



# Search for the doubly charmed baryon $\Xi_{cc}^+$

LHCb collaboration<sup>†</sup>

## Abstract

A search for the doubly charmed baryon  $\Xi_{cc}^+$  is performed through its decay to the  $\Lambda_c^+ K^- \pi^+$  final state, using proton-proton collision data collected with the LHCb detector at centre-of-mass energies of 7, 8 and 13 TeV. The data correspond to a total integrated luminosity of  $9 \text{ fb}^{-1}$ . No significant signal is observed in the mass range from 3.4 to  $3.8 \text{ GeV}/c^2$ . Upper limits are set at 95% credibility level on the ratio of the  $\Xi_{cc}^+$  production cross-section times the branching fraction to that of  $\Lambda_c^+$  and  $\Xi_{cc}^{++}$  baryons. The limits are determined as functions of the  $\Xi_{cc}^+$  mass for different lifetime hypotheses, in the rapidity range from 2.0 to 4.5 and the transverse momentum range from 4 to  $15 \text{ GeV}/c$ .

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# 1 Introduction

The constituent quark model [1, 2] predicts the existence of weakly decaying doubly charmed baryons with spin-parity  $J^P = 1/2^+$ . These include one isospin doublet  $\Xi_{cc}$  ( $\Xi_{cc}^+ = ccd$  and  $\Xi_{cc}^{++} = ccu$ ), and one isospin singlet  $\Omega_{cc}$  ( $\Omega_{cc}^+ = ccs$ ). The masses of the two  $\Xi_{cc}$  states are predicted to be in the range from 3500 to 3700 MeV/ $c^2$  [3–27], with an isospin splitting of a few MeV/ $c^2$  [28–30]. Predictions of the  $\Xi_{cc}^+$  lifetime span the range of 50 to 250 fs, while the  $\Xi_{cc}^{++}$  lifetime is predicted to be three to four times larger due to the  $W$ -exchange contribution in the  $\Xi_{cc}^+$  decay and the destructive Pauli interference in the  $\Xi_{cc}^{++}$  decay [4, 8, 9, 20, 31–36].

Doubly charmed baryons have been searched for by several experiments in the past decades. The SELEX collaboration reported the observation of the  $\Xi_{cc}^+$  baryon decaying into  $\Lambda_c^+ K^- \pi^+$  and  $p D^+ K^-$  final states [37, 38], using a 600 GeV/ $c$  charged hyperon beam impinging on a fixed target. The mass of the  $\Xi_{cc}^+$  baryon, averaged over the two decay modes, was found to be  $3518.7 \pm 1.7$  MeV/ $c^2$ . The lifetime was measured to be less than 33 fs at 90% confidence level. It was estimated that about 20% of  $\Lambda_c^+$  baryons in the SELEX experiment were produced from  $\Xi_{cc}^+$  decays [37]. Searches in different production environments by the FOCUS [39], BaBar [40], LHCb [41] and Belle [42] experiments did not confirm the SELEX results. Recently, the  $\Xi_{cc}^{++}$  baryon was observed by the LHCb experiment in the  $\Lambda_c^+ K^- \pi^+ \pi^+$  final state [43], and confirmed in the  $\Xi_c^+ \pi^+$  final state [44]. The weighted average of the  $\Xi_{cc}^{++}$  mass of the two decay modes was determined to be  $3621.24 \pm 0.65$  (stat)  $\pm 0.31$  (syst) MeV/ $c^2$  [44], which is about 100 MeV/ $c^2$  higher than the mass of the  $\Xi_{cc}^+$  baryon reported by SELEX. The lifetime of the  $\Xi_{cc}^{++}$  baryon was measured to be  $0.256_{-0.022}^{+0.024}$  (stat)  $\pm 0.014$  (syst) ps [45], which establishes its weakly decaying nature. The  $\Xi_{cc}^{++} \rightarrow D^+ p K^- \pi^+$  decay has been searched for by the LHCb collaboration with a data sample corresponding to an integrated luminosity of  $1.7 \text{ fb}^{-1}$ , but no signal was found [46].

This paper presents the result of a search for the  $\Xi_{cc}^+$  baryon in the mass range from 3400 to 3800 MeV/ $c^2$ , where the  $\Xi_{cc}^+$  baryon is reconstructed through the  $\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+$ ,  $\Lambda_c^+ \rightarrow p K^- \pi^+$  decay chain. The inclusion of charge-conjugate decay processes is implied throughout this paper. The data set comprises  $pp$  collision data recorded with the LHCb detector at centre-of-mass energies  $\sqrt{s} = 7$  TeV in 2011,  $\sqrt{s} = 8$  TeV in 2012 and  $\sqrt{s} = 13$  TeV in 2015–2018, corresponding to an integrated luminosity of  $1.1 \text{ fb}^{-1}$ ,  $2.1 \text{ fb}^{-1}$  and  $5.9 \text{ fb}^{-1}$ , respectively. This data sample is about ten times larger than that of the previous  $\Xi_{cc}^+$  search by the LHCb collaboration using only 2011 data [41].

The search was performed with the whole analysis procedure defined before inspecting the data in the 3400 to 3800 MeV/ $c^2$  mass range. The analysis strategy is defined as follows: first a search for a  $\Xi_{cc}^+$  signal is performed and the significance of the signal as a function of the  $\Xi_{cc}^+$  mass is evaluated; then if the global significance, after considering the look-elsewhere effect, is above 3 standard deviations, the  $\Xi_{cc}^+$  mass is measured; otherwise, upper limits are set on the production rates for different centre-of-mass energies. Two sets of selections, with different multivariate classifiers and trigger requirements, denoted as Selection A and Selection B, are used in these two cases. Selection A is used in the signal search and is designed to maximise its sensitivity. Selection B is optimised for setting upper limits on the ratio of the  $\Xi_{cc}^+$  production rate to that of  $\Xi_{cc}^{++}$  and  $\Lambda_c^+$  baryons. It uses the same selection for  $\Lambda_c^+$  baryons from  $\Xi_{cc}$  decays and prompt  $\Lambda_c^+$  baryons in order to have better control over sources of systematic uncertainty on the ratio. For the limit

setting, only the data recorded at  $\sqrt{s} = 8$  TeV in 2012 and at  $\sqrt{s} = 13$  TeV in 2016–2018 is used. The 2015 data is excluded because there were significant variations in trigger thresholds during this data-taking period, and because this sample only accounts for 6% of the  $pp$  collision data at  $\sqrt{s} = 13$  TeV. The production ratio,  $\mathcal{R}$ , is defined as

$$\mathcal{R}(\Lambda_c^+) \equiv \frac{\sigma(\Xi_{cc}^+) \times \mathcal{B}(\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+)}{\sigma(\Lambda_c^+)} \quad (1)$$

relative to the prompt  $\Lambda_c^+$  baryons decaying to  $pK^- \pi^+$ , and

$$\mathcal{R}(\Xi_{cc}^{++}) \equiv \frac{\sigma(\Xi_{cc}^+) \times \mathcal{B}(\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+)}{\sigma(\Xi_{cc}^{++}) \times \mathcal{B}(\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+)} \quad (2)$$

relative to the  $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$  decay, where  $\sigma$  is the production cross-section and  $\mathcal{B}$  is the decay branching fraction. The determination of the ratio  $\mathcal{R}(\Lambda_c^+)$  allows a direct comparison with previous experiments, while that of  $\mathcal{R}(\Xi_{cc}^{++})$  provides information about the ratio of the branching fractions of the  $\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+$  and  $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$  decays assuming that the members of the isospin doublet have a similar production cross-section [9, 47, 48]. The production ratios are evaluated as

$$\mathcal{R} = \frac{\varepsilon_{\text{norm}}}{\varepsilon_{\text{sig}}} \frac{N_{\text{sig}}}{N_{\text{norm}}} \equiv \alpha N_{\text{sig}}, \quad (3)$$

where  $\varepsilon_{\text{sig}}$  and  $\varepsilon_{\text{norm}}$  refer to the selection efficiencies of the  $\Xi_{cc}^+$  signal decay mode and the  $\Lambda_c^+$  or  $\Xi_{cc}^{++}$  normalisation decay modes respectively,  $N_{\text{sig}}$  and  $N_{\text{norm}}$  are the corresponding yields, and  $\alpha$  is the single-event sensitivity. Because the  $\Xi_{cc}^+$  selection efficiency depends strongly on the lifetime, limits on  $\mathcal{R}(\Lambda_c^+)$  and  $\mathcal{R}(\Xi_{cc}^{++})$  are quoted as functions of the  $\Xi_{cc}^+$  signal mass for a discrete set of lifetime hypotheses.

## 2 Detector and simulation

The LHCb detector [49, 50] 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 includes a high-precision tracking system consisting of a silicon-strip vertex detector surrounding the  $pp$  interaction region [51], a large-area silicon-strip detector located upstream of a dipole magnet with a bending power of about 4 Tm, and three stations of silicon-strip detectors and straw drift tubes [52, 53] placed downstream of the magnet. 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 GeV/ $c$ . The minimum distance of a track to a primary vertex (PV), the impact parameter (IP), is measured with a resolution of  $(15 + 29/p_T)$   $\mu\text{m}$ , where  $p_T$  is the component of the momentum transverse to the beam, in GeV/ $c$ . Different types of charged hadrons are distinguished using information from two ring-imaging Cherenkov detectors [54]. The online event selection is performed by a trigger [55], which consists of a hardware stage, based on information from the calorimeter and muon systems, followed by a software stage, which applies a full event reconstruction.

Simulated samples are required to develop the event selection and to estimate the efficiency of the detector acceptance and the imposed selection requirements. Simulated

$pp$  collisions are generated using PYTHIA [56] with a specific LHCb configuration [57]. A dedicated generator, GENXICC2.0 [58], is used to simulate the  $\Xi_{cc}$  baryon production. Decays of unstable particles are described by EVTGEN [59], in which final-state radiation is generated using PHOTOS [60]. The interaction of the generated particles with the detector, and its response, are implemented using the GEANT4 toolkit [61] as described in Ref. [62]. Unless otherwise stated, simulated events are generated with a  $\Xi_{cc}$  mass of  $3621 \text{ MeV}/c^2$  and a  $\Xi_{cc}^+$  ( $\Xi_{cc}^{++}$ ) lifetime of 80 fs (256 fs).

### 3 Reconstruction and selection

For the  $\Xi_{cc}^+$  signal and each of the normalisation modes,  $\Lambda_c^+$  candidates are reconstructed in the  $pK^-\pi^+$  final state. At least one of the three  $\Lambda_c^+$  decay products is required to pass an inclusive software trigger, which requires that a track with associated large transverse momentum is inconsistent with originating from any PV. For data recorded at  $\sqrt{s} = 13 \text{ TeV}$ , at least one of the three  $\Lambda_c^+$  decay products is required to pass a multivariate selection applied at the software trigger level [63, 64]. The  $\chi_{\text{IP}}^2$  is defined as the difference in  $\chi^2$  of the PV fit with and without the particle in question. The PV of any single particle is defined to be that with respect to which the particle has the smallest  $\chi_{\text{IP}}^2$ . Candidate  $\Lambda_c^+$  baryons are formed from the combination of three tracks of good quality that do not originate from any PV and have large transverse momentum. Particle identification (PID) requirements are imposed on all three tracks to suppress combinatorial background and misidentified charm-meson decays. The  $\Lambda_c^+$  candidates are also required to have a mass in the range from 2211 to  $2362 \text{ MeV}/c^2$ .

The  $\Xi_{cc}^+$  candidates are reconstructed by combining a  $\Lambda_c^+$  candidate with two tracks, identified as  $K^-$  and  $\pi^+$  mesons using PID information. The kaon and pion tracks are required to have a large transverse momentum and a good track quality. To suppress duplicate tracks, the angle between each pair of the five final-state tracks with the same charge is required to be larger than 0.5 mrad. The  $\Xi_{cc}^+$  candidate is required to have  $p_{\text{T}} > 4 \text{ GeV}/c$  and to originate from a PV. Similar requirements are imposed to reconstruct the  $\Xi_{cc}^{++}$  candidates in the  $\Xi_{cc}^{++}$  normalisation mode, with an additional charged pion in the final state.

Multivariate classifiers based on the gradient boosted decision tree (BDTG) [65, 66] are developed to further improve the signal purity. To train the classifier, simulated  $\Xi_{cc}^+$  events are used as the signal sample and wrong-sign (WS)  $\Lambda_c^+ K^- \pi^-$  combinations selected from the data sample are used as the background sample. For Selection A, the classifier is trained using candidates with a  $\Lambda_c^+$  mass in the window of 2270 to  $2306 \text{ MeV}/c^2$  (corresponding to  $\pm 3$  times the resolution on the  $\Lambda_c^+$  mass) and a  $\Xi_{cc}^+$  mass in the signal search region. Eighteen input variables that show good discrimination for  $\Xi_{cc}^+$  and intermediate  $\Lambda_c^+$  candidates between signal and background samples are used in the training. These variables can be subdivided into two sets; in the choice of the first set of variables, no strong assumptions are made about the source of the  $\Lambda_c^+$  candidates, while for the second set of variables the properties of the  $\Xi_{cc}^+$  candidates as the source of the  $\Lambda_c^+$  candidates are exploited. The first set of variables are: the  $\chi^2$  per degree of freedom of the  $\Lambda_c^+$  vertex fit; the  $p_{\text{T}}$  of the  $\Lambda_c^+$  candidate and of its decay products; and the flight-distance  $\chi^2$  between the PV and the decay vertex of the  $\Lambda_c^+$  candidate. The second set of variables are: the  $\chi^2$  per degree of freedom of the  $\Xi_{cc}^+$  vertex fit and of the kinematic refit [67] of the

decay chain requiring  $\Xi_{cc}^+$  to originate from its PV; the largest distance of closest approach (DOCA) between the decay products of the  $\Xi_{cc}^+$  candidate; the  $p_T$  of the  $\Xi_{cc}^+$  candidate, and of the kaon and pion from the  $\Xi_{cc}^+$  decay; the  $\chi_{IP}^2$  of the  $\Xi_{cc}^+$  and  $\Lambda_c^+$  candidates, and of the  $K^-$  and  $\pi^+$  mesons from the  $\Xi_{cc}^+$  decay; the angle between the momentum and displacement vector of the  $\Xi_{cc}^+$  candidate; and the flight-distance  $\chi^2$  between the PV and the decay vertex of the  $\Xi_{cc}^+$  candidate. For Selection B, the multivariate selection comprises two stages. In the first stage, one classifier is trained with  $\Lambda_c^+$  signal in the simulated  $\Xi_{cc}^+$  sample and background candidates in the  $\Lambda_c^+$  mass sideband, and is applied to both the signal mode and the  $\Lambda_c^+$  normalisation mode. The same input variables are used as for the first set of variables in Selection A, with four additional variables that enhance the discriminating power: the largest DOCA between the decay products of the  $\Lambda_c^+$  candidate and the  $\chi_{IP}^2$  of the decay products of the  $\Lambda_c^+$  candidate. In the second stage, another classifier is trained for the signal mode using candidates in the mass window of the intermediate  $\Lambda_c^+$  and the  $\Xi_{cc}^+$  signal search region. Candidates used in the training are also required to pass a BDTG response threshold of the first classifier. The input variables are those from the second set of Selection A with an additional variable, the angle between the momentum and displacement vector of the  $\Lambda_c^+$  candidate.

The thresholds of the BDTG responses for both Selection A and B are determined by maximising the expected value of the figure of merit  $\varepsilon / (\frac{5}{2} + \sqrt{N_B})$  [68], where  $\varepsilon$  is the estimated signal efficiency, 5/2 corresponds to 5 standard deviations in a Gaussian significance test, and  $N_B$  the expected number of background candidates under the signal peak. The quantity  $N_B$  is estimated with the WS control sample in the mass region of  $\pm 12.5 \text{ MeV}/c^2$  around the known  $\Xi_{cc}^{++}$  mass [69], taking into account the difference of the background level for the signal sample and the WS control sample. The performance of the BDTG classifier is tested and found to be stable against the  $\Xi_{cc}^+$  lifetimes in the range from 40 to 120 fs. Following the same procedure, a two-stage multivariate selection is developed for the  $\Xi_{cc}^{++}$  normalisation mode.

Events that pass the multivariate selection may contain more than one  $\Xi_{cc}^+$  candidate in the search region although the probability to produce more than one  $\Xi_{cc}^+$  is small. According to studies of simulated decays and the WS control sample, multiple candidates in the same event do not form a peaking background except for one case in which the candidates are obtained from the same five final-state tracks, but with two tracks interchanged (e.g. the  $K^-$  from the  $\Lambda_c^+$  decay and the  $K^-$  from the  $\Xi_{cc}^+$  decay). In this case, only one candidate is chosen randomly.

For Selection B, an additional hardware trigger requirement is imposed on candidates of both the signal and the normalisation mode to minimise systematic differences in efficiency between the modes. This hardware trigger requirement selects candidates in which at least one of the three  $\Lambda_c^+$  decay products deposits high transverse energy in the calorimeters. Finally,  $\Xi_{cc}^+$  baryon candidates in the signal mode and  $\Lambda_c^+$  and  $\Xi_{cc}^{++}$  baryons in the normalisation modes are required to be reconstructed in the fiducial region of rapidity  $2.0 < y < 4.5$  and transverse momentum  $4 < p_T < 15 \text{ GeV}/c$ .

## 4 Yield measurements

Selection A described above is applied to the full data sample. Figure 1 shows the  $M([pK^-\pi^+]_{\Lambda_c^+})$  and  $m(\Lambda_c^+ K^-\pi^+)$  distributions in the  $\Lambda_c^+$  mass range from  $2270 \text{ MeV}/c^2$

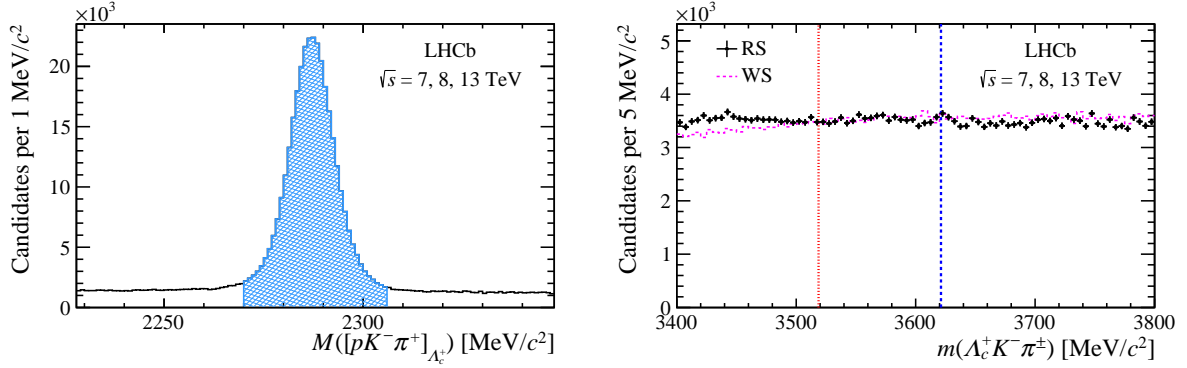


Figure 1: Mass distributions of the (left) intermediate  $\Lambda_c^+$  and (right)  $\Xi_{cc}^+$  candidates for the full data sample. Selection A is applied, including the  $\Lambda_c^+$  mass requirement, indicated by the cross-hatched region in the left plot, of  $2270 \text{ MeV}/c^2 < M([pK^- \pi^+]_{\Lambda_c^+}) < 2306 \text{ MeV}/c^2$ . The right-sign (RS)  $m(\Lambda_c^+ K^- \pi^+)$  distribution is shown in the right plot, along with the wrong-sign (WS)  $m(\Lambda_c^+ K^- \pi^-)$  distribution normalised to have the same area. The dotted red line at  $3518.7 \text{ MeV}/c^2$  indicates the mass of the  $\Xi_{cc}^+$  baryon reported by SELEX [38] and the dashed blue line at  $3621.2 \text{ MeV}/c^2$  indicates the mass of the isospin partner, the  $\Xi_{cc}^{++}$  baryon [44].

to  $2306 \text{ MeV}/c^2$ . The quantity  $m(\Lambda_c^+ K^- \pi^+)$  is defined as

$$m(\Lambda_c^+ K^- \pi^+) \equiv M([pK^- \pi^+]_{\Lambda_c^+} K^- \pi^+) - M([pK^- \pi^+]_{\Lambda_c^+}) + M_{\text{PDG}}(\Lambda_c^+), \quad (4)$$

where  $M([pK^- \pi^+]_{\Lambda_c^+} K^- \pi^+)$  is the reconstructed mass of the  $\Xi_{cc}^+$  candidate,  $M([pK^- \pi^+]_{\Lambda_c^+})$  is the reconstructed mass of the  $\Lambda_c^+$  candidate, and  $M_{\text{PDG}}(\Lambda_c^+)$  is the known value of the  $\Lambda_c^+$  mass [69]. As a comparison, the  $m(\Lambda_c^+ K^- \pi^-)$  distribution of the WS control sample is also shown in the right plot of Fig. 1. The dotted red line indicates the mass of the  $\Xi_{cc}^+$  baryon reported by SELEX [37, 38], and the dashed blue line refers to the mass of the  $\Xi_{cc}^{++}$  baryon [43, 44]. The small enhancement below  $3500 \text{ MeV}/c^2$ , compared to the WS sample, is due to partially reconstructed  $\Xi_{cc}^{++}$  decays. There is no excess near a mass of  $3520 \text{ MeV}/c^2$ . A small enhancement is seen near a mass of  $3620 \text{ MeV}/c^2$ . To determine the statistical significance of this enhancement, an extended unbinned maximum-likelihood fit is performed to the  $m(\Lambda_c^+ K^- \pi^+)$  distribution. The signal component is described with the sum of a Gaussian function and a modified Gaussian function with power-law tails on both sides [70]. The parameters of the signal model are fixed from simulation except for the common peak position of the two functions that is allowed to vary freely in the fit. The background component is described by a second-order Chebyshev polynomial with all parameters free. A local  $p$ -value is evaluated with the likelihood ratio test for rejection of the background-only hypothesis assuming a positive signal [71, 72] and is shown in Fig. 2. The largest local significance, corresponding to 3.1 standard deviations (2.7 standard deviations after considering systematic uncertainties), occurs around  $3620 \text{ MeV}/c^2$ . Taking into account the look-elsewhere effect in the mass range of  $3500 \text{ MeV}/c^2$  to  $3700 \text{ MeV}/c^2$  following Ref. [73], the global  $p$ -value is  $4.2 \times 10^{-2}$ , corresponding to a significance of 1.7 standard deviations. Since no excess above 3 standard deviations is observed, upper limits on the production ratios are set using the data recorded at  $\sqrt{s} = 8 \text{ TeV}$  in 2012 and at  $\sqrt{s} = 13 \text{ TeV}$  in 2016–2018 after applying Selection B.

To measure the production ratios, it is necessary to determine the yields of the

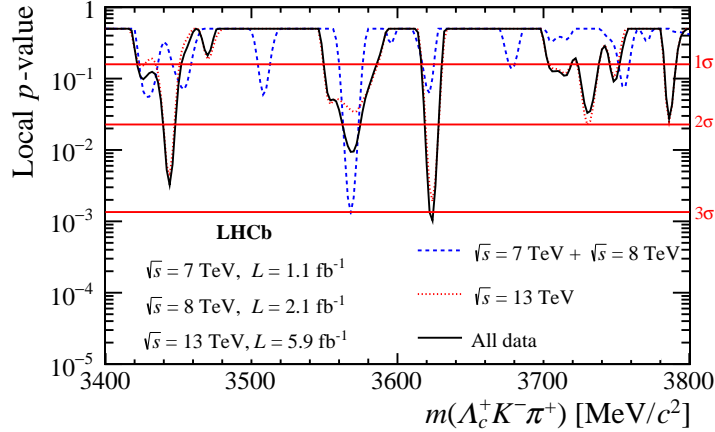


Figure 2: Local  $p$ -value (statistical only) at different  $\Xi_{cc}^+$  mass values evaluated with the likelihood-ratio test, for the data sets recorded at  $\sqrt{s} = 7$  TeV,  $\sqrt{s} = 8$  TeV and  $\sqrt{s} = 13$  TeV. Selection A is applied, including the  $\Lambda_c^+$  mass requirement of  $2270 \text{ MeV}/c^2 < M([pK^-\pi^+]_{\Lambda_c^+}) < 2306 \text{ MeV}/c^2$ .

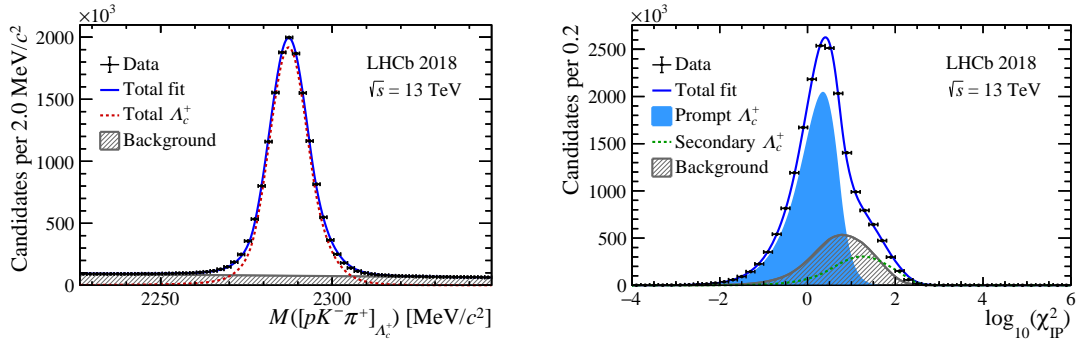


Figure 3: Distributions of (left)  $M([pK^-\pi^+]_{\Lambda_c^+})$  and (right)  $\log_{10}(\chi_{\text{IP}}^2)$  of the selected  $\Lambda_c^+$  candidates with associated fit results for the 2018 data set.

normalisation modes. The yield determination procedure of the prompt  $\Lambda_c^+$  decays is complicated by the substantial secondary  $\Lambda_c^+$  contribution from  $b$ -hadron decays, and is done in two steps. First, the total number of  $\Lambda_c^+$  candidates is determined with an extended unbinned maximum-likelihood fit to the  $M([pK^-\pi^+]_{\Lambda_c^+})$  distribution. Then, a fit to the  $\log_{10}(\chi_{\text{IP}}^2)$  distribution is performed to discriminate between prompt and secondary  $\Lambda_c^+$  candidates. Information from the  $\Lambda_c^+$  mass fit is used to constrain the total number of  $\Lambda_c^+$  candidates. The shapes of the prompt and secondary  $\log_{10}(\chi_{\text{IP}}^2)$  distributions are described by a Bukin function [74]. The shape parameters of the prompt and secondary components are determined from simulation, except for the mean and the width parameters of the Bukin function, which are allowed to vary in the fit. The background component is described by a nonparametric function generated using the data from the  $\Lambda_c^+$  mass sideband regions. As an illustration, the  $M([pK^-\pi^+]_{\Lambda_c^+})$  and  $\log_{10}(\chi_{\text{IP}}^2)$  distributions of the  $\Lambda_c^+$  normalisation mode candidates in the 2018 data set are shown in Fig. 3. The prompt  $\Lambda_c^+$  yields are summarised in Table 1.

To determine the  $\Xi_{cc}^{++}$  yield, an extended unbinned maximum-likelihood fit is performed to the  $m(\Lambda_c^+ K^- \pi^+ \pi^+)$  distribution, which is defined in a similar way to Eq. 4. The same signal and background parameterisations are used as for the signal mode. For the data



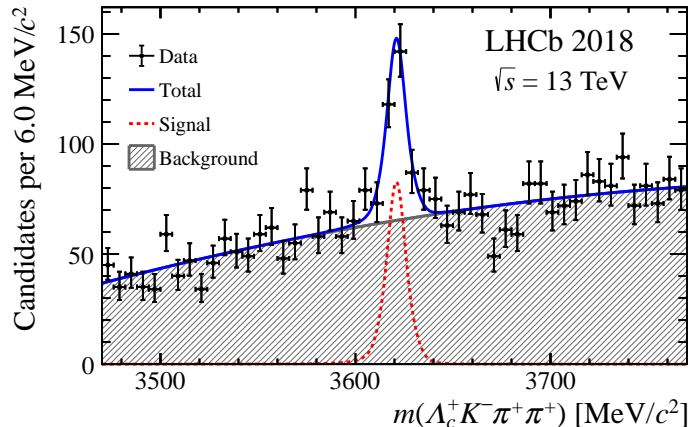


Figure 4: Mass distribution of  $\Xi_{cc}^{++}$  candidates in the 2018 data set. The result of a fit to the distribution is shown.

Table 1: Signal yields for prompt  $\Lambda_c^+ \rightarrow pK^-\pi^+$  and  $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^-\pi^+\pi^+$  normalisation modes, split by data-taking period. The integrated luminosity  $\mathcal{L}$  is also shown for each data-taking period.

Period	$\mathcal{L}$ [ $\text{fb}^{-1}$ ]	$N(\Lambda_c^+)$ [ $\times 10^3$ ]	$N(\Xi_{cc}^{++})$
2012	2.1	$1175.3 \pm 2.5$	$38 \pm 10$
2016	1.7	$7339 \pm 12$	$121 \pm 19$
2017	1.7	$9883 \pm 9$	$153 \pm 22$
2018	2.2	$11184 \pm 13$	$188 \pm 24$

sample recorded at  $\sqrt{s} = 13 \text{ TeV}$ , a simultaneous fit is performed to the  $m(\Lambda_c^+ K^- \pi^+ \pi^+)$  distributions of the candidates in the 2016, 2017 and 2018 data sets with the shared mean and resolution parameter. As an illustration, the  $m(\Lambda_c^+ K^- \pi^+ \pi^+)$  distribution for the 2018 data set is shown in Fig. 4 along with the associated fit result. The  $\Xi_{cc}^{++}$  yields are summarised in Table 1.

## 5 Efficiency ratio measurement

To set upper limits on the production ratios, the efficiency ratio  $\varepsilon_{\text{norm}}/\varepsilon_{\text{sig}}$  is determined from simulation. The signal efficiency is estimated with mass and lifetime hypotheses of  $m(\Xi_{cc}^+) = 3621 \text{ MeV}/c^2$  and  $\tau(\Xi_{cc}^+) = 80 \text{ fs}$ . The kinematic distribution of the  $\Xi_{cc}^+$  baryon is assumed to be the same as for its isospin partner  $\Xi_{cc}^{++}$  and the  $p_T$  distribution of simulated  $\Xi_{cc}^+$  decays is corrected according to the data-simulation discrepancy observed in the  $\Xi_{cc}^{++}$  normalisation mode. The Dalitz distributions of the simulated  $\Lambda_c^+$  decays are corrected to match the distribution observed in background-subtracted data, obtained using the *sPlot* technique [75]. Corrections are applied to the tracking efficiency and PID response of the simulated samples using calibration data samples [76–78]. The efficiency ratio obtained for the  $\Lambda_c^+$  and  $\Xi_{cc}^{++}$  normalisation modes and for different data-taking years are summarised in Table 2, where the uncertainties are due to the limited sizes of the

Table 2: Efficiency ratios between the normalisation and signal modes for different data-taking periods. The uncertainties are due to the limited size of the simulated samples.

	2012	2016	2017	2018
$\varepsilon_{\text{norm}}(\Lambda_c^+)/\varepsilon_{\text{sig}}$	$54 \pm 17$	$22.0 \pm 1.9$	$22.4 \pm 1.3$	$26.1 \pm 1.8$
$\varepsilon_{\text{norm}}(\Xi_{cc}^{++})/\varepsilon_{\text{sig}}$	$2.1 \pm 0.7$	$1.17 \pm 0.11$	$1.91 \pm 0.11$	$1.99 \pm 0.12$

Table 3: Single-event sensitivity of the  $\Lambda_c^+$  normalisation mode  $\alpha(\Lambda_c^+)$  [ $\times 10^{-5}$ ] for different lifetime hypotheses of the  $\Xi_{cc}^+$  baryon in the different data-taking years. The uncertainties are due to the limited sizes of the simulated samples and the statistical uncertainties on the measured  $\Lambda_c^+$  baryon yields.

	$\tau = 40$ fs	$\tau = 80$ fs	$\tau = 120$ fs	$\tau = 160$ fs
2012	$14.2 \pm 4.8$	$4.6 \pm 1.4$	$2.65 \pm 0.77$	$1.91 \pm 0.53$
2016	$0.60 \pm 0.08$	$0.29 \pm 0.02$	$0.20 \pm 0.01$	$0.16 \pm 0.01$
2017	$0.46 \pm 0.04$	$0.23 \pm 0.01$	$0.15 \pm 0.01$	$0.12 \pm 0.01$
2018	$0.52 \pm 0.04$	$0.23 \pm 0.02$	$0.15 \pm 0.01$	$0.11 \pm 0.01$

simulated samples. The increase in the efficiency ratio of the  $\Xi_{cc}^{++}$  normalisation mode in 2017–2018 compared to that in 2016 is due to the improvement of the online event selection following the observation of the  $\Xi_{cc}^{++}$  baryon.

The signal efficiency of the event selection has a strong dependence on the  $\Xi_{cc}^+$  lifetime. To estimate the efficiency for other lifetime hypotheses, the decay time of the simulated  $\Xi_{cc}^+$  events are weighted to have different exponential distributions and the efficiency is re-calculated. A discrete set of hypotheses (40 fs, 80 fs, 120 fs, and 160 fs) is motivated by the measured  $\Xi_{cc}^{++}$  lifetime of 256 fs [45] and the expectation that the  $\Xi_{cc}^+$  lifetime is three to four times smaller than that of the  $\Xi_{cc}^{++}$  baryon [4, 8, 9, 20, 31–36]. Combining the yields of the normalisation modes obtained in the previous section, the values of the single-event sensitivity of the  $\Lambda_c^+$  and  $\Xi_{cc}^{++}$  modes for several lifetime hypotheses are shown in Table 3 and Table 4, respectively. The uncertainties on the single-event sensitivities are due to the limited sizes of the simulated samples and the statistical uncertainties on the measured yields.

The efficiency could depend on the  $\Xi_{cc}^+$  mass, since it affects the kinematic distributions

Table 4: Single-event sensitivity of the  $\Xi_{cc}^{++}$  normalisation mode  $\alpha(\Xi_{cc}^{++})$  [ $\times 10^{-2}$ ] for different lifetime hypotheses of the  $\Xi_{cc}^+$  baryon in the different data-taking years. The uncertainties are due to the limited size of the simulated samples and the statistical uncertainty on the measured  $\Xi_{cc}^{++}$  baryon yield.

	$\tau = 40$ fs	$\tau = 80$ fs	$\tau = 120$ fs	$\tau = 160$ fs
2012	$16.7 \pm 7.1$	$5.4 \pm 2.2$	$3.1 \pm 1.2$	$2.3 \pm 0.8$
2016	$1.96 \pm 0.42$	$0.96 \pm 0.18$	$0.65 \pm 0.12$	$0.52 \pm 0.09$
2017	$2.51 \pm 0.42$	$1.25 \pm 0.19$	$0.84 \pm 0.13$	$0.69 \pm 0.11$
2018	$2.36 \pm 0.34$	$1.06 \pm 0.15$	$0.68 \pm 0.10$	$0.52 \pm 0.08$

of the decay products of the  $\Xi_{cc}^+$  baryon. To test other mass hypotheses, two simulated samples are generated with  $m(\Xi_{cc}^+) = 3518.7 \text{ MeV}/c^2$  and  $m(\Xi_{cc}^+) = 3700.0 \text{ MeV}/c^2$ . The  $p_T$  distributions of the three decay products of the  $\Xi_{cc}^+$  in the simulated sample with  $m(\Xi_{cc}^+) = 3621.4 \text{ MeV}/c^2$  are weighted to match those in the other mass hypotheses, and the efficiency is re-calculated with the weighted sample. Despite the variations of individual efficiency components, the total efficiency is found to be independent of such variations. The mass dependence can be effectively ignored for the evaluation of the single-event sensitivities.

## 6 Systematic uncertainties

The systematic uncertainties on the measured production ratio  $\mathcal{R}$  are presented in Table 5. The total systematic uncertainty is calculated as the quadratic sum of the individual uncertainties, assuming all sources to be independent.

The largest systematic uncertainty arises from the evaluation of the efficiency of the hardware-trigger requirement. The cancellation of the hardware-trigger efficiencies in the ratio of the signal and the normalisation decay channels is studied with the  $\Lambda_c^+$  and  $\Lambda_b^0$  control samples, using a tag-and-probe method [55]. The difference between the efficiency ratio in data and in simulation is assigned as systematic uncertainty.

The systematic uncertainty on the yield determination is evaluated by varying the choice of the model used to fit the data. For the  $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$  decay, an alternative model is used where the signal is described by the sum of two Gaussian functions and the background is described by a second-order polynomial function. For the  $\Lambda_c^+ \rightarrow p K^- \pi^+$  normalisation mode, the yield of the prompt  $\Lambda_c^+$  is determined by the fit to the  $\log_{10}(\chi_{\text{IP}}^2)$  distribution. The uncertainty on the determined signal yield may arise from signal modelling and the limited size of the sample in the background region of the  $\Lambda_c^+$  invariant mass used to model the background. For the signal modelling, a bifurcated Gaussian with an exponential tail is used. The effect of the background is evaluated through the use of pseudoexperiments. The background population in each bin of the  $\log_{10}(\chi_{\text{IP}}^2)$  template is fluctuated randomly, and the fit procedure is repeated.

The PID efficiency is determined in bins of particle momentum and pseudorapidity using calibration data samples. The effect of the limited size of the calibration samples is studied with a large number of pseudoexperiments and that of the binning scheme is studied by increasing the number of bins by a factor of two. The sum in quadrature of these effects is taken as systematic uncertainty arising from PID efficiency.

The tracking efficiency is corrected with calibration data samples [76]. There are three sources of systematic uncertainties related to this correction. The first is due to the limited size of the calibration samples and is estimated with pseudoexperiments. The second is due to the calibration method and an uncertainty of 0.8% (0.4%) per track is assigned for the 13 TeV (7 TeV) data [76]. The third is due to the imperfect knowledge of the material budget in the detector. The above contributions to the systematic uncertainty are summed in quadrature.

Table 5: Summary of the systematic uncertainties of the production ratio measurement.

Source	$\sqrt{s} = 8 \text{ TeV}$		$\sqrt{s} = 13 \text{ TeV}$	
	$\mathcal{R}(\Lambda_c^+)$	$\mathcal{R}(\Xi_{cc}^{++})$	$\mathcal{R}(\Lambda_c^+)$	$\mathcal{R}(\Xi_{cc}^{++})$
Trigger efficiency	11.7%	17.7%	4.9%	11.2%
Yield measurement	5.8%	8.9%	0.6%	0.4%
PID efficiency	2.5%	4.6%	0.9%	0.8%
Tracking	4.3%	2.6%	4.4%	3.1%
Total	14.0%	20.5%	6.7%	11.7%

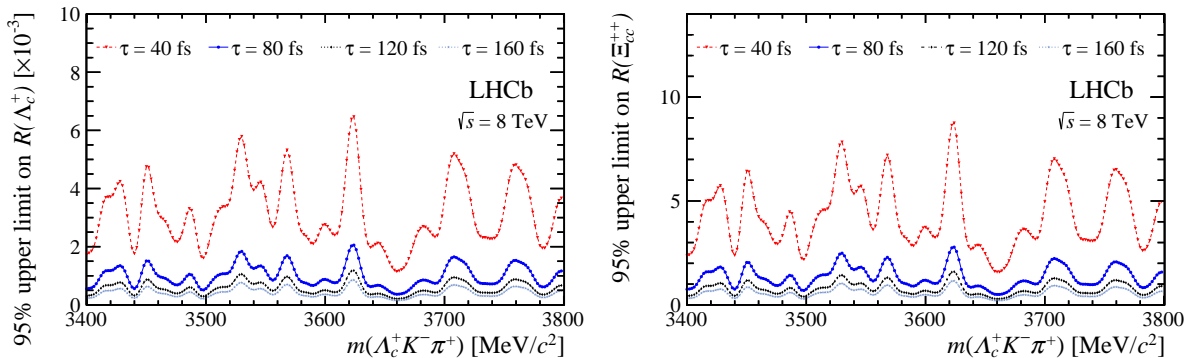


Figure 5: Upper limits on (left)  $\mathcal{R}(\Lambda_c^+)$  and (right)  $\mathcal{R}(\Xi_{cc}^{++})$  at 95% credibility level as a function of  $m(\Lambda_c^+ K^- \pi^+)$  at  $\sqrt{s} = 8 \text{ TeV}$  for four  $\Xi_{cc}^+$  lifetime hypotheses.

## 7 Upper limits

Upper limits at 95% credibility level are set on the production ratio  $\mathcal{R}(\Lambda_c^+)$  and  $\mathcal{R}(\Xi_{cc}^{++})$  at centre-of-mass energies  $\sqrt{s} = 8 \text{ TeV}$  and  $\sqrt{s} = 13 \text{ TeV}$ , in the fiducial region of rapidity  $2.0 < y < 4.5$  and transverse momentum  $4 < p_T < 15 \text{ GeV}/c$ . Upper limits are calculated in  $2.5 \text{ MeV}/c^2$  intervals over the  $m(\Lambda_c^+ K^- \pi^+)$  mass range of 3400 to 3800  $\text{MeV}/c^2$  for the four different lifetime hypotheses. For each fixed value of the  $\Xi_{cc}^+$  mass and lifetime, the likelihood profile  $\mathcal{L}(\mathcal{R})$  is determined as a function of  $\mathcal{R}$ . The likelihood profile for the data recorded at  $\sqrt{s} = 13 \text{ TeV}$  is obtained with a simultaneous fit to the  $m(\Lambda_c^+ K^- \pi^+)$  distributions using the same fit model as described in Sec. 4. Then the likelihood profile  $\mathcal{L}(\mathcal{R})$  is convolved with a Gaussian distribution whose width is equal to the square root of the quadratic combination of the statistical and systematic uncertainty on the single-event sensitivity. The upper limit at 95% credibility level is defined as the value of  $\mathcal{R}$  at which the integral starting from zero equals 95% of the total area under the curve. Figures 5 and 6 show the 95% credibility level upper limits at centre-of-mass energies of  $\sqrt{s} = 8 \text{ TeV}$  and  $\sqrt{s} = 13 \text{ TeV}$ , respectively.

## 8 Conclusion

A search for the doubly charmed baryon  $\Xi_{cc}^+$  is performed through its decay to  $\Lambda_c^+ K^- \pi^+$ , with the  $pp$  collision data collected by the LHCb experiment at centre-of-mass energies of 7,

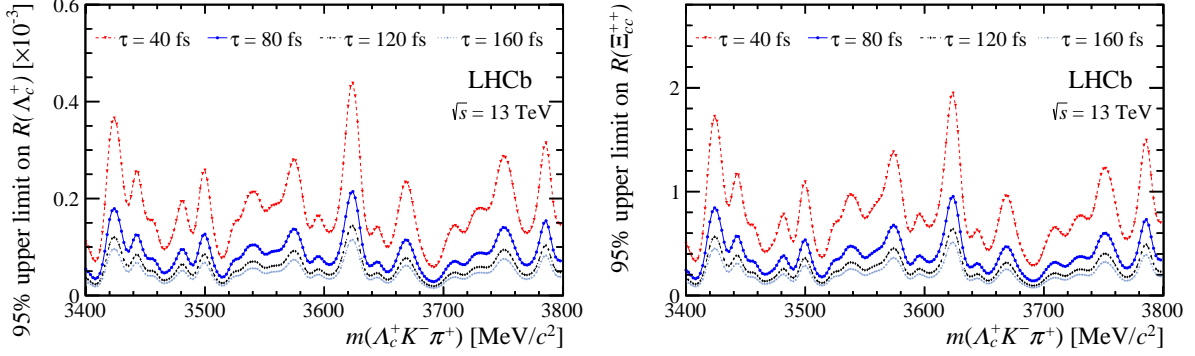


Figure 6: Upper limits on (left)  $\mathcal{R}(\Lambda_c^+)$  (right)  $\mathcal{R}(\Xi_{cc}^{++})$  at 95% credibility level as a function of  $m(\Lambda_c^+ K^- \pi^+)$  at  $\sqrt{s} = 13$  TeV, for four  $\Xi_{cc}^+$  lifetime hypotheses.

Table 6: Summary of the largest upper limits on production ratios at 95% credibility level for four lifetime hypotheses and different centre-of-mass energies.

Lifetime	$\sqrt{s} = 8$ TeV		$\sqrt{s} = 13$ TeV	
	$\mathcal{R}(\Lambda_c^+) [\times 10^{-3}]$	$\mathcal{R}(\Xi_{cc}^{++})$	$\mathcal{R}(\Lambda_c^+) [\times 10^{-3}]$	$\mathcal{R}(\Xi_{cc}^{++})$
40 fs	6.5	8.8	0.45	2.0
80 fs	2.1	2.8	0.22	1.0
120 fs	1.2	1.6	0.15	0.6
160 fs	0.9	1.2	0.12	0.5

8 and 13 TeV, corresponding to an integrated luminosity of  $9 \text{ fb}^{-1}$ . No significant signal is observed in the mass range from 3.4 to  $3.8 \text{ GeV}/c^2$ . Upper limits are set at 95% credibility level on the ratio of the  $\Xi_{cc}^+$  production cross-section times the branching fraction to that of the  $\Lambda_c^+$  and  $\Xi_{cc}^{++}$  baryons. The limits are determined as functions of the  $\Xi_{cc}^+$  mass for different lifetime hypotheses, in the rapidity range from 2.0 to 4.5 and the transverse momentum range from 4 to  $15 \text{ GeV}/c$ . The upper limit on the production ratio  $\mathcal{R}(\Lambda_c^+)$  ( $\mathcal{R}(\Xi_{cc}^{++})$ ) depends strongly on the considered mass and lifetime of the  $\Xi_{cc}^+$  baryon, varying from  $0.45 \times 10^{-3}$  (2.0) for 40 fs to  $0.12 \times 10^{-3}$  (0.5) for 160 fs, as summarised in Table 6. The upper limits on  $\mathcal{R}(\Lambda_c^+)$  are improved by one order of magnitude compared to the previous LHCb search [41] and are significantly below the value reported by SELEX [37], albeit in a different production environment. Future searches by the LHCb experiment with further improved trigger conditions, additional  $\Xi_{cc}^+$  decay modes, and larger data samples should significantly increase the  $\Xi_{cc}^+$  signal sensitivity.

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