First Observation of Excited Ω[superscript -][subscript b] States

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Editors' Suggestion

First Observation of Excited Ω_b^- States

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We report four narrow peaks in the $\Xi_b^0 K^-$ mass spectrum obtained using pp collisions at center-of-mass energies of 7, 8, and 13 TeV, corresponding to a total integrated luminosity of 9 fb^{-1} recorded by the LHCb experiment. Referring to these states by their mass, the mass values are $m[\Omega_b(6316)^-] = 6315.64 \pm 0.31 \pm 0.07 \pm 0.50$ MeV, $m[\Omega_b(6330)^-] = 6330.30 \pm 0.28 \pm 0.07 \pm 0.50$ MeV, $m[\Omega_b(6340)^-] = 6339.71 \pm 0.26 \pm 0.05 \pm 0.50$ MeV, $m[\Omega_b(6350)^-] = 6349.88 \pm 0.35 \pm 0.05 \pm 0.50$ MeV, where the uncertainties are statistical, systematic, and the last is due to the knowledge of the Ξ_b^0 mass. The natural widths of the three lower mass states are consistent with zero, and the 90% confidence-level upper limits are determined to be $\Gamma[\Omega_b(6316)^-] < 2.8$ MeV, $\Gamma[\Omega_b(6330)^-] < 3.1$ MeV and $\Gamma[\Omega_b(6340)^-] < 1.5$ MeV. The natural width of the $\Omega_b(6350)^-$ peak is $1.4^{+1.0}_{-0.8} \pm 0.1$ MeV, which is 2.5σ from zero and corresponds to an upper limit of 2.8 MeV. The peaks have local significances ranging from 3.6σ to 7.2σ. After accounting for the look-elsewhere effect, the significances of the $\Omega_b(6316)^-$ and $\Omega_b(6330)^-$ peaks are reduced to 2.1σ and 2.6σ, respectively, while the two higher mass peaks exceed 5σ. The observed peaks are consistent with expectations for excited Ω_b^- resonances.

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The study of hadrons containing heavy (b or c) quarks has undergone a renaissance over the last couple of decades. During this time a plethora of new states have been observed, including candidates for four-quark (tetraquark) states, and more recently five-quark (pentaquark) states [1–3] (see Refs. [4–6] for recent reviews). In addition, a number of observations of peaking structures in the invariant-mass spectra of final states containing $\Xi_c^+ K^-$ [7], $\Xi_b^0 \pi^-$ [8], $\Lambda_b^0 \pi^-$ [9], and $\Lambda_b^0 \pi^+ \pi^-$ [10,11] have provided valuable experimental information to improve our understanding of quantum chromodynamics (QCD), the theory of the strong interaction.

Fueled by these observations, there has been a renewed interest in gaining a deeper theoretical understanding of hadronic structure. The constituent quark model [12,13] has been very successful in describing the types of hadrons that form in nature and how they fit into multiplets [14] based on the quantum numbers of the states. While conventional baryons are understood to be states that contain three valence quarks, a deep understanding of how best to describe these and other multiquark states in terms of their fundamental constituents is still an open question. For example, in QCD, two quarks can exhibit attraction when in a $J^P = 0^+$ quantum state, giving rise to the notion that conventional baryons can be described as the bound state of a quark and a qq' diquark [15,16]. These ideas are naturally extensible to describe tetraquark and pentaquark candidates [4–6].

Recently, the LHCb experiment observed five narrow states, assumed to be excited Ω_c^0 baryons, which decay into $\Xi_c^+ K^-$ [7]. These states have been analyzed from the perspective of constituent quark models and lattice QCD [17–30,30–33], quark-diquark models [34–44], as well as molecular models [45–50] and pentaquark states [51–53]. Several of the models that seek to describe these peaks also make predictions for $\Xi_b^0 K^-$ resonances. Since the quark contents of the Ω_c^0 and Ω_b^- baryons are css and bss, respectively, it is of great interest to search for analogous states in the $\Xi_b^0 K^-$ mass spectrum.

This Letter reports on a search for narrow resonances in the $\Xi_b^0 K^-$ mass spectrum close to the kinematic threshold. The search uses data collected in pp collisions with the LHCb detector at center-of-mass energies of 7, 8, and 13 TeV, corresponding to integrated luminosities of 1, 2, and 6 fb^{-1}, respectively. Charge-conjugate processes are implicitly included, and natural units with $\hbar = c = 1$ are used throughout.

The LHCb detector [54,55] is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, designed for the study of particles containing b or c quarks. Events are selected online by a trigger, which consists of a hardware stage, based on information from the calorimeter and muon systems, followed by a software stage, which

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applies a full event reconstruction [56,57]. Simulated data samples are produced using the software packages described in Refs. [58–64], and are used to optimize selection requirements and to quantify the invariant-mass resolution of the LHCb detector.

Samples of Ξ_b^0 candidates are formed by pairing Ξ_c^+ and π^- candidates, where the Ξ_c^+ decays are reconstructed in the $pK^-\pi^+$ final state. All final-state hadrons must have particle-identification (PID) information consistent with the assigned particle hypothesis. The final-state particles are also required to be inconsistent with originating from a primary pp collision vertex (PV) by requiring that they have large $\chi^2_{\rm IP}$ with respect to all PVs in the event. The quantity $\chi^2_{\rm IP}$ is the difference in χ^2 of the vertex fit of a given PV when the particle (here p, K^-, or π^+) is included and excluded from the fit.

The Ξ_c^+ candidates must have a fitted vertex that is significantly displaced from all PVs in the event and have an invariant mass within 18 MeV of the known Ξ_c^+ mass [14]. About 20% of the Ξ_c^+ background comprises misidentified $D^+ \to K^-\pi^+\pi^+$, $D^+ \to K^+K^-\pi^+$, $D_s^+ \to K^+K^-\pi^+$, and $D^{*+} \to (D^0 \to K^-\pi^+)\pi^+$ decays, as well as misidentified ϕ mesons with $\phi \to K^+K^-$ combined with an additional particle from elsewhere in the event. These background contributions are removed by employing tighter PID requirements on candidates that are consistent with any of these decay hypotheses, resulting in about 1% loss of signal efficiency. The $pK^-\pi^+$ invariant-mass distribution of Ξ_c^+ candidates satisfying these selection requirements is shown in Fig. 1 (left).

The Ξ_b^0 candidates are formed from $\Xi_c^+\pi^-$ combinations that have a significantly displaced decay vertex from all PVs in the event and a trajectory that is consistent with originating from one of them. The PV for which the Ξ_b^0 candidate has the smallest $\chi^2_{\rm IP}$ is assigned to be the associated PV, and it is used subsequently to compute quantities such as the Ξ_b^0 decay time. Candidates satisfying the requirement $5.6 < M(\Xi_c^+\pi^-) < 6.0$ GeV are retained, where M designates the invariant mass of the system.

To further suppress background in the $\Xi_b^0 \to \Xi_c^+\pi^-$ sample, a boosted decision tree (BDT) discriminant [65] is used. The BDT exploits 21 input variables: the decay times of the Ξ_c^+ and Ξ_b^0 candidates and the χ^2 values associated with their decay-vertex fits; the angle between the Ξ_b^0 momentum vector and the line that joins the Ξ_b^0 decay vertex and its associated PV; and for each final state particle the momentum, transverse momentum, $\chi^2_{\rm IP}$, and a PID response variable. The PID response for final-state hadrons in the signal decay is obtained from large $D^{*+} \to (D^0 \to K^-\pi^+)\pi^+$ and $\Lambda \to p\pi^-$ calibration samples in data [66,67]. Simulated signal decays and background from the Ξ_c^+ mass sidebands $(30 < |M(pK^-\pi^+) - m_{\Xi_c^+}| < 50\,\text{MeV})$ in data are used to train the BDT, where m refers to the mass of the indicated particle [14]. The chosen requirement on the BDT response provides a relative signal efficiency of 90%, and reduces the combinatorial background by about a factor of 2.5. Overall, the off-line selection requirements are about 75% efficient on simulated decays, while reducing the background by about a factor of 40.

Figure 1 (right) shows the $\Xi_c^+\pi^-$ mass spectrum for candidates passing the above selection criteria. The spectrum is fit with the sum of two Crystal Ball [68] functions with a common mean and opposite-side power-law tails to model the signal, and an exponential function to describe the background distribution. The fitted Ξ_b^0 signal yield is 19200 ± 200.

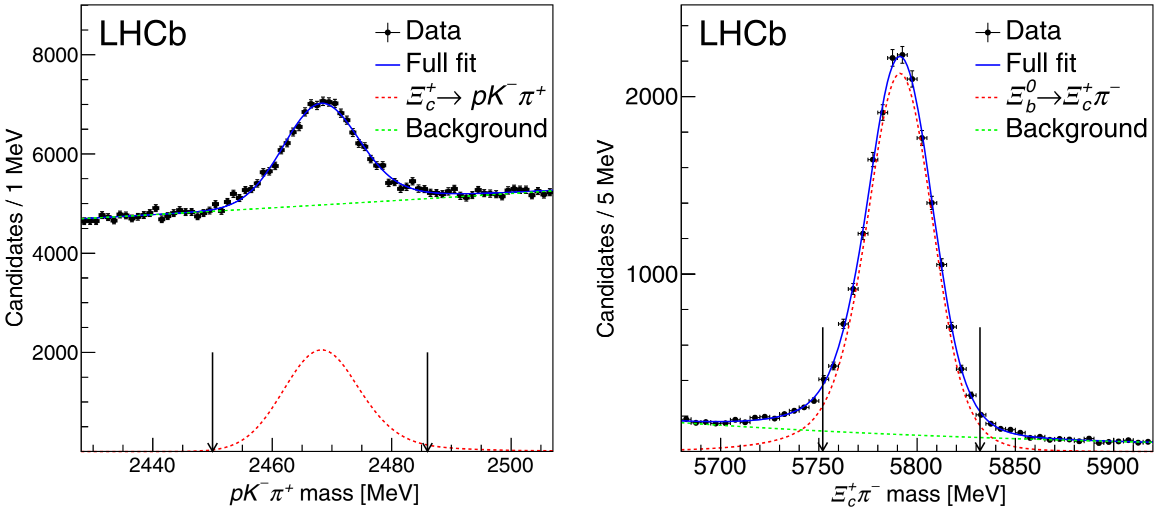

FIG. 1. Invariant-mass spectrum for (left) $\Xi_c^+ \to pK^-\pi^+$ and (right) $\Xi_b^0 \to \Xi_c^+\pi^-$ candidates in data passing the selection requirements described in the text. The arrows indicate the requirements on the invariant masses that are applied in the subsequent stages of the analysis.

To search for peaking structures in the $\Xi_b^0 K^-$ mass spectrum, a requirement that $|M(\Xi_c^+\pi^-) - m_{\Xi_b^0}| < 40\,\mathrm{MeV}$ is imposed, which reduces the number of Ξ_b^0 signal decays to about 18 000. Each Ξ_b^0 candidate is combined with a K^- candidate that is consistent with originating from a PV in the event. The Ξ_b^0 and K^- trajectories are fitted to a common vertex, and that vertex is kinematically constrained to coincide with the PV associated with the Ξ_b^0 candidate [69]. The additional PV constraint improves the resolution on the mass difference $\delta M \equiv M(\Xi_b^0 K^-) - M(\Xi_b^0)$ by about a factor of 2.

Random combinations of Ξ_b^0 baryons with a K^- candidate are the largest source of background in the $\Xi_b^0 K^-$ mass spectrum. To improve the expected signal-to-background ratio, a figure of merit, $\epsilon/(\sqrt{B} + 5/2)$ [70], is used to optimize the requirements on the PID information of the K^- candidates. Here, ϵ is the efficiency as determined from simulation, and B is the number of wrong-sign $\Xi_b^0 K^+$ combinations in the region $520 < \delta M < 570$ MeV passing the PID requirement, scaled to a 10 MeV mass window. The 10 MeV width is chosen based on the search for narrow peaks, since the low signal yields expected would make wide peaks difficult to separate from the combinatorial background. The optimal requirement on the K^- PID provides an efficiency of about 85% and suppresses the background by a factor of about 2.5.

The decay of a resonance to $\Xi_b^0 K^-$ will produce peaks in the δM spectrum. The experimental δM resolution is obtained from simulated samples generated at several masses, m_{res}. The resolution function is described by the sum of two Gaussian functions with a common mean. In addition, the width of the narrower Gaussian component, σ_{core}, is fixed to be 45% of that of the wider component, and its contribution is required to constitute 80% of the total shape. A smooth, monotonically increasing function, denoted as $\sigma(m_{\mathrm{res}})$, is then used to parameterize σ_{core} as a function of m_{res}. In the δM interval of interest, $\sigma(m_{\mathrm{res}})$ is in the range of 0.7–0.8 MeV.

The δM distributions for right-sign (RS) and wrong-sign (WS) candidates are shown in Fig. 2, along with fits to the

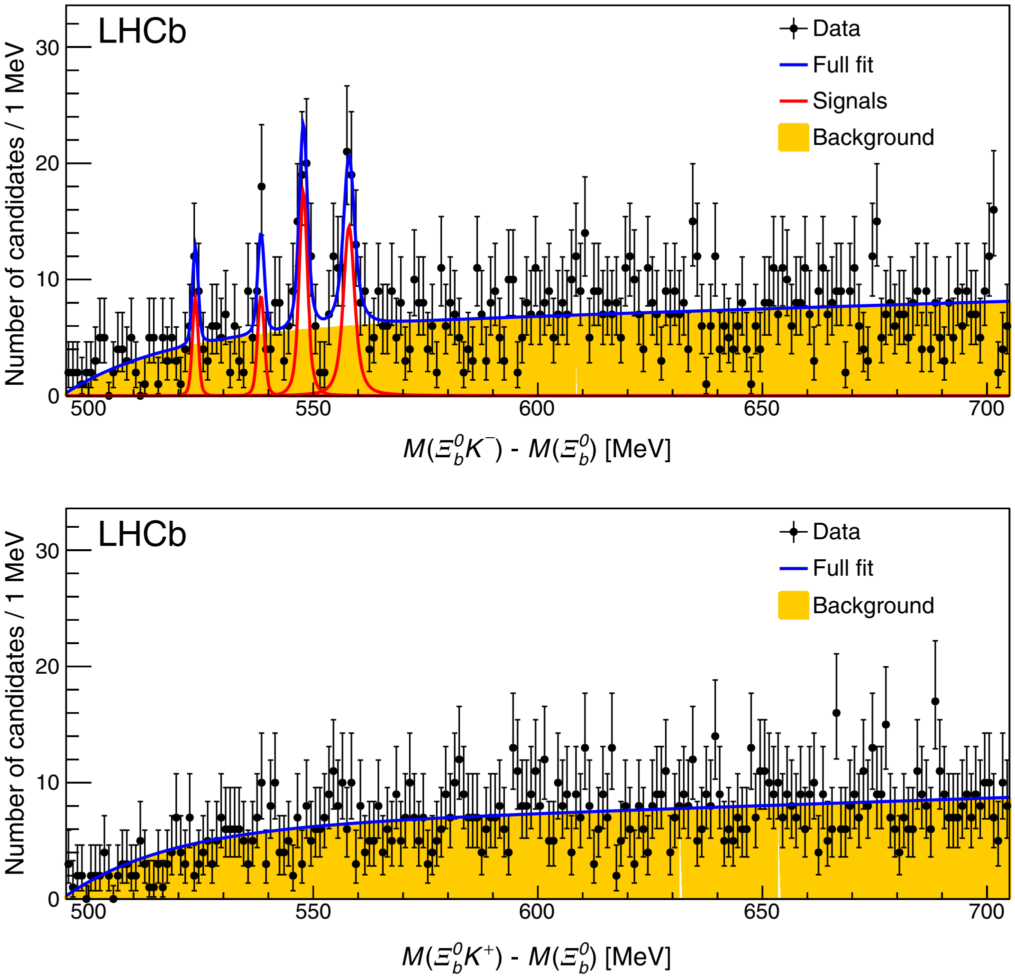

FIG. 2. Distribution of the mass difference for (top) right-sign $\Xi_b^0 K^-$ candidates, and (bottom) wrong-sign $\Xi_b^0 K^+$ candidates, as described in the text.

TABLE I. Peak positions, widths, signal yields, and local and global significances of the four mass peaks observed in the $\Xi_b^0 K^-$ mass spectra, as described in the text. The uncertainties are statistical only.

Peak of δM [MeV]	Width [MeV]	Signal yield	Significances [σ] Local	Global
523.74 ± 0.31	$0.00^{+0.7}_{-0.0}$	15^{+6}_{-5}	3.6	2.1
538.40 ± 0.28	$0.00^{+0.4}_{-0.0}$	18^{+6}_{-5}	3.7	2.6
547.81 ± 0.26	$0.47^{+0.6}_{-0.5}$	47^{+11}_{-10}	7.2	6.7
557.98 ± 0.35	$1.4^{+1.0}_{-0.8}$	57^{+14}_{-13}	7.0	6.2

TABLE II. Systematic uncertainties on the measured peak positions in the $\delta M = M(\Xi_b^0 K^-) - M(\Xi_b^0)$ spectrum. The peaks are numbered in order of increasing mass.

Source	Peak 1 [MeV]	Peak 2 [MeV]	Peak 3 [MeV]	Peak 4 [MeV]
Momentum scale	0.01	0.02	0.02	0.03
Energy loss	0.04	0.04	0.04	0.04
Signal shape	0.02	0.02	0.02	0.02
Background	0.05	0.05	0.01	0.01
Total	0.07	0.07	0.05	0.05

spectra as described below. Four peaks are seen in the RS spectrum of $\Xi_b^0 K^-$ candidates (red curves), whereas no significant peaks are seen in the corresponding WS $\Xi_b^0 K^+$ distribution. To obtain the parameters of the peaks, a simultaneous unbinned extended maximum-likelihood fit is performed to the RS and WS spectra. Each signal peak is described by an S-wave relativistic Breit-Wigner function [71] with a Blatt-Weisskopf barrier factor [72], convoluted with the resolution function $\sigma(m_{\rm res})$ described above. A common background shape is used to describe both the RS and WS spectra, and is described by a smooth three-parameter monotonic function that accounts for the $\Xi_b^0 K^-$ threshold.

The peak values of δM, natural widths, signal yields, and the local and global significances are summarized in Table I. The local significance is obtained as $\mathcal{S}_{\rm data} = \sqrt{2\log(\mathcal{L}_{\rm max}/\mathcal{L}_0)}$, where $\mathcal{L}_{\rm max}$ is the maximum value of the fit likelihood and $\mathcal{L}_0$ is the value obtained when a given peak's yield is fixed to zero. All peaks have natural width consistent with zero. The highest-mass peak has the largest width, which differs from zero by 2.5 standard deviations, as determined from a likelihood scan of the width parameter.

To account for the look-elsewhere effect [73], which considers that the peak search extends over about a 200 MeV wide mass region, a large number of pseudoexperiments (pe) are generated. The pseudoexperiments use the nominal parameters from the fit to the data, with the signal yield of each peak, in turn, set to zero. The full mass region is scanned in 0.5 MeV steps to identify the most significant positive fluctuation outside of the region of the three retained peaks, from which the significance $\mathcal{S}_{\rm pe}$ is computed. From the corresponding distribution of $\mathcal{S}_{\rm pe}$ and the value $\mathcal{S}_{\rm data}$, a p value—expressed in Gaussian standard deviations—is obtained for each peak, as shown in Table I.

The sources of systematic uncertainty that affect the measured masses are summarized in Table II. The momentum scale uncertainty is assessed by shifting the momentum scale of all charged tracks by ±0.03% [74] in simulated decays, and evaluating the change in δM. The imperfect modeling of the energy loss in the detector material results in a systematic uncertainty of 0.04 MeV [75]. The uncertainty due to the choice of signal model is assigned by fitting the data with an alternative signal model composed of two Gaussian functions with a common mean. The largest change, 0.02 MeV, is assigned as a systematic uncertainty to all of the peak positions. The background shape uncertainty is assessed by removing the influence of the WS data on the background shape, and fitting only the RS data; the difference in the peak positions with respect to the nominal fit is assigned as a systematic uncertainty. The relativistic Breit-Wigner signal shape in the nominal fit assumes that the decay proceeds through an S wave, with an interaction radius in the Blatt-Weisskopf barrier factor of $R = 3\ \mathrm{GeV}^{-1}$. Changing the angular momentum in the decay to $L = 2$ (D wave), and separately varying R between 1 and 5 GeV^{-1}, leads to a negligible change in the peak positions. For the absolute mass determination, the world-average Ξ_b^0 mass of 5791.9 ± 0.5 MeV [14] is used. The uncertainty of 0.5 MeV on this mass dominates the systematic uncertainty and is quoted separately in the final results.

The primary source of systematic uncertainty on the natural widths of the observed peaks is from an imperfect knowledge of the δM resolution, which is obtained from simulation. Based on previous studies of $D^{*+} \to D^0 \pi^+$ decays [76], the δM resolution in simulation agrees with that of data within 10%. The impact of a ±10% variation in the resolution is evaluated using pseudoexperiments, where each experiment is generated using the nominal signal resolution function, and fitted with a 10% smaller or larger δM resolution. Deviations of ±0.10 MeV relative to the true value of the width are found for a range of input widths corresponding to that which is observed in data. The upper limits on the natural width of the observed peaks are evaluated by convoluting the likelihoods with this 0.10 MeV uncertainty, and finding the values of the widths that contain 90% and 95% of the integrated probability. For both the mass differences and widths, the total uncertainty is dominated by the statistical component.

The measured masses and widths of the four peaks in the $\Xi_b^0 K^-$ mass spectrum are summarized in Table III. They are

TABLE III. Summary of the peak parameters of the four peaks, showing the peak positions of $\delta M = M(\Xi_b^0 K^-) - M(\Xi_b^0)$, the masses, and 90% (95%) confidence level upper limits on the natural widths. The indicated uncertainties are statistical, systematic, and due to the world-average value of the Ξ_b^0 mass (for the masses). For the $\Omega_b(6350)^-$ peak, the central value of the width is also indicated.

	δM_{peak} [MeV]	Mass [MeV]	Width [MeV]
$\Omega_b(6316)^-$	$523.74 \pm 0.31 \pm 0.07$	$6315.64 \pm 0.31 \pm 0.07 \pm 0.50$	$<2.8(4.2)$
$\Omega_b(6330)^-$	$538.40 \pm 0.28 \pm 0.07$	$6330.30 \pm 0.28 \pm 0.07 \pm 0.50$	$<3.1(4.7)$
$\Omega_b(6340)^-$	$547.81 \pm 0.26 \pm 0.05$	$6339.71 \pm 0.26 \pm 0.05 \pm 0.50$	$<1.5(1.8)$
$\Omega_b(6350)^-$	$557.98 \pm 0.35 \pm 0.05$	$6349.88 \pm 0.35 \pm 0.05 \pm 0.50$	$<2.8(3.2)$ $1.4^{+1.0}_{-0.8} \pm 0.1$

qualitatively similar to those observed in the $\Xi_c^+ K^-$ mass spectrum [7]. Arguably, the simplest interpretation of these peaks is that they correspond to excited Ω_b^- states, in particular the $L = 1$ angular momentum excitations of the ground state, or possibly $n = 2$ radial excitations. Many of the quark model calculations predict $L = 1$ states in this mass region [17–26,28,33], and at least some of the states should be narrow [21,23,33]. In particular, using the ${}^3P_0$ model, five states in this mass region are predicted, with approximately 8 MeV mass splittings; the four lightest have partial width, $\Gamma(\Xi_b^0 K^-)$, below 1 MeV, while that with the largest mass has $\Gamma(\Xi_b^0 K^-) = 1.49$ MeV [23]. On the other hand, predictions using the chiral quark-model indicate that the $J^P = \frac{3}{2}^-$ and $\frac{5}{2}^-$ states are narrow, but the $\frac{1}{2}^-$ states are wide, in the 50–100 MeV range [33].

Quark-diquark models have also predicted several excited Ω_b^- states in the region around 6.3 GeV [34,35,42,77], with mass splittings similar to those observed here. In an implementation of the ${}^3P_0$ model, the $J^P = \frac{3}{2}^-$ and $\frac{3}{2}^-$ are predicted to be narrow [77]. Molecular models have also been employed, where two narrow $J^P = \frac{1}{2}^-$ states are predicted at 6405 and 6465 MeV [78]; no statistically significant peaks are seen at those masses with the current dataset.

An alternate interpretation for one or more of the observed peaks is that they arise from the decay of a higher-mass excited Ω_b^- state, $\Omega_b^{**-} \to \Xi_b'^0 (\to \Xi_b^0 \pi^0) K^-$, where the π^0 meson is undetected. While the $\Xi_b'^-$, Ξ_b^{*-} [76], and Ξ_b^{*0} [79,80] baryons have been observed, the $\Xi_b'^0$ resonance is yet to be seen. If the $\Xi_b'^0$ mass is in the interval $m_{\Xi_b^0} + m_{\pi^0} < m_{\Xi_b'^0} < m_{\Xi_b'^-}$, each of the observed narrow peaks can be interpreted as having originated from the above decay, provided that the corresponding Ω_b^{**-} state is narrow. In this case, their masses can be evaluated as $m_{\Omega_b^{**-}} = m_{\Xi_b'^0} + \delta M_{\text{peak}}$, where the values of δM_{peak} are taken from Table III. If the $\Xi_b'^0$ baryon can only decay electromagnetically to $\Xi_b^0 \gamma$, then the $\Xi_b^0 K^-$ peaks would be significantly broader and inconsistent with our data.

In summary, pp collision data collected with the LHCb experiment at center-of-mass energies of 7, 8, and 13 TeV, corresponding to integrated luminosities of 1, 2, and 6 fb^{-1}, respectively, have been used to search for near-threshold $\Xi_b^0 K^-$ resonances. Four new peaks are seen. Two of the peaks, the $\Omega_b(6340)^-$ and $\Omega_b(6350)^-$, are observed with global (local) significance of 6.7 (7.2) and 6.2 (7.0), respectively, while the two lower-mass peaks have global (local) significance of 2.1 (3.6) and 2.6 (3.7). The peaks are consistent with expectations for excited Ω_b^- resonances.

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