

Observation of New Resonances in the $\Lambda_b^0\pi^+\pi^-$ SystemR. Aaij *et al.**
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We report the observation of a new structure in the $\Lambda_b^0\pi^+\pi^-$ spectrum using the full LHCb data set of pp collisions, corresponding to an integrated luminosity of 9 fb^{-1} , collected at $\sqrt{s} = 7, 8, \text{ and } 13\text{ TeV}$. A study of the structure suggests its interpretation as a superposition of two almost degenerate narrow states. The masses and widths of these states are measured to be $m_{\Lambda_b(6146)^0} = 6146.17 \pm 0.33 \pm 0.22 \pm 0.16\text{ MeV}$, $m_{\Lambda_b(6152)^0} = 6152.51 \pm 0.26 \pm 0.22 \pm 0.16\text{ MeV}$, $\Gamma_{\Lambda_b(6146)^0} = 2.9 \pm 1.3 \pm 0.3\text{ MeV}$, $\Gamma_{\Lambda_b(6152)^0} = 2.1 \pm 0.8 \pm 0.3\text{ MeV}$, with a mass splitting of $\Delta m = 6.34 \pm 0.32 \pm 0.02\text{ MeV}$, where the first uncertainty is statistical, the second systematic. The third uncertainty for the mass measurements derives from the knowledge of the mass of the Λ_b^0 baryon. The measured masses and widths of these new excited states suggest their possible interpretation as a doublet of $\Lambda_b(1D)^0$ states.

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In the constituent quark model [1,2], baryons containing a beauty quark form multiplets according to the internal symmetries of flavor, spin, and parity [3]. Beyond the Λ_b^0 baryon, which is the lightest beauty baryon, a rich spectrum of radially and orbitally excited states is expected at higher masses. Several new baryon states have been discovered in recent years [4–8]. The spectrum of excited states decaying to the $\Lambda_b^0\pi^+\pi^-$ final state has already been studied by the LHCb experiment with the discovery of two narrow states [4], denoted $\Lambda_b(5912)^0$ and $\Lambda_b(5920)^0$. The heavier of these states was later confirmed by the CDF collaboration [9]. Mass predictions for the ground-state beauty baryons and their orbital and radial excitations are given in many theoretical works, e.g., Refs. [10–13]. In addition to the already observed doublet of first orbital excitations, more states are predicted in the mass region near or above 6.1 GeV (natural units with $c = \hbar = 1$ are used throughout this Letter).

In this Letter, we document the study of the $\Lambda_b^0\pi^+\pi^-$ spectrum (charge conjugation is implied throughout this Letter) in the extended mass region between 6.10 and 6.25 GeV, using pp collision data collected by the LHCb experiment at center-of-mass energies of 7, 8, and 13 TeV. The combined data set corresponds to an integrated luminosity of 9 fb^{-1} .

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The LHCb detector [14,15] 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 [16], 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 [17] 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. The momentum scale of the tracking system is calibrated using samples of $J/\psi \rightarrow \mu^+\mu^-$ and $B^+ \rightarrow J/\psi K^+$ decays collected concurrently with the data sample used for this analysis [18,19]. The relative accuracy of this procedure is estimated to be 3×10^{-4} using samples of other fully reconstructed b hadron, K_S^0 , and narrow $\Upsilon(1S)$ resonance decays. Different types of charged hadrons are distinguished using information from two ring-imaging Cherenkov detectors [20]. The online event selection is performed by a trigger [21] 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. The software trigger requires a two-, three- or four-track secondary vertex with significant displacement from all primary pp interaction vertices. A multivariate algorithm [22] is used for the identification of secondary vertices consistent with the decay of a b hadron. Simulated data samples are produced using the software packages described in Refs. [23–29].

Samples of Λ_b^0 candidates are formed from $\Lambda_c^+\pi^-$ combinations, where the Λ_c^+ baryon is reconstructed in the $pK^-\pi^+$ final state. All charged final-state particles are

required to have particle-identification information consistent with their respective mass hypotheses. Misreconstructed tracks are suppressed by the use of a neural network [30]. To suppress prompt background, the Λ_b^0 decay products are required to have significant χ_{IP}^2 with respect to all primary vertices (PVs) in the event, where χ_{IP}^2 of a particle is the difference in χ^2 of the vertex fit of a given PV, when the particle is included or excluded from the fit. The reconstructed Λ_c^+ vertex is required to have a good fit quality and to be significantly displaced from all PVs. The reconstructed Λ_c^+ mass must be within a mass window of ± 25 MeV of the known value [31]. Pion candidates are combined with Λ_c^+ candidates to form Λ_b^0 candidates, requiring good vertex-fit quality and separation of the Λ_b^0 decay point from any PV in the event. A boosted decision tree (BDT) discriminant [32,33] is used to further reduce the background level. The BDT exploits fifteen variables, including kinematic variables of the Λ_c^+ and Λ_b^0 candidates, the lifetime of the Λ_b^0 candidate, kinematic variables and quality of particle identification for the final-state pions, kaons, and protons, and variables describing the consistency of the selected candidates with the $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$ decay of a Λ_b^0 baryon [34]. The BDT is trained using background-subtracted [35] Λ_b^0 candidates as a signal sample and Λ_b^0 candidates from the data sidebands, in the $\Lambda_c^+ \pi^-$ mass range $5.7 < m_{\Lambda_c^+ \pi^-} < 6.1$ GeV, as a background sample. The k -fold cross-validation technique with $k = 11$ is used in the BDT training [36]. The use of a multivariate discriminant allows the small level of Λ_b^0 background candidates in the analysis to be reduced by a further factor of 2, keeping almost 100% efficiency for the signal. The resulting yield of $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$ decays is $(892.8 \pm 1.2) \times 10^3$. A sample of $\Lambda_b^0 \rightarrow J/\psi p K^-$ candidates, with $J/\psi \rightarrow \mu^+ \mu^-$, is also selected in a similar way as a cross-check. The yield for this decay mode is smaller, corresponding to $(217.5 \pm 0.7) \times 10^3$ decays. The mass spectra of the selected $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$ and $\Lambda_b^0 \rightarrow J/\psi p K^-$ candidates are shown in Fig. S1 of the Supplemental Material [37] of this Letter.

The selected Λ_b^0 candidates are combined with pairs of pions compatible with originating from the same PV as the Λ_b^0 candidate. Only pion pairs with $p_T^{\pi^+ \pi^-} > 500$ MeV are used, to suppress the otherwise large combinatorial background from soft dipion combinations. This background is further reduced by using a dedicated BDT discriminant tuned on each of the two samples with $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$ and $\Lambda_b^0 \rightarrow J/\psi p K^-$ decays. It exploits the transverse momentum of the $\Lambda_b^0 \pi^+ \pi^-$ combination, the χ^2 value for the $\Lambda_b^0 \pi^+ \pi^-$ vertex, the transverse momenta of both individual pions, and the pion pair, as well as particle-identification and reconstruction-quality [30] variables for both pions. The BDT is trained on simulated samples of excited beauty baryons with a mass of 6.15 GeV as signal and *same-sign*

$\Lambda_b^0 \pi^+ \pi^-$ combinations in data, with $m_{\Lambda_b^0 \pi^+ \pi^-} < 6.22$ GeV, as background. In simulation, unpolarized production of excited beauty baryons is assumed, followed by decays to the $\Lambda_b^0 \pi^+ \pi^-$ final state according to a three-body phase-space decay model.

In order to improve the $\Lambda_b^0 \pi^+ \pi^-$ mass resolution, the $\Lambda_b^0 \pi^+ \pi^-$ combinations are refitted constraining the masses of the Λ_c^+ baryon (or J/ψ meson) to their known values [31] and requiring consistency of the $\Lambda_b^0 \pi^+ \pi^-$ vertex with the PV associated with the Λ_b^0 candidate [34]. The mass of the Λ_b^0 baryon in the fit is constrained to the central value of $m_{\Lambda_b^0} = 5618.62 \pm 0.16 \pm 0.13$ MeV [38], obtained from a combination of the measurements of the Λ_b^0 mass in $\Lambda_b^0 \rightarrow \chi_{c1,2} p K^-$ [38], $\Lambda_b^0 \rightarrow \psi(2S) p K^-$, $\Lambda_b^0 \rightarrow J/\psi \pi^+ \pi^- p K^-$ [39] and $\Lambda_b^0 \rightarrow J/\psi \Lambda$ decay modes [18,40] by the LHCb Collaboration. The mass distributions for selected $\Lambda_b^0 \pi^+ \pi^-$ candidates are shown in Fig. 1. Only Λ_b^0 candidates with a mass within $\pm 50(20)$ MeV (approximately 3 times the resolution) of the known Λ_b^0 mass for $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$ ($\Lambda_b^0 \rightarrow J/\psi p K^-$) candidates are used. There is a clear excess of $\Lambda_b^0 \pi^+ \pi^-$ candidates around 6.15 GeV over the background for both Λ_b^0 decay modes. The excess is initially treated as originating from a single broad state. The distributions are parametrized by the sum of signal and background components. The signal component is modeled by a relativistic S-wave Breit-Wigner function with Blatt-Weisskopf form factors [41]. The relativistic Breit-Wigner function is convolved with the detector resolution described by the sum of two Gaussian functions with common mean and parameters, which are fixed from simulation. The obtained

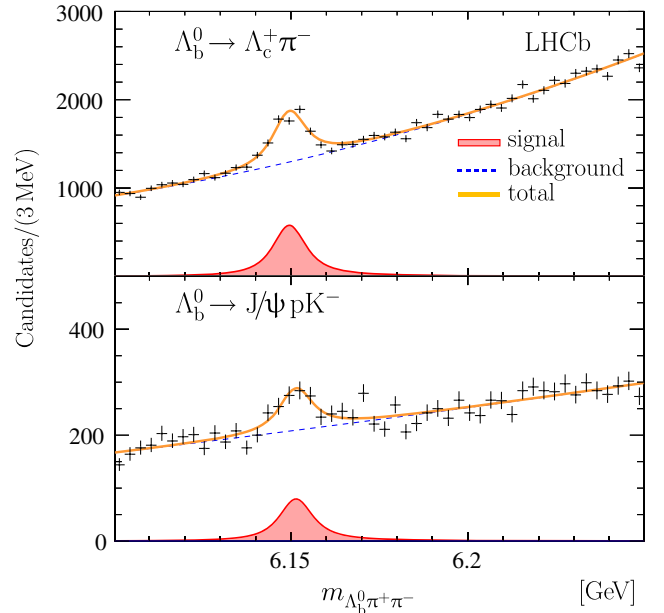


FIG. 1. Mass distribution of selected $\Lambda_b^0 \pi^+ \pi^-$ candidates for the (top) $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$ and (bottom) $\Lambda_b^0 \rightarrow J/\psi p K^-$ decay modes.

TABLE I. The yields, N , masses, m , and natural widths, Γ , from the fits of a single broad state to the $\Lambda_b^0 \pi^+ \pi^-$ mass spectra.

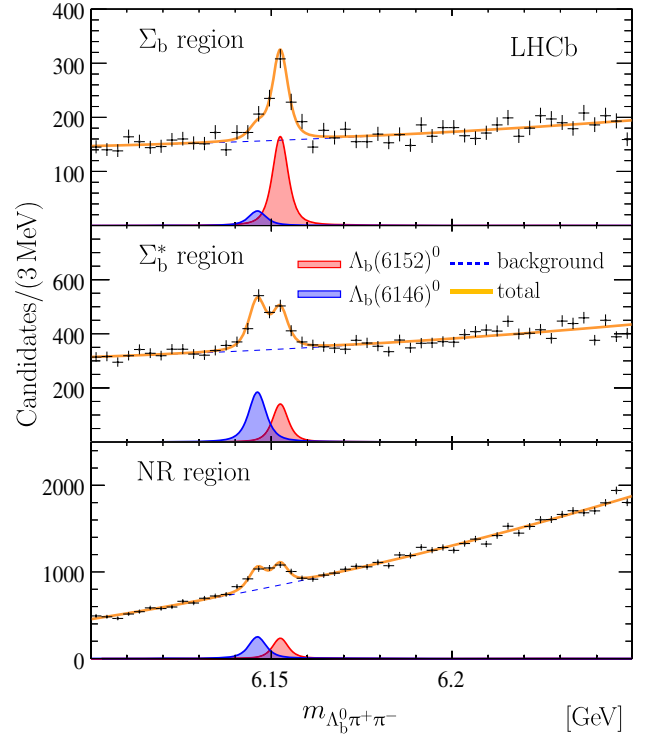
	$\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$	$\Lambda_b^0 \rightarrow J/\psi p K^-$
$N_{\Lambda_b^0 \pi^+ \pi^-}$	3117 ± 240	431 ± 97
$m[\text{MeV}]$	6149.64 ± 0.34	6151.51 ± 0.97
$\Gamma[\text{MeV}]$	9.61 ± 0.98	9.67 ± 2.89

effective resolution (rms) is 1.7 MeV. The background component is parametrized with a second-order polynomial function. Extended unbinned maximum-likelihood fits to the $\Lambda_b^0 \pi^+ \pi^-$ mass spectra are shown in Fig. 1. The corresponding parameters of interest are listed in Table I.

The mass and width of the structure agree between the $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$ and $\Lambda_b^0 \rightarrow J/\psi p K^-$ samples. The statistical significance for the signals is estimated using Wilks' theorem [42]. It is found to exceed 26 and 9 standard deviations for the $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$ and $\Lambda_b^0 \rightarrow J/\psi p K^-$ decay modes, respectively. The fitted parameters exhibit very modest dependence on the choice of the orbital momentum for the relativistic Breit-Wigner function and the Blatt-Weiskopf breakup momenta [41]. The signal yields, masses, and widths are found to be consistent for the different data-taking periods and between the $\Lambda_b^0 \pi^+ \pi^-$ and $\bar{\Lambda}_b^0 \pi^+ \pi^-$ final states.

Since the mass of the new structure is above the $\Sigma_b^{(*)\pm} \pi^\mp$ kinematic thresholds, the $\Lambda_b^0 \pi^+ \pi^-$ mass spectrum is investigated in $\Lambda_b^0 \pi^\pm$ mass regions populated by the $\Sigma_b^{(*)\pm}$ resonances. The data are split into three nonoverlapping regions: candidates with a $\Lambda_b^0 \pi^\pm$ mass within the natural width of the known Σ_b^\pm mass; candidates with a $\Lambda_b^0 \pi^\pm$ mass within the natural width of the known $\Sigma_b^{*\pm}$ mass; and the remaining nonresonant (NR) region. The $\Lambda_b^0 \pi^+ \pi^-$ mass spectra in these three regions are shown in Fig. 2. Only the larger sample of Λ_b^0 candidates selected via the $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$ decay mode is used here and in the remainder of this Letter. The spectra in the Σ_b and Σ_b^* regions look different and suggest the presence of two narrow peaks.

Doublets of orbitally excited states are predicted in the mass region near the observed peaks [10–13]. The spins and parities of the states in the doublet determine the lowest allowed orbital angular momentum in the two-body $\Sigma_b^{(*)\pm} \pi^\mp$ transition. The intensities of the transitions can be enhanced or suppressed depending on the angular momentum assignment. Heavy quark effective theory (HQET) also predicts different decay rates of the doublet members to the $\Sigma_b^\pm \pi^\mp$ and $\Sigma_b^{*\pm} \pi^\mp$ final states [43]. To probe the two-resonance hypothesis, a simultaneous fit to the mass spectra in the three $\Lambda_b^0 \pi^\pm$ mass regions is performed. For each region, the fit function consists of two signal components and a background component


 FIG. 2. Mass distributions of selected $\Lambda_b^0 \pi^+ \pi^-$ candidates for the three regions in $\Lambda_b^0 \pi^\pm$ mass: (top) Σ_b , (middle) Σ_b^* , and (bottom) nonresonant (NR) region.

described by a second-order polynomial function. The signal components are modeled by relativistic Breit-Wigner functions convolved with the detector resolution. For the Σ_b region, the signal components describe two-body intermediate states $\Sigma_b^\pm \pi^\mp$ in P and D waves for the low-mass and high-mass states, respectively. For the Σ_b^* region, S and P waves are chosen for decays of low- and high-mass states, respectively. These choices are motivated by the possible interpretation of the new states as a doublet of $\Lambda_b(1D)^0$ states [10–13]. The masses and widths of the two states are taken as common parameters for the three regions, while the other parameters, namely, the signal and background yields and background shape parameters, are allowed to vary independently. The two signal components are added incoherently, assuming interference effects are negligible, since a coherent production of the states in the complex environment of pp interactions is unlikely.

The results of the simultaneous extended unbinned maximum-likelihood fit to the $\Lambda_b^0 \pi^+ \pi^-$ mass spectra in the three $\Lambda_b^0 \pi^\pm$ mass regions are shown in Fig. 2. The two-signal hypothesis is favored with respect to the single-signal hypothesis with a statistical significance exceeding 7 standard deviations. The masses, m , and the natural widths, Γ , of the two narrow states, referred to hereafter as $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$, are measured to be

$$\begin{aligned}
 m_{\Lambda_b(6146)^0} &= 6146.17 \pm 0.33 \text{ MeV}, \\
 m_{\Lambda_b(6152)^0} &= 6152.51 \pm 0.26 \text{ MeV}, \\
 \Gamma_{\Lambda_b(6146)^0} &= 2.9 \pm 1.3 \text{ MeV}, \\
 \Gamma_{\Lambda_b(6152)^0} &= 2.1 \pm 0.8 \text{ MeV},
 \end{aligned}$$

with a mass splitting of $\Delta m = 6.34 \pm 0.32$ MeV, where the uncertainties are statistical only. While these new states are denoted as Λ_b , their interpretation as other excited beauty baryons, such as neutral Σ_b^0 states, cannot be excluded.

To probe further the resonance structure of the $\Lambda_b(6146)^0 \rightarrow \Lambda_b^0 \pi^+ \pi^-$ and $\Lambda_b(6152)^0 \rightarrow \Lambda_b^0 \pi^+ \pi^-$ decays, the background-subtracted $\Lambda_b^0 \pi^\pm$ mass spectra are studied. The sPLOT technique [35] is used here; it projects out the signal components from the combined signal-plus-background densities using $m_{\Lambda_b^0 \pi^\pm}$ as a discriminating variable. The resulting $\Lambda_b^0 \pi^\pm$ mass spectra are shown in Fig. 3. The spectra are fit with three components, describing the contributions from Σ_b^\pm , $\Sigma_b^{*\pm}$ and nonresonant decays. Relativistic *S*- and *P*-wave Breit-Wigner functions are used to describe $\Sigma_b^\pm \rightarrow \Lambda_b^0 \pi^\pm$ and $\Sigma_b^{*\pm} \rightarrow \Lambda_b^0 \pi^\pm$ decays, respectively. The choice of the orbital angular momentum is based on the quark model expectation of spin $\frac{1}{2}$ for Λ_b^0 and Σ_b baryons and $\frac{3}{2}$ for Σ_b^* states. Since the resolution on the $\Lambda_b^0 \pi^\pm$ mass is much better than the natural widths of the

$\Sigma_b^{(*)\pm}$ states, resolution effects are neglected. The nonresonant component is parametrized as a product of two-from-three-body decay phase space functions [44] and a first-order polynomial function. The masses and widths of the $\Sigma_b^{(*)\pm}$ states are fixed to their known values [8]. The results of extended unbinned maximum-likelihood fits to the background-subtracted $\Lambda_b^0 \pi^\pm$ mass distributions are shown in Fig. 3, and are presented in Table S3 of the Supplemental Material [37]. Significant $\Lambda_b(6152)^0 \rightarrow \Sigma_b^\pm \pi^\mp$ and $\Lambda_b(6152)^0 \rightarrow \Sigma_b^{*\pm} \pi^\mp$ signals are observed, accounting for approximately one third and one quarter of the signal decays in the sample, respectively. The statistical significance of the contributions is in excess of 7 and 5 standard deviations, respectively. For the $\Lambda_b(6146)^0$ state, $\Lambda_b(6146)^0 \rightarrow \Sigma_b^{*\pm} \pi^\mp$ decays account for about half of the observed decay rate with a statistical significance in excess of 6 standard deviations. No significant $\Lambda_b(6146)^0 \rightarrow \Sigma_b^\pm \pi^\mp$ signals are observed.

Several sources of systematic uncertainty are considered. The most important source of systematic uncertainty on the mass measurements derives from the knowledge of the momentum scale. This uncertainty is evaluated by varying the momentum scale within its known uncertainty [19] and rerunning the mass fit. The second uncertainty arises from the assumed parameters of the Breit-Wigner functions. To estimate this uncertainty, the orbital angular momentum is changed from $L = 0$ to 2 for all signal components and the Blatt-Weisskopf breakup radii are varied from 1.5 to 5 GeV^{-1} . Since the states are narrow and far from the thresholds, the fitted masses and widths have only very small dependency on the assumed parameters. The maximal changes to the fitted parameters with respect to the baseline fit are assigned as systematic uncertainties. The impact of the background model is evaluated by varying the order of the polynomial functions from two to four. A further source of uncertainty on the determination of the natural widths arises from known differences in resolution between data and simulation. This effect is assessed by varying conservatively the width of the resolution function by $\pm 10\%$, based on previous studies [5,7,45–48].

The different sources of systematic uncertainty are summarized in Table II. In all cases they are smaller than the statistical uncertainties. A large part of the systematic uncertainty cancels for the mass splitting, Δm , between the $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$ states. The remaining systematic uncertainty for Δm is 20 keV. An additional uncertainty arises due to the value of the Λ_b^0 mass used in the constrained fit. The statistical uncertainty on the Λ_b^0 mass introduces an uncertainty of 0.16 MeV on the $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$ masses. This uncertainty is quoted separately. The systematic uncertainty on the constraint is correlated, through the momentum scale, with the masses measured in this analysis and is instead included in the final systematic uncertainty in Table II.

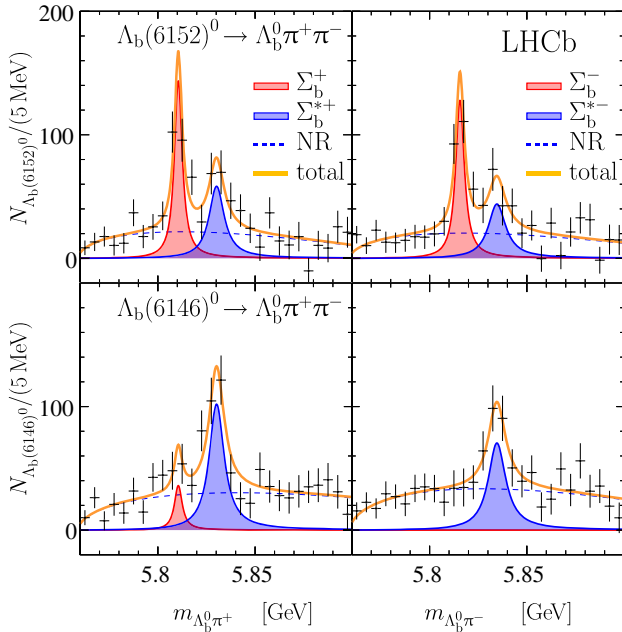


FIG. 3. Background-subtracted mass distribution of (left) $\Lambda_b^0 \pi^+$ and (right) $\Lambda_b^0 \pi^-$ combinations from (top) $\Lambda_b(6152)^0 \rightarrow \Lambda_b^0 \pi^+ \pi^-$ and (bottom) $\Lambda_b(6146)^0 \rightarrow \Lambda_b^0 \pi^+ \pi^-$ decays. Results of fits with a model comprising Σ_b , Σ_b^* and nonresonant (NR) components are superimposed.

TABLE II. Summary of the systematic uncertainties for the masses, m , and widths, Γ , of the $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$ states. All values are in keV.

Source	$\Lambda_b(6146)^0$		$\Lambda_b(6152)^0$	
	m	Γ	m	Γ
Momentum scale	80	...	80	...
Signal model	50	50	50	50
Resolution model	15	270	< 10	310
Background model	30	30	30	20
Total	100	280	100	320
Including Λ_b^0 mass systematic	220	280	220	320

In summary, a new structure with high statistical significance is observed in the $\Lambda_b^0 \pi^+ \pi^-$ mass spectrum using $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$ decays, and confirmed using a sample of Λ_b^0 baryons reconstructed through the $\Lambda_b^0 \rightarrow J/\psi p K^-$ decay. An analysis of the $\Lambda_b^0 \pi^+ \pi^-$ mass spectra for the regions enriched by the $\Sigma_b^{(*)\pm}$ resonances suggests the interpretation of the structure as two almost degenerate narrow states, denoted as $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$. The masses and natural widths of these states are measured to be

$$m_{\Lambda_b(6146)^0} = 6146.17 \pm 0.33 \pm 0.22 \pm 0.16 \text{ MeV},$$

$$m_{\Lambda_b(6152)^0} = 6152.51 \pm 0.26 \pm 0.22 \pm 0.16 \text{ MeV},$$

$$\Gamma_{\Lambda_b(6146)^0} = 2.9 \pm 1.3 \pm 0.3 \text{ MeV},$$

$$\Gamma_{\Lambda_b(6152)^0} = 2.1 \pm 0.8 \pm 0.3 \text{ MeV},$$

where the first uncertainty is statistical, the second systematic, and the third for the mass measurements due to imprecise knowledge of the mass of the Λ_b^0 baryon. The mass differences with respect to the Λ_b^0 mass are measured to be

$$m_{\Lambda_b(6146)^0} - m_{\Lambda_b^0} = 526.55 \pm 0.33 \pm 0.10 \text{ MeV},$$

$$m_{\Lambda_b(6152)^0} - m_{\Lambda_b^0} = 532.89 \pm 0.26 \pm 0.10 \text{ MeV},$$

and the mass difference between the two states is measured to be $6.34 \pm 0.32 \pm 0.02 \text{ MeV}$.

The masses of the two states measured in this analysis are consistent with the predictions for the doublet of $\Lambda_b(1D)^0$ states with quantum numbers (spin J and parity P) $J^P = \frac{3}{2}^+$ and $\frac{5}{2}^+$ [10,13]. Similar natural widths are expected for the two states of the doublet in HQET [43]. The observed decay pattern, where one of the states decays to both Σ_b with $J^P = \frac{1}{2}^+$ and Σ_b^* with $J^P = \frac{3}{2}^+$, while the other decays primarily to Σ_b^* , is also consistent with the above assignment. However, the interpretation of these states as excited Σ_b^0 states cannot be excluded.

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