Abstract

Quantum Chromo-Dynamics (QCD) is the theory describing the strong interactions between quarks and gluons, the fundamental constituents of hadrons. Lattice QCD calculations predict a transition from colour-neutral hadrons to a colour-deconfined state called Quark-Gluon Plasma (QGP) under extreme temperature and energy density conditions, which can be reached in the laboratory by colliding high-energy heavy ions.

Heavy-flavour quarks (charm and beauty) are produced in the earliest stages of the collision and interact with the formed medium, losing energy through interactions with its constituents, making heavy-flavour hadrons excellent probes of the properties of the QGP. The hadronisation process is the transition from colour-charged partons (quarks and gluons) produced in a collision into colour-neutral hadrons. It is typically parametrised using fragmentation functions, assuming the universality of the process (i.e., independence from the collision system and energy) and the independence of the quark hadronisation via fragmentation. This approach fails in describing the measured charm-baryon production measured in proton-proton (pp) and p–Pb collisions at the Large Hadron Collider (LHC), suggesting that the hadronisation process is not universal. The hadronisation mechanism is expected to be modified by the presence of the QGP, as a novel process, called recombination, is expected to occur. In this process, the produced heavy-flavour quarks combine with other quarks from the medium to form hadrons. The observed baryon enhancement in pp collisions is qualitatively described by models that include QGP droplets formation, as well as by event generators such as PYTHIA 8 in which colour reconnections are considered in modelling the parton shower and the fragmentation in the parton-rich environment created in pp collisions at the LHC.

In the presence of QGP, the production of strange quarks is expected to be enhanced due to the increase in their thermal production owing to the high temperatures reached in the medium. An increased production of strange hadrons relative to pions is observed in Pb–Pb collisions with respect to pp collisions, where the production of QGP is not expected. However, a smooth increase of strange-hadron relative abundances with the number of charged-particles produced in the collision has been observed in pp collisions, raising the question of whether small droplets of QGP could also be produced in high-multiplicity pp collisions.

Therefore, because of the recombination mechanism and the enhanced production of strange quarks, an increase in the strange over non-strange $\mathrm{D_s^+}/\mathrm{D^+}$ production yield ratio is expected in the presence of QGP.

The ALICE detector installed at the LHC is designed to address the physics of strongly-interacting matter and QGP produced in ultra-relativistic heavy-ion collisions. During the LHC Long Shutdown 2 (2019–2021) the detector was upgraded by enhancing the tracking performance and increasing the readout rate to collect larger data samples, improving its capabilities to probe the QGP with heavy-flavours.

This Thesis is devoted to the precise measurement of the transverse-momentum-(p_{T}-)differential $\mathrm{D_s^+}/\mathrm{D^+}$ production-yield ratio at midrapidity ($|y| < 0.5$) in pp collisions at $\sqrt{s} = 13.6$ TeV with the data collected by the ALICE experiment during the ongoing LHC Run 3 data-taking period. This ratio of strange over non-strange charm meson yields allows for a direct access to information on charm-quark hadronisation mechanisms. Due to their small lifetime ($\tau \sim 100 - 300$ µm/c), $\mathrm{D_s^+}$ and $\mathrm{D^+}$ mesons cannot be directly detected and are reconstructed through their decay products. They are reconstructed through the same hadronic decay channel

$$\mathrm{D_s^+}, \mathrm{D^+} \rightarrow \phi\pi^+ \rightarrow \mathrm{K^+K^-}\pi^+ \quad ,$$

allowing for the cancellation of some of the systematic uncertainties related to the measurement. Multiclass Machine Learning (ML) algorithms have been employed to suppress the large combinatorial background arising from the combination of three independent tracks produced in the pp collision and increase the statistical significance of the measurement. Additionally, the ML-based selections were used to increase the relative contribution of prompt $\mathrm{D_s^+}$ and $\mathrm{D^+}$ mesons (i.e., those directly produced in the hadronisation of a charm quark or through the strong decay of a directly produced excited charm hadron or charmonium state) in the selected sample. The signal is extracted in 14 p_T intervals within the $0.5 < p_\mathrm{T} < 24$ GeV/c range by fitting the invariant mass distribution of candidates passing the ML selections.

The extracted signal is then corrected for the geometrical acceptance of the ALICE detector, the selection efficiency, and the residual non-prompt contamination arising from D mesons produced in the decay of a beauty hadron and surviving the ML selections.

The measured $\mathrm{D_s^+}/\mathrm{D^+}$ production-yield ratio is compared to results obtained by the ALICE Collaboration with the data collected during the LHC Run 2 data-taking period at the different centre-of-mass energies of $\sqrt{s} = 5.02, 7$, and 13 TeV and with measurements performed by the LHCb Collaboration at the LHC in the forward-rapidity range $2.0 < y < 4.5$ in pp collisions at $\sqrt{s} = 13$ TeV. The results are compatible with those obtained in Run 2 by both ALICE and LHCb Collaborations, indicating no significant dependence of the $\mathrm{D_s^+}/\mathrm{D^+}$ ratio on the centre-of-mass energy and rapidity. Thanks to the larger data samples collected during the LHC Run 3 data-taking period, a more precise and granular measurement of the $\mathrm{D_s^+}/\mathrm{D^+}$ production-yield ratio than that measured in Run 2 is achieved. Furthermore, the p_T reach of the measurement has been extended to lower values, reaching as low as 0.5 GeV/c. These measurements provide state-of-the-art results on the production of charm-strange mesons in pp collisions.

Lastly, to study the performance of the ALICE experiment in heavy-ion collisions, the reconstruction of $\mathrm{D_s^+}$ and $\mathrm{D^+}$ mesons was performed in Pb–Pb collisions at $\sqrt{s_\mathrm{NN}} = 5.36$ TeV for different centrality intervals, which represent the degree of overlap of the two colliding nuclei, using rectangular selection criteria. The results in the 10–30% centrality class have been used as benchmarks of the performance of the upgraded ALICE experiment in heavy-ion collisions. These results will provide a solid baseline for the study of the $\mathrm{D_s^+}/\mathrm{D^+}$ production-yield ratio in Pb–Pb collisions, to be performed in the future. By comparing the results obtained in Pb–Pb collisions and the measurements in pp collisions described in this Thesis, insights into the hadronisation mechanisms of charm quarks in the presence of the QGP, where strange quarks are more abundant, will be obtained.

Chapter 9

Summary, conclusions, and perspectives

This Thesis presented the measurement of the p_{T}-differential $\mathrm{D_s^+}/\mathrm{D^+}$ production-yield ratio in proton-proton collisions at $\sqrt{s} = 13.6$ TeV, performed with the upgraded ALICE detector and the data collected during the LHC Run 3 data-taking period. This allowed the study of the charm-quark hadronisation (i.e., the transition from a colour-charged quark into colour neutral hadrons) via strange over non-strange charm meson production-yield ratios.

The analysis was performed via the full reconstruction of displaced decay topologies through the same hadronic decay channel $\mathrm{D_s^+}, \mathrm{D^+} \to \phi\pi^+ \to \mathrm{K^+K^-}\pi^+$. Multiclass Machine Learning models using the Boosted Decision Tree algorithm provided by the XGBoost library were employed to enhance the selection efficiency of the signal candidates and to reduce the combinatorial background. Additionally, they were used to increase the relative contribution of prompt $\mathrm{D_s^+}$ and $\mathrm{D^+}$ mesons (i.e., those directly produced in the hadronisation of a charm quark or through the strong decay of a directly produced excited charm-hadron or charmonium state) in the selected sample. The measurement was performed in 14 transverse-momentum intervals in the range $0.5 < p_{\mathrm{T}} < 24$ GeV/c, and extended the p_{T} coverage at low p_{T} with respect to previous measurements performed by the ALICE Collaboration at $\sqrt{s} = 5.02, 7,$ and 13 TeV, reported in Refs. [1, 2, 3], respectively. Additionally, thanks to the larger data sample collected during the LHC Run 3 data-taking period, and the reconstruction of both D-meson species in the same decay channel, the results presented in this Thesis significantly reduced both the statistical and systematic uncertainties of the measurement, and improved its granularity with respect to the measurements performed by both the ALICE and LHCb [4] Collaborations at mid and forward rapidities, respectively.

The measurements performed at midrapidity ($|y| < 0.5$) at the centre-of-mass energies of $\sqrt{s} = 5.02, 7, 13$ and 13.6 TeV by the ALICE Collaboration indicate no significant energy-dependence of the $\mathrm{D_s^+}/\mathrm{D^+}$ production-yield ratio. Furthermore, the comparison of the results presented in this Thesis, performed at midrapidity ($|y| < 0.5$) at $\sqrt{s} = 13.6$ TeV with the ALICE experimental apparatus, with those obtained by the LHCb Collaboration in the $2.0 < y < 4.5$ interval at forward rapidity at $\sqrt{s} = 13$ TeV, shows a good agreement within the uncertainties. This indicates no significant dependence of the D_s^+/D^+ ratio on the rapidity within the range covered by the ALICE and LHCb measurements.

This measurement provides state-of-the-art results for the understanding of the hadronisation mechanisms of charm quarks in high-energy hadronic collisions. As described in Chapter **??**, the hadronisation mechanism is expected to be modified in the presence of a deconfined medium, the Quark-Gluon Plasma (QGP), which is formed in high-energy nuclear collisions. In a thermalised deconfined medium, charmed hadrons can be produced through coalescence of charm quarks, which are produced before the QGP is formed, with light quarks from the medium. Additionally, in the presence of a QGP, the production of strange quarks is expected to be enhanced, as the high temperatures reached in the medium allow for the thermal production of strange-antistrange quark pairs. The measurement of the D_s^+/D^+ production-yield ratio is a powerful tool to investigate the hadronisation mechanisms of charm quarks, and is a sensitive probe to the phenomenon of strangeness enhancement.

Several measurements confirmed the formation of the QGP in high-energy nuclear collisions, which are summarised in Refs. [5, 6, 7]. The production of an extended QGP phase is not expected in proton-proton collisions. However, recent measurements performed at the LHC [8, 9, 10] provide evidence for the presence of some effects, such as collective behaviours and strangeness enhancement, in small collision systems, as proton-proton and proton-lead collisions, which are usually associated with the formation of a QGP. The ALICE Collaboration reported the observation of a smooth increase in the strange- and multi-strange-hadron production with the charged-particle multiplicity in proton-proton collisions at $\sqrt{s} = 7$ TeV [11], reaching, for the highest multiplicity classes, values compatible with those measured in the most central lead-lead collisions.

Previous measurements of the multiplicity-dependence of the strange over non-strange D_s^+/D^0 production-yield ratio in different multiplicity intervals performed at midrapidity ($|y| < 0.5$) by the ALICE Collaboration [12] did not provide a clear indication of the strangeness enhancement in proton-proton collisions at $\sqrt{s} = 13$ TeV. The results are illustrated in Fig. 9.1, where the measured D_s^+/D^0 production-yield ratio is shown as a function of p_T for two different multiplicity classes. The results show a slight increase of the D_s^+/D^0 production-yield ratio with the charged-particle multiplicity, although the two p_T-differential measurements are compatible within their uncertainties. The methodologies and results presented in this Thesis provide a solid foundation for future studies of the strangeness enhancement in the heavy-flavour sector. The strategy of using the D^+ meson as a reference for the non-strange production, as well as the reconstruction of both D_s^+ and D^+ mesons in the same hadronic decay channel allows for a significant reduction of the systematic uncertainties of the measurement. The measurement of the multiplicity dependence of the D_s^+/D^+ production-yield ratio along with the larger data samples that will be available from the LHC Run 3 data-taking period may provide more precise results than those achieved through the usage of the D^0 meson as a reference for non-strange D meson production, and, thereby, provide a more sensitive probe to the phenomenon of strangeness enhancement in proton-proton collisions. Additionally, the much larger data sample collected during the LHC Run 3 data-taking period

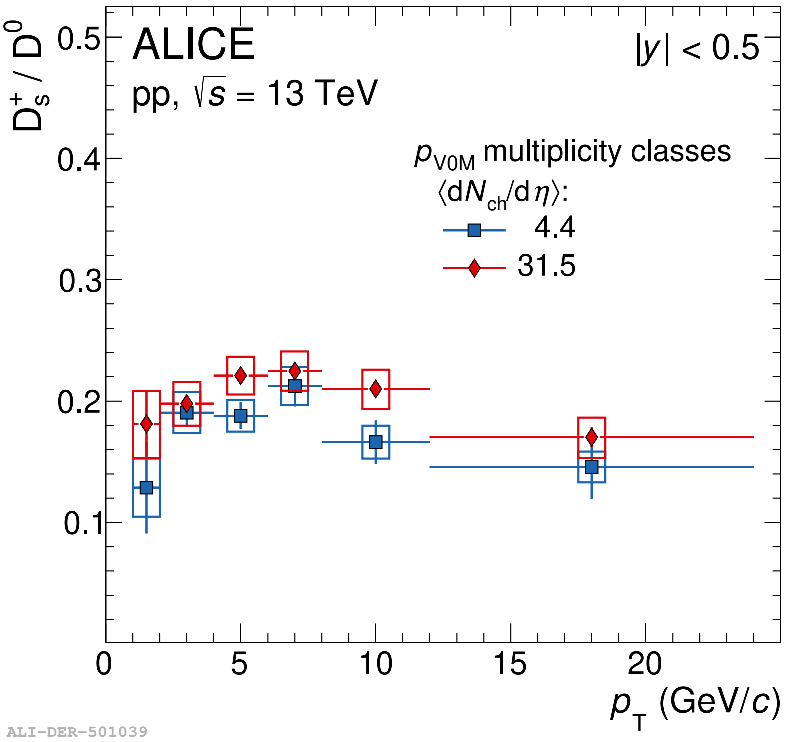

Figure 9.1: Strange over non-strange D_s^+/D^0 production-yield ratio as a function of p_T for two different multiplicity classes measured at midrapidity ($|y| < 0.5$) in proton-proton collisions at $\sqrt{s} = 13$ TeV by the ALICE Collaboration [12]. Figure taken from the ALICE figure repository [13].

will allow for the extension of the measurement to lower p_T values and perform the measurement in finer intervals of p_T and multiplicity.

The multiplicity phase space can be further explored by measuring the strange over non-strange D meson production-yield ratio in Pb–Pb collisions, where much higher charged-particle multiplicities are reached. Previous measurements performed by the ALICE experiment at a centre-of-mass energy per nucleon pair of $\sqrt{s_{NN}} = 5.02$ TeV [14] did not allow to draw firm conclusions on the possible enhancement of strange-hadron production in the charm sector.

The results from the measurement of the D_s^+/D^0 production-yield ratios in central (0–10%) Pb–Pb collisions compared to pp collisions are shown in Fig. 9.2. While the measured ratio is consistent within the uncertainties between the two collision systems for $p_T < 4$ GeV/c and $p_T > 8$ GeV/c, the average values of the measured D_s^+/D^0 production-yield ratio in the $2 < p_T < 8$ GeV/c interval in Pb–Pb collisions are larger than those in pp collisions by about 2.3σ of the combined statistical and systematic uncertainties.

The results are also compared to different theoretical predictions. The Catania model [15, 16], already introduced in Chapter **??** for pp collisions, assumes that a colour-deconfined state of matter is formed in both pp and Pb–Pb collisions and implements the heavy-quark transport via the Boltzmann equation. The hadronisation can occur via instantaneous coalescence, in addition to the fragmentation. In

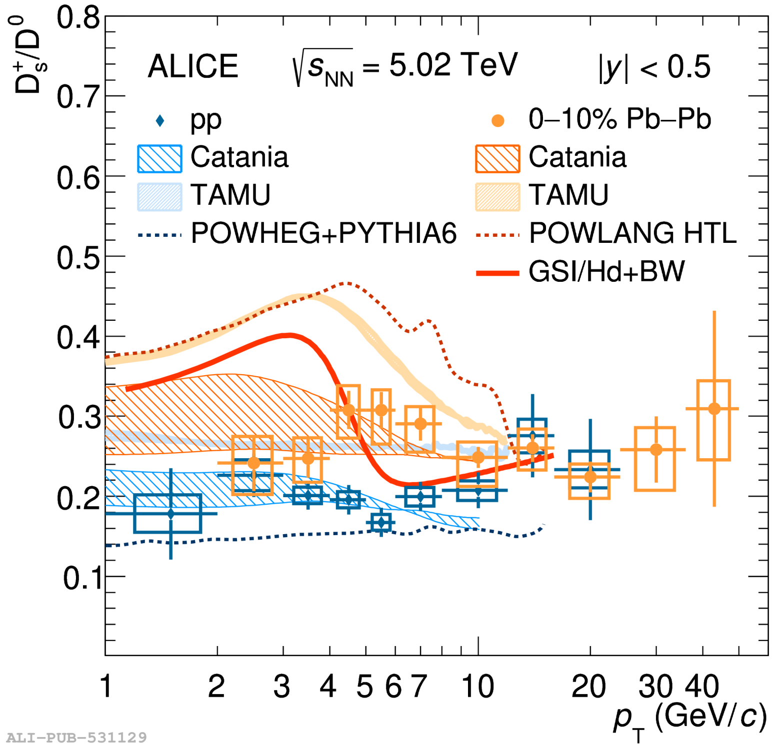

Figure 9.2: D_s^+/D^0 production-yield ratio as a function of p_T in pp collisions and in the 10% most central Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV compared to different model calculations. Figure taken from Ref. [5].

the TAMU [17] model, a combined recombination and fragmentation approach is implemented. The former is realized in Pb–Pb via the Resonance Recombination Model (RRM) [18] where the recombination probability for the two-body case is controlled by resonance amplitudes and is expressed as a relativistic Breit-Wigner cross-section. In pp collisions, the abundances of the different charm-hadron species are instead determined with a statistical hadronisation approach [19]. The charm-quark transport in a hydrodynamically expanding medium is described by the Langevin equation. POWHEG [20] NLO pQCD calculations for the charm-quark productuction, matched with PYTHIA 6 to generate the parton shower are reported for pp collisions. Predictions from the GSI-Heidelberg Statistical Hadronisation Model [21] and POWLANG [22] with transport coefficients calculated with weak-coupling calculations [23] (Hard-Thermal-Loop, HTL) are shown for Pb–Pb collisions. In the former, the p_T spectra of charm hadrons are modelled with a core-corona approach. In the low-p_T region, the charm production is dominated by the core contribution, described with a Blast Wave function, which is used to describe the velocity profile of the collectively expanding system, as introduced in Chapter **??**. The corona contribution is parametrised from measurements in pp collisions and is relevant at high p_T. The p_T-spectra modification due to resonance decays is computed using the FastReso package [24]. In the latter, a Langevin-based transport of heavy quarks in the QGP is followed by in-medium hadronisation. At the hadronisation stage charm quarks are recombined with light thermal quark or di-quark states from the medium into colour-singlet clusters.

The Catania model reproduces within the uncertainties the measured D_s^+/D^0 production-yield ratios both in pp and Pb–Pb collisions. The TAMU model overestimates the measured D_s^+/D^0 ratio by a similar amount in the two colliding systems. A similar magnitude and p_T shape is predicted by the POWLANG model, while POWHEG calculations with PYTHIA 6 slightly underestimate the D_s^+/D^0 production-yield ratio in pp collisions. The GSI-Heidelberg SHMc model provides a similar p_T shape for the D_s^+/D^0 production-yield ratio as that provided by the TAMU and POWLANG models. The results do not allow for drawing firm conclusions on the phenomenon of strangeness enhancement in Pb–Pb collisions given the large uncertainties. However, they provide indications about the role of the charm-quark hadronisation via coalescence in the QGP.

The results discussed above do not allow for drawing firm conclusions on the phenomenon of strangeness enhancement in Pb–Pb collisions given the large uncertainties. The increase in the D_s^+/D^0 porduction-yield ratio in the $2 < p_T < 8$ GeV/c interval is compatible with the expectations from the modification of the charm-quark hadronisation in the presence of a deconfined medium and the phenomenon of strangeness enhancement. However, as also discussed in Chapter **??**, a measurement performed in the $p_T > 2$ GeV/c does not allow the disentanglenent of an enhancement in the D_s^+ meson production from a difference in the momentum spectra in the two collision systems. Furthermore, the collective radial expansion of the medium may play a role in the increase of the D_s^+/D^0 production-yield ratio in Pb–Pb collisions because of the different masses of the D_s^+ and D^0 mesons. Additionally, the studied centrality classes do not provide a complete picture of a possible trend in the production of strange hadrons as a function of the centrality of the collision (which, in turn, provides information on the partonic densities reached in the formed medium). A more comprehensive study would require to also explore both the intermediate centrality (10–30%) and the most peripheral collisions (50–100%), which could not be studied with the LHC Run 2 samples because of the limited number of recorded events.

The measurement of the double ratio of D_s^+/D^+ production-yield ratios in Pb–Pb and pp collisions will provide a clearer insight into the charm-quark hadronisation in a strangeness rich medium. This measurement would doubly benefit from the reduction of the systematic uncertainties from the reconstruction of both D meson species in the same decay channel, as the improvement would affect both the numerator (results in Pb–Pb collisions) and the denominator (results in pp collisions) of the double ratio. Additionally, the statistical uncertainties of the measurement will be significantly reduced thanks to the improved spatial resolution of the upgraded Inner Tracking System (ITS 2) and the larger data samples collected during the LHC Run 3. This will allow the extension of the measurement to lower p_T values, where the effects of the hadronisation via recombination are expected to be more pronounced, and to explore a wide multiplicity interval from pp collisions up to the most central Pb–Pb collisions. With these perspectives, the ALICE Collaboration will provide a state-of-the-art measurement of the strangeness enhancement in the heavy-flavour sector, with a comprehensive study of the hadronisation mechanisms of charm quarks in high-energy nuclear collisions.

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