

Open heavy-flavour and quarkonium measurements with ALICE at the LHC

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Abstract. The ALICE Collaboration at the LHC measured open heavy flavours and quarkonia over a wide rapidity and transverse momentum range, and in several decay channels in pp, p-Pb and Pb-Pb collisions. An overview of recent results in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV is presented. A particular emphasis is placed on the nuclear modification factors.

1. Introduction

The ALICE experiment [1] at the LHC aims at investigating the properties of the hot and dense state of strongly-interacting matter, the Quark Gluon Plasma (QGP), produced in high-energy heavy-ion collisions. Heavy quarks (charm and beauty) that are created in a short time scale with respect to that of the QGP formation and subsequently interact with the medium, are regarded as efficient probes of the QGP properties. Open heavy-flavour hadrons are expected to be sensitive to the energy density of the system through the mechanism of in-medium energy loss of heavy quarks. According to QCD, quarks should lose less energy than gluons, and due to the dead cone effect [2], heavy-quark energy loss should be further reduced with respect to that of light quarks. Quarkonia could provide an estimate of the medium temperature through their dissociation in the QGP, due to colour screening [3]. In this scenario, the different binding energy of the various states should lead to a sequential suppression pattern where the strongly bound states (J/ψ , $\Upsilon(1S)$) melt at higher temperatures than the more loosely bound states ($\psi(2S)$, χ_c , $\Upsilon(2S)$, $\Upsilon(3S)$). On the other hand, due to the abundant production of charm quarks in heavy-ion collisions at LHC energies, charmonium suppression could be counteracted by regeneration from recombination of c and \bar{c} quarks in the QGP and/or at hadronization [4]. The medium properties are usually investigated by means of the nuclear modification factor, R_{AA} , defined as the ratio of the particle yield measured in Pb-Pb to that observed in pp collisions scaled with the number of binary nucleon-nucleon collisions. Further insights into the properties of the medium created in heavy-ion collisions can be gained from the study of the azimuthal anisotropy of open heavy flavours and quarkonia in semi-central collisions (not discussed here, see [5]). The heavy-ion physics program requires also the study of pp and p-Pb collisions. Besides providing the essential reference for the nuclear modification factor, pp collisions allow a sensitive test of models describing the production of heavy flavours in elementary hadronic collisions at LHC energies. The study of p-Pb collisions is crucial to access cold nuclear matter (CNM) effects in the initial and final state, assuming that an extended QGP is not formed in these collisions.

2. Open heavy-flavour and quarkonium measurements with ALICE

The ALICE experiment, described in detail in [1], consists of a central barrel ($|\eta| < 0.9$), a muon spectrometer ($-4 < \eta < -2.5$) and a set of smaller detectors located in the forward and backward pseudo-rapidity regions for global collision characterization and triggering purposes. At mid-rapidity, tracking is performed by combining information from the Time Projection Chamber (TPC) and the Inner Tracking System (ITS). Charged particle identification is provided by their specific energy loss in the TPC and their time of flight measured with the TOF detector. The electron identification can include, in addition, information from the Transition Radiation Detector (TRD) and the Electromagnetic Calorimeter (EMCAL). Muons with $p > 4$ GeV/c, p being the total momentum, are identified at forward rapidity with the muon spectrometer.

Open heavy flavours are measured in the charm hadronic decay channels (including $D^0 \rightarrow K^- \pi^+$, $D^+ \rightarrow K^- \pi^+ \pi^+$, $D^{*+} \rightarrow D^0 \pi^+$, $D_s^+ \rightarrow \phi \pi^+$ with $\phi \rightarrow K^+ K^-$ and charge conjugates in $|y| < 0.5$) and with electrons from semi-leptonic decays of charm and/or beauty at mid-rapidity, and in the semi-muonic decay of charm and beauty hadrons at forward rapidity. Electrons from beauty decays can be isolated at mid-rapidity by exploiting the precise measurement of the track impact parameter and their displacement from the interaction vertex. J/ψ are reconstructed down to $p_T = 0$, p_T being the transverse momentum, via unlike-sign dielectrons and unlike-sign dimuons at mid-rapidity ($|y| < 0.9$) and forward rapidity ($2.5 < y < 4$), respectively. In addition, $\psi(2S)$ and $\Upsilon(1S)$ are also measured down to $p_T = 0$ at forward rapidity via unlike-sign muon pairs. Details on the reconstruction of D mesons, J/ψ , $\psi(2S)$ and $\Upsilon(1S)$, and on the identification of electrons and muons from heavy-flavour hadron decays can be found in [6, 7, 8, 9, 10, 11].

3. Results

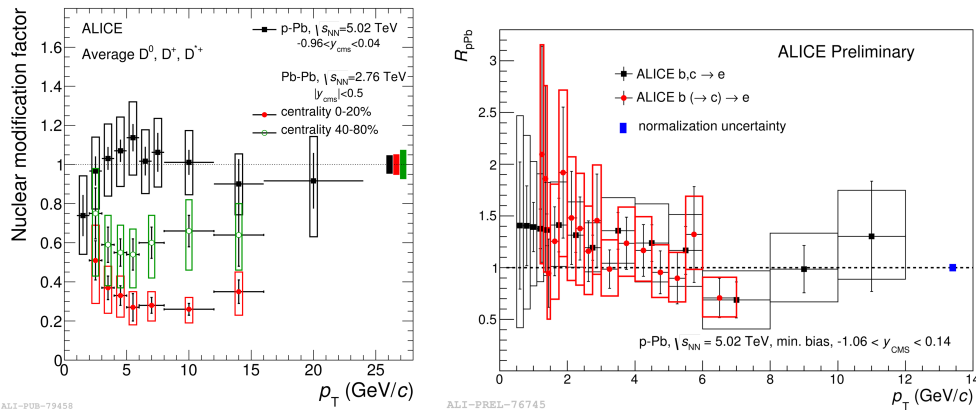


Figure 1. Left: p_T -differential R_{pPb} of D mesons in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV for the 0–20% and 40–80% centrality classes [6]. Right: p_T -differential R_{pPb} of electrons from heavy-flavour (c, b) and beauty-hadron decays. Statistical (bars), systematic (empty boxes) and normalization (filled boxes) uncertainties are displayed.

Figure 1 (left) presents the average of the nuclear modification factors of prompt D^0 , D^+ and D^{*+} as a function of p_T , measured at mid-rapidity in minimum bias p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV (R_{pPb}), and central (0–20%) and peripheral (40–80%) Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. In the region $p_T > 2$ GeV/c, R_{pPb} is consistent with unity within uncertainties (see also [6]). A similar behaviour is also reported for electrons from heavy-flavour (c, b) and beauty-hadron decays (Fig. 1, right). This indicates that cold nuclear matter effects are small and that the significant suppression observed in central collisions for D mesons (Fig. 1, left) and electrons from heavy-flavour (b,c) and beauty-hadron decays [12] is a final state effect due to the dense

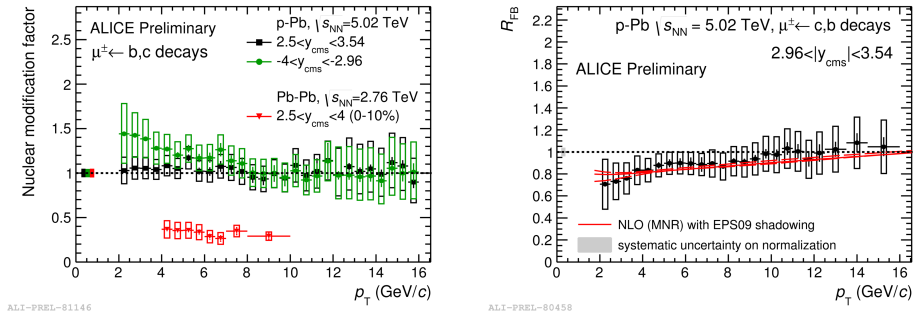


Figure 2. Left: p_T -differential R_{pPb} of muons from heavy-flavour decays measured at forward and backward rapidity, compared to the R_{AA} in central Pb–Pb collisions. Right: p_T -differential R_{FB} compared to model calculations including shadowing. Statistical (bars), systematic (empty boxes) and normalization (filled boxes) uncertainties are displayed.

medium. Cold nuclear matter effects have been also investigated at forward (p-beam direction, $2.5 < y_{cms} < 3.5$) and backward (Pb-going direction, $-4 < y_{cms} < -2.96$) rapidity with muons from heavy-flavour decays in the range $2 < p_T < 16$ GeV/c, as shown in Fig. 2. R_{pPb} is compatible with unity over the whole p_T range at forward rapidity. This evidences that the strong suppression measured in central Pb–Pb collisions results from the dense medium [10]. At backward rapidity, the R_{pPb} is slightly larger than unity in $2 < p_T < 4$ GeV/c and close to unity at higher p_T . Cold nuclear matter effects can be also quantified using the forward-to-backward ratio, R_{FB} , defined as the ratio of the p_T -differential production cross sections in a rapidity range symmetric with respect to $y_{cms} = 0$. This common y interval is limited to $2.96 < |y_{cms}| < 3.53$. R_{FB} is slightly smaller than unity in $2 < p_T < 4$ GeV/c and close to unity at higher p_T (Fig. 2, right). Next-to-leading order perturbative calculations including the EPS09 parameterization of nuclear parton distribution functions (PDFs) [13] describe reasonably well the R_{FB} ratio. A similar agreement between the measured R_{pPb} of D mesons and electrons from heavy-flavour decays and these predictions was also reported in [6, 14].

The ALICE Collaboration studied inclusive J/ψ and $\psi(2S)$ production in p–Pb collisions over a wide rapidity range. The p_T -integrated R_{pPb} of inclusive J/ψ shows a suppression of about a factor 1.4 at forward rapidity ($2.03 < y_{cms} < 3.53$) and mid-rapidity ($-1.37 < y_{cms} < 0.43$), while the measurement at backward rapidity ($-4.46 < y_{cms} < -2.96$) is consistent with unity (Fig. 3, left). Charmonium production was also investigated as a function of p_T , as shown in Fig. 3 (middle) for the results at forward rapidity. The p_T -differential R_{pPb} of inclusive J/ψ increases significantly with increasing p_T and becomes close to unity for $p_T > 5$ GeV/c. Furthermore, the $\psi(2S)$ R_{pPb} indicates a stronger suppression than the J/ψ , with a slight p_T dependence. Theoretical predictions valid for both resonances [8], based on shadowing [15] or coherent energy loss [16] describe the J/ψ R_{pPb} behaviour but overestimate the $\psi(2S)$ R_{pPb} . This indicates the presence of sizeable final state CNM effects on the $\psi(2S)$ production. Calculations based on the Color Glass Condensate [17] do not reproduce the inclusive J/ψ R_{pPb} at forward rapidity (Fig. 3, left). The inclusive J/ψ suppression measured at forward rapidity in central Pb–Pb collisions increases with increasing p_T and is smaller than that measured in Au–Au collisions at $\sqrt{s_{NN}} = 0.2$ TeV (Fig. 3, right). These trends are consistent with a significant fraction of J/ψ from regeneration at low p_T . In the high- p_T region, one can conclude that the measured suppression is due to the hot medium (R_{pPb} shows that cold nuclear matter effects are small in this p_T region).

Bottomonia have also been measured in the dimuon channel. These studies [9, 18], not

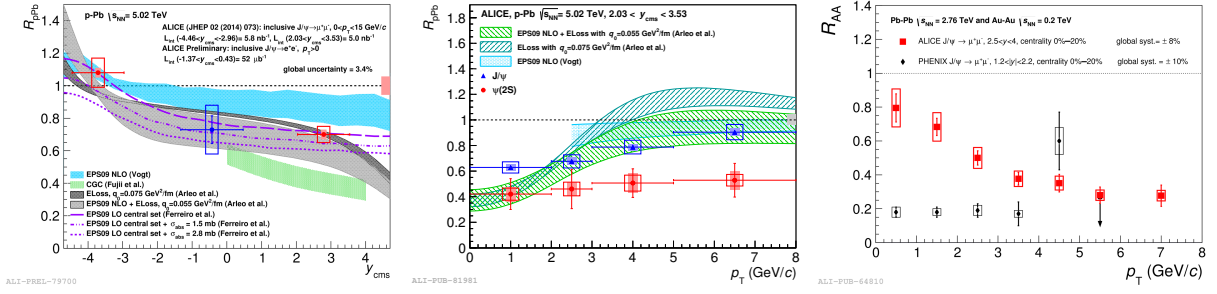


Figure 3. Left: p_T -integrated R_{pPb} of inclusive J/ψ as function of y_{cms} . Middle: p_T -differential R_{pPb} of inclusive J/ψ and $\psi(2S)$ at forward rapidity. Right: p_T -differential R_{AA} of inclusive J/ψ in central Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV and Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Statistical (bars), systematic (boxes) and normalization (filled boxes) uncertainties are displayed. The results in p–Pb collisions are compared to model predictions.

reported here, demonstrated in particular that the strong suppression of the $\Upsilon(1S)$ yield observed in Pb–Pb collisions (R_{AA} of about 0.3 in the 0–90% centrality class) cannot be attributed to CNM effects only and is underestimated by transport models.

4. Conclusion

Measurements of open heavy flavours and quarkonia have been successfully carried out with the ALICE experiment at the LHC. Open heavy-flavour R_{pPb} results provide evidence that CNM effects are small and confirm that the strong suppression seen in Pb–Pb collisions is a final state effect due to in-medium parton energy loss. The inclusive J/ψ and $\Upsilon(1S)$ R_{pPb} behaviour at forward rapidity is described by models including initial state CNM effects such as nuclear modification of the PDFs and/or energy loss. Final state effects are evidenced on the $\psi(2S)$ production in p–Pb collisions. The study of the inclusive J/ψ R_{AA} in Pb–Pb collisions suggests a non-negligible contribution from J/ψ produced via combination of charm quarks in the QGP and/or at hadronization. High expectations are placed in the upcoming LHC run 2 which should allow to perform more precise and differential measurements.

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