Heavy flavour production and spectroscopy

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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.

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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 $B\_\text{s}^0$ 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 $\Lambda^+_c/D^0$ and $\Xi^-/D^0$ have clear dependence on the transverse momentum, as shown in Fig. 4. The trend of the $\Lambda^+_c/D^0$ production ratio is well described 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-
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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].

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 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 \( \Lambda_b^0 \) and \( \Lambda_b^0 \) 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 \( \Lambda_b^0 \to \Lambda_c^+ \mu^- \nu \mu X \). The measured production asymmetry as functions of \( \Lambda_b^0 \) 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) $\Lambda_c^+/D^0$ and (right) $\Xi_c/D^0$, 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 $A_b^0$ 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)^+ → B_c^+(π^+π^-) branching fractions, are determined to be \((3.47\pm0.63\pm0.33)\%\), \((4.69\pm0.71\pm0.56)\%\), and \(1.35\pm0.32\pm0.09\), 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 \(m_R = 2591\pm6\pm7\) MeV, \(\Gamma_R = 89\pm16\pm12\) MeV, and \(J^P = 0^-\).

In the study of the \(\Omega_b^- \to \Xi_c^+K^-\pi^-\) decay, four excited \(\Omega_b^0\) baryons, \(\Omega_b(3000)^0\), \(\Omega_b(3050)^0\), \(\Omega_b(3065)^0\), \(\Omega_b(3090)^0\), 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 \((1/2, 1/2, 2/3, 2/3)\) 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 \(B_c^0\) 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: \(m_1 = 6063.5\pm1.2\pm0.8\) MeV, \(\Gamma_1 = 26\pm4\pm4\) MeV, \(m_2 = 6114\pm3\pm5\) MeV, \(\Gamma_2 = 66\pm18\pm21\) 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 \(\Xi_b^-\) is reconstructed via its decays to \(J/\psi\Xi^-\) and \(J/\psi\Lambda\bar{K}^-\), and the \(\Xi_b^-\pi^+\pi^-\) mass spectrum with the fully reconstructed \(\Xi_b^-\) is shown in Fig. 10. The \(\Xi_b(6100)^-\) mass is determined to be \(6100.3\pm0.2\pm0.1\pm0.6(\Xi_b^-)\) MeV, where the last uncertainty reflects the precision of the \(\Xi_b^-\) baryon mass. An upper limit of 1.9 MeV at 95% CL is set on its natural width. A new excited \(\Xi_b^0\) resonance, \(\Xi_b(6227)^0\), is observed in the \(\Xi_b^-\pi^+\) mass spectrum by the LHCb collaboration [40]. The \(\Xi_b^-\) state is reconstructed in the fully hadronic decay modes \(\Xi_b^0\pi^-\) and \(\Xi_b^0\pi^-\pi^-\), and the \(\Xi_b^-\pi^+\) mass spectrum with \(\Xi_b^- \to \Xi_b^0\pi^-\) is shown in Fig. 11. The mass and natural widths are determined to be \(m = 6227.1^{+1.4}_{-1.5}\pm0.5\) MeV, \(\Gamma = 18.6^{+5.0}_{-4.1}\pm1.4\) MeV. Improved measurements of the mass and natural width of the previously observed \(\Xi_b(6227)^-\) state [41], along with the mass of the \(\Xi_b^-\) baryon, are also reported [40].

A search for the doubly charmed baryon \(\Xi_{cc}^+\) 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 \(\Xi_{cc}^+\) 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 \(\Xi_{cc}^+\) [44], including systematic uncertainties.

The LHCb collaboration performed the first search for the doubly charmed baryon with strangeness \(\Omega_{cc}^+\) via its decay to \(\Xi_c^+K^-\pi^+\) [45], the doubly heavy baryon \(\Xi_{bc}^0\) via its decay to \(D^0pK^-\) [46], and \(\Xi_{bc}^+\Omega_{bc}^-\) 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.
In the amplitude analysis of the $B^+ \rightarrow D^+ K^-\pi^+$ 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, $X_0(2900): M = 2866 \pm 7 \pm 2$ MeV, $\Gamma = 57 \pm 12 \pm 4$ MeV, $X_1(2900): M = 2904 \pm 5 \pm 1$ MeV, $\Gamma = 110 \pm 11 \pm 4$ MeV.

In the amplitude analysis of the $B^+ \rightarrow J/\psi\phi K^+$ 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 $4003 \pm 6^{+4}_{-3}$ 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 ($m = 3982.5^{+1.8}_{-2.6} \pm 2.1$ MeV, $\Gamma = 12.8^{+5.3}_{-4.4} \pm 3.0$ MeV) observed by the BESIII collaboration [51].

In the study of the invariant mass spectrum of $J/\psi$ 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 $B^0_\psi \rightarrow J/\psi\rho\bar{\rho}$ performed by the LHCb collabora-
Figure 11: Distribution of the reconstructed mass difference between the $m(\Xi_c^0, \pi^+)$ and the $\Xi_b^-$ and $\pi^+$ masses [40].

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

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

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

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

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

In the amplitude analysis of the $B^- \rightarrow D^- K^+$ 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 $D_0 \Lambda^+_c, \Xi_c, \Lambda_b^0, B_c^+(2S)^+$, and observations of $D_{s0}(2590)^+$, excited $\Xi_b^-$ states, $X(2900)$, $Z_c^+, X(6900)$, and evidence of $P_{c}(3337)^+$ and $P_{cs}$. These results are very helpful for understanding the strong interaction.
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