Measurement of open-charm hadrons with ALICE

Marcel Figueredo, for the ALICE Collaboration

University of Liverpool, Oxford Street, Liverpool L69 7ZE, UK

E-mail: marcel.figueredo@cern.ch

Abstract. Heavy-flavour hadrons constitute a very good probe of the hot and dense medium created in high-energy Pb–Pb collisions. ALICE results on open-charm hadron production in Pb–Pb and p–Pb collisions are presented. Additionally, the perspectives for heavy-flavour measurements after the ALICE upgrade are discussed.

1. Introduction

ALICE [1] is the LHC experiment dedicated to the study of the nuclear matter at high temperatures and densities reached in the most central heavy ion collisions, where a transition of the QCD matter from a nuclear state to a QGP (Quark Gluon Plasma) is expected.

Heavy quarks, i.e. charm and beauty, are produced in hard scattering processes in the early stages of high-energy nucleus-nucleus collisions. The produced quarks propagate through the medium and interact with its constituents, losing energy via elastic collisions and gluon radiation. Therefore, they represent an effective probe to study the QGP. The measurement of D^0, D^+, D^{*+}, D_s^+ and Λ_c^+ production in pp and Pb–Pb collisions can be used to investigate the energy-loss mechanisms of the heavy quarks in the QGP and also their hadronisation. For the latter, in particular, the production of Λ_c^+ baryons and D_s^+ mesons relative to non-strange D mesons at low and intermediate p_T is expected to be sensitive to hadronisation via quark recombination [2].

One experimental observable used to study such effects in Pb–Pb collisions and to assess Cold Nuclear Matter (CNM) effects in p–Pb collisions is the nuclear modification factor, which is defined as $R_\mathrm{AA}(p_\mathrm{T}) = \frac{1}{\langle N_\mathrm{coll}\rangle} \times \frac{\mathrm{d}N_\mathrm{AA}/\mathrm{d}p_\mathrm{T}}{\mathrm{d}N_\mathrm{pp}/\mathrm{d}p_\mathrm{T}}$ or $R_\mathrm{pPb}(p_\mathrm{T}) = \frac{1}{A} \times \frac{\mathrm{d}\sigma_\mathrm{pPb}/\mathrm{d}p_\mathrm{T}}{\mathrm{d}\sigma_\mathrm{pp}/\mathrm{d}p_\mathrm{T}}$, where $\langle N_{coll}\rangle$ represents the average number of binary collisions and A is the mass number of the Pb nucleus. A deviation of the nuclear modification factor from unity could be due to energy loss in the QGP (Pb–Pb) or CNM effects in p–Pb collisions. The energy loss in Pb–Pb collisions is expected to follow a mass hierarchy $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$ [3, 4, 5], which could lead to $R_\mathrm{AA}(\mathrm{B}) > R_\mathrm{AA}(\mathrm{D}) > R_\mathrm{AA}(\pi)$, with some caveats due to the fact that R_AA is sensitive also to the different production and fragmentation kinematics of light partons, c and b quarks.

In Pb-Pb collisions, a collective expansion of the medium is established due to multiple interactions among its constituents. In non-central collisions, these interactions can convert the initial spatial anisotropy of the overlap region of the colliding nuclei into a final-state particle momentum anisotropy [6]. The elliptic flow, v_2, is the second order Fourier coefficient of the particle azimuthal distribution relative to the reaction plane [6]. At low p_T, a positive D-meson v_2 can reflect the participation of charm quarks in the collective motion of the medium, and, at high p_T, v_2 can be used to study the path-length dependence of in-medium energy loss.

2. Analysis and Results

The open-charm hadron decays $\mathrm{D}^0 \to \mathrm{K}^-\pi^+$ (BR $3.88 \pm 0.05\%$), $\mathrm{D}^+ \to \mathrm{K}^-\pi^+\pi^+$ (BR $9.13 \pm 0.19\%$), $\mathrm{D}^{*+} \to \mathrm{D}^0\pi^+$ (BR $67.7 \pm 0.5\%$), $\mathrm{D}_\mathrm{s}^+ \to \pi^+\phi \to \mathrm{K}^+\mathrm{K}^-\pi^+$ (BR $2.28 \pm 0.12\%$), as well

as their charge conjugates, were reconstructed in the central rapidity region ($|\eta| < 0.9$) in pp collisions at $\sqrt{s}$=7 and 2.76 TeV, p-Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV and Pb-Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV.

The analysis is based on the selection of fully reconstructed decay topologies displaced from the interaction vertex. A combination of topological cuts and particle identification (PID) of the decay products was applied to reduce the combinatorial background. The PID of pions, kaons and protons was based on information on the specific ionisation $\mathrm{d}E/\mathrm{d}x$ in the Time Projection Chamber (TPC) gas and a time-of-flight measurement with the TOF detector [7]. The topological cuts were based on the displaced vertex analysis, exploiting the high resolution on the track position in the vicinity of the interaction vertex provided by the Inner Tracking System (ITS). The pp reference cross section for the nuclear modification factors $R_{\rm AA}$ and $R_{\rm pPb}$ was obtained by scaling the D-meson cross sections measured at $\sqrt{s} = 7$ TeV to the $\sqrt{s_{\rm NN}}$ energies of Pb-Pb and p-Pb collisions based on FONLL pQCD calculations, as explained in [8].

The average $R_{\rm AA}$ of D^0, D^+ and D^{*+} as a function of $p_{\rm T}$ for Pb-Pb collisions in the centrality class 0-7.5% is shown in Fig. 1, along with the $R_{\rm AA}$ of charged particles and pions in the 0-10% centrality class. The D-meson yield is strongly suppressed at high $p_{\rm T}$ with respect to binary-scaled pp collisions and the $R_{\rm AA}$(D) is compatible with $R_{\rm AA}(\pi)$ within the current uncertainties. The available statistics are not sufficient to conclude on the mass hierarchy, that is, $R_{\rm AA}$(D) $> R_{\rm AA}(\pi)$ at moderate $p_{\rm T}$. In the high $p_{\rm T}$ region, as shown in the Fig. 2, $R_{\rm AA}$ of D mesons measured with ALICE is lower than that of J/ψ from B decays measured with CMS [9]. These data are described by model calculations that include mass-dependent energy loss.

$\mathrm{D_s^+}$ $R_{\rm AA}$ was also measured [10], showing a suppression similar to the non-strange D-meson $R_{\rm AA}$ in the interval $8 < p_{\rm T} < 12$ GeV/c. At lower $p_{\rm T}$, a conclusion cannot be drawn with the current uncertainties.

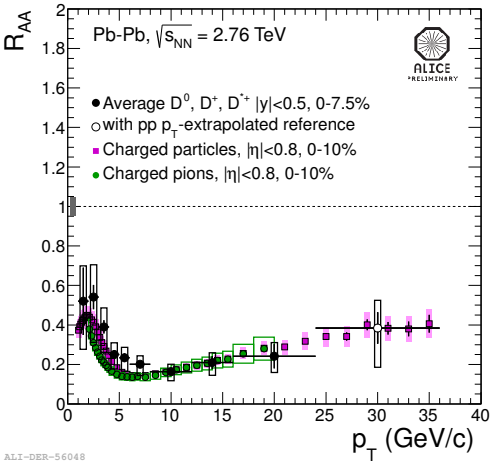

Figure 1: Average $R_{\rm AA}$ of D^0, D^+ and D^{*+} mesons as a function of $p_{\rm T}$ compared with that of charged particles and pions.

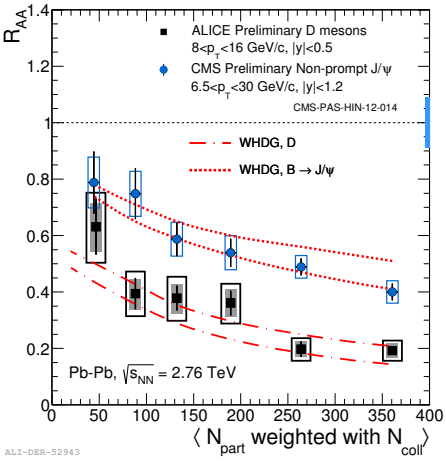

Figure 2: $R_{\rm AA}$ of D mesons compared with $R_{\rm AA}$ of non-prompt J/ψ measured with CMS [9] at high $p_{\rm T}$, as a function of the centrality of the collision expressed in terms of number of participant nucleons, compared with model calculations [3].

The D-meson v_2 was measured using the event plane method, as explained in [11]. Fig. 3 shows the elliptic flow of charmed hadrons measured in the centrality class 30-50% compared with the charged particle v_2. The v_2 of D mesons is positive in the region $2 < p_{\rm T} < 6$ GeV/c (with 5σ significance), suggesting that charm quarks participate in the collective motion. On the other hand, given the current statistics, it is not possible to come to a conclusion on the path-length dependence of the energy loss at high $p_{\rm T}$. As shown in Fig. 4, some of the in-medium energy-loss models describe the measured v_2 reasonably well within uncertainties. However, a simultaneous description of both v_2 and $R_{\rm AA}$ still represents a challenge for the models (for a discussion see e.g.[11]).

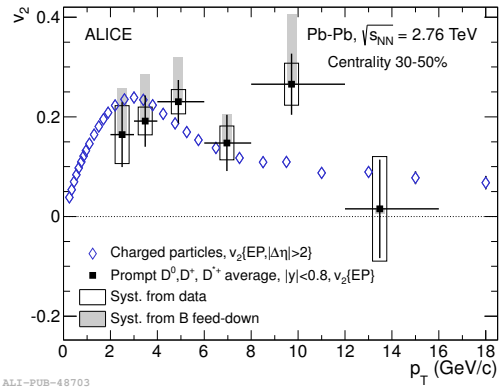

Figure 3: Average v_2 of D^0, D^+ and D^{*+} mesons as a function of p_T compared with v_2 of charged particles [11].

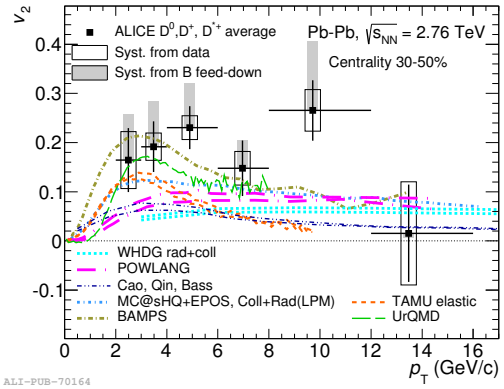

Figure 4: Average v_2 of D^0, D^+ and D^{*+} mesons as a function of p_T compared with model calculations [11].

Fig. 5 shows the measurement of the average $R_{\rm pPb}$ of D^0, D^+ and D^{*+} as a function of p_T for p-Pb collisions at $\sqrt{s_{NN}}$ =5.02 TeV. The $R_{\rm pPb}$ is compatible with unity for $p_T > 2$ GeV/c, which suggests that CNM effects are small and that the suppression observed in Pb–Pb collisions is dominated by the influence of the hot and dense medium. Models including CNM effects describe the data within uncertainties (for a more detailed discussion see e.g.[12]).

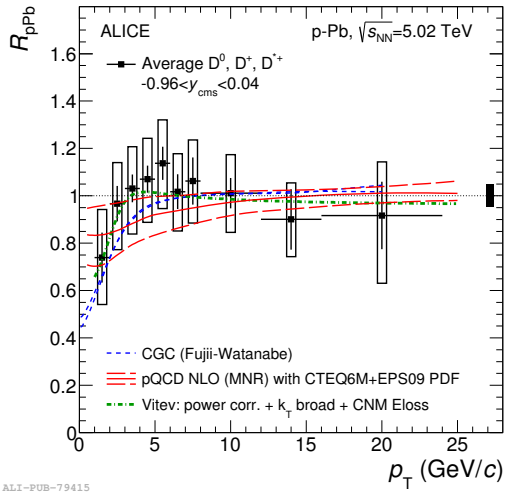

Figure 5: Average $R_{\rm pPb}$ of D^0, D^+ and D^{*+} as a function of p_T [12], compared with model calculations [13, 14, 15, 16, 17].

3. ALICE upgrade studies

An upgrade of the ALICE experiment is planned for the next long shutdown of the LHC (2018-2019). The heavy-flavour measurements will benefit in particular from the upgrade of the Inner Tracking System (ITS) and the Time Projection Chamber (TPC). As one of the main objectives, the resolution of the track impact-parameter measurement will be improved by a factor of 3 in the plane transverse to the beam direction. This will largely enhance the rejection of the combinatorial background in the heavy-flavour reconstruction. The upgrade of the readout capabilities of the TPC and several other detectors will allow to record minimum bias Pb–Pb collisions – which are used for open charm measurements at low momentum – at hundred times the rate compared to the current detector.

The expected performance for the open charm and beauty measurements with the upgraded ALICE detector was studied with simulations of Pb-Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.5 TeV. These simulations included the upgraded Inner Tracking System, a seven-layer silicon tracker with about 25 billion pixel cells [18]. The studies shown here consider the expected integrated luminosity after the ALICE upgrade ($\mathcal{L}_{int}$ = 10 nb^{-1}). As shown in Fig. 6 and Fig. 7, the $R_{\rm AA}$

of charmed mesons will be measured with percent-level precision and down to low p_{T}, enabling a precise comparison between strange and non-strange D mesons, as well as open beauty and charm. As discussed in [18], the R_{AA} of Λ_{c}^{+} will be measured for the first time, as well as the v_2 of Λ_{c}^{+} and $\mathrm{D_s^+}$.

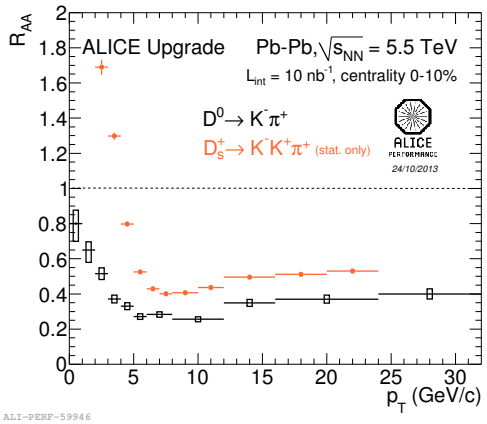

Figure 6: Perspective for R_{AA} of D^0 in comparison with R_{AA} of D_s^+ with the upgraded ALICE detector [18].

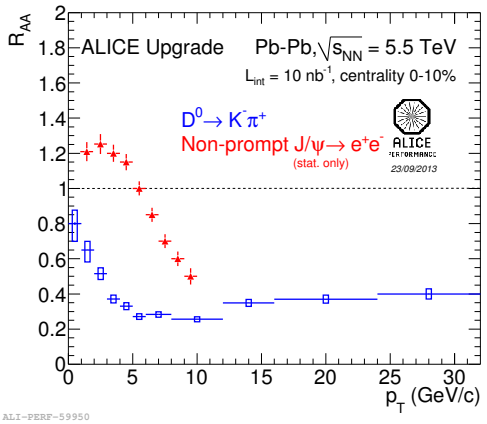

Figure 7: Perspective for R_{AA} of D^0 in comparison with R_{AA} of non-prompt J/ψ with the upgraded ALICE detector [18].

4. Conclusions

Open charm production cross sections are well described by pQCD calculations in pp collisions and models including CNM effects in p-Pb collisions. The strong suppression observed at high p_{T} in Pb–Pb collisions is due to final state effects, since CNM effects are small as indicated by R_{pPb} being close to unity. The different R_{AA} of D mesons and J/ψ from B-meson decays is described by model calculations including mass-dependent energy loss. Nevertheless, more statistics are needed to draw a conclusion on the comparison between the R_{AA} of D mesons and pions. The positive elliptic flow suggests collective motion of charm quarks in the medium. More statistics are needed to put more stringent constraints to models. As a perspective for the ALICE upgrade, high precision measurements of R_{AA} and v_2 of several heavy-flavour hadron species will become available for the first time.

References

[1] ALICE Collaboration 2008 *JINST* **3** S08002
[2] Kuznetsova I and Rafelski J 2007 *Eur. Phys. J. C* **51** 113–133
[3] Wicks S, Horowitz W, Djordjevic M and Gyulassy M 2007 *Nuc. Phys. A* **784** 426 – 442
[4] Djordjevic M and Heinz U 2008 *Phys.Rev.* **C77** 024905
[5] Dokshitzer et al 2001 *Phys. Lett. B* **519** 199–206
[6] Snellings R 2011 *New J. Phys.* **13** 055008
[7] ALICE Collaboration 2006 *Phys. G* **32** 1295
[8] Averbeck R, Bastid N, del Valle Z C, Crochet P, Dainese A *et al.* 2011 *arXiv:1107.3243*
[9] 2012 Tech. Rep. CMS-PAS-HIN-12-014 CERN Geneva
[10] Innocenti G M 2013 *Nuclear Physics A* **904905** 433c – 436c
[11] Abelev B *et al.* (ALICE Collaboration) 2014 *Phys. Rev. C* **90**(3) 034904
[12] Abelev B *et al.* (ALICE Collaboration) 2014 *arXiv:1405.3452*
[13] Mangano M L, Nason P and Ridolfi G 1992 *Nucl. Phys. B* **373** 295 – 345
[14] Eskola K, Paukkunen H and Salgado C 2009 *J. High Energy Phys.* **2009** 065
[15] Herzog C P and Son D T 2003 *J. High Energy Phys.* **2003** 046
[16] Fujii H and Watanabe K 2013 *Nucl. Phys. A* **920** 78 – 93
[17] Sharma R, Vitev I and Zhang B W 2009 *Phys. Rev. C* **80**(5) 054902
[18] ALICE Collaboration 2013 Tech. Rep. CERN-LHCC-2013-024. ALICE-TDR-017 CERN Geneva