Letter

Observation of excited Ω_c^0 baryons in $\Omega_b^- \to \Xi_c^+ K^- \pi^-$ decays

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(Received 8 July 2021; accepted 14 September 2021; published 24 November 2021)

The first observation of the $\Omega_b^- \to \Xi_c^+ K^- \pi^-$ decay is reported using $p\,p$ collision data at center of mass energies of 7, 8, and 13 TeV collected by the LHCb experiment, corresponding to an integrated luminosity of 9 fb^{-1}. Four excited Ω_c^0 baryons are observed in the $\Xi_c^+ K^-$ mass projection of the $\Omega_b^- \to \Xi_c^+ K^- \pi^-$ decays with the significance of each exceeding five standard deviations. They coincide with the states previously observed in prompt pp and e^+e^- production. Relative production rates, masses, and natural widths of the states are measured, and a test of spin hypotheses is performed. Moreover, the branching ratio of $\Omega_b^- \to \Xi_c^+ K^- \pi^-$ is measured relative to the $\Omega_b^- \to \Omega_c^0 \pi^-$ decay mode and a precise measurement of the Ω_b^- mass of $6044.3 \pm 1.2 \pm 1.1^{+0.19}_{-0.22}$ MeV is obtained.

DOI: 10.1103/PhysRevD.104.L091102

I. INTRODUCTION

The spectrum of the baryons with a single heavy quark Qqq' ($Q = b$ or c and $q, q' = u$, d, or s) is well classified using the heavy quark-diquark degrees of freedom. Heavy-quark effective theory [1–8] provides the basis for factoring out the heavy-quark dynamics up to corrections of the first order of $1/m_Q$, where m_Q is the heavy-quark mass. Therefore, the observation of new baryons and measurements of their properties provide information about the role played by diquarks in baryons, and can also help to tune tetraquark and pentaquark models.

In recent years, the LHCb experiment has made numerous contributions to the spectroscopy of heavy baryons by observing several new states [9–16]. Among them, the spectrum of excited Ω_c^0 baryons has drawn special attention. Five new excited narrow Ω_c^0 states, herein denoted Ω_c^{**0}, and promptly produced in proton-proton (pp) collisions, have been observed in the $\Xi_c^+ K^-$ mass spectrum [16,17].

Many theoretical approaches including potential models, QCD sum rules, and lattice QCD predict the Ω_c^{**0} spectrum and interpret the newly discovered states as orbitally or radially excited Ω_c^0 states [18–36], while a few studies suggest that some of them may be either molecular states or pentaquarks [37–43]. Most of the predictions propose the mass ordering of the states, while widths and relative production rates remain unexploited on the theoretical side. Seven excited P-wave Ω_c^0 baryons are expected: five λ-mode excited states where the constituent c quark and the ss diquark are in a P-wave, and two ρ-mode excited states where the two s quarks are in a P-wave. One of the most popular interpretations is that the observed Ω_c^{**0} states correspond to the five λ-mode excited Ω_c^0 baryons with quantum numbers $J^P = 1/2^-, 1/2^-, 3/2^-, 3/2^-$, and $5/2^-$. The determination of the spin-parity quantum numbers of the Ω_c^{**0} states would help to discriminate between the proposed models and to probe the internal structure of the baryons.

This paper presents the first observation of the Ω_c^{**0} states produced in exclusive Ω_b^- decays. These are studied in the previously unobserved $\Omega_b^- \to \Xi_c^+ K^- \pi^-$ decays [44,45], where the Ξ_c^+ baryons are reconstructed in the $pK^-\pi^+$ final state. The mass of the Ω_b^- baryon has been measured in decays to the $\Omega_c^0 \pi^-$ and $\Omega^- J/\psi$ final states. The new decay mode $\Omega_b^- \to \Xi_c^+ K^- \pi^-$ is a prominent reaction to measure also the Ω_b^- mass due to a multiparticle final state and smaller phase space with respect to the $\Omega_c^0 \pi^-$ mode.[1] The analysis is based on samples of pp collision data at center of mass energies of $\sqrt{s} = 7$, 8 and 13 TeV, corresponding to an integrated luminosity of 9 fb^{-1}.

II. DETECTOR AND SIMULATION

The LHCb detector [46,47] 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, a large-area silicon-strip detector

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[1]Unless otherwise stated, charge-conjugate processes are implicitly included, and natural units with $\hbar = c = 1$ are used throughout.

located upstream of a dipole magnet with a bending power of about 4 Tm, and three stations of silicon-strip detectors together with straw drift tubes placed downstream of the magnet. Simulation is necessary to train a multivariate algorithm used to suppress background, model shapes of mass distributions, and calculate efficiencies. In the simulation, pp collisions are generated using PYTHIA [48] with a specific LHCb configuration [49]. Decays of unstable particles are described by EvtGen [50]. The interaction of the generated particles with the detector is implemented using the Geant4 toolkit [51] as described in Ref [52].

III. SELECTION OF $\Omega_b^- \to \Xi_c^+ K^- \pi^-$ DECAYS

The Ξ_c^+ candidates are formed by combining three tracks that are detached from any primary pp interaction vertex (PV) in the event. A good-quality vertex fit is required to select tracks originating from the same secondary vertex. The Ω_b^- candidates are selected by combining the Ξ_c^+ candidate with two tracks identified as a K^- and a π^- meson. Loose particle identification (PID) requirements are applied to all five final-state tracks in order to reduce background. The Ω_b^- candidates are required to have a transverse momentum $p_{\mathrm{T}} > 3.5$ GeV and are constrained to originate from the PV by requiring a small χ^2_{IP}, where χ^2_{IP} is defined as the difference in the vertex-fit χ^2 of a given PV reconstructed with and without the candidate under consideration. The Ω_b^- decay time is required to be larger than 0.2 ps, making the overlap with the prompt sample analyzed in Ref. [16] negligible.

A boosted decision tree (BDT) classifier, implemented using the TMVA toolkit [53], is used to further reduce the background. Variables found to provide good discrimination between signal and background are the PID information and p_{T} of the final-state tracks, the Ξ_c^+ p_{T}, the Ξ_c^+ and Ω_b^- χ^2_{IP}, the Ξ_c^+ and Ω_b^- vertex-fit χ^2, the Ω_b^- flight-distance significance, defined as the measured flight distance divided by its uncertainty, and the cosine of the Ξ_c^+ and Ω_b^- direction angles. The direction angle is defined as the angle between the Ξ_c^+ (Ω_b^-) momentum and the vector joining the PV and the Ξ_c^+ (Ω_b^-) decay vertex. The training of the BDT classifier is performed using simulated samples as signal and data as background separately for Run 1 and Run 2 data samples. The candidates used for the background sample are in the 6200 MeV–6300 MeV range of the $\Xi_c^+ K^- \pi^-$ mass spectrum, which is not populated by partially reconstructed Ω_b^- decays. The optimal selection criterion on the BDT response is found by maximizing the figure of merit $\epsilon/(5/2 + \sqrt{B_P})$ [54], where ϵ is the signal efficiency in simulation, and B_P is the number of $\Xi_c^+ K^- \pi^-$ candidates in the mass region $6200\ \mathrm{MeV} < m(\Xi_c^+ K^- \pi^-) < 6256$ MeV, roughly matching the expected number of background events in the Ω_b^- mass window. Roughly 4% of selected events contain more than one candidate and are removed. Finally, a kinematic fit [55] is applied to the Ω_b^- decays to improve the mass resolution where the Ξ_c^+ candidate mass is constrained to its known value [56], and the Ω_b^- candidate is constrained to originate from its associated PV, defined as the PV to which the impact parameter of the combination of two-track and Ξ_c^+ candidate is the smallest.

The resulting $\Xi_c^+ K^- \pi^-$ mass spectrum is shown in Fig. 1 (left) and an extended unbinned maximum-likelihood fit is performed. The signal shape is modeled by the combination of two Gaussian functions with a common mean, where the ratios of the resolutions and yields between the functions are fixed according to the simulation. The main sources of background are due to the partially reconstructed decays $\Omega_b^- \to \Xi_c^+ K^- \rho^- (\to \pi^- \pi^0)$ and $\Omega_b^- \to \Xi_c'^+ (\to \Xi_c^+ \gamma) K^- \pi^-$, where the π^0 and γ are not reconstructed. The combinatorial background shape is fixed according to a wrong-sign sample, consisting of $\Xi_c^+ K^- \pi^+$ combinations processed in the same way as the right-sign Ξ_c^+ K^- π^- combinations. The shape of the partially reconstructed decays is taken from simulated samples generated using the RapidSim

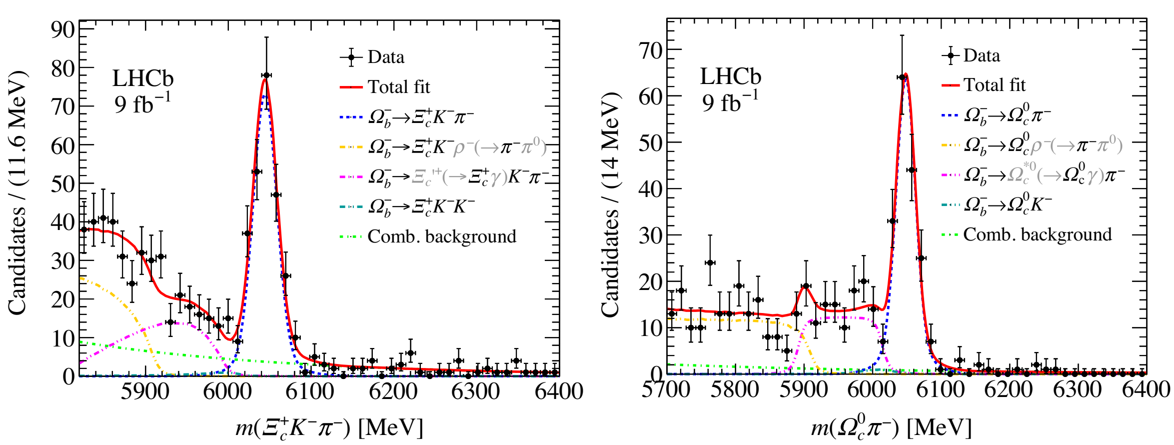

FIG. 1. Distribution of the reconstructed invariant mass (left) $m(\Xi_c^+ K^- \pi^-)$ with $\Xi_c^+ \to p K^- \pi^+$ and (right) $m(\Omega_c^0 \pi^-)$ with $\Omega_c^0 \to p K^- K^- \pi^+$ for all candidates passing the selection requirements. The black symbols show the data. The result of a fit is overlaid (solid red line). The missing particles in partially reconstructed decays are indicated in gray in the legends.

package [57]. The shape of misidentified decays $\Omega_b^- \to \Xi_c^+ K^- K^-$ is fixed based on simulation. The yield ratio $N_{\Xi_c^+ K^- K^-}/N_{\Xi_c^+ K^- \pi^-}$ is fixed to 2.8% based on $|V_{us}|^2/|V_{ud}|^2 \approx 5\%$ corrected by the difference in reconstruction efficiency and the phase space. The fit returns a combined mass resolution of 17.9 ± 1.3 MeV, a yield of $N_{\Xi_c^+ K^- \pi^-} = 240 \pm 17$ and an Ω_b^- mass, $m(\Omega_b^-) = 6044.3 \pm 1.2$ MeV, where the uncertainty is statistical only (see Table I). The Dalitz plot distribution of the candidates, with a mass within two standard deviations of the Ω_b^- peak, is shown in Fig. 2. Excited Ω_c^0 baryons appear in the $\Xi_c^+ K^-$ projection while no excited Ξ_c^0 states are clearly visible in the $\Xi_c^+ \pi^-$ system.

The branching fraction of $\Omega_b^- \to \Xi_c^+ K^- \pi^-$ decays is measured relative to the normalization channel $\Omega_b^- \to \Omega_c^0 \pi^-$, with $\Omega_c^0 \to p K^- K^- \pi^+$. Similar selection requirements as the $\Omega_b^- \to \Xi_c^+ K^- \pi^-$ mode are applied to the $\Omega_b^- \to \Omega_c^0 \pi^-$ candidates. The selections of the two decay modes differ in the requirements applied to the invariant mass of the $pK^-\pi^+$ and $pK^-K^-\pi^+$ systems to select Ξ_c^+ and Ω_c^0 candidates, respectively. A kinematic fit is applied to the Ω_b^- decay where the Ω_c^0 candidate mass is constrained to its known value [56]. The two largest background components are due to the partially reconstructed decays $\Omega_b^- \to \Omega_c^0 \rho^- (\to \pi^- \pi^0)$, and $\Omega_b^- \to \Omega_c^{*0} (\to \Omega_c^0 \gamma) \pi^-$. The result of an unbinned maximum-likelihood fit is overlaid to the data in Fig. 1 (right). All decays are modeled in the same way as for the $\Omega_b^- \to \Xi_c^+ K^- \pi^-$ channel. The combinatorial background shape is fixed according to the projection of the Ω_c^0 sidebands in the $\Omega_c^0\ \pi^-$ mass spectrum, where the Ω_c^0 sidebands are defined as the 2650 MeV–2670 MeV and 2720 MeV–2740 MeV ranges in the $p\ K^-\ K^-\ \pi^+$ invariant mass distribution. The yield of reconstructed Ω_b^- candidates is $N_{\Omega_c^0 \pi^-} = 174 \pm 14$, and the mass resolution is 18.4 ± 1.5 MeV.

TABLE I. Results on the Ω_b^- mass, relative branching fraction of the $\Xi_c^+ K^- \pi^-$ decay mode, measured mass differences (ΔM), masses (m), natural widths (Γ) and production fraction ($\mathcal{P}$) of Ω_c^{**0} baryons where the first uncertainty is statistical and the second systematic. The third asymmetric uncertainty on the Ω_b^- and Ω_c^{**0} masses is due to the uncertainty in the Ξ_c^+ mass. Upper limits are given for the width of the $\Omega_c(3050)^0$ state and the production rate of the $\Omega_c(3120)^0$ baryon, which are measured to be consistent with zero. The results of the spin analysis are also listed (J rejection).

State	Observable	Measurement
Ω_b^-	m	$6044.3 \pm 1.2 \pm 1.1^{+0.19}_{-0.22}$ MeV
	$\mathcal{R}$	$1.35 \pm 0.11 \pm 0.05$
Threshold structure	Significance	4.3σ
$\Omega_c(3000)^0$	Significance	6.2σ
	ΔM	$37.6 \pm 0.9 \pm 0.9$ MeV
	m	$2999.2 \pm 0.9 \pm 0.9^{+0.19}_{-0.22}$ MeV
	Γ	$4.8 \pm 2.1 \pm 2.5$ MeV
	$\mathcal{P}$	$0.11 \pm 0.02 \pm 0.04$
	J rejection	$0.5\sigma(J=1/2), 0.8\sigma(J=3/2), 0.4\sigma(J=5/2)$
$\Omega_c(3050)^0$	Significance	9.9σ
	ΔM	$88.5 \pm 0.3 \pm 0.2$ MeV
	m	$3050.1 \pm 0.3 \pm 0.2^{+0.19}_{-0.22}$ MeV
	Γ	< 1.6 MeV, 95% CL
	$\mathcal{P}$	$0.15 \pm 0.02 \pm 0.02$
	J rejection	$2.2\sigma(J=1/2), 0.1\sigma(J=3/2), 1.2\sigma(J=5/2)$
$\Omega_c(3065)^0$	Significance	11.9σ
	ΔM	$104.3 \pm 0.4 \pm 0.4$ MeV
	m	$3065.9 \pm 0.4 \pm 0.4^{+0.19}_{-0.22}$ MeV
	Γ	$1.7 \pm 1.0 \pm 0.5$ MeV
	$\mathcal{P}$	$0.23 \pm 0.02 \pm 0.02$
	J rejection	$3.6\sigma(J=1/2), 0.6\sigma(J=3/2), 1.2\sigma(J=5/2)$
$\Omega_c(3090)^0$	Significance	7.8σ
	ΔM	$129.4 \pm 1.1 \pm 1.0$ MeV
	m	$3091.0 \pm 1.1 \pm 1.0^{+0.19}_{-0.22}$ MeV
	Γ	$7.4 \pm 3.1 \pm 2.8$ MeV
	$\mathcal{P}$	$0.19 \pm 0.02 \pm 0.04$
	J rejection	$0.3\sigma(J=1/2), 0.8\sigma(J=3/2), 0.5\sigma(J=5/2)$
$\Omega_c(3120)^0$	$\mathcal{P}$	< 0.03, 95% CL

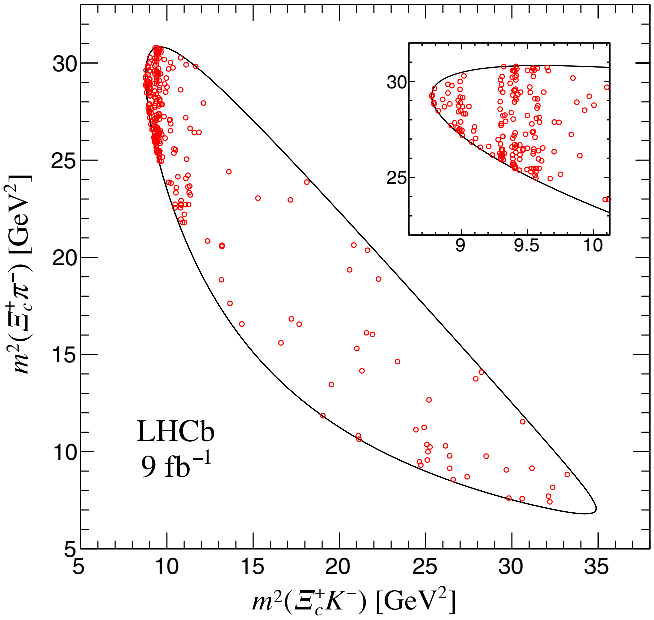

FIG. 2. Dalitz plot distribution of $\Omega_b^- \to \Xi_c^+ K^- \pi^-$ candidates in the signal region, including background contributions. The inset shows an expanded view of the upper left corner where the vertical bands correspond to excited Ω_c^0 states.

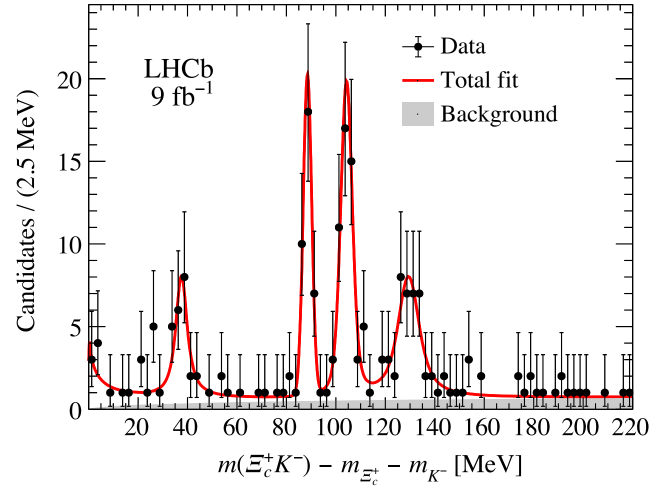

FIG. 3. Distribution of the reconstructed mass difference between the Ξ_c^+ K^- invariant mass and the Ξ_c^+ and K^- masses. The four peaking structures are consistent with being the previously observed $\Omega_c(3000)^0$, $\Omega_c(3050)^0$, $\Omega_c(3065)^0$, and $\Omega_c(3090)^0$ baryons. The distribution shows an enhancement at the threshold, as seen in the previous analysis [16]. The total fit is overlaid in red. The background distribution (gray shaded area) is the combination of the combinatorial and nonresonant Ξ_c^+ K^- backgrounds.

The ratio of branching fractions is obtained as

$$\mathcal{R} \equiv \frac{\mathcal{B}(\Omega_b^- \to \Xi_c^+ K^- \pi^-)\mathcal{B}(\Xi_c^+ \to pK^-\pi^+)}{\mathcal{B}(\Omega_b^- \to \Omega_c^0 \pi^-)\mathcal{B}(\Omega_c^0 \to pK^-K^-\pi^+)} = 1.35 \pm 0.11,$$

which is calculated from the ratio of efficiency-corrected yields, where the error is statistical only (see Table I).

IV. THE $\Xi_c^+ K^-$ MASS SPECTRUM

A search for excited Ω_c^0 baryons is performed in the Ξ_c^+ K^- mass projection of $\Omega_b^- \to \Xi_c^+ K^- \pi^-$ candidates. In order to increase the selection efficiency of the Ω_c^{**0} states, an additional BDT classifier is deployed for the study of the $\Xi_c^+ K^-$ spectrum, where a sample of simulated $\Omega_b^- \to \Xi_c^+ K^- \pi^-$ decays, with an additional requirement of $m(\Xi_c^+ K^-) < 3.3$ GeV, is used as the signal sample. For the background, the upper region of the $\Xi_c^+ K^- \pi^-$ mass distribution is used, as in the previous BDT classifier. After the optimization of the BDT response, the Ω_b^- candidates with a mass within two standard deviations of the Ω_b^- peak are selected. Figure 3 shows the distribution of the mass difference $\Delta M \equiv m(\Xi_c^+ K^-) - m_{\Xi_c^+} - m_{K^-}$, where $m(\Xi_c^+ K^-)$ is the invariant mass of the $\Xi_c^+ K^-$ system, and $m_{\Xi_c^+}$ and m_{K^-} are the world averages of the Ξ_c^+ and K^- masses, respectively [56]. Four narrow-peaking structures are clearly visible close to the Ξ_c^+ K^- kinematic threshold.

An extended maximum-likelihood fit is performed to the ΔM distribution, where each signal is modeled by an S-wave relativistic Breit-Wigner function multiplied by the phase-space function and convolved with a Gaussian function to describe the mass resolution. The widths and masses of the relativistic BW functions vary freely. The background consists of two components; the combinatorial background under the Ω_b^- signal peak [Fig. 1 (left)] and the nonresonant $\Xi_c^+ K^-$ component. The former (combinatorial) is modeled by projecting the Ω_b^- sideband into the $\Xi_c^+ K^-$ invariant mass distribution and the latter (nonresonant $\Xi_c^+ K^-$) according to phase space. While the shapes of the two contributions and the yield of the combinatorial component are fixed, the yield of the nonresonant background can vary freely. The $\Xi_c^+ K^-$ spectrum also features an excess at the $\Xi_c^+ K^-$ mass threshold which is modeled by an S-wave BW component.

Fit results superimposed to the data are shown in Fig. 3. The yields attributed to the four peaks are 24 ± 7, 33 ± 6, 51 ± 8, and 41 ± 9 respectively. The resulting BW parameters of the four signals, which are listed in Table I, are consistent with those of the previously observed $\Omega_c(3000)^0$, $\Omega_c(3050)^0$, $\Omega_c(3065)^0$, and $\Omega_c(3090)^0$ baryons [16]. The natural width of the $\Omega_c(3050)^0$ is consistent with zero, therefore an upper limit is set. In order to determine the significance of the peaking structures, another fit is performed by fixing the masses and widths of the Ω_c^{**0} states to the previously measured values [16]. Therefore, the statistical significance of each peak is calculated using $\sqrt{2\Delta(\mathrm{NLL})}$, where $\Delta(\mathrm{NLL})$ is the variation of the fit log-likelihood when the corresponding BW function is excluded from the reference fit model. The local significance exceeds six standard deviations (6σ) for each of the four main states. For the threshold structure, the null hypothesis of the background fluctuation is tested using the likelihood ratio of two fits. The p-value expressed in standard deviations using the one-sided convention corresponds to 4.3σ after systematic uncertainties are accounted for. Finally, the production rate of the Ω_c^{**0} states relative to the $\Omega_b^- \to \Xi_c^+ K^- \pi^-$ mode is defined as

$$\mathcal{P}_{\Omega_c^{**0}} \equiv \frac{\mathcal{B}(\Omega_b^- \to \Omega_c^{**0}\pi^-)\mathcal{B}(\Omega_c^{**0} \to \Xi_c^+ K^-)}{\mathcal{B}(\Omega_b^- \to \Xi_c^+ K^- \pi^-)}. \quad (1)$$

The rate is measured for the $\Omega_c(3000)^0$, $\Omega_c(3050)^0$, $\Omega_c(3065)^0$ and $\Omega_c(3090)^0$, and an upper limit on the production of the $\Omega_c(3120)^0$ state is set. The results are reported in Table I with the statistical error computed using the binomial distribution.

V. SPIN TEST FOR THE EXCITED Ω_c^0 BARYONS

In order to probe the spin of the Ω_c^{**0} baryons, the distribution of the helicity angle in the $\Omega_b^- \to \Omega_c^{**0}(\to \Xi_c^+ K^-)\pi^-$ decay is studied. The helicity angle θ is defined as the angle between the $\vec{p}_{K^-}$ and the $-\vec{p}_{\pi^-}$ directions in the $\Xi_c^+ K^-$ rest frame, where $\vec{p}$ is the momentum of the meson. The spin projection of the Ω_c^{**0} baryon in the direction of the π^- meson is limited to $1/2$ as it is produced in the $\Omega_b^- \to \Omega_c^{**0}\pi^-$ decay. Additionally, it cannot exceed $1/2$ in the direction of either decay product, Ξ_c^+ or K^-, due to their spins. Therefore, the angular distribution for a Ω_c^{**0} state with spin J is given as

$$I_J(\cos\theta) = \frac{(2J+1)}{2}\Big(|d^J_{1/2,-1/2}(\cos\theta)|^2 + |d^J_{1/2,+1/2}(\cos\theta)|^2\Big), \quad (2)$$

where $d^J_{\nu,\lambda}$ is the Wigner d-function. The first (second) index, ν (λ), gives the spin projections of the Ω_c^{**0} in the direction opposite to the pion (kaon) momentum, $-\vec{p}_{\pi^-}$ ($-\vec{p}_{K^-}$), in the $\Xi_c^+ K^-$ rest frame. The angular distributions are not affected by a possible polarization of the Ω_b^- baryon since its production angles are integrated over. The Ω_c^{**0} candidates are selected in the small nonoverlapping regions around the peaks. The $\cos\theta$ distributions for the Ω_c^{**0} states are shown in Fig. 4. The $\Omega_c(3050)^0$ and $\Omega_c(3065)^0$ distributions show an enhancement at $\cos\theta = -1$, hinting at a preference for a spin larger than $J = 1/2$.

The expectations for the angular density function, $D_J(\cos\theta)$, shown by the colored lines in Fig. 4, are calculated as a sum of the signal PDF and the two background components (combinatorial and nonresonant $\Xi_c^+ K^-$) by

$$D_J(\cos\theta) \equiv f_s I_J(\cos\theta)\epsilon(\cos\theta) + f_b B_1(\cos\theta) + (1 - f_s - f_b)B_2(\cos\theta)\epsilon(\cos\theta), \quad (3)$$

where f_s and f_b are the fractions of the signal and the combinatorial background fixed according to the result of the mass fit. The angular distribution for the combinatorial background, $B_1(\cos\theta)$, is fixed by selecting candidates in the $\Xi_c^+ K^- \pi^-$ mass range above the Ω_b^- peak. A flat distribution is assumed for nonresonant background, $B_2(\cos\theta)$. The efficiency, $\epsilon(\cos\theta)$, is calculated separately for each signal region using simulation. The efficiency maps are combined according to the fraction of the signal candidates in the corresponding data-taking periods. The efficiency for the helicity angle is calculated by convolving the efficiency map with the Ω_c^{**0} line shape profile. The fall of the curves at $\cos\theta = 1$ indicates the smaller reconstruction efficiency for candidates with a low momentum K^- in the Ω_b^- rest frame. Discrimination of different spin hypotheses is based on the likelihood-ratio test statistic,

$$t_{H_J|H_{J'}} = \frac{1}{N}\sum_{i=1}^{N} \log\left[D_{H_J}(\cos\theta_i)/D_{H_{J'}}(\cos\theta_i)\right], \quad (4)$$

where H_J and $H_{J'}$ are the compared hypotheses for the state to have spin J and J', respectively, N is the number of candidates in the mass region around the peak. The test statistic $\vec{t}^{(\mathrm{data})} = (t^{(\mathrm{data})}_{J=1/2|J=3/2}, t^{(\mathrm{data})}_{J=3/2|J=5/2})$ is evaluated in data and compared to the t distribution in simulated pseudoexperiments. A set of 20,000 pseudoexperiments with the number of signal and background events obtained from data are simulated for each spin hypothesis and for every Ω_c^{**0} state. The two-dimensional distribution of t is well described by the multivariate normal distribution from which we extract the covariance matrix and the two-dimensional mean, $t^{(\mathrm{mean})}$. The p-value in the double-tailed convention is calculated by $\exp(-r^2/2)$, where r is the Mahalanobis distance [58] between $\vec{t}^{(\mathrm{data})}$ and $\vec{t}^{(\mathrm{mean})}$. All results are summarized in Table I. The significance of the rejection of the $J = 1/2$ hypothesis for $\Omega_c(3050)^0$ and $\Omega_c(3065)^0$ is 2.2σ and 3.6σ respectively, including systematic effects listed in the next section. The combined hypothesis of the four peaks to have quantum numbers in the order 1/2, 1/2, 3/2, 3/2, is tested and rejected with a significance of 3.5σ.

VI. SYSTEMATIC UNCERTAINTIES

Various systematic uncertainties for each observable are considered, where the largest deviation from the default model on every source is used. A summary of the systematic uncertainties is provided in the supplemental material [59]. The uncertainties from different sources are combined in quadrature. A source of systematic uncertainty

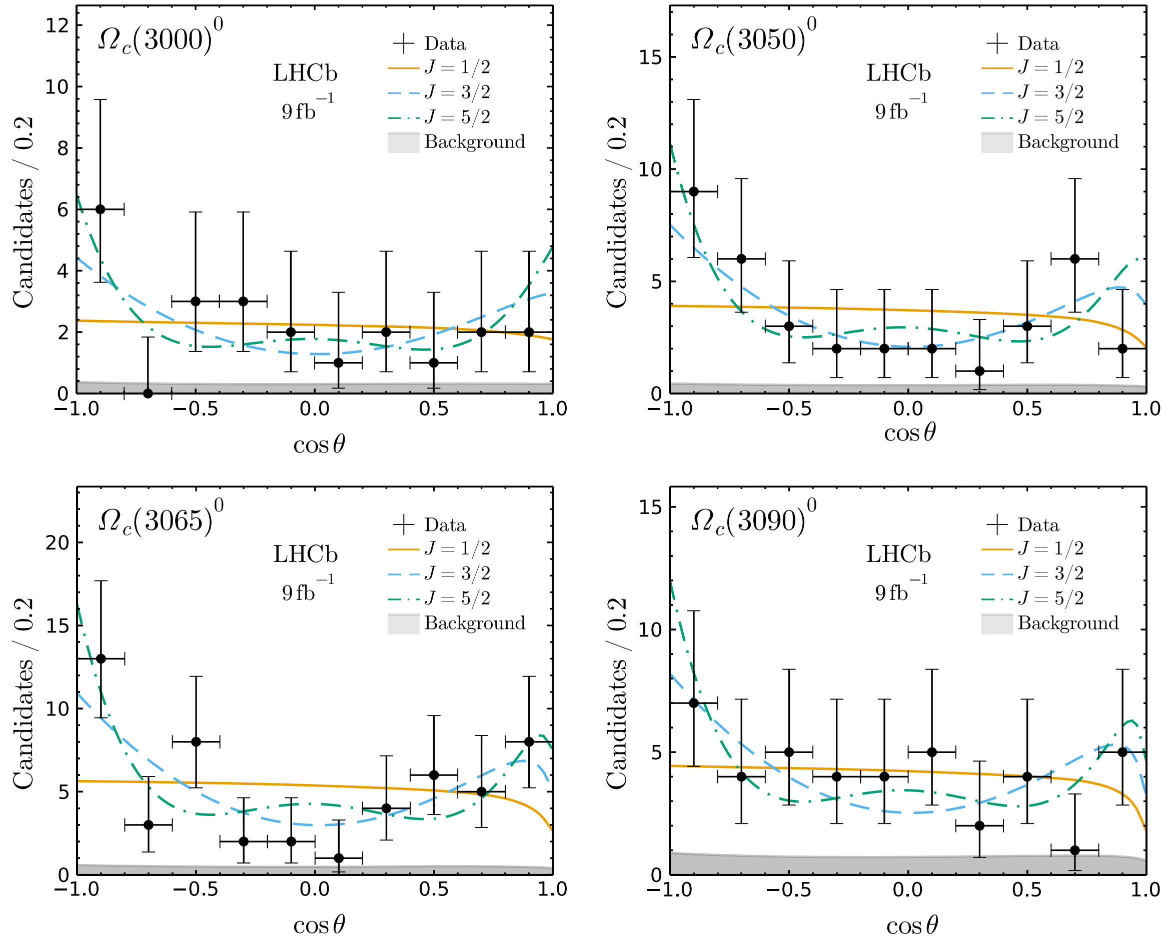

FIG. 4. Distributions of the Ω_c^{**0} helicity angle (θ) in the Ω_b^- decay. Solid, dashed, and dot-dashed lines indicate the expectations under the spin hypotheses, $J = 1/2$, $3/2$, and $5/2$, respectively. The gray shaded area shows the cumulative distribution of the combinatorial and nonresonant $\Xi_c^+ K^-$ backgrounds.

is determined from varying components of the Ω_b^- -fit model. The helicity couplings of the partially reconstructed decays in the $\Omega_c^0 \pi^-$ invariant mass spectrum are modified as well as the shape used to describe the signal peaks. The uncertainty in the yield of misidentified decays is quantified by varying the fractional contribution by $\pm 40\%$ relative to the default value. In simulation, the $\Xi_c^+ \to p K^- \pi^+$ Dalitz plot is generated according to phase space and a binned weighting is performed to match the data. A systematic uncertainty is found by varying the binning scheme.

The uncertainty in the mass measurements due to momentum calibration is determined following Ref. [60] as $\pm 0.03\%$ of the energy released in the decay. The PID variables in simulation are corrected in order to match the PID performance in data. To calculate an uncertainty, a modified weighting is applied to the PID variables. For the uncertainty in the Ω_b^- kinematics, the p_{T} and η of the Ω_b^- candidates, as well as the track multiplicity in simulation, are weighted according to data. Several alternative models are considered for $\Xi_c^+ K^-$ fit. Firstly, the resolution of each Gaussian function is varied by $\pm 10\%$. In addition, different orbital angular momenta ($L = 1$, 2) are tested along with the variation of the Blatt-Weisskopf factors [61,62] from 1.5 to 5 GeV^{-1}. A constant-width BW approximation and the scattering-length approximation are probed for the threshold structure. Lastly, for each signal peak, interference with neighbors and the nonresonant $\Xi_c^+ K^-$ background is tested. The full list of results including systematic uncertainties are listed in Table I.

VII. SUMMARY AND CONCLUSION

In summary, data collected by the LHCb experiment at center of mass energies 7, 8, and 13 TeV corresponding to an integrated luminosity of 9 fb^{-1} are used to observe the new decay mode $\Omega_b^- \to \Xi_c^+ K^- \pi^-$ and to measure its branching fraction relative to the $\Omega_b^- \to \Omega_c^0 \pi^-$ decay mode. A precise measurement of the Ω_b^- mass, $m(\Omega_b^-) = 6044.3 \pm 1.2 \pm 1.1^{+0.19}_{-0.22}$ MeV, is obtained where the first uncertainty is statistical, the second is systematic, and the third asymmetric error is due to the uncertainty in the Ξ_c^+

mass. Averaging with the previous LHCb measurements [63,64], taking correlated systematic uncertainties into account, gives a mass of $m(\Omega_b^-) = 6044.8 \pm 1.3$ MeV, which is the most precise to date.

The investigation of the $\Xi_c^+ K^-$ mass spectrum has revealed four excited Ω_c^0 baryons, $\Omega_c(3000)^0$, $\Omega_c(3050)^0$, $\Omega_c(3065)^0$, $\Omega_c(3090)^0$, and a threshold enhancement as also seen in Ref. [16]. The $\Omega_c(3120)^0$ state is not observed, therefore an upper limit on its production rate is set by scanning the likelihood profile, $\mathcal{P}_{\Omega_c(3120)^0} < 0.03$ at 95% confidence level (CL). Measurements of the Ω_c^{**0} masses and widths, together with an upper limit of $\Gamma_{\Omega_c(3050)^0} < 1.6$ MeV at 95% CL are reported. Their spin assignments are tested based on the distribution of the helicity angle in the decay chain $\Omega_b^- \to \Omega_c^{**0}\pi^-$, $\Omega_c^{**0} \to \Xi_c^+ K^-$. Significance values of excluding the $J = 1/2$ spin hypothesis for $\Omega_c(3050)^0$ and $\Omega_c(3065)^0$ are 2.2σ and 3.6σ, respectively. All results are summarized in Table I. The combined hypothesis on the spin of the four peaks in the order $J = 1/2,\ 1/2,\ 3/2,\ 3/2$, as proposed in several works [20,31,36], is rejected with a p-value corresponding to 3.5 standard deviations once systematic uncertainties are taken into account.

The results of the angular analysis together to the absence of the $\Omega_c(3120)^0$ state in the $\Xi_c^+ K^-$ spectrum in Ω_b^- decays and in $e^+ e^-$ collisions at Belle [17], suggest that the interpretation of the five peaks observed in Ref. [16] as λ-mode excited states might be invalid. In such a scenario, only the four peaks observed in this analysis would be λ-mode excitations (with quantum numbers $J = 1/2,\ 3/2,\ 3/2$, and $5/2$) and a spin $1/2$ λ-mode state would be still to be observed. The non-observation of the $\Omega_c(3120)^0$ baryon would be consistent with the state being either one of the $2S$ doublet, decaying to $\Xi_c^+ K^-$ in P-wave [27,31], or a ρ-mode P-wave excitation with spin $3/2^-$ that requires D-wave between Ξ_c^+ and K^-. Finally, the $\Xi_c^+ K^-$ spectrum also features an excess at the $\Xi_c^+ K^-$ mass threshold. An analogous enhancement was observed in the inclusive $\Xi_c^+ K^-$ spectrum [16] and interpreted as the partially reconstructed decay $\Omega_c(3065)^0 \to \Xi_c'^+(\to \Xi_c^+\gamma)K^-$ with the photon escaping detection. However, such an explanation does not hold here, given that the partially reconstructed decay $\Omega_b^- \to \Xi_c'^+ K^- \pi^-$ does not populate the mass region selected for the exclusive $\Omega_b^- \to \Xi_c^+ K^- \pi^-$ decay. While the current data do not provide enough sensitivity to determine the parameters of the structure, such as the mass, natural width and spin, future data acquired with the upgraded LHCb detector will provide insights to establish its nature.

ACKNOWLEDGMENTS

We express our gratitude to our colleagues in the CERN accelerator departments for the excellent performance of the LHC. We thank the technical and administrative staff at the LHCb institutes. We acknowledge support from CERN and from the national agencies: CAPES, CNPq, FAPERJ and FINEP (Brazil); MOST and NSFC (China); CNRS/IN2P3 (France); BMBF, DFG and MPG (Germany); INFN (Italy); NWO (Netherlands); MNiSW and NCN (Poland); MEN/IFA (Romania); MSHE (Russia); MICINN (Spain); SNSF and SER (Switzerland); NASU (Ukraine); STFC (United Kingdom); DOE NP and NSF (USA). We acknowledge the computing resources that are provided by CERN, IN2P3 (France), KIT and DESY (Germany), INFN (Italy), SURF (Netherlands), PIC (Spain), GridPP (United Kingdom), RRCKI and Yandex LLC (Russia), CSCS (Switzerland), IFIN-HH (Romania), CBPF (Brazil), PL-GRID (Poland) and OSC (USA). We are indebted to the communities behind the multiple open-source software packages on which we depend. Individual groups or members have received support from AvH Foundation (Germany); EPLANET, Marie Skłodowska-Curie Actions and ERC (European Union); A*MIDEX, ANR, Labex P2IO and OCEVU, and Région Auvergne-Rhône-Alpes (France); Key Research Program of Frontier Sciences of CAS, CAS PIFI, CAS CCEPP, Fundamental Research Funds for the Central Universities, and Sci. & Tech. Program of Guangzhou (China); RFBR, RSF and Yandex LLC (Russia); GVA, XuntaGal and GENCAT (Spain); the Royal Society and the Leverhulme Trust (United Kingdom).

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