Latest results on baryons at LHCb

Roberta Cardinale
on behalf of the LHCb Collaboration

University of Genova and INFN Genova

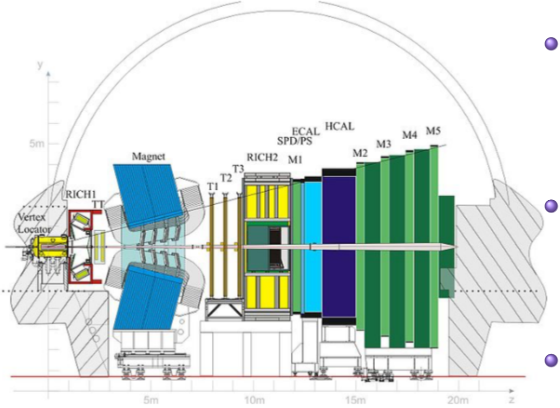
NSTAR 2022, 19 October 2022

Introduction

- Studying heavy flavour spectroscopy allows us to understanding of how conventional hadrons, tetraquarks and pentaquarks are formed
- Hadron spectroscopy provides tests of QCD effective theories and models
- Thanks to the huge charm and beauty production cross-section in the forward direction in pp collisions at LHC energies and to the excellent performance of the detector, LHCb is the ideal place to perform spectroscopy studies
- Interesting results have been shown in the last years both in conventional and exotic hadron spectroscopy sector

The LHCb detector [JINST 3 (2008) S08005, IJMPA 30 (2015) 1530022]

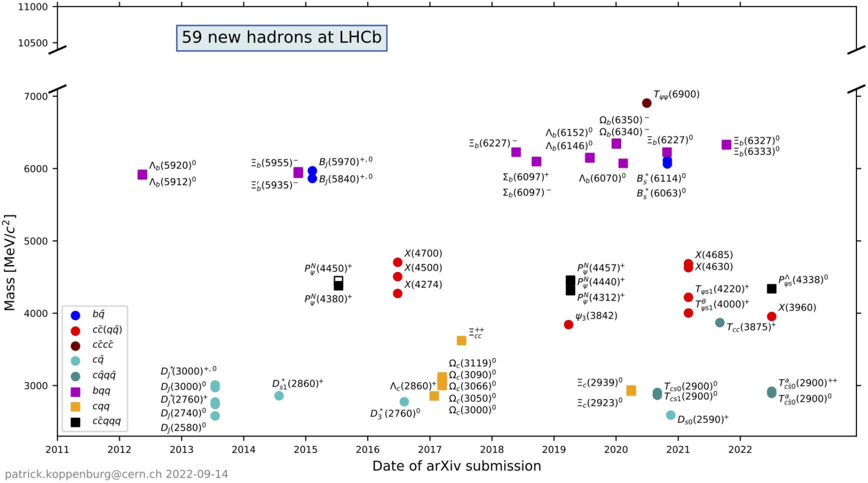
LHCb is a single-arm forward spectrometer dedicated to heavy flavor physics at the LHC



- Precise vertex resolution able to separate production and decay vertices:
  $\sigma_{IP} < 100\,\mu\text{m}$
  $\sigma_{\tau} \sim 50\,\text{fs}$
- Excellent particle identification:
  $\epsilon(K \to K) \sim 95\%$ with misID
  $\epsilon(\pi \to K) \sim 5\%$
  $\epsilon(\mu \to \mu) \sim 97\%$ with misID
  $\epsilon(\pi \to \mu) \sim 1\text{-}3\%$
- Good momentum resolution:
  $\frac{\sigma p}{p} = (0.5\text{-}1.2)\%$

Hadrons observed at LHCb

- Over the past 10 years, 67(59) new hadrons discovered at LHC(LHCb).

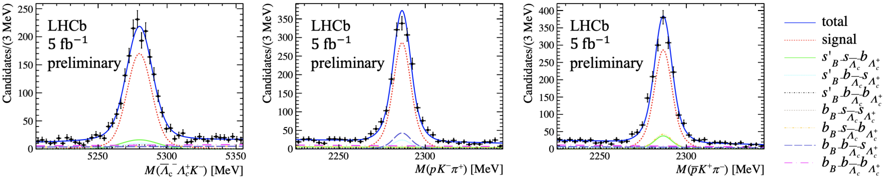


https://www.nikhef.nl/~pkoppenb/particles.html

LHCb "Exotic hadron naming convention" [arXiv: 2206.15233]

Study of $B^- \to \Lambda_c^+ \bar{\Lambda}_c^- K^-$ [LHCb-PAPER-2022-028, in preparation]

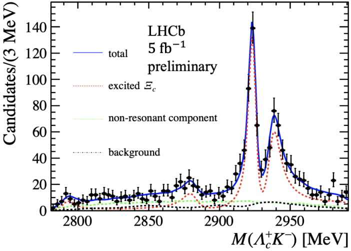
- The $B^- \to \Lambda_c^+ \bar{\Lambda}_c^- K^-$ decay with $\Lambda_c^+ \to p K^- \pi^+$ is interesting for
  - search for $\Xi_c^{0**} \to \Lambda_c^+ K^-$ with lower background and no feed-down contribution as in prompt $\Lambda_c^+ K^-$ already studied by LHCb [PRL 124 (2020) 222001] with the observation of $\Xi_c(2923)^0$ and $\Xi_c(2939)^0$
  - search for possible exotic candidates in $\Lambda_c^+ \bar{\Lambda}_c^-$ and $\bar{\Lambda}_c^- K^-$
- $5\,\mathrm{fb}^{-1}$ LHCb data at $\sqrt{s} = 13\,\mathrm{TeV}$
- Using $B^- \to D^+ D^- K^-$ decay as normalization channel
- 3D fit to $(m_{B^-}, m_{\Lambda_c^+}, m_{\bar{\Lambda}_c^-})$
- Signal yield: $N = 1365 \pm 42$ with high-purity



$$\frac{\mathcal{B}(B^- \to \Lambda_c^+ \bar{\Lambda}_c^- K^-)}{\mathcal{B}(B^- \to D^+ D^- K^-)} = 2.36 \pm 0.11 \pm 0.22 \pm 0.25 \text{ [preliminary]}$$

$\Lambda_c^+ K^-$ mass spectrum [LHCb-PAPER-2022-028, in preparation]

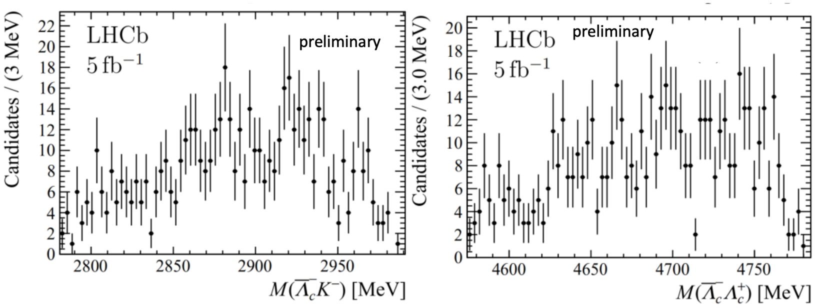
- Included in the nominal $M(\Lambda_c^+ K^-)$ fit: $\Xi_c(2790)^0$, $\Xi_c(2880)^0$, $\Xi_c(2923)^0$ and $\Xi_c(2939)^0$
- $\Xi_c(2815)^0$ not included since no significant peak found
- Considered interference between the $\Xi_c(2923)^0$ and $\Xi_c(2939)^0$ states
- Quantum numbers fixed, J^P: $1/2^-$ (known) for $\Xi_c(2790)^0$, $1/2^-$ for $\Xi_c(2880)^0$, $3/2^-$ for $\Xi_c(2923)^0$ and $\Xi_c(2939)^0$



State	Mass (MeV)	Width (MeV)
$\Xi_c(2880)^0$	$2881.8 \pm 3.1 \pm 8.5$	$12.4 \pm 5.2 \pm 5.8$
$\Xi_c(2923)^0$	$2924.5 \pm 0.4 \pm .1.1$	$4.8 \pm 0.9 \pm 1.5$
$\Xi_c(2939)^0$	$2938.5 \pm 0.9 \pm 2.3$	$11.0 \pm 1.9 \pm 7.5$

- $\Xi_c(2790)^0$ (3.7σ): evidence of new decay mode
- $\Xi_c(2880)^0$ (3.8σ): evidence of new state
- $\Xi_c(2923)^0$ and $\Xi_c(2939)^0$: observed in prompt production [PRL 124 (2020) 222001], confirmation in different production mechanism

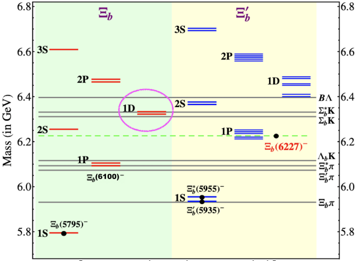
Search for exotic structures in $M(\Lambda_c^+\bar{\Lambda}_c^-)$ and $M(\bar{\Lambda}_c^- K^-)$ [LHCb-PAPER-2022-028, in preparation]



- No significant structures seen in $\bar{\Lambda}_c^- K^-$ and $\Lambda_c^+\bar{\Lambda}_c^-$ spectra!

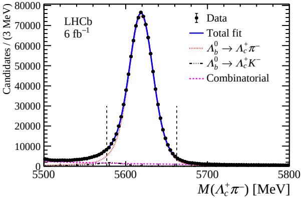
Excited Ξ_b^0 states [PRL 128 (2022) 162001]

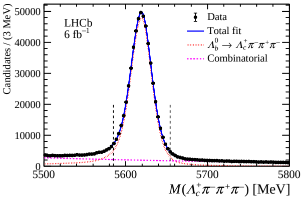
- Several excited Λ_b^0 states observed in the recent years leading the investigation of excited Ξ_b states
- Observation of the $\Xi_b(6227)^-$ [PRL 121, 072002] and $\Xi_b(6227)^0$ [PRD 103, 012004] by LHCb and of the $\Xi_b(6100)^-$ by CMS [PRL 126, 252003 (2021)]
- Two predicted 1D Ξ_b^0 states predicted decaying mainly in $\Sigma_b^* K$ and $\Xi_b^{*\prime}\pi$ modes



[PRD 98 (2018) 031502(R)]

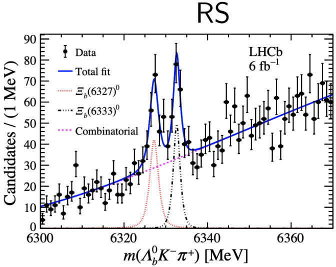
- Study of the $\Lambda_b^0 K^- \pi^+$ final state with $\Lambda_b^0 \to \Lambda_c^+ \pi^-$ and $\Lambda_b^0 \to \Lambda_c^+ \pi^- \pi^+ \pi^-$
- $6\,\mathrm{fb}^{-1}$ LHCb data at $\sqrt{s} = 13\,\mathrm{TeV}$

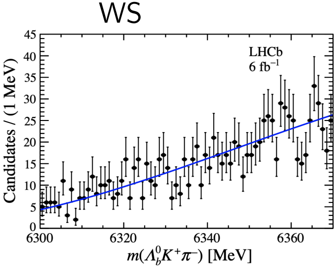




Two new excited Ξ_b^0 states [PRL 128 (2022) 162001]

- Candidates with mass in a 2.5σ window around the Λ_b^0 mass to form $m(\Lambda_b^0 K^- \pi^+)$
- Combinatorial background from wrong sign (WS) $\Lambda_b^0 K^+ \pi^-$ candidates
- Relativistic BW convolved with resolution function for the two peaks in the right sign sample (RS)





- Large significance of 2-peaks hypothesis wrt to one and no-peak hypotheses

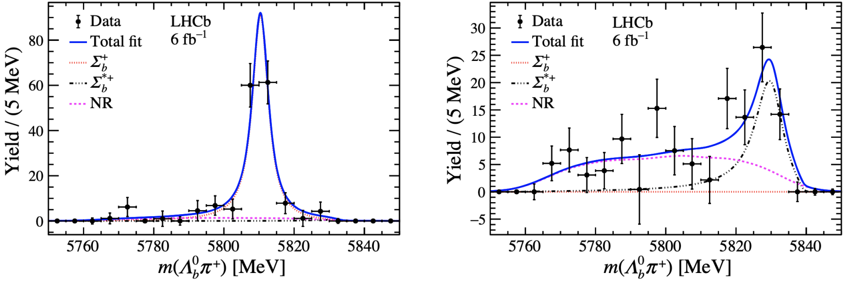
State	Mass [MeV]	Width [MeV]
$\Xi_b(6327)^0$	$6327.28^{+0.23}_{-0.21} \pm 0.12 \pm 0.24$	$< 2.20(2.56)$ 90% (95%) CL
$\Xi_b(6333)^0$	$6332.69^{+0.17}_{-0.18} \pm 0.03 \pm 0.22$	$< 1.60(1.92)$ 90% (95%) CL

Observation of two new excited Ξ_b^0 states

[PRL 128 (2022) 162001]

- Study of the resonant structure in the excited Ξ_b^0 decays by mass fits to the data samples in $5\,\mathrm{MeV}$ wide slices of $\Lambda_b^0\pi$

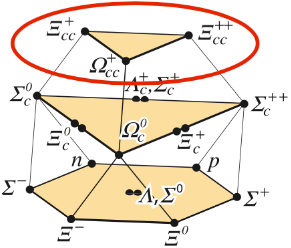
$\Xi_b(6327)^0 \to \Sigma_b^+(\to \Lambda_b^0\pi^+)K^-$ $\qquad$ $\Xi_b(6333)^0 \to \Sigma_b^{*+}(\to \Lambda_b^0\pi^+)K^-$



- $\Xi_b(6327)^0$ and $\Xi_b(6330)^0$ consistent with the predicted 1D Ξ_b^0 doublet with $J^P = 3/2^+$ and $5/2^+$

Doubly heavy baryons at LHCb

- Doubly heavy baryon: baryon with two heavy quarks (b or c) and one light quark (u, d, s)
- Predicted in the Quark Model
- Interesting to test several thoretical models (perturbative QCD, non relativistic QCD, ...)
- Several searches have been performed in LHCb
  - Doubly charmed baryons: Ξ_{cc}^{+} (ccd), Ω_{cc}^{+} (ccs), Ξ_{cc}^{++} (ccu)
  - bc baryons: Ξ_{bc}^{0} (bcd), Ω_{bc}^{0} (bcs), Ξ_{bc}^{+} (bcu)



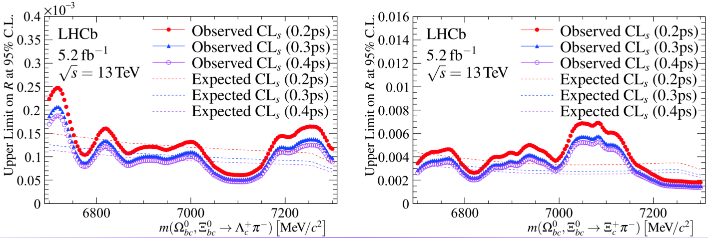
Doubly heavy baryons at LHCb

- Doubly charmed baryons Ξ_{cc}^{+} (ccd), Ω_{cc}^{+} (ccs), Ξ_{cc}^{++} (ccu)
    - Expected masses: $[3500\text{-}3700]\,\mathrm{MeV}$
    - Expected lifetimes: $\tau(\Xi_{cc}^{+}) \approx \tau(\Omega_{cc}^{+}) < \tau(\Xi_{cc}^{++})$
        - $\tau(\Omega_{cc}^{+}) = 75\text{-}180\,\mathrm{fs}$
        - $\tau(\Xi_{cc}^{+}) = 50\text{-}250\,\mathrm{fs}$
        - $\tau(\Xi_{cc}^{++}) \approx 200$ to $700\,\mathrm{fs}$
- Ground state baryons containing one b and one c quark Ξ_{bc}^{0} (bcd), Ω_{bc}^{0} (bcs), Ξ_{bc}^{+} (bcu)
    - Expected masses: $[6700\text{-}7200]\,\mathrm{MeV}$
    - Expected lifetime
        - $\tau(\Omega_{bc}^{0}) = 0.22 \pm 0.04\,\mathrm{ps}$
        - $\tau(\Xi_{bc}^{0}) = 0.09\text{-}0.28\,\mathrm{ps}$
        - $\tau(\Xi_{bc}^{+}) = 0.24\text{-}0.61\,\mathrm{ps}$
- Several experimental searches to compare measurements with theoretical predictions and improve the understanding of the dynamics of production and decays of doubly heavy baryons

Search for Ω_{bc}^0 and Ξ_{bc}^0 [Chin. Phys C45 (2021) 093002]

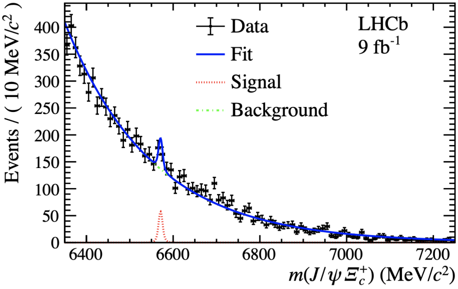
- Search of Ξ_{bc}^0 already performed using D^0pK^- final state: not seen [JHEP 11 (2020) 095]
- Search for Ξ_{bc}^0 and Ω_{bc}^0 in $\Lambda_c^+\pi^-$ and $\Xi_c^+\pi^-$ final states with Λ_c^+,$\Xi_c^+ \to pK^-\pi^-$
- $5.2\,\mathrm{fb}^{-1}$ LHCb data at $\sqrt{s} = 13\,\mathrm{TeV}$
- No evidence for Ξ_{bc}^0 and Ω_{bc}^0
- Determination of mass-dependent 95% upper limits on the relative production rate of Ξ_{bc}^0 and Ω_{bc}^0 wrt the $\Lambda_b^0 \to \Lambda_c^+\pi^-$ and $\Xi_b^0 \to \Xi_c^+\pi^-$ normalisation channels respectively for lifetime hypotheses $(0.2,\ 0.3,\ 0.4\,\mathrm{ps})$

$$R(\Xi_{bc}^0/\Omega_{bc}^0) = \frac{\sigma(\Xi_{bc}^0/\Omega_{bc}^0) \times \mathcal{B}(\Xi_{bc}^0/\Omega_{bc}^0 \to \Lambda_c^+/\Xi_c^+(\to pK^-\pi^+)\pi^-)}{\sigma(\Lambda_b^0/\Xi_b^0) \times \mathcal{B}(\Lambda_b^0/\Xi_b^0 \to \Lambda_c^+/\Xi_c^+(\to pK^-\pi^+)\pi^-)}$$



Search for $\Xi_{bc}^{+} \to J/\psi \Xi_{c}^{+}$ [arXiv:2204.09541]

- Search of Ξ_{bc}^{+} using $J/\psi\Xi_{c}^{+}$ decay with $J/\psi \to \mu^{+}\mu^{-}$ and $\Xi_{c}^{+} \to pK^{-}\pi^{+}$
- $9\,\mathrm{fb}^{-1}$ LHCb data at $\sqrt{s} = 7{,}8$ and $13\,\mathrm{TeV}$
- Expected larger lifetime wrt Ξ_{bc}^{0} and high selection efficiency thanks to muons in the final state wrt fully hadronic final states
- Normalisation mode: $B_{c}^{+} \to J/\psi D_{s}^{+}$ with $J/\psi \to \mu^{+}\mu^{-}$ and $D_{s}^{+} \to K^{+}K^{-}\pi^{+}$



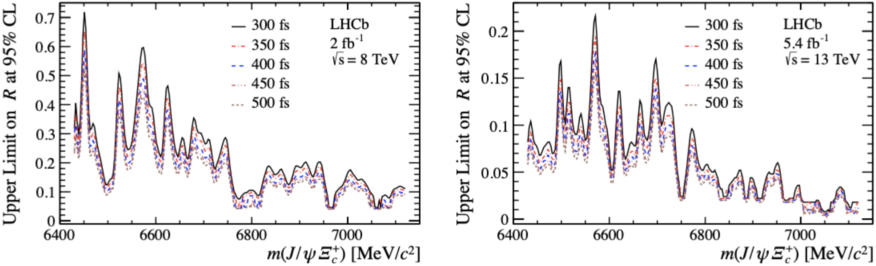
- No evidence for Ξ_{bc}^{+} (2.8σ)

Search for $\Xi_{bc}^{+} \to J/\psi \Xi_c^{+}$ [arXiv:2204.09541]

- Determination of mass-dependent 95% upper limits on the relative production rate wrt the $B_c^+ \to J/\psi D_s^+$ normalisation channel

$$R = \frac{\sigma(\Xi_{bc}^{+}) \times \mathcal{B}(\Xi_{bc}^{+} \to J/\psi \Xi_c^{+}) \times \mathcal{B}(\Xi_c^{+} \to pK^-\pi^+)}{\sigma(B_c^+) \times \mathcal{B}(B_c^+ \to J/\psi D_s^+) \times \mathcal{B}(D_s^+ \to K^+K^-\pi^+)}$$

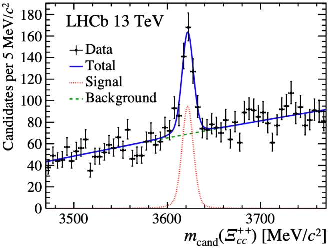
- both for $8\,\mathrm{TeV}$ and $13\,\mathrm{TeV}$ samples
- for lifetime hypotheses from $300\,\mathrm{fs}$ to $500\,\mathrm{fs}$



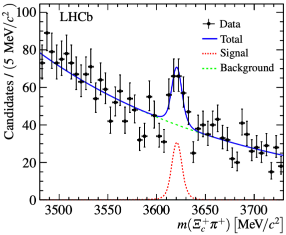
Ξ_{cc}^{++} state

- Ξ_{cc}^{++} (ccu) baryon discovered by LHCb [PRL 119 (2017) 11, 112001]
- Up to now, observed in two different decay modes: $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ [PRL 119 (2017) 11, 112001] and $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$ [PRL 121 (2018) 16, 162002]

$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$



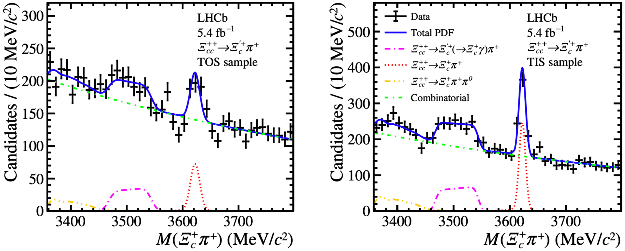
$\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$



- Mass $m = 3621.55 \pm 0.23 \pm 0.30\,\text{MeV}$ [JHEP 02(2020) 049]
- Lifetime $\tau = 0.256^{+0.024}_{-0.022} \pm 0.014\,\text{ps}$ [PRL 121 (2018) 5, 052002]

Observation of $\Xi_{cc}^{++} \to \Xi_c'^{+}\pi^+$ [JHEP 05 (2022) 038]

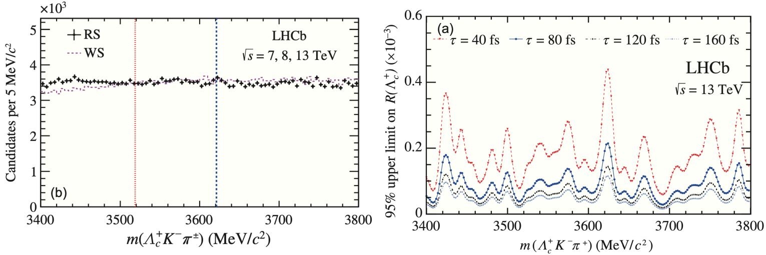
- Search in the $\Xi_c^+\pi^+$ mass using $\Xi_{cc}^{++} \to \Xi_c'^{+}(\to \Xi_c^+(\to pK^-\pi^+)\gamma)\pi^+$ where the photon is not reconstructed: distorted peaking structure at lower mass wrt the $\Xi_{cc}^{++} \to \Xi_c^+(\to pK^-\pi^+)\pi^+$
- Measurement of $\mathcal{B}$ relative to $\Xi_{cc}^{++} \to \Xi_c^+\pi^+$
- $5.4\,\mathrm{fb}^{-1}$ LHCb data at $\sqrt{s} = 13\,\mathrm{TeV}$
- Separated samples on trigger decision (on signal (TOS) and independently of signal (TIS))



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

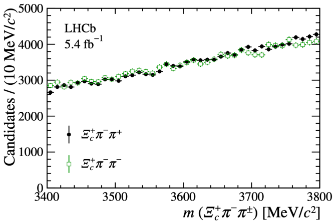
Ξ_{cc}^{+}

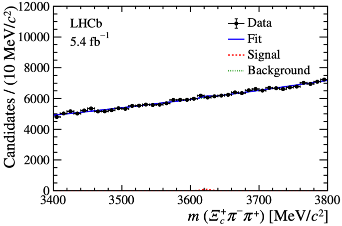
- Ξ_{cc}^{+} is the elusive isospin partner of Ξ_{cc}^{++}
- SELEX collaboration observed the Ξ_{cc}^{+} state in $\Xi_{cc}^{+} \to \Lambda_c^+ K^- \pi^+$ and $\Xi_{cc}^{+} \to p D^+ K^-$ decays with $m = 3518.7 \pm 1.7\,\mathrm{MeV}$ [PLB 628 (2005) 18-24]
- LHCb updated the search for $\Xi_{cc}^{+} \to \Lambda_c^+ K^- \pi^+$ [JHEP 12(2013)090] using $9\,\mathrm{fb}^{-1}$ LHCb data at $\sqrt{s} = 7{,}8$ and $13\,\mathrm{TeV}$ both near the observed Ξ_{cc}^{++} mass and at the SELEX's claimed Ξ_{cc}^{+} mass [Sci.China Phys.Mech.Astron.63(2020)2, 221062]
- Not evidence for Ξ_{cc}^{++}
- Upper limits on the relative production rate wrt to Λ_c^+ and Ξ_{cc}^{++} as function of mass for several hypothetical lifetimes



Search for $\Xi_{cc}^{+} \to \Xi_c^{+}\pi^{+}\pi^{-}$ [JHEP 12 (2021) 107]

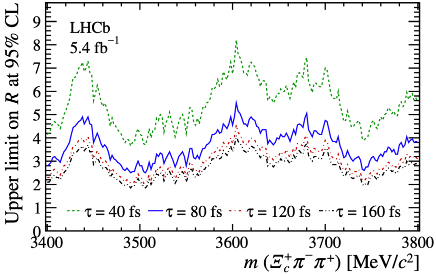
- $5.4\,\mathrm{fb}^{-1}$ LHCb data at $\sqrt{s} = 13\,\mathrm{TeV}$
- Two different trigger selections:
  - Default trigger: selection matched to the $\Xi_{cc}^{++} \to \Xi_c^{+}\pi^{+}$ control sample to maximise the precision on the upper limits
  - Extended trigger: inclusive set of triggers to enhance the probability of observing a significant signal

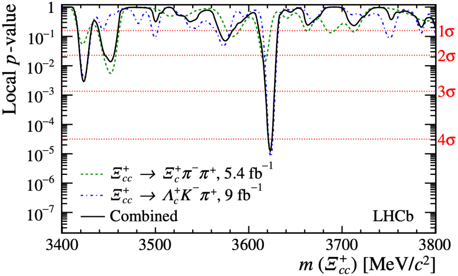




Search for $\Xi_{cc}^{+} \to \Xi_{c}^{+}\pi^{+}\pi^{-}$ [JHEP 12 (2021) 107]

- No evidence for $\Xi_{cc}^{+} \to \Xi_{c}^{+}\pi^{-}\pi^{+}$
- Determination of upper limits on the relative production rate wrt to $\Xi_{cc}^{++} \to \Xi_{c}^{+}\pi^{+}$ as function of mass for several hypothetical lifetimes
  $R = \frac{\sigma(\Xi_{cc}^{+})\times\mathcal{B}(\Xi_{cc}^{+}\to\Xi_{c}^{+}\pi^{-}\pi^{+})}{\sigma(\Xi_{cc}^{++})\times\mathcal{B}(\Xi_{cc}^{++}\to\Xi_{c}^{+}\pi^{+})}$

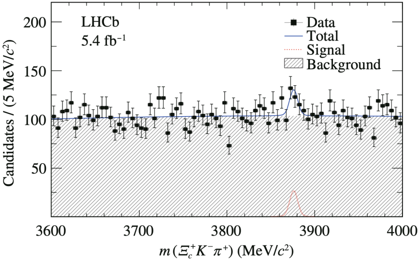




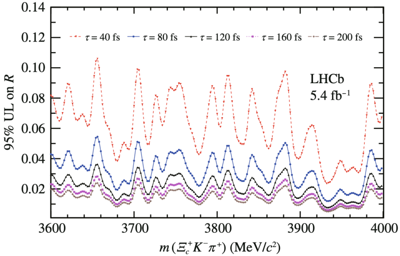
- Statistical combination with $\Xi_{cc}^{+} \to \Lambda_c^{+}K^{-}\pi^{+}$ search
- No evidence for Ξ_{cc}^{+}
- Maximum deviation: 2.9σ

Search for Ω_{cc}^{+} [Sci.China Phys. Mech.Astron. 64 (2021) 10, 101062]

- Search of the Ω_{cc}^{+} via $\Omega_{cc}^{+} \to \Xi_c^{+} K^{-} \pi^{+}$
- $5.4\,\mathrm{fb}^{-1}$ LHCb data at $\sqrt{s} = 13\,\mathrm{TeV}$
- No significant signal in the mass range $3600\text{-}4000\,\mathrm{MeV}$
  - Maximum global significance: 1.8σ at $3876\,\mathrm{MeV}$



- Determination of mass-dependent 95% upper limits on the relative production rate wrt the $\Xi_{cc}^{++} \to \Lambda_c^{+} K^{-} \pi^{+} \pi^{-}$ normalisation channel for several hypothetical lifetimes



$$R = \frac{\sigma(\Omega_{cc}^{+}) \times \mathcal{B}(\Omega_{cc}^{+} \to \Xi_c^{+} K^{-} \pi^{-}) \times \mathcal{B}(\Xi_c^{+} \to p K^{-} \pi^{+})}{\sigma(\Xi_{cc}^{++}) \times \mathcal{B}(\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+} \pi^{-}) \times \mathcal{B}(\Lambda_c^{+} \to p K^{-} \pi^{+}}$$

Conclusions

- Heavy baryon spectroscopy is a rich field not only for exotic states but also for conventional states
- Conventional states are crucial to understand QCD
- LHCb is the major player discovering new states every year thanks to the large b and c production cross-section and to its excellent performance
- Many new states are still to be discovered
- Run3 with an upgraded detector is starting with significant improvements on the fully-hadronic final states!