PROCEEDINGS OF SCIENCE

Beauty-hadron spectroscopy at LHCb

Hongjie Mu* **on behalf of the LHCb collaboration**

Center for High Energy Physics, Tsinghua University, Beijing, China

E-mail: hongjie.mu@cern.ch

The latest results of conventional beauty-hadron spectroscopy from the LHCb experiment are introduced in this proceeding. These results contain the observation of new excited B_s^0 states in B^+K^- final state, the observation of a new excited Ξ_b^0 state in $\Xi_b^-\pi^+$ final state, the observation of two new exited Ξ_b^0 states decaying to $\Lambda_b^0K^-\pi^+$ and a search for doubly heavy baryons Ξ_{bc}^0 and Ω_{bc}^0 decaying to $\Lambda_c^+\pi^-$ and $\Xi_c^+\pi^-$.

**** The European Physical Society Conference on High Energy Physics (EPS-HEP2021), ****
**** 26-30 July 2021 ****
**** Online conference, jointly organized by Universität Hamburg and the research center DESY ****

*Speaker

© Copyright owned by the author(s) under the terms of the Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License (CC BY-NC-ND 4.0).

PoS(EPS-HEP2021)410

1. Introduction

The constituent quark model [1, 2] was proposed for classifying and describing the hadrons composed by light quarks (u, d, s) and later extended to the heavy flavor hadrons containing b or c quarks. The spectroscopy of hadrons containing a b quark (beauty-hadron) provides important information understanding the hadronic structure and nonperturbative quantum chromodynamics (QCD). This proceeding focuses on the recent results of beauty-hadron spectroscopy from the LHCb experiment.

2. Observation of new excited B_s^0 states

Potential models exploiting heavy-quark symmetry [3] are used to calculate properties of B_s^0 meson ($b\overline{s}$). It is still difficult to precisely predict masses and widths of B_s^0 mesons. Therefore, the experimental results could provide more inputs and constraints for theories. A peaking structure is observed in the B^+K^- mass spectrum [4] with the full $9\,\text{fb}^{-1}$ LHCb dataset, which is interpreted as the overlapping excited B_s^0 states. The inclusion of charge-conjugated processes is implied and natural units with $\hbar = c = 1$ are used throughout this proceeding.

The B^+ candidates are reconstructed with the decays $B^+ \to J/\psi K^+$ and $B^+ \to \overline{D}^0\pi^+$, where the J/ψ meson subsequently decays to the $\mu^+\mu^-$ final state and the $\overline{D}^0$ meson decays to the $K^+\pi^-$ final state. The selected B^+ candidates are further combined with a K^- candidate from the primary pp interaction vertex (prompt kaon) to form the B_s^{**0} candidates. The B_s^{**0} candidates are studied in bins of transverse momentum (p_{T}) of the prompt kaon, as it is a strongest discriminant between resonant signal and the combinatorial background. The spectrum of mass difference, $\Delta m \equiv m_{B^+K^-} - m_{B^+} - m_{K^-}$, is shown in Fig. 1. A clear excess at approximately 300 MeV above the mass threshold can be seen in the Δm spectrum, especially in the high p_{T} region. Two models of signal decay are considered: one assuming the B_s^{**0} state directly decays to the B^+K^- final state and for the other one, it decays through intermediate B^{*+} meson, which further decays to the $B^+\gamma$ final state. The latter case result in approximately 45 MeV shift of peak position due to the unreconstructed photon. The local significance is lager than 20 standard deviations (σ) for one-peak fit with respect to the no-peak hypothesis and 7.7σ for the two-peak fit with respect to the one-peak hypothesis. With the two-peak hypothesis, the masses and widths of two states decaying directly to the B^+K^- system are determined to be $m_1 = 6063.5 \pm 1.2\,(\text{stat}) \pm 0.8\,(\text{syst})\,\text{MeV}$, $\Gamma_1 = 26 \pm 4\,(\text{stat}) \pm 4\,(\text{syst})\,\text{MeV}$, $m_2 = 6114 \pm 3\,(\text{stat}) \pm 5\,(\text{syst})\,\text{MeV}$, $\Gamma_2 = 66 \pm 18\,(\text{stat}) \pm 21\,(\text{syst})\,\text{MeV}$. If the decay proceeds through $B^{*+}K^-$, the corresponding masses and widths are also measured [4]. A single resonance that decays in both the B^+K^- and $B^{*+}K^-$ channels is disfavored by more than 2σ with respect to the two-state hypothesis and cannot be completely excluded. The production ratio relative to the B_{s2}^{*0} meson is determined to be $R = 0.87 \pm 0.15\,(\text{stat}) \pm 0.19\,(\text{syst})$, where the production ratio is defined as the product of the cross-section times branching fractions of the new states divided by the corresponding product for B_{s2}^{*0}.

3. Observation of a new Ξ_b^0 state

Recently, the LHCb collaboration reported the observation of $\Xi_b(6227)^-$ baryon in the $\Lambda_b^0 K^-$ and $\Xi_b^0\pi^-$ mass spectrum [5]. The isospin partner of the $\Xi_b(6227)^-$ state is expected to decay

PoS(EPS-HEP2021)410

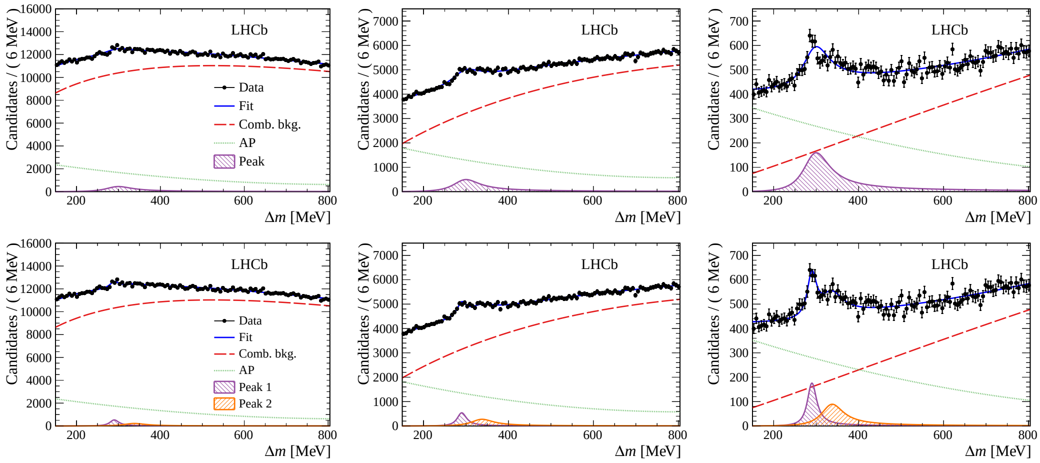

Figure 1: The $B^{+}K^{-}$ mass difference distributions in data, overlaid with the fit: (top) one-peak hypothesis and (bottom) two-peak hypothesis. In each row, the columns are the candidates with prompt kaon p_{T}: (left) $0.5 < p_{\mathrm{T}} < 1\,\mathrm{GeV}$, (middle) $1 < p_{\mathrm{T}} < 2\,\mathrm{GeV}$ and (right) $p_{\mathrm{T}} > 2\,\mathrm{GeV}$.

through $\Xi_b^-\pi^+$ mode. In this analysis, the observation of a new excited Ξ_b^0 resonance decaying to the $\Xi_b^-\pi^+$ final state with the full LHCb dataset is presented [6]. With the enlarged data sample, the measurement of Ξ_b^- and $\Xi_b(6227)^-$ states is also updated.

The Ξ_b^- candidates are reconstructed with the $\Xi_c^0\pi^-$ and $\Xi_c^0\pi^-\pi^+\pi^-$ decays, while the Λ_b^0 candidates reconstructed with $\Lambda_c^+\pi^-$ and $\Lambda_c^+\pi^-\pi^+\pi^-$ final states. The charm baryons, Ξ_c^0 and Λ_c^+, are reconstructed with the decays $\Xi_c^0 \to pK^-K^-\pi^+$ and $\Lambda_c^+ \to pK^-\pi^+$. The $\Xi_b(6227)^0$ candidates are formed by combining a Ξ_b^- candidate with a prompt π^+ candidate, while $\Xi_b(6227)^-$ candidates formed by combining Λ_b^0 and prompt K^- candidates. The spectrum of mass difference, $\delta M \equiv M(\Xi_b^-\pi^+) - M(\Xi_b^-)$, of right-sign ($\Xi_b^-\pi^+$) and wrong-sign ($\Xi_b^-\pi^-$) combinations is shown in Fig. 2. A clear signal is observed in the right-sign final state, while there are no significant structure in the wrong-sign mass spectrum. The statistical significance of the signal is about 10σ. The mass and width of $\Xi_b(6227)^0$ state are $m(\Xi_b(6227)^0) = 6227.1\,^{+1.4}_{-1.5} \pm 0.5\,\mathrm{MeV}$ and $\Gamma(\Xi_b(6227)^0) = 18.6\,^{+5.0}_{-4.1} \pm 1.4\,\mathrm{MeV}$. The relative production rate of the $\Xi_b(6227)^0$ state at $\sqrt{s} = 13\,\mathrm{TeV}$ is measured to be $R(\Xi_b^-\pi^+) = 0.045 \pm 0.008 \pm 0.004$, where $R(\Xi_b^-\pi^+)$ is defined as the ratio of signal yield of $\Xi_b(6227)^0$ and Ξ_b^- baryon divided by the relative efficiency between the $\Xi_b(6227)^0$ and Ξ_b^- selections. The mass and with of $\Xi_b(6227)^-$ state, along with the mass of the Ξ_b^- baryon, are also measured with better precision.

4. Observation of two new excited Ξ_b^0 states decaying to $\Lambda_b^0K^-\pi^+$

The LHCb collaboration reported the observation of two excited Λ_b^0 resonances in the $\Lambda_b^0\pi^+\pi^-$ system [7], which are consistent with the 1D Λ_b^0 states [8]. This observation motivates the investigation of 1D Ξ_b^0 states, as the Λ_b^0 and Ξ_b^0 baryons have similar properties due to the approximate $SU(3)$ flavor symmetry [8]. The two 1D Ξ_b^0 states are predicted to decay through $\Sigma_b^{(*)}K$ modes [8], which result in a $\Lambda_b^0K^-\pi^+$ final state. Two new excited Ξ_b^0 states are observed in the $\Lambda_b^0K^-\pi^+$ system with the LHCb dataset at $\sqrt{s} = 13\,\mathrm{TeV}$ [9].

PoS(EPS-HEP2021)410

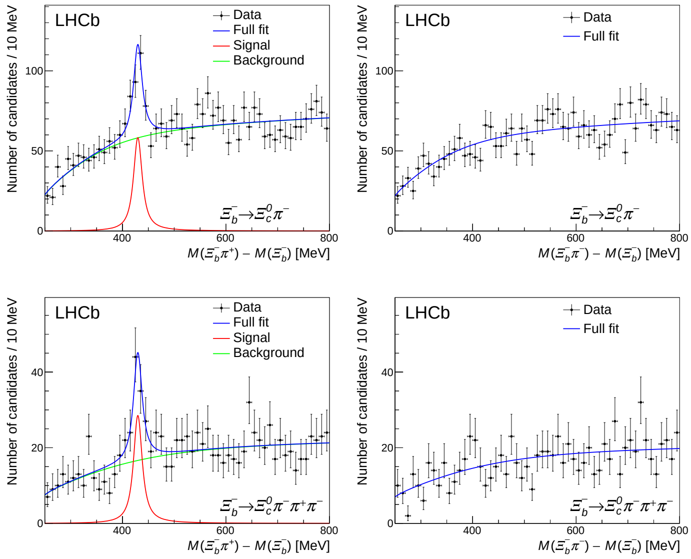

Figure 2: Distributions of mass difference δM of (left) right-sign and (right) wrong-sign $\Xi_b(6227)^0$ candidates, with (top) $\Xi_b^- \to \Xi_c^0 \pi^-$ and (bottom) $\Xi_b^- \to \Xi_c^0 \pi^- \pi^+ \pi^-$ decays.

The Λ_b^0 candidates are reconstructed with the $\Lambda_c^+\pi^-$ and $\Lambda_c^+\pi^-\pi^+\pi^-$ decays, where the Λ_c^+ baryon subsequently decays to the $pK^-\pi^+$ final state. The selected Λ_b^0 candidates are combined with a prompt kaon and pion to form the $\Lambda_b^0 K\pi$ candidates. To improve the mass resolution, the mass of $\Lambda_b^0 K^-\pi^+$ candidates is redefined with the reconstructed mass difference between $\Lambda_b^0 K^-\pi^+$ and Λ_b^0 candidates plus the measured Λ_b^0 mass. The mass spectrum of right-sign ($\Lambda_b^0 K^-\pi^+$) and wrong-sign ($\Lambda_b^0 K^+\pi^-$) combinations is shown in Fig.3. Two narrow peaks can be seen in the $\Lambda_b^0 K^-\pi^+$ mass spectrum, while no significant peaking structure is visible in the $\Lambda_b^0 K^+\pi^-$ system. The significance of two-peak hypothesis is larger than 9σ (5σ) compared to the no-peak (one-peak) hypothesis. The masses of these two states are $m(\Xi_b(6327)^0) = 6327.28^{+0.23}_{-0.21} \pm 0.08 \pm 0.24\,\text{MeV}$, $m(\Xi_b(6333)^0) = 6332.69^{+0.17}_{-0.18} \pm 0.03 \pm 0.22\,\text{MeV}$, where the uncertainties are statistical, systematic and due to Λ_b^0 mass measurement. The corresponding widths are consistent with zero, and upper limits at 90% (95%) credibility level are set, $\Gamma(\Xi_b(6327)^0) < 2.20\ (2.56)\,\text{MeV}$, $\Gamma(\Xi_b(6333)^0) < 1.55\ (1.85)\,\text{MeV}$. The resonant structure in the excited Ξ_b^0 decays is shown in Fig. 4. The $\Xi_b(6327)^0$ state predominantly decays to $\Sigma_b^+ K^-$. About half of the $\Xi_b(6333)^0$ baryons decay without $\Lambda_b^0\pi^+$ resonances, while the rest is dominated the decay through Σ_b^{*+} resonance. The masses, widths and decay patterns of the two observed Ξ_b^0 states are consistent with the predictions [8] for a doublet of 1D Ξ_b^0 states.

5. Search for doubly heavy baryons Ξ_{bc}^0 and Ω_{bc}^0 decaying to $\Lambda_c^+\pi^-$ and $\Xi_c^+\pi^-$

No baryons containing b and c quarks have been observed experimentally. An observation would improve the understanding of the quark structure inside baryons. This analysis presents a search for Ξ_{bc}^0 and Ω_{bc}^0 decaying to $\Lambda_c^+\pi^-$ and $\Xi_c^+\pi^-$ with the LHCb dataset collected in 2016–2018 [10].

PoS(EPS-HEP2021)410

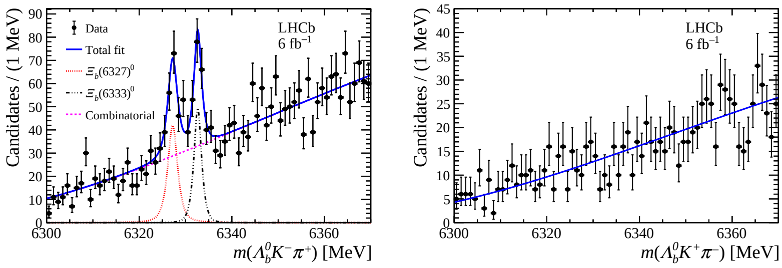

Figure 3: Invariant mass distributions of $\Lambda_b^0 K\pi$ candidates of (left) right-sign and (right) wrong-sign samples.

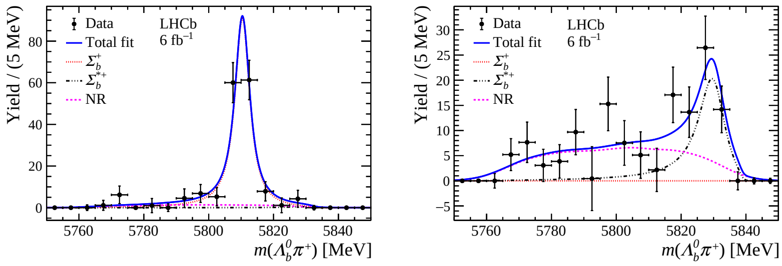

Figure 4: Signal yields of the (left) $\Xi_b(6327)^0$ and (right) $\Xi_b(6333)^0$ states in bins of $\Lambda_b^0\pi$ mass spectrum.

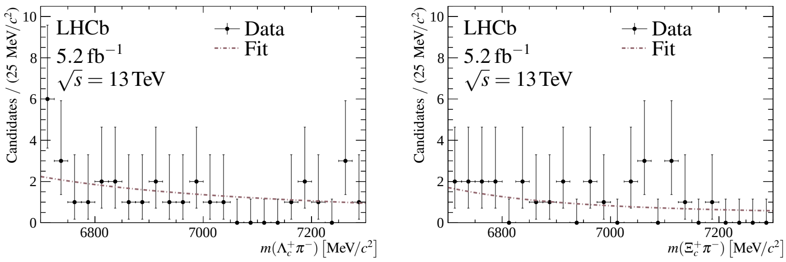

Figure 5: Invariant mass distributions of selected (left) $H_{bc}^0 \to \Lambda_c^+\pi^-$ and (right) $H_{bc}^0 \to \Xi_c^+\pi^-$ candidates.

The Ξ_{bc}^0 and Ω_{bc}^0 baryons have similar properties and are denoted as H_{bc}^0 hereafter. The Λ_c^+ and Ξ_c^+ candidates are reconstructed with the $pK^-\pi^+$ final state. A pion is combined with the Λ_c^+ (Ξ_c^+) candidate to form H_{bc}^0 candidate. The invariant mass distribution of H_{bc}^0 candidates are shown in Fig. 5. No significant excess is observed across the searched mass range. The decays of $\Lambda_b^0 \to \Lambda_c^+\pi^-$ and $\Xi_b^0 \to \Xi_c^+\pi^-$ are selected as the control channel to measure the relative production ratio of $H_{bc}^0 \to \Lambda_c^+\pi^-$ and $H_{bc}^0 \to \Xi_c^+\pi^-$ decays. The production ratio $\mathcal{R}$ is defined as the H_{bc}^0 production cross-section multiplied by the branching fraction of $H_{bc}^0 \to \Lambda_c^+\pi^-$ and $H_{bc}^0 \to \Xi_c^+\pi^-$ decays relative to that of the Λ_b^0 (Ξ_b^0) baryon. The upper limits on the ratio $\mathcal{R}(\Lambda_c^+\pi^-)$ and $\mathcal{R}(\Xi_c^+\pi^-)$ are set at 95% confidence level under different mass and lifetime hypothesis for Ξ_{bc}^0 and Ω_{bc}^0 baryons, and shown in Fig. 6.

6. Summary

The recent results of beauty-hadron spectroscopy at LHCb are presented in this proceeding, including the observation of new excited B_s^0 states in the B^+K^- final system, the observation of a

PoS(EPS-HEP2021)410

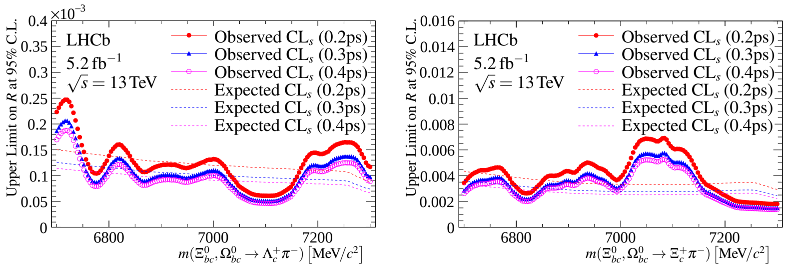

Figure 6: Upper limits on the production ratio for H_{bc}^0 decays to (left) $\Lambda_c^+\pi^-$ and (right) $\Xi_c^+\pi^-$.

new Ξ_b^0 state in $\Xi_b^-\pi^+$ final state, the observation of two new excited Ξ_b^0 states decaying to $\Lambda_b^0 K^-\pi^+$ and a search for doubly heavy baryons Ξ_{bc}^0 and Ω_{bc}^0 decaying to $\Lambda_c^+\pi^-$ and $\Xi_c^+\pi^-$. These would improve the understanding of hadronic structure and nonperturbative QCD.

References

[1] M. Gell-Mann, *A schematic model of baryons and mesons*, Phys. Lett. **8** (1964) 214

[2] G. Zweig, *An SU$_3$ model for strong interaction symmetry and its breaking; Version 1* CERN-TH-401, CERN, Geneva, 1964

[3] M. Neubert, *Heavy quark symmetry*, Phys. Rept. **245** (1994) 259, `arXiv:hep-ph/9306320`

[4] LHCb collaboration, R. Aaij *et al.*, *Observation of new excited B_s^0 states*, Eur. Phys. J. C **81** (2021) 601, `arXiv:2010.15931`

[5] LHCb collaboration, R. Aaij *et al.*, *Observation of a new Ξ_b^- resonance*, Phys. Rev. Lett. **121** (2018) 072002, `arXiv:1805.09418`

[6] LHCb collaboration, R. Aaij *et al.*, *Observation of a new Ξ_b^0 state*, Phys. Rev. **D103** (2021) 012004, `arXiv:2010.14485`

[7] LHCb collaboration, R. Aaij *et al.*, *Observation of new resonances in the $\Lambda_b^0\pi^+\pi^-$ system*, Phys. Rev. Lett. **123** (2019) 152001, `arXiv:1907.13598`

[8] B. Chen, S.-Q. Luo, X. Liu, and T. Matsuki, *Interpretation of the observed $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$ states as 1D bottom baryons*, Phys. Rev. **D100** (2019) 094032, `arXiv:1910.03318`

[9] LHCb collaboration, R. Aaij *et al.*, *Observation of two new excited Ξ_b^0 states decaying to $\Lambda_b^0 K^-\pi^+$*, `arXiv:2110.04497`

[10] LHCb collaboration, R. Aaij *et al.*, *Search for the doubly heavy baryons Ω_{bc}^0 and Ξ_{bc}^0 decaying to $\Lambda_c^+\pi^-$ and $\Xi_c^+\pi^-$*, Chin. Phys. **C45** (2021) 093002, `arXiv:2104.04759`

PoS(EPS-HEP2021)410