Charmed baryons at LHCb

Dana Seman Bobulska
on behalf of the LHCb collaboration

•••

CHARM 2020

31 May 2021 - 4 June 2021

Overview

- Introduction
- Charmed baryons
  - Measurement of the lifetimes of Ω_c^0 and Ξ_c^0 baryons with prompt production

NEW

- Doubly charmed baryons
  - Search for the Ξ_{cc}^+ baryon in the $\Xi_c^+\pi^-\pi^+$ final state

NEW

  - Search for the Ω_{cc}^+ baryon in the $\Xi_c^+K^-\pi^+$ final state
- Charm-beauty baryons
  - Search for doubly heavy baryons Ξ_{bc}^0 and Ω_{bc}^0
- Summary

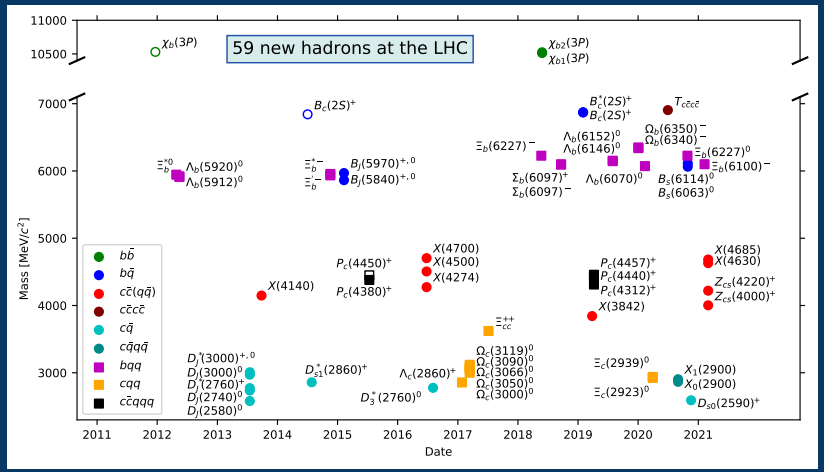
Teotihuacan [Image source: DR Travel Photo and Video / shutterstock]

Introduction

Introduction

- Many new hadrons observed and studied by LHCb in the last decade
- Measurement of heavy-flavour hadron properties (masses, lifetimes, branching fractions) is of great importance
  - Valuable input for testing QCD predictions
  - Deeper understanding of the hadronic structure
- Doubly charmed baryon studies
  - Unique platform to study the nonperturbative dynamics in the presence of two heavy quarks
  - Completion of the experimental observation of all baryons in the SU(4) baryon 20-plets

[59 new hadrons, CDS record]



This presentation describes the latest results on (doubly) charmed baryons from LHCb

Charmed baryon lifetimes

Ω_c^0 and Ξ_c^0 lifetimes - motivation

- Predicted lifetime hierarchy: $\tau(\Xi_c^+) > \tau(\Lambda_c^+) > \tau(\Xi_c^0) > \tau(\Omega_c^0)$
  - Heavy Quark Expansion (HQE) is used to calculate the lifetimes of heavy flavour hadrons [ref.]
    - Expansion in inverse powers of the mass of the heavy quark – works well for *b*-hadrons
    - Higher-order expansions needed for the charmed hadrons
    - Ω_c^0 expected to be the shortest-lived due to the constructive Pauli interference
- In 2018/2019, LHCb collaboration performed a measurement of charmed baryon lifetimes using semileptonic *b*-hadron decays [Phys. Rev. Lett. 121 (2018) 9 092003, Phys. Rev. D100 (2019) 032001]
  - $\tau_{\Omega_c^0} = 268 \pm 24 \pm 10 \pm 2$ fs [▵] – inconsistent with the world average (WA) at the level of 7σ
  - $\tau_{\Xi_c^0} = 154.5 \pm 1.7 \pm 1.6 \pm 1.0$ fs [▵] – in tension with the WA at the level of 3.3σ
  - Measurement changed the lifetime hierarchy: $\tau(\Xi_c^+) > \tau(\Omega_c^0) > \tau(\Lambda_c^+) > \tau(\Xi_c^0)$

Additional measurements to resolve this puzzle are essential

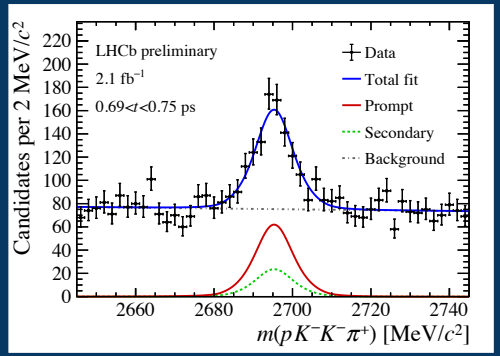
[▵] The uncertainties are statistical, systematic, and due to the uncertainty of the D^+ lifetime

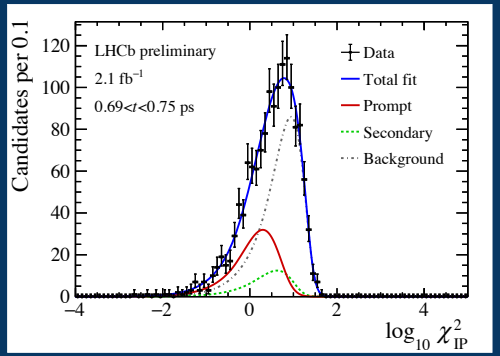
NEW

Ω_c^0 and Ξ_c^0 lifetimes – signal yields

LHCb-PAPER-2021-021
(in preparation)

- New measurement using promptly produced Ω_c^0 and Ξ_c^0 baryons using 5.4 fb^{-1} of LHCb data
  - Ω_c^0 and Ξ_c^0 reconstructed through their decay to $pK^-K^+\pi^+$
  - Statistically independent of the previous LHCb measurement
  - Analysis treated as blinded until the full procedure finalised
- Lifetimes measured relative to the D^0 lifetime using prompt $D^0 \to K^-K^+\pi^-\pi^+$ decays
- Prompt signal yields extracted with 2D extended ML fits to (m, $\log_{10}\chi^2_{IP}$)
  - mass to discriminate between signal and combinatorial background
  - $\log_{10}\chi^2_{IP}$ (relative significance of an impact parameter) to discriminate between prompt and secondary signal decays





NEW

Ω_c^0 and Ξ_c^0 lifetimes - results

LHCb-PAPER-2021-021
(in preparation)

- Dominant systematic uncertainties are due to fit model, the kinematic corrections to the simulated data and decay-time resolution
- Lifetimes determined with extended ML fits to (m, $\log_{10}\chi^2_{IP}$) yields simultaneously in decay-time bins measured to be

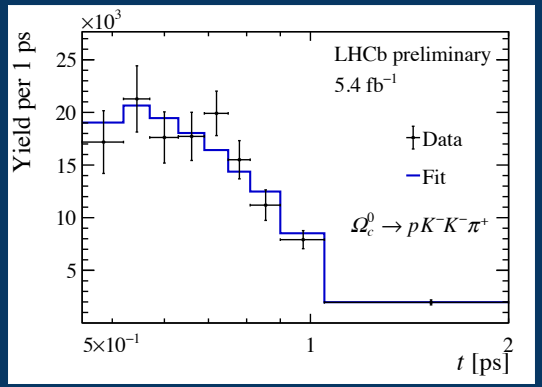
The most precise measurement up to date!

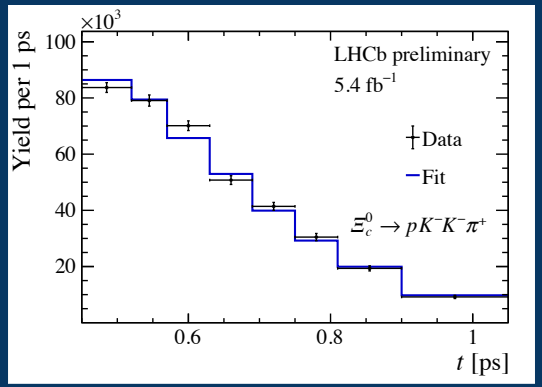
$$\tau_{\Omega_c^0} = 276.5 \pm 13.4 \pm 4.4 \pm 0.7 \text{ fs (preliminary)}$$

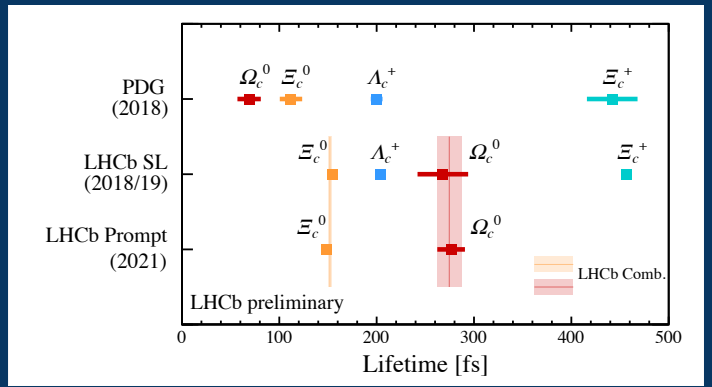
$$\tau_{\Xi_c^0} = 148.0 \pm 2.3 \pm 2.2 \pm 0.2 \text{ fs (preliminary)}$$

Consistent with the previous LHCb measurement!

where the uncertainties are statistical, systematic, and due to the uncertainty of the D^0 lifetime



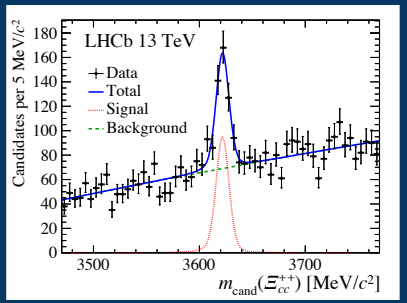


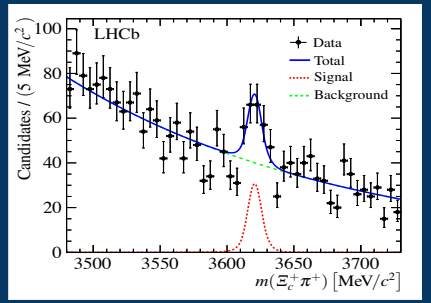


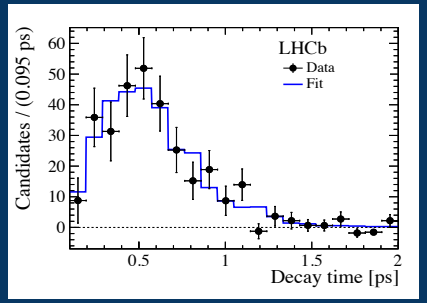
Doubly charmed baryon searches

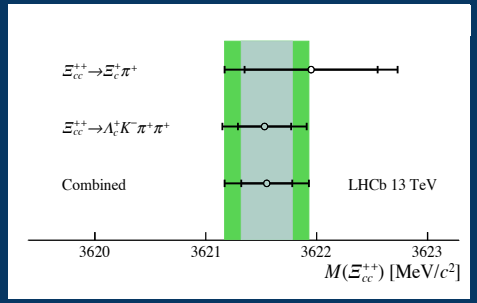
Ξ_{cc}^{++} baryon observation and studies by LHCb

- In 2017, the first observation of the doubly charmed baryon Ξ_{cc}^{++} (ccu) in the final state of $\Lambda_c^+ K^- \pi^+ \pi^+$ was announced by the LHCb collaboration [Phys. Rev. Lett. 119 (2017) 112001]
- More studies of the Ξ_{cc}^{++} baryon followed its observation:
  - Confirmation in the $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$ decay mode [Phys. Rev. Lett. 121 (2018) 162002]
  - Search for the $\Xi_{cc}^{++} \to D^+ p K^- \pi^+$ decays [JHEP 10 (2019) 124]
  - Lifetime measurement [Phys. Rev. Lett. 121 (2018) 052002]
  - Production measurement [Chinese Physics C44 (2020) 022001]
  - Precise mass measurement [JHEP 02 (2020) 049]



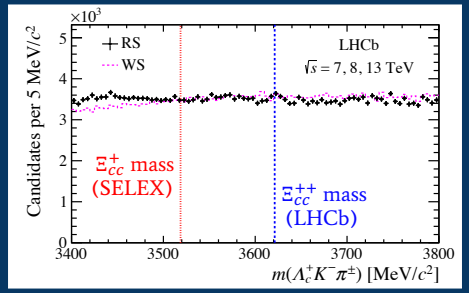


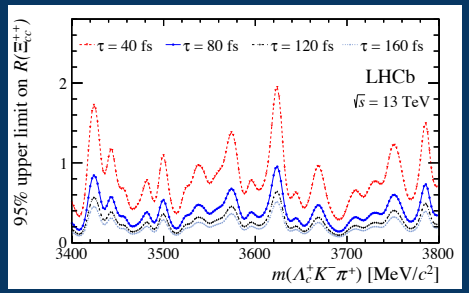


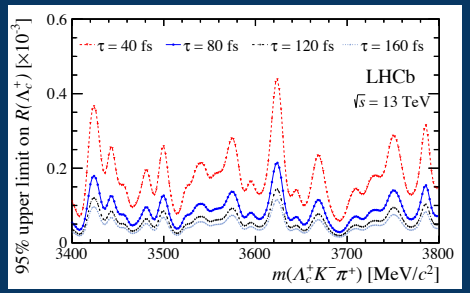


Previous searches for the Ξ_{cc}^{+} baryon

- Observation of the doubly charmed baryon Ξ_{cc}^{+} (ccd) reported by the SELEX experiment in 2002 (Phys. Rev. Lett. 89 (2002) 112001, Phys. Lett. B628 (2005) 18), not confirmed by searches with BaBar, Belle, FOCUS and LHCb
- Search for the Ξ_{cc}^{+} baryon in $\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+}$ decay channel using all available LHCb data (9 fb^{-1}) published last year (Sci. China Phys. Mech. Astron. 63 (2020) 221062) – no significant signal visible using selection optimised for the search of the signal, upper limits on $R(\Lambda_c^{+})$ and $R(\Xi_{cc}^{++})$ determined
- Production cross-section and mass of the Ξ_{cc}^{+} baryon are expected to be similar to its isospin partner Ξ_{cc}^{++}, however **Ξ_{cc}^{+} lifetime is predicted to be ~2-4 times shorter than the lifetime of Ξ_{cc}^{++}** (measured to be 256 fs) – more experimentally challenging





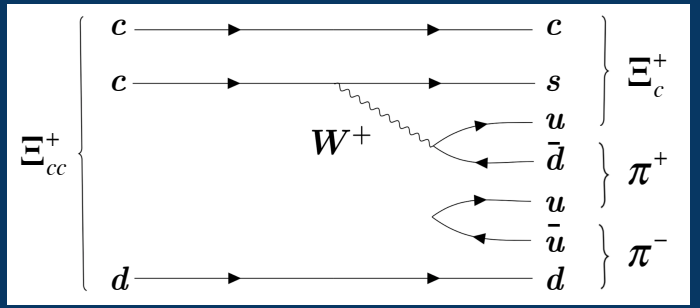


NEW

LHCb-PAPER-2021-019
(in preparation)

New search for the Ξ_{cc}^{+} baryon - introduction

- Search for the doubly charmed baryon Ξ_{cc}^{+} in $\Xi_{cc}^{+} \to (\Xi_{c}^{+} \to pK^{-}\pi^{+})\pi^{-}\pi^{+}$ decay using 5.4 fb^{-1} of LHCb data
- Blinded analysis in the mass window of 3.3-3.8 GeV/c^2
- Four main stages of the selection
  - Hardware and software trigger selection
  - Preselection based on sequential requirements
  - Multivariate-analysis (MVA) based selection
  - Removal of some duplicate candidates



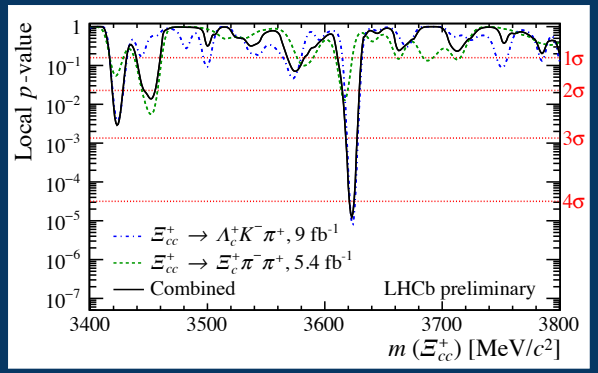
- Simulation events used as a signal proxy and $\Xi_{c}^{+}\pi^{-}\pi^{-}$ combinations from data used as a background proxy

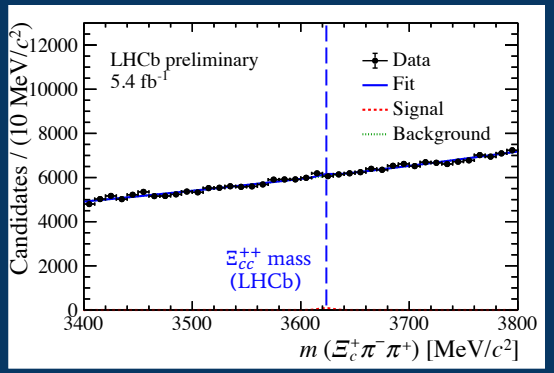
NEW

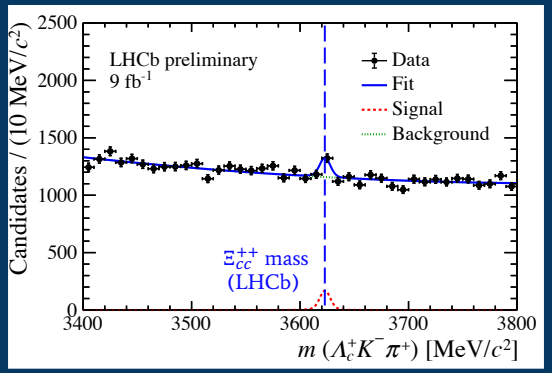
New search for the Ξ_{cc}^{+} baryon - significance

LHCb-PAPER-2021-019
(in preparation)

- No significant signal observed (<3σ local significance) in the $\Xi_c^+\pi^-\pi^+$ final state
- Combined fit with $\Lambda_c^+K^-\pi^+$ final state (using its selection for the UL determination)
  - The minimal combined p-value corresponds to the significance of 4σ ▵
  - The combined global significance (in the 3.5–3.7 GeV/c^2 mass window) found to be 2.9σ ▵
  - The best mass fit found to be 3623.0 ± 1.4 (stat) MeV/c^2







▵ Including the systematic uncertainties, preliminary

NEW

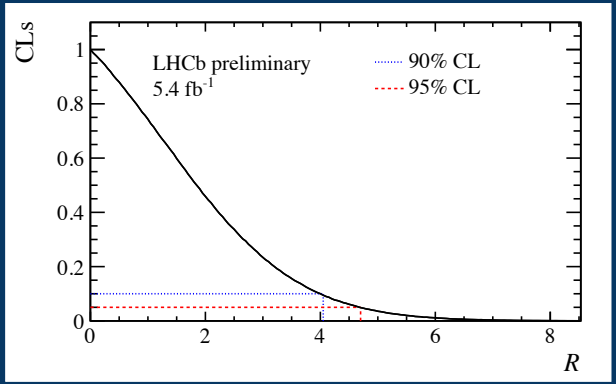
New search for the Ξ_{cc}^{+} baryon – UL results

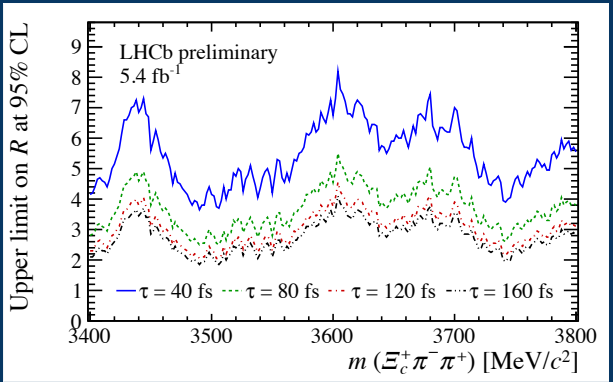
LHCb-PAPER-2021-019
(in preparation)

- Upper limit (UL) on the ratio of production cross sections times the ratio of branching fractions between the signal and the normalisation channel $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$

$$R = \frac{\sigma(\Xi_{cc}^{+}) \times \mathcal{B}(\Xi_{cc}^{+} \to \Xi_c^+ \pi^- \pi^+)}{\sigma(\Xi_{cc}^{++}) \times \mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^+ \pi^+)} = \frac{\varepsilon_{norm}}{\varepsilon_{sig}} \frac{N_{sig}}{N_{norm}}$$

  - UL evaluated as a function of mass in an invariant mass window of (3400, 3800) MeV/c² for four lifetime hypotheses - 40, 80, 120, 160 fs
  - CLs method used - toy experiments using Poisson and Gaussian distributions as test statistics

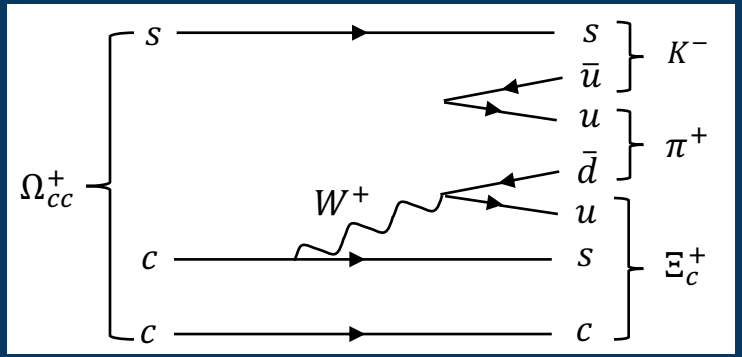




LHCb-PAPER-2021-011
(submitted arXiv:2105.06841)

Search for the Ω_{cc}^{+} baryon - introduction

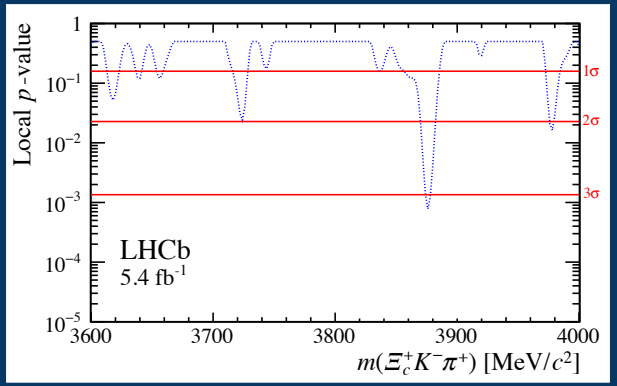
- First search for the doubly charmed baryon Ω_{cc}^{+} (ccs)
- Search performed with the $\Xi_c^+ K^- \pi^+$ final state using 5.4 fb^{-1} of LHCb data
- $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ decay is used as a normalisation channel for the determination of $R = \dfrac{\sigma(\Omega_{cc}^+) \times \mathcal{B}(\Omega_{cc}^+ \to \Xi_c^+ K^- \pi^+) \times \mathcal{B}(\Xi_c^+ \to p K^- \pi^+)}{\sigma(\Xi_{cc}^{++}) \times \mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+) \times \mathcal{B}(\Lambda_c^+ \to p K^- \pi^+)}$
- Blinded analysis in (3.5, 4.0) GeV/c^2 mass window
- Two selections developed:
  - one optimised to maximise the signal sensitivity
  - one optimised for the determination of R

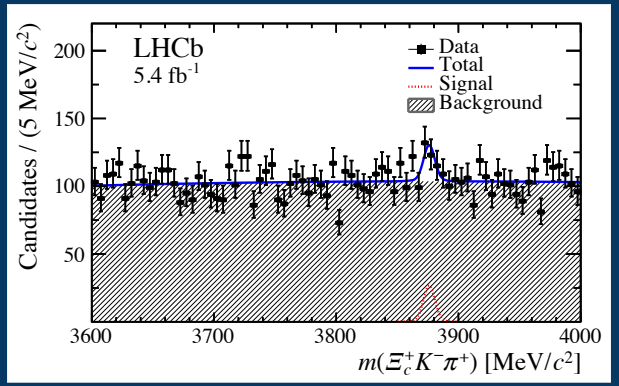


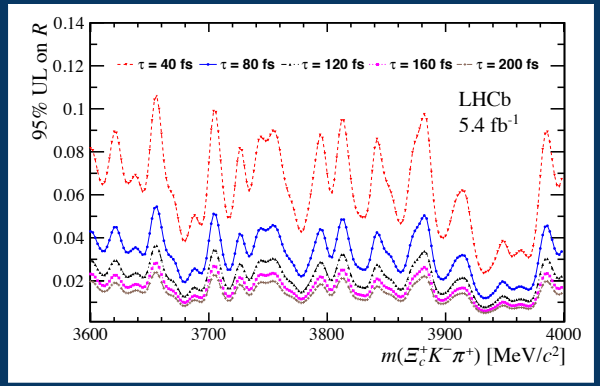
LHCb-PAPER-2021-011
(submitted arXiv:2105.06841)

Search for the Ω_{cc}^{+} baryon - results

- The largest local significance found at 3876 MeV/c^2, corresponding to 3.2σ ▵
- The global significance (in the 3.6–4.0 GeV/c^2 mass range) estimated to be 1.8σ ▵
- UL evaluated as a function of mass in an invariant mass window of (3600, 4000) GeV/c^2 for five lifetime hypotheses – 40, 80, 120, 160 and 200 fs
  - ➢ Determined from the integral of the likelihood profile of the mass fits







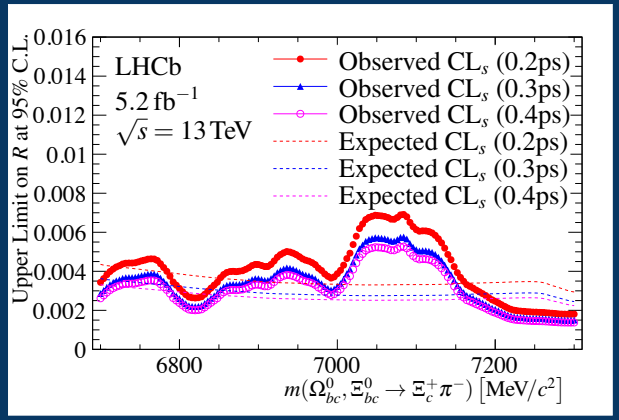
▵ Without the systematic uncertainties

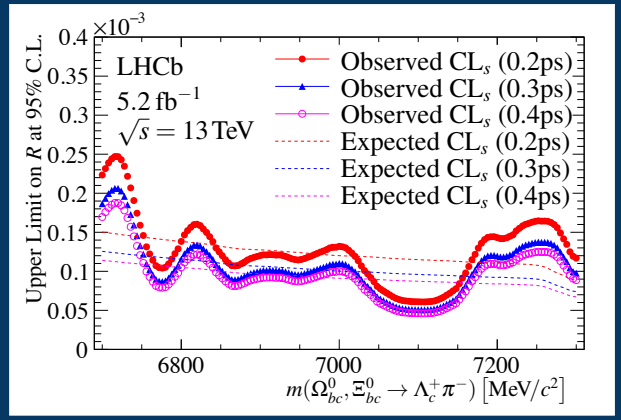
Charm-beauty baryon searches

LHCb-PAPER-2021-002
(submitted arXiv:2104.04759)

Search for doubly heavy baryons Ξ_{bc}^0 and Ω_{bc}^0

- No baryons containing one c and one b quark have been observed yet
- First search for the Ω_{bc}^0 baryon and a new search for the Ξ_{bc}^0 baryon (previous search in D^0pK^- final state [JHEP 11 (2020) 095]) perfromed
- $\Lambda_c^+\pi^-$ and $\Xi_c^+\pi^-$ final states explored for both baryons
- No significant signal observed
  - The UL on R with respect to $\Lambda_b^0 \to \Lambda_c^+\pi^-$ and $\Xi_b^0 \to \Xi_c^+\pi^-$ decays set

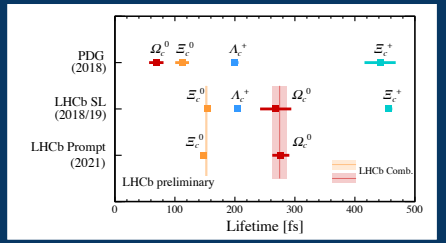


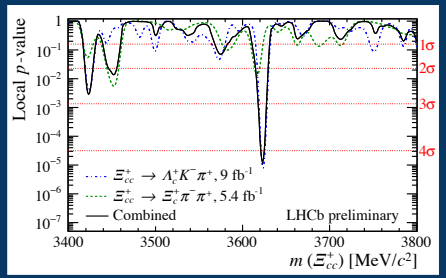


Summary

Summary

- LHCb keeps producing many interesting results on charmed baryons
- New measurement of the lifetimes of the Ω_c^0 and Ξ_c^0 baryons
- Doubly heavy baryon searches
  - First search for the Ξ_{cc}^+ baryon in the $\Xi_c^+\pi^-\pi^+$ final state
  - First search for the Ω_{cc}^+ baryon
  - Search for the Ξ_{bc}^0 and Ω_{bc}^0 baryons
- More studies and searches to be performed
  - Still exploiting the recorded data samples to perform more charmed baryon studies and searches
  - The upgraded LHCb detector with increased instantaneous luminosity and fully software trigger system with improved efficiency





More results to come from LHCb in the future – stay tuned!

Thank you for your attention

Backup

LHCb-PAPER-2021-021
(in preparation)

Ω_c^0 and Ξ_c^0 lifetimes – fit model

- Lifetimes determined with binned χ^2 fit to the data collected in 2016–2018 as

$$\chi^2(\tau, \vec{C}) = \sum_{\text{year}} \sum_{i} \frac{\left(N^{\text{sig}}_{i,\text{year}} - C_{\text{year}} \times F_i(\tau) \times \frac{N^{\text{con}}_{i,\text{year}}}{M^{\text{con}}_{i,\text{year}}} \times M^{\text{sig}}_{i,\text{year}} \right)^2}{\sigma^2_{N^{\text{sig}}_{i,\text{year}}} + C^2_{\text{year}} \times F_i^2(\tau) \times \sigma^2_{\left(\frac{N^{\text{con}}_{i,\text{year}}}{M^{\text{con}}_{i,\text{year}}} \times M^{\text{sig}}_{i,\text{year}} \right)}}$$

where $N^{sig}_{i,year}$ ($N^{con}_{i,year}$) is the signal yield in data for the signal (control) mode in decay-time bin i and for the data taking period "year", M is the effective yield predicted from simulation, C is a normalisation factor to account for the difference in size between the data and the simulated samples, and σ is the uncertainty of the relevant quantity

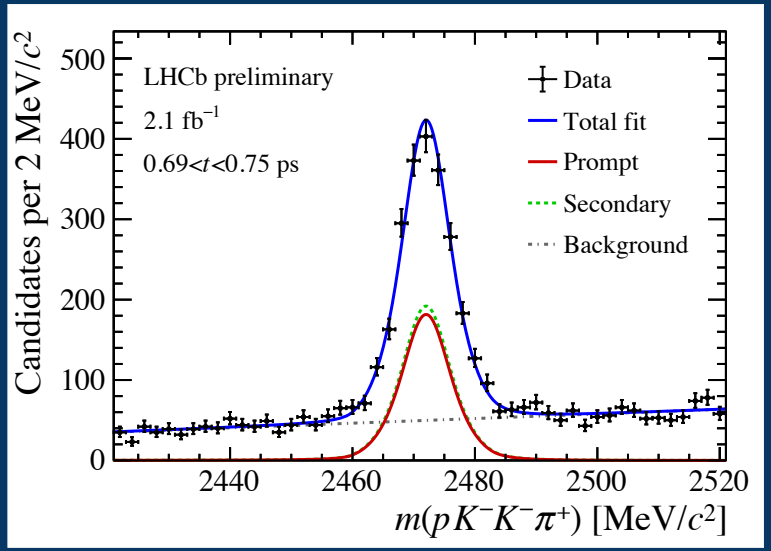
- F_i is a quantity to account for the difference in lifetime between the data and the simulated samples

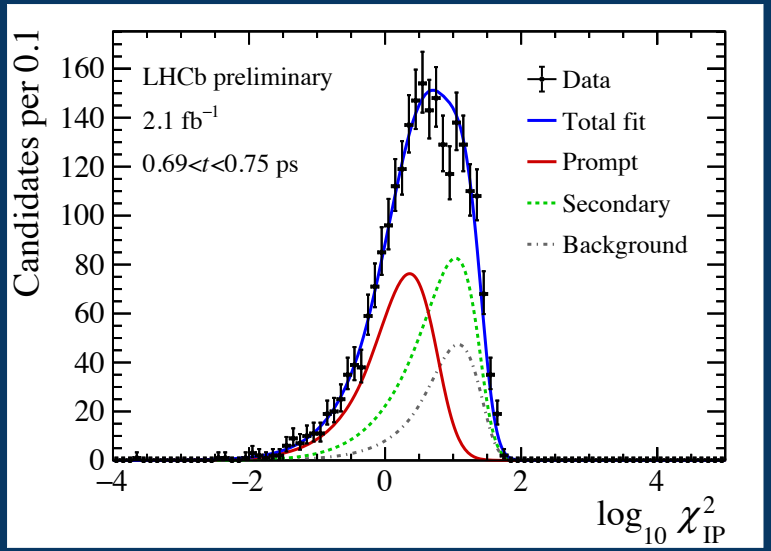
$$F_i(\tau) = \frac{\int_i \exp(-t/\tau)\mathrm{d}t}{\int_i \exp(-t/\tau_{\text{sim}})\mathrm{d}t} \Big/ \frac{\int_i \exp(-t/\tau^{\text{con}})\mathrm{d}t}{\int_i \exp(-t/\tau^{\text{con}}_{\text{sim}})\mathrm{d}t}$$

where τ_{sim} = 250 fs is the signal mode lifetime in simulation, and τ^{con} = τ^{con}_{sim} τcon sim is the known D^0 lifetime

Ω_c^0 and Ξ_c^0 lifetimes – Ξ_c^0 2D fit

LHCb-PAPER-2021-021
(in preparation)





LHCb-PAPER-2021-019
(in preparation)

Possible resonant contributions in $\Xi_{cc}^{+} \to \Xi_{c}^{+}\pi^{-}\pi^{+}$ decay

- Additional cross-check performed after unblinding - a mass cut of (2638,2653) MeV/c^2 in the $\Xi_c^+\pi^-$ invariant-mass spectrum is applied in order to evaluate the statistical significances for the potential resonant decay $\Xi_{cc}^{+} \to (\Xi_{c}^{**0} \to \Xi_{c}^{+}\pi^{-})\,\pi^{+}$
  - The evaluated local significance is under 3σ → no evidence for this resonant decay either
- Consideration that the resonant decay $\Xi_{cc}^{+} \to \Xi_{c}^{+}\rho^{0}$ can represent a significant contribution in the final state
  - The effect of its possible contribution is considered as a systematic uncertainty by re-weighting the $\pi^{-}\pi^{+}$ invariant mass spectrum in MC to match the ρ^{0} line shape (as an extreme case in which 100% of the bachelor pions would come from the ρ^{0} resonance)
  - The correction for this possible contribution is estimated by averaging over the nominal ratio (0% resonance contribution) and the ratio after the ρ^{0} re-weighting (100% resonance contribution)

LHCb-PAPER-2021-011
(submitted arXiv:2105.06841)

Search for the Ω_{cc}^{+} baryon – systematic uncertainties

Source	R [%]
Fit model	3.5
Hardware trigger	11.2
Tracking	2.7
PID	0.9
Ξ_{cc}^{++} lifetime	12.0
Simulation/data difference	5.0
Total	17.7

Search for doubly heavy baryons Ξ_{bc}^0 and Ω_{bc}^0

LHCb-PAPER-2021-002
(submitted arXiv:2104.04759)