Open-charm production measurements in pp, p-Pb and Pb-Pb collisions with ALICE at the LHC

Elisa Meninno^{1,a} on behalf of the ALICE Collaboration

¹ INFN Sezione di Salerno, Università Degli Studi di Salerno, Salerno, Italy

Abstract. ALICE (A Large Ion Collider Experiment) is designed to study the strongly interacting matter, the Quark-Gluon Plasma (QGP), created in heavy-ion collisions at LHC energies. Charm and beauty quarks are powerful probes to study the QGP. Produced in hard partonic scattering processes on a short time scale, they are expected to traverse the QCD medium, interacting with its constituents and losing energy through radiative and collisional processes. In ALICE, open-charm production is studied through the reconstruction of the hadronic decays of D^0 , D^+ , D^{*+} and D_s^+ mesons at mid-rapidity. High precision tracking, good vertexing capabilities and excellent particle identification offered by ALICE allow for the measurement of particles containing heavy quarks (particularly D mesons) in a wide transverse momentum range in pp, p-Pb and Pb-Pb collisions. A review of the main results on D-meson production in pp collisions at $\sqrt{s} = 7$ TeV, p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV will be presented.

1 Introduction

The ALICE experiment at the LHC aims to investigate the properties of the *Quark-Gluon Plasma* (QGP), the hot and dense state of strongly-interacting matter produced in high-energy heavy-ion collisions. Charm and beauty quarks are among to the most powerful probes to study the QGP. Produced in hard parton scattering processes occurring in the early stages of the collision, they traverse the QCD medium, interact with its constituents and experience the whole evolution of the medium. Open heavy-flavour hadron production is expected to be sensitive to the energy density of the system through the mechanism of in-medium energy loss of heavy quarks [1–3]. Theoretical calculations based on Quantum Chromo-Dynamics (QCD) predict a dependence of the energy loss on the colour charge and on the mass of the parton traversing the medium. This results in an expected hierarchy of the parton energy loss, with beauty quarks losing less energy than charm quarks, and charm quarks losing less energy than light quarks and gluons.

One of the observables that are sensitive to the interaction of hard partons with the medium is the *nuclear modification factor* R_{AA} , defined as the ratio of the particle yield measured in Pb-Pb collisions and the cross section in pp collisions, scaled with the nuclear overlap integral. R_{AA} is expected to be unity in the absence of medium effects. The expected hierarchy of the energy loss described above can be probed comparing the R_{AA} of different particle species, namely B-, D- and

^ae-mail: elisa.meninno@cern.ch

light-hadron R_{AA} .

Further knowledge of the properties of the medium created in heavy-ion collisions can be gained from the study of the *azimuthal anisotropy* of open heavy flavours: the initial spatial asymmetry of non-central collisions is transformed into an asymmetry in momentum via hydrodynamic expansion of the medium. This is quantified in terms of the second coefficient v_2 in a Fourier expansion of the D-meson azimuthal distribution. The elliptic flow v_2 brings information on the medium transport properties, on the question if heavy quarks take part in the collective expansion of the medium, and on the path-length dependence of energy loss.

The interpretation of particle production measurements in Pb-Pb collisions requires detailed studies also in pp and p-Pb collisions:

- pp collisions provide the essential reference for the nuclear modification factor and a sensitive test of perturbative QCD (pQCD) predictions describing the production of heavy flavours in elementary hadronic collisions at the LHC energies;
- the study of p-Pb collisions is crucial to access *cold nuclear matter* (CNM) effects in the initial and final state, such as modification of the Parton Distribution Functions in nuclei (nPDF) [4] [5], gluon saturation at low Bjorken- x [6], k_T broadening, assuming that an extended, long-lived QGP is not expected to be formed in these collisions.

Some insight into the role of multi-parton interactions (MPI) and the interplay between hard and soft mechanism for particle production can be obtained by studying heavy-flavour production as a function of the multiplicity of charged particles produced in pp and p-Pb collisions [7] [8].

Furthermore, the measurements of angular correlations between heavy-flavour hadrons and charged particles provides information on the heavy-quark fragmentation processes and is sensitive to their production mechanism. Differences between the measurements in pp and p-Pb collisions can give insight on how CNM effects affect heavy-quark production and hadronization. In particular, this measurement in p-Pb collisions allows the study of the so-called *long-range ridge-like structures* (double ridge) in the heavy-flavour sector, already observed in hadron-hadron correlations [9].

2 Open heavy-flavour measurements with ALICE

The ALICE detector, described in detail in [10], consists of a central barrel at mid-rapidity ($|\eta| < 0.9$), a muon spectrometer at forward rapidity ($-4.0 < \eta < -2.5$) and a set of detectors (at forward and backward rapidity) for global collision characterization and triggering purposes.

Open heavy flavors are measured in several charm hadronic decay channels and via electrons from semi-leptonic decays of charm and beauty hadrons at mid-rapidity. At forward rapidity, open heavy-flavor production is studied in the semi-muonic decay channel. Electrons are identified at mid-rapidity through their specific ionization energy loss in the *Time Projection Chamber* (TPC) gas combined with the information from the *Time Of-Flight* (TOF) detector and from the electromagnetic calorimeter (EMCal). TPC and TOF are also used to identify pions/kaons/protons for hadronic decays (e.g., D mesons and Λ_c). Muons are reconstructed in the five tracking stations of the Muon Spectrometer ($-4 < \eta < -2.5$) (due to lack of space, measurements of open heavy flavours from semi-leptonic decay will not covered in these proceedings).

2.0.1 D-meson reconstruction and selection

D mesons are reconstructed in ALICE via their hadronic decays at central rapidity:

- $D^0 \rightarrow K^- \pi^+$, $c\tau = 123 \mu\text{m}$, branching ratio (BR) = $(3.88 \pm 0.05)\%$
- $D^+ \rightarrow K^- \pi^+ \pi^+$, $c\tau = 312 \mu\text{m}$, BR = $(9.13 \pm 0.19)\%$
- $D^{*+} \rightarrow D^0 \pi^+$, strong decay, BR = $(67.7 \pm 0.5)\%$
- $D_s^+ \rightarrow \phi (\rightarrow K^- K^+) \pi^+$, $c\tau = 312 \mu\text{m}$, BR = $(2.28 \pm 0.12)\%$

D-meson selection is based on the reconstruction of decay vertices displaced by a few hundred μm from the interaction vertex, exploiting the high track-position resolution close to the interaction vertex provided by the Inner Tracking System (ITS). The large combinatorial background is reduced by selections applied on the decay topology and by the identification of charged kaons and pions via their specific energy loss in the TPC and their time of-flight measured with the TOF detector. Raw D-meson yields are obtained from an invariant mass analysis of the pairs/triplets of candidates. Then, the contribution from B-meson decay feed-down is subtracted, based on FONLL calculations and on data-driven approach, in order to obtain the prompt D-meson yields.

3 Results

3.1 D-meson measurements down to $p_T = 0$ in pp and p-Pb collisions

Production cross section measurements of prompt D mesons were performed with ALICE in pp collisions at $\sqrt{s} = 7$ TeV and 2.76 TeV [11–13] and found well described by perturbative QCD calculations. The p_T -differential cross sections for D^+ and D^{*+} and D_s^+ at $\sqrt{s} = 7$ TeV are shown in Fig. 1, together with FONLL [14], GM-VFNS [15] and k_T -factorization calculation [16–18]. Within uncertainties, theoretical predictions and measurements agree with each other although the measurements tend to be higher than the central value of the FONLL predictions, as it was observed at lower collision energies, at RHIC and at the Tevatron [19] [20]. For GM-VFNS, instead, the data lie on the lower side of the predictions.

In order to extend the D^0 measurement down to $p_T = 0$, where the decay-vertex selection becomes very inefficient, a different analysis technique based on PID and background subtraction was recently developed [21]. The cross section measurement for prompt D^0 in pp collisions, using this analysis technique, denoted as *without decay-vertex reconstruction* is shown in the Fig. 2 together with the results using selection on the secondary vertex. The results with the two different analysis techniques are in good agreement with each other.

In p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, CNM effects are expected to affect the heavy-quark yield and p_T distributions relative to pp collisions. In particular, by measuring heavy-flavour hadron production in different p_T intervals, it is possible to access different Bjorken- x regimes. The nuclear modification factor R_{pPb} quantifies the D-meson cross section in p-Pb collisions relative to the one in pp collisions scaled by the atomic mass number $A = 208$ of the lead nucleus. In p-Pb collisions, the nuclear modification factor of prompt D^0 mesons in the interval $0 < p_T < 12$ GeV/c was computed using the cross sections in pp and p-Pb collisions resulting from the analysis without decay vertex reconstruction. Figure 3 shows the combined measurement of the nuclear modification factor of prompt (non strange) D mesons, obtained by using the D^0 measurement without decay-vertex reconstruction for the interval $0 < p_T < 1$ GeV/c and the average of the measurements for D^0 , D^+ and D^{*+} mesons in the interval $1 < p_T < 24$ GeV/c [22]. In this figure, the combined R_{pPb} from data is compared with theoretical results: on the left the comparison is made with models including CNM effects [4, 23–26], describing quite well the experimental results within uncertainties. On the right, the comparison is also done with the transport model calculations Duke and POWLANG [27], which assume that a

Figure 1. p_T -differential inclusive cross sections for prompt D^+ , D^{*+} [11] and D_s^+ [12], in pp collisions at $\sqrt{s} = 7$ TeV compared with FONLL, GM-VFNS and k_T -factorization theoretical predictions.

Quark-Gluon Plasma is formed in p-Pb collisions. The current precision of the measurement does not allow to discriminate between the two scenarios, with only CNM effects or also with QGP formed, even though the data seem to disfavor a suppression larger than 15-20% in the p_T interval $5 < p_T < 10 \text{ GeV}/c$.

Figure 2. p_T -differential production cross section of D^0 mesons with $|y| < 0.5$ in pp collisions at $\sqrt{s} = 7$ TeV. The comparison between the prompt D^0 cross sections measured with [11] and without decay-vertex reconstruction is shown.

3.2 Multiplicity dependence of D-meson yields in pp and p-Pb collisions

The self-normalized yields of D^0 , D^+ and D_s^+ were evaluated as a function of the charged-particle multiplicity normalized by their average in multiplicity-integrated events, for different p_T ranges of the D mesons in pp and p-Pb collisions [28] [29]. The average D-meson self-normalized yields in pp collisions are shown in the left panel of Fig. 4 for different D-meson p_T ranges from 1 to 20 GeV/c. A faster-than-linear increase with the multiplicity can be observed, with a trend independent of the D-meson p_T within uncertainties.

In the right panel of the same figure, the self-normalized yields are compared with predictions from a percolation model [30], [31], EPOS 3 [32] [33] and PYTHIA [34], all of which include a contribution from MPI to particle production. A qualitative agreement with data is observed for all the models, though at high multiplicities PYTHIA 8 and EPOS 3 without hydrodynamical evolution of the collision seem to underestimate the increasing trend with multiplicity observed in data.

Also in p-Pb collisions [29] a similar increase of charmed-meson yield with the multiplicity is observed (see Fig. 5, left plot). In p-Pb collisions however we have to take into account that the multiplicity dependence is also affected by the presence of *multiple binary nucleon-nucleon* interactions, and also that the initial conditions of the collisions are affected by CNM effects. The measurements in p-Pb collisions are compatible within uncertainties with EPOS3 model calculations including a viscous hydrodynamical evolution of the collisions (see right plot of Fig. 5).

The increase is independent of the η range in which the multiplicity is measured, in both the collisions systems, since is observed even when an η -gap is introduced between the regions where the D mesons and the multiplicity are measured.

Figure 3. Left: Nuclear modification factor R_{pPb} of prompt D mesons in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV: average R_{pPb} of D^0 , D^+ and D^{*+} mesons in the interval $1 < p_T < 24$ GeV/c [22], shown together with the D^0 R_{pPb} in $0 < p_T < 1$ GeV/c [21]. The data are compared with results of theoretical calculations including only CNM effects (CGC [23], NLO pQCD [24] with EPS09 nPDFs [4]), a LO pQCD calculation with CNM effects [25] and a calculation based on incoherent multiple scatterings [26]. **Right:** Same data as on the left. Here the results are compared to the results of the Duke and POWLANG [27] transport models.

3.3 Azimuthal correlations between D-mesons and charged hadrons

The comparison of D-hadrons correlations in pp and p-Pb collisions is shown in Fig. 6, after the subtraction of the baseline and for different kinematics regions. A near-side peak ($\Delta\varphi \sim 0$) and a wider and lower peak in the away-side region ($\Delta\varphi \sim \pi$) can be clearly seen in both systems. The correlation pattern is compatible within uncertainties for pp and p-Pb collisions.

A more quantitative comparison between pp and p-Pb results for the near-side peak can be done extrapolating the yields of the near-side peaks by fitting the correlation distribution with a Gaussian function for the peaks and a flat baseline. In Fig. 7 the near-side associated yields in function of the D-meson p_T for different associate tracks p_T , obtained in pp and p-Pb collisions are compared. The near-side peak associated yield shows an increasing trend with D meson- p_T and the yields in pp and p-Pb collisions look compatible within uncertainties. In the bottom row, the width (σ_{fitNS}) of the near-side Gaussian term is also shown. The current level of uncertainty is large and does not allow us to quantify the dependence of σ_{fitNS} on D-meson and associated charged particle p_T , as well as a possible difference between the values measured for pp and p-Pb collisions. This is expected to improve in future measurements with larger data samples, where a smaller $\Delta\varphi$ range for the baseline calculation could be used.

In the same figure, the results are also compared with the theoretical expectations. An overall compatibility within uncertainties is found between data and predictions made using POWHEG+PYTHIA6 simulations, meaning that the simulations reproduce the correlation distributions within uncertainties.

Figure 4. Left: Average of D^0 , D^+ and D^{*+} relative yields in pp collisions at $\sqrt{s} = 7$ TeV, as a function of the relative charged-particle multiplicity at central rapidity in several p_T intervals. The results are presented with their statistical (vertical bars) and systematic (boxes) uncertainties, except for the feed-down fraction uncertainty that is drawn separately in the bottom panels. **Right:** Results compared with calculations of several event generators with hard and soft components. The position of the points on the abscissa is the average value of $(dN_{ch}/d\eta)$ [28].

3.4 Results in Pb-Pb collisions

In Pb-Pb collisions, the open heavy-flavour R_{AA} measured with ALICE for D^0 , D^+ , D^{*+} [36] [37] and for D_s^+ [38] shows a strong reduction of the yields at large transverse momenta ($p_T > 5$ GeV/c) in the most central collisions relative to a binary-scaled pp reference (see Fig. 8). This suppression is interpreted as due to charm quark in-medium energy loss.

The expected mass ordering of the energy-loss has been also investigated. Figure 9 [39] (left) shows the D-meson R_{AA} as a function of the average number of nucleons participating in the interaction, compared to the one of J/Ψ from beauty-hadron decays measured by CMS [40]. The D-meson p_T range was chosen in order to obtain a significant overlap with the p_T distribution of B mesons decaying to J/Ψ with $6.5 < p_T < 30$ GeV/c, thus allowing a consistent comparison. A similar trend as a function of centrality is observed, but the D-meson R_{AA} is systematically lower than the one of J/Ψ from B decays in central collisions. This is consistent with the expectation from the predicted energy loss hierarchy, with a smaller in-medium energy loss for beauty than for charm. Calculations including mass-dependent radiative and collisional energy-loss [41] predict a difference between the R_{AA} of D mesons and non-prompt J/Ψ similar to the measurement. Figure 9 (right panel) also shows the comparison of the D-meson R_{AA} with that of charged hadrons and pions: a similar suppression is observed within uncertainties. More in details, the R_{AA} of D mesons and light-flavour hadrons are consistent for $p_T > 6$ GeV/c. For $p_T < 6$ GeV/c, the R_{AA} of D mesons tends to be slightly higher than that of pions, even if more data are needed to study the effect of charm quark mass at low p_T .

The D-meson v_2 measured in different centrality classes in Pb-Pb collisions [42], shown in Fig. 10, is larger than zero with a significance ~ 6 in the interval $2 < p_T < 6$ GeV/c and comparable in magnitude to the one of charged hadrons, dominated by light-flavour hadrons [43] [44]. These results

Figure 5. Left: Average of D^0 , D^+ and D^{*+} relative yields in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, as a function of the relative charged-particle multiplicity at central rapidity in several p_T intervals. **Right:** Average D-meson per-event yields vs relative charged-particle multiplicity at central rapidity, compared with EPOS 3 [33].

indicate that at low p_T charm quarks participate in the collective motion of the system. v_2 results at high p_T could give insight into the path-length dependence of the in-medium energy loss, but the present statistics does not allow to give a conclusion on this.

Figure 6. Comparison of azimuthal-correlation distributions of D mesons with charged particles in pp collisions at $\sqrt{s} = 7$ TeV and in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, after baseline subtraction [35].

Figure 7. Azimuthal angular correlations of D mesons with charged particles: comparison of near-side peak associated yield and width in pp and p-Pb collisions with Monte Carlo generator expectations [35].

Figure 8. R_{AA} of prompt D_s^+ and non-strange D mesons (average of D^0 , D^+ and D^{*+}) in the 0-10% centrality class, compared to TAMU model predictions [38].

Figure 9. Left: R_{AA} of D mesons in $8 < p_T < 16$ GeV/c and preliminary non-prompt J/Ψ mesons from CMS in $6.5 < p_T < 30$ GeV/c; Right: Prompt D-meson R_{AA} (average of D^0 , D^+ and D^{*+}) as a function of p_T compared to the nuclear modification factor of pions and charged particles in the 0-10% centrality range.

Figure 10. Comparison of prompt D^0 meson and charged-particle v_2 [42] in three centrality classes as a function of p_T .

4 Conclusions

Measurements of open charm production were carried out successfully with the ALICE experiment at the LHC. p_T -differential cross sections for prompt D mesons in pp collisions are reproduced within uncertainties by theoretical predictions based on pQCD calculations.

The D-meson self-normalized yields exhibit an increasing trend with increasing charged-particle multiplicity in pp collisions. This trend is consistent with models considering that MPIs affect the hard momentum scale relevant for heavy-flavour production. A similar increase is observed in p-Pb collisions, but in this case a higher number of binary nucleon-nucleon collisions also contributes to high-multiplicity events.

The D meson-charged particle azimuthal correlation distributions, measured in pp and p-Pb collisions, are in agreement between each other within uncertainties, and are well described by Monte Carlo simulations.

R_{pPb} of prompt D mesons in p-Pb collisions is consistent with unity within uncertainties, providing evidence that CNM effects are small in the measured p_T range.

In Pb-Pb collisions a strong suppression of heavy-flavour yields is observed at intermediate and high p_T . As the influence of CNM effects is small in the measured p_T range, these results in Pb-Pb collisions can be interpreted as a final-state effect due to in-medium parton energy loss.

The v_2 measured in semi-central Pb-Pb collisions is larger than zero at low p_T , suggesting that heavy quarks participate in the collective motion of the system.

References

- [1] M. Gyulassy and M. Plumer, *Phys. Lett. B* **243**, 432 (1990)
- [2] R. Baier, Y. L. Dokshitzer, A. H. Mueller, S. Peigne and D. Schiff, *Nucl. Phys. B* **484**, 265 (1997)
- [3] M. H. Thoma and M. Gyulassy, *Nucl. Phys. B* **351**, 491 (1991)
- [4] K. Eskola, H. Paukkunen and C. Salgado, *JHEP* **04** 065 (2009)
- [5] D. de Florian and R. Sassot, *Phys. Rev. D* **69**, 074028 (2004)
- [6] I. Vitev et al., *Phys. Rev. C* **75**, 064906 (2007)
- [7] T. Sjöstrand and M. van Zijl, *Phys. Rev. D* **36** 2019 (1987)
- [8] S. Porteboeuf et al., *Nucl. Phys. Proc. Suppl.* **214**, 181–184 (2011)
- [9] B. Abelev et al., ALICE Collaboration, *Phys. Lett. B* **719** 29 (2013)
- [10] K. Aamodt et al., ALICE Collaboration, *JINST* **3** S08002 (2008)
- [11] B. Abelev et al., ALICE Collaboration, *JHEP* **1201**, 128 (2012)
- [12] B. Abelev et al., ALICE Collaboration, *Phys. Lett. B* **718** 279-294 (2012)
- [13] B. Abelev et al., ALICE Collaboration, *JHEP* **1207**, 191 (2012)
- [14] M. Cacciari et al., CERN-PH/TH/2011 227
- [15] G. Aad et al., ATLAS Collaboration, *Eur. Phys. J. C* **72** (2012)
- [16] M. Cacciari et al., CERN-PH-TH/2011-227 (2011)
- [17] B.A. Kniehl, G. Kramer, I. Schienbein et al., *Eur. Phys. J. C* **72** 2082 (2012)
- [18] Rafal Maciula and Antoni Szczure, *EPJ Web Conf.* **37** 06008 (2012)
- [19] A. Adare et al., PHENIX Collaboration, *Phys. Rev. Lett.* **97** 252002 (2006)
- [20] S. Alekhin et al., arXiv:hep-ph/0601013, capt 4 (2006)
- [21] J. Adam et al., ALICE Collaboration, *Phys. Rev. C* **94**, 054908 (2016)
- [22] B. Abelev et al., ALICE Collaboration, *Phys. Rev. Lett.* **113** 23, 232301 (2014)

- [23] H. Fujii and K. Watanabe, Nucl. Phys. A920, 78–93 (2013)
- [24] M. L. Mangano, P. Nason, and G., Nucl. Phys. B373, 295–345 (1992)
- [25] R. Sharma, I. Vitev, and B.-W. Zhang, Phys. Rev. C80, 054902 (2009)
- [26] Z.-B. Kang, I. Vitev, E. Wang, H. Xing, and C. Zhang, Phys. Lett. B740, 23–29 (2015)
- [27] A. Beraudo, A. De Pace, M. Monteno, M. Nardi, and F. Prino, JHEP 03, 123 (2016)
- [28] J. Adam et al., ALICE Collaboration, JHEP 09, 148 (2015)
- [29] ALICE Collaboration, arXiv:1602.07240
- [30] E.G. Ferreira, C. Pajares, Phys. Rev. C86, 034903 (2012)
- [31] E.G. Ferreira, C. Pajares, arXiv:1501.03381[hep-ph]
- [32] H. Drescher, M. Hladik, S. Ostapchenko, T. Pierog, K. Werner, Phys. Rept. 350, 93 (2001)
- [33] K. Werner, B. Guiot, I. Karpenko, T. Pierog, Phys. Rev. C89, 064903 (2014)
- [34] T. Sjostrand, S. Mrenna, P.Z. Skands, Comput. Phys. Commun. 178, 852 (2008)
- [35] J. Adam et al., ALICE Collaboration, arXiv:1605.06963
- [36] B. Abelev et al., ALICE Collaboration, Phys. Rev. Lett. 109 112301 (2012)
- [37] B. Abelev et al., ALICE Collaboration, JHEP 9 112 (2012)
- [38] J. Adam et al., ALICE Collaboration, JHEP 03 082 (2016)
- [39] J. Adam et al., ALICE Collaboration, JHEP 1511 205 (2015)
- [40] V. Khachatryan et al., CMS Collaboration, arXiv:1610.00613v1
- [41] M. Djordjevic, Phys. Lett. B734 286-289 (2014)
- [42] B. Abelev et al., ALICE Collaboration, Phys. Rev. Lett. 111, 102301 (2013)
- [43] B. Abelev et al., ALICE Collaboration, Phys. Lett. B 719 18 (2013)
- [44] B. Abelev et al., ALICE Collaboration, Phys. Rev. C90 3, 034904 (2014)