LHCb 实验利用瞬发产生过程测量粲重子 Ω_c^0 和 Ξ_c^0 的寿命

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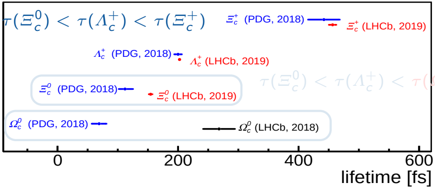
Lifetimes of weakly-decay singly charmed baryons

- Lifetime hierarchy in the past 20 years
  - Precisions in the range of 3–17%

$\tau(\Omega_c^0) < \tau(\Xi_c^0) < \tau(\Lambda_c^+) < \tau(\Xi_c^+)$



$\tau(\Xi_c^0) < \tau(\Lambda_c^+) < \tau(\Omega_c^0) < \tau(\Xi_c^+)$

- LHCb measurements with 2011–12 data changed the landscape dramatically
  - Use signals from semileptonic *b*-hadron decays
  - Precisions in the range of 1–10%
- Independent measurements helpful to understand the large discrepancy in Ω_c^0 and Ξ_c^0 lifetimes

LHCb SL

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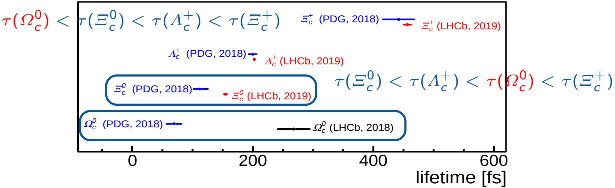
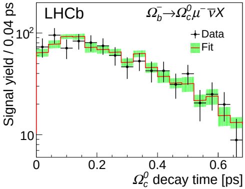


[PRL 121 (2018) 092003]



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  - Use signals from semileptonic b-hadron decays
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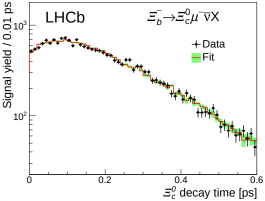
[PRD 100 (2019) 032001]



LHCb SL

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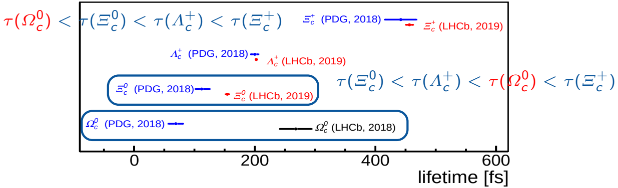

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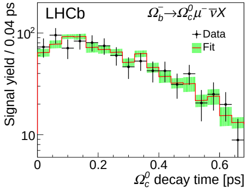

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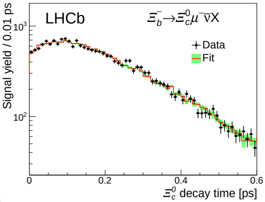

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LHCb SL

Measurement of Ω_c^0 and Ξ_c^0 lifetimes

NEW

[arXiv:2109.01334]

- Independent from LHCb SL
  - (Data) $\mathcal{L} = 5.4\,\mathrm{fb}^{-1}$ LHCb data collected in 2016–18
  - (Method) Prompt Ω_c^0/Ξ_c^0 signals through $pK^-K^-\pi^+$ decays
- Results not examined until full procedure had been finalised
- Method in a nutshell
  1. Determine signal yield in bins of decay time

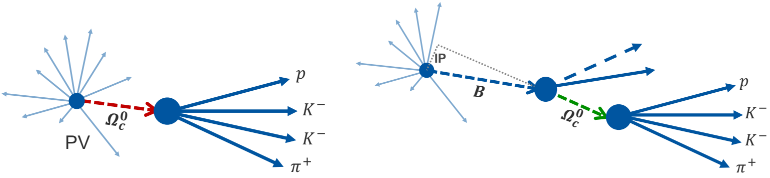
$$t = m \times \frac{\vec{p}\cdot\vec{r}}{p^2}$$

  2. Determine lifetime with least chi-square fit

$$\chi^2(\tau) = \sum_i \frac{\left(N_i^{\mathrm{sig}} - N_i^{\mathrm{exp}}\right)^2}{\sigma^2_{N_i^{\mathrm{sig}}} + \sigma^2_{N_i^{\mathrm{exp}}}}$$

Boost in signal yield

- Prompt $\Omega_c^0/\Xi_c^0 \to pK^-K^-\pi^+$ decays
  - Signals produced directly from pp collisions (PV)

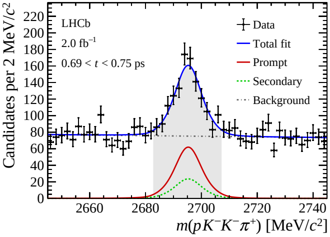


Prompt **Secondary**

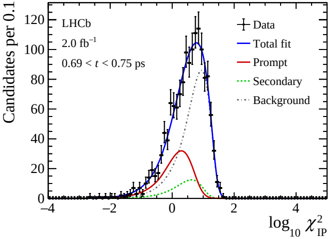
	Fixed target	LHCb SL	LHCb prompt
Ω_c^0	180	1 K	12 K
Ξ_c^0	160	22 K	36 K

Complicated background components

- Combinatorial: random combination of tracks
  - Linear in the invariant-mass distribution
- Secondary: true signals from b-hadron decays
  - Larger peak positions in the logorithm of $\chi^2_{\text{IP}} \approx \frac{IP^2}{\sigma^2_{IP}}$



Invariant-mass of Ω_c^0



$\log \chi^2_{\text{IP}}$ of Ω_c^0

Efficiency variation with decay time

- Efficiency of selection criteria is different at different decay time
  - Need to be considered for an unbiased estimation of decay time
- Simulated signal samples used to evaluate efficiency
- $D^0 \to K^- K^+ \pi^- \pi^+$ as normalisation channel to further reduce systematic uncertainties

Least chi-square fit to decay time

- Chi-square

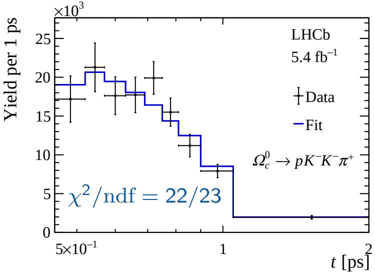
$$\chi^2(\tau) = \sum_i \frac{\left(N_i^{\mathrm{sig}} - N_i^{\mathrm{exp}}\right)^2}{\sigma^2_{N_i^{\mathrm{sig}}} + \sigma^2_{N_i^{\mathrm{exp}}}}$$

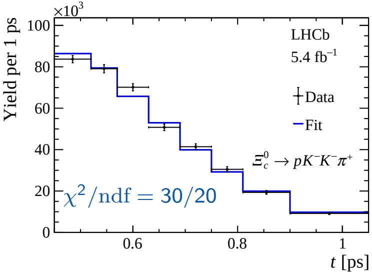
  - N_i^{sig} is signal yield in decay-time bin i
  - N_i^{exp} is expected yield in decay-time bin i

$$N_i^{\mathrm{exp}} = M_i^{\mathrm{sig}} \times \frac{\int_i \exp(-t/\tau)\mathrm{d}t}{\int_i \exp(-t/\tau_{\mathrm{sim}})\mathrm{d}t} \times \frac{N_i^{\mathrm{con}}}{M_i^{\mathrm{con}}}$$

- Unbiased estimator validated with pseudo-experiment

- Signal yields per ps in decay-time bins





$\tau_{\Omega_c^0} = 276.5 \pm 13.4(\textbf{stat})$ $\tau_{\Xi_c^0} = 148.0 \pm 2.3(\textbf{stat})$

Cross and consistency checks

- D^0 lifetime measured with normalisation channel $D^0 \to K^- K^+ \pi^- \pi^+$
  - Good agreement with its world average
- Consistent results measured with sub-samples split by
  - Data-taking periods
  - Magnetic polarities of the LHCb dipole magnet
- Consistent results measured with
  - Different decay-time binning scheme
  - Different lifetime assumption in simulation

Systematic uncertainties

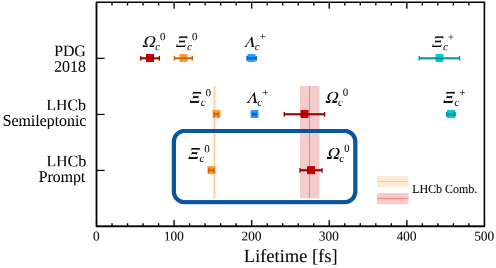
- Dominant uncertainties stem from fit model and difference between data and simulation

Sources	$\tau_{\Omega_c^0}$ [fs]	$\tau_{\Xi_c^0}$ [fs]
Fit model	2.2	1.0
Kinematic correction	3.4	0.4
Decay-time resolution	1.3	1.8
χ^2_{IP} scaling	1.1	0.5
Calibration sample size	0.1	0.1
Decay-length scale	0.1	0.1
D^0–$\bar{D}^0$ mixing	0.8	0.6
Total systematic uncertainty	4.4	2.2
D^0 lifetime	0.7	0.2
Statistical uncertainty	13.4	2.3

Results

$$\tau_{\Omega_c^0} = 276.5 \pm 13.4(\text{stat}) \pm 4.4(\text{syst}) \pm 0.7(D^0)\ \text{fs}$$
$$\tau_{\Xi_c^0} = 148.0 \pm 2.3(\text{stat}) \pm 2.2(\text{syst}) \pm 0.2(D^0)\ \text{fs}$$

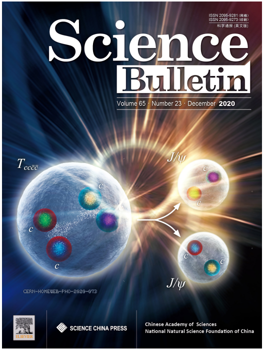
- Most precise measurement of Ω_c^0 lifetime so far
- Consistent with LHCb SL measurements



- Is Heavy Quark Expansion still valid in the Ω_c^0 system? [arXiv:2109.01216]

Summary

- Lifetimes of Ω_c^0 and Ξ_c^0 are measured precisely
- New hierarchy of charmed baryons established



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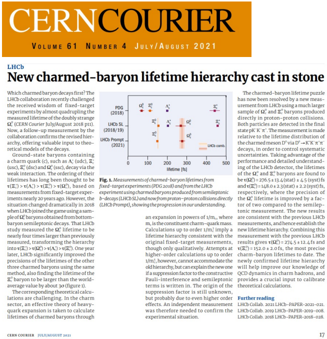

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LHCb

New charmed-baryon lifetime hierarchy cast in stone

Which charmed baryon decays first? The LHCb collaboration recently challenged the received wisdom of fixed-target experiments by almost quadrupling the measured lifetime of the doubly strange Ω_c^0 (*CERN Courier* July/August 2018 p11). Now, a follow-up measurement by the collaboration confirms the revised hierarchy, offering valuable input to theoretical models of the decays.

Ground-state baryons containing a charm quark (c), such as Λ_c^+ (udc), Ξ_c^+ (usc), Ξ_c^0 (dsc) and Ω_c^0 (ssc), decay via the weak interaction. The ordering of their lifetimes has long been thought to be $\tau(\Xi_c^+) > \tau(\Lambda_c^+) > \tau(\Xi_c^0) > \tau(\Omega_c^0)$, based on measurements from fixed-target experiments nearly 20 years ago. However, the situation changed dramatically in 2018 when LHCb joined the game using a sample of Ω_c^0 baryons obtained from bottom-baryon semileptonic decays. That LHCb study measured the Ω_c^0 lifetime to be nearly four times larger than previously measured, transforming the hierarchy into $\tau(\Xi_c^+) > \tau(\Omega_c^0) > \tau(\Lambda_c^+) > \tau(\Xi_c^0)$. One year later, LHCb significantly improved the precisions of the lifetimes of the other three charmed baryons using the same method, also finding the lifetime of the Ξ_c^0 baryon to be larger than the world-average value by about 3σ (figure 1).

The corresponding theoretical calculations are challenging. In the charm sector, an effective theory of heavy-quark expansion is taken to calculate lifetimes of charmed baryons through an expansion in powers of $1/m_c$, where m_c is the constituent charm-quark mass. Calculations up to order $1/m_c^3$ imply a lifetime hierarchy consistent with the original fixed-target measurements, though only qualitatively. Attempts at higher-order calculations up to order $1/m_c^4$, however, cannot accommodate the old hierarchy, but can explain the new one if a suppression factor to the constructive Pauli-interference and semileptonic terms is written in. The origin of the suppression factor is still unknown, but probably due to even higher order effects. An independent measurement was therefore needed to confirm the experimental situation.

Fig. 1. *Measurements of charmed-baryon lifetimes from fixed-target experiments (PDG 2018) and from the LHCb experiment using charmed baryons produced from semileptonic b-decays (LHCb SL) and now from proton–proton collisions directly (LHCb Prompt), showing the progression in our understanding.*

The charmed-baryon lifetime puzzle has now been resolved by a new measurement from LHCb using a much larger sample of Ω_c^0 and Ξ_c^0 baryons produced directly in proton–proton collisions. Both particles are detected in the final state $pK^-K^-\pi^+$. The measurement is made relative to the lifetime distribution of the charmed meson D^0 via $D^0 \to K^+K^-\pi^+\pi^-$ decays, in order to control systematic uncertainties. Taking advantage of the performance and detailed understanding of the LHCb detector, the lifetimes of the Ω_c^0 and Ξ_c^0 baryons are found to be $\tau(\Omega_c^0) = 276.5 \pm 13.4\,(\text{stat}) \pm 4.5\,(\text{syst})$ fs and $\tau(\Xi_c^0) = 148.0 \pm 2.3\,(\text{stat}) \pm 2.2\,(\text{syst})$ fs, respectively, where the precision of the Ω_c^0 lifetime is improved by a factor of two compared to the semileptonic measurement. The new results are consistent with the previous LHCb measurements, and hence establish the new lifetime hierarchy. Combining this measurement with the previous LHCb results gives $\tau(\Omega_c^0) = 274.5 \pm 12.4$ fs and $\tau(\Xi_c^0) = 152.0 \pm 2.0$ fs, the most precise charm-baryon lifetimes to date. The newly confirmed lifetime hierarchy will help improve our knowledge of QCD dynamics in charm hadrons, and provides a crucial input to calibrate theoretical calculations.

Further reading

LHCb Collab. 2021 LHCb-PAPER-2021-021.
LHCb Collab. 2019 LHCb-PAPER-2019-008.
LHCb Collab. 2018 LHCb-PAPER-2018-028.

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Backup

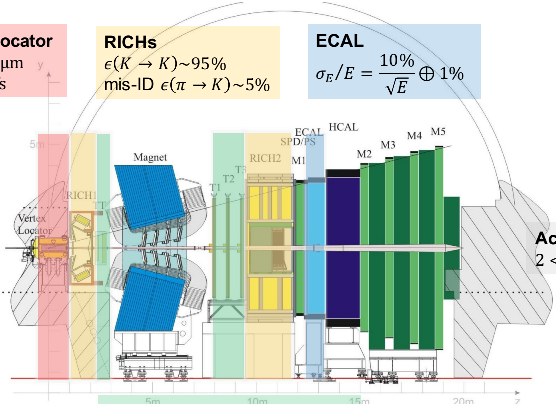
[JINST 3 (2008) S08005, IJMPA 30 (2015) 1530022]

- A single-arm forward spectrometer at LHC

Vertex Locator
$\sigma_{IP} = 20\ \mu m$
$\sigma_\tau = 45$ fs

RICHs
$\epsilon(K \to K) \sim 95\%$
mis-ID $\epsilon(\pi \to K) \sim 5\%$

ECAL
$\sigma_E/E = \frac{10\%}{\sqrt{E}} \oplus 1\%$



Acceptance
$2 < \eta < 5$

Tracking stations
$\epsilon_{\text{tracking}} \sim 96\%$
$\sigma_p/p \sim 0.5\% - 1\% (5 - 200\ \text{GeV})$

LHCb data taking

- About $\mathcal{L} = 9\,\text{fb}^{-1}$ data accumulated in Run 1–2