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Measurement of the lifetimes of promptly produced Ω_c^0 and Ξ_c^0 baryons

LHCb collaboration[†]

Abstract

A measurement of the lifetimes of the Ω_c^0 and Ξ_c^0 baryons is reported using proton–proton collision data at a centre-of-mass energy of 13 TeV, corresponding to an integrated luminosity of $5.4\,\text{fb}^{-1}$ collected by the LHCb experiment. The Ω_c^0 and Ξ_c^0 baryons are produced directly from proton interactions and reconstructed in the $pK^-K^-\pi^+$ final state. The Ω_c^0 lifetime is measured to be $276.5 \pm 13.4 \pm 4.4 \pm 0.7\,\text{fs}$, and the Ξ_c^0 lifetime is measured to be $148.0 \pm 2.3 \pm 2.2 \pm 0.2\,\text{fs}$, where the first uncertainty is statistical, the second systematic, and the third due to the uncertainty on the D^0 lifetime. These results confirm previous LHCb measurements based on semileptonic beauty-hadron decays, which disagree with earlier results of a four times shorter Ω_c^0 lifetime, and provide the single most precise measurement of the Ω_c^0 lifetime.

Keywords: Charmed baryon, Flavour physics, QCD, Lifetime, Charm physics, LHCb

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1 Introduction

The LHCb collaboration has previously measured the lifetimes of Ω_c^0 and Ξ_c^0 baryons, with valence quark content of ssc and dsc, respectively, using candidates from semileptonic beauty-hadron decays [1, 2]. The measured Ω_c^0 lifetime, $\tau_{\Omega_c^0}$, is nearly four times larger than the previous world average [3], which is inconsistent at a level of seven standard deviations. The measured Ξ_c^0 lifetime, $\tau_{\Xi_c^0}$, is larger than the previous world average by three standard deviations. Resolving these discrepancies is important for theoretical calculations. Lifetime measurements of hadrons containing heavy quarks Q, *i.e.* charm or beauty quarks, provide input needed to test precisely the Standard Model and search for physics beyond.

Heavy quark expansion [4–10] is an effective theory used to calculate the lifetimes of these hadrons through an expansion in inverse powers of the mass of the heavy quark, m_Q. The lowest-order term in the expansion depends only on m_Q and contributes equally to the decay width of all hadrons with the same heavy quark. Differences in predicted lifetimes are expected to arise from higher-order effects, such as weak W-annihilation and Pauli interference, due to the presence of different spectator quarks. Measurements of charmed-hadron lifetimes are particularly sensitive to these higher-order contributions, as these corrections typically increase as m_Q decreases and are large for charmed hadrons [11–16]. A lifetime hierarchy of $\tau_{\Xi_c^+} > \tau_{\Lambda_c^+} > \tau_{\Xi_c^0} > \tau_{\Omega_c^0}$ is obtained considering higher-order effects [12, 14–17], whereas the ordering of $\tau_{\Xi_c^+} > \tau_{\Omega_c^0} > \tau_{\Lambda_c^+} > \tau_{\Xi_c^0}$ can be obtained depending on the treatment of even higher-order effects [16, 18, 19]. Knowledge on the lifetimes is also required to make comparisons between measured branching fractions of charmed baryons and corresponding theoretical predictions for their partial decay widths.

The LHCb experiment has recorded an unprecedented number of charmed baryons, produced both at the primary proton–proton (pp) collision vertex (PV), referred to as prompt, and from decays of beauty hadrons. In this paper, a measurement of the lifetimes of Ω_c^0 and Ξ_c^0 baryons is reported based on a sample of Ω_c^0 and Ξ_c^0 baryons promptly produced in pp collisions at a centre-of-mass energy of 13 TeV. The data sample was collected by the LHCb experiment between 2016–2018 and corresponds to an integrated luminosity of $5.4\,\mathrm{fb}^{-1}$. The Ω_c^0 and Ξ_c^0 baryons are reconstructed in the $pK^-K^-\pi^+$ final state.[1] In order to avoid experimenter's bias, the results of the analysis were not examined until the full procedure had been finalised. Prompt $D^0 \to K^+K^-\pi^+\pi^-$ decays are used as a control mode in order to reduce systematic uncertainties and to validate the analysis procedure.

2 Detector and simulation

The LHCb detector [20, 21] is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, designed for the study of particles containing b or c quarks. The tracking system provides a measurement of the momentum, p, of charged particles with a relative uncertainty that varies from 0.5% at low momentum to 1.0% at $200\,\mathrm{GeV}/c$. The minimum distance of a track to a PV, the impact parameter (IP), is measured with a resolution of $(15 + 29/p_\mathrm{T})\,\mu\mathrm{m}$, where p_T is the component of the

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[1] The inclusion of charge-conjugate processes is implied throughout.

momentum transverse to the beam, in GeV/c. Different types of charged hadrons are distinguished using information from two ring-imaging Cherenkov detectors. Photons, electrons and hadrons are identified by a calorimeter system consisting of scintillating-pad and preshower detectors, an electromagnetic and a hadronic calorimeter. The online event selection is performed by a trigger, which consists of a hardware stage, based on information from the calorimeter and muon systems, followed by a two-level software stage, which applies a full event reconstruction. Between the two software stages, an alignment and calibration of the detector is performed in near real-time and their results are used in the trigger. The same alignment and calibration information is propagated to the offline reconstruction, ensuring consistent and high-quality particle identification (PID) information between the trigger and offline software. The identical performance of the online and offline reconstruction offers the opportunity to perform physics analyses directly using candidates reconstructed in the trigger [22, 23], which this analysis utilises.

Simulated samples are used to model the effects of the detector acceptance and the imposed selection requirements, and to study the modelling of the discriminating variables between signal and background candidates. In the simulation, pp collisions are generated using Pythia [24, 25] with a specific LHCb configuration [26]. Decays of unstable particles are described by EvtGen [27], in which final-state radiation is generated using Photos [28]. The interaction of the generated particles with the detector, and its response, are implemented using the Geant4 toolkit [29] as described in Ref. [30]. The underlying pp interaction is reused multiple times, with an independently generated signal decay for each [31].

3 Candidate selection

Candidate decays of charmed hadrons are reconstructed through the $\Omega_c^0 \to pK^-K^-\pi^+$, $\Xi_c^0 \to pK^-K^-\pi^+$, and $D^0 \to K^+K^-\pi^+\pi^-$ decay modes. All final-state charged particle candidates are required to be inconsistent with originating from any PV. The PV associated to a single charged particle is defined to be the PV with the smallest χ^2_{IP}, where χ^2_{IP} is defined as the difference in the vertex-fit χ^2 of a given PV reconstructed with and without the given particle. Each of the final-state particles is required to have good track quality, large transverse and total momentum, and particle-identification information consistent with the corresponding p, K, or π hypothesis. The angle between each pair of final-state particles is required to be larger than 0.5 mrad to avoid selecting duplicate tracks. The charmed hadron candidates are required to have a decay vertex with good quality that is displaced from its associated PV. The angle between the reconstructed momentum vector of a charmed baryon candidate and the direction from its associated PV to its decay vertex, the direction angle, is required to be small to suppress combinatorial background.

To improve further the signal purity, a multivariate classifier is trained based on the adaptive boosted decision tree (BDT) algorithm [32, 33] implemented in the TMVA toolkit [34]. The classifier is trained using simulated prompt $\Omega_c^0 \to pK^-K^-\pi^+$ decays as signal, and data from the Ω_c^0 mass sidebands of $25 < |m(pK^-K^-\pi^+) - m_{\Omega_c^0}| < 75\,\text{MeV}/c^2$ as background. Here, $m(pK^-K^-\pi^+)$ is the invariant mass of the decay products of the charmed baryon candidate and $m_{\Omega_c^0}$ is the known Ω_c^0 mass [35]. The sideband ranges from 5 to 14 times the invariant-mass resolution. The lifetime of the simulated Ω_c^0 decays is 250 fs. Eleven input variables are used in the training, including: the χ^2 of the Ω_c^0 decay-vertex fit; the transverse momentum, pseudorapidity and the direction angle of the Ω_c^0 candidate; the transverse momenta as well as the minimal transverse momentum of the four final-state particles; and the natural logarithm of the sum and minimum $\chi^2_{\rm IP}$ of the four final-state particles. A requirement on the BDT response is chosen which selects approximately 99% of Ω_c^0 signal decays while rejecting about 60% of the background. The same requirement is also applied to the Ξ_c^0 signal decays. The number of signal candidates for the Ω_c^0, Ξ_c^0, and D^0 decay modes are determined using the $[2645, 2745]\,{\rm MeV}/c^2$, $[2421, 2521]\,{\rm MeV}/c^2$, and $[1835, 1915]\,{\rm MeV}/c^2$ invariant-mass regions, respectively.

Specific trigger requirements are applied to candidates to ensure a precise estimation of the selection efficiency as a function of decay time. In the offline selection, trigger signals are associated with reconstructed particles. Selection requirements can therefore be made on the trigger selection itself and if the decision was due to the signal candidate. At the hardware stage, at least one of the final-state tracks is required to deposit large transverse energy in the hadronic calorimeter. At the software stage, at least one of the final-state tracks is required to pass a MatrixNet classifier [36], which is trained to select displaced tracks [37].

4 Prompt yield determination

Charmed hadron candidates are split into intervals of their decay time, which is calculated using the PV, its decay vertex, and its measured momentum. The signal yields are then determined in each interval. The interval boundaries of the Ω_c^0 sample are chosen to have a similar yield of Ω_c^0 signals in each interval, and correspond to $[0.45, 0.52, 0.57, 0.63, 0.69, 0.75, 0.81, 0.90, 1.05, 2.00]\,{\rm ps}$. For the Ξ_c^0 sample, the same boundaries are used except the last interval, which, for computational simplicity, is not included as the yield is consistent with zero. The same boundaries are used for the D^0 control mode as for the signal modes. Two variables are used to discriminate signal decays from different background contributions. One is the invariant mass of the charmed hadron, which is used to distinguish decays from combinatorial background due to the random combinations of tracks. The other is the logarithm of the $\chi^2_{\rm IP}$ of the charmed hadron, $\log_{10}\chi^2_{\rm IP}$, which is used to separate prompt candidates from those produced in decays of beauty hadrons. The $\log_{10}\chi^2_{\rm IP}$ distribution for signal decays has smaller mean values than for those originating from beauty-hadron decays due to the lifetime of the ancestor beauty hadron.

Example distributions of invariant mass and $\log_{10}\chi^2_{\rm IP}$, in reduced mass regions around the peak, are presented in Fig. 1; the decay-time interval of $[0.69, 0.75]\,{\rm ps}$ for data collected in 2018 is shown. To obtain the Ω_c^0, Ξ_c^0, and D^0 signal yields in each decay-time interval, two-dimensional unbinned extended maximum likelihood fits are performed to the invariant-mass and $\log_{10}\chi^2_{\rm IP}$ distributions. For each mode, the fits are performed simultaneously in all decay-time intervals and the three data-taking periods, 2016, 2017, and 2018. The invariant-mass distribution of the signal candidates is described with the sum of a Gaussian function and a double-sided Crystal Ball function [38] with a shared mean. The fit parameters are fixed to values obtained from simulation except for the mass peak and the effective resolution, which are obtained directly from data, but shared among the different decay-time intervals. The invariant-mass distribution of the combinatorial background contribution is described by a linear function with a slope left free to vary in the fit. The $\log_{10}\chi^2_{\text{IP}}$ distributions of both the signal and background components are described by a Bukin function [39]. For signal components, parameters of the Bukin function are fixed to values obtained from simulation except for the peak position that depends on the decay time. Here, an offset parameter is added to account for the disagreement between data and simulation. The offset parameter is free to vary and shared between decay-time intervals and data-taking periods in the fit. The parameters of the Bukin function of the combinatorial background contribution are fixed to values obtained from fits to the data samples in the sideband region as defined in the BDT training. The two-dimensional model used for signal, secondary decays, and background components is the product of the models for the invariant-mass and for the $\log_{10}\chi^2_{\text{IP}}$ distributions. Fit projections to the invariant-mass and $\log_{10}\chi^2_{\text{IP}}$ distribution are shown in Fig 1.

5 Decay time fit

The lifetimes of the $\mathit{\Omega}_c^0$ and $\mathit{\Xi}_c^0$ baryons are determined from a binned χ^2 fit comparing the signal yields in data with those from the simulation, where the lifetime is known. The latter is corrected using the control mode, as follows

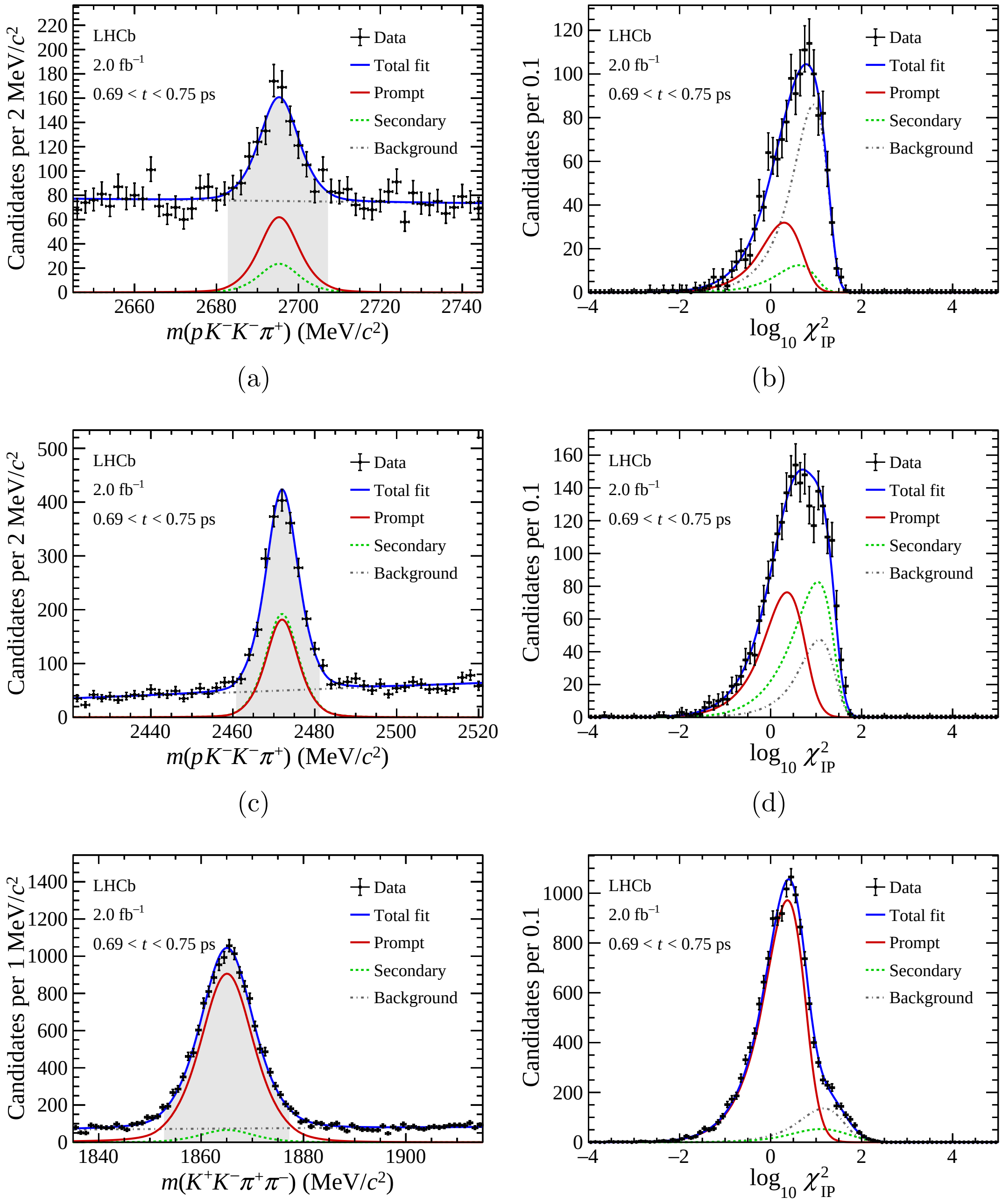
$$\chi^2(\tau,\vec{C}) = \sum_j \sum_i \frac{\left(N^{\text{sig}}_{i,j} - C_j \times F_i(\tau) \times R_{i,j}\right)^2}{\sigma^2_{N^{\text{sig}}_{i,j}} + C_j^2 \times F_i^2(\tau) \times \sigma^2_{R_{i,j}}}, \qquad R_{i,j} \ = \frac{N^{\text{con}}_{i,j}}{M^{\text{con}}_{i,j}} \times M^{\text{sig}}_{i,j}, \tag{1}$$

where: $N^{\text{sig}}_{i,j}$ ($N^{\text{con}}_{i,j}$) is the signal yield in data for the signal (control) mode in decay-time interval i and for the data-taking period j; $M_{i,j}$ is the effective yield predicted from simulation; C_j 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. The difference in lifetime between data and simulated samples is accounted for by

$$F_i(\tau) = \frac{\int_i \exp(-t/\tau)\mathrm{d}t}{\int_i \exp(-t/\tau_{\text{sim}})\mathrm{d}t} \times \frac{\int_i \exp(-t/\tau^{\text{con}}_{\text{sim}})\mathrm{d}t}{\int_i \exp(-t/\tau^{\text{con}})\mathrm{d}t}, \tag{2}$$

where $\tau_{\text{sim}} = 250\,\text{fs}$ is the signal mode lifetime in simulation and $\tau^{\text{con}} = \tau^{\text{con}}_{\text{sim}}$ is the known D^0 lifetime [35], but is allowed to vary for estimating the systematic uncertainty. The resulting lifetime is $\tau_{\mathit{\Omega}_c^0} = 276.5 \pm 13.4\,\text{fs}$ with $\chi^2/\text{ndf} = 22/23$ and $\tau_{\mathit{\Xi}_c^0} = 148.0 \pm 2.3\,\text{fs}$ with $\chi^2/\text{ndf} = 30/20$, where the uncertainty is due to the limited size of the data and simulation samples. The result of the χ^2 fit to data is illustrated in Fig. 2, which shows the signal yield N^{sig} for selected candidates as a function of decay time, divided by the width of the corresponding decay-time interval, where the fit results are superimposed.

Several cross-checks are performed to ensure the robustness of the results. The χ^2 fit is performed to data of the $D^0 \to K^+K^-\pi^+\pi^-$ control mode for each data-taking period to validate the analysis procedure. The obtained lifetimes are consistent between data-taking periods and with the known D^0 lifetime [35]. The data samples are split into sub-samples according to data-taking periods and magnetic polarities of the LHCb dipole magnet, and the lifetimes are measured for each sub-sample. The resulting lifetimes are in good agreement with each other and with the default results. The measurement is repeated



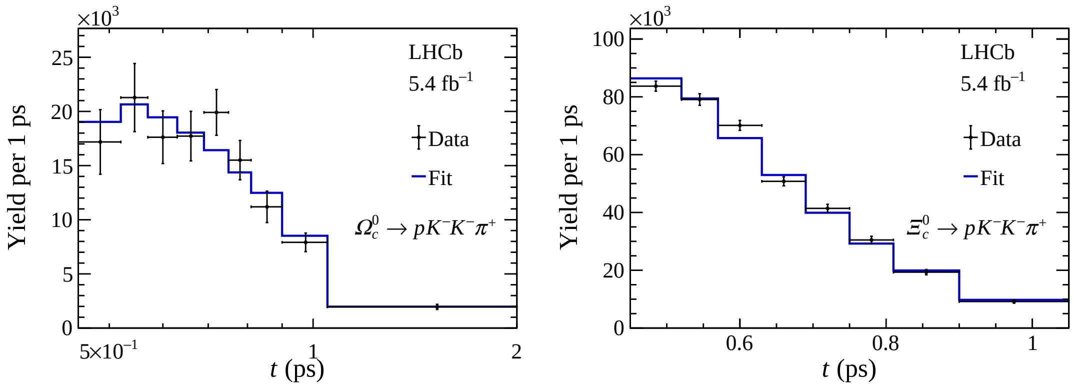
(a) (b)

(c) (d)

(e) (f)

Figure 1: (Color online) Distributions of (a) invariant mass and (b) $\log_{10}\chi^2_{\rm IP}$ in the reduced mass region of $[2683, 2707]\,{\rm MeV}/c^2$ for the Ω_c^0 data sample, (c) invariant mass and (d) $\log_{10}\chi^2_{\rm IP}$ in the reduced mass region of $[2461, 2481]\,{\rm MeV}/c^2$ for the Ξ_c^0 data sample, (e) invariant mass and (f) $\log_{10}\chi^2_{\rm IP}$ in the reduced mass region of $[1853, 1877]\,{\rm MeV}/c^2$ for the D^0 data sample, along with the fit results. The sample is collected in 2018 in the decay-time interval of $[0.69, 0.75]$ ps. The contributions of the signal, the secondary decays, and the combinatorial background are shown in red (solid), green (dashed), and gray (dash-dotted), respectively.

with two alternative boundaries of decay-time intervals and the obtained lifetimes are consistent with the default results within their statistical uncertainties. To ensure that



(a) (b)

Figure 2: (Color online) Decay-time distributions for the (a) Ω_c^0 mode and the (b) Ξ_c^0 mode with the χ^2 fit superimposed. The uncertainty on the data distribution is statistical only.

the result is independent of the input lifetime used in simulation, the simulated signal decays are weighted to have alternative effective lifetimes within seven times the statistical uncertainty around the default lifetime. The χ^2 fit is then repeated. The difference of the obtained lifetimes with regard to the default fit is negligible.

6 Systematic uncertainties

Sources of systematic uncertainty are investigated and summarised in Table 1, including those due to the fit model, the limited size of the calibration samples, differences between data and simulation, and the uncertainty due to the choice of the D^0 control mode. The systematic uncertainty due to the modelling of $\log_{10}\chi^2_{\rm IP}$ is studied with the D^0 control mode. The following alternative models were tried and their impact on the signal yields studied. First, the effect due to fixed parameters in the Bukin function is studied by

Table 1: Systematic uncertainties for the Ω_c^0 and Ξ_c^0 lifetimes.

Sources	$\tau_{\Omega_c^0}$ [fs]	$\tau_{\Xi_c^0}$ [fs]
Fit model	2.2	1.0
Calibration sample size	0.1	0.1
Kinematic correction	3.4	0.4
Decay-time resolution	1.3	1.8
$\chi^2_{\rm IP}$ scaling	1.1	0.5
Decay-length scale	0.1	0.1
D^0–$\overline{D}^0$ 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

removing these constraints one at a time in the fit to the invariant-mass and $\log_{10}\chi^2_{\text{IP}}$ distributions. Second, the uncertainty due to the choice of a single offset parameter for the peak positions of the Bukin functions across different decay-time intervals is studied by allowing independent offsets in each decay-time interval. Third, an alternative model for the $\log_{10}\chi^2_{\text{IP}}$ distribution of the combinatorial background is obtained with the *sPlot* technique [40] using the invariant mass as the discriminating variable. Half of the largest difference between the signal yields from the alternative model fits is taken as the systematic uncertainty. The obtained systematic uncertainties on the signal yields are propagated to the measured lifetime using pseudoexperiments. In each pseudoexperiment, the yields of the signal and control modes are varied according to a Gaussian distribution whose mean is the value obtained with the default fit model and standard deviation the systematic uncertainty obtained with alternative models in the corresponding decay-time interval, and the lifetime is fit. The standard deviation of the distribution for the fitted lifetime is taken as the systematic uncertainty.

The selection efficiency of the hardware trigger is estimated in data using $\mathit{\Lambda}_c^+$ candidates from semileptonic $\mathit{\Lambda}_b^0$ decays [41]. The uncertainty due to the limited size of the calibration sample is estimated using pseudoexperiments, where the efficiency determined from the calibration sample is varied according to its uncertainty. The standard deviation of the distribution of the fitted lifetime is taken as the systematic uncertainty. The kinematic distributions of the simulated signal decays, including the transverse momentum and rapidity of the charmed hadron and the transverse momentum of final-state tracks, are weighted according to the distributions observed in data for each mode. The impact of the limited size of the data samples, which is more pronounced for the $\mathit{\Omega}_c^0$ mode, is studied with pseudoexperiments following the same procedure as described above.

Decay-time resolution in data is known to be different from simulation, although it cannot be accurately determined for the signal modes due to their limited yields in data. Nonetheless, the impact of this difference on the measured charm-hadron lifetimes largely cancels due to taking the ratio with the D^0 control mode. The residual effect is studied using pseudoexperiments and assigned as a systematic uncertainty. For these pseudoexperiments the D^0 control mode is generated with both a 30% larger and smaller decay-time resolution in the pseudo-data compared to pseudo-simulation, and the lifetime is fit. The difference between the input lifetime and the mean value of the distribution of the fitted lifetimes is taken as the systematic uncertainty.

The χ^2_{IP} variables of the final-state tracks in simulation are scaled to account for differences between data and simulation for the data-taking periods of 2017 and 2018. The scaling factor is obtained by comparing data distributions in the control mode. The uncertainty on the scaling factor is determined to be 2%, based on χ^2 comparisons of data distributions with alternate scaling factors. The difference between the default fitted lifetime and the lifetime determined with a scaling factor varied by 2% is taken as the systematic uncertainty.

The measurement of the distance between the PV and the charmed-hadron decay vertex depends on the relative longitudinal positions of the vertex locator modules of the LHCb detector with respect to the beam axis. The uncertainty on the positions of the modules is estimated using survey measurements and the track based alignment [42, 43], where the latter has the larger contribution. Its uncertainty does not cancel in the decay-time ratio and is taken as a relative systematic uncertainty of the measured lifetime.

The D^0 signal decays are reconstructed in a self-conjugate final state and D^0–$\overline{D}^0$

mixing is not considered in the χ^2 fit of the lifetime. The impact of D^0 mixing is estimated using pseudoexperiments in which the D^0 decay-time distribution is generated with mixing terms and the default χ^2 fit is performed to obtain the lifetime. The obtained difference between the input and resultant lifetime is assigned as a systematic uncertainty.

The known value of 410.1 fs [35] is assigned as D^0 lifetime in the default decay-time fit. The uncertainty on the D^0 lifetime, 1.5 fs [35], is propagated to the measured lifetime using pseudoexperiments. In each pseudoexperiment, the D^0 lifetime is varied according to its uncertainty. The standard deviation of the distribution for the fitted lifetime is taken as the systematic uncertainty.

7 Conclusion

In summary, a measurement of the lifetimes of the Ω_c^0 and Ξ_c^0 baryons is reported with Ω_c^0 and Ξ_c^0 baryons produced directly in proton–proton collisions at a centre-of-mass energy of 13 TeV, corresponding to an integrated luminosity of $5.4\,\text{fb}^{-1}$ collected by the LHCb experiment. The Ω_c^0 lifetime is measured to be

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

and the Ξ_c^0 lifetime is measured to be

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

where the first uncertainty is statistical, the second systematic, and the third due to the uncertainty of the D^0 lifetime. This result is consistent with the previous LHCb measurements of the Ω_c^0 and Ξ_c^0 lifetimes, obtained from semileptonic beauty-hadron decays [1,2], and confirms the charmed-hadron lifetime hierarchy of $\tau_{\Xi_c^+} > \tau_{\Omega_c^0} > \tau_{\Lambda_c^+} > \tau_{\Xi_c^0}$. The precision of the Ω_c^0 lifetime is improved by a factor of two compared to that of the previous result [1].

This result is independent of previous LHCb measurements [1, 2] due to the choice of independent data sample and analysis technique. Combining this measurement with previous LHCb measurements [1, 2], given that both the statistical uncertainties and the dominant systematic uncertainties are uncorrelated, results in the weighted average lifetimes of

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

The uncertainty includes both the statistical and systematic uncertainties.

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