Heavy-flavour hadron production

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The conventional description of heavy-flavour hadron production in pp collisions is based on a factorisation approach, assuming universal fragmentation functions among collision systems. Recent results on heavy-flavour baryon measurements from the LHC experiments show tensions with model calculations based on this approach and employing fragmentation functions constrained from e^+e^- and e^-p collision experiments. In this contribution, the most recent results from ALICE, ATLAS, CMS and LHCb experiments on the heavy-flavour hadron production in pp collisions at the TeV scale are reported. The comparison with the theoretical predictions that address the baryon enhancement in hadronic collisions at the LHC is also discussed.
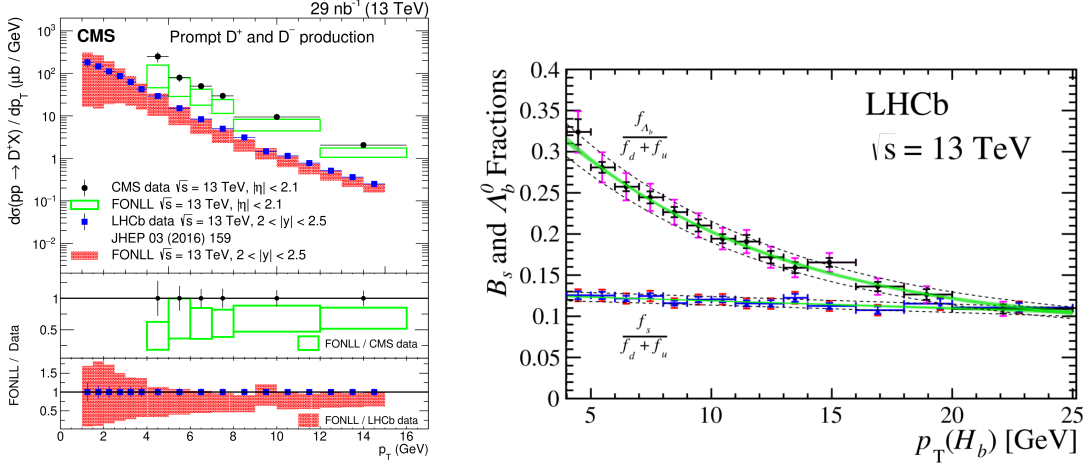
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Figure 1: Left: production cross section of D$^+$ mesons at mid pseudorapidity ($|\eta|$ < 2.1) and forward rapidity (2 < y < 2.5) measured by the CMS [1] and LHCb [2] experiments respectively in pp collisions at $\sqrt{s}$ = 13 TeV, in comparison with FONLL predictions. Right: B^0_s/($\bar{\text{B}}^0$ + B$^-$) and Λ^0_b/($\bar{\text{B}}^0$ + B$^-$) ratios as a function of p_T in pp collisions at $\sqrt{s}$ = 13 TeV measured by the LHCb experiment [3].

The measurements of heavy-flavour hadron production at the LHC are fundamental tests of perturbative QCD calculations in proton-proton (pp) collisions. The standard description of heavy-flavour hadron production is based on a factorization approach, according to which it can be expressed as the convolution of: (a) the parton distribution functions (PDFs), describing how the partons are distributed within the colliding protons; (b) the cross section of the partonic scattering, producing the heavy quarks; (c) the fragmentation functions, which quantify the probability for a quark to produce a hadron of a certain species with a given momentum fraction. The latter ingredients, usually considered universal among collision systems, are constrained from e$^+$e$^-$ and e$^-$p collision measurements. The theoretical calculations based on this approach successfully describe the precise measurements of heavy-flavour meson production in pp collisions at the LHC [1, 2, 4–7] (left panel of Fig. 1). The relative abundances of charm hadrons are sensitive to the charm quark hadronization and they provide a tool for the measurement of the charm fragmentation fraction ratios. The prompt D$^+$/D^0 and D^+_s/D^0 ratios measured in pp collisions at mid and forward rapidity at the LHC are almost independent on the meson transverse momentum (p_T) and are in agreement with e$^+$e$^-$ measurements, as well as with calculations relying on universal fragmentation functions [2, 4]. Similar observations are valid for the beauty mesons, for example, the B^0_s/($\bar{\text{B}}^0$ + B$^-$) ratio shown in the right panel of Fig. 1 [3]. The ratios between strange and non-strange mesons for the charm and beauty sectors are compatible with each other, and they do not show any strong dependence on the collision energy within uncertainties [4, 8]. Instead, the baryon-to-meson ratio shows a clear p_T dependence visible in the Λ^0_b/($\bar{\text{B}}^0$ + B$^-$) ratio measured by the LHCb experiment (right panel of Fig. 1), which is significantly enhanced compared to the B^0_s/($\bar{\text{B}}^0$ + B$^-$) ratio at low p_T. A proposed hypothesis is based on the mass difference among the hadrons involved ($m_{\Lambda^0_b}$($\sim$ 5.6 GeV/c^2) > m_B($\sim$ 5.3 GeV/c^2)), where a coalescence-like process may enhance the production of heavier particles. Such an explanation is not supported by the B^-_c production in pp collisions at the LHC, as measured by the LHCb and ATLAS experiments [9, 10] (left panel of Fig. 2). The
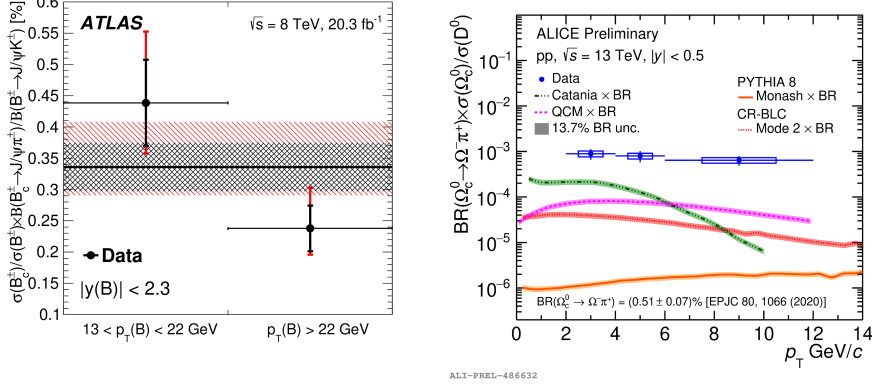
Figure 2: Left: ratio of $\sigma \times$BR between $B_c^\pm$ and $B^\pm$ as a function of transverse momentum at midrapidity ($|y(B)| < 2.3$) measured by the ATLAS experiment in pp collisions at $\sqrt{s} = 8$ TeV [10]. Right: Ω_c^0/D^0 ratio measured in pp collisions at $\sqrt{s} = 13$ TeV by the ALICE experiment, in comparison with different theoretical predictions.

$B_c^-/(\bar{B}^0 + B^-)$ ratio shows a milder p_T dependence with respect to the $\Lambda_b^0/(\bar{B}^0 + B^-)$ despite the larger mass of the B_c^- hadron ($m_{B_c^-}(\sim 6.3 \text{ GeV}/c^2) > m_{\Lambda_b^0}(\sim 5.6 \text{ GeV}/c^2)$). Recently, the CMS collaboration measured the $B_c(2S)^+$ and $B_c^*(2S)^+$ production in pp collisions at $\sqrt{s} = 13$ TeV [11], which can provide useful insights in the ground-state B_c^- production. Their ratios compared to B_c^- do not show any significant dependence on p_T. The baryon-to-meson ratio is studied also for the charm sector and a significant p_T dependence is observed for the Λ_c^+/D^0 ratio measured by the ALICE and CMS experiments in pp collisions at $\sqrt{s} = 5.02, 7, 13$ TeV [12–16]. This ratio is higher by a factor of 2.5 to 5, depending on the p_T, to the results from e^+e^- and e^-p collisions, which are almost independent on the hadron p_T. The baryon-to-meson ratio enhancement observed at low p_T may suggest that the fragmentation functions of the heavy-flavour sector are not universal. The baryon enhancement observed in pp collisions at the LHC was investigated also by the theory community. In the PYTHIA 8 event generator with improved colour reconnection mechanisms [17] the baryon production is enhanced by the junction topology, a colour reconnection mechanism beyond the leading colour approximation, giving the possibility to partons from all the multi-parton interactions in the colliding protons and those from the beam remnants to combine. In the Quark (re-)Combination Mechanism (QCM [18]) model the charm hadron production at low p_T is explained by the coalescence of charm quarks produced in hard scatterings with equal-velocity light quarks from fragmentation. This mechanism rules the charm hadron production at low p_T also in the Catania model [19], where the hadronization is conceived as an interplay between fragmentation and coalescence with light quarks present in a thermalised system of u, d, s quarks and gluons. Another approach is based on the Statistical Hadronization Model (SHM), where the hadronization is ruled by thermo-statistical weights governed by the hadron masses, and on the presence of an augmented set of excited charm baryons predicted by the Relativistc Quark Model (RQM), whose strong decays increment the amount of ground-state charm baryons [20].

Precise measurements of charm hadron production are fundamental to understand the underlying mechanisms ruling the charm quark hadronization in pp collisions at the LHC. The ALICE experiment measured for the first time the $\Sigma_c^{0,+,++}(2455)$ production in pp collisions at $\sqrt{s} = 13$ TeV

at midrapidity [16] where the ratio to D^0 production yield is shown to be significantly higher than those in e^+e^- and e^-p results, showing a larger relative enhancement compared to that of the Λ_c^+/D^0 ratio. The $\Sigma_c^{0,+,++}(2455)/D^0$ enhancement partially accounts for the Λ_c^+/D^0 one and it is described within uncertainties by the model predictions mentioned above. The fraction of Λ_c^+ baryons from strong decays of $\Sigma_c^{0,+,++}(2455)$ states amounts to about 38% in the range $2 < p_T < 12$ GeV/c, more than a factor 2 higher than e^+e^- and e^-p collisions. This result is overestimated by the PYTHIA 8 colour reconnection modes, suggesting that some ingredients are missing for the description of the direct Λ_c^+ production. A significant enhancement with respect to the e^+e^- and e^-p results is observed also for the $\Xi_c^{0,+}/D^0$ ratio in pp collisions at $\sqrt{s} = 5.02, 13$ TeV [21, 22], but in this case all the model predictions significantly underestimate the measurement. A similar comparison is observed for the Ω_c^0/D^0 ratio, (right panel of Fig. 2), where the baryon-to-meson ratio measured by the ALICE experiment is significantly higher than the model predictions. This new result suggests that a sizeable contribution of charm hadronization in pp collisions at the LHC energies may be ascribed to the Ω_c^0 production. Thanks to the measurement of the production cross section of all charm ground-state hadrons, the ALICE experiment measured the charm fragmentation fractions in pp collisions at $\sqrt{s} = 5.02$ TeV [23], as the cross section of each species normalised by the sum of those of all ground states. A decrease of a factor $1.2 \div 1.4$ is observed for D^0 and D^+ mesons in pp collisions with respect to e^+e^- and e^-p collisions, accompanied by an increase of a factor 3 for the Λ_c^+ fragmentation fraction and a Ξ_c^0 and Ξ_c^+ production of the same order of D_s^+ meson. Such a baryon enhancement observed at the LHC challenges the universality of fragmentation functions. The production cross section of each charm ground-state hadron enabled the measurement of the $c\bar{c}$ production cross section in pp collisions at $\sqrt{s} = 5.02$ TeV at midrapidity as the sum of the ground-state hadron cross sections and to improve the previously published results at $\sqrt{s} = 2.76, 7$ TeV from D mesons with the measured fragmentation fractions. Due to the baryon enhancement, the $c\bar{c}$ production cross sections at $\sqrt{s} = 2.76, 7$ TeV increased of about 40%. The results at $\sqrt{s} = 2.76, 5.02, 7$ TeV lie on the upper edge of FONLL [24] and NLO [25] calculations.

Further insights in the charm quark hadronization may come from the measurement of multi-charm baryons. A first measurement of the Ξ_{cc}^{++} double-charm baryon production relative to that of the Λ_c^+ in pp collisions at $\sqrt{s} = 13$ TeV is provided by the LHCb collaboration [26], but more differential measurements are necessary to further understand the mechanisms underlying the charm quark hadronization. Finally, the charm hadron production is studied as a function of event multiplicity via the measurement of the Λ_c^+/D^0 in pp collisions at $\sqrt{s} = 13$ TeV by the ALICE experiment. The measured ratio smoothly increases from pp to lead-lead (Pb–Pb) collisions in $2 < p_T < 8$ GeV/c, suggesting that similar processes may rule the charm hadronization in several collision systems. This conclusion is still under debate, due to flow effects that may be relevant in Pb–Pb collisions.

In conclusion, the recent results on heavy-flavour hadron production in pp collisions at the LHC from ALICE, ATLAS, CMS and LHCb experiments challenge the assumed universality of fragmentation functions, given an enhanced charm baryon production observed in pp collisions at the TeV scale. A joint effort between theory and experiments is required to understand this phenomenon and a complete comprehension of the mechanisms ruling the charm quark hadronization can benefit from the measurement of multi-charm baryon and quarkonium production.

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