The role of strangeness in heavy-quark hadronisation from small to large collision systems with ALICE

Mattia Faggin[1,*], on behalf of the ALICE Collaboration

[1]CERN, Espl. des Particules 1, 1211 Meyrin (CH)

Abstract. Production measurements of strange hadrons originating from the hadronisation of charm quarks (prompt) and from beauty-hadron decays (non-prompt) offer a unique tool to study the heavy-quark hadronisation across different collision systems. This contribution discusses the final results of the ALICE Collaboration obtained by measuring strange D mesons in pp, p–Pb, and Pb–Pb collisions collected during the LHC Run 2. The first measurement of the production of orbitally excited charm-strange mesons in pp collisions is also reported. Additionally, the production measurements of prompt D_s^+ mesons are compared to those of non-strange mesons across the different collision systems, along with the measurement of non-prompt D_s^+ mesons in heavy-ion collisions. Lastly, the first studies of strange and non-strange D mesons using the large data sample of pp collisions at $\sqrt{s}$ =13.6 TeV harvested from the start of LHC Run 3 are presented.

1 Introduction

Due to their large mass ($m_c \sim 1.3$ GeV/c^2, $m_b \sim 4.2$ GeV/c^2), charm and beauty quarks are mainly produced in hard scattering processes among partons in the early stages of a hadronic collision at the LHC. In ultrarelativistic heavy-ion collisions, they are produced before the quark gluon plasma (QGP) formation, and since their number is preserved during the QGP phase they experience its full evolution. Therefore, charm and beauty quarks are unique probes of the colour-rich environment produced in hadronic collisions at the LHC, and their dynamics can be studied by reconstructing charm and beauty hadrons. Their measurement in pp collisions are important to test the predictions of perturbative QCD (pQCD)-based calculations and to put constraints on heavy-quark production, parton distribution functions (PDFs) and hadronisation processes. They also provide a fundamental reference to understand the results in larger collision systems. In fact, such measurements in p–Pb collisions are sensitive to cold-nuclear-matter effects, such as PDF modification in bound nucleons, while those in heavy-ion collisions are influenced by the in-medium parton energy loss, collective motion and modified hadronisation. In particular, the formation of heavy-flavour (HF) hadrons in Pb–Pb collisions can occur via the coalescence of a charm or beauty quark with lighter ones thermalised in the QGP. Interestingly, a smooth strangeness enhancement as function of event multiplicity has been observed at the LHC, without a clear collision system dependence [1]. One can speculate whether a similar interplay between an enhanced formation of $s\bar{s}$ pairs and hadronisation via coalescence occur in the three collision systems. This can be effectively studied via the measurement of strange heavy-flavour hadron production.

*e-mail: mattia.faggin@cern.ch

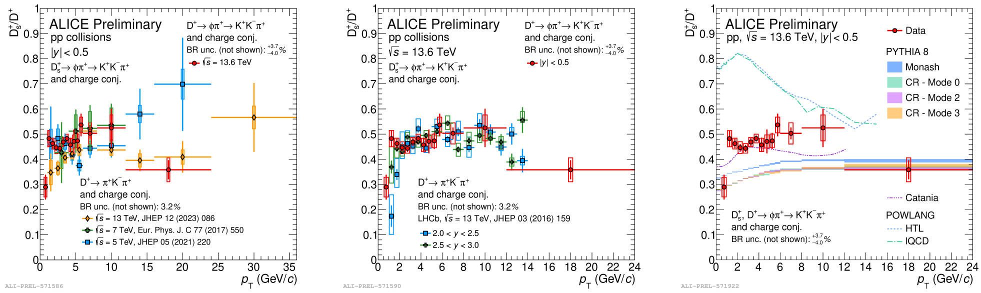

Figure 1. p_T-differential D_s^+/D^+ ratio at midrapidity in pp collisions at $\sqrt{s}$ = 13.6 TeV by ALICE compared with the same result at lower collision energies at midrapidity (left) and at forward rapidity by LHCb (middle), as well as with model predictions (right).

2 The ALICE experiment

The measurements described above are possible with the data collected during the LHC Run 1 and 2 by the ALICE experiment. The innermost subsystem in the central barrel ($|\eta| < 0.9$) is the Inner Tracking System (ITS), a silicon tracker fundamental to reconstruct and resolve the beam collision point (primary vertex, PV) and the heavy-flavour hadron decay point. The Time Projection Chamber (TPC), a gaseous detector, is the main tracker of the experiment, which also provides particle identification (PID) via the measurement of ionization energy loss per unit length dE/dx. Finally, the Time-Of-Flight (detector) provides PID via the measurement of the time-of-flight of charged particles. During the long shutdown 2 (LS2) of the LHC the experiment underwent a major upgrade program. The most significant upgrades involved the ITS, the readout of the TPC, now utilising Gas Electron Multipliers (GEMs), and the new Fast Interaction Trigger (FIT) detector. Thanks to these upgrades, during the LHC Run 3 ALICE can collect significantly larger data samples in a continuous readout mode and can exploit a $\sim \times 2$ better pointing resolution of tracks to the PV compared to Run 2.

3 Measurements of charm-strange meson production

The prompt and non-prompt $D_s^+/(D^+ + D^0)$ p_T-differential ratios have been measured in pp collisions at $\sqrt{s}$ = 5.02 TeV and $\sqrt{s}$ = 13 TeV [2, 3]. The results do not show any significant dependence neither on p_T nor on collision energy. The same holds also for the charm and beauty p_T-integrated strange-to-non-strange fragmentation-fraction ratio $f_s/(f_u + f_d)$ [3, 4]. They are compatible within each other, and with the results from e^+e^-, e^-p and $p\bar{p}$ collisions at lower energy.

ALICE provided the first measurement of the p_T-differential production-yield ratio of prompt D_s^+/D^+ mesons at midrapidity in pp collisions at $\sqrt{s}$ = 13.6 TeV (Fig. 1) using a sample of $\mathcal{L} \sim 1$ pb^{-1} collected in 2022. This measurement extends down to p_T = 0.5 GeV/c and it is $\times 2$ more granular in the range $1 < p_T < 6$ GeV/c than the result obtained with the Run 2 sample at $\sqrt{s}$ = 13 TeV. The results do not show any significant collision-energy and rapidity dependence, being compatible with the same results at midrapidity at $\sqrt{s}$ = 5.02 TeV, $\sqrt{s}$ = 7 TeV and $\sqrt{s}$ = 13 TeV [2, 4, 5], as well as with those at forward rapidity in pp collisions at $\sqrt{s}$ = 13 TeV [6]. In the right panel of Fig. 1, the measurement is compared with predictions from model calculations assuming different mechanisms for the heavy-quark hadronisation. The measured D_s^+/D^+ ratio is underestimated by the predictions of PYTHIA

8 [7], where colour reconnections among multi-parton interactions (MPI) beyond leading-colour topologies are assumed to explain the observed baryon enhancement at midrapidity. The measurement is also compared with calculations from POWLANG [8] and Catania [9] models, in which the formation of a thermalised system of light partons is foreseen, and the heavy quarks can hadronise via coalescence. The measurement is significantly overestimated by POWLANG, while the prediction from the Catania model better describes the data.

The production of heavy-strange hadrons in pp collisions has been studied also as a function of event multiplicity [10]. The prompt p_{T}-differential $\mathrm{D_s}^+/\mathrm{D}^0$ ratio does not show any significant dependence on p_{T} or multiplicity. The measurement shows some tension with the predictions from the Canonical-Ensemble Statistical Hadronisation Model (CE-SHM [11]), where the quantum-number conservation volume is assumed to increase with the event multiplicity. In fact, the model calculations overestimate the measurement in high-multiplicity pp collisions. The $\mathrm{D_s}^+/\mathrm{D}^0$ ratio is well described by the predictions of PYTHIA 8. On the contrary, PYTHIA 8 predictions significantly underestimate the prompt Ξ_{c}^0 production and the p_{T}-differential $\Xi_{\mathrm{c}}^0/\mathrm{D}^0$ ratio in pp collisions at the LHC [12]. The charm-quark fragmentation fraction into Ξ_{c}^0 has been observed to be compatible with that of prompt $\mathrm{D_s}^+$ in both pp and p–Pb collisions. The charm-quark fragmentation fractions $f(\mathrm{c} \to \mathrm{h_c})$ in these two collision systems are compatible within each other and show a significant enhancement of baryon relative production compared to collision systems involving leptons (e.g. $\mathrm{e^+e^-}$, $\mathrm{e^-p}$) [13]. Further information about the charm-quark hadronisation and its dependence on collision system and multiplicity are provided by the measurement of $\mathrm{D_{s1}^+}(2536)$ and $\mathrm{D_{s2}^{*+}}(2573)$ resonance production. The measured $\mathrm{D_{s1}^+}(2536)/\mathrm{D_s}^+$ and $\mathrm{D_{s2}^{*+}}(2573)/\mathrm{D_s}^+$ ratios do not show a significant dependence on the event multiplicity within the current uncertainties.

The production of prompt $\mathrm{D_s}^+$ mesons at midrapidity has been measured by ALICE also in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. The prompt-$\mathrm{D_s}^+$ nuclear modification factor (R_{AA}) has been observed to be significantly lower than unity for $p_{\mathrm{T}} \gtrsim 4$ GeV/c, as a consequence of the in-medium energy loss of the charm quark. In addition, the $R_{\mathrm{AA}}(\mathrm{D_s}^+)$ has been observed to be larger than that of non-strange D mesons for $p_{\mathrm{T}} < 6$ GeV/c. This is in agreement with the scenario of a relative enhancement of $\mathrm{D_s}^+$ production in Pb–Pb collisions compared to pp due to the interplay of the charm-quark hadronisation via coalescence and the enhanced strangeness production in the QGP [14]. A hint of similar ordering between strange and non-strange D-meson R_{AA} has been observed also for non-prompt D mesons [15]. In addition, the measurements show a hint of higher R_{AA} for non-prompt $\mathrm{D_s}^+$ compared to that of prompt $\mathrm{D_s}^+$ for $p_{\mathrm{T}} < 6$ GeV/c, showing sensitivity to the different diffusion and collisional energy loss for charm and beauty quarks in the QGP, given that the spatial diffusion coefficient is proportional to the inverse of the mass. The current experimental uncertainties are still too large to be sensitive to the different radiative energy loss for charm and beauty at high p_{T} due to the dead-cone effect. However, the comparison with the predictions from TAMU transport model [16, 17], which overestimates the measurement of prompt $R_{\mathrm{AA}}(\mathrm{D_s}^+)$ at high p_{T}, indicates that the heavy-quark radiative energy loss in the QGP, ignored in these model calculations, is important to describe the measurement. Finally, ALICE measured the elliptic flow coefficient (v_2) of prompt $\mathrm{D_s}^+$ and observed a deviation from 0 of about 6.4σ. With the current uncertainties, no significant differences are observed with respect to the non-strange D-meson v_2. The measured $v_2(\mathrm{D_s}^+)$ is well described for $p_{\mathrm{T}} < 10$ GeV/c by transport models implementing charm-quark hadronisation via coalescence with a flowing strange-quark.

In conclusion, the ALICE Collaboration measured the prompt and non-prompt strange D-meson production in pp and Pb–Pb collisions. Such measurements are useful to probe the charm- and beauty-quark hadronisation in hadronic collisions and their dynamics in the QGP produced in heavy-ion collisions at the LHC. More insights will be provided by the analysis of the Run 3 data.

References

[1] S. Acharya et al. (ALICE), Multiplicity dependence of π, K, and p production in pp collisions at $\sqrt{s} = 13$ TeV, Eur. Phys. J. C **80**, 693 (2020), 2003.02394. 10.1140/epjc/s10052-020-8125-1

[2] S. Acharya et al. (ALICE), Measurement of beauty and charm production in pp collisions at $\sqrt{s} = 5.02$ TeV via non-prompt and prompt D mesons, JHEP **05**, 220 (2021), 2102.13601. 10.1007/JHEP05(2021)220

[3] S. Acharya et al. (ALICE), Measurement of beauty-quark production in pp collisions at $\sqrt{s} = 13$ TeV via non-prompt D mesons (2024), 2402.16417.

[4] S. Acharya et al. (ALICE), Charm production and fragmentation fractions at midrapidity in pp collisions at $\sqrt{\mathrm{s}} = 13$ TeV, JHEP **12**, 086 (2023), 2308.04877. 10.1007/JHEP12(2023)086

[5] S. Acharya et al. (ALICE), Measurement of D-meson production at mid-rapidity in pp collisions at $\sqrt{s} = 7$ TeV, Eur. Phys. J. C **77**, 550 (2017), 1702.00766. 10.1140/epjc/s10052-017-5090-4

[6] R. Aaij et al. (LHCb), Measurements of prompt charm production cross-sections in *pp* collisions at $\sqrt{s} = 13$ TeV, JHEP **03**, 159 (2016), [Erratum: JHEP 09, 013 (2016), Erratum: JHEP 05, 074 (2017)], 1510.01707. 10.1007/JHEP03(2016)159

[7] J.R. Christiansen, P.Z. Skands, String Formation Beyond Leading Colour, JHEP **08**, 003 (2015), 1505.01681. 10.1007/JHEP08(2015)003

[8] A. Beraudo, A. De Pace, D. Pablos, F. Prino, M. Monteno, M. Nardi, Heavy-flavor transport and hadronization in pp collisions, Phys. Rev. D **109**, L011501 (2024), 2306.02152. 10.1103/PhysRevD.109.L011501

[9] V. Minissale, S. Plumari, V. Greco, Charm hadrons in pp collisions at LHC energy within a coalescence plus fragmentation approach, Phys. Lett. B **821**, 136622 (2021), 2012.12001. 10.1016/j.physletb.2021.136622

[10] S. Acharya et al. (ALICE), Observation of a multiplicity dependence in the pT-differential charm baryon-to-meson ratios in proton–proton collisions at s=13 TeV, Phys. Lett. B **829**, 137065 (2022), 2111.11948. 10.1016/j.physletb.2022.137065

[11] Y. Chen, M. He, Charged-particle multiplicity dependence of charm-baryon-to-meson ratio in high-energy proton-proton collisions, Phys. Lett. B **815**, 136144 (2021), 2011.14328. 10.1016/j.physletb.2021.136144

[12] J. Zhu (ALICE), Latest ALICE results on charm and beauty hadronisation in hadronic collisions, EPJ Web Conf. **296**, 15008 (2024), 2312.09705. 10.1051/epjconf/202429615008

[13] S. Acharya et al. (ALICE), Charm fragmentation fractions and $c\bar{c}$ cross section in p−Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV (2024), 2405.14571.

[14] S. Acharya et al. (ALICE), Measurement of prompt D_s^+-meson production and azimuthal anisotropy in Pb–Pb collisions at $\sqrt{s_{NN}}$=5.02TeV, Phys. Lett. B **827**, 136986 (2022), 2110.10006. 10.1016/j.physletb.2022.136986

[15] S. Acharya et al. (ALICE), Measurement of beauty-strange meson production in Pb–Pb collisions at sNN=5.02TeV via non-prompt Ds+ mesons, Phys. Lett. B **846**, 137561 (2023), 2204.10386. 10.1016/j.physletb.2022.137561

[16] M. He, R.J. Fries, R. Rapp, Heavy Flavor at the Large Hadron Collider in a Strong Coupling Approach, Phys. Lett. B **735**, 445 (2014), 1401.3817. 10.1016/j.physletb.2014.05.050

[17] M. He, R. Rapp, Hadronization and Charm-Hadron Ratios in Heavy-Ion Collisions, Phys. Rev. Lett. **124**, 042301 (2020), 1905.09216. 10.1103/PhysRevLett.124.042301