Measurement of the Lifetime of the Doubly Charmed Baryon $\Xi_{cc}^{++}$

R. Aaij et al.*
(LHCb Collaboration)

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The first measurement of the lifetime of the doubly charmed baryon $\Xi_{cc}^{++}$ is presented, with the signal reconstructed in the final state $\Lambda_c^+ K^-\pi^+\pi^+$. The data sample used corresponds to an integrated luminosity of 1.7 fb$^{-1}$, collected by the LHCb experiment in proton-proton collisions at a center-of-mass energy of 13 TeV. The $\Xi_{cc}^{++}$ lifetime is measured to be $0.256^{+0.024}_{-0.022}$ (stat) ± 0.014 (syst) ps.

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The quark model of hadrons predicts the existence of weakly decaying baryons that contain two beauty or charm quarks, and are therefore referred to as doubly heavy baryons. Such states provide a unique system for testing models of quantum chromodynamics (QCD), the theory that describes the strong interaction. In the quark model, the doubly charmed baryon $\Xi_{cc}$ forms an isodoublet, consisting of the $\Xi_{cc}^{++}$ and $\Xi_{cc}^{+}$ baryons with quark content $ccu$ and $ccd$, respectively. Predictions for the $\Xi_{cc}^{++}$ lifetime span the range from 50 to 250 fs, while the $\Xi_{cc}^{+}$ lifetime is expected to be three to four times larger, from 200 to 1050 fs [1–10]. The predicted larger $\Xi_{cc}^{+}$ lifetime is due to the destructive Pauli interference of the charm-quark decay products and the valence (up) quark in the initial state, whereas the $\Xi_{cc}^{++}$ lifetime is shortened due to an additional contribution from $W$-exchange between the charm and down quarks [1–10]. Charge-conjugate processes are implied throughout this Letter.

The SELEX Collaboration [11,12] reported the observation of the $\Xi_{cc}^{+}$ baryon in the final states $\Lambda_c^+ K^-\pi^+$ and $pD^+K^-$, with a measured mass of $3518.7 \pm 1.7$ MeV/$c^2$. Its lifetime was found to be less than 33 fs at the 90% confidence level. However, the signal has not been confirmed in searches performed at the FOCUS [13], BABAR [14], Belle [15], and LHCb [16] experiments. Recently, the LHCb Collaboration observed a resonance in the $\Lambda_c^+ K^-\pi^+\pi^+$ mass spectrum at a mass of $3621.40 \pm 0.78$ MeV/$c^2$ [17], which is consistent with expectations for the $\Xi_{cc}^{++}$ baryon (see, e.g., Ref. [18]). The difference in masses between the two reported states, $103 \pm 2$ MeV/$c^2$, is much larger than the few MeV/$c^2$ expected by the breaking of isospin symmetry [19–21], and that is observed in all other isodoublets. While the resonance seen in the $\Lambda_c^+ K^-\pi^+\pi^+$ mass spectrum by LHCb is consistent with being the $\Xi_{cc}^{++}$ baryon, a measurement of its lifetime is critical to establish its nature. The lifetime is also a necessary ingredient for theoretical predictions of branching fractions of $\Xi_{cc}$ decays, and can offer insight into the interplay between strong and weak interactions in these decays.

This Letter reports the first measurement of the $\Xi_{cc}^{++}$ lifetime, with the $\Xi_{cc}^{++}$ baryon reconstructed through the decay chain $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^-\pi^+\pi^+$, $\Lambda_c^+ \rightarrow pK^-\pi^+\pi^+$. The data sample used, the same as in Ref. [17], corresponds to an integrated luminosity of 1.7 fb$^{-1}$, collected by the LHCb experiment in proton-proton collisions at a center-of-mass energy of 13 TeV. Since the combined reconstruction and selection efficiency varies as a function of the decay time, the decay-time distribution is measured relative to that of a control mode with similar topology and known lifetime [22,23], $\Lambda_c^0 \rightarrow \Lambda_c^+\pi^-\pi^-\pi^-$. This technique, used in a number of lifetime measurements at LHCb [22,24–31], leads to a reduced systematic uncertainty as it is only sensitive to the ratio of the decay-time acceptances.

The LHCb detector [32,33] 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 detector elements that are particularly relevant to this analysis are a silicon-strip vertex detector [34] surrounding the $pp$ interaction region that allows $c$ and $b$ hadrons to be identified from their characteristically long flight distance, a tracking system [35], placed upstream and downstream of a dipole magnet, that provides a measurement of momentum, $p_t$, of charged particles, and two ring-imaging Cherenkov detectors [36] that are able to discriminate between different species of charged hadrons. The magnetic field polarity can be reverted periodically throughout the data-taking. The online event selection is performed by a trigger [37], which consists of a hardware stage, based on information from the calorimeter and muon systems [38,39], followed by a software stage, which applies a full event reconstruction incorporating near-real-time alignment and calibration of
the detector [40]. The output of the reconstruction performed in the software trigger [41] is used as input to the present analysis.

Samples of simulated \( pp \) collisions are generated using PYTHIA [42] with a specific LHCb configuration [43]. A dedicated generator, GENXICC2.0 [44], is used to simulate the production of the \( \Xi_{cc}^{++} \) baryon. Decays of hadrons are described by EVTGEN [45], in which final-state radiation is simulated using PHOTOS [46]. The interaction of the generated particles with the detector, and its response, are implemented using the GEANT4 toolkit [47] as described in Ref. [48].

Candidate \( \Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+ \) decays are reconstructed and selected with a multivariate selector following the same procedure as in the previous analysis [17], except for two additional selection criteria. The first requires that the events are selected, at the hardware-trigger level, either by large transverse energy deposits in the calorimeter from the decay products of the \( \Xi_{cc}^{++} \) candidate or by activity in the calorimeter or muon system from particles other than the \( \Xi_{cc}^{++} \) decay products. This requirement removes events for which the efficiency cannot be determined precisely. The second is a requirement on the reconstructed decay time of the \( \Xi_{cc}^{++} \) candidates, \( t \), which must lie in the range 0.1–2.0 ps, where the lower limit on \( t \) is imposed to avoid biases from resolution effects. Candidate \( \Lambda_b^0 \to \Lambda_c^+ \pi^- \pi^- \pi^- \) decays are reconstructed and selected in exactly the same way as \( \Xi_{cc}^{++} \) decays, except that the allowed invariant-mass range is centred around the \( \Lambda_b^0 \) mass and both negatively charged \( \Lambda_b^0 \) decay products are required to be identified as pions. The same hardware and software trigger criteria are applied to both \( \Xi_{cc}^{++} \) and \( \Lambda_b^0 \) candidates.

To obtain better resolution, the invariant mass of a candidate is calculated as

\[
m = M(\Lambda_c^+ h\pi\pi) - M([pK^-\pi^+]_{\Lambda_c^+}) + M_{\text{PDG}}(\Lambda_c^+),
\]

where \( h\pi\pi \) indicates \( K^-\pi^+\pi^- (\pi^-\pi^+\pi^-) \) for \( \Xi_{cc}^{++} (\Lambda_b^0) \) candidates, \( M(\Lambda_c^+ h\pi\pi) \) is the invariant mass of the \( \Xi_{cc}^{++} \) or \( \Lambda_b^0 \) candidate, \( M([pK^-\pi^+]_{\Lambda_c^+}) \) is the invariant mass of the \( \Lambda_c^+ \) candidate, and \( M_{\text{PDG}}(\Lambda_c^+) \) is the known value of the \( \Lambda_c^+ \) mass [23]. The distributions of the mass \( m \) of selected \( \Lambda_c^+ K^-\pi^+\pi^- \) and \( \Lambda_c^+ \pi^-\pi^-\pi^- \) candidates are shown in Fig. 1. Unbinned extended maximum-likelihood fits to these distributions are performed as in Ref. [17], with the signal described by the sum of a Gaussian function and a double-sided Crystal Ball function [49], and the background parametrized by a second-order Chebyshev polynomial. The same fit models are used for both the \( \Xi_{cc}^{++} \) and \( \Lambda_b^0 \) samples, but with different resolution parameters. Signal yields of \( 304 \pm 35 \) \( \Xi_{cc}^{++} \) and \( 3397 \pm 119 \) \( \Lambda_b^0 \) decays are obtained. The small decrease in the \( \Xi_{cc}^{++} \) yield compared with the value of \( 313 \pm 33 \) reported in Ref. [17] is due to the two additional selection requirements described above.

![Graph](image)

**FIG. 1.** Invariant-mass distributions of (a) \( \Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+ \) and (b) \( \Lambda_b^0 \to \Lambda_c^+ \pi^- \pi^- \pi^- \) candidates, with fit results shown.

The decay time of \( \Xi_{cc}^{++} \) or \( \Lambda_b^0 \) candidates is computed with a kinematic fit [50] in which the momentum vector of the candidate is required to be aligned with the line joining the production and decay vertices. The decay-time resolution, determined from simulation, is 63 fs (32 fs) for the \( \Xi_{cc}^{++} (\Lambda_b^0) \) decay, which is much less than the \( \Xi_{cc}^{++} (\Lambda_b^0) \) lifetime and has negligible dependence on the decay time within the current precision. The normalized decay-time distributions of the \( \Xi_{cc}^{++} \) and \( \Lambda_b^0 \) baryons are shown in Fig. 2, where the background contributions have been subtracted according to the fit results shown in Fig. 1 using the \( sPlot \) technique [51].

The decay-time acceptance is defined as the ratio between the reconstructed and the generated decay-time distributions, and is determined with samples of simulated events containing \( \Xi_{cc}^{++} (\Lambda_b^0) \) decays, in which the \( \Xi_{cc}^{++} (\Lambda_b^0) \) lifetime is set to 0.333 ps (1.451 ps), as shown in Fig. 3. This decay-time acceptance, which is described by a histogram in this analysis, takes into account the reconstruction efficiency, as well as the bin migration effect caused by the decay-time resolution. A potential bias in the relative decay-time acceptance due to the assumed lifetimes is considered a source of systematic uncertainty. The simulated \( \Xi_{cc}^{++} \) and \( \Lambda_b^0 \) decays are weighted to match their observed transverse-momentum
distributions in data. The difference between the $\Xi^{++}_{cc}$ or $\Lambda^0_b$ decay-time acceptances is mainly due to the larger $\Lambda^0_b$ mass, which results in higher momentum of the decay products and larger opening angles in the decay. An exponential function is fitted to the background-subtracted and acceptance-corrected decay-time distribution of $\Lambda^0_b$ candidates, and a lifetime of $1.474 \pm 0.077$ ps is obtained, where the uncertainty is statistical only. This is consistent with the known value $1.470 \pm 0.010$ ps [23], and validates that the detector simulation correctly reproduces the decay-time acceptance.

The $\Xi^{++}_{cc}$ lifetime is measured by performing a weighted, unbinned maximum-likelihood fit [52] to the decay-time distribution of the selected $\Xi^{++}_{cc}$ sample. Each candidate is assigned a signal weight for background subtraction, which is computed using its invariant mass $m$ as the discriminating variable following the sPlot technique [51]. The probability density function describing the decay-time distribution of the $\Xi^{++}_{cc}$ signal candidates, denoted by $f_{\Xi^{++}_{cc}}(t)$, is defined as

$$f_{\Xi^{++}_{cc}}(t) = H_{N_0}(t) \times \frac{e_{\Xi^{++}_{cc}}(t)}{e_{\Lambda^0_b}(t)} \times \exp\left(\frac{t}{\tau(\Lambda^0_b)} - \frac{t}{\tau(\Xi^{++}_{cc})}\right),$$

where $H_{N_0}(t)$ is the background-subtracted decay-time distribution of the $\Lambda^0_b$ control channel, $e_{\Xi^{++}_{cc}}(t)$ and $e_{\Lambda^0_b}(t)$ are the decay-time acceptance distributions for the $\Xi^{++}_{cc}$ and $\Lambda^0_b$ decays, and $\tau(\Lambda^0_b) = 1.470 \pm 0.010$ ps is the known value [23] of the $\Lambda^0_b$ lifetime [22]. Here $H_{N_0}(t)$, $e_{\Xi^{++}_{cc}}(t)$, and $e_{\Lambda^0_b}(t)$ are the histograms shown in Figs. 2 and 3. The binning scheme is chosen to minimize the systematic uncertainty on the lifetime due to the finite bin width. The background-subtracted $\Xi^{++}_{cc}$ decay-time distribution is shown in Fig. 4 with the fit result superimposed. The only free parameter of the fit is the $\Xi^{++}_{cc}$ lifetime, which is measured to be $\tau(\Xi^{++}_{cc}) = 0.256^{+0.024}_{-0.022}$ ps. Here the uncertainties are statistical only, and include contributions due to the limited sizes of the simulated samples (0.007 ps) and of the $\Lambda^0_b$ sample (0.006 ps). These contributions are estimated with a bootstrapping method [53], where candidates are randomly selected from the original simulated or $\Lambda^0_b$ samples to form statistically independent samples of pseudodata. The standard deviations of the lifetime measurements obtained in these samples are then taken as the corresponding statistical uncertainty.

Sources of systematic uncertainty on the $\Xi^{++}_{cc}$ lifetime are summarized in Table I and described below. The effects of the choice of signal and background models are studied by using alternative mass shapes, namely a sum of two Gaussian functions for signal and an exponential function for background. The change in the measured lifetime, 0.005 ps, is assigned as a systematic uncertainty. In the baseline fit, the signal and background mass shapes are assumed to be independent of the decay time. The effect of this assumption is investigated by fitting the invariant-mass distribution of the $\Xi^{++}_{cc}$ and $\Lambda^0_b$ samples in four independent intervals of decay time and recalculating the signal weights.

![FIG. 2. Background-subtracted decay-time distributions of (dots) $\Xi^{++}_{cc} \rightarrow \Lambda^{++}_{cc} K^- \pi^+ \pi^+$ and (triangles) $\Lambda^0_b \rightarrow \Lambda^+_b \pi^- \pi^+ \pi^-$ candidates after the selection, not corrected for decay-time acceptance.](image)

![FIG. 3. Decay-time acceptances for (dots) $\Xi^{++}_{cc} \rightarrow \Lambda^{++}_{cc} K^- \pi^+ \pi^+$ and (triangles) $\Lambda^0_b \rightarrow \Lambda^+_b \pi^- \pi^+ \pi^-$ decays.](image)

![FIG. 4. Background-subtracted decay-time distribution of selected $\Xi^{++}_{cc} \rightarrow \Lambda^{++}_{cc} K^- \pi^+ \pi^+$ candidates. The rate-averaged fit result across each decay-time bin is shown as the continuous line.](image)
The input lifetime used in the simulation for the measured lifetime, 0.002 ps, is taken as a systematic uncertainty. The measurement is repeated and the change in the measurement is applied to the data with a higher (uniform) threshold. In influence of this difference, the hardware trigger requirement is not fully described by the simulation. To investigate the hardware trigger varied during data taking, and this variation is assessed as a systematic uncertainty. The result of the difference, the simulation is weighted to match the distributions seen in data. The resulting systematic uncertainty. The simulated between the result from this procedure and the original decay-time acceptance is recomputed. The difference weighted to match this output distribution in data and the total systematic uncertainty on the measured \( \Xi^{++}_{cc} \) lifetime is found to be 0.014 ps.

In summary, the \( \Xi^{++}_{cc} \) lifetime is measured using a data sample corresponding to an integrated luminosity of 1.7 fb\(^{-1}\), collected by the LHCb experiment in \( pp \) collisions at a center-of-mass energy of 13 TeV, and is found to be

\[
\tau(\Xi^{++}_{cc}) = 0.256^{+0.024}_{-0.022} \text{(stat)} \pm 0.014 \text{(syst)} \text{ ps}.
\]

This is the first measurement of the \( \Xi^{++}_{cc} \) lifetime, which establishes the weakly decaying nature of the recently discovered \( \Xi^{++}_{cc} \) state. The result favors smaller values in the range of the theoretical predictions [1–10]. If the lifetime of the isospin partner state \( \Xi^{+}_{cc} \) is shorter by a factor of 3 to 4 as predicted [1–10], it would be roughly 60–90 ps. This provides important information to guide the search for the \( \Xi^{+}_{cc} \) state at the Large Hadron Collider.

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<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty (ps)</th>
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<tbody>
<tr>
<td>Signal and background mass models</td>
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<td>Correlation of mass and decay time</td>
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<td>Binning</td>
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<td>Data-simulation differences</td>
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<tr>
<td>Resonant structure of decays</td>
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<tr>
<td>Hardware trigger threshold</td>
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<tr>
<td>Simulated ( \Xi^{++}_{cc} ) lifetime</td>
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<tr>
<td>( \Lambda^{0}_{b} ) lifetime uncertainty</td>
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<tr>
<td>Sum in quadrature</td>
<td>0.014</td>
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71National Research Tomsk Polytechnic University, Tomsk, Russia
[associated with Institute of Theoretical and Experimental Physics (ITEP), Moscow, Russia]
72Instituto de Fisica Corpuscular, Centro Mixto Universidad de Valencia-CSIC, Valencia, Spain
[associated with ICCUB, Universitat de Barcelona, Barcelona, Spain]
73University of Michigan, Ann Arbor, USA [associated with Syracuse University, Syracuse, New York, USA]
74Los Alamos National Laboratory (LANL), Los Alamos, New Mexico, USA
[associated with Syracuse University, Syracuse, New York, USA]

Also at Università di Ferrara, Ferrara, Italy.
Also at Laboratoire Leprince-Ringuet, Palaiseau, France.
Also at Università di Milano Bicocca, Milano, Italy.
Also at Università di Modena e Reggio Emilia, Modena, Italy.
Also at Novosibirsk State University, Novosibirsk, Russia.
Also at LIFAEELS, La Salle, Universitat Ramon Llull, Barcelona, Spain.
Also at Università di Bologna, Bologna, Italy.
Also at Università di Genova, Genova, Italy.
Also at Università di Pisa, Pisa, Italy.
Also at Università di Bari, Bari, Italy.
Also at Sezione INFN di Trieste, Trieste, Italy.
Also at Università degli Studi di Milano, Milano, Italy.
Also at Universidade Federal do Triângulo Mineiro (UFTM), Uberaba-MG, Brazil.
Also at AGH - University of Science and Technology, Faculty of Computer Science, Electronics and Telecommunications, Kraków, Poland.
Also at Università di Padova, Padova, Italy.
Also at Università di Cagliari, Cagliari, Italy.
Also at MSU - Iligan Institute of Technology (MSU-IIT), Iligan, Philippines.
Also at Escuela Agrícola Panamericana, San Antonio de Oriente, Honduras.
Also at Scuola Normale Superiore, Pisa, Italy.
Also at Hanoi University of Science, Hanoi, Vietnam.
Also at P.N. Lebedev Physical Institute, Russian Academy of Science (LPI RAS), Moscow, Russia.
Also at National Research University Higher School of Economics, Moscow, Russia.
Also at Università di Roma Tor Vergata, Roma, Italy.
Also at Università di Roma La Sapienza, Roma, Italy.
Also at Università della Basilicata, Potenza, Italy.
Also at Università di Urbino, Urbino, Italy.
Also at Physics and Micro Electronic College, Hunan University, Changsha City, China.
Also at School of Physics and Information Technology, Shaanxi Normal University (SNNU), Xi’an, China.