Observation of New Ξ_c^0 Baryons Decaying to $\Lambda_c^+ K^-$

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The $\Lambda_c^+ K^-$ mass spectrum is studied with a data sample of pp collisions at a center-of-mass energy of 13 TeV corresponding to an integrated luminosity of 5.6 fb^{-1} collected by the LHCb experiment. Three Ξ_c^0 states are observed with a large significance and their masses and natural widths are measured to be $m[\Xi_c(2923)^0] = 2923.04 \pm 0.25 \pm 0.20 \pm 0.14$ MeV, $\Gamma[\Xi_c(2923)^0] = 7.1 \pm 0.8 \pm 1.8$ MeV, $m[\Xi_c(2939)^0] = 2938.55 \pm 0.21 \pm 0.17 \pm 0.14$ MeV, $\Gamma[\Xi_c(2939)^0] = 10.2 \pm 0.8 \pm 1.1$ MeV, $m[\Xi_c(2965)^0] = 2964.88 \pm 0.26 \pm 0.14 \pm 0.14$ MeV, $\Gamma[\Xi_c(2965)^0] = 14.1 \pm 0.9 \pm 1.3$ MeV, where the uncertainties are statistical, systematic, and due to the limited knowledge of the Λ_c^+ mass. The $\Xi_c(2923)^0$ and $\Xi_c(2939)^0$ baryons are new states. The $\Xi_c(2965)^0$ state is in the vicinity of the known $\Xi_c(2970)^0$ baryon; however, their masses and natural widths differ significantly.

Singly charmed baryons are composed of a charm quark and two light quarks. Because of the large mass difference between the charm and the lighter quarks, these baryons provide an insight into the spectrum of states using symmetries described by the heavy quark effective theory [1,2]. Numerous theoretical predictions of the properties of heavy baryons, containing either a charm or a beauty quark, have been made in recent years [3–13]. In many of these models, the heavy quark interacts with a lighter diquark, which is treated as a single object. Other predictions are based on lattice QCD calculations [14].

In 2017, the LHCb Collaboration reported the observation of five new narrow Ω_c^0 baryons decaying to the $\Xi_c^+ K^-$ final state [15], four of which were later confirmed by the Belle Collaboration [16]. It is currently not understood why the natural widths of these resonances are small [17,18], although a similar trend has recently been observed in the excited Ω_b^- states decaying to $\Xi_b^0 K^-$ [19]. Investigating a different charmed mass spectrum could lead to a better understanding of this feature.

A natural extension to the $\Xi_c^+ K^-$ analysis is the study of the $\Lambda_c^+ K^-$ spectrum. The *BABAR* Collaboration was the first to observe a structure in the $\Lambda_c^+ K^-$ mass spectrum in $B^- \to K^- \Lambda_c^+ \bar{\Lambda}_c^-$ decays peaking at 2.93 GeV in 2007 [20]. However, it was not interpreted as a new state due to the absence of an amplitude analysis. Unless otherwise stated, charge-conjugate processes are implicitly included, and

natural units with $\hbar = c = 1$ are used throughout. Later that year, another analysis was published [21], looking at strongly interacting prompt decays of charm-strange baryons to several final states, one of which was $\Lambda_c^+ K^-$. No resonances were reported in the $\Lambda_c^+ K^-$ mass spectrum. The Belle Collaboration also reported the study of $B^- \to K^- \Lambda_c^+ \bar{\Lambda}_c^-$ decays [22]. A peaking structure was observed in the $\Lambda_c^+ K^-$ mass spectrum compatible with the results of Ref. [20] and interpreted as a new Ξ_c^0 baryon, dubbed $\Xi_c(2930)^0$. Similarly, evidence of the isospin partner $\Xi_c(2930)^+$ in $\bar{B}^0 \to \bar{K}^0 \Lambda_c^+ \bar{\Lambda}_c^-$ decays has been claimed [23].

This Letter presents a search for excited Ξ_c^0 baryons, hereafter referred to as Ξ_c^{**0}, in the $\Lambda_c^+ K^-$ spectrum in a mass region around the $\Xi_c(2930)^0$ state, with the Λ_c^+ baryons reconstructed in the $pK^-\pi^+$ final state. Defining $\Delta M \equiv m(\Lambda_c^+ K^-) - m(\Lambda_c^+) - m(K^-)$, the region considered is $\Delta M < 300$ MeV. The data are collected in pp collisions with the LHCb detector at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 5.6 fb^{-1}.

The LHCb detector [24,25] 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 surrounding the pp interaction region that allows c and b hadrons to be identified from their characteristic long flight distance; a tracking system that provides a measurement of the momentum of charged particles; and two ring-imaging Cherenkov detectors that are able to discriminate between different species of charged hadrons. 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 [26,27]. Simulated data samples are produced with the software packages described in Refs. [28–32] and are used to optimize the selection requirements, to quantify the invariant-mass resolution, and to model physics processes which may constitute peaking backgrounds in the analysis.

Candidate Λ_c^+ baryons are formed from the combination of three tracks of good quality which are inconsistent with originating from any primary proton-proton interaction vertex (PV) and have large transverse momentum (p_T). Particle identification (PID) requirements are imposed on all three tracks to suppress combinatorial background and misidentified charm-meson decays. The Λ_c^+ candidates are required to have $p_T > 2$ GeV and are constrained to originate from the associated PV by requiring a small χ_{IP}^2, defined as the difference between the vertex fit χ^2 of the PV reconstructed with and without the candidate in question. The Λ_c^+ vertex must also be displaced from the associated PV such that the Λ_c^+ decay time is longer than 0.3 ps. A multivariate classifier based on a boosted decision tree (BDT) algorithm [33,34] implemented in the TMVA toolkit [35] is used to further improve the Λ_c^+ signal purity. The input variables given to the BDT are the χ^2 value of the Λ_c^+ decay-vertex fit, the Λ_c^+ flight distance between the production and decay vertex, the angle between the Λ_c^+ momentum vector and the line that joins the Λ_c^+ decay vertex with its associated PV, the χ_{IP}^2 and p_T of the Λ_c^+ candidate, and the χ_{IP}^2 and PID responses of the Λ_c^+ decay particles. The background sample used in the BDT training consists of the lower and upper sidebands of the $pK^-\pi^+$ invariant mass distribution, 2230–2250 and 2320–2340 MeV, respectively. The signal sample used is the Λ_c^+ sample in the data after subtracting the background by means of the sPlot technique [36], exploiting $m(pK^-\pi^+)$ as a discriminating variable. The training of the multivariate algorithm is carried out by using 20 000 candidates of the reconstructed Λ_c^+ candidates from the data recorded in 2016. The requirement on the BDT response is determined using 200 000 Λ_c^+ candidates by maximizing the figure of merit $S/\sqrt{S+B}$, where S is the Λ_c^+ signal yield extracted from a fit to the mass spectrum of Λ_c^+ candidates passing a given BDT requirement and B is the expected background yield. The value for B is extrapolated by scaling the background yield over the full mass range of the fit to a ± 15 MeV mass range around the Λ_c^+ peak.

Misidentified $D^+ \to K^-\pi^+\pi^+$, $D^+ \to K^+K^-\pi^+$, and $D_s^+ \to K^+K^-\pi^+$ background decays are observed after changing the mass hypothesis of the proton into a kaon or a pion. These background components are reduced by employing a tighter PID selection and requiring the invariant mass $m(K^+K^-)$ to differ by at least 10 MeV from the known $\phi(1020)$ mass [37]. Removing all candidates in mass windows around the $D_{(s)}^+$ mass distributions
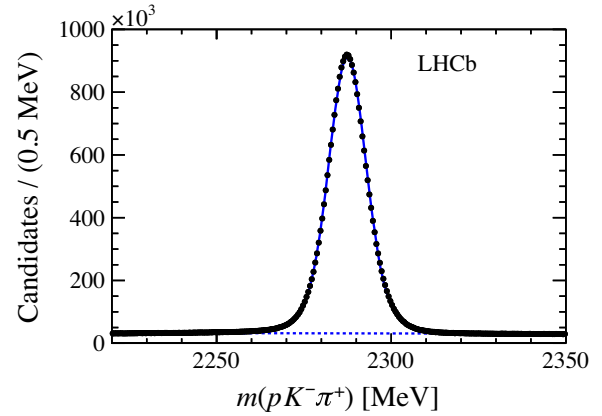

FIG. 1. Distribution of the reconstructed invariant mass $m(pK^-\pi^+)$ for 20% of the candidates in the Λ_c^+ sample passing the selection described in the text. The solid blue curve shows the result of the fit, and the dashed blue line indicates the background component of the fit.

would result in a large loss of signal efficiency and, therefore, is not implemented. However, it is checked that the results of the analysis are stable when these background components are removed fully. About 125 million Λ_c^+ signal decays are selected for further analysis with a purity of 93%. The invariant-mass distribution of 20% of the Λ_c^+ candidates satisfying these selection requirements is shown in Fig. 1.

The Ξ_c^{**0} candidates are formed from $\Lambda_c^+K^-$ combinations, where the Λ_c^+ candidate mass is required to be within 20 MeV of the known Λ_c^+ mass [37]. Each Λ_c^+ candidate is combined with a K^- candidate that is consistent with originating from the associated PV. The Λ_c^+ and K^- particles are fitted to a common vertex, which is required to be consistent with the associated PV.

The main contribution to the combinatorial background in the $\Lambda_c^+K^-$ mass spectrum is due to the large number of kaon candidates from the PV. The signal to background ratio is improved by optimising the PID criteria of the K^- candidates and the p_T requirement on the Ξ_c^{**0} candidates using the figure of merit $\epsilon/(\sqrt{B_P} + 5/2)$ [38]. Here, ϵ is the efficiency determined using simulated $\Xi_c(2930)^0 \to \Lambda_c^+K^-$ decays, and B_P is the number of $\Lambda_c^+K^-$ candidates in the mass region $260 < \Delta M < 290$ MeV, corresponding to the background expected in a mass window around the expected $\Xi_c(2930)^0$ signal, with width $\Gamma[\Xi_c(2930)^0] = 26 \pm 8$ MeV [37]. Based on the optimization above, the p_T of the Ξ_c^0 candidates is required to be larger than 7350 MeV, and the kaon PID is required to satisfy a tight criterion. The fraction of events with multiple candidates is found to be 0.88% in the entire ΔM range. All candidates are included in the analysis.

The resulting ΔM distribution of the signal candidates is shown in Fig. 2, where a fit to the data is superimposed. Three narrow structures are observed in the $\Lambda_c^+K^-$ candidate spectrum. These peaking structures are not seen in the
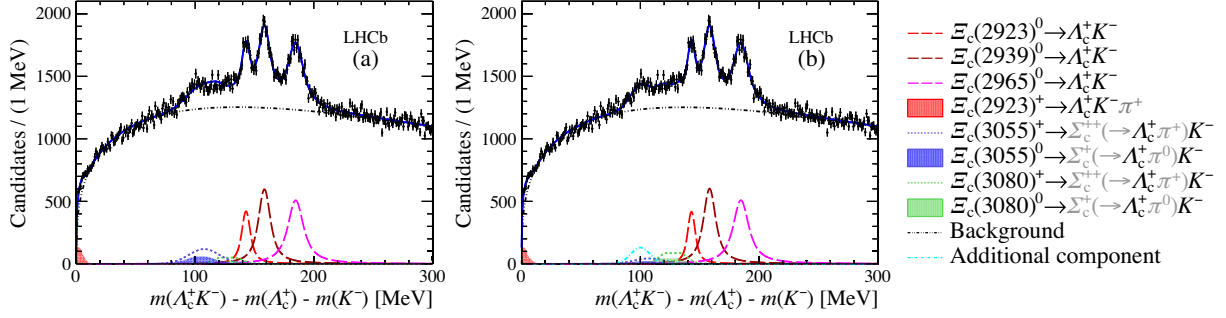
FIG. 2. Distributions of the reconstructed invariant-mass difference $\Delta M = m(\Lambda_c^+ K^-) - m(\Lambda_c^+) - m(K^-)$ for all candidates passing the selection requirements described in the text. The black symbols show the selected signal candidates. The result of a fit, described in the text, is overlaid (solid blue line). In (a), the reference fit is shown. (b) shows an alternative description to the data, where an additional Gaussian component given by the cyan dot-dashed line is added to the fit model around $\Delta M \simeq 100$ MeV. The missing child particles in the reconstruction are indicated in gray in the legend.

wrong-sign $\Lambda_c^+ K^+$ candidates or Λ_c^+ sideband distributions. The ΔM distribution also shows a broad structure to the left of the three narrow structures consistent with being partially reconstructed $\Xi_c(3055) \to \Sigma_c(2455)(\to \Lambda_c^+ \pi)K^-$ and $\Xi_c(3080) \to \Sigma_c(2455)(\to \Lambda_c^+ \pi)K^-$ decays, where the pion is not reconstructed.

An unbinned maximum-likelihood fit, henceforth denoted the reference fit, is performed to the ΔM distribution to measure the parameters of each peak. The background is modeled by an empirical function of the form $\Delta M^a \times \exp(-b \times \Delta M)$, where a and b vary freely. Each signal peak is described by an S-wave relativistic Breit-Wigner function convolved with a mass-resolution function. The experimental mass resolution is determined using simulated $\Xi_c^{**0} \to \Lambda_c^+ K^-$ decays at several Ξ_c^{**0} masses. In the ΔM interval where the three narrow peaks occur, the mass resolution varies between 1.7 and 2.2 MeV. Simulated data are also generated to determine the shape of partially reconstructed $\Xi_c(3055)$ and $\Xi_c(3080)$ decays. The shapes of these contributions are allowed to shift in ΔM by the uncertainties in the decay-product masses, where the shift is Gaussian constrained. From isospin symmetry, the yields of the $\Xi_c(3055)^+$ and $\Xi_c(3080)^+$ components are constrained to be twice as large as the corresponding $\Xi_c(3055)^0$ and $\Xi_c(3080)^0$ components. The fit model outlined so far does not accurately describe the data in the mass region close to the kinematic threshold, and, thus,

an additional component is considered. There are no known decays of $\Sigma_c(2455)(\to \Lambda_c^+ \pi)K^-$ or $\Sigma_c(2520)(\to \Lambda_c^+ \pi)K^-$ which could enter the sample as partially reconstructed components at $\Delta M \simeq 0$. It is observed that the missing component is consistent with being due to the partial reconstruction of the state that peaks around $\Delta M \simeq 140$ MeV when it decays directly to the $\Lambda_c^+ K^- \pi^+$ final state without any intermediate resonance. The shape of these partially reconstructed decays is taken from simulated samples generated using the RapidSim package [39], and the yield is a free parameter in the fit.

The ΔM distribution with the fit to the data superimposed is shown in Fig. 2(a). The goodness-of-fit value is $\chi^2/\mathrm{ndof} = 301/(300 - 19) = 1.07$, where ndof is the number of degrees of freedom. Table I shows the results for the parameters of the signal peaks of the reference fit, hereafter named $\Xi_c(2923)^0$, $\Xi_c(2939)^0$, and $\Xi_c(2965)^0$.

To validate the presence of the signal components and test the stability of the fit parameters, several additional checks are performed. The data are fitted in samples according to the year of data taking and to different data-taking conditions depending on the LHCb magnet configuration. The $\Lambda_c^+ K^-$ sample and its charge conjugate are also studied separately. The results are consistent among all samples.

The data and the reference fit show the least compatibility in the region around $\Delta M \simeq 100$ MeV. This may be due to a mismodeling of the partially reconstructed distributions, but it could also be due to the presence of further new Ξ_c^{**0} baryon states. Figure 2(b) shows the ΔM distribution for the signal sample where an additional component, parametrized by an empirical Gaussian function, has been added to the reference fit. The fit has a goodness-of-fit value of $\chi^2/\mathrm{ndof} = 278/(300 - 22) = 1.00$. As a cross-check, this structure is tested in subsamples of the dataset divided by data-taking year and showed an inconsistency in the scaling of the yield with respect to the integrated luminosity. Furthermore, the feed-down components are highly suppressed when this contribution

TABLE I. Peak positions in the invariant-mass difference distribution ΔM, natural widths Γ, signal yields, and local significances of the three mass peaks obtained from the fit to the $\Lambda_c^+ K^-$ mass spectrum, where the systematic uncertainties are statistical.

Peak of ΔM [MeV]	Γ [MeV]	Signal yields
142.91 ± 0.25	7.1 ± 0.8	5400 ± 400
158.45 ± 0.21	10.2 ± 0.8	10400 ± 600
184.75 ± 0.26	14.1 ± 0.9	11700 ± 600

TABLE II. Summary of the contributions to the systematic uncertainties on the resonance parameters. Absolute deviations from the nominal fit are quoted.

Source	$\Xi_c(2923)^0$		$\Xi_c(2939)^0$		$\Xi_c(2965)^0$	
	m[MeV]	Γ[MeV]	m[MeV]	Γ[MeV]	m[MeV]	Γ[MeV]
Alternative fit model	0.15	1.6	0.14	0.4	0.04	1.1
Resonance interferences	0.08	0.7	0.06	1.0	0.11	0.7
Momentum scale	0.04	$\cdots$	0.05	$\cdots$	0.06	$\cdots$
Energy losses	0.04	$\cdots$	0.04	$\cdots$	0.04	$\cdots$
Resolution calibration	$\cdots$	0.6	$\cdots$	0.2	$\cdots$	0.3
Total	0.20	1.8	0.17	1.1	0.14	1.3

is included. More data are required to understand the cause of this additional structure. It is accounted for when calculating the systematic uncertainties.

Several sources of systematic uncertainty may affect the measured parameters. The fit model uncertainty is evaluated by replacing the background model by an alternative function, consisting of a combination of the wrong-sign $m(\Lambda_c^+ K^+)$ invariant-mass distribution shape and the shape obtained from candidates in the Λ_c^+ sideband. In addition, the choice of the relativistic Breit-Wigner model is changed by setting the values of the angular momentum L between the child particles to $L = 1, 2$ and separately varying the Blatt-Weisskopf factors [40] from 2 to 4 GeV^{-1}. Furthermore, the fit is adapted to include any partially reconstructed decays $\Xi_c^{**} \to \Sigma_c(2455/2520)(\to \Lambda_c^+ \pi)K^-$ that are found to not contribute significantly to the reference fit. Finally, deviations in fit parameters between the reference fit and the fit shown in Fig. 2(b) are included in the fit model uncertainty. The largest deviation from the reference fit is quoted as the systematic uncertainty for the fit model. Resonances with the same spin parity that are close in mass can interfere. An interference term is introduced between neighboring resonances, for one pair of resonances at a time. With the interference term, the line shape takes the form $A = |c_j \mathrm{BW}_j + c_k \mathrm{BW}_k e^{i\phi}|^2$, where j and k denote the two resonances, $\mathrm{BW}_{j,k}$ are Breit-Wigner functions, and $c_{j,k}$ and ϕ are free real parameters. The largest difference between the reference fit and a fit where resonance interference is allowed is used as the systematic uncertainty. In addition, several other sources of systematic uncertainty affect only the mass measurement. These include the momentum-scale uncertainty, evaluated by shifting the momentum scale of charged

tracks by $\pm 0.03\%$ [41] in simulated decays, and the imperfect modeling of the energy loss in the detector material, resulting in a systematic uncertainty of 0.04 MeV [42]. Finally, a systematic uncertainty is attributed to the width measurement, to account for the fact that the simulation may not reproduce the absolute mass resolution perfectly. The corresponding systematic uncertainty is obtained by the change in the width when the value of the resolution, determined on simulated data, is varied by 10% [43]. The systematic uncertainties are summarized in Table II, and in Table III their measured masses and natural widths are summarized.

The observations described in this Letter and the lack of any $\Xi_c(2930)^0$ signal indicates that the broad bump observed in $B^- \to K^- \Lambda_c^+ \bar{\Lambda}_c^-$ decays [20,22] might be due to the overlap of two narrower states, such as the $\Xi_c(2923)^0$ and $\Xi_c(2939)^0$ baryons. The $\Xi_c(2965)^0$ baryon is in the vicinity of the known $\Xi_c(2970)^0$ baryon, which has been observed in different decay modes: $\Sigma_c(2455)^0 K_S^0$ [21], $\Xi_c'^+ \pi^-$ [44], and $\Xi_c(2645)^+ \pi^-$ [45]. Furthermore, the $\Xi_c(2965)^0$ resonance has a natural width and mass which differ significantly from those of the $\Xi_c(2970)^0$ baryon: $\Gamma[\Xi_c(2970)^0] = 28.1^{+3.4}_{-4.0}$ MeV and $m[\Xi_c(2970)^0] = 2967.8^{+0.9}_{-0.7}$ MeV [37]. Further studies are required to establish whether the $\Xi_c(2965)^0$ state is indeed a different baryon. The equal spacing rule [46,47] succeeded to predict the mass of the Ω baryon and holds for other flavor multiplets such as the sextet of the $J^P = 3/2^+$ charmed ground states:

$$m[\Omega_c(2770)^0] - m[\Xi_c(2645)^0]$$
$$\simeq m[\Xi_c(2645)^0] - m[\Sigma_c(2520)^0] \simeq 125 \text{ MeV}.$$

TABLE III. Summary of the parameters for the studied states, showing the measured ΔM values, the masses, and the natural widths, where the first uncertainty is statistical and the second uncertainty is systematic. For the mass measurement, the third uncertainty denotes the uncertainty on the known Λ_c^+ mass [37].

Resonance	Peak of ΔM [MeV]	Mass [MeV]	Γ [MeV]
$\Xi_c(2923)^0$	$142.91 \pm 0.25 \pm 0.20$	$2923.04 \pm 0.25 \pm 0.20 \pm 0.14$	$7.1 \pm 0.8 \pm 1.8$
$\Xi_c(2939)^0$	$158.45 \pm 0.21 \pm 0.17$	$2938.55 \pm 0.21 \pm 0.17 \pm 0.14$	$10.2 \pm 0.8 \pm 1.1$
$\Xi_c(2965)^0$	$184.75 \pm 0.26 \pm 0.14$	$2964.88 \pm 0.26 \pm 0.14 \pm 0.14$	$14.1 \pm 0.9 \pm 1.3$

It is noted that the rule also seems to hold for the $\Xi_c(2923)^0$, $\Xi_c(2939)^0$, and $\Xi_c(2965)^0$ baryons within a precision of a few MeV:

$$m[\Omega_c(3050)^0] - m[\Xi_c(2923)^0]$$
$$\simeq m[\Xi_c(2923)^0] - m[\Sigma_c(2800)^0] \simeq 125 \text{ MeV},$$
$$m[\Omega_c(3065)^0] - m[\Xi_c(2939)^0] \simeq 125 \text{ MeV},$$
$$m[\Omega_c(3090)^0] - m[\Xi_c(2965)^0] \simeq 125 \text{ MeV}.$$

This pattern may indicate that the new states reported in this analysis are related to the excited Ω_c^0 baryons observed in the $\Xi_c^+ K^-$ spectrum. Measurements of spin parities will be crucial to confirm whether they belong to the same flavor multiplets.

In summary, pp collision data collected by the LHCb experiment at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 5.6 fb^{-1}, are used to search for excited Ξ_c^0 resonances in the $\Lambda_c^+ K^-$ mass spectrum. Three different Ξ_c^0 baryons, $\Xi_c(2923)^0$, $\Xi_c(2939)^0$, and $\Xi_c(2965)^0$, are unambiguously observed. The two baryons at lower mass are observed for the first time, while an investigation of additional final states is required to establish whether the $\Xi_c(2965)^0$ and $\Xi_c(2970)^0$ states are different baryons.

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