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 \( B_s^+ \bar{K}^- \) final state, the observation of a new excited \( \Xi_b^0 \) state in \( \Xi_b^- \pi^+ \) final state, the observation of two new exited \( \Xi_b^0 \) states decaying to \( \Lambda_b^0 K^- \pi^+ \) and a search for doubly heavy baryons \( \Xi_{bc}^0 \) and \( \Omega_{bc}^0 \) decaying to \( \Lambda_c^+ \pi^- \) and \( \Xi_c^+ \pi^- \).

*Speaker

*** 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 ***
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 ($b\bar{s}$). 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 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 $B^+ \rightarrow J/\psi K^+$ and $B^+ \rightarrow \overline{D}^0 \pi^+$, where the $J/\psi$ 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 $p p$ 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 discriminator between resonant signal and the combinatorial background. The spectrum of mass difference, $\Delta m = m_{B^*K^-} - m_{B^+} - m_{K^-}$, is shown in Fig. 1. A clear excess at approximately 300 MeV above the mass threshold can be seen in the $\Delta m$ 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 results in approximately 45 MeV shift of peak position due to the unreconstructed photon. The local significance is larger than 20 standard deviations ($\sigma$) for one-peak fit with respect to the no-peak hypothesis and 7.7$\sigma$ 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 $m_1 = 6063.5 \pm 1.2$ (stat) $\pm 0.8$ (syst) MeV, $\Gamma_1 = 26 \pm 4$ (stat) $\pm 4$ (syst) MeV, $m_2 = 6114 \pm 3$ (stat) $\pm 5$ (syst) MeV, $\Gamma_2 = 66 \pm 18$ (stat) $\pm 21$ (syst) 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 2$\sigma$ 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 $R = 0.87 \pm 0.15$ (stat) $\pm 0.19$ (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 $\Xi_{b}^{0}$ state

Recently, the LHCb collaboration reported the observation of $\Xi_{b}(6227)^-$ baryon in the $\Lambda_c^0K^-$ and $\Xi_{b}^{*0}\pi^-$ mass spectrum [5]. The isospin partner of the $\Xi_{b}(6227)^-$ state is expected to decay
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) $0.5 < p_T < 1$ GeV, (middle) $1 < p_T < 2$ GeV and (right) $p_T > 2$ GeV.

through $\Xi_b^-\pi^+$ mode. In this analysis, the observation of a new excited $\Xi_b^0$ 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 $\Xi_b^-$ and $\Xi_b(2627)^-$ states is also updated.

The $\Xi_b^-$ candidates are reconstructed with the $\Xi_b^0\pi^-$ and $\Xi_b^0\pi^-\pi^+\pi^-$ decays, while the $\Lambda_b^0$ candidates reconstructed with $\Lambda_b^+\pi^-$ and $\Lambda_b^+\pi^+\pi^-\pi^+$ final states. The charm baryons, $\Xi_b^0$ and $\Lambda_b^+$, are reconstructed with the decays $\Xi_b^0\rightarrow pK^-\pi^+$ and $\Lambda_b^+\rightarrow pK^-\pi^+$. The $\Xi_b(2627)^0$ candidates are formed by combining a $\Xi_b^-$ candidate with a prompt $\pi^+$ candidate, while $\Xi_b(2627)^-$ candidates formed by combining $\Lambda_b^0$ and prompt $K^-$ candidates. The spectrum of mass difference, $\delta M = M(\Xi_b^-\pi^+) - M(\Xi_b^-)$, 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 10$\sigma$. The mass and width of $\Xi_b(2627)^0$ state are $m(\Xi_b(2627)^0) = 2627.1^{+1.4}_{-1.3} \pm 0.5$ MeV and $\Gamma(\Xi_b(2627)^0) = 18.6^{+5.0}_{-4.1} \pm 1.4$ MeV. The relative production rate of the $\Xi_b(2627)^0$ state at $\sqrt{s} = 13$ 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 $\Xi_b(2627)^0$ and $\Xi_b^-$ baryon divided by the relative efficiency between the $\Xi_b(2627)^0$ and $\Xi_b^-$ selections. The mass and with of $\Xi_b(2627)^-$ state, along with the mass of the $\Xi_b^-$ baryon, are also measured with better precision.

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

The LHCb collaboration reported the observation of two excited $\Lambda_b^0$ resonances in the $\Lambda_b^0\pi^+\pi^-$ system [7], which are consistent with the 1D $\Lambda_b^0$ states [8]. This observation motivates the investigation of 1D $\Xi_b^0$ states, as the $\Lambda_b^0$ and $\Xi_b^0$ baryons have similar properties due to the approximate $SU(3)$ flavor symmetry [8]. The two 1D $\Xi_b^0$ states are predicted to decay through $\Sigma_b^{(+)\,K}$ modes [8], which result in a $\Lambda_b^0K^-\pi^-$ final state. Two new excited $\Xi_b^0$ states are observed in the $\Lambda_b^0K^-\pi^+$ system with the LHCb dataset at $\sqrt{s} = 13$ TeV [9].
The $\Lambda_b^0$ candidates are reconstructed with the $\Lambda^+_c\pi^-$ and $\Lambda^+_c\pi^+\pi^-\pi^-$ decays, where the $\Lambda^+_c$ baryon subsequently decays to the $pK^-\pi^+$ final state. The selected $\Lambda_b^0$ candidates are combined with a prompt kaon and pion to form the $\Lambda_b^0K\pi$ candidates. To improve the mass resolution, the mass of $\Lambda_b^0K^-\pi^+$ candidates is redefined with the reconstructed mass difference between $\Lambda_b^0K^-\pi^+$ and $\Lambda_b^0$ candidates plus the measured $\Lambda_b^0$ mass. The mass spectrum of right-sign ($\Lambda_b^0K^-\pi^+$) and wrong-sign ($\Lambda_b^0K^+\pi^-$) combinations is shown in Fig.3. Two narrow peaks can be seen in the $\Lambda_b^0K^-\pi^+$ mass spectrum, while no significant peaking structure is visible in the $\Lambda_b^0K^+\pi^-$ system. The significance of two-peak hypothesis is larger than $9\sigma$ ($5\sigma$) compared to the no-peak (one-peak) hypothesis. The masses of these two states are $m(\Xi_b(6327)^0) = 6327.28^{+0.23}_{-0.21} \pm 0.08 \pm 0.24$ MeV, $m(\Xi_b(6333)^0) = 6332.69^{+0.17}_{-0.18} \pm 0.03 \pm 0.22$ MeV, where the uncertainties are statistical, systematic and due to $\Lambda_b^0$ 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) MeV, $\Gamma(\Xi_b(6333)^0) < 1.55$ (1.85) MeV. The resonant structure in the excited $\Xi_b^0$ 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 $\Sigma_b^+\pi^-$ resonance. The masses, widths and decay patterns of the two observed $\Xi_b^0$ states are consistent with the predictions [8] for a doublet of 1D $\Xi_b^0$ states.

5. **Search for doubly heavy baryons $\Xi_{bc}^0$ and $\Omega_{bc}^0$ 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 $\Xi_{bc}^0$ and $\Omega_{bc}^0$ decaying to $\Lambda_c^+\pi^-$ and $\Xi_c^+\pi^-$ with the LHCb dataset collected in 2016–2018 [10].
The \( \Xi_{bc}^0 \) and \( \Omega_{bc}^0 \) baryons have similar properties and are denoted as \( H_{bc}^0 \) hereafter. The \( \Lambda_c^+ \) and \( \Xi_c^+ \) candidates are reconstructed with the \( pK^-\pi^+ \) final state. A pion is combined with the \( \Lambda_c^+ \) (\( \Xi_c^+ \)) 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 \( R \) 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 \( \Lambda_b^0 \) (\( \Xi_b^0 \)) baryon. The upper limits on the ratio \( R(\Lambda_c^+\pi^-) \) and \( R(\Xi_c^+\pi^-) \) are set at 95% confidence level under different mass and lifetime hypothesis for \( \Xi_{bc}^0 \) and \( \Omega_{bc}^0 \) 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 \( B_{sq}^0 \) states in the \( B^+K^- \) final system, the observation of a
new $\Xi^0_{bc}$ state in $\Xi^{-}_{bc}\pi^{+}$ final state, the observation of two new excited $\Xi^0_{bc}$ states decaying to $\Lambda^0_b K^-\pi^+$ and a search for doubly heavy baryons $\Omega^0_{bc}$ and $\Omega^0_{bc}$ decaying to $\Lambda^+_c\pi^-$ and $\Xi^+_c\pi^-$. These would improve the understanding of hadronic structure and nonperturbative QCD.

References

[9] LHCb collaboration, R. Aaij *et al.*, *Observation of two new excited $\Xi^0_{bc}$ states decaying to $\Lambda^0_b K^-\pi^+$*, arXiv:2110.04497
[10] LHCb collaboration, R. Aaij *et al.*, *Search for the doubly heavy baryons $\Omega^0_{bc}$ and $\Xi^0_{bc}$ decaying to $\Lambda^+_c\pi^-$ and $\Xi^+_c\pi^-$*, Chin. Phys. C45 (2021) 093002, arXiv:2104.04759