{p\phi}$

- The ratio of the branching fractions with respect to the $\Xi_c \to pK^-\pi^+$ decay is measured to be

$$R_{\rho\phi} = (19.8 \pm 0.7 \pm 0.9 \pm 0.2) \times 10^{-3}$$

- The third uncertainty here is the knowledge of the $\phi \to K^+K^-$ branching fraction.

Observation of new exited Ξ_c^0 baryons

Observation of new Ξ_c^0 baryons decaying to $\Lambda_c^+ K^-$, Phys. Rev. Lett. 124 222001

- With new data collected in RUN II the LHCb is perfect tool for baryon spectroscopy

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The Particle Data Group provides information about two excited states of Ξ_c^0 baryon in range of interest:

- The $\Xi_c(2930)^0$ baryon was observed in 2018 by Belle in $B^- \to K^- \Lambda_c^+ \bar{\Lambda}_c^-$ decays [6]
- The $\Xi_c(2970)^0$ is well studied in several decay modes [7] [8]

The LHCb observes three narrow structure in this region: $\Xi_c(2923)^0$, $\Xi_c(2939)^0$ and $\Xi_c(2965)^0$

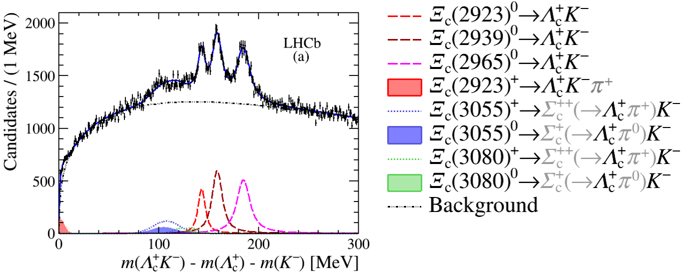

Figure 4.1: Distributions of the invariant-mass difference $\Delta M = m(\Lambda_c^+ K^-) - m(\Lambda_c^+) - m(K^-)$

Observation of new exited Ξ_c^0 baryons

Observation of new Ξ_c^0 baryons decaying to $\Lambda_c^+K^-$, Phys. Rev. Lett. 124 222001

- The lineshapes of entire $\Lambda_c^+K^-$ are S-wave relativistic Breit-Wigner distr. convolved with resolution
- The lineshapes of partially reconstructed decays $\Xi_c(3055)$ and $\Xi_c(3080)$ was determined by MC
- The experimental mass resolution in ΔM internal varies between 1.7 and 2.2 MeV

- This research uses same approach as recent investigation of Ω_c baryon [9]
- The sample is the pp collision data, integrated luminosity of 5.6 fb $^{-1}$,$\sqrt{s} = 13$ TeV

Table 3: Summary of the parameters for the studied states

Resonance	Peak of ΔM [MeV]	Mass [MeV]	Γ [MeV]
$\Xi_c(2923)^0$	$142.91 \pm 0.25 \pm 0.20$	$2923.04 \pm 0.25 \pm 0.20 \pm 0.14$	$7.1 \pm 0.8 \pm 1.8$
$\Xi_c(2939)^0$	$158.45 \pm 0.21 \pm 0.17$	$2938.55 \pm 0.21 \pm 0.17 \pm 0.14$	$10.2 \pm 0.8 \pm 1.1$
$\Xi_c(2965)^0$	$184.75 \pm 0.26 \pm 0.14$	$2964.88 \pm 0.26 \pm 0.14 \pm 0.14$	$14.1 \pm 0.9 \pm 1.3$

- Third uncertainty denotes the uncertainty on the known Λ_c^+ mass

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- The $\Xi_c(2923)^0$ and $\Xi_c(2939)^0$ baryons are observed for the first time.
- The state previously observed by Belle might be an overlap of $\Xi_c(2923)^0$ and $\Xi_c(2939)^0$.
- An investigation of additional final states is required to establish whether the $\Xi_c(2965)^0$ and $\Xi_c(2970)^0$ states are different baryons.

First branching fraction measurement for the suppressed decay $\Xi_c^0 \to \Lambda_c^+\pi^-$

First branching fraction measurement for the suppressed decay $\Xi_c^0 \to \Lambda_c^+\pi^-$, Phys. Rev. D102 071101(R)

- A signal interpreted as a $\Xi_c^0 \to \Lambda_c^+\pi^-$ decay was observed for the first time by Belle in 2014 [10]

Two possible processes:

- Transition $s \to u$ with $W^- \to \bar{u}d$ (SUUD).
- Decay via $cs \to dc$ weak scattering (WS)

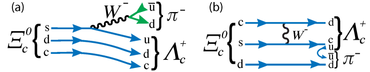


Figure 5.1: Decay diagrams for $\Xi_c^0 \to \pi^-\Lambda_c^+$ (a) The SUUD amplitude, and (b) the WS amplitude

- There is no suitable branching fractions for normalization in the direct measurement approach
- It is possible to determine $\mathcal{B}(\Xi_c^0 \to \pi^-\Lambda_c^+)$ by following ratios and two external values:

$$\mathcal{R}_1 = \frac{N(\Xi_c^0)}{N(\Lambda_c^+)} = \frac{f_{\Xi_c^0}}{f_{\Lambda_c^+}} \cdot \mathcal{B}(\Xi_c^0 \to \pi^-\Lambda_c^+)$$

$$\mathcal{R}_2 = \frac{N(\Xi_c^0)}{N(\Xi_c^+)} = \frac{f_{\Xi_c^0}}{f_{\Xi_c^+}} \cdot \frac{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)}{\mathcal{B}(\Xi_c^+ \to pK^-\pi^+)} \cdot \mathcal{B}(\Xi_c^0 \to \pi^-\Lambda_c^+)$$

- The $f_{\Xi_c^0}/f_{\Lambda_c^+}$ can be estimated from recent LHCb measurements [11] for production fractions of beauty baryons with help of heavy-quark symmetry(HQS)
- Using HQS $f_{\Xi_c^0}/f_{\Lambda_c^+} = C f_{\Xi_b^-}/f_{\Lambda_b^0}$, where C is a correction for feed-downs of excited Ξ_b baryons
- The $\mathcal{B}(\Xi_c^+ \to pK^-\pi^+)$ is taken from recent Belle measurement [12]

First branching fraction measurement for the suppressed decay $\Xi_c^0 \rightarrow \Lambda_c^+ \pi^-$

First branching fraction measurement for the suppressed decay $\Xi_c^0 \rightarrow \Lambda_c^+ \pi^-$, Phys. Rev. D102 071101(R)

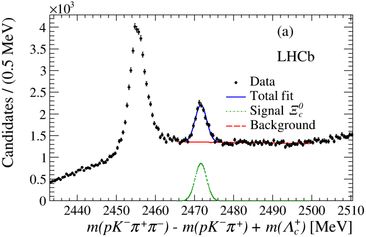


Figure 5.2: Reconstructed invariant-mass distribution and signal fit of $M(pK^-\pi^+\pi^-)$

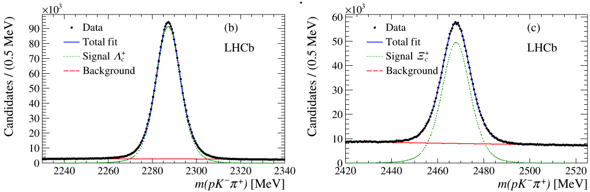


Figure 5.3: Distributions of the mass spectrum $M(pK^-\pi^+)$ **Left:** Λ_c^+ region, **Right:** Ξ_c^+ region

First branching fraction measurement for the suppressed decay $\Xi_c^0 \to \Lambda_c^+\pi^-$

First branching fraction measurement for the suppressed decay $\Xi_c^0 \to \Lambda_c^+\pi^-$, Phys. Rev. D102 071101(R)

- $f_{\Xi_b^-}/f_{\Lambda_b^0}$ from LHCb measurement [11]
- $\mathcal{B}(\Xi_c^+ \to pK^-\pi^+)$ from Belle [12]
- Ghost tracks refer to uncertainties from falsely reconstructed tracks
- PID refers to particle identification efficiencies
- The intermediate decays are uncertainties of the inexact modeling of the resonant structures for the charmed baryons decays.
- The b-decay sources refer to charmed baryons originating from b-baryon decays

Table 4: Systematic uncertainties in the branching fraction measurements.

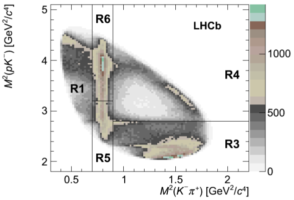
Source	Estimate (%)		
	$\mathcal{B}(\Xi_c^0 \to \pi^-\Lambda_c^+)$		$\mathcal{B}(\Xi_c^+ \to pK^-\pi^+)$
	$\mathcal{B}_1$	$\mathcal{B}_2$	$\mathcal{B}_3$
$f_{\Xi^-b}/f_{\Lambda^0 b}$	32	–	32
$f_{\Xi^0 c}/f_{\Lambda^+ c} = \mathcal{C} \cdot f_{\Xi^- b}/f_{\Lambda^0 b}$	6	–	6
$f_{\Xi^0 c}/f_{\Xi^+ c} = 1$	–	1	1
$\mathcal{B}(\Xi_c^+ \to pK^-\pi^+)$	–	49	–
$\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)$	–	5	5
Simulation statistics	4	3	2
Trigger efficiency	7	8	2
Ghost tracks	2	2	0
PID	1	1	1
Tracking efficiencies	2	2	0
Fit yields	6	6	3
Intermediate decays	2	2	2
b-decay sources	2	0	2
Lifetimes	3	3	2
Relative $\int \mathcal{L}$	–	1	1
Sum of external	33	49	33
Sum of intrinsic	12	13	6
Sum of all	35	51	34

- First measurement for $\mathcal{B}(\Xi_c^0 \to \pi^-\Lambda_c^+)$ to be $(0.55 \pm 0.02 \pm 0.18) \times 10^{-2}$

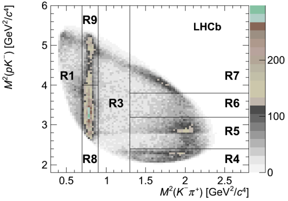
Search for CP violation in $\Xi_c^+ \to pK^-\pi^+$ using model-independent techniques

Search for CP violation in $\Xi_c^+ \to pK^-\pi^+$ using model-independent techniques, Eur. Phys. J. C80 986

- Observation of CP violation in charm meson D^0 decays was done by LHCb in 2019 [13]
- The research uses the pp collision data , integrated luminosity of 3.0 fb $^{-1}$, with $\sqrt{s} = 7$ and 8 TeV
- Analysis was done by both binned and unbinned methods in the Dalitz plot



(a) Dalitz plot for $\Lambda_c^+ \to pK^-\pi^+$



(b) Dalitz plot for $\Xi_c^+ \to pK^-\pi^+$

- Binned method is based on comparison between the Dalitz plots using χ^2 test
- Under the hypothesis of CPV, difference between bins should show deviation from normal distribution

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- Unbinned method is based on a concept of a k-nearest neighbours

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- The obtained results are consistent with the absence of CP violation in $\Xi_c^+ \to pK^-\pi^+$ decays

Conclusions

- The LHCb detector is perfect and stable tool for precise measurements in charm physics sector
- We expect more interesting results from LHCb soon

Thank You

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