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ALICE results on heavy-flavour and quarkonium production at the LHC

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Abstract. In this paper, the ALICE results on heavy-flavour and quarkonium production in pp and Pb–Pb collisions at the LHC are discussed. The study of heavy flavours and quarkonia provides valuable information to characterize the hot medium created in heavy-ion collisions. Heavy-flavours are measured at mid- and forward-rapidity via their hadronic and semi-leptonic decays. J/ψ mesons are reconstructed from their e^+e^- and $\mu^+\mu^-$ decays at central and forward rapidity, respectively.

1 Introduction

Heavy-ion collisions at ultra-relativistic energies are aimed at studying nuclear matter under extreme conditions of temperature and energy density, where calculations of Quantum Chromodynamics (QCD) on the lattice predict the matter to be in a state where quarks and gluons are deconfined. Such a state is called Quark Gluon Plasma (QGP). Heavy-flavour hadrons, containing charm (c) or beauty (b), and quarkonia ($c\bar{c}$ and $b\bar{b}$ bound states) are effective probes of the medium formed in nucleus–nucleus collisions at high energy. Charm and beauty quarks, due to their large mass, are produced at the initial stage of the collision in high-virtuality scattering processes. Their production in nuclear (A–A) interactions is expected to scale with the number of nucleon–nucleon collisions occurring in the nucleus–nucleus collision (binary scaling). The experimental observable used to verify the binary collision scaling is the nuclear modification factor R_{AA}, defined as the ratio between the yields measured in heavy-ion and pp collisions after normalizing the A–A yield to the average number of nucleon-nucleon collisions, $\langle N_{coll}\rangle$:

$$R_{AA} = \frac{\text{Yield in AA}}{\langle N_{coll}\rangle \cdot \text{Yield in pp}}\,. \qquad (1)$$

$R_{AA} = 1$ indicates that the binary scaling holds, and that nucleus-nucleus collisions can be considered as a incoherent superposition of nucleon-nucleon interactions. It is anticipated that the medium created in A–A collisions affects the spectra of the originally produced heavy-quarks and the abundance of quarkonia, resulting in a break-down of the binary scaling and in a R_{AA} value different from unity.

Partons are expected to lose energy while traversing the strongly interacting medium, via gluon radiation and elastic collisions with the partonic constituents, resulting in a modification of the transverse momentum spectra of the observed hadrons in A–A with respect to pp collisions. $R_{AA} < 1$ is thus expected, and indeed observed, for hadrons with intermediate and large transverse momenta [1]. Radiative energy loss models predict that quarks lose less energy than gluons (that have a larger colour charge) and that the amount of radiated energy decreases with increasing quark mass. Hence, a hierarchy in the values of the nuclear modification factor is anticipated: the R_{AA} of B mesons should be larger than that of D mesons that should in turn be larger than that of light-flavour hadrons (e.g. pions), which mostly originate from gluon fragmentation. Finally, if in-medium recombination is the predominant hadronization mechanism at low momentum, the relative production of strange over non-strange charmed hadrons should be enhanced with respect to pp collisions [2].

Quarkonium states are expected to be suppressed ($R_{AA} < 1$) in the QGP, due to the color screening of the force which binds the $c\bar{c}$ (or $b\bar{b}$) state [3]. According to this scenario, quarkonium suppression is anticipated to occur sequentially according to the binding energy of each meson: strongly bound states, J/ψ and Υ(1S), should melt at higher temperatures with respect to more loosely bound states. For collisions at high $\sqrt{s}$, it is predicted that the abundant production of charm quarks in the initial state would lead to charmonium generation from (re)combination of c and $\bar{c}$ quarks along the collision history [4] and/or at the hadronization [5], resulting in an enhancement in the observed J/ψ yield. Moreover, in the J/ψ case, feed-down from higher quarkonium states and from beauty hadron decays has to be considered.

It is worth noting that other effects related to the presence of nuclei in the initial state (e.g. nuclear modifications of the Parton Distribution Functions, gluon saturation, break-up of quarkonia) can break the expected binary scaling. Hence, for the interpretation of the Pb–Pb results, data from proton-nucleus collisions are crucial because they allow one to disentangle these cold-nuclear-matter effects from those due to the hot QCD medium.

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Further insight into the interaction mechanisms of heavy quarks with the medium, the transport properties of the medium, and the charmonium (re)generation can be obtained by studying the azimuthal anisotropy of heavy-flavour and quarkonia in non-central heavy-ion collisions. The anisotropy of the momenta of the produced particles is characterized by the Fourier coefficients $v_n = \langle \cos[n(\varphi - \Psi_n)] \rangle$, where n is the order of the harmonic, φ is the particle azimuthal angle and Ψ_n is the azimuthal angle of the initial state spatial plane of symmetry. The second harmonic coefficient v_2 is called elliptic flow. Collective outward flow at low p_{T} ($< 4-5$ GeV/c) originates from the build-up of a collective motion of the medium constituents under the pressure gradients generated by the high energy densities reached in the collision. For non-central collisions, due to the almond-shaped overlap region, these pressure gradients are larger along the impact parameter than orthogonal to it, resulting in a v_2 larger than zero. 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. Another source of azimuthal anisotropy is the path-length dependence of parton energy loss, which causes, for non-central collisions, a v_2 larger than zero for hadrons notably seen in the high momentum region.

Measurements in pp collisions are needed as an essential reference for the nuclear modification factor. Furthermore, a precise determination of heavy flavour and quarkonium cross sections in pp provides a crucial test for their production models in elementary hadronic collisions at LHC energies.

2 ALICE experiment and data analysis

The ALICE detector [6] consists of a central barrel ($|\eta| < 0.9$), a muon spectrometer ($-4.0 < \eta < -2.5$) and a set of detectors for trigger and event characterization purposes. The central barrel detectors, located inside a solenoid magnet delivering a 0.5 T magnetic field, provide reconstruction and identification of charged particles, photons and jets. The muon spectrometer, equipped with a dipole magnet, is used for muon tracking and identification in the forward rapidity region. Pb–Pb collisions are classified according to their centrality, defined in terms of percentiles of the hadronic Pb–Pb cross section. For the data reported in this paper, the centrality intervals are determined from the distribution of the sum of the amplitudes of the signals in the VZERO detectors, which cover the pseudo-rapidity ranges $-3.7 < \eta < -1.7$ and $2.8 < \eta < 5.1$.

Heavy-flavour hadrons are reconstructed from their hadronic decays in the central rapidity region and from semi-leptonic decays both at mid- and forward-rapidity. In particular, charm mesons are reconstructed through their hadronic decays: $\mathrm{D}^0 \to \mathrm{K}^-\pi^+$, $\mathrm{D}^+ \to \mathrm{K}^-\pi^+\pi^+$, $\mathrm{D}^{*+} \to \mathrm{D}^0\pi^+ \to \mathrm{K}^-\pi^+\pi^+$, $\mathrm{D}_s^+ \to \phi\pi^+ \to \mathrm{K}^-\mathrm{K}^+\pi^+$ and their charge conjugates. The D meson yields are extracted from an invariant mass analysis of fully reconstructed decay topologies displaced with respect to the interaction vertex. Heavy-flavour decay electrons, $\mathrm{D/B} \to \mathrm{e} + \mathrm{X}$, are studied in $|\eta| < 0.8$. Their transverse momentum spectrum is obtained by subtracting from the inclusive electron spectrum a cocktail of the non-heavy-flavour electron sources. Beauty decay electrons are separated from charm decay electrons exploiting the larger lifetime of beauty hadrons that results in a larger separation from the interaction vertex. Alternatively, the fraction of beauty decay electrons is estimated from the azimuthal correlations of heavy-flavour decay electrons and charged hadrons. The width of the near-side peak is indeed larger for beauty than charm hadron decays. Heavy-flavour decay muons are reconstructed in the muon spectrometer ($-4.0 < \eta < -2.5$). The background contribution, mainly from decays of light hadrons, is evaluated with Monte Carlo simulations in pp collisions, and from the extrapolation of the π and K yields measured at mid-rapidity in Pb–Pb collisions. J/ψ mesons are reconstructed down to zero p_{T} in the central barrel ($|y| < 0.9$) through the $\mathrm{e}^+\mathrm{e}^-$ decay channel, and in the muon spectrometer at forward rapidity ($-4 < y < -2.5$) through their $\mu^+\mu^-$ decays. The signal extraction is performed by analyzing the di-lepton invariant mass distributions. In the di-electron channel case, the J/ψ raw yield is extracted via bin counting after subtracting the combinatorial background, which is evaluated using the event mixing technique. In the di-muon channel case, the J/ψ signal is extracted by fitting the invariant mass distribution of opposite sign muon pairs, using a phenomenological shape for the background, and a Crystal Ball shape for the signal.

The results shown in this paper come from the analysis of the pp ($\sqrt{s}$ of 7 and 2.76 TeV) and Pb–Pb ($\sqrt{s_{\mathrm{NN}}}$=2.76 TeV) samples collected in the 2010 and 2011 data taking periods. Similar trigger strategies were used for pp and Pb–Pb collisions. Here, we give some details for the heavy-ion running case. For the measurement in the central barrel, hadronic interaction events were collected with a minimum bias condition (MB), which was based on the signals in the two VZERO detectors. The integrated luminosity collected with the MB trigger during the 2010 Pb–Pb run was of about 2 $\mu\mathrm{b}^{-1}$. During the 2011 data taking period with Pb–Pb collisions, an online selection based on the VZERO signal amplitude was used to enhance the samples of very central and semi-central collisions. This allowed the collection of an integrated luminosity of about 28 $\mu\mathrm{b}^{-1}$ for the 10% most central collisions and of about 6 $\mu\mathrm{b}^{-1}$ in the 10–50% centrality range. In addition, triggers based on the electromagnetic calorimeter (EMCAL) were also used in 2011 to enhance the electron sample ($L_{\mathrm{int}} \approx 22\,\mu\mathrm{b}^{-1}$). For the $\mathrm{J}/\psi \to \mu^+\mu^-$ and heavy-flavour decay muon analyses, specific muon triggers were used, based on the request of one or two candidate muons in the forward spectrometer in addition to the MB condition. The results for heavy-flavour decay muons are taken from the Pb–Pb 2010 sample and they correspond to an integrated luminosity of 2.7 $\mu\mathrm{b}^{-1}$. The Pb–Pb results for quarkonia at forward rapidity refer to the 2011 data sample, collected with a di-muon trigger and corresponding to an integrated luminosity of about 70 $\mu\mathrm{b}^{-1}$.

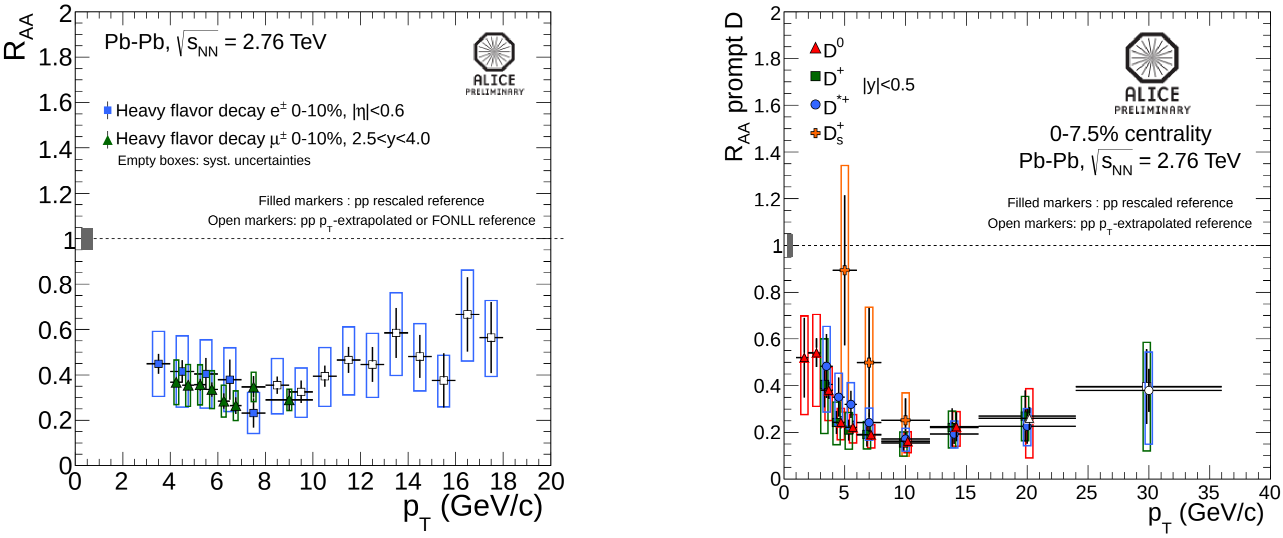

Figure 1. R_{AA} as a function of p_{T} for central Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$=2.76 TeV. Left: Heavy-flavour decay electrons at mid-rapidity and heavy-flavour decay muons at forward rapidity. Right: Prompt D^0, D^+, D^{*+} and D_s^+ mesons at central rapidity. The boxes around the points are the uncorrelated systematic uncertainties, the global systematic uncertainties are shown as filled boxes at $R_{\mathrm{AA}} = 1$.

3 Results

3.1 Heavy flavours

The p_{T}-differential production cross sections of prompt D^0, D^+, D^{*+} and D_s^+, heavy-flavour decay electrons, beauty-decay electrons, and heavy-flavour decay muons were measured in pp collisions at $\sqrt{s}$ = 7 TeV [7–11]. Measurements at $\sqrt{s}$ = 2.76 TeV were also published for heavy-flavour decay muons and charmed mesons (D^0, D^+ and D^{*+}) [12, 13]. The results are consistent within uncertainties with perturbative QCD (pQCD) predictions. Furthermore, at $\sqrt{s}$ = 7 TeV, the D^0, D^+ and D^{*+} yields were measured as a function of the charged multiplicity of the event. The preliminary results show an approximately linear increase of the D meson yield with the event multiplicity, similar to that observed for J/ψ mesons [14].

The nuclear modification factors of heavy-flavour hadrons in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 2.76 TeV were published for heavy-flavour decay muons [13] and for D^0, D^+ and D^{*+} mesons [15] as a function of p_{T} in different centrality classes. The $R_{\mathrm{AA}}(p_{\mathrm{T}})$ of heavy-flavour decay muons is shown in the left-hand panel of Fig. 1 for the 10% most central collisions. The cross section measured in pp collisions at $\sqrt{s}$ = 2.76 TeV is used as reference for the R_{AA}. The nuclear modification factor of heavy-flavour decay electrons, measured in the 0-10% centrality class using the 2011 Pb–Pb data sample with EMCAL triggers is also shown in Fig. 1(left). In this case, the reference for the R_{AA} was obtained by a pQCD-driven $\sqrt{s}$-scaling of the pp cross sections measured at $\sqrt{s}$ = 7 TeV. The scaling factor was defined as the ratio of the FONLL [16] cross sections at the two energies, and its uncertainty was evaluated from the envelope of the results obtained by varying the factorization and renormalization scales and the heavy-quark masses in the pQCD calculation. For $p_{\mathrm{T}} > 8$ GeV/c, where the pp measurement is not available, the cross section from FONLL was used as reference. The heavy-flavour electron R_{AA} shows a suppression of the yield in Pb–Pb collisions in the transverse momentum range $3 < p_{\mathrm{T}} < 18$ GeV/c. In particular, for $3 < p_{\mathrm{T}} < 10$ GeV/c the suppression amounts to a factor of 1.5–3. Heavy-flavour decay electrons and muons, measured in two different rapidity intervals, show a similar suppression and p_{T} dependence.

In the right-hand panel of Fig. 1, the $R_{\mathrm{AA}}(p_{\mathrm{T}})$ of prompt D mesons, measured in $|y| < 0.5$ in the 0–7.5% centrality class with the 2011 data sample, is shown. The measurement extends over the transverse momentum range 1–36 GeV /c. The pp reference, due to the limited statistics of the pp sample collected at $\sqrt{s}$ = 2.76 TeV, was computed with a pQCD-driven $\sqrt{s}$-scaling of the cross sections measured at $\sqrt{s}$ = 7 TeV, as in the case of heavy-flavour decay electrons. FONLL predictions were also used for a p_{T}-extrapolation of the measured cross sections to the highest p_{T} bin where the pp measurement is not available. The nuclear modification factors of D^0, D^+ and D^{*+} mesons agree within uncertainties and show a suppression of a factor of 5 at $p_{\mathrm{T}} \approx 10$ GeV/c. The D meson R_{AA} is similar both in magnitude and p_{T} dependence to that of charged particles and pions. A hint for $R^{\mathrm{D}}_{\mathrm{AA}} > R^{\mathrm{charged}}_{\mathrm{AA}}$ is observed, although not conclusive within the present uncertainties [15]. The first measurement of D_s^+ R_{AA} in heavy-ion collisions is also shown. In the highest measured p_{T} bin (8–12 GeV /c), the R_{AA} of D_s^+ mesons is compatible with that of non-strange charmed mesons. At lower p_{T}, D_s^+ R_{AA} seems to increase, but with the current statistical and systematic uncertainties no conclusion can be drawn on the expected enhancement of D_s^+ mesons with respect to non-strange D mesons at low p_{T}, due to c-quark coalescence with the abundant strange quarks [2].

The effect of nuclear shadowing on heavy-flavour R_{AA} was estimated using the NLO pQCD calculations with EPS09NLO [17] parametrization for the nuclear modification of the parton distribution functions. The measured

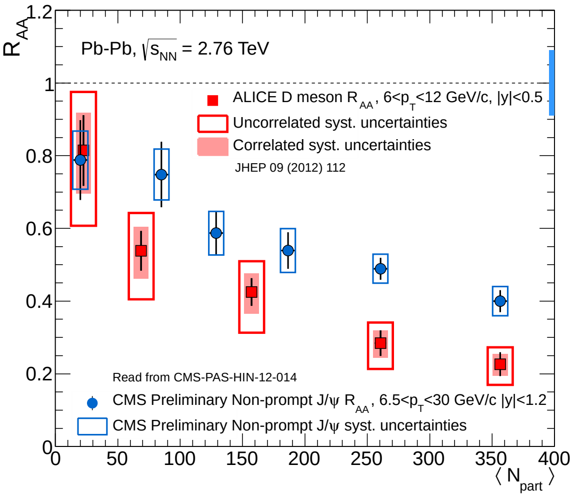

Figure 2. Average R_{AA} of D^0, D^+ and D^{*+} as a function of centrality measured by ALICE compared to that of J/ψ from B decays from CMS.

R_{AA} of D mesons and heavy-flavour decay leptons for $p_T > 4$ GeV/c can not be explained by nuclear shadowing only, indicating that the strong suppression observed in the data is a final-state effect, predominantly due to in-medium parton energy loss. Theoretical models based on different implementations of radiative and collisional parton energy loss can describe within uncertainties the measured R_{AA} of D mesons, heavy-flavour decay leptons, as well as that of light-flavour hadrons [15].

The R_{AA} was measured also as a function of centrality for D mesons in $|y| < 0.5$ and $6 < p_T < 12$ GeV/c. The result is shown in Fig. 2 together with the R_{AA} of non-prompt J/ψ (i.e. J/ψ from decays of B mesons) measured by the CMS Collaboration for $p_T > 6.5$ GeV/c and $|y| < 1.2$. The larger R_{AA} of J/ψ from beauty decays with respect to that of prompt D mesons is a first indication for the b quarks to lose less energy than the c quarks in the coloured medium, as anticipated by energy loss models.

The measurement of the elliptic flow v_2 was carried out for D mesons and heavy-flavour decay electrons at central rapidity using the Pb–Pb data sample collected in 2011 [18]. The elliptic flow was measured as a function of p_T in the transverse momentum range $1.5 < p_T < 13$ GeV/c for heavy-flavour decay electrons in the 20–40% centrality class, and in the range $2 < p_T < 18$ GeV/c for prompt D^0, D^+ and D^{*+} mesons in the 30–50% centrality class. The $v_2(p_T)$ of the three meson species are in agreement within uncertainties. At low p_T, a value of v_2 larger than zero, with a 3σ significance, is observed both for heavy-flavour decay electrons in the range $2 < p_T < 3$ GeV/c, and for prompt D mesons in $2 < p_T < 6$ GeV/c. These results indicate that the interactions with the medium constituents transfer to charm quarks information on the azimuthal anisotropy of the system. Theoretical models implementing heavy-quark transport in the medium can compute the azimuthal anisotropy of heavy-flavour mesons and their decay electrons. The simultaneous comparison of data and calculations for R_{AA} and v_2 reveals that it is challenging for the models to describe at the same time the large suppression in central collisions and their anisotropy in non-central collisions.

3.2 Quarkonia

Inclusive production cross sections of J/ψ ($d^2\sigma/dydp_T$) were measured at both central and forward rapidity for pp collisions at $\sqrt{s}$ = 7 TeV [19]. At $\sqrt{s}$ = 2.76 TeV a differential study was possible only in the forward region, while at midrapidity, due to the small MB integrated luminosity, a p_T-integrated cross section was measured [20]. These results, obtained at the same centre-of-mass energy of the Pb–Pb collisions, are used as reference in the R_{AA} calculation. At $\sqrt{s}$ = 7 TeV, the inclusive J/ψ yield was studied as a function of the charged multiplicity measured at central rapidity. The results show an approximately linear increase of the J/ψ yield with the charged multiplicity [14]. This result might either indicate that J/ψ production in pp collisions is connected with a strong hadronic activity, or that multi-parton interactions also affect the hard momentum scales relevant for quarkonia production.

In Fig. 3, the nuclear modification factor of inclusive J/ψ (i.e. without subtracting those coming from feed-down from higher charmonium states and beauty decays) for Pb–Pb collisions at the LHC is displayed as a function of collision centrality and compared to the results obtained by PHENIX at RHIC. There is a clear evidence for a smaller J/ψ suppression at the LHC than at RHIC. Furthermore, the R_{AA} measured in ALICE shows a suppression of J/ψ yield in Pb–Pb almost independent of centrality, while lower energy results show a suppression that increases from peripheral to central collisions. Such a behaviour is indeed predicted by partonic transport models that include J/ψ (re)generation due to recombination of $c\bar{c}$ pairs along the medium evolution [4]. A similar behaviour is obtained by the statistical model, where the J/ψ yield is determined by the chemical freeze-out conditions and by the abundance of $c\bar{c}$ pairs [5, 21].

The inclusive J/ψ R_{AA} was also measured in the $\mu^+\mu^-$ channel at forward rapidity in bins of transverse momentum [22]. A larger R_{AA} is observed at low p_T with respect to high p_T, in particular for central collisions. This is expected in partonic transport models because the impact of (re)generation mechanisms is more important at low momentum [4]. Similar conclusions are obtained by measuring the p_T dependence of R_{AA}. A measurement of the rapidity dependence of inclusive J/ψ R_{AA} was also carried out. An increase of the suppression with increasing y is observed. This can be accounted for by a larger contribution from (re)combination at central rapidity, where the $c\bar{c}$ density is larger, and/or by a different size of cold nuclear matter effects at different rapidities.

The elliptic flow of inclusive J/ψ was measured in the forward rapidity region through the di-muon decay channel. Theoretical models including charmonium (re)generation predict a non-zero v_2 for J/ψ at intermediate p_T. Indeed, if (re)generation effects are sizable, and charm quarks participate in the collective motion of the expanding medium, the J/ψ formed from $c\bar{c}$ (re)combination

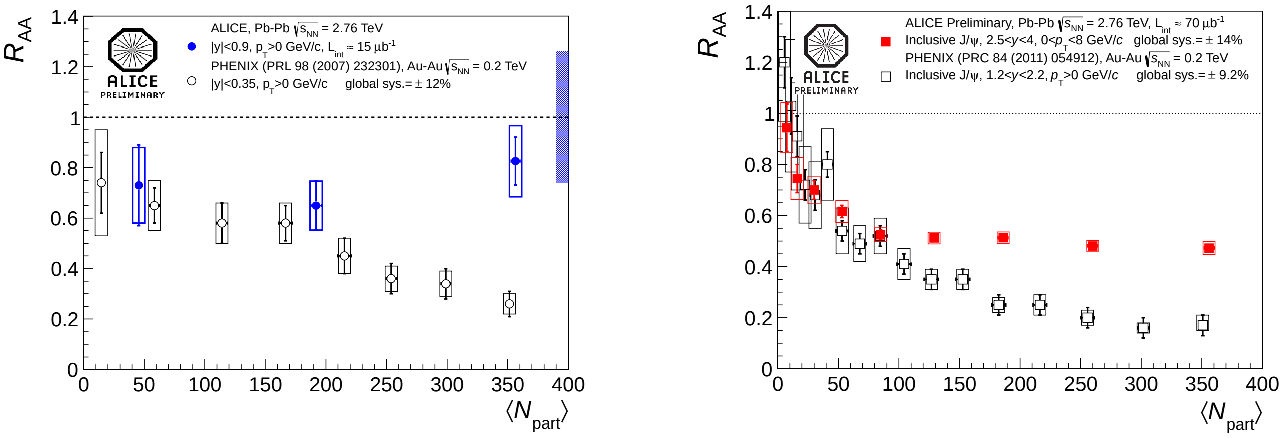

Figure 3. Inclusive J/ψ R_{AA} as a function of centrality, expressed in terms of the number of participant nucleons, compared with results from PHENIX. Left: central rapidity. Right: forward rapidity. The boxes around the points are the uncorrelated systematic uncertainties, the global systematic uncertainties are shown as filled boxes at R_{AA} = 1.

would inherit the azimuthal anisotropy of their constituent quarks. For collisions in the centrality interval 20–60%, a hint for a v_2 larger than zero is observed at intermediate p_T (2–4 GeV/c) [22]. It is interesting to notice that a similar measurement carried out at RHIC energy by the STAR Collaboration showed a value of v_2 compatible with zero in the p_T range between 2 and 10 GeV/c [23].

4 Conclusions

The ALICE Collaboration has carried out a rich set of measurements of open heavy-flavour and inclusive J/ψ production in pp and Pb-Pb collisions at the LHC. Important insights on the in-medium energy loss of heavy quarks and their participation in the collective flow were obtained by measuring the nuclear modification factor and the elliptic flow of D mesons and heavy-flavour decay leptons. 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. The forthcoming p–Pb data sample will help to quantify shadowing effects for both open heavy flavours and charmonia, and to study the J/ψ break-up probability via interactions with cold nuclear matter.

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