Summary of charm results from ALICE

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Abstract. An overview of the most recent charm measurements from the ALICE Collaboration is presented in this document. The study of heavy-flavour production is important to understand the properties of the hot and dense medium formed in ultra-relativistic heavy-ion collisions. In this document the journey of charm in the medium, from the production to the hadronisation into hadrons, is described. Both open charm and quarkonium measurements are presented, starting from D-meson and J/ψ production cross sections in pp collisions and their comparison with theoretical calculations. Recent measurements of relative abundances of different particle species are discussed, in particular the D_s^+/D^0 and Λ_c^+/D^0 ratios, that are sensitive to the hadronisation mechanisms and to the strangeness and to the baryon-to-meson enhancement. The energy loss mechanisms and the collective motion in the medium are investigated through the D-meson and J/ψ nuclear modification factor and the elliptic flow measurements. Further investigations on possible medium-like effects observed in high-multiplicity pp and p-Pb collisions are also addressed.

1. Introduction
One of the main goal of the ALICE experiment at the LHC is the characterization of the extremely hot and strongly coupled medium, the quark-gluon plamsa (QGP), formed in high-energy heavy-ion collisions. Heavy quarks, i.e. charm and beauty, are ideal probes of the medium, since, due to their large mass, they are produced in the initial stages of the collisions via hard partonic scattering processes. Therefore they probe the whole evolution of the QGP, loosing energy, and possibly thermalising as a consequence of their interactions via elastic scatterings and gluon radiation in the medium. Precise measurements of the yield modifications of heavy-flavor hadrons in heavy-ion collisions with respect to measurements in proton-proton (pp) collisions, and studies of azimuthal anisotropy for particles with charm quarks, could help to put constraints on the transport coefficients of the QGP, as the heavy-quark diffusion coefficient and its dependence on the temperature (see [1] for a recent review). Heavy quarks are also sensitive to the QGP temperature, that is reflected in the observed suppression of charmonium states, that probe the color screening and regeneration in medium.

Smaller colliding systems such as pp or p-Pb, are not only useful as reference for Pb–Pb measurements, but they are also interesting for the study of Quantum chromodynamics (QCD) and Cold Nuclear Matter (CNM) effects. Furthermore, recent observations reveal the interplay, in particle production, between fragmentation mechanisms in vacuum and quark-coalescence mechanisms in the hot medium [2, 3]. In addition, in high-multiplicity events in small systems, signatures of medium-like effects, that resemble those characteristic to QGP production, have been observed [4, 5]. Heavy-flavor measurements versus event activity play a key role in clarifying the origin of such signatures.
2. Heavy flavour hadron production cross sections

The study of the production of hadrons containing heavy quarks in pp collisions is a sensitive test of QCD calculations with the factorisation approach. In this scheme, the $p_T$ differential production cross sections of hadrons containing charm quarks are calculated as a convolution of three terms: (i) the parton distribution functions (PDFs) of the incoming protons, (ii) the partonic scattering cross section, calculated as a perturbative series in powers of the strong coupling constant $\alpha_s$, and (iii) the fragmentation function, which parametrises the non-perturbative evolution of a heavy quark into a given species of heavy-flavour hadron [6]. The heavy-flavour $p_T$-differential production cross section is measured by ALICE in different systems and different center-of-mass energies. In Fig. 1 the charmed $D^0$ meson production cross section measured at central rapidity, on the left, and the preliminary results of the $J/\psi$ production cross section measured at forward rapidity, on the right, are shown, both measured down to $p_T = 0$ in pp collisions at $\sqrt{s} = 5.02$ TeV. They are also compared with models that are based on the factorization approach, with NLO calculations and different schemes [7, 8]. The uncertainties on the theoretical predictions, which are dominated by the choice of the scales of the perturbative calculation are significantly larger than the uncertainties on the measured data points. The precise measurements of the production cross sections down to $p_T = 0$ provide important constraints to pQCD calculations and to low-$x$ gluon PDFs and represent an essential reference for the study of effects induced by cold and hot strongly-interacting matter in the case of proton–nucleus and nucleus–nucleus collisions, respectively.

![Figure 1](image)

**Figure 1.** $p_T$-differential production cross section measured at central rapidity for $D^0$ (left) and at forward rapidity for $J/\psi$ (right) down to $p_T = 0$, in pp collisions at $\sqrt{s} = 5.02$ TeV. Theoretical calculations based on the QCD calculations describe data within uncertainties [7, 8].

3. Particle specie ratios in pp, p-Pb and Pb–Pb

The relative abundances of open charmed hadron species are sensitive to the fragmentation fractions of the charm quark, and, more in general, test the hadronisation scenario of charm quarks into hadrons, which has been supposed since long to be independent of the collision system and energy.

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3.1. D-meson cross-section ratios

In Fig. 2 the ratios of the $p_T$-differential cross sections for prompt $D^+/D^0$, on the left, and $D_s^+/D^0$, on the right, are reported, respectively, in different collisions systems (pp and Pb–Pb collisions at $\sqrt{s_{NN}}=5.02$ TeV) and different center-of-mass energies (pp collisions at $\sqrt{s}=5.02$, 7, 13 TeV).

![Figure 2. Ratios of $D^+/D^0$ production cross sections in different collision systems (pp, Pb–Pb collisions, on the left) and $D_s^+/D^0$ in different center-of-mass energy in pp collisions (on the right), as a function of $p_T$.](image)

The measurements do not show a significant $p_T$ dependence within the uncertainties. The agreement across different collisions systems suggests no difference between the fragmentation functions of charm quarks to $D^0$, $D^+$ in pp and Pb–Pb collisions. No differences are observed in the measurements of $D_s^+$ mesons in pp collisions at different center-of-mass energies. The ratios of D-meson particle species are also in agreements with measurements done at $e^+e^-$ colliders.

Within the present uncertainties, these observations suggest that, looking uniquely in the meson sector, the universality of the fragmentation fractions for charm can not be ruled out.

3.2. Charmed baryon-to-meson cross-section ratios in pp collisions

$\Lambda_c$ production cross section is measured by ALICE in pp, p–Pb and Pb–Pb collisions at central rapidity. In Fig. 3 the $\Lambda_c^+/D^0$ ratio is shown as a function of $p_T$, for pp collisions at $\sqrt{s}=5.02$, 7 TeV, and for p-Pb collisions at $\sqrt{s_{NN}}=5.02$ TeV, and a strong $p_T$ dependence is evident. In the hadronic collision systems the $\Lambda_c^+/D^0$ ratio is larger with respect to measurements done at $e^+e^-$ colliders, and it is underestimated by models tuned on $e^+e^-$ measurements [9].

Theoretical calculations based on standard PYTHIA tunes with hadronisation processes modelled via simple string fragmentation mechanisms and other MC generators [19, 20] also tuned on $e^+e^-$ measurements, fail to describe the data and the $p_T$ trend. This could indicate that the fragmentation fractions of charm quarks are non-universal with respect to collision system and energy.

While theoretical calculations based on PYTHIA8.243 with hadronisation processes implemented via color reconnection mechanisms beyond the leading color approximation, and with an enhanced baryon formation [11], and a Statistical Hadronisation Models (SHM) with
enhanced set of baryons [10], are closer to the data, and well describe the $p_T$ shape of the measurements.

**Figure 3.** $\Lambda_c^+/D^0$ ratio as a function of $p_T$ measured in pp collisions at $\sqrt{s} = 5.02$ and 7 TeV, and in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, compared to theoretical models (see text for details).

3.3. Strange to non-strange $D$-meson and baryon-to-meson ratios in Pb–Pb collisions
The modification of the charm-quark hadronisation mechanisms in the presence of QGP is investigated comparing the ratios between the measured yields of hadronic species in Pb–Pb and pp collisions. A modification is expected for strange $D$ mesons with respect to non-strange $D$ mesons, and baryon over meson states, in particular if the recombination (or coalescence) plays a role in Pb–Pb collisions. In Fig. 4, on the left panel the $D_s^+/D^0$ ratio is shown in the most central (0–10%) and semi-central (30–50%) collisions in Pb–Pb, in comparison with measurements done in pp collisions. A hint of larger ratio up to $p_T = 8$ GeV/c in Pb–Pb is observed for $D_s^+/D^0$, and could be explained as different hadronisation processes that occur in Pb–Pb, where a charm quark hadronises via coalescence with a strange quark in the QGP, and the enhancement noticed for $D_s^+$ is due to the strangeness enhancement in the medium [12].

In Fig. 4, on the right, the baryon-to-meson $\Lambda_c^+/D^0$ ratio in Pb–Pb collisions is shown for two centrality classes, and it is compared to the one measured in pp collisions. There is a hint of a higher $\Lambda_c^+/D^0$ ratio in Pb–Pb with respect to pp collisions at intermediate $p_T$ for both 0–10% and 30–50% centrality classes, that could be interpreted as an interplay between recombination in medium that favours the formation of baryons, and the radial-flow that pushes the spectra towards harder $p_T$ in Pb–Pb.

In Fig. 5, the double ratio of $D_s^+/D^0$ in Pb–Pb versus pp collisions, and the $\Lambda_c^+/D^0$ ratio are shown in comparisons with models that include fragmentation and coalescence mechanisms in the QGP, and describe the data within uncertainties [14, 16]. For $\Lambda_c^+/D^0$, in addition, also a model based on SHM calculations describes the data within uncertainties [15].
Figure 4. $D_0^+ / D^0$ ratio of prompt yields as function of $p_T$ for pp and Pb–Pb collisions (left). $\Lambda^+_c / D^0$ baryon-to-meson ratio in pp and Pb–Pb collisions (right).

Figure 5. The double ratio $D_0^+ / D^0$ in Pb–Pb and pp collisions in comparison with models that include fragmentation and coalescence in Pb–Pb (right) and the baryon-to-meson ratio of $\Lambda^+_c / D^0$ compared with models that include fragmentation and coalescence, with statistical hadronisation model and with PYTHIA8 color reconnection tune.

Finally, profiting of the large sample of pp collisions collected at $\sqrt{s} = 13$ TeV in Run 2, ALICE went a step further in the investigation of the baryon hadronisation mechanisms, with a more differential analysis, measuring the $\Lambda^+_c / D^0$ ratio as a function of charged particle multiplicity. The ratios are shown in Fig. 6 as a function of charged particle multiplicity, for different $p_T$ intervals, and across different collision systems, from pp to p–Pb and Pb–Pb. At intermediate $p_T$, i.e. from $2 < p_T < 8$ GeV/c, focusing on the pp measurements,
a hint of increasing ratio from low to high multiplicity ranges is observed, and the higher multiplicity measurements are close to the Pb–Pb measurements. The smooth increasing trend with multiplicity is also observed from pp to Pb–Pb measurements at low $p_T$, while the trend is flat at higher $p_T$. This could suggest that some peculiar mechanisms, probably in the hadronisation processes, related to the increase of multiplicity is present also in pp collisions, at low-intermediate $p_T$, that bring the ratios very close to Pb–Pb measurements. Theoretical calculations based on the color reconnection mechanisms with enhanced processes for baryons formations [11], describe the data in pp versus multiplicity, within the uncertainties.

Figure 6. $\Lambda_c^+/D^0$ ratio as a function of charged particle multiplicity, from measurements performed in pp, p–Pb, to Pb–Pb, in different $p_T$ intervals.

4. Nuclear modification factor in p–Pb and Pb–Pb
The energy loss mechanisms of charm in the QGP are investigated comparing the production of charmed hadron species in Pb–Pb collisions, scaled by the number of binary nucleon-nucleon collisions, with the production in pp collisions, measuring the nuclear modification factor $R_{AA}$. In the left panel of Fig. 7, the D-meson $R_{AA}$ for three different centrality classes is shown. For the first time at LHC, the D-meson spectra is measured down to $p_T=0$ in Pb–Pb collisions, in central 0–10% collisions. A large suppression is observed at low-intermediate $p_T$, and it is larger for the most central class, than for the semi-peripheral centrality class [22]. The suppression is due to final-state effects, and this is confirmed by the observation of the nuclear modification
factor measured in p–Pb collisions, $R_{pPb}$, that is compatible with unity within uncertainty, as shown in the right panel of Fig. 7. The $R_{pPb}$ is compatible with models that include CNM effects, while models that include the formation of QGP in the p–Pb collisions are disfavoured by the data [21].

A hierarchy in the nuclear modification factor $R_{AA}(\text{gluons, } u,d) < R_{AA}(c) < R_{AA}(b)$ is expected at low-intermediate $p_T$, that could reflects the one expected for the energy loss of gluons, light and heavy quarks in the medium. The first part of this hierarchy is visible in Fig. 8, where the D-meson $R_{AA}$ is compared with the charged particle $R_{AA}$. On the left panel: a larger suppression is observed for the light flavour particles at low $p_T$, while a similar suppression between charged particles and D-mesons is measured at high $p_T$. In the same figure, the $D^+_s$ and $\Lambda^+_c$ $R_{AA}$ are also shown, and a hint of smaller suppression is visible, confirming the role of coalescence for strange and baryon states at intermediate $p_T$, that enhances the $D^+_s$ and $\Lambda^+_c$ in Pb–Pb collisions.

In the right panel of the figure 8, the non-prompt $D^0$ $R_{AA}$, i.e. the $D^0$ coming from a beauty meson, is shown in comparison with the prompt $D^0$ $R_{AA}$. The observation of a less suppressed non-prompt $D^0$ yield in the intermediate $p_T$ reflects the expected quark mass ordering of the $R_{AA}$, since a smaller suppression for b than c quarks is predicted.

The $J/\psi$ $R_{AA}$ is presented in Fig. 9, for central and forward rapidity measurements (left panel). A rapidity dependence of the $R_{AA}$ is observed, indicating that the $R_{AA}$ measured at central rapidity is less suppressed in comparison to the one measured at forward rapidity. This observation is consistent with models that include a regeneration mechanisms of the quarkonia states in the medium [23]. In the right panel of the same figure, the $J/\psi$ $R_{AA}$ at central rapidity down to very low $p_T$ is compared with a SHM model and a transport model, that agree with data within uncertainties [15, 18].
Figure 8. Left panel: Charmed hadron $R_{AA}$ (non-strange D mesons, $D_s^+$, $\Lambda_c^+$) in comparison with charged particle $R_{AA}$ in centrality classes 0-10% in Pb–Pb collisions. Right panel: prompt and non-prompt $D^0$ $R_{AA}$ in 0-10% centrality class in Pb–Pb collisions.

Figure 9. $J/\psi$ $R_{AA}$ in Pb–Pb collisions. Left panel: comparison of $J/\psi$ $R_{AA}$ measured at central and forward rapidity. Right panel: $J/\psi$ $R_{AA}$ at central rapidity, in comparison with models.

5. Nuclear modification factor, elliptic flow and constraint to models
The left panel of Fig. 10 shows the $R_{AA}$ of D-mesons compared to several model calculations with different ingredients and different schemes for the implementation of heavy flavor transport modelling, hadronisation mechanisms, and radiative/collisional processes for energy loss [22]. Models that contain fragmentation and coalescence and both radiative and collisional processes, generally provide better description of the measurements at low and high $p_T$. The $v_2$ coefficient ("elliptic flow"), that quantifies the azimuthal anisotropy of D-mesons in semi-central Pb–Pb collisions, is shown in the right panel of Fig.10. A positive $v_2$ is observed for heavy-flavour hadrons, and this suggests that charm quarks largely thermalise in the QGP. To achieve a
stronger discriminating power of data over models, a simultaneous description of $R_{AA}$ and $v_2$ in the whole measured $p_T$ range should be achieved. This is still a challenge for the models. With the precision nowadays achieved, the experimental measurements start to provide constraints to the models, for the characterisation of the charm and beauty interaction with the medium. This would be very useful for an improved constraint of the medium transport parameters, such as the heavy-quark diffusion coefficient, one of the main goal of the future prospects with data collected in Run 3 of the LHC [25].

Figure 10. $R_{AA}$ and $v_2$ in comparison with same set of models [24, ?]

6. Conclusions
An overview of selected recent heavy-flavor results from ALICE in pp, p-Pb and Pb-Pb colliding systems has been presented. Production of charmed mesons in pp collisions are well described by QCD-inspired models within uncertainties. Ratios of different particle species are sensitive to the hadronisation mechanisms in vacuum and in medium. D meson ratios are found to be universal among different collision systems and center of mass energies, while baryon-over-meson ratios are underestimated by theoretical calculations, and different with respect to measurements done at the electron colliders, indicating that baryon-hadronisation mechanisms are not universal, and that they are probably not fully understood. The suppression of charmed non-strange and strange D-mesons, charmed baryons, non-prompt D mesons and charged particles follow the expected hierarchy, suggested by the energy loss expectations of different quarks in the medium. A positive azimuthal anisotropy is observed for charmed mesons, that indicates that charm participates to the collective motion in the medium reaching thermalisation before freeze out. The Run 3 phase of LHC with increased luminosity and detector upgrades will bring the era of precision charmed baryon and beauty measurements and will help to better constraint the properties of the QGP.

References
[1] Prino F and Rapp R 2016 Journal of Phys. G: Nucl. and Part. Phys. 43
[2] Acharya S et al. (ALICE) 2018 J.High Ener. Phys. 1810, 1742019
[3] Acharya S et al. (ALICE) 2019 *Phys. Letters B* **793** 212-223
[4] Abelev B et al. (ALICE) 2013 *Phys. Lett. B* **726** 164–177
[5] Adam J et al. (ALICE) 2017 *Nature Phys* **13**, 535-539
[6] Collins J C, Soper Davison E and Sterman G F 1989 *Adv. Ser. Direct. High Energy Phys.* **5** 1-91
[7] Acharya S et al. (ALICE) 2019 *Eur.Phys.J.C* **79** no.5, 388
[8] Acharya S et al. (ALICE) 2019 *J. High Ener. Phys.* **84**
[9] Acharya S et al. (ALICE) 2018 *J. High Ener. Phys* **04** 108 523
[10] He M and Rapp R, 2019 *Phys. Lett. B* **795** 117
[11] Christiansen R and Skands P Z 2015, *JHEP* **08** 003531
[12] Rapp R et al., 2020 *Phys. Rev. Lett.* **124** 042301
[13] Song T et al., 2015 *Phys. Rev. C* **92** 014910
[14] Plumari S et al. 2018 *Eur. Phys. J. C* **78** no.4, 348
[15] Andronic A. et al., 2019 *Phys. Lett. B* **797** 134836
[16] He M, Fries R J and Rapp R, 2014 *Phys. Lett. B* **735** 445
[17] Acharya S et al. (ALICE) 2020 *Phys. Lett. B* **805** 135434
[18] Du et al. 2011 *Nucl. Phys. A* **859** 114-125
[19] Bahr M et al. 2008 *Eur. Phys. J. C* **58** 639–707
[20] Bierlich C and Christiansen J R, 2015 *Phys. Rev. D* **92** no. 9, 094010
[21] Acharya S et al. (ALICE) 2019 *JHEP* **92**
[22] Acharya S et al. (ALICE) 2018 *JHEP* **1810** 174
[23] Acharya S et al. (ALICE) 2020 *Phys. Lett. B* **805** 135434
[24] Acharya S et al. (ALICE) 2020 *CERN-EP-2020-082*, arXiv:2005.11131
[25] Citron Z, et al, 2019 *CERN-LPCC-2018-07*, arXiv:1812.06772