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Editors' Suggestion

Measurement of the Lifetime of the Doubly Charmed Baryon Ξ_{cc}^{++}

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The first measurement of the lifetime of the doubly charmed baryon Ξ_{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 Ξ_{cc}^{++} lifetime is measured to be $0.256^{+0.024}_{-0.022}(\mathrm{stat}) \pm 0.014(\mathrm{syst})$ 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 Ξ_{cc} forms an isodoublet, consisting of the Ξ_{cc}^{++} and Ξ_{cc}^{+} baryons with quark content ccu and ccd, respectively. Predictions for the Ξ_{cc}^{+} lifetime span the range from 50 to 250 fs, while the Ξ_{cc}^{++} lifetime is expected to be three to four times larger, from 200 to 1050 fs [1–10]. The predicted larger Ξ_{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 Ξ_{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 Ξ_{cc}^{+} baryon in the final states $\Lambda_c^+ K^- \pi^+$ and pD^+K^-, with a measured mass of $3518.7 \pm 1.7\ \mathrm{MeV}/c^2$. 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 $3621.40 \pm 0.78\ \mathrm{MeV}/c^2$ [17], which is consistent with expectations for the Ξ_{cc}^{++} baryon (see, e.g., Ref. [18]). The difference in masses between the two reported states, $103 \pm 2\ \mathrm{MeV}/c^2$, 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 Ξ_{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 Ξ_{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 Ξ_{cc}^{++} lifetime, with the Ξ_{cc}^{++} baryon reconstructed through the decay chain $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$, $\Lambda_c^+ \to pK^-\pi^+$. 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], $\Lambda_b^0 \to \Lambda_c^+ \pi^- \pi^+ \pi^-$. 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, 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

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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 Ξ_{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 used 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 Ξ_{cc}^{++} candidate or by activity in the calorimeter or muon system from particles other than the Ξ_{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 Ξ_{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 Ξ_{cc}^{++} decays, except that the allowed invariant-mass range is centred around the Λ_b^0 mass and both negatively charged Λ_b^0 decay products are required to be identified as pions. The same hardware and software trigger criteria are applied to both Ξ_{cc}^{++} and Λ_b^0 candidates.

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

$$m = M(\Lambda_c^+ h\pi\pi) - M([pK^-\pi^+]_{\Lambda_c^+}) + M_{\rm PDG}(\Lambda_c^+), \quad (1)$$

where $h\pi\pi$ indicates $K^-\pi^+\pi^+$ ($\pi^-\pi^+\pi^-$) for Ξ_{cc}^{++} (Λ_b^0) candidates, $M(\Lambda_c^+ h\pi\pi)$ is the invariant mass of the Ξ_{cc}^{++} or Λ_b^0 candidate, $M([pK^-\pi^+]_{\Lambda_c^+})$ is the invariant mass of the Λ_c^+ candidate, and $M_{\rm PDG}(\Lambda_c^+)$ is the known value of the Λ_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 Ξ_{cc}^{++} and Λ_b^0 samples, but with different resolution parameters. Signal yields of 304 ± 35 Ξ_{cc}^{++} and 3397 ± 119 Λ_b^0 decays are obtained. The small decrease in the Ξ_{cc}^{++} yield compared with the value of 313 ± 33 reported in Ref. [17] is due to the two additional selection requirements described above.

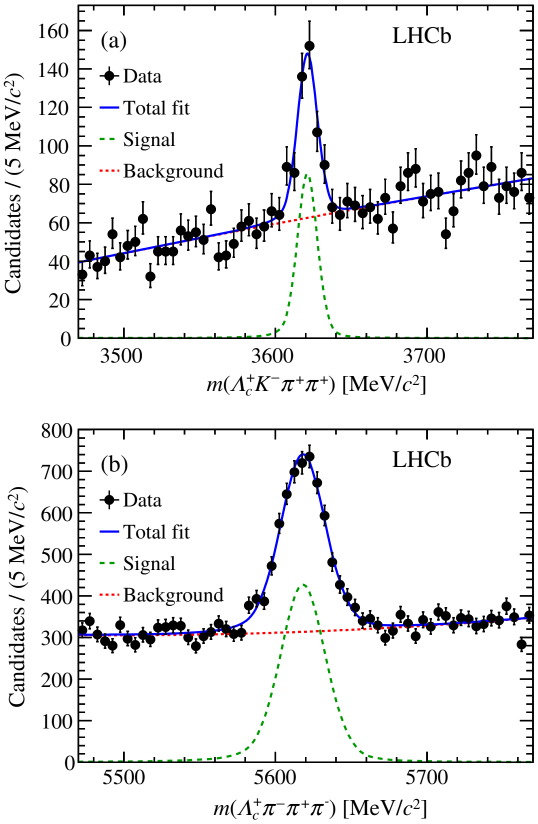

FIG. 1. Invariant-mass distributions of (a) $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ and (b) $\Lambda_b^0 \to \Lambda_c^+ \pi^- \pi^+ \pi^-$ candidates, with fit results shown.

The decay time of Ξ_{cc}^{++} or Λ_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 Ξ_{cc}^{++} (Λ_b^0) decay, which is much less than the Ξ_{cc}^{++} (Λ_b^0) lifetime and has negligible dependence on the decay time within the current precision. The normalized decay-time distributions of the Ξ_{cc}^{++} and Λ_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 Ξ_{cc}^{++} (Λ_b^0) decays, in which the Ξ_{cc}^{++} (Λ_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 Ξ_{cc}^{++} and Λ_b^0 decays are weighted to match their observed transverse-momentum

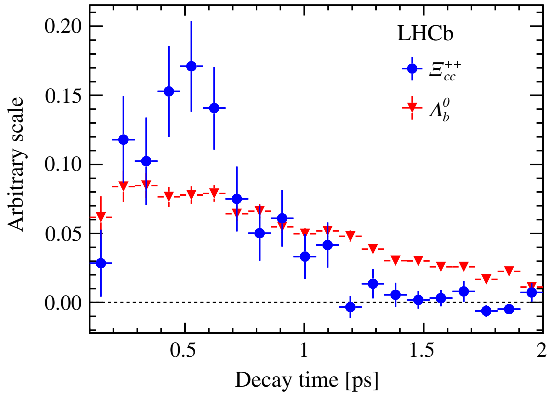

FIG. 2. Background-subtracted decay-time distributions of (dots) $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ and (triangles) $\Lambda_b^0 \to \Lambda_c^+ \pi^- \pi^+ \pi^-$ candidates after the selection, not corrected for decay-time acceptance.

distributions in data. The difference between the Ξ_{cc}^{++} or Λ_b^0 decay-time acceptances is mainly due to the larger Λ_b^0 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 Λ_b^0 candidates, and a lifetime of 1.474 ± 0.077 ps is obtained, where the uncertainty is statistical only. This is consistent with the known value 1.470 ± 0.010 ps [23], and validates that the detector simulation correctly reproduces the decay-time acceptance.

The Ξ_{cc}^{++} lifetime is measured by performing a weighted, unbinned maximum-likelihood fit [52] to the decay-time distribution of the selected Ξ_{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 Ξ_{cc}^{++} signal candidates, denoted by $f_{\Xi_{cc}^{++}}(t)$, is defined as

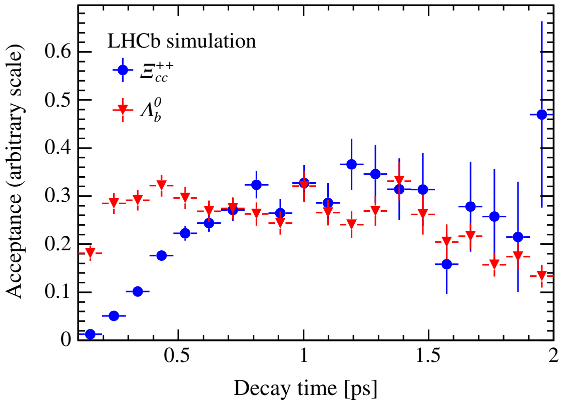

FIG. 3. Decay-time acceptances for (dots) $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ and (triangles) $\Lambda_b^0 \to \Lambda_c^+ \pi^- \pi^+ \pi^-$ decays.

$$f_{\Xi_{cc}^{++}}(t) = H_{\Lambda_b^0}(t) \times \frac{\epsilon_{\Xi_{cc}^{++}}(t)}{\epsilon_{\Lambda_b^0}(t)} \times \exp\left(\frac{t}{\tau(\Lambda_b^0)} - \frac{t}{\tau(\Xi_{cc}^{++})}\right), \quad (2)$$

where $H_{\Lambda_b^0}(t)$ is the background-subtracted decay-time distribution of the Λ_b^0 control channel, $\epsilon_{\Xi_{cc}^{++}}(t)$ and $\epsilon_{\Lambda_b^0}(t)$ are the decay-time acceptance distributions for the Ξ_{cc}^{++} and Λ_b^0 decays, and $\tau(\Lambda_b^0) = 1.470 \pm 0.010$ ps is the known value [23] of the Λ_b^0 lifetime [22]. Here $H_{\Lambda_b^0}(t)$, $\epsilon_{\Xi_{cc}^{++}}(t)$, and $\epsilon_{\Lambda_b^0}(t)$ 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 Ξ_{cc}^{++} decay-time distribution is shown in Fig. 4 with the fit result superimposed. The only free parameter of the fit is the Ξ_{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 Λ_b^0 sample (0.006 ps). These contributions are estimated with a bootstrapping method [53], where candidates are randomly selected from the original simulated or Λ_b^0 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 Ξ_{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 Ξ_{cc}^{++} and Λ_b^0 samples in four independent intervals of decay time and recalculating the signal weights

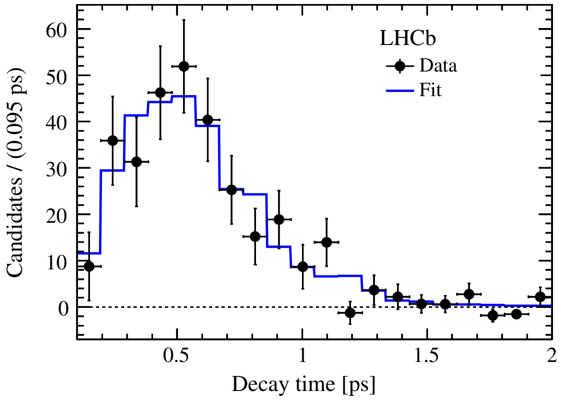

FIG. 4. Background-subtracted decay-time distribution of selected $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ candidates. The rate-averaged fit result across each decay-time bin is shown as the continuous line.

TABLE I. Summary of systematic uncertainties.

Source	Uncertainty (ps)
Signal and background mass models	0.005
Correlation of mass and decay time	0.004
Binning	0.001
Data-simulation differences	0.004
Resonant structure of decays	0.011
Hardware trigger threshold	0.002
Simulated Ξ_{cc}^{++} lifetime	0.002
Λ_b^0 lifetime uncertainty	0.001
Sum in quadrature	0.014

based on these fit results. Using these weights in the fit, the Ξ_{cc}^{++} lifetime changes by 0.004 ps, which is taken as the systematic uncertainty due to the correlation between the mass and decay time. It is found that the measured lifetime depends slightly upon the binning scheme. With the nominal binning, a difference of 0.001 ps with respect to the input lifetime is measured, which is taken as a systematic uncertainty.

The kinematic distributions of the Ξ_{cc}^{++} and Λ_b^0 signals in the simulation are generally found to be in good agreement with those in data. However, some differences are observed in the output distribution of the multivariate selector. To assess the impact of such differences, the simulation is weighted to match this output distribution in data and the decay-time acceptance is recomputed. The difference between the result from this procedure and the original one is 0.004 ps, which is assigned as the corresponding systematic uncertainty. The simulated $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ and $\Lambda_b^0 \to \Lambda_c^+ \pi^- \pi^+ \pi^-$ samples are generated assuming that the decay products are distributed uniformly across the available phase space. The possible effect of intermediate resonances is evaluated by weighting the simulated invariant mass distributions of the three hadrons, i.e., $M(K^- \pi^+ \pi^+)$ for Ξ_{cc}^{++} and $M(\pi^- \pi^+ \pi^-)$ for Λ_b^0 candidates, to match the distributions seen in data. The resulting difference in the measured lifetime, 0.011 ps, is assigned as a systematic uncertainty.

The transverse-energy threshold in the calorimeter hardware trigger varied during data taking, and this variation is not fully described by the simulation. To investigate the influence of this difference, the hardware trigger requirement is applied to the data with a higher (uniform) threshold. The measurement is repeated and the change in the measured lifetime, 0.002 ps, is taken as a systematic uncertainty. The input lifetime used in the simulation for the Ξ_{cc}^{++} baryon is 0.333 ps. The simulated events are weighted to be distributed according to the measured lifetime and the decay-time acceptance is recomputed. The resulting difference in the measured lifetime, 0.002 ps, is taken as a systematic uncertainty. The Λ_b^0 lifetime is precisely known [22,23]. An alternative fit in which $\tau(\Lambda_b^0)$ is allowed to vary within its uncertainty leads to a change in the measured Ξ_{cc}^{++} lifetime of less than 0.001 ps, which is assigned as a systematic uncertainty.

Other systematic effects, including the threshold applied to the multivariate selector, the decay-time resolution, and the uncertainty on the length scale of the vertex detector, are studied and found to be negligible; no systematic uncertainties are assigned for these effects. As further checks, the measured lifetime is compared between subsets of the data, including Ξ_{cc}^{++} versus $\bar{\Xi}_{cc}^{--}$, opposite LHCb magnet polarities, and different numbers of primary vertices, and is found to be stable. A separate measurement carried out with an alternative method, in which both the Ξ_{cc}^{++} and Λ_b^0 decay-time distributions are binned, gives a consistent result. All sources of systematic uncertainty, listed in Table I, are added in quadrature, and the total systematic uncertainty on the measured Ξ_{cc}^{++} lifetime is found to be 0.014 ps.

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

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