PROCEEDINGS OF SCIENCE

Studies of b-hadrons at LHCb

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A large data set collected at the LHCb experiment in proton-proton collisions during Runs 1 and 2 of the Large Hadron Collider has opened a unique possibility to study heavy beauty hadron states and to broaden knowledge of their spectroscopy and production. Recent results on searches for new excited b-hadron states, and studies of b-hadron production, are reviewed. In particular, the observation of new excited Ω_b^- states, the observation of two new narrow $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$ states, the observation of new Λ_b^{**0} state consistent with the $\Lambda_b(2S)^0$ prediction, a precise measurement of the mass and width of $\Lambda_b(5912)^0$ and $\Lambda_b(5920)^0$ states, and a measurement of the B_c^- meson production fraction and $B_c^- - B_c^+$ production asymmetry in 7 and 13 TeV of proton-proton collisions are presented.

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1. Introduction

Over the last few years numerous outstanding results have been obtained within the analyses of b-hadrons. Among those there are observation of pentaquark and tetraquark resonances, observation of series of excited heavy baryons and many others. Still, many of the conventional states remain unobserved, parameters of some of the known hadron states are poorly measured and on top of that there are a number of the states which do not fit into the conventional quarkonium spectrum. Hence study of b-hadrons spectroscopy is of particular interest in the modern high energy physics.

The results described below are based on the data samples collected by the LHCb experiment in proton-proton (pp) collision at the Large Hadron Collider (LHC) with centre-of-mass energies $\sqrt{s}$ = 7 and 8 TeV corresponding to a total integrated luminosity of 3 fb^{-1} (LHC Run 1) and with centre-of-mass energy $\sqrt{s}$ = 13 TeV corresponding to a total integrated luminosity of 6 fb^{-1} (LHC Run 2).

2. Observation of excited Ω_b^- states

Recently, the new five narrow excited Ω_c^0 baryons has been observed [1]. Some of the theoretical models describing Ω_c^0 peaks also predict Ω_b^- states decaying to $\Xi_b^0 K^-$ final state. Therefore, it is of great interest to search for the analogous excited states with the LHCb experiment data. The $\Xi_b^0 K^-$ mass spectrum is studied to search for narrow resonances close to the kinematic threshold [2]. The analysis is done using pp collision data samples corresponding to an integrated luminosity of 9.0 fb^{-1} (LHC Run 1 and 2). The Ξ_b^0 baryons are reconstructed using $\Xi_c^+\pi^-$ decay mode, where Ξ_c^+ baryons are reconstructed with the $pK^-\pi^+$ final state. The distributions of right-sign combination mass difference $M(\Xi_b^0 K^-) - M(\Xi_b^0)$ and wrong-sign combination mass difference $M(\Xi_b^0 K^+) - M(\Xi_b^0)$ are shown in Fig. 1 (a) and (b), respectively. Four narrow peaks are seen in right-sign distribution. Simultaneous fit to wrong-sign and right-sign spectra with common background shape is performed. The peak parameters obtained from the fit results together with the significance of the peaks are shown in Table 1. The mass and width of the new resonances are consistent with expectations for excited Ω_b^- states.

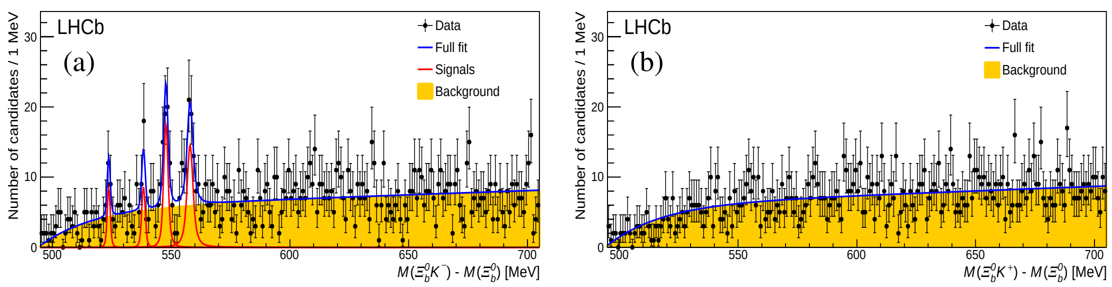

Figure 1: The distributions of (a) right-sign $M(\Xi_b^0 K^-) - M(\Xi_b^0)$ and (b) wrong-sign $M(\Xi_b^0 K^+) - M(\Xi_b^0)$ mass differences. Different components employed in the fit are indicated in the legend.

Table 1: The masses, 90% (95%) confidence level upper limits on the natural widths and global (local) significance for the four peaks. The 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.

	Mass [MeV]	Width [MeV]	Significance [σ]
$\Omega_b(6316)^-$	$6315.64 \pm 0.31 \pm 0.07 \pm 0.50$	< 2.8 (4.2)	2.1 (3.6)
$\Omega_b(6330)^-$	$6330.30 \pm 0.28 \pm 0.07 \pm 0.50$	< 3.1 (4.7)	2.6 (3.7)
$\Omega_b(6340)^-$	$6339.71 \pm 0.26 \pm 0.05 \pm 0.50$	< 1.5 (1.8)	6.7 (7.2)
$\Omega_b(6350)^-$	$6349.88 \pm 0.35 \pm 0.05 \pm 0.50$	< 2.8 (3.2)	6.2 (7.0)
		$1.4\,^{+1.0}_{-0.8} \pm 0.1$	

3. Excited Λ_b^0 baryons

Beyond the lightest beauty baryon, Λ_b^0 baryon, a rich spectrum of radially and orbitally excited states is expected at higher masses. The excited states has been searched in the $\Lambda_b^0\pi^+\pi^-$ spectrum by the LHCb experiment with the discovery of two narrow states [3]. Therefore, it is both interesting and promising to study the $\Lambda_b^0\pi^+\pi^-$ spectrum with the full statistics collected by the LHCb experiment. The $\Lambda_b^0\pi^+\pi^-$ mass spectrum is studied by the LHCb experiment using the full LHC Run 1 and 2 data sample of pp collisions, corresponding to an integrated luminosity of 9 fb^{-1} [4, 5]. The Λ_b^0 baryon is reconstructed using two decay modes $\Lambda_c^+\pi^-$ and $J/\psi\, pK^-$. The study is performed in three $\Lambda_b^0\pi^+\pi^-$ mass intervals: high-, middle- and low-mass. In the high $\Lambda_b^0\pi^+\pi^-$ mass interval a new peaking structure at approximately 6.15 GeV is observed [4]. The peak is above $\Sigma_b^{(*)\mp}\pi^\pm$ threshold, hence, spectrum is investigated in three non-overlapping $\Lambda_b^0\pi^\pm$ mass regions: two resonant $\Sigma_b^\mp$ and $\Sigma_b^{*\mp}$ regions and nonresonant one. Simultaneous fit to the three $\Lambda_b^0\pi^+\pi^-$ mass distributions is performed. The two-peak hypothesis is favoured with respect to the single-peak hypothesis with more than 7 σ statistical significance. The $\Lambda_b^0\pi^+\pi^-$ mass distributions are shown in Fig. 2 (a). Mass

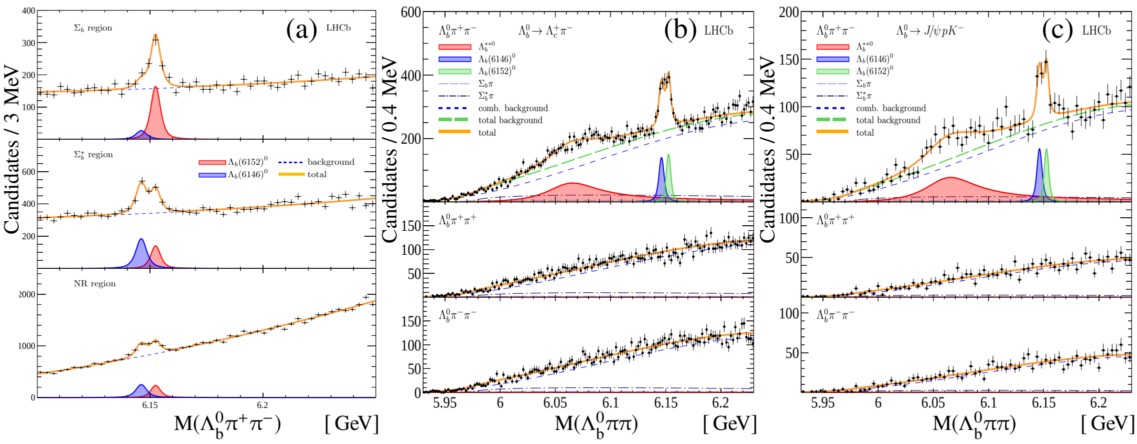

Figure 2: (a) Mass distributions of $\Lambda_b^0\pi^+\pi^-$ combination for the three regions in $\Lambda_b^0\pi^\pm$ mass: (top) $\Sigma_b^\mp$, (middle) $\Sigma_b^{*\mp}$ and (bottom) nonresonant region. Mass spectra of (top) $\Lambda_b^0\pi^+\pi^-$, (middle) $\Lambda_b^0\pi^+\pi^+$ and (bottom) $\Lambda_b^0\pi^+\pi^+$ combinations for the (b) $\Lambda_b^0 \to \Lambda_c^+\pi^-$ and (c) $\Lambda_b^0 \to J/\psi\, pK^-$ sample. Different components employed in the fit are indicated in the legend.

and width of the two peaks are

$$M_{\Lambda_b(6146)^0} = 6146.17 \pm 0.33 \pm 0.22 \pm 0.16\,\text{MeV}, \quad \Gamma_{\Lambda_b(6146)^0} = 2.9 \pm 1.3 \pm 0.3\,\text{MeV}, \tag{1}$$

$$M_{\Lambda_b(6152)^0} = 6152.51 \pm 0.26 \pm 0.22 \pm 0.16\,\text{MeV}, \quad \Gamma_{\Lambda_b(6152)^0} = 2.1 \pm 0.8 \pm 0.3\,\text{MeV}, \tag{2}$$

here and throughout the Section the first uncertainty is statistical, the second one is systematic and third one is due to the uncertainty in the nominal Λ_b^0 baryon mass. The measured masses are consistent with predictions for $\Lambda_b(1D)^0$ doublet with $J^P = \frac{3}{2}^+$ and $\frac{5}{2}^+$ [6, 7].

In the intermediate $\Lambda_b^0\pi^+\pi^-$ mass interval a new baryon state is observed [5]. The simultaneous fit to the six mass distributions where Λ_b^0 baryon is reconstructed via two different decay modes and in each case for one right-sign $\Lambda_b^0\pi^+\pi^-$ and two wrong-sign $\Lambda_b^0\pi^\pm\pi^\pm$ spectra is performed. The $\Lambda_b^0\pi^+\pi^-$ mass distributions are shown in Fig. 2 (b) and (c). Mass and width of the new peak are

$$M_{\Lambda_b^{**0}} = 6072.3 \pm 2.9 \pm 0.6 \pm 0.2\,\text{MeV}, \quad \Gamma_{\Lambda_b^{**0}} = 72 \pm 11 \pm 2\,\text{MeV}. \tag{3}$$

The observed peak is consistent with broad excess reported by the CMS experiment [8]. The measured mass and width are in agreement with expectations for the $\Lambda_b(2S)^0$ state. The contributions from $\Sigma_b^{(*)\pm}$ resonances are also studied and the nonresonant component is found to give a dominant contribution.

In the low $\Lambda_b^0\pi^+\pi^-$ mass interval the two states observed earlier [3] are confirmed. The simultaneous fit to the six mass distributions where Λ_b^0 baryon is reconstructed via two different decay modes and in each case for one right-sign $\Lambda_b^0\pi^+\pi^-$ and two wrong-sign $\Lambda_b^0\pi^\pm\pi^\pm$ spectra is performed. The mass spectra are shown in Fig. 3. The mass and width of the states are measured to be

$$M_{\Lambda_b(5912)^0} = 5912.21 \pm 0.03 \pm 0.01 \pm 0.21\,\text{MeV}, \quad \Gamma_{\Lambda_b(5912)^0} < 0.25\,(0.28)\,\text{MeV}, \tag{4}$$

$$M_{\Lambda_b(5920)^0} = 5920.11 \pm 0.02 \pm 0.01 \pm 0.21\,\text{MeV}, \quad \Gamma_{\Lambda_b(5920)^0} < 0.19\,(0.20)\,\text{MeV}. \tag{5}$$

For the natural widths the upper limits at 90% (95%) confidence level is specified. The parameters are measured with about four times higher precision with respect to those reported in Ref. [3].

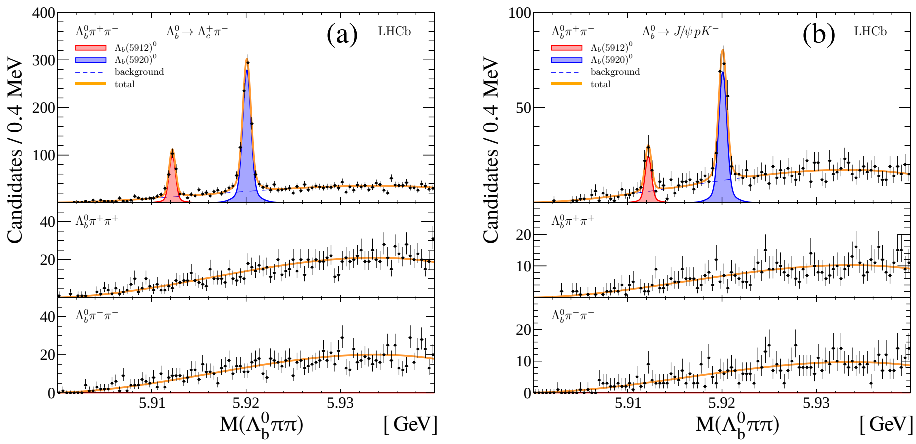

Figure 3: Mass spectra of (top) $\Lambda_b^0\pi^+\pi^-$, (middle) $\Lambda_b^0\pi^+\pi^+$ and (bottom) $\Lambda_b^0\pi^+\pi^+$ combinations for the (a) $\Lambda_b^0 \to \Lambda_c^+\pi^-$ and (b) $\Lambda_b^0 \to J/\psi\, pK^-$ sample. Different components employed in the fit are indicated in the legend.

4. Measurement of the B_c^- meson production fraction and asymmetry in pp collisions at 7 and 13 TeV

The b-hadrons cross-sections as functions of transverse momentum (p_T) and pseudorapidity (η) are predicted using non-relativistic quantum chromodynamics along with fragmentation functions. The corresponding literature is systematically reviewed in the Ref. [9]. The measurement of the B_c^- production fraction would allow to further probe quantum chromodynamics.

The production fraction ratio $\frac{f_c}{f_u + f_d}$ and the $B_c^- - B_c^+$ production asymmetry are measured by the LHCb experiment [10]. The analysis is done using data samples of 7 and 13 TeV pp collisions corresponding to an integrated luminosity of 1.0 and 1.6 fb^{-1}, respectively. The B mesons in the analysis are reconstructed using the $B_c^- \to J/\psi\,\mu^-\overline{\nu}_\mu$, $B^0 \to D^+X\mu^-\overline{\nu}_\mu$ and $B^- \to D^0X\mu^-\overline{\nu}_\mu$ decay modes. The X symbol is used here and throughout to refer to any additional undetected particles. The production fractions are obtained as a function of p_T and η of the B mesons. The measured production fraction for the 7 TeV data sample is shown in Fig. 4 (a) and (b). There is a small dependence on the transverse momentum, but no dependence on η is observed. The ratio of production fractions averaged over p_T and η of the B mesons are measured to be

$$\frac{f_c}{f_u + f_d} = (3.63 \pm 0.08 \pm 0.12 \pm 0.86) \times 10^{-3} \text{ for 7 TeV,} \tag{6}$$

$$\frac{f_c}{f_u + f_d} = (3.78 \pm 0.04 \pm 0.15 \pm 0.89) \times 10^{-3} \text{ for 13 TeV,} \tag{7}$$

where the first uncertainty is statistical, the second one is systematic and third one is due to the spread of theoretical predictions of the $B_c^- \to J/\psi\,\mu^-\overline{\nu}_\mu$ branching fraction available in literature (see references in Ref. [10]). Recently the HPQCD collaboration provided the first lattice prediction of the $B_c^- \to J/\psi\,\mu^-\overline{\nu}_\mu$ decay width, which has an uncertainty of only 10% [11].

The $B_c^- - B_c^+$ production asymmetry is measured in different intervals of p_T and η of the B mesons, no significant asymmetry is observed. The B_c^- meson production asymmetries, averaged over p_T and η, are measured to be $(-2.5 \pm 2.1 \pm 0.5)\%$ and $(-0.5 \pm 1.1 \pm 0.4)\%$ for the 7 and 13 TeV data samples, respectively.

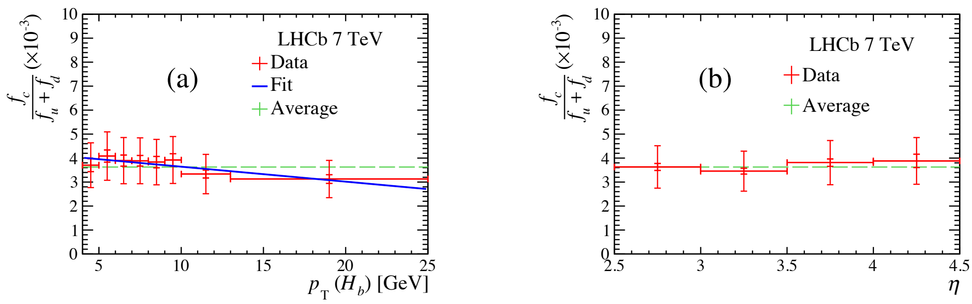

Figure 4: Ratio of production fractions as a function of (a) p_T and (b) η of B mesons for the 7 TeV data sample. The statistical uncertainties are shown with smaller error bars, whereas larger bars include both statistical and systematic uncertainties.

5. Conclusion

A significant contribution to the knowledge of beauty hadron spectroscopy is provided by the LHCb experiment. In particular, the new excited Ω_b^- and Λ_b^0 states are observed, mass and width of newly observed states are measured. The production fraction of B_c^- meson with respect to B^+ and B^0 mesons and $B_c^- - B_c^+$ production asymmetry are measured in pp collisions at centre-of mass energies of 7 and 13 TeV.

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References

[1] LHCb collaboration, *Observation of five new narrow Ω_c^0 states decaying to $\Xi_c^+ K^-$*, *Phys. Rev. Lett.* **118** (2017) 182001 [1703.04639].

[2] LHCb collaboration, *First observation of excited Ω_b^- states*, *Phys. Rev. Lett.* **124** (2020) 082002 [2001.00851].

[3] LHCb collaboration, *Observation of excited Λ_b^0 baryons*, *Phys. Rev. Lett.* **109** (2012) 172003 [1205.3452].

[4] LHCb collaboration, *Observation of new resonances in the $\Lambda_b^0\pi^+\pi^-$ System*, *Phys. Rev. Lett.* **123** (2019) 152001 [1907.13598].

[5] LHCb collaboration, *Observation of a new baryon state in the $\Lambda_b^0\pi^+\pi^-$ mass spectrum*, *JHEP* **06** (2020) 136 [2002.05112].

[6] B. Chen, K.-W. Wei and A. Zhang, *Assignments of Λ_Q and Ξ_Q baryons in the heavy quark-light diquark picture*, *Eur. Phys. J. A* **51** (2015) 82 [1406.6561].

[7] S. Capstick and N. Isgur, *Baryons in a relativized quark model with chromodynamics*, *Phys. Rev. D* **34** (1986) 2809.

[8] CMS collaboration, *Study of excited Λ_b^0 states decaying to $\Lambda_b^0\pi^+\pi^-$ in proton-proton collisions at $\sqrt{s} = 13$ TeV*, *Phys. Lett. B* **803** (2020) 135345 [2001.06533].

[9] N. Brambilla et al., *Heavy quarkonium: progress, puzzles, and opportunities*, *Eur. Phys. J. C* **71** (2011) 1534 [1010.5827].

[10] LHCb collaboration, *Measurement of the B_c^- meson production fraction and asymmetry in 7 and 13 TeV pp collisions*, *Phys. Rev.* **D100** (2019) 112006 [1910.13404].

[11] HPQCD collaboration, $B_c^- \to J/\psi$ *Form Factors for the full q^2 range from Lattice QCD*, 2007.06957.