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 7

D_s^+/D^+ production-yield ratio

The p_T-differential D_s^+/D^+ production-yield ratio can be evaluated using the raw yields and the correction factors obtained in Chapters ?? and ??. The D_s^+/D^+ production-yield ratio is defined using Eq. ??, here reported for convenience:

$$D_s^+/D^+ = \frac{N_{\rm raw}^{D_s^+} \cdot f_{\rm prompt}^{D_s^+}}{({\rm Acc}\times\varepsilon)_{\rm prompt}^{D_s^+} \cdot {\rm BR}^{D_s^+}} \cdot \left(\frac{N_{\rm raw}^{D^+} \cdot f_{\rm prompt}^{D^+}}{({\rm Acc}\times\varepsilon)_{\rm prompt}^{D^+} \cdot {\rm BR}^{D^+}} \right)^{-1} .$$

Previous measurements of this ratio have been performed in pp collisions at different centre-of-mass energies and rapidity windows, and it is therefore interesting to investigate whether the D_s^+/D^+ production-yield ratio depends on either of these variables. In addition, several models have been developed to describe the production of the two D-meson species in pp collisions. They are all based on perturbative QCD calculations for the description of the charm-quark production in the hard-scattering processes (although through different approaches), but differ in the description of the parton shower and hadronisation process, as discussed in Chapter ??. The prompt D_s^+/D^+ production-yield ratio is a sensitive probe of the hadronisation mechanism of charm quarks, and the comparison between the measured values and the predictions from these models can be used to test their validity. Furthermore, these results provide a baseline for analogous measurements in Pb–Pb collisions.

Using the factorisation theorem [1], from Eq. ??, the D_s^+/D^+ production-yield ratio is sensitive to the fragmentation functions of the charm quark into the two D-meson species, as the description of the parton distribution functions of the colliding protons and the charm production in the partonic scattering is the same for the two D-meson species. The ratio of the p_T-differential cross-sections of the two D-meson species can be expressed as:

$$\frac{\left.\frac{{\rm d}^2\sigma}{{\rm d}p_{\rm T}{\rm d}y}\right|_{\rm prompt}^{D_s^+}}{\left.\frac{{\rm d}^2\sigma}{{\rm d}p_{\rm T}{\rm d}y}\right|_{\rm prompt}^{D^+}} = \frac{\int {\rm d}z D_{{\rm c}\to D_s^+}(z,\mu_{\rm F}^2)}{\int {\rm d}z D_{{\rm c}\to D^+}(z,\mu_{\rm F}^2)} = \frac{f_{{\rm c}\to D_s^+}}{f_{{\rm c}\to D^+}} ,$$

where $D_{{\rm c}\to D_s^+(D^+)}(z,\mu_{\rm F}^2)$ are the fragmentation functions of the charm quark for the hadronisation into a D_s^+ (D^+) meson and their integrals with respect to z, $f_{{\rm c}\to D_s^+(D^+)}$, are called *fragmentation fractions*. These studies therefore provide information on

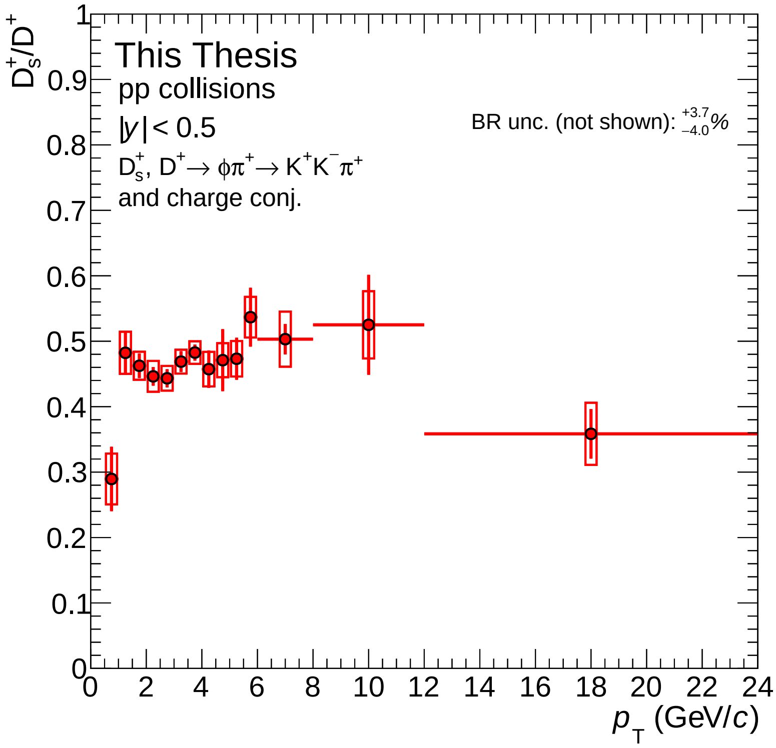

Figure 7.1: p_{T}-differential $\mathrm{D_s^+/D^+}$ production-yield ratio measured in this Thesis at midrapidity ($|y| < 0.5$) in pp collisions at $\sqrt{s} = 13.6$ TeV with the ALICE experimental apparatus.

the energy and rapidity dependence of the fragmentation functions, and, potentially, constraints for these quantities, which are crucial ingredients for the perturbative calculation of the open-charm hadron production cross-section in pp collisions in the framework of the factorisation theorem.

The p_{T}-differential $\mathrm{D_s^+/D^+}$ production-yield ratio measured in this Thesis at midrapidity ($|y| < 0.5$) in pp collisions at $\sqrt{s} = 13.6$ TeV with the ALICE detector is shown in Fig. 7.1. The statistical uncertainties are reported using vertical bars, while the systematic uncertainties are shown as boxes. The results present a steeply-increasing $\mathrm{D_s^+/D^+}$ production-yield ratio between the first two p_{T} intervals, followed by a flat trend with p_{T} for $p_{\mathrm{T}} > 1$ GeV/c.

7.1 Dependence on centre-of-mass energy

Measurements performed in heavy-ion collisions at the SPS observed an enhancement in the production of strange hadrons with respect to non-strange hadrons [2, 3], which was attributed to the modification of the hadronisation process in the QGP and the augmented thermal production of strange quarks as compared to pp collisions owing to the high temperatures reached in the medium. At the LHC, measurements performed in pp, p–Pb, and Pb–Pb collisions by the ALICE Collaboration [4, 5, 6] showed that the phenomenon of strangeness enhancement is also

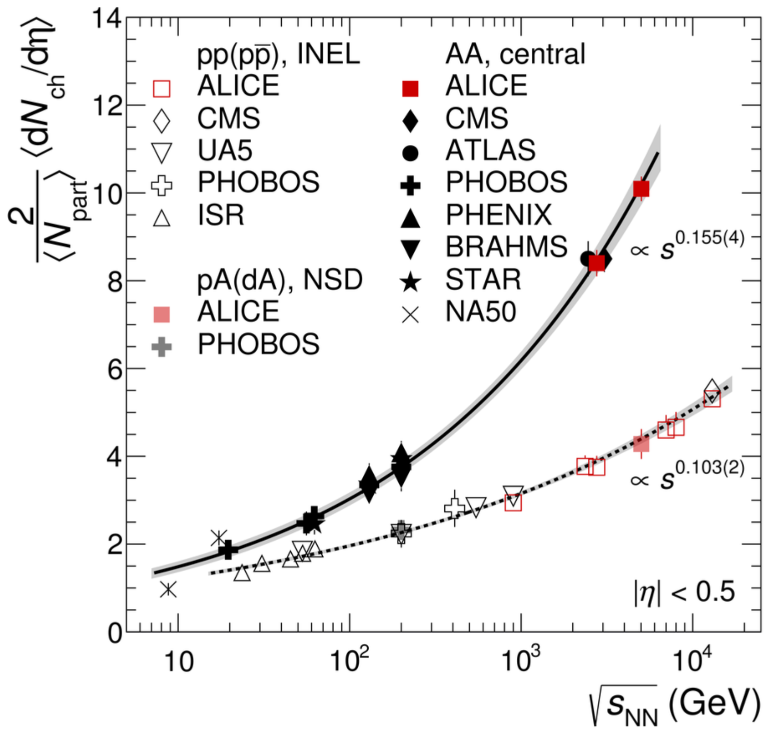

Figure 7.2: Charged-particle multiplicity density, normalised to the number of nucleons participating in the collision divided by a factor 2 ($\langle N_{\text{part}} \rangle/2$) as a function of the centre-of-mass energy per nucleon pair of the collision for central nucleus-nucleus, proton-nucleus, and pp collisions. The s_{NN}-dependence of the charged-particle multiplicity density is parametrised using a power-law function, and is shown with solid and dashed lines for cental nucleus-nucleus collisions and smaller collision systems, respectively. Figure taken from Ref. [10]

present in small collision systems, in high charged-particle multiplicity collisions. The $K_s^0/\pi, \Lambda/\pi, \Xi/\pi$, and Ω/π production-yield ratios were observed to follow a smoothly increasing trend with multiplicity from pp to Pb–Pb collisions. This behaviour is described by different models (such as PYTHIA with colour-reconnection plus rope hadronisation [7], Statistical Hadronisation Model [8], and the Catania coalescence model [9]), which implement different approaches to describe the hadronisation process, but all assume the establishment of a parton-rich environment in the collision.

The charged-particle multiplicity of a collision is observed to increase with the centre-of-mass energy of the event [10, 11] because the larger energy available can be used to produce more particles. This is shown in Fig. 7.2, where the charged-particle multiplicity density, normalised to the number of nucleons participating in the collision divided by a factor 2 ($\langle N_{\text{part}} \rangle/2$), is shown as a function of the centre-of-mass energy per nucleon pair of the collision ($\sqrt{s_{\text{NN}}}$) ffor central nucleus-nucleus, proton-nucleus, and pp collisions. The s_{NN}-dependence of the charged-particle multiplicity density is parametrised using a power-law function, and is shown with solid and dashed lines for cental nucleus-nucleus collisions and smaller collision systems, respectively.

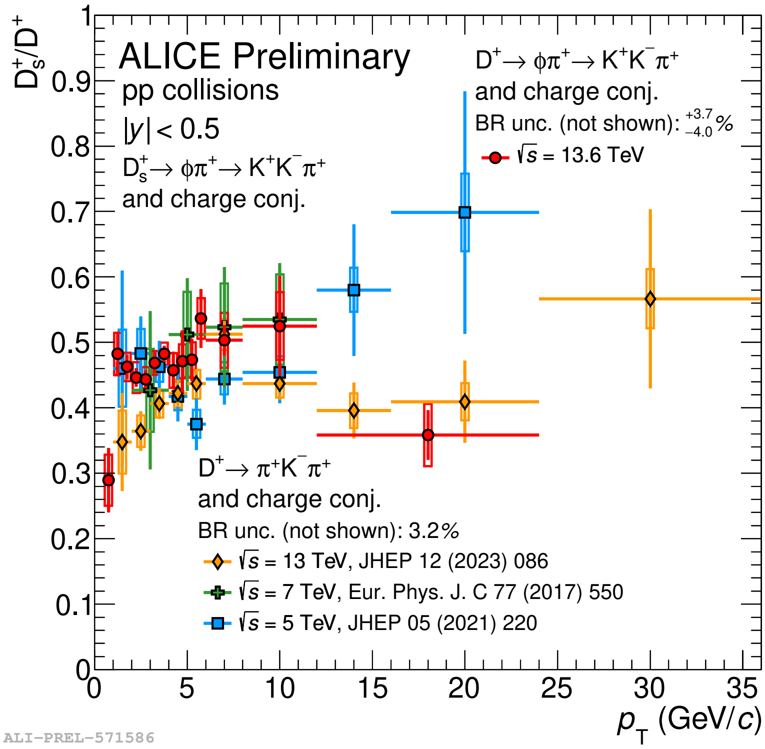

Figure 7.3: p_{T}-differential D_s^+/D^+ production-yield ratio measured at midrapidity ($|y| < 0.5$) in pp collisions by the ALICE Collaboration. The results obtained in this Thesis at $\sqrt{s} = 13.6$ TeV (red) are compared with previous measurements in pp collisions at $\sqrt{s} = 5$, 7, and 13 TeV (blue, green, and orange, respectively).

Therefore, an enhancement in the production of strange hadrons might be expected with the increase in the energy available in the collision. The dependence on the centre-of-mass energy of the D_s^+/D^+ production-yield ratio can be studied by comparing the results obtained in this Thesis in pp collisions at $\sqrt{s} = 13.6$ TeV with those obtained, in the same rapidity window of $|y| < 0.5$, by the ALICE Collaboration in pp collisions at the centre-of-mass energies of $\sqrt{s} = 5$, 7, and 13 TeV (taken from Refs. [12, 13, 14], respectively). Given the small difference of a few TeV between the considered measurements, a very small effect on the D_s^+/D^+ production-yield ratio is expected. Using the parametrisations of the charged-particle multiplicity density as a function of the centre-of-mass energy per nucleon pair of the collision reported in Ref [10] and shown in Fig. 7.2, a factor of about $(13.6/5.02)^{0.206} \sim 1.2$ is expected between the multiplicities measured at $\sqrt{s} = 13.6$ TeV and $\sqrt{s} = 5.02$ TeV (since the number of participating nucleons N_{part} in a pp collision is always 2: the two protons).

The comparison is shown in Fig. 7.3, with red markers being used for the measurement performed in this Thesis. Thanks to the upgrade to the ALICE experimental apparatus [15], a very large number of minimum-bias events was recorded. In one year of Run 3 data-taking, an integrated luminosity larger than that of the entire Run 2 was collected. In addition, previous measurements of the D_s^+/D^+ production-yield ratio reconstructed the D^+ meson through the $D^+ \to \pi^+K^-\pi^+$ decay channel, which differs from that exploited in this analysis. Despite being characterised by a larger BR of $(9.38 \pm 0.16) \times 10^{-2}$ [16], which leads to a larger amount of reconstructed D^+ mesons, the reconstruction through the same decay channel used for the D_s^+ meson, $D^+ \to \phi\pi^+ \to K^+K^-\pi^+$, allows for the cancellation of some of the systematic uncertainties in the D_s^+/D^+ ratio. Thereby, a high-precision measurement of the D_s^+/D^+ production-yield ratio was achieved in this Thesis. Both statistical and systematic uncertainties have been significantly reduced with respect to previous results. The p_T reach of the measurement has been extended to lower values, down to $p_T = 0.5$ GeV/c, and narrower p_T intervals have been analysed. At higher p_T, the worse p_T resolution on the tracks due to the increase of the electric field distortions in the TPC is more impactful, and the uncertainties increase. For the same reason, the p_T reach of the measurement is limited to $p_T < 24$ GeV/c, with no improvements in the granularity of the measurement at high p_T. The comparison with previous measurements at midrapidity performed by the ALICE Collaboration at the centre-of-mass energies of $\sqrt{s} = 5$, 7, and 13 TeV shows no significant dependence on the centre-of-mass energy, with results being compatible within uncertainties across the whole analysed p_T and $\sqrt{s}$ ranges. The comparison with the results obtained at $\sqrt{s} = 13$ TeV shows that a slightly larger D_s^+/D^+ production-yield ratio is measured at low p_T at $\sqrt{s} = 13.6$ TeV. However, the large uncertainties in the previous measurement prevent any firm conclusion on any energy dependence of the observable. In addition, large fluctuations may be present in the D_s^+ and D^+ measurements at $\sqrt{s} = 13$ TeV, as can be deduced from the different trends of their production-yield ratio to the D^0 meson compared to that measured at $\sqrt{s} = 5.02$ TeV.

7.2 Dependence on rapidity

Measurements of the D_s^+/D^+ production-yield ratio in different rapidity intervals can provide further insights into the hadronisation mechanism. At forward rapidities, the production of particles closer to the beam remnants is probed. In this phase space region, interactions may occur between the fragments of the colliding hadrons and the partons produced in the hard-scattering processes. Therefore, the parton shower and the hadronisation might differ from those at midrapidity. Measurements performed at forward rapidity by colliding a beam of 340 GeV/c π^- on a nuclear target at the SPS by the WA82 Collaboration [18] and by colliding a beam of $\pi^\pm$, $K^\pm$, or protons on a nuclear target at the low energy of 250 GeV by the E769 Collaboration at Fermilab [19] indicated the presence of an asymmetric production of leading and subleading charm particles. The term *leading* particle refers in this context to a charm particle that shares at least one light quark or antiquark flavour with the beam particle. On the contrary, recent measurements performed by the ALICE Collaboration demonstrated a balance in the production of particles and antiparticles at midrapidity [20]. This suggests that the hadronisation may undergo a change in the vicinity of the beam remnants. These asymmetries at rapidities close to the beam rapidity can be interpreted in the framework of hadronisation via coalescence, by assuming that the charm quark hadronises via recombination with some other quarks belonging to the beam remnants [21, 22]. At LHC energies,

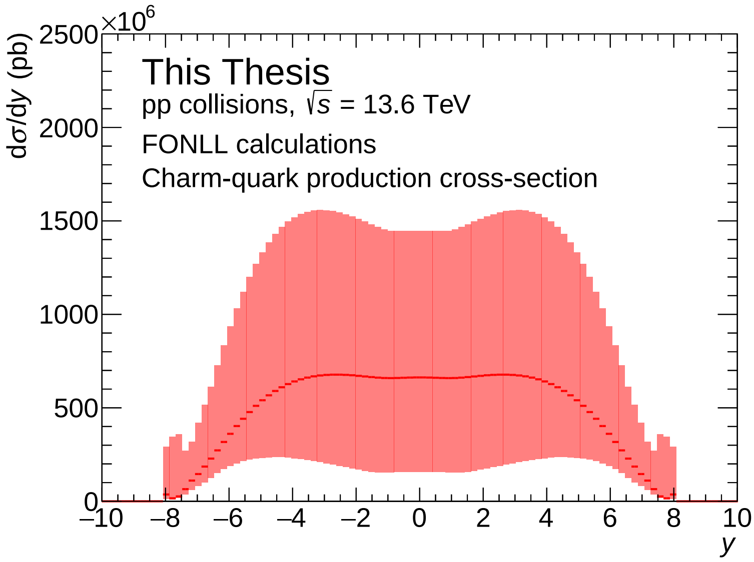

Figure 7.4: y-differential charm-quark production cross-section in pp collisions at $\sqrt{s} = 13.6$ TeV predicted by FONLL [17] calcualations.

rapidities of around 10 in the laboratory frame are reached by both colliding protons. FONLL calculations [17] for the y-differential charm-quark production cross-section in pp collisions at $\sqrt{s} = 13.6$ TeV predict an almost rapidity-independent cross-section for charm hadron production in $|y| < 4$ and a steeply-falling trend with rapidity for $|y| > 4$, as shown in Fig. 7.4. The LHCb experimental apparatus is able to perform measurements at forward rapidity in $2.0 < y < 4.5$, but does not reach the large y values of the beam remnants. Therefore, it is not expected to observe significant differences between measurements performed in the ALICE and LHCb rapidity ranges.

The rapidity dependence of the D_s^+/D^+ produciton-yield ratio can be investigated by comparing the measurement at midrapidity ($|y| < 0.5$) performed in this Thesis in pp collisions at $\sqrt{s} = 13.6$ TeV with those performed at forward rapidities by the LHCb Collaboration [23] at a similar centre-of-mass energy of $\sqrt{s} = 13$ TeV. Given the energy-independence of the observable which has been discussed above, it is possible to directly compare the two measurements. Figure 7.5 shows the comparison between the D_s^+/D^+ production-yield ratio measured in this work compared to that from the LHCb Collaboration measured in pp collisions in the $2.0 < y < 2.5$ and $2.5 < y < 3.0$ rapidity intervals (left panel), and in the $3.0 < y < 3.5$, $3.5 < y < 4.0$, and $4.0 < y < 4.5$ rapidity intervals (right panel). Thanks to the large dataset available and the reconstruction of the two D-meson species through the same decay channel, the uncertainties of the measurement are significantly smaller than those of the results obtained by the LHCb Collaboration across a wide p_T range. In addition, the p_T reach of the measurement is extended to lower values. The results obtained at midrapidity and forward rapidity show a similar trend, with the D_s^+/D^+ production-yield ratios being compatible within uncertainties across the whole studied p_T and y range. The comparison between the results obtained at midrapidity and forward rapidity shows no significant dependence of the D_s^+/D^+ production-yield ratio on

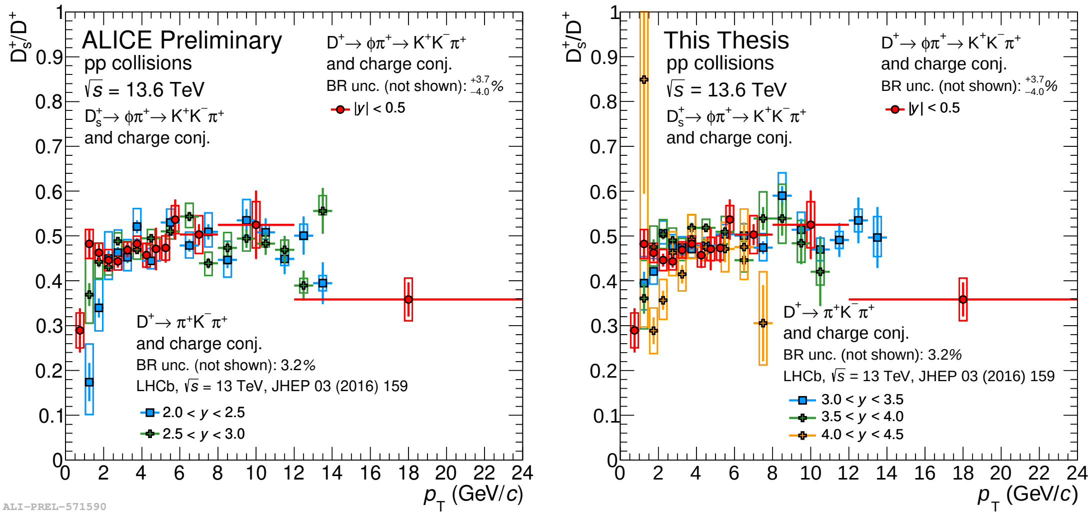

Figure 7.5: p_T-differential D_s^+/D^+ production-yield ratio measured at midrapidity ($|y| < 0.5$) in pp collisions at $\sqrt{s} = 13.6$ TeV by the ALICE Collaboration (red), obtained in this Thesis, compared with previous measurement in pp collisions at $\sqrt{s} = 13$ TeV performed by the LHCb Collaboration in the forward-rapidity intervals of $2.0 < y < 2.5$ (blue) and $2.5 < y < 3.0$ (green) in the left panel and the $3.0 < y < 3.5$ (blue), $3.5 < y < 4.0$ (green), and $4.0 < y < 4.5$ (orange) rapidity intervals in the right panel.

the rapidity of the measurement.

Other measurements performed at forward rapidity by the LHCb Collaboration in p–Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV [24] present an enhancement of the D_s^+/D^+ production-yield ratio as a function of the charged-particle multiplicity across the studied $2 < p_T < 12$ GeV/c interval. These results were obtained by determining the charged-particle multiplicity of the collision using a detector capable of measuring the number of produced particles in the same rapidity interval in which the D-meson production is measured. This may lead to possible biases in the measurement, as heavy-flavour hadrons are typically produced in jets, and auto-correlations between the charged-particle multiplicity and the D-meson production may be present. This could also cause the different slope of the measured D_s^+/D^+ production between forward and backward rapidities. The ALICE apparatus overcomes these limitations, as the charged-particle multiplicity of events containing D mesons in the central barrel can be measured with forward-rapidity detectors, such as the FV0 and the two arrays of the FT0 detector. Therefore, future measurements of the multiplicity dependence of the D_s^+/D^+ production-yield ratio in pp collisions performed by the ALICE Collaboration are expected to provide a more accurate determination of the observable, and to be less affected by biases due to the presence of auto-correlations between the D-meson production and the charged-particle multiplicity of the collision.

7.3 Comparison to models

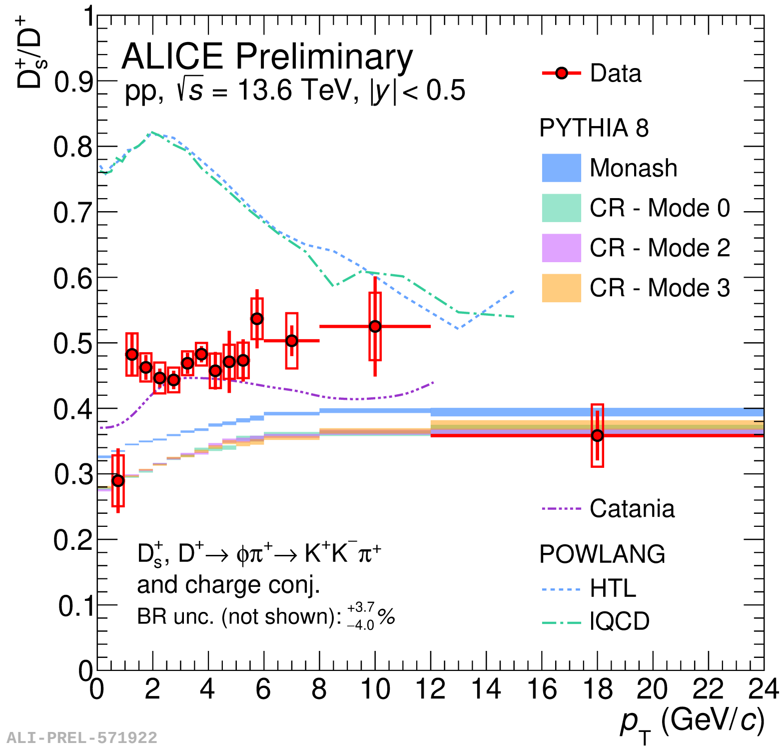

Figure 7.6: p_{T}-differential D_s^+/D^+ production-yield ratio measured at midrapidity ($|y| < 0.5$) in pp collisions at $\sqrt{s} = 13.6$ TeV by the ALICE Collaboration. The results obtained in this Thesis (red) are compared with different theoretical predictions.

The D_s^+/D^+ production-yield ratio can be used to test the validity of models describing the production of the two D-meson species, and set constraints on their description of the hadronisation process. Figure 7.6 presents a comparison between the D_s^+/D^+ production-yield ratio measured in this Thesis at midrapidity ($|y| < 0.5$) in pp collisions at $\sqrt{s} = 13.6$ TeV with the ALICE experiment (red markers) and theoretical predictions.

Predictions from PYTHIA 8 [25] are reported using the Monash 2013 tune [26] (blue filled boxes), which tunes its hadronisation description on results from e^+e^- collisions, and CR tunes implementing colour-reconnections beyond the leading-colour approximation [27]. The width of the PYTHIA 8 bands in Fig. 7.6 represents the statistical uncertainty due to the limited amount of simulated pp collision events. Three colour reconnection modes (Mode 0,2,3) are reported in green, violet, and orange, and present similar trends with p_{T}, with values compatible within uncertainties. PYTHIA 8 predictions with Monash 2013 tune present a similar dependence on p_{T}, with a predicted D_s^+/D^+ production-yield ratio that is larger than that with colour-reconnections beyond the leading-colour approximation. Nonetheless, the four predictions underestimate the measured D_s^+/D^+ ratio, by a factor of about 1.5 at intermediate p_{T}. This discrepancy is also observed in the measurement of the

p_T integrated D_s^+/D^0 and D^+/D^0 production-yield ratio in pp collisions at 5.02 TeV performed by the ALICE Collaboration [28], where the same PYTHIA 8 predictions were found to slightly underestimate the D_s^+-meson production and overestimate that of D^+ mesons.

Predictions from the Catania model [9], which assumes the production of small droplets of QGP in pp collisions, implementing both the coalescence and fragmentation mechanisms for charm quark hadronisation, are reported with a violet dot-dashed line. The model provides a good description of the D_s^+/D^+ production-yield ratio, managing to reproduce both the magnitude and the general trend with transverse momentum in the range $2 < p_T < 6$ GeV/c, showing some tension with the data at low and high p_T.

Lastly, predictions from POWLANG [29], are also reported. Similarly to the Catania model, POWLANG assumes the formation of a small deconfined system in pp collisions, and the same in-medium hadronization mechanism developed for heavy-ion collisions, based on local colour neutralisation via the formation of clusters of quarks and diquarks, is employed. Two sets of predictions are reported, employing transport coefficients calculated with weak-coupling calculations [30] (Hard-Thermal-Loop, HTL) and lattice-QCD simulations [31], using blue and green dashed lines, respectively. Both predictions overestimate the measured D_s^+/D^+ production-yield ratio, by a factor of about 1.5 at intermediate p_T. In addition, a strong decreasing trend with p_T is predicted in the $2 < p_T < 12$ GeV/c, but not observed in the data. These discrepancies are also observed in the measurement of the p_T-differential D_s^+/D^0 production-yield ratio in pp collisions at 5.02 TeV performed by the ALICE Collaboration [29], where the POWLANG predictions overestimate the D_s^+-meson production, with similar differences in the description of the p_T-dependence, while an accurate description of the D^+/D^0 production-yield ratio is achieved.

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