Open heavy-flavour measurements in p–Pb and Pb–Pb collisions with ALICE at the LHC

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Abstract. Heavy flavours are sensitive probes of the hot and dense QCD medium formed in high-energy heavy-ion collisions. Measurements of their production in p–Pb collisions are crucial for the interpretation of heavy-ion results, by investigating the cold nuclear matter effects. The open heavy-flavour production studied with ALICE at the LHC in p–Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV and in Pb–Pb collisions at $\sqrt{s_{\rm NN}}$ = 2.76 TeV are presented. Emphasis is given to the recent measurements of $\rm D^0$ production cross section down to $p_{\rm T}$=0, the nuclear modification factor of heavy-flavour hadron decay electrons in p–Pb collisions, the nuclear modification factor of D-meson, and heavy-flavour hadron decay electron elliptic flow in Pb–Pb collisions, as a function of centrality.

1. Introduction

The main goal of the ALICE experiment [1] is the characterization of the Quark-Gluon Plasma (QGP), the hot and dense matter created in high-energy nuclear collisions. Heavy quarks (charm and beauty) are unique probes of the QGP because they are dominantly produced in hard partonic scattering processes occurring in the initial stage of the collisions, and thus probe the entire evolution of the system. The nuclear modification factor $R_{\rm AA}$ and the elliptic flow v_2 are among the key observables for the QGP characterization. The nuclear modification factor is sensitive to the quark in-medium energy loss, providing a test of its colour-charge and parton-mass dependence. Theoretical calculations predict a hierarchy in partonic energy loss: $\Delta E_{\rm g}>$ $\Delta E_{\rm light_q}> \Delta E_{\rm c}> \Delta E_{\rm b}$. This can be studied with the $R_{\rm AA}$ of light and heavy-flavored hadrons. The v_2 is the second coefficient of the Fourier expansion of the $p_{\rm T}$-dependent particle azimuthal distribution with respect to the reaction plane. It is related to the azimuthal anisotropy of particle production in non-central collisions and represents an effective tool to investigate to what extent heavy quarks participate in the collective expansion in the medium. The measurement of the heavy-flavour production in p–Pb collisions provides insight into the role of cold nuclear matter effects (CNM). In this contribution, the ALICE measurements of D-meson and heavy-favour hadron decay lepton production in Pb-Pb and p-Pb collisions, focusing on the results from recent publications, are presented.

2. Open heavy-flavour reconstruction in ALICE

The ALICE detector provides precise tracking, vertexing and charged particle identification over a broad momentum range. D mesons are reconstructed via the $\rm D^0$, $\rm D^{*+}$, $\rm D^+$ and $\rm D_s^+$ hadronic decay channels at mid-rapidity ($|y_{\rm lab}|$<0.5) through the topological selection of the reconstructed decay vertices displaced by a few hundred μm from the interaction vertex, in $1< p_{\rm T}< 24$ GeV/c [2, 3]. In addition, the prompt $\rm D^0$ production was measured in p–Pb collisions down to $p_{\rm T} = 0$ using an analysis technique based on the estimation and subtraction of the combinatorial background, without reconstructing its decay vertex [4]. The open heavy-flavour production is also accessible via semi-leptonic decays of charm and beauty hadrons, both at mid-rapidity (electrons, $|y_{\rm lab}|<0.7$) and at forward rapidity (muons, $2.5 < y_{\rm lab} < 4$). Muons are selected and identified with the muon tracking and trigger chambers, with acceptance and geometrical cuts and MC cocktail methods to subtract the background from K and π decay muons [5]. Electrons are identified through a combination of electron identification strategies with different detectors. The background is subtracted via an invariant mass reconstruction of the couples of $\rm e^-e^+$ pairs, or cocktail method based on data [6, 7].

3. Highlights in p–Pb collisions

The initial-state effects are expected to have a small impact on D-meson production at high $p_{\rm T}$, but they can induce a modification of the D-meson cross section with $p_{\rm T}$ below a few GeV/c. For this reason, a measurement of the D-meson production down to $p_{\rm T} = 0$ provides important information. Below 1-2 GeV/c, the D-meson decay topology can not be efficiently resolved because of the small Lorentz boost. Furthermore, the selection criteria based on secondary-vertex displacement tend to select non-prompt D mesons from beauty-hadron decays with higher efficiency, increasing the systematic uncertainty on the subtraction of the beauty feed-down contribution. Using an analysis technique based on particle identification and on the estimation and subtraction of combinatorial background, via event mixing, like-sign pairs, track rotation and side-band fit, it was possible to measure the $\rm D^0$-meson yield down to $p_{\rm T}= 0$ in p–Pb collisions, with reduced feed-down systematic uncertainties and large efficiency [4]. In Fig. 1, on the left, our most precise measurement of prompt $\rm D^0$ $p_{\rm T}$-differential cross section is presented. The results are obtained with the background subtraction method for $0 <p_{\rm T}< 2$ GeV/c [4] and with the vertexing method for $p_{\rm T}> 2$ GeV/c [2]. The total cross section for prompt $\rm D^0$-meson production per unit of rapidity in $-0.96<y_{\rm cms}<0.04$ is:

$$\mathrm{d}\sigma^{\rm prompt\,D^0}_{\rm p-Pb,\,5.02\,TeV}/\mathrm{d}y = 79.0 \pm 7.3\,({\rm stat.})^{+\ 7.1}_{-13.4}\,({\rm syst.}) \pm 2.9\,({\rm lumi.}) \pm 1.0\,({\rm BR})\ {\rm mb}.$$

The $R_{\rm pPb}$ for D mesons in p–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV is shown in Fig. 1 (middle): this is the average $R_{\rm pPb}$ of $\rm D^0$, $\rm D^{*+}$, $\rm D^+$ mesons in the interval $1 <p_{\rm T}<24$ GeV/c [2], together with the $\rm D^0$ $R_{\rm pPb}$ in $0 <p_{\rm T}< 1$ GeV/c. The data are compared with results of theoretical calculations including only CNM effects [8, 9, 10, 11] and it is consistent with unity within the uncertainties. The $p_{\rm T}$-integrated nuclear modification factor of prompt $\rm D^0$ mesons in $-0.96<y_{\rm cms}<0.04$ is: $R^{\rm D^0}_{\rm pPb} = 0.89 \pm 0.11$ (stat.)$^{+0.13}_{-0.18}$ (syst.). On the right the heavy-flavour decay electron $R_{\rm pPb}$ is shown. It is consistent with unity within the uncertainties, but also consistent with an enhancement in the region $1<p_{\rm T}<6$ GeV/c, as observed in d–Au collisions at $\sqrt{s_{\rm NN}}$=200 GeV [6]. Data are compared with theoretical models that include initial-state effects [11, 10] or radial flow [12].

4. Highlights in Pb–Pb collisions

The left panel of Fig. 2 shows the $R_{\rm AA}$ of prompt non-strange D mesons, $\rm D^0$, $\rm D^{*+}$, $\rm D^+$, in comparison with that of $\rm D^+_s$ [13]. The maximum suppression of the D-meson $R_{\rm AA}$ (factor 5-6) is observed at $p_{\rm T}$=10 GeV/c in central Pb–Pb collisions. The $R_{\rm pPb}$ shown in Fig. 1 in the middle, which is consistent with unity, indicates that the suppression in central Pb–Pb collisions is induced by final-state effects due to quark energy loss in the medium. If hadronization via recombination occurs at low $p_{\rm T}$, the relative abundance of $\rm D^+_s$ with respect to non-strange D mesons should be larger in Pb–Pb than in pp collisions, due to the expected strangeness abundance. An indication of less suppression for $\rm D^+_s$ is observed at low $p_{\rm T}$, and is in agreement

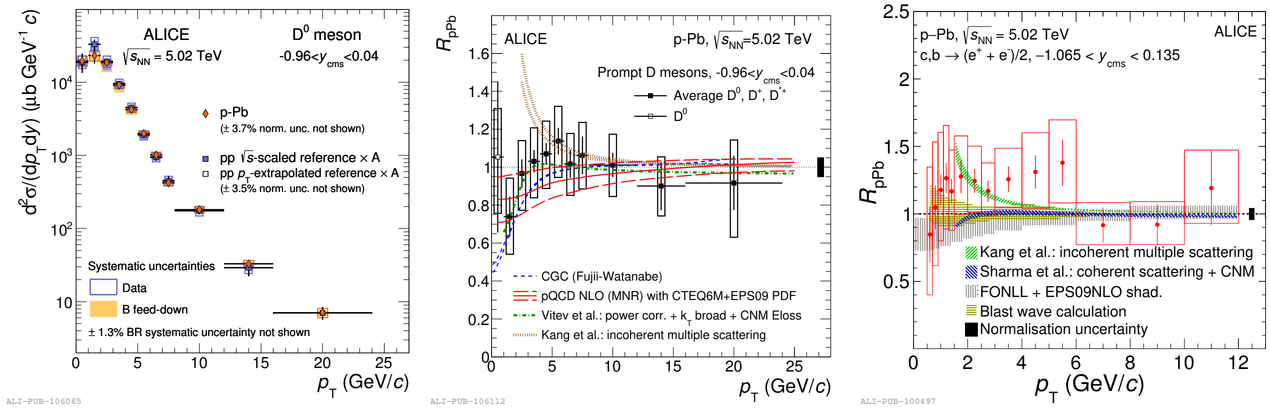

Figure 1. Measurements in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Left:p_T-differential production cross section of D^0 mesons in $0<p_T<16$ GeV/c [4]. Middle:R_{pPb} of D mesons (with D^0 in $0<p_T<1$ GeV/c) [4]. Right: heavy-flavour electrons R_{pPb} [6]. Data are compared with models.

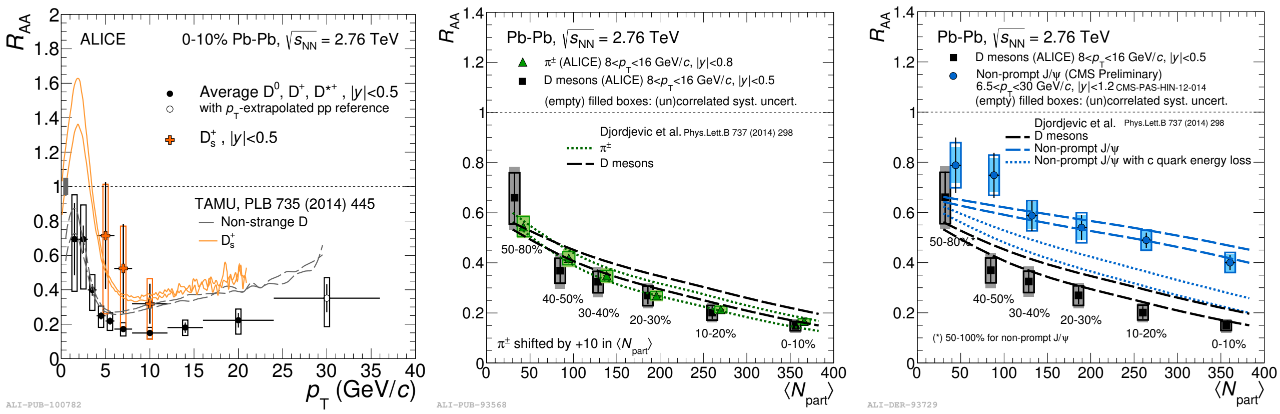

Figure 2. Left: R_{AA} in the 0-10% centrality class, of prompt non-strange D mesons and R_{AA} of D_s^+ compared with TAMU model [13]. Middle and Right: R_{AA} of D mesons in $8< p_T<16$ GeV/c as a function of centrality in comparison with model [14]. Middle: compared with charged pions. Right: compared with non-prompt J/ψ in $6.5<p_T<30$ GeV/c, measured by CMS [15]

with TAMU models [13] within uncertainties. In the middle panel of Fig. 2 the R_{AA} of prompt D mesons in the transverse momentum region $8 < p_T < 16$ GeV/c is shown as a function of centrality in comparison with the R_{AA} of pions [3]. The two R_{AA} are compatible within uncertainties. This observation is described by a model that takes into account the mass dependences of energy loss and the softer p_T spectrum and fragmentation of gluons and light quarks with respect to charm quarks [14]. The comparison of the R_{AA} of D mesons and of J/ψ from B-hadron decays (measured by the CMS Collaboration [15]) is displayed in the right panel of Fig. 2. It shows a stronger suppression for charm than for beauty hadrons at high p_T in central Pb–Pb collisions, consistent with the expectation $R_{AA}(D) < R_{AA}(B)$. The two measurements are described by the predictions based on a pQCD model including mass-dependent radiative and collisional energy loss [14]. In this model the difference in the R_{AA} of charm and beauty mesons is mainly due to the mass dependence of quark energy loss, as demonstrated by comparing with the curve in which the non-prompt J/ψ R_{AA} is calculated assuming that b quarks have the same energy loss as c quarks. The elliptic flow of heavy-flavour hadron decay electrons at

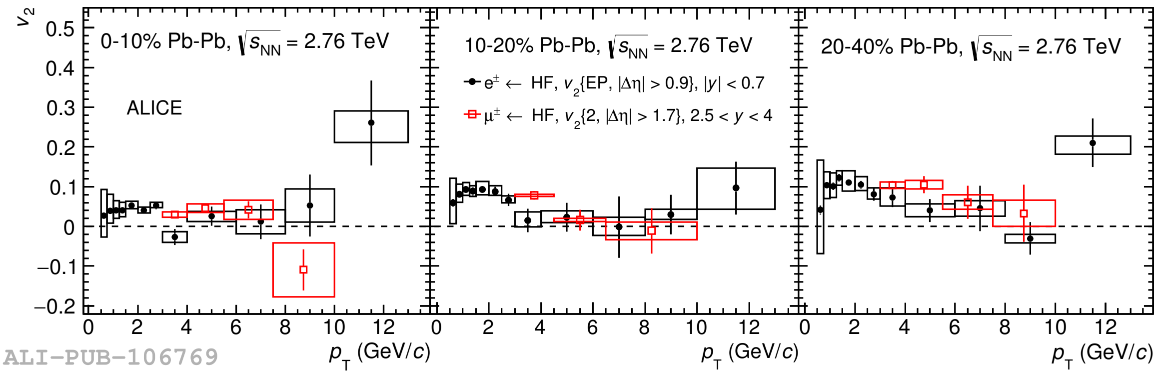

Figure 3. Elliptic flow of heavy-flavour hadron decay electrons at mid-rapidity and muons at forward rapidity in Pb–Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV for three centrality intervals [7, 5].

mid-rapidity [7] and muons at forward rapidity [5], measured with the event-plane method and with two-particle Q-cumulant, respectively, in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV is shown in Fig. 3 for three centrality classes. The measurements in the two rapidity regions are comparable in magnitude and the v_2 increases from central to semi-central collisions. In semi-central (20-40%) Pb–Pb collisions a positive v_2 is observed with a significance of 3 in $2 < p_T < 3$ GeV/c for electrons and in $3 < p_T < 5$ GeV/c for muons. These results suggest the significant interaction of heavy quarks, mainly charm in these p_T intervals, with the medium. Furthermore, the measured v_2 of prompt D mesons (not shown) is larger than zero in semi-central (30-50%) Pb–Pb collisions with a significance of 5.7 in $2 < p_T < 6$ GeV/c [16].

5. Conclusions

The ALICE results on open heavy-flavour production show a R_{pPb} consistent with unity and with models including CNM effects. The first measurement of D^0 meson production down to p_T=0 in p–Pb collisions was presented. The strong suppression observed in Pb–Pb collisions for p_T>3 GeV/c is due to final-state effects, and can be described by models with collisional and radiative energy loss mechanisms. The positive elliptic flow indicates that heavy quarks participate to the collective expansion at low p_T.

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