Measurement of open-charm hadrons with ALICE

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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 as those 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 D⁰, D⁺, D*⁺, D_s⁺ and Λ_c⁰ production in p–Pb 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_c⁰ 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 $R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$ or $R_{pPb}(p_T) = \frac{1}{A} \frac{d\sigma_{pPb}/dp_T}{d\sigma_{pp}/dp_T}$, 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] (where $\Delta E_g$ represents the energy loss by gluons and $\Delta E_{u,d,s,c,b}$ the energy loss by the respective quarks), which could lead to $R_{AA}(B) > R_{AA}(D) > R_{AA}(\pi)$, 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 $D^0 \to K^-\pi^+$ (BR $3.88 \pm 0.05\%$), $D^+ \to K^-\pi^+\pi^+$ (BR $9.13 \pm 0.19\%$), $D^{*+} \to D^0\pi^+$ (BR $67.7 \pm 0.5\%$), $D_s^+ \to \pi^+\phi \to K^+K^-\pi^+$ (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 $\sqrt{s_{NN}} = 5.02$ TeV and Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ 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 $dE/dx$ 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 $R_{AA}$ and $R_{pPb}$ was obtained by scaling the D-meson cross sections measured at $\sqrt{s} = 7$ TeV to the $\sqrt{s_{NN}}$ energies of Pb-Pb and p-Pb collisions based on FONLL pQCD calculations, as explained in [8].

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

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

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 $2 < p_T < 6$ GeV/c (with $5\sigma$ 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 $p_T$. 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 $R_{AA}$ still represents a challenge for the models (for a discussion see e.g. [11]).

Fig. 3 shows the measurement of the average $R_{pPb}$ of $D^0$, $D^+$ and $D^{++}$ as a function of $p_T$ for p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The $R_{pPb}$ 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]).

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 $\sqrt{s_{NN}} = 5.5$ TeV. These
simulations included the upgraded Inner Tracking System, a seven-layer silicon tracker with billions of pixel cells [18]. The studies shown here consider the expected integrated luminosity after the ALICE upgrade \((L_{\text{int}} = 10 \text{ nb}^{-1})\). As shown in Fig. 6 and Fig. 7, the \(R_{AA}\) of charm 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 \(\Lambda_c^+\) will be measured for the first time, as well as the \(v_2\) of \(\Lambda_c^+\) and \(D_s^+\).

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 \(J/\psi\) with the upgraded ALICE detector [18].

4. Conclusions

Open charm production cross sections in pp collisions are well described by pQCD calculations and in p-Pb by models including CNM effects 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 \(R_{p\text{Pb}}\) being close to unity. The different \(R_{AA}\) of D mesons and \(J/\psi\) 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.

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