Studies of b-hadrons and quarkonia at LHCb

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Abstract

LHCb has productive studies of quarkonia and b-hadrons which provide essential inputs to study quantum chromodynamics (QCD). In this proceeding, seven recent results are reported: the observation of a new excited Ξ_b^0 resonance in $\Xi_b^- \pi^+$ final states, the new excited B_s^0 state is observed in $B^+ K^-$ mass spectrum, the first observation of suppressed semileptonic $B_s^0 \to K^- \mu^+ \nu_\mu$ decay, the first observation of the decay $B^0 \to D^0 \bar{D}^0 K^+ \pi^-$, the first observation of the Cabibbo-suppressed decay $\Lambda_b^0 \to \chi_{c1} p \pi^-$, the first observation of $\Lambda_b^0 \to \Lambda_c^+ K^+ K^- \pi^-$ decay, and end this report with the first search for the doubly heavy baryon Ω_{bc}^0 and a search for Ξ_{bc}^0 baryon.

1 Introduction

Heavy flavour hadrons are among the most important tools for the study of QCD in high-energy hadronic collisions. At the LHC, b-hadrons production is dominated by the gluon-fusion heavy quark pair production subprocess and can be predicted by considering the partonic cross section for heavy quark pair production with input parton distribution function and fragmentation functions. In addition, many aspects of b-decays can be understood through the Heavy Quark Effective Theory (HQET) [1]. So the study of b-hadrons provides a crucial testing ground for perturbative and nonperturbative QCD. The LHCb detector [2,3], with its high momentum resolution, great particle identification capability and flexible trigger strategy, is perfectly suited to study features.

2 Observation of a new Ξ_b^0 state

The Ξ_b^0 and Ξ_b^- states form an isodoublet of bsq bound states is allowed in the constituent quark model [4], where q is a u or d quark, respectively. Three such isodoublets are predicted

which have different j_{qs} and J^P quantum numbers, where j_{qs} is the spin of the light diquark system qs, and J^P represents the spin and parity of the baryon state. Beyond these lowest-lying states, a spectrum of heavier states is also expected. The Ξ_b^- excitation with a mass of 6227 MeV/c^2 have been observed in the $\Lambda_b^0 K^-$ and $\Xi_b^0 \pi^-$ invariant-mass spectra, which is consistent with a P-wave excitation in subsequent constituent quark model but could also be wholly or partially molecular in some other investigations. More information on the observed states, or observation of additional excited beauty-baryon states, will provide additional input for these theoretical works.

Using pp collision data with an integrated luminosity of 8.5 fb^{-1} recorded by the LHCb at $\sqrt{s} = 7, 8$ and 13 TeV, a new Ξ_b^0 state, mass value around 6227 MeV/c^2, is seen through its decay to the $\Xi_b^- \pi^+$ final state [5]. The mass and natural width of $\Xi_b(6227)^0$ are measured to be

$$m(\Xi_b(6227)^0) = 6227.1^{+1.4}_{-1.5} \pm 0.5 \text{ MeV}/c^2,$$

$$\Gamma(\Xi_b(6227)^0) = 18.6^{+5.0}_{-4.1} \pm 1.4 \text{ MeV}/c^2,$$

where the first uncertainty is statistical and the second is experimental systematic. The relative production rate of the $\Xi_b(6227)^0$ state at $\sqrt{s} = 13$ TeV is measured through its decay to $\Xi_b^- \pi^+$ and found to be consistent with that of $\Xi_b(6227)^- \to \Xi_b^0 \pi^-$ decay.

3 Observation of new excited B_s^0 states

Potential models exploiting heavy-quark symmetry [6] are used to calculate properties of mesons containing one heavy and one light quark, including those with $\bar{b}s$ quark content, termed collectively the mesons B_s^{**0} mesons. Yet it is still difficult to predict precise masses and widths of such states. Experimental measurements are therefore essential.

LHCb observed a structure in the $B^+ K^-$ invariant mass spectrum in a data sample of pp collisions at $\sqrt{s} = 7, 8$ and 13 TeV, corresponding to a total integrated luminosity of 9 fb^{-1} [7]. Take the candidates with the prompt kaon $p_{\mathrm{T}} > 2$ GeV as an example. An obvious structure appears in the mass difference Δm around 300 MeV/c^2, where $\Delta m = m_{B^+ K^-} - m_{B^+} - m_{K^-}$, as shown in Figure 1. The fit results compare first the one-peak hypothesis to the null hypothesis, and then the two-peak to the one-peak hypothesis. The minimum of the test statistics across each fit with different associated production descriptions gives local significances of more than 20σ for the one-peak fit with respect to the null hypothesis and 7.7σ for the two-peak description with respect to the one-peak hypothesis.
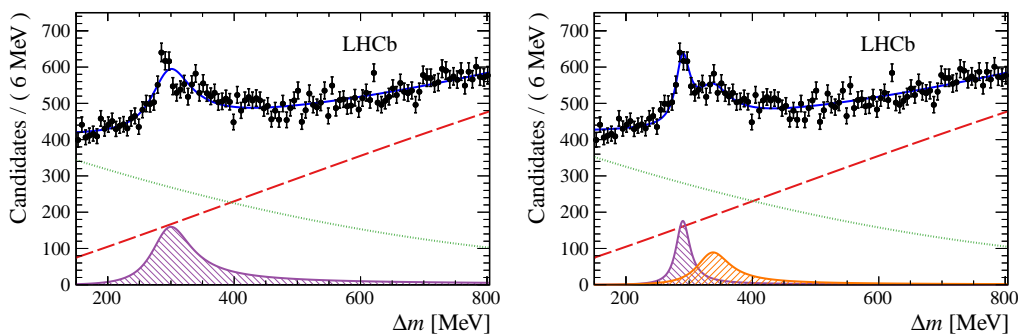

Figure 1: For candidates with the prompt kaon $p_{\mathrm{T}} > 2$ GeV, the $B^+ K^-$ mass difference distributions in data, overlaid with the fit models: (left plot) one-peak hypothesis and (right plot) two-peak hypothesis.

A single resonance which can decay through both $B^+ K^-$ and $B^{*+} K^-$ is disfavoured but can't

be excluded. If consider the decay is directly to B^+K^-, the measured parameters are

$$m_1 = 6063.5 \pm 1.2 \text{ (stat)} \pm 0.8 \text{ (syst) MeV/}c^2,$$

$$\Gamma_1 = 26 \pm 4 \text{ (stat)} \pm 4 \text{ (syst) MeV/}c^2,$$

$$m_2 = 6114 \pm 3(\text{ stat }) \pm 5 \text{ (syst) MeV/}c^2,$$

$$\Gamma_2 = 66 \pm 18(\text{ stat }) \pm 21 \text{ (syst) MeV/}c^2.$$

4 Observation of $B_s^0 \to K^- \mu^+ \nu_\mu$ and a measurement of $|V_{ub}|/|V_{cb}|$

The precision measurement of the Cabibbo-Kobayashi-Maskawa (CKM) matrix elements could be a probe on physics beyond Standard Model. b-hadrons can decay weakly via $b \to c(W^* \to \ell\nu)$ and $b \to u(W^* \to \ell\nu)$. The involved V_{ub} and V_{cb} obey the observed hierarchy $|V_{ub}|/|V_{cb}| \sim 0.1$. Their exclusive measurements show a discrepancy with inclusive results.

$B_s^0 \to K^- \mu^+ \nu_\mu$ is observed firstly using pp collision data collected by LHCb at $\sqrt{s} = 8$ TeV, with a total integrated luminosity of 2 fb^{-1} [8]. To measure $|V_{ub}|/|V_{cb}|$ and reduce the systematics on its branching fraction, the $B_s^0 \to D_s^- \mu^+ \nu_\mu$ is taken as normalization channel. The measurement is performed in two $B_s^0 \to K^-$ momentum transfer regions, $q^2 < 7\,\text{GeV}^2/c^4$ (low) and $q^2 > 7\,\text{GeV}^2/c^4$ (high). To discriminate signal and different backgrounds, The B_s^0 mass is represented by the corrected mass, defined as $m_{\text{corr}} = \sqrt{m_{Y\mu}^2 + p_\perp^2/c^2} + p_\perp/c$, where $Y = K^-$ or D_s^- and $p_\perp$ is the momentum of this pair transverse to the B_s^0 flight direction.

As shown in Figure 2, the m_{corr} fit template for the signal is obtained from simulation, while the shapes for the background components are derived from either simulation or control samples. With obtained about 13 thousand $B_s^0 \to K^- \mu^+ \nu_\mu$ candidates and about 200 thousand

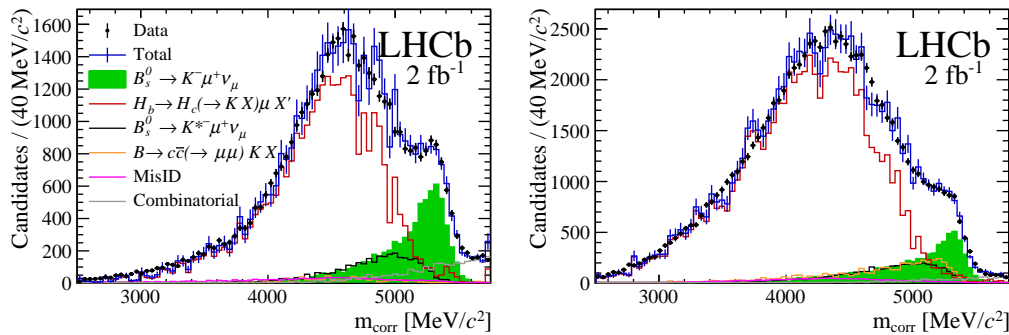Figure 2: Distribution of m_{corr} for the signal $B_s^0 \to K^- \mu^+ \nu_\mu$ with (low) $q^2 < 7\,\text{GeV}^2/c^4$ and (high) $q^2 > 7\,\text{GeV}^2/c^4$ region.

$B_s^0 \to D_s^- \mu^+ \nu_\mu$ candidates, the ratio of branching fractions between signal and normalisation channels is determined to be

$$R_{\text{BF}}(\text{ low }) = (1.66 \pm 0.08(\text{ stat }) \pm 0.07 \text{ (syst) } \pm 0.05\,(D_s)) \times 10^{-3},$$

$$R_{\text{BF}}(\text{ high }) = \left(3.25 \pm 0.21(\text{ stat })^{+0.16}_{-0.17}(\text{ syst }) \pm 0.09\,(D_s)\right) \times 10^{-3},$$

$$R_{\text{BF}}(\text{ all }) = \left(4.89 \pm 0.21(\text{ stat })^{+0.20}_{-0.21}(\text{ syst }) \pm 0.14\,(D_s)\right) \times 10^{-3}.$$

The ratio of CKM elements $|V_{ub}|/|V_{cb}|$ is measured to be

$$|V_{ub}|/|V_{cb}|(\text{ low }) = 0.0607 \pm 0.0015 \text{ (stat) } \pm 0.0013 \text{ (syst) } \pm 0.0008\,(D_s) \pm 0.0030(\text{FF}),$$

$$|V_{ub}|/|V_{cb}|(\text{ high }) = 0.0946 \pm 0.0030 \text{ (stat) }^{+0.0024}_{-0.0025}(\text{ syst }) \pm 0.0013\,(D_s) \pm 0.0068(\text{FF}),$$

where the last term refer to the form factor integrals. The discrepancy of obtained $|V_{ub}|/|V_{cb}|$ between low and high q^2 region related to the difference in the theoretical calculations of the form factors.

5   First observation of the decay $B^0 \to D^0\bar{D}^0 K^+\pi^-$

The $b \to c\bar{c}s$ transitions involved $B \to D^{(*)}\bar{D}^{(*)}K$ decay offering the opportunity to search for new $c\bar{s}$ or $c\bar{c}$ states. These processes can also provide important information to calculations of the $c\bar{c}$ contribution above the open-charm threshold in $b \to s\ell^+\ell^-$ decays. Yet the decay involving $B \to D^{(*)}\bar{D}^{(*)}K\pi$ transitions have not been observed.

Recently, the $B^0 \to D^0\bar{D}^0 K^+\pi^-$ decay, excluding contributions from $B^0 \to D^{*-}D^0 K^+$ transitions, first observed using pp collision data at $\sqrt{s} = 7, 8$ and 13 TeV collected by LHCb [9], corresponding to an integrated luminosity of 4.7 fb^{-1}. The fit results on mass spectra are shown in Figure 3. The normalization mode $B^0 \to D^{*-}D^0 K^+$ is excluded in signal range by the requirement of $|m(\bar{D}^0\pi^-) - m(\bar{D}^0) - [m_{\text{PDG}}(D^{*-}) - m_{\text{PDG}}(\bar{D}^0)]| > (4 \times 0.724)\,\text{MeV}/c^2$. The absolute branching fraction of $B^0 \to D^0\bar{D}^0 K^+\pi^-$ is determined to be $(3.50 \pm 0.27 \pm 0.26 \pm 0.30) \times 10^{-4}$, where the first uncertainty is statistical, the second is systematic and the third is related to the uncertainties in the branching fractions of the $B^0 \to D^{*-}D^0 K^+$.
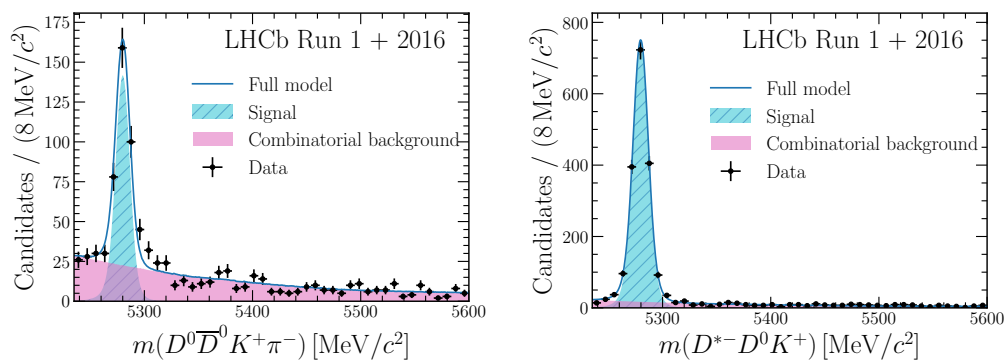

Figure 3: Invariant-mass distributions and fit projections for B^0 candidates in (left) the signal and (right) control mode for all subsamples combined. The small single-charm and charmless background is included in the signal component.

6   Observation of the decay $\Lambda_b^0 \to \chi_{c1}p\pi^-$

The hidden-charm pentaquark resonances have been observed only in the $J/\psi p$, $J/\psi \Lambda$ systems. It also possible hidden in other decay modes, such as $\eta_c p$, $\chi_{c1}p$ and $\chi_{c2}p$ systems. Using pp collision data with an integrated luminosity of 6 fb^{-1} recorded by the LHCb at $\sqrt{s} = 13$ TeV, a search for the $\Lambda_b^0 \to \chi_{c1}p\pi^-$ and $\Lambda_b^0 \to \chi_{c2}p\pi^-$ is performed [10]. The χ_{c1} and χ_{c2} mesons are reconstructed via $J/\psi\gamma$ final states. The $\Lambda_b^0 \to \chi_{c1}p\pi^-$ decay is observed for the first time and the $\Lambda_b^0 \to \chi_{c2}p\pi^-$ decay is obtained with a significance of 3.5σ, as shwon in Figure 4. With the current statistics of $\Lambda_b^0 \to \chi_{c1}p\pi^-$ decay, no evidence for contributions from exotic states is

found. The ratios of the branching fractions are measured to be

$$R_{\pi/K} = \frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c1} p \pi^-)}{\mathcal{B}(\Lambda_b^0 \to \chi_{c1} p K^-)} = (6.59 \pm 1.01 \pm 0.22) \times 10^{-2},$$

$$R_{2/1}^\pi = \frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c2} p \pi^-)}{\mathcal{B}(\Lambda_b^0 \to \chi_{c1} p \pi^-)} = 0.95 \pm 0.30 \pm 0.04 \pm 0.04,$$

$$R_{2/1}^K = \frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c2} p K^-)}{\mathcal{B}(\Lambda_b^0 \to \chi_{c1} p K^-)} = 1.06 \pm 0.05 \pm 0.04 \pm 0.04,$$

where the first uncertainty is statistical, the second is systematic and the third is related to the uncertainties in the branching fractions of the $\chi_{c1,2} \to J/\psi\gamma$.
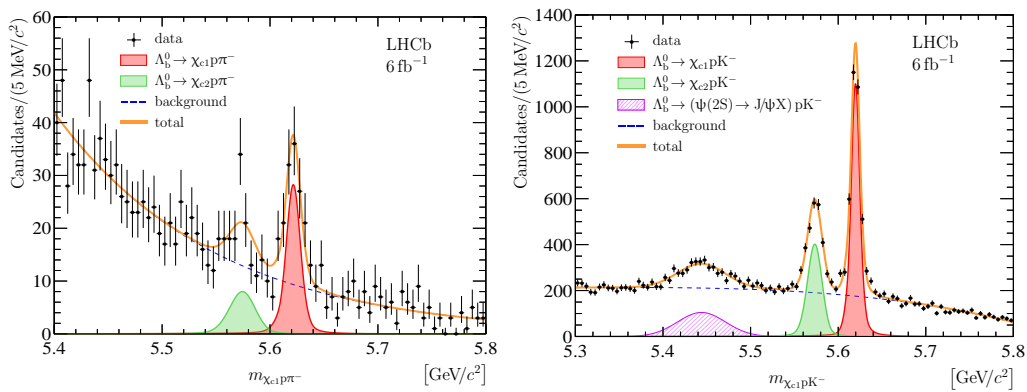

Figure 4: Mass distribution for selected $\Lambda_b^0 \to \chi_{c1} p \pi^-$ (left) and $\Lambda_b^0 \to \chi_{c1} p K^-$ (right).

7 Observation of the $\Lambda_b^0 \to \Lambda_c^+ K^+ K^- \pi^-$ decay

Many b-baryon decays have not been observed or poorly measured. The $\Lambda_b^0 \to \Lambda_c^+ K^+ K^- \pi^-$ decay is observed for the first time by LHCb using a data sample of pp collisions at $\sqrt{s} = 7, 8$ TeV, corresponding to a total integrated luminosity of 3 fb^{-1} [11]. This decay provides a laboratory to search for open-charm pentaquarks with valence quark content $c\bar{s}uud$ that could decay strongly to the $\Lambda_c^+ K^+$ final state. With obtained signal statistics, 3400 ± 80, no structure is observed in $\Lambda_c^+ K^+$ mass spectrum. The branching fraction is determined, using the $\Lambda_b^0 \to \Lambda_c^+ D_s^-$ decay as a normalisation channel, to be

$$\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ K^+ K^- \pi^-) = (1.02 \pm 0.03 \pm 0.05 \pm 0.10) \times 10^{-3},$$

where the first uncertainty is statistical, the second is systematic, and the third is due to the knowledge of the $\Lambda_b^0 \to \Lambda_c^+ D_s^-$ branching fraction.

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

The baryons with two heavy quarks are of interest for the theoretical consideration, because in this system the interaction of light quark with the heavy quarks is essential as well as the interaction between the heavy quarks. A first search for the doubly-heavy Ξ_{bc}^0 baryon using its decay to the $D^0 p K^-$ final state is performed by LHCb [12], no significant signal is found.

In $\Lambda_c^+ \pi^-$ or $\Xi_c^+ \pi^-$ final states, a new search for the Ξ_{bc}^0 and the first search for the Ω_{bc}^0 are performed using pp collision data collected by LHCb at $\sqrt{s} = 13$ TeV [13], corresponding to an integrated luminosity of 5.2 fb^{-1}. No significant excess is found in the invariant mass range from 6.7 to 7.3 GeV/c^2. Upper limits are set at 95% confidence level on the ratio of the Ξ_{bc}^0 and Ω_{bc}^0 production cross-section times its branching fraction to $\Lambda_c^+ \pi^-$ ($\Xi_c^+ \pi^-$) relative to that of the Λ_b^0 (Ξ_b^0) baryon for different lifetime hypotheses in range of $0.2 - 0.4$ fs. The upper limits change from 0.5×10^{-4} to 2.5×10^{-4} for the $\Omega_{bc}^0 \to \Lambda_c^+ \pi^-$ ($\Xi_{bc}^0 \to \Lambda_c^+ \pi^-$) decay, and from 1.4×10^{-3} to 6.9×10^{-3} for the $\Omega_{bc}^0 \to \Xi_c^+ \pi^-$ ($\Xi_{bc}^0 \to \Xi_c^+ \pi^-$) decay.

9 Conclusion

Several recent LHCb results on quarkonia and b-hadrons in pp collisions have been reported. The observation of a new excited state $\Xi_b(6227)^0$. The new excited B_s^0 state is observed in $B^+ K^-$ final state. The first observation of suppressed semileptonic $B_s^0 \to K^- \mu^+ \nu_\mu$ decay and a measurement of $|V_{ub}|/|V_{cb}|$. The first observation of the decay $B^0 \to D^0 \bar{D}^0 K^+ \pi^-$. The first observation of the decay $\Lambda_b^0 \to \chi_{c1} p \pi^-$. The first observation of $\Lambda_b^0 \to \Lambda_c^+ K^+ K^- \pi^-$ decay. The upper limit set for the doubly heavy baryon Ω_{bc}^0 and Ξ_{bc}^0. More results of quarkonia and b-hadrons at LHCb are expected in the near future.

References

[1] H. Georgi, *An effective field theory for heavy quarks at low energies*, Phys. Lett. B **240**, 447 (1990), doi:10.1016/0370-2693(90)91128-X.

[2] A. A. Alves Jr. et al., *The LHCb Detector at the LHC*, J. Inst. **3**, S08005 (2008), doi:10.1088/1748-0221/3/08/S08005.

[3] R. Aaij et al., *LHCb detector performance*, Int. J. Mod. Phys. A **30**, 1530022 (2015), doi:10.1142/S0217751X15300227.

[4] M. Gell-Mann, *A schematic model of baryons and mesons*, Phys. Lett. **8**, 214 (1964), doi:10.1016/S0031-9163(64)92001-3.

[5] R. Aaij et al., *Observation of a new Ξ_b^0 state*, Phys. Rev. D **103**, 012004 (2021), doi:10.1103/PhysRevD.103.012004.

[6] S. Godfrey and N. Isgur, *Mesons in a relativized quark model with chromodynamics*, Phys. Rev. D **32**, 189 (1985), doi:10.1103/PhysRevD.32.189.

[7] R. Aaij et al., *Observation of new excited B_s^0 states*, Eur. Phys. J. C **81**, 601 (2021), doi:10.1140/epjc/s10052-021-09305-3.

[8] R. Aaij et al., *First Observation of the Decay $B_s^0 \to K^- \mu^+ \nu_\mu$ and a measurement of $|V_{ub}|/|V_{cb}|$*, Phys. Rev. Lett. **126**, 081804 (2021), doi:10.1103/PhysRevLett.126.081804.

[9] R. Aaij et al., *First observation of the decay $B^0 \to D^0 \bar{D}^0 K^+ \pi^-$*, Phys. Rev. D **102**, 051102 (2020), doi:10.1103/PhysRevD.102.051102.

[10] R. Aaij et al., *Observation of the decay $\Lambda_b^0 \to \chi_{c1} p \pi^-$*, J. High Energy Phys. **05**, 095 (2021), doi:10.1007/JHEP05(2021)095.

[11] R. Aaij et al., *Observation of the $\Lambda_b^0 \to \Lambda_c^+ K^+ K^- \pi^-$ decay*, Phys. Lett. B **815**, 136172 (2021), doi:10.1016/j.physletb.2021.136172.

[12] R. Aaij et al., *Search for the doubly heavy Ξ_{bc}^0 baryon via decays to $D^0 p K^-$*, J. High Energy Phys. **11**, 095 (2020), doi:10.1007/JHEP11(2020)095.

[13] 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. C **45**, 093002 (2021) doi:10.1088/1674-1137/ac0c70.