OPEN HEAVY–FLAVOUR AND QUARKONIUM MEASUREMENTS WITH ALICE AT THE LHC

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The ALICE detector provides excellent capabilities to study heavy quark (i.e. charm and beauty) production in proton–proton (pp) and heavy–ion collisions (AA) at the Large Hadron Collider (LHC). In ALICE, open heavy–flavour hadron production is studied through the hadronic decays of D mesons at central rapidity ($|y| < 0.9$), and in the semi–leptonic decays of charm and beauty hadrons both at mid–rapidity and at forward rapidity ($2.5 < y < 4$). Quarkonia are measured in their di–electron and di–muon decay channels in the central barrel and in the muon spectrometer respectively, reaching in both cases zero transverse momentum. The latest results on open heavy–flavour and quarkonium production in pp ($\sqrt{s} = 2.76$ TeV and $\sqrt{s} = 7$ TeV) and PbPb ($\sqrt{s_{NN}} = 2.76$ TeV) collisions are presented.

1 Introduction

In ultra–relativistic nuclear collisions the nuclear matter is predicted to undergo a phase transition into a plasma of deconfined quarks and gluons (QGP). Heavy–flavour particles are unique probes to investigate the properties of such a medium, since they are predominantly produced via hard scatterings in the initial phase of the collision and therefore could experience the full evolution of the collision. Partons are expected to lose energy while traversing the strongly interacting medium via gluon radiation and elastic collisions with the partonic constituents [1]. One observable used to study the energy loss is the nuclear modification factor (R_{AA}), which is the ratio of particle yields in heavy–ion collisions compared to pp, scaled by the number of binary nucleon–nucleon collisions $\langle N_{\mathrm{coll}}\rangle$: $R_{\mathrm{AA}}(p_{\mathrm{T}}) = \left(\frac{1}{\langle N_{\mathrm{coll}}\rangle}\right) \cdot \left(\frac{dN_{\mathrm{AA}}}{dp_{\mathrm{T}}}\right) / \left(\frac{dN_{\mathrm{pp}}}{dp_{\mathrm{T}}}\right)$. A value of R_{AA} lower than unity indicates suppression. According to QCD, quarks should lose less energy than gluons, which have a larger colour charge. In addition the gluon radiation induced by the medium causes a mass dependence due to the so–called "dead–cone" effect, which predicts that small angle radiation is suppressed for heavy quarks [2]. Therefore, the following hierarchy should be observed in the measured R_{AA} : $R^{\pi}_{\mathrm{AA}} < R^{\mathrm{D}}_{\mathrm{AA}} < R^{\mathrm{B}}_{\mathrm{AA}}$.

Quarkonium states are expected to be suppressed in the QGP due to the color–screening [3]. However, at LHC energies it is predicted that due to their abundant production in the initial state, the charm quarks would (re)combine into charmonium states along the collision history [4,5] and/or at phase boundary by statistical hadronization [6,7]. This would result in an enhancement in the observed J/ψ yield.

Further insight into the interaction mechanisms of heavy quarks with the medium and the charmonium (re)generation can be obtained by studying the azimuthal anisotropy of heavy–flavour and quarkonium production in non–central heavy–ion collisions. In particular, the second order coefficient in the Fourier expansion of the azimuthal distribution of produced particles, commonly referred to as elliptic flow v_2, was measured for D mesons, heavy–flavour decay electrons and J/ψ's. If heavy quarks thermalize in the medium or if they interact strongly with it, the heavy–flavour hadrons and the J/ψ formed by (re)combination should inherit the medium azimuthal anisotropy.

2 Heavy–flavour measurements in ALICE

ALICE (A Large Ion Collider Experiment) is specifically optimized for the study of heavy–ion collisions at the LHC. Open and hidden heavy–flavour particles are studied in proton–proton (pp), lead–lead (Pb–Pb) and proton–lead (p–Pb) and their detection is performed at both central rapidity ($|\eta| < 0.9$) in the central barrel detectors and at forward rapidity ($2.5 < \eta < 4$) in the muon spectrometer.

A detailed description of ALICE set–up can be found in [8]. The central barrel includes the Inner Tracking System (ITS) surrounded by the Time Projection Chamber (TPC). Both are embedded in a magnetic field of 0.5 T and provide high precision in terms of vertex reconstruction and tracking of charged particles. The ITS is composed of six layers of high resolution silicon detectors with the two innermost layers consisting of Silicon Pixel Detectors (SPD). Hadron identification is provided by the ionization energy loss dE/dx in the TPC gas and information from the Time Of Flight (TOF) detector. Electrons are identified with TPC and TOF and at higher momenta using the ElectroMagnetic Calorimeter (EMCal) and the Transition Radiation Detector (TRD). In the forward region muon tracking and identification is provided by the muon spectrometer. This is equipped with a dipole magnet with a total field integral $\mathrm{B} \cdot \mathrm{l} = 3$ Tm. The spectrometer is composed of a passive absorber, a beam shield, five stations of cathode pad chambers (tracking stations), an iron wall, and two stations of resistive plate chambers (trigger stations).

Open heavy–flavour hadrons are reconstructed from their hadronic decays at mid–rapidity through the following decay channels $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$, $D^{*+} \to D^0\pi^+$, $D_s^+ \to K^+K^-\pi^+$ (and their charge conjugates) and from semi–leptonic decays both at mid–rapidity ($D, B \to e + X$) and forward–rapidity ($D, B \to \mu + X$).

Quarkonia measurements are performed in the central region via the dielectron channel ($J/\psi \to e^+e^-$) and in the forward rapidity region via the dimuon channel ($J/\psi \to \mu^+\mu$), reaching in both cases $p_\mathrm{T} = 0$.

3 Results

In the upper left–hand panel of Fig. 1 the nuclear modification factor for (prompt) D mesons (average of D^0, D^+ and D^{*+}) measured in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV is shown as a function of centrality for $6 < p_\mathrm{T} < 12$ GeV/c. Due to the limited statistics of the pp sample at the same energy the reference for Pb–Pb is obtained by applying a $\sqrt{s}$ scaling to the cross section measured at $\sqrt{s} = 7$ TeV. The scaling factor is obtained from FONLL pQCD calculations [9]. In the figure, the nuclear modification of non–prompt J/ψ from B decays, measured by the CMS Collaboration [10], is also shown. The comparison with D mesons indicates a different suppression for charm and beauty hadrons in central collisions, consistent with the expectation $R^D_{AA} < R^B_{AA}$. However, due to the different p_T and rapidity ranges, no firm conclusion can be drawn on this point.

A large suppression is also observed for heavy–flavour decay muons and electrons, at forward and central rapidity as shown for the centrality class 0–10% in the upper right–hand side of Fig. 1. Both lepton species exhibit a suppression by a factor of about 3 for $p_\mathrm{T} < 10$ GeV/c which decreases to ∼2 for electrons around $p_\mathrm{T} = 18$ GeV/c, which is a momentum range where beauty decays should be dominant. The cross section measured in pp collisions at $\sqrt{s} = 2.76$ TeV is used as the reference for the R_AA of heavy–flavour decay muons. For electrons, the reference was obtained with a pQCD–driven $\sqrt{s}$–scaling of the cross sections measured at $\sqrt{s} = 7$ TeV, as done in the case of the D mesons. For $p_\mathrm{T} > 8$ GeV/c, where the pp measurement is not

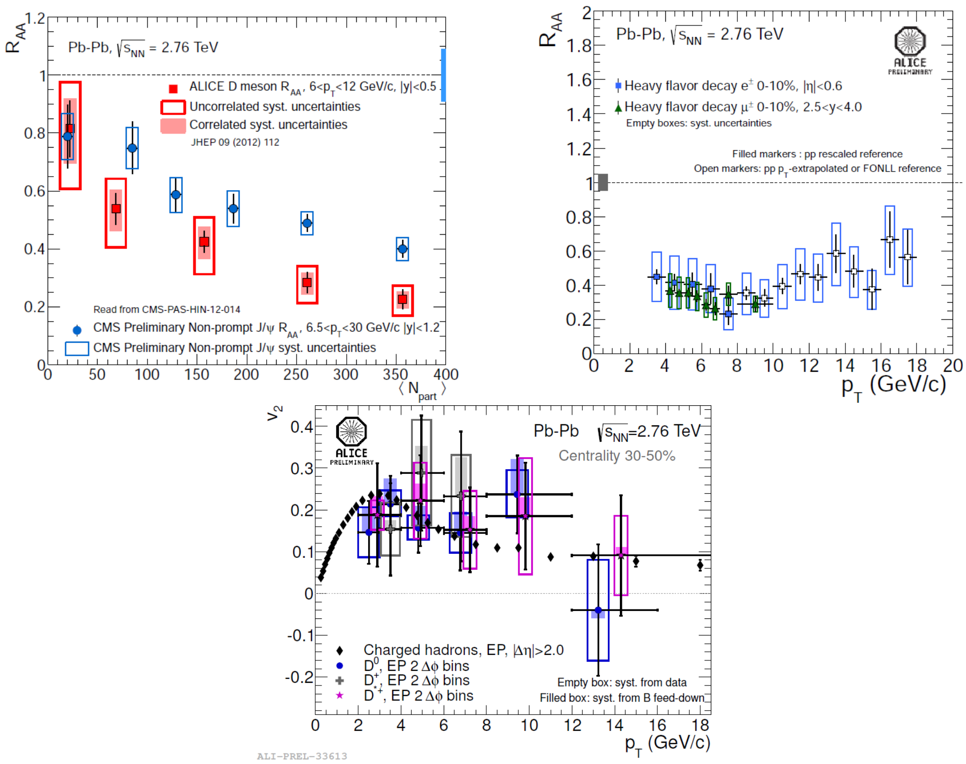

Figure 1: Upper left–hand side: average R_{AA} of D mesons as a function of centrality compared to that of non–prompt J/ψ from B decays. Upper right–hand side: Nuclear modification factors as a function of p_T for heavy–flavour decay muons at forward rapidity and electrons at central rapidity in central (0–10%) Pb–Pb collisions. Lower panel: D^0, D^+, D^{*+} v_2 in the 30–50% centrality. Black points show the v_2 for charged hadrons.

available, the cross section from FONLL was used as the reference.

The elliptic flow was measured for D mesons and for heavy–flavour decay electrons. The lower panel of Fig. 1 shows the D meson elliptic flow as a function of p_T for D^0, D^+ and D^{*+} mesons, measured in the centrality class 30–50%. All three D mesons agree within statistical uncertainties and show a non–zero v_2 resulting comparable in magnitude to that of charged hadrons [11] (also shown in the figure).

In Fig. 2, the nuclear modification factor of inclusive J/ψ in Pb–Pb collisions at the LHC is shown as a function of the collision centrality at central and forward rapidity in the upper left– and upper right–hand side, respectively. The pp data at $\sqrt{s}$ = 2.76 TeV were used as the reference at both central and forward rapidity. The large uncertainty on the (midrapidity) pp reference prevents a final conclusion on the question whether there is a significantly different behaviour at mid–rapidity with respect to forward rapidity. The comparison with the J/ψ R_{AA} measured at $\sqrt{s_{NN}}$ = 200 GeV by the PHENIX Collaboration suggests a stronger centrality dependence at lower energy, resulting in a sistematically lower R_{AA} for central events compared to ALICE data. Such a behaviour is indeed qualitatively expected by theoretical models that include J/ψ (re)generation. However, for a final interpretation a precise understanding of CNM effects, which will be addressed with the recent p–Pb data, is mandatory.

The elliptic flow of inclusive J/ψ was measured in the forward rapidity region. The elliptic flow v_2 as a function of p_T in the centrality interval 20–60% is shown in the lower panel of Fig. 2 and is compared to predictions from parton transport models [12,13]. A hint for a v_2 larger than zero is observed at intermediate p_T (2–4 GeV/c), whereas a similar measurement performed by the STAR collaboration at RHIC showed a value of v_2 compatible with zero in the p_T range between 2 and 10 GeV/c [14]. The magnitude of the effect is in agreement with transport model calculations that include regeneration effects. This result nicely complements the indications for

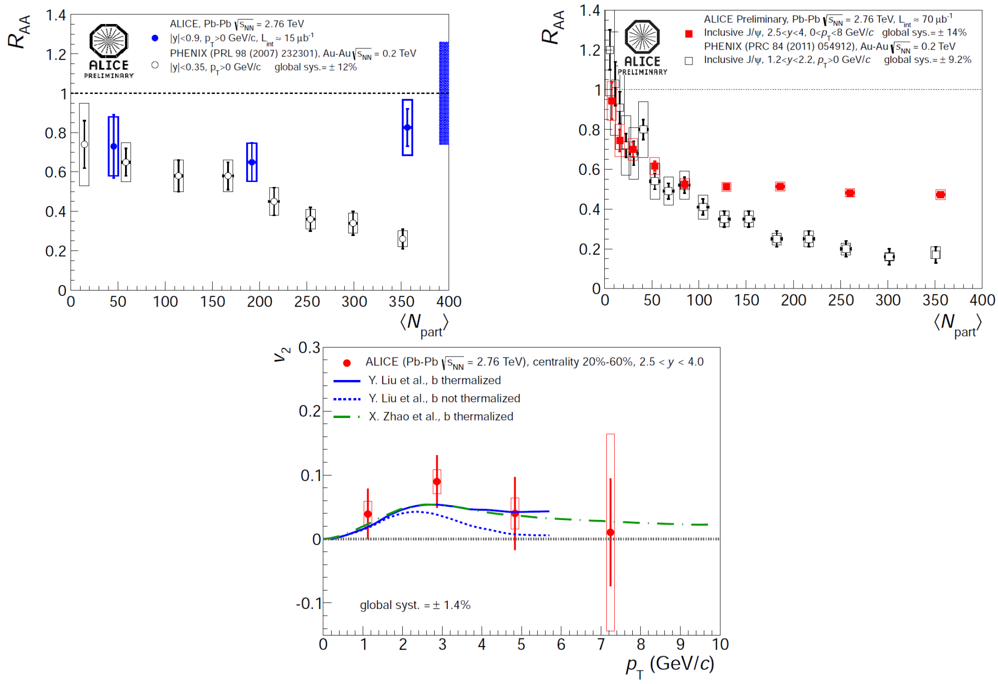

Figure 2: Upper panel: inclusive J/ψ R_{AA} as a function of centrality, expressed in terms of the number of participant nucleons, at central rapidity (left–hand panel) and forward rapidity (right–hand panel) respectively, compared with results from PHENIX. Lower panel: inclusive J/ψ v_2 measured in the 20–60% centrality class of Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, compared to predictions from parton transport models.

a coalescence contribution to the J/ψ production as obtained from the R_{AA} studies.

4 Conclusions

The ALICE Collaboration has measured the nuclear modification factor and elliptic flow for open heavy-flavour hadrons and quarkonia. Results obtained for D mesons and heavy–flavour decay leptons give an important insight on in–medium energy loss of heavy quarks and on their partecipation in the collective flow. The measured J/ψ R_{AA} and v_2 are found to be consistent with a scenario where (re)combination processes play a sizable role.

Data in proton–nucleus (p–Pb) collisions will help to understand cold nuclear matter effects, allowing a correct interpretation of the Pb–Pb results.

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