PROCEEDINGS OF SCIENCE

Heavy flavour production and spectroscopy

Jibo He[*†]
University of Chinese Academy of Sciences (UCAS), Beijing, China
E-mail: jibo.he@cern.ch

Latest results on the heavy flavour production and spectroscopy at the LHC are reviewed. These include measurements of production rates of the charmed and beauty hadrons, and observations of new excited charmed and beauty hadrons and exotic states.

The Ninth Annual Conference on Large Hadron Collider Physics - LHCP2021
7-12 June 2021
Online

[*]Speaker.
[†]on behalf of the ALICE, ATLAS, CMS and LHCb collaborations.

PoS(LHCP2021)140

1. Introduction

Study of heavy flavour production and spectroscopy is important to understand the strong interaction. Large production rates of the heavy flavour particles at the LHC open the doors to extend analyses to unexplored phase spaces, and bring new information to help understand the QCD. More than fifty new conventional or exotic states have been observed at the LHC. Precise measurements of heavy flavour production cross-sections and distributions are important to test the theoretical predictions being used to estimate backgrounds to new physics searches. Measurements of heavy flavour production in proton-proton (pp) collisions also provide a reference for those in heavy-ion collisions to understand nuclear effects.

2. Heavy flavour production

Production cross-sections of prompt D^0, D^+, D_s^+ mesons and those from b-decay (non-prompt) in pp collisions at $\sqrt{s} = 5.02\,\text{TeV}$ are measured by the ALICE collaboration [1]. The results are found to agree with predictions by FONLL calculations [2, 3], as shown in Fig. 1. Figure 2 shows comparisons of both the charm-quark and beauty-quark fragmentation-fraction ratio $f_s/(f_u + f_d)$ with previous measurements performed by the ALICE [4], ATLAS [5, 6], CDF [7], LHCb [8, 9], H1 [10], ZEUS [11] collaborations and to the average of LEP measurements [12, 13]. No significant dependence on centre-of-mass energy and collision system is seen within the current precision.

The beauty-quark fragmentation-fraction ratio, f_s/f_d in pp collisions is obtained from a combined analysis [14] of different B-decay modes measured by the LHCb experiment. The ratio f_s/f_d has clear dependence on the transverse momentum, as shown in Fig. 3, while there is no evident dependence on the collision centre-of-mass energy. Branching fractions of B_s^0 meson are also updated.

Production cross-sections of charmed baryons in pp collisions are measured by the ALICE collaboration [17, 18]. The production cross-section ratios of Λ_c^+/D^0 and Ξ_c/D^0 have clear dependence on the transverse momentum, as shown in Fig. 4. The trend of the Λ_c^+/D^0 production ratio is well decribed by PYTHIA 8 with a new Colour-Reconnection (CR) mode [19], the statistical Hadronisation (SH) including additional excited charm baryons predicted by Relativistic Quark Model (RQM) [20], and the Catania model assuming that the hadronisation can occur via coales-

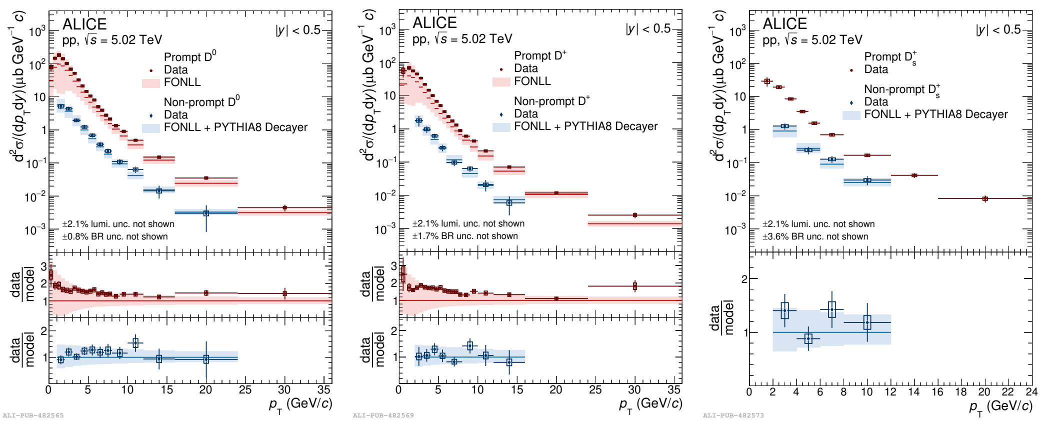

Figure 1: Production cross-sections of prompt and non-prompt D^0, D^+, D_s^+ mesons [1] compared to predictions obtained with FONLL calculations [2, 3], combined with PYTHIA 8 [15, 16] for the $H_b \to D + X$ decay kinematics.

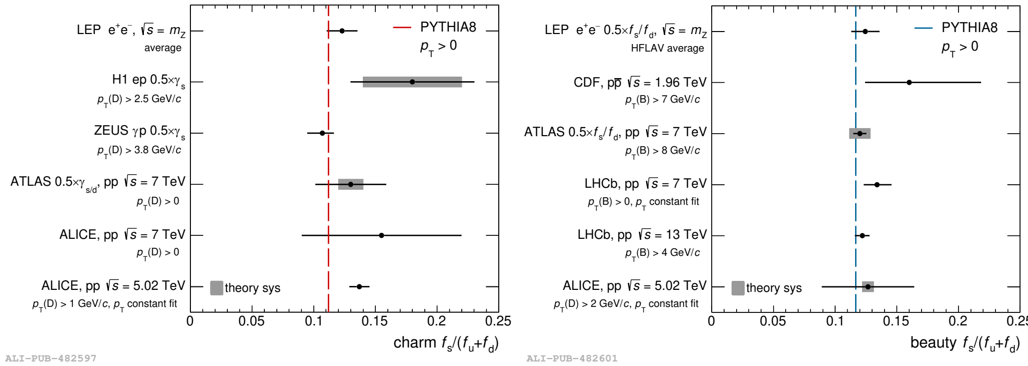

Figure 2: (Left) Charm-quark fragmentation-fraction ratio $f_s/(f_u+f_d)$ [1] compared with previous measurements performed by the ALICE [4], ATLAS [5], H1 [10], and ZEUS [11] collaborations and to the average of LEP measurements [12]. (Right) Bottom-quark fragmentation-fraction ratio $f_s/(f_u+f_d)$ [1] compared with previous measurements performed by the ATLAS [6], CDF [7], and LHCb [8, 9] collaborations and to the average of LEP measurements [13].

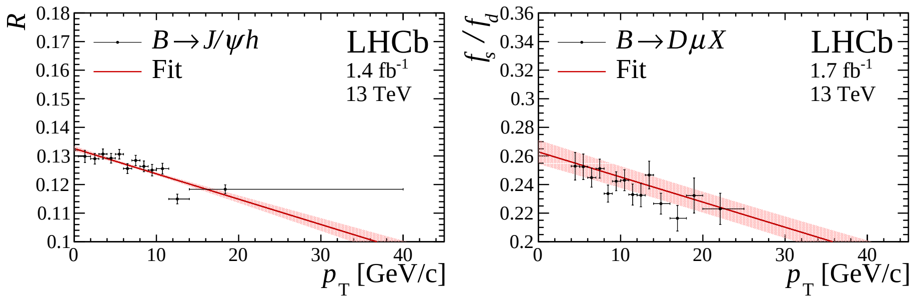

Figure 3: Ratio of the beauty-quark fragmentation-fraction, f_s/f_d in pp collisions at $\sqrt{s}=13$ TeV, as a function of the B transverse momentum [14].

cence in addition to fragmentation [21]. However, none of the theoretical models can describe the trend of the Ξ_c/D^0 production ratio yet. Such trend of the baryon-to-meson production ratio was also seen in beauty system by the LHCb experiment, using both the semileptonic decays [8] and fully reconstructed decays [22, 23].

Charm-quark fragmentation fractions are measured by the ALICE collaboration [24] and are compared with previous measurements in other collision systems, as shown in Fig. 5. One can see that the fragmentation fractions in pp collisions differ significantly from those obtained in the e^+e^- or ep collision system when the baryons are included. Figure 5 also shows charm production cross-section at midrapidity as a function of the collision energy [24, 25, 26], which is at the upper edge of the FONLL [2, 3] and NNLO [27] calculations.

Differential measurements of the asymmetry between Λ_b^0 and $\overline{\Lambda}_b^0$ baryon production rates in pp collisions at centre-of-mass energies of $\sqrt{s}=7$ and 8 TeV are performed by the LHCb collaboration [29] using the inclusive semileptonic decay $\Lambda_b^0 \to \Lambda_c^+\mu^-\overline{\nu}_\mu X$. The measured production asymmetry as functions of Λ_b^0 rapidity y and transverse momentum p_{T}, and comparisons to predictions from hadronisation models in PYTHIA [19, 30] and heavy-quark recombination [31], are shown in Fig. 6, which shows a moderate agreement. This is the first observation of a particle-antiparticle asymmetry in b-hadron production at LHC energies.

The $B_c^{(*)}(2S)^+$ states were observed by the CMS and LHCb collaborations [32, 33], and their production rates were measured by the CMS collaboration [34]. The $B_c(2S)^+$ to B_c^+, $B_c^*(2S)^+$ to

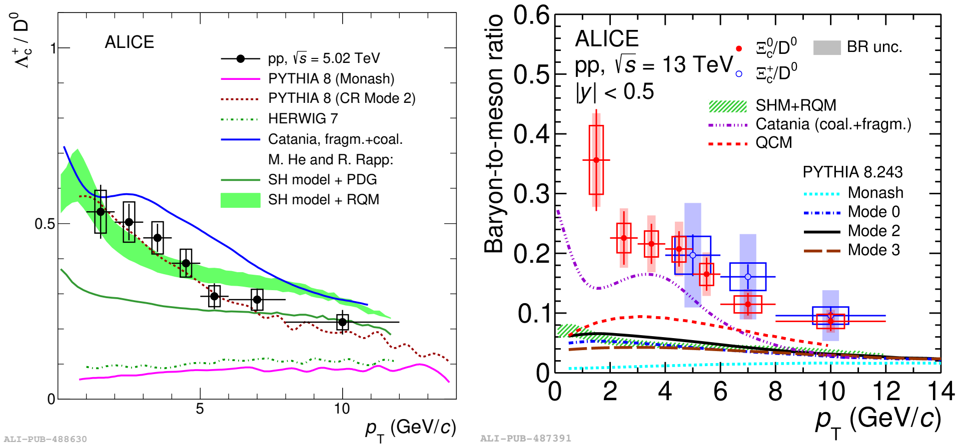

Figure 4: Production cross-section ratio of (left) Λ_c^+/D^0 and (right) Ξ_c/D^0, as function of the transverse momentum [17, 18].

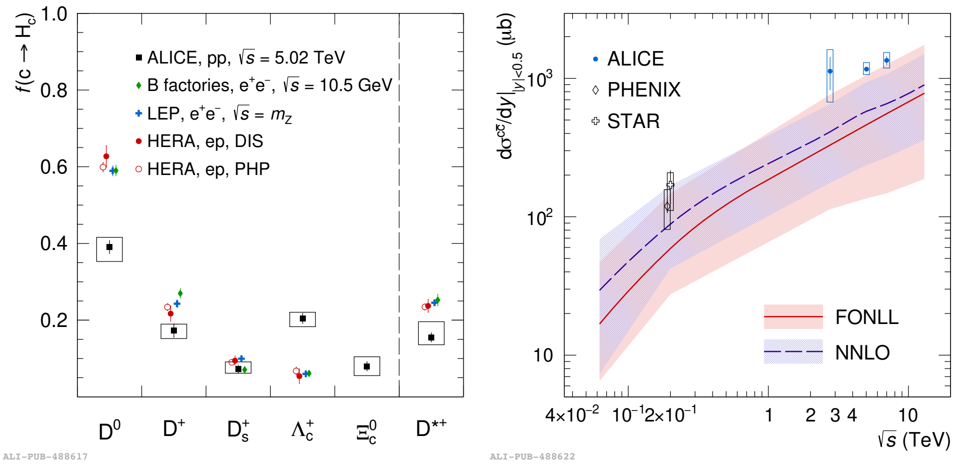

Figure 5: (Left) Charm-quark fragmentation fractions into charm hadrons measured in pp collisions at $\sqrt{s} = 5.02$ TeV [24] in comparison with experimental measurements performed in e^+e^- collisions at LEP and at B factories, and in ep collisions at HERA [28]. (Right) Charm production cross-section at midrapidity per unit of rapidity as a function of the collision energy [24, 25, 26], and comparison with FONLL [2, 3] and NNLO [27] calculations.

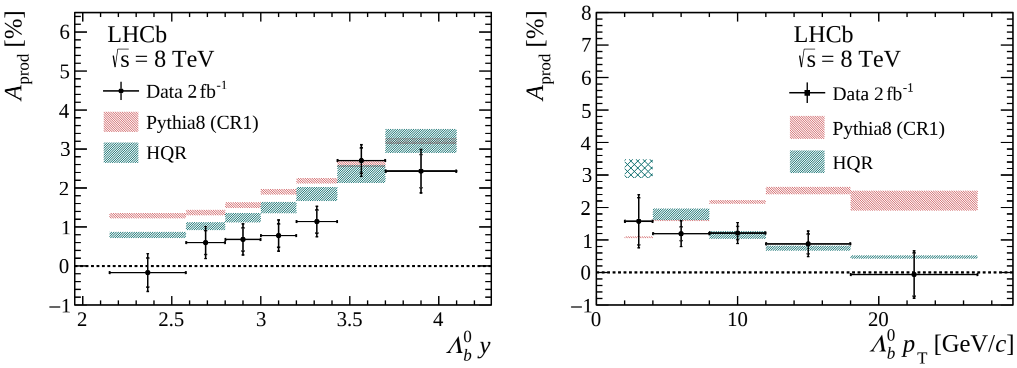

Figure 6: Comparison of the measured Λ_b^0 production asymmetry [29] with the predictions by the most compatible Pythia model [19, 30] and the heavy-quark recombination model (HQR) [31].

B_c^+, and $B_c^*(2S)^+$ to $B_c(2S)^+$ cross-section ratios, including the unknown $B_c^{(*)}(2S)^+ \to B_c^{(*)+}\pi^+\pi^-$ branching fractions, are determined to be $(3.47 \pm 0.63 \pm 0.33)\%$, $(4.69 \pm 0.71 \pm 0.56)\%$, and $1.35 \pm 0.32 \pm 0.09$, respectively. They have no significant dependence on the B_c^+ p_{T} and y.

3. Heavy flavour spectroscopy

In the study of the $B^0 \to D^- D^+ K^+ \pi^-$ decay, a new excited D_s^+ state decaying to $D^+K^+\pi^-$ is observed by the LHCb collaboration [35], as shown in Fig. 7. The pole mass and width, and the spin-parity of the new state are measured with an amplitude analysis to be $m_R = 2591 \pm 6 \pm 7\,\mathrm{MeV}$, $\Gamma_R = 89 \pm 16 \pm 12\,\mathrm{MeV}$, and $J^P = 0^-$.

In the study of the $\Omega_b^- \to \Xi_c^+ K^- \pi^-$ decay, four excited Ω_c^0 baryons, $\Omega_c(3000)^0$, $\Omega_c(3050)^0$, $\Omega_c(3065)^0$, $\Omega_c(3090)^0$, are observed in the $\Xi_c^+K^-$ mass projection [36], and there is a structure at threshold with a significance of 4.3σ, as shown in Fig. 8. A test of spin hypotheses is performed, the combined hypothesis of the four peaks to have quantum numbers in the order $(1/2, 1/2, 3/2, 3/2)$ is tested and rejected with a significance of 3.5σ. These four states, in addition to the $\Omega_c(3119)^0$ state that is not seen in this analysis, were observed previously in the prompt $\Xi_c^+K^-$ mass spectrum [37].

A structure, interpreted as the result of overlapping excited B_s^0 states, is observed in the B^+K^- mass spectrum by the LHCb collaboration [38], as shown in Fig. 9. Assuming they decay directly to B^+K^-, their masses and widths are determined to be: $m_1 = 6063.5 \pm 1.2 \pm 0.8\,\mathrm{MeV}, \Gamma_1 = 26 \pm 4 \pm 4\,\mathrm{MeV}, m_2 = 6114 \pm 3 \pm 5\,\mathrm{MeV}, \Gamma_2 = 66 \pm 18 \pm 21\,\mathrm{MeV}$. Alternative values assuming a decay through $B^{*+}K^-$, with a missing photon from the $B^{*+} \to B^+\gamma$ decay, would be shifted by approximately 45 MeV.

For excited b-baryon states, a narrow resonance $\Xi_b(6100)^-$ is observed in the $\Xi_b^-\pi^+\pi^-$ mass spectrum by the CMS collaboration [39]. The Ξ_b^- is reconstructed via its decays to $J/\psi\Xi^-$ and $J/\psi\Lambda K^-$, and the $\Xi_b^-\pi^+\pi^-$ mass spectrum with the fully reconstructed Ξ_b^- is shown in Fig. 10. The $\Xi_b(6100)^-$ mass is determined to be $6100.3 \pm 0.2 \pm 0.1 \pm 0.6(\Xi_b^-)\,\mathrm{MeV}$, where the last uncertainty reflects the precision of the Ξ_b^- baryon mass. An upper limit of 1.9 MeV at 95% CL is set on its natural width. A new excited Ξ_b^0 resonance, $\Xi_b(6227)^0$, is observed in the $\Xi_b^-\pi^+$ mass spectrum by the LHCb collaboration [40]. The Ξ_b^- state is reconstructed in the fully hadronic decay modes $\Xi_c^0\pi^-$ and $\Xi_c^0\pi^-\pi^+\pi^-$, and the $\Xi_b^-\pi^+$ mass spectrum with $\Xi_b^- \to \Xi_c^0\pi^-$ is shown in Fig. 11. The mass and natural widths are determined to be $m = 6227.1^{+1.4}_{-1.5} \pm 0.5\,\mathrm{MeV}, \Gamma = 18.6^{+5.0}_{-4.1} \pm 1.4\,\mathrm{MeV}$. Improved measurements of the mass and natural width of the previously observed $\Xi_b(6227)^-$ state [41], along with the mass of the Ξ_b^- baryon, are also reported [40].

A search for the doubly charmed baryon Ξ_{cc}^+ is performed in the $\Xi_c^+\pi^+\pi^-$ decay mode by the LHCb collaboration [42]. No significant signal is seen, and upper limits on its production rate are set for different Ξ_{cc}^+ mass and lifetime hypotheses. The results from this search are combined with a previously published search for the $\Xi_{cc}^+ \to \Lambda_c^+K^-\pi^+$ decay mode [43], yielding a maximum local (global) significance of 4.0σ (2.9σ) around the known mass of its isospin partner Ξ_{cc}^{++} [44], including systematic uncertainties.

The LHCb collaboration performed the first search for the doubly charmed baryon with strangeness Ω_{cc}^+ via its decay to $\Xi_c^+K^-\pi^+$ [45], the doubly heavy baryon Ξ_{bc}^0 via its decay to D^0pK^- [46], and $\Xi_{bc}^0, \Omega_{bc}^0$ via their decays to $\Lambda_c^+(\Xi_c^+)\pi^-$ [47], no significant signal is seen yet, and upper limits on their production rates are set for different mass and lifetime hypotheses.

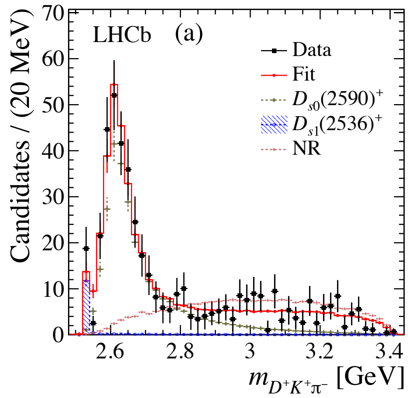

Figure 7: Projection of $m(D^+K^+\pi^-)$ in the amplitude analysis of the $B^0 \to D^-D^+K^+\pi^-$ decay [35].

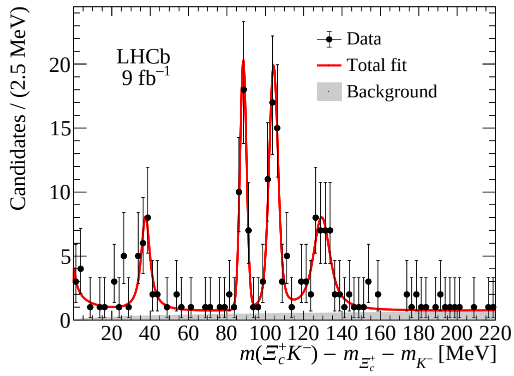

Figure 8: Distribution of the reconstructed mass difference between $m(\Xi_c^+K^-)$ and the Ξ_c^+ and K^- masses [36].

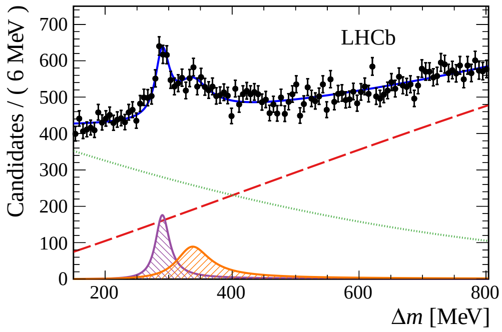

Figure 9: Distribution of the reconstructed mass difference between the $m(B^+K^-)$ and the B^+ and K^- masses [38]. Associated production (combinatorial) is shown as the green dotted (red dashed) line.

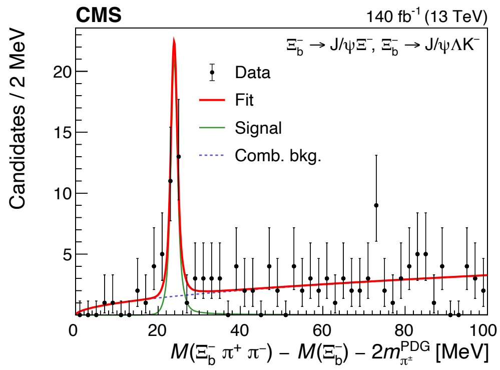

Figure 10: Distribution of the reconstructed mass difference between the $\Xi_b^-\pi^+\pi^-$ invariant mass and the Ξ_b^- and 2π masses [39].

In the amplitude analysis of the $B^+ \to D^+D^-K^+$ decay performed by the LHCb collaboration [48], it is found to be necessary to include new spin-0 and spin-1 resonances in the D^-K^+ channel with masses around 2.9 GeV and a new spin-0 charmonium resonance in proximity to the spin-2 $\chi_{c2}(3930)$ state, as shown in Fig. 12. This is also supported by a model-independent study [49]. The masses and natural widths of the two exotic states in the D^-K^+ channel are determined to be, $X_0(2900) : M = 2866 \pm 7 \pm 2\,\text{MeV}, \Gamma = 57 \pm 12 \pm 4\,\text{MeV}$, $X_1(2900) : M = 2904 \pm 5 \pm 1\,\text{MeV}, \Gamma = 110 \pm 11 \pm 4\,\text{MeV}$.

In the amplitude analysis of the $B^+ \to J/\psi\phi K^+$ decay performed by the LHCb collaboration [50], two Z_{cs} states are observed. The most significant one, $Z_{cs}(4000)^+$, as shown in Fig. 13, has a mass of $4003 \pm 6^{+4}_{-14}$ MeV, and a width of $131 \pm 15 \pm 26$ MeV, which is ten times higher than the natural width of the $Z_{cs}(3985)^+$ state ($m = 3982.5^{+1.8}_{-2.6} \pm 2.1\,\text{MeV}$, $\Gamma = 12.8^{+5.3}_{-4.4} \pm 3.0\,\text{MeV}$) observed by the BESIII collaboration [51].

In the study of the invariant mass spectrum of J/ψ pairs by the LHCb collaboration [52], a narrow structure around 6.9 GeV is observed, as shown in Fig. 14. Its mass and natural width are determined to be $6905 \pm 11 \pm 7$ MeV, $80 \pm 19 \pm 33$ MeV assuming no interference with the nonresonant SPS continuum. This could be the hadron state consisting of four charm quarks $T_{cc\bar{c}\bar{c}}$.

In the amplitude analysis of flavour-untagged $B_s^0 \to J/\psi p\bar{p}$ performed by the LHCb collabora-

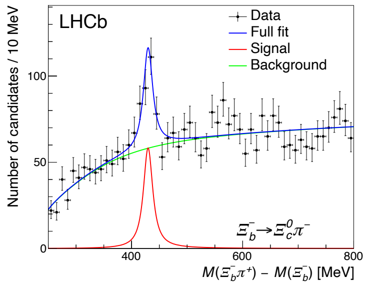

Figure 11: Distribution of the reconstructed mass difference between the $m(\Xi_b^- \pi^+)$ and the Ξ_b^- and π^+ masses [40].

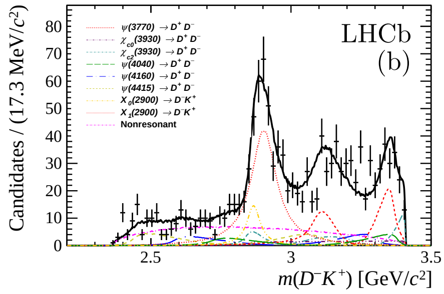

Figure 12: Projection of $m(D^- K^+)$ in the amplitude analysis of the $B^+ \to D^+ D^- K^+$ decay [48].

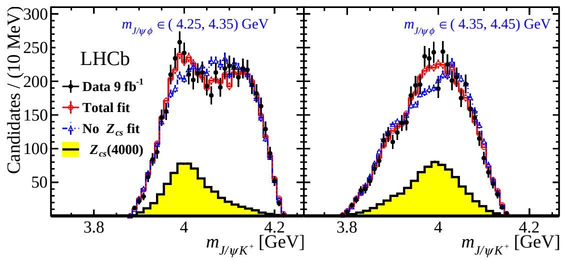

Figure 13: Projection of $m(J/\psi K^+)$ in the amplitude analysis of the $B^+ \to J/\psi \phi K^+$ decay in two slices of $m(J/\psi \phi)$ [50].

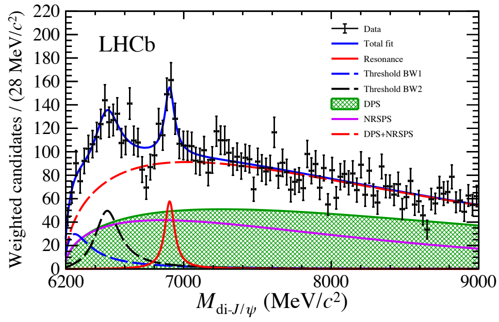

Figure 14: Distribution of invariant mass of weighted di-J/ψ candidates [52].

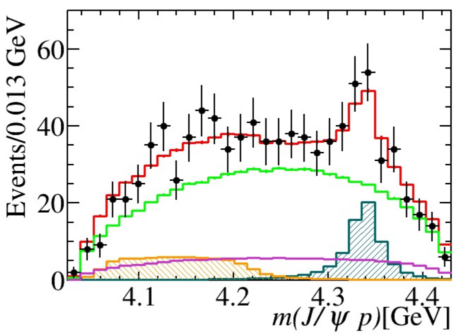

Figure 15: Projection of $m(J/\psi p)$ in the amplitude analysis of the $B_s^0 \to J/\psi p\bar{p}$ decay [53].

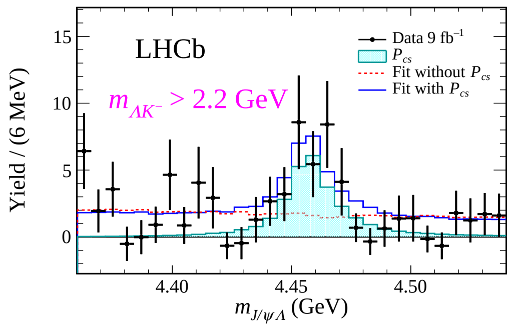

Figure 16: Projection of $m(J/\psi \Lambda)$ in the amplitude analysis of the $\Xi_b^- \to J/\psi \Lambda K^-$ decay with $m(\Lambda K^-) > 2.2\,\text{GeV}$ [54].

tion [53], evidence for a new structure in the $J/\psi p$ and $J/\psi \bar{p}$ systems is found, as shown in Fig. 15. Its mass and width are determined to be $4337^{+7}_{-1}{}^{+2}_{-1}$ MeV, $29^{+26}_{-12}{}^{+14}_{-14}$ MeV, respectively. In the amplitude analysis of the $\Xi_b^- \to J/\psi \Lambda K^-$ decay performed by the LHCb collaboration [54], first evidence for a charmonium pentaquark with strangeness is found, with a mass of $4458.8 \pm 2.9^{+4.7}_{-1.1}$ MeV and a width of $17.3 \pm 6.5^{+8.0}_{-5.7}$ MeV, as shown in Fig. 16.

4. Summary

Great progress has been made on studies of the heavy flavour production and spectroscopy at the LHC. This includes measurements of productions of $D, \Lambda_c^+, \Xi_c, \Lambda_b^0, B_c^{(*)}(2S)^+$, and observations of $D_{s0}(2590)^+$, excited Ξ_b^- states, $X(2900)$, Z_{cs}^+, $X(6900)$, and evidence of $P_c(4337)^+$ and P_{cs}. These results are very helpful for understanding the strong interaction.

References

[1] ALICE collaboration, S. Acharya *et al.*, *Measurement of beauty and charm production in pp collisions at $\sqrt{s}$ = 5.02 TeV via non-prompt and prompt D mesons*, JHEP **05** (2021) 220, arXiv:2102.13601.

[2] M. Cacciari, M. Greco, and P. Nason, *The p_T spectrum in heavy flavor hadroproduction*, JHEP **05** (1998) 007, arXiv:hep-ph/9803400.

[3] M. Cacciari, S. Frixione, and P. Nason, *The p_T spectrum in heavy flavor photoproduction*, JHEP **03** (2001) 006, arXiv:hep-ph/0102134.

[4] ALICE collaboration, B. Abelev *et al.*, *D_s^+ meson production at central rapidity in proton–proton collisions at $\sqrt{s} = 7$ TeV*, Phys. Lett. **B718** (2012) 279, arXiv:1208.1948.

[5] ATLAS collaboration, G. Aad *et al.*, *Measurement of $D^{*\pm}$, $D^{\pm}$ and $D_s^{\pm}$ meson production cross sections in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector*, Nucl. Phys. **B907** (2016) 717, arXiv:1512.02913.

[6] ATLAS collaboration, G. Aad *et al.*, *Determination of the ratio of b-quark fragmentation fractions f_s/f_d in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector*, Phys. Rev. Lett. **115** (2015) 262001, arXiv:1507.08925.

[7] CDF collaboration, T. Aaltonen *et al.*, *Measurement of ratios of fragmentation fractions for bottom hadrons in $p\bar{p}$ collisions at $\sqrt{s}$ = 1.96-TeV*, Phys. Rev. **D77** (2008) 072003, arXiv:0801.4375.

[8] LHCb collaboration, R. Aaij *et al.*, *Measurement of b hadron production fractions in 7 TeV pp collisions*, Phys. Rev. **D85** (2012) 032008, arXiv:1111.2357.

[9] LHCb collaboration, R. Aaij *et al.*, *Measurement of b-hadron fractions in 13 TeV pp collisions*, Phys. Rev. **D100** (2019) 031102(R), arXiv:1902.06794.

[10] H1 collaboration, A. Aktas *et al.*, *Inclusive production of D^+, D^0, D_s^+ and D^{*+} mesons in deep inelastic scattering at HERA*, Eur. Phys. J. **C38** (2005) 447, arXiv:hep-ex/0408149.

[11] ZEUS collaboration, H. Abramowicz *et al.*, *Measurement of charm fragmentation fractions in photoproduction at HERA*, JHEP **09** (2013) 058, arXiv:1306.4862.

[12] L. Gladilin, *Fragmentation fractions of c and b quarks into charmed hadrons at LEP*, Eur. Phys. J. **C75** (2015) 19, arXiv:1404.3888.

[13] HFLAV, Y. S. Amhis *et al.*, *Averages of b-hadron, c-hadron, and τ-lepton properties as of 2018*, Eur. Phys. J. **C81** (2021) 226, arXiv:1909.12524.

[14] LHCb collaboration, R. Aaij *et al.*, *Precise measurement of the f_s/f_d ratio of fragmentation fractions and of B_s^0 decay branching fractions*, arXiv:2103.06810, to appear in PRD.

[15] T. Sjöstrand, S. Mrenna, and P. Skands, *PYTHIA 6.4 physics and manual*, JHEP **05** (2006) 026, arXiv:hep-ph/0603175.

[16] T. Sjöstrand *et al.*, *An introduction to PYTHIA 8.2*, Comput. Phys. Commun. **191** (2015) 159, arXiv:1410.3012.

[17] ALICE collaboration, S. Acharya *et al.*, *Λ_c^+ production and baryon-to-meson ratios in pp and p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV at the LHC*, arXiv:2011.06078.

[18] ALICE collaboration, S. Acharya *et al.*, *Measurement of the cross sections of Ξ_c^0 and Ξ_c^+ baryons and branching-fraction ratio BR($\Xi_c^0 \to \Xi^- e^+ \nu_e$)/BR($\Xi_c^0 \to \Xi^- \pi^+$) in pp collisions at 13 TeV*, arXiv:2105.05187.

[19] J. R. Christiansen and P. Z. Skands, *String formation beyond leading colour*, JHEP **08** (2015) 003, arXiv:1505.01681.

[20] M. He and R. Rapp, *Charm-baryon production in proton-proton collisions*, Phys. Lett. **B795** (2019) 117, arXiv:1902.08889.

[21] V. Minissale, S. Plumari, and V. Greco, *Charm hadrons in pp collisions at LHC energy within a coalescence plus fragmentation approach*, Phys. Lett. **B821** (2021) 136622, arXiv:2012.12001.

[22] LHCb collaboration, R. Aaij *et al.*, *Study of the kinematic dependences of Λ_b^0 production in pp collisions and a measurement of the $\Lambda_b^0 \to \Lambda_c^+ \pi^-$ branching fraction*, JHEP **08** (2014) 143, arXiv:1405.6842.

[23] LHCb collaboration, R. Aaij *et al.*, *Study of the productions of Λ_b^0 and $\bar{B}^0$ hadrons in pp collisions and first measurement of the $\Lambda_b^0 \to J/\psi pK^-$ branching fraction*, Chin. Phys. **C40** (2016) 011001, arXiv:1509.00292.

[24] ALICE collaboration, S. Acharya *et al.*, *Charm-quark fragmentation fractions and production cross section at midrapidity in pp collisions at the LHC*, arXiv:2105.06335.

[25] STAR collaboration, L. Adamczyk *et al.*, *Measurements of D^0 and D^* production in $p+p$ collisions at $\sqrt{s} = 200$ GeV*, Phys. Rev. **D86** (2012) 072013, arXiv:1204.4244.

[26] PHENIX collaboration, A. Adare *et al.*, *Heavy quark production in $p+p$ and energy loss and flow of heavy quarks in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV*, Phys. Rev. **C84** (2011) 044905, arXiv:1005.1627.

[27] D. d'Enterria and A. M. Snigirev, *Triple parton scatterings in high-energy proton-proton collisions*, Phys. Rev. Lett. **118** (2017) 122001, arXiv:1612.05582.

[28] M. Lisovyi, A. Verbytskyi, and O. Zenaiev, *Combined analysis of charm-quark fragmentation-fraction measurements*, Eur. Phys. J. **C76** (2016) 397, arXiv:1509.01061.

[29] LHCb collaboration, R. Aaij *et al.*, *Observation of a $\Lambda_b^0 - \bar{\Lambda}_b^0$ production asymmetry in proton-proton collisions at $\sqrt{s} = 7$ and 8 TeV*, arXiv:2107.09593, to appear in JHEP.

[30] S. Argyropoulos and T. Sjöstrand, *Effects of color reconnection on $t\bar{t}$ final states at the LHC*, JHEP **11** (2014) 043, arXiv:1407.6653.

[31] W. K. Lai and A. K. Leibovich, *Λ_c^+/Λ_c^- and $\Lambda_b^0/\bar{\Lambda}_b^0$ production asymmetry at the LHC from heavy quark recombination*, Phys. Rev. **D91** (2015) 054022, arXiv:1410.2091.

[32] CMS collaboration, A. M. Sirunyan *et al.*, *Observation of two excited B_c^+ states and measurement of the $B_c^+(2S)$ mass in pp collisions at $\sqrt{s} = 13$ TeV*, Phys. Rev. Lett. **122** (2019) 132001, arXiv:1902.00571.

[33] LHCb collaboration, R. Aaij *et al.*, *Observation of an excited B_c^+ state*, Phys. Rev. Lett. **122** (2019) 232001, arXiv:1904.00081.

[34] CMS collaboration, A. M. Sirunyan *et al.*, *Measurement of $B_c(2S)^+$ and $B_c^*(2S)^+$ cross section ratios in proton-proton collisions at $\sqrt{s} = 13$ TeV*, Phys. Rev. **D102** (2020) 092007, arXiv:2008.08629.

[35] LHCb collaboration, R. Aaij *et al.*, *Observation of a new excited D_s^+ state in $B^0 \to D^- D^+ K^+ \pi^-$ decays*, Phys. Rev. Lett. **126** (2021) 122002, arXiv:2011.09112.

[36] LHCb collaboration, R. Aaij *et al.*, *Observation of excited Ω_c^0 baryons in $\Omega_b^- \to \Xi_c^+ K^- \pi^+$ decays*, arXiv:2107.03419, to appear in PRD Lett.

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

[38] LHCb collaboration, R. Aaij *et al.*, *Observation of new excited B_s^0 states*, Eur. Phys. J. **C81** (2021) 601, arXiv:2010.15931.

[39] CMS collaboration, A. M. Sirunyan *et al.*, *Observation of a new excited beauty strange baryon decaying to $\Xi_b^- \pi^+ \pi^-$*, Phys. Rev. Lett. **126** (2021) 252003, arXiv:2102.04524.

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

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

[42] LHCb collaboration, R. Aaij *et al.*, *Search for the doubly charmed baryon Ξ_{cc}^+ in the $\Xi_c^+ \pi^- \pi^+$ final state*, arXiv:2109.07292, submitted to JHEP.

[43] LHCb collaboration, R. Aaij *et al.*, *Search for the doubly charmed baryon Ξ_{cc}^+*, Sci. China Phys. Mech. Astron. **63** (2020) 221062, arXiv:1909.12273.

[44] LHCb collaboration, R. Aaij *et al.*, *Precision measurement of the Ξ_{cc}^{++} mass*, JHEP **02** (2020) 049, arXiv:1911.08594.

[45] LHCb collaboration, R. Aaij *et al.*, *Search for the doubly charmed baryon Ω_{cc}^+*, Sci. China Phys. Mech. Astron. **64** (2021) 101062, arXiv:2105.06841.

[46] LHCb collaboration, R. Aaij *et al.*, *Search for the doubly heavy baryon Ξ_{bc}^0 in the $D^0 pK^-$ final state*, JHEP **11** (2020) 095, arXiv:2009.02481.

[47] 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.

[48] LHCb collaboration, R. Aaij *et al.*, *Amplitude analysis of the $B^+ \to D^+ D^- K^+$ decay*, Phys. Rev. **D102** (2020) 112003, arXiv:2009.00026.

[49] LHCb collaboration, R. Aaij *et al.*, *Model-independent study of structure in $B^+ \to D^+ D^- K^+$ decays*, Phys. Rev. Lett. **125** (2020) 242001, arXiv:2009.00025.

[50] LHCb collaboration, R. Aaij *et al.*, *Observation of new resonances decaying to $J/\psi K^+$ and $J/\psi\phi$* , Phys. Rev. Lett. **127** (2021) 082001, arXiv:2103.01803.

[51] BESIII collaboration, M. Ablikim *et al.*, *Observation of a near-threshold structure in the K^+ recoil-mass spectra in $e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$*, Phys. Rev. Lett. **126** (2021) 102001, arXiv:2011.07855.

[52] LHCb collaboration, R. Aaij *et al.*, *Observation of structure in the J/ψ-pair mass spectrum*, Science Bulletin **65** (2020) 1983, arXiv:2006.16957.

[53] LHCb collaboration, R. Aaij *et al.*, *Evidence for a new structure in the $J/\psi p$ and $J/\psi \bar{p}$ systems in $B_s^0 \to J/\psi p \bar{p}$ decays*, arXiv:2108.04720, submitted to PRL.

[54] LHCb collaboration, R. Aaij *et al.*, *Evidence of a $J/\psi\Lambda$ structure and observation of excited Ξ^- states in the $\Xi_b^- \to J/\psi \Lambda K^-$ decay*, Science Bulletin **66** (2021) 1278, arXiv:2012.10380.