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Heavy-flavor measurements in heavy-ion collisions with the ALICE experiment

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Abstract

Open and hidden heavy-flavor measurements with the ALICE experiment at the LHC are reported. Emphasis goes to the recent results in p–Pb and Pb–Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 and 2.76 TeV respectively. Heavy-flavor measurements are presented in the form of either the ratio of the production cross sections in heavy-ion and pp collisions normalized by the average number of nucleon-nucleon collisions, or the per-event yields as a function of charged-particle multiplicity. Possible interpretations of these results in pp, p–Pb or Pb–Pb collisions in terms of multi-parton interactions, gluon saturation, initial or final state energy loss, system collective motion, color-charge screening or recombination of uncorrelated quarks are discussed.

Keywords: Heavy flavor, Charm, Quarkonia, Heavy Ion, QGP, LHC

1. Introduction

Heavy-flavor hadrons containing charm or beauty quarks provide information on the different mechanisms at play in hadronic collisions. The large mass of heavy quarks makes their production cross section calculable via perturbative Quantum ChromoDynamics (pQCD). The non-perturbative hadronization phase, i.e. the transition of heavy quarks to hadrons, is mimicked via the fragmentation functions. Heavy-flavor production measurements in pp collisions at the LHC are therefore a test of pQCD and collinear or $k_{\rm T}$ factorization calculations in the high-energy regime [1–6]. Heavy-quark production in a nuclear environment, i.e. in p–Pb collisions, is influenced by the modification of the parton distributions in nuclei. The saturation of low fractional momentum (x) gluons becomes important at the LHC. These effects are modeled by either phenomenological modifications of the Parton Distribution Functions in nuclei (nPDFs) [7], or the Colour Glass Condensate (CGC) theory [8, 9]. Heavy quarks (Q) produced in nuclei might also undergo inelastic collisions causing a transverse momentum broadening [10, 11], or lose energy radiating gluons either before or after the $Q\bar{Q}$ pair is formed [12, 13]. In addition, in Pb–Pb collisions the formation of hot and dense QCD matter might also alter parton momentum distributions. Heavy quarks traversing extremely dense QCD matter lose energy via elastic or inelastic interactions with the medium constituents. Theoretical calculations of the radiative contribution predict it to be proportional to the Casimir coupling factor, implying a smaller energy loss for quarks than gluons [14–17]. Moreover, gluon bremsstrahlung off heavy quarks is expected to be suppressed at angles smaller than the ratio of the quark mass to its energy [18]. At a given parton energy, beauty quarks should then lose less energy than charm quarks. The formation of bound $Q\bar{Q}$ (quarkonia) states is suppressed in this medium at extremely high temperature due to the Debye-like color-charge screening [19]. It has also been hypothesized that if heavy quarks are abundant in the medium, uncorrelated pairs could recombine into quarkonia bound states in the QGP or at the hadronization phase [20, 21]. In addition, if heavy quarks interact strongly with the medium or hadronize in it, they should inherit its azimuthal anisotropy [22]. This would result in an azimuthal anisotropy of both open and hidden heavy-flavor production.

In this report, open heavy-flavor measurements

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(Sec. 2) concern heavy-flavor decay leptons (electrons and muons) and prompt D mesons reconstructed via their hadronic decays. Hidden heavy-flavor results (Sec. 3) refer to J/ψ, $\psi(2S)$ and Υ mesons. J/ψ's are reconstructed both via their dielectron and dimuon decays, while $\psi(2S)$ and Υ are measured from their dimuon decay. These analyses exploit different detectors of the ALICE apparatus. The central barrel detector ($|\eta| < 0.9$) is equipped, among others, with an Inner Tracking System and a Time Projection Chamber that allow vertex finding, and particle tracking and identification. Their abilities are complemented by the Time-Of-Flight detector, the Transition Radiation Detector and the Electromagnetic Calorimeter that contribute to e/p/K/π particle identification. The forward muon spectrometer ($-4.0 < \eta < -2.5$) consists of a set of absorbers and a Muon Tracking and Trigger system that make possible muon reconstruction and identification. The VZERO scintillator arrays ($-3.7 < \eta < -1.7$ and $2.8 < \eta < 5.1$) provide the information needed for trigger and centrality determination. The ALICE experimental setup is completed with a set of detectors that are not used in the analyses reported here.

Focus is given to the results obtained from the data samples of p–Pb and Pb–Pb collisions, at $\sqrt{s_{\rm NN}}$ = 5.02 TeV and 2.76 TeV respectively, collected during the LHC Run-I. Most of the results are presented here in the form of the nuclear modification factor, $R_{\rm AB}$, i.e. the relative particle production rates in heavy-ion, or proton-ion, and pp data per nucleon-nucleon collision:

$$R_{\rm AB}(p_{\rm T}) = \frac{1}{\langle T_{\rm AB}\rangle} \cdot \frac{{\rm d}N_{\rm AB}/{\rm d}p_{\rm T}}{{\rm d}\sigma_{\rm pp}/{\rm d}p_{\rm T}} \quad (1)$$

where ${\rm d}N_{\rm AB}/{\rm d}p_{\rm T}$ represents the particle yield in AB collisions, ${\rm d}\sigma_{\rm pp}/{\rm d}p_{\rm T}$ is the production cross section in pp collisions, and $\langle T_{\rm AB}\rangle$ is the nuclear overlap function of nucleus A, or proton, and nucleus B.

2. Open heavy-flavor production

The transverse momentum ($p_{\rm T}$) and rapidity (y) differential heavy-flavor decay lepton and prompt D-meson production was studied in p–Pb collisions [23]. In particular, Fig. 1 presents the heavy-flavor decay muon $R_{\rm pPb}$ as a function of $p_{\rm T}$. Forward (backward) rapidity measurements refer to data collected in the p(Pb)-going direction and probe the Pb nuclei Bjorken-x ($x_{\rm Bj}$) of $O \sim 10^{-5}(10^{-2})$, while mid-rapidity data probe $x_{\rm Bj}$ values of $O \sim 10^{-4}$. $R_{\rm pPb}$ is compatible with unity at high $p_{\rm T}$. In particular, prompt D mesons at mid-rapidity with $p_{\rm T} > 2-3$ GeV/c, and heavy-favor decay muons

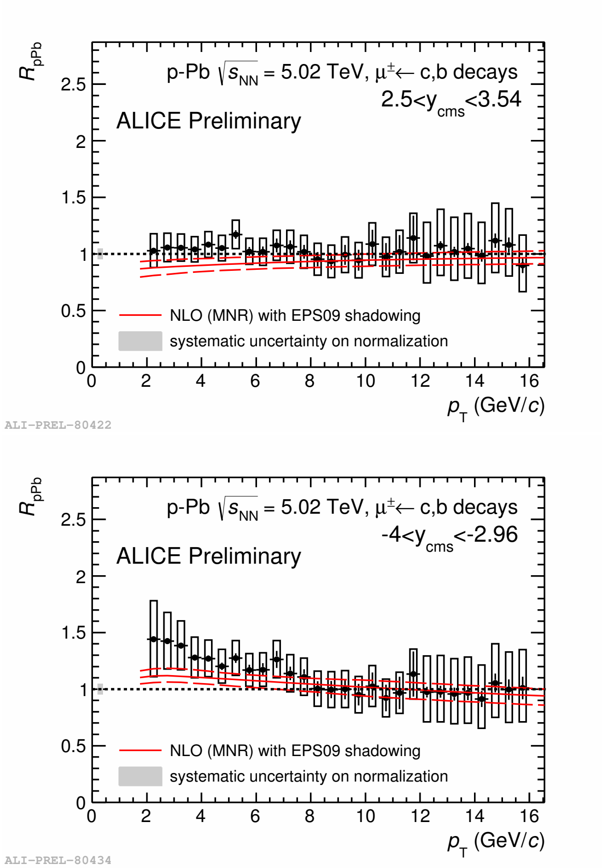

Figure 1: $R_{\rm pPb}$ of heavy-flavor decay muons as a function of $p_{\rm T}$ at forward and backward rapidity in p–Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV, as compared to pQCD calculations at NLO (MNR) [24] with the EPS09 nPDF parameterization [7].

at forward (backward) rapidity with $p_{\rm T} > 2-3$ GeV/c ($p_{\rm T} > 6-8$ GeV/c) show $R_{\rm pPb} \sim 1$. The results are in good agreement with models considering: *(i)* pQCD calculations with EPS09 shadowing [7, 24], *(ii)* CGC estimates [9], *(iii)* calculations including $k_{\rm T}$-broadening, nuclear energy loss and nPDFs [12]. The calculations of *(i)* are available for mid, forward and backward rapidities, while *(ii)* and *(iii)* were only evaluated at mid rapidity. As a consequence, initial-state effects on open heavy-flavor production are expected to be small at high $p_{\rm T}$ in heavy-ion collisions.

To complete this picture, open heavy-flavor production has also been studied in p–Pb collisions as a function of the multiplicity of particles produced in the collision. As an example, Fig. 2 shows the per-event yield of prompt D mesons ($|y| < 0.5$) as a function of the charged-particle multiplicity at mid-rapidity ($|\eta| < 1$) in pp collisions at $\sqrt{s}$ = 7 TeV and p–Pb collisions at

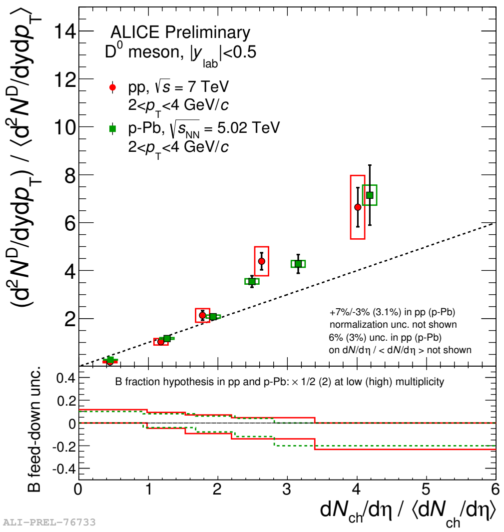

Figure 2: D^0 yields ($|y| < 0.5$) per event as a function of charged-particle multiplicity at mid rapidity ($|\eta| < 1$) in pp collisions at $\sqrt{s}$ = 7 TeV and p–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV. Both the D-meson yields and the charged-particle multiplicity are shown normalized to their multiplicity integrated values.

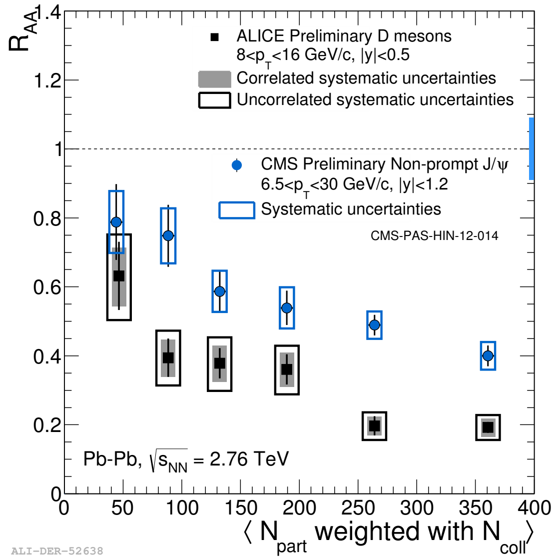

Figure 3: R_{AA} of prompt D mesons, measured by ALICE, and non-prompt J/ψ, measured by CMS [27], in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV as a function of the collision centrality, expressed in terms of the number of nucleons participating in the interaction.

$\sqrt{s_{NN}}$ = 5.02 TeV for 2 < p_T < 4 GeV/c. In this representation, both the D-meson yields and the charged-particle multiplicity are normalized to their multiplicity integrated values. The relative D-meson yields increase with the relative charged-particle multiplicity. It has been conjectured that the origin of such behavior in pp data could be due to a larger contribution of Multi-Parton Interactions (MPIs) [4] in high-multiplicity events. Alternative scenarios consider percolation calculations or an increase of the QCD radiation associated to short distance processes. A similar trend is observed in p–Pb data, which remains to be understood. Two competing mechanisms could be at play, either the MPI's or the larger number of binary nucleon-nucleon collisions occurring in a high multiplicity p–Pb interaction.

Open heavy-flavor R_{AA} measurements were also performed in Pb–Pb collisions as a function of p_T and the collision centrality [25, 26]. Figure 3 displays the ALICE prompt D meson and the CMS non-prompt J/ψ [27] R_{AA} at high p_T as a function of centrality, represented by the average number of nucleons participating in the interaction. Open heavy-flavor production is suppressed at high p_T in Pb–Pb reactions with respect to the binary scaled pp production cross section, and the magnitude of this suppression increases from peripheral to central events. This confirms that open heavy-flavor production is affected by partonic energy loss, and the magnitude of the suppression depends on the medium density, increasing from peripheral to central collisions. In addition, in the semi-central and most central events high p_T non-prompt J/ψ are less suppressed than prompt D mesons. Although in those measurements the p_T and y intervals are different, the probed average p_T of D and B hadrons is similar. This observation is consistent with various calculations including the quark-mass dependence of the energy loss [14–18].

The azimuthal anisotropy of particle production in Pb–Pb collisions has also been quantified evaluating the second coefficient of the Fourier decomposition of the azimuthal distribution, v_2. Heavy-flavor decay lepton v_2 results at mid and forward rapidity in semi-central Pb–Pb collisions are shown in Fig. 4 as a function of p_T. The v_2 values are similar at mid and forward rapidity. A positive v_2 value is observed at intermediate p_T, 1.5 < p_T < 4 GeV/c, that is consistent with the positive prompt D-meson v_2 in a comparable kinematic range [28, 29]. The magnitude of prompt D-meson v_2 at intermediate p_T is also comparable to the charged-particle v_2, which suggests that low-p_T charm quarks take part in the system collective motion. The high-p_T v_2 results are expected to convey information on the path-length dependence of the energy loss, but the current measurement precision is limited by the statistics.

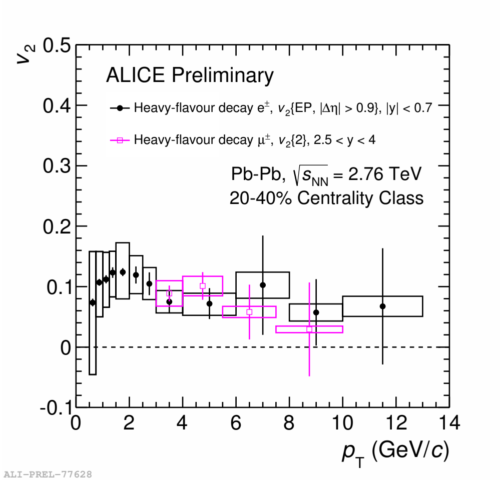

Figure 4: Heavy-flavor decay electron ($|y| < 0.7$) and muon ($2.5 < y < 4$) azimuthal anisotropy, v_2, for Pb–Pb collisions at $\sqrt{s_{\rm NN}}$ = 2.76 TeV in the 20–40% centrality class as a function of the lepton $p_{\rm T}$.

3. Hidden heavy-flavor production

Charmonium ($c\bar{c}$ bound state) production has been measured in p–Pb collisions. The measurement of the J/ψ yield has been carried out in the dimuon and di-electron decay channels as a function of rapidity [30]. The $p_{\rm T}$ dependence of the forward and backward rapidity yields has also been studied [31]. Figure 5 shows the J/ψ $p_{\rm T}$-integrated $R_{\rm pPb}$ as a function of rapidity. Negative rapidity J/ψ originate from partons with large $x_{\rm Bj}$ values in the Pb nucleus and exhibit an $R_{\rm pPb}$ close to unity. On the contrary, positive rapidity J/ψ correspond to partons with small $x_{\rm Bj}$ values in the Pb nucleus, which manifests on $R_{\rm pPb}$ values smaller than unity. The results are compared to four different theoretical calculations including either one or a combination of: EPS09 nPDF parameterization, nuclear absorption, coherent parton energy loss in nuclei, or the CGC framework [7, 8, 13]. The measurements are well described by either of these calculations except that of the CGC, which can not give predictions at negative rapidities and seems to underestimate the positive rapidity $R_{\rm pPb}$ value.

$\psi(2S)$ measurements have also been examined as a function of y and $p_{\rm T}$ in p–Pb collisions [31]. Figure 6 presents the double ratio of the $\psi(2S)$ over J/ψ production cross sections in p–Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV and pp collisions at $\sqrt{s}$ = 7 TeV as a function

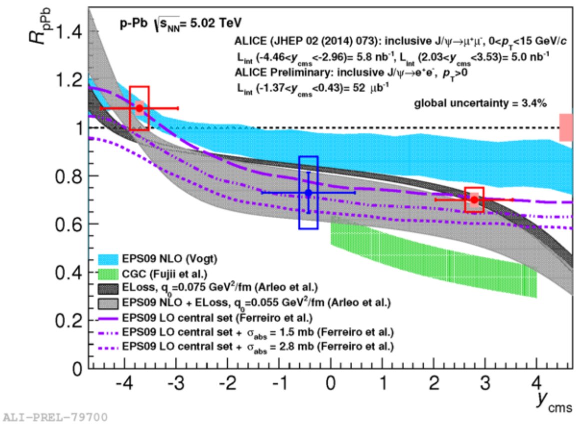

Figure 5: J/ψ $p_{\rm T}$-integrated $R_{\rm pPb}$ as a function of rapidity in p–Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV [30].

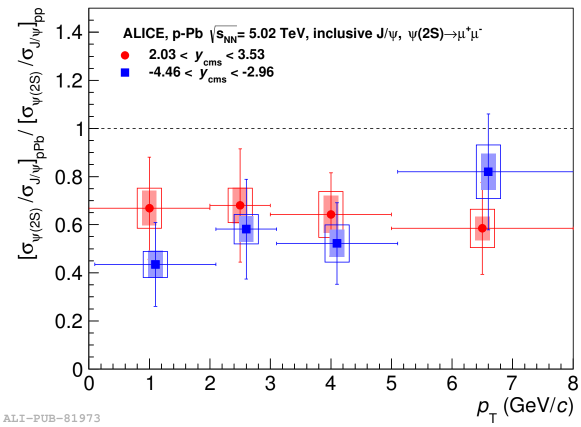

Figure 6: Double ratio of the production cross section of $\psi(2S)$ over J/ψ in p–Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV and pp collisions at $\sqrt{s}$ = 7 TeV as a function of $p_{\rm T}$ in two rapidity intervals [31].

of $p_{\rm T}$ in two rapidity intervals. While initial-state models predict this double ratio to be equal to one within a few percent due to the slightly different $x_{\rm Bj}$ involved, the measurements evidence that the double ratio is below unity without a visible $p_{\rm T}$ dependence. This observation presumably points to unexpected final-state effects that could differentiate between J/ψ and $\psi(2S)$ in p–Pb collisions.

J/ψ production rates have also been measured in Pb–Pb collisions at $\sqrt{s_{\rm NN}}$ = 2.76 TeV. J/ψ $R_{\rm AA}$ was scrutinized as a function of y, $p_{\rm T}$, collision centrality and its azimuthal anisotropy [32–34]. Figure 7 (top) reports the $p_{\rm T}$-integrated J/ψ $R_{\rm AA}$ as a function of centrality. J/ψ production is suppressed in the most central Pb–Pb collisions at the LHC, but the suppression is smaller than the one measured at RHIC [35]. The p_T dependence of J/ψ R_{AA} in the most central collisions is shown in Fig. 7 (bottom). While at RHIC there is no visible p_T dependence up to $p_T \sim 5$ GeV/c, at the LHC there is a significant deviation, the low p_T J/ψ's being less suppressed than the high p_T ones, and the high p_T ones showing a similar suppression than at RHIC. J/ψ azimuthal anisotropy was discussed in reference [34], suggesting positive v_2 values in semi-central collisions at intermediate p_T. The current partial understanding of these results assumes a large charmonium suppression in the hot and dense QCD matter, and considers that at high energies another mechanism counterbalances this suppression at low p_T. A possible scenario for this offset is the recombination of uncorrelated c and $\bar{c}$ quarks either in the QGP or at hadronization.

The production of bottomonium ($b\bar{b}$ bound state) has also been measured at forward rapidity in Pb–Pb collisions. Υ yields were measured in the dimuon decay channel as a function of rapidity and centrality. Υ and J/ψ R_{AA} are compared in Fig. 8 as a function of rapidity. Υ production is more suppressed than J/ψ production. In addition, the comparison to CMS Υ results [36] suggests a slightly larger suppression at forward than at mid-rapidity. J/ψ and Υ p_T-integrated R_{AA} show a similar rapidity dependence. The state-of-the-art model calculations expect a smaller contribution of recombination processes for Υ than for J/ψ production. These models are therefore not able to reproduce the Υ R_{AA} rapidity trend and underestimate its suppression at forward rapidity.

4. Summary

Heavy-flavor measurements in p–Pb and Pb–Pb collisions at the LHC with the ALICE detector at $\sqrt{s_{NN}}$ = 5.02 and 2.76 TeV, respectively, have been summarized.

Open heavy-flavor production in p–Pb collisions is described reasonably well by pQCD calculations including initial-state effects. However, a complete modeling of all observables might require to consider, in addition to nPDF or CGC calculations, the possible influence of other effects such as: quark fragmentation functions, multi-parton interactions, k_T-broadening or energy loss in cold nuclear matter.

Hidden heavy-flavor production in p–Pb collisions is also globally well reproduced by model calculations. Nevertheless, $\psi(2S)$ results suggest that some unexpected final-state effects that could distinguish among J/ψ and $\psi(2S)$ might be at play, besides the nPDF, CGC or coherent energy loss contributions.

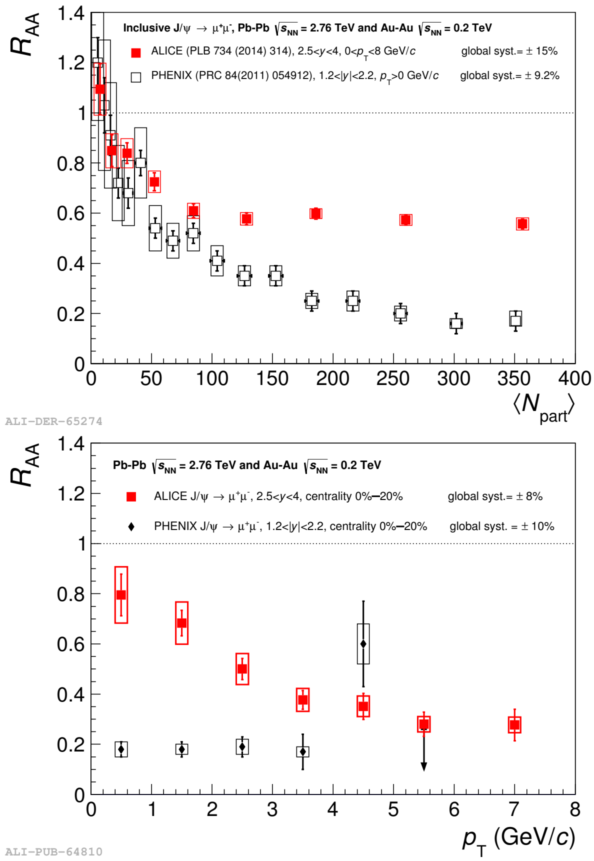

Figure 7: J/ψ R_{AA} at forward rapidity as measured by ALICE in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV and PHENIX in Au–Au collisions at $\sqrt{s_{NN}}$ = 0.2 TeV [32, 33, 35]. The p_T-integrated R_{AA} as a function of the collision centrality, expressed by the number of participating nucleons, is shown in the top figure. The variation as a function of p_T in the 20% most central collisions is shown in the bottom plot.

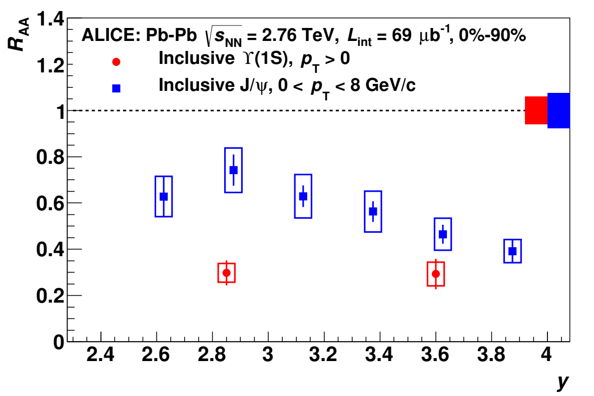

Figure 8: Υ and J/ψ p_T-integrated R_{AA} as a function of rapidity for Pb–Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV in the 0–90% centrality range.

The results in Pb–Pb collisions evidence a suppression of heavy-flavor production at high p_T with respect to that of pp collisions scaled by the average number of nucleon-nucleon interactions. Since initial-state effects are expected to be small at high p_T for open heavy flavors, their suppression in the most central Pb–Pb interactions is assumed to come from final-state effects. This corroborates that heavy quarks experience partonic energy loss in the medium. The magnitude and centrality dependence of high-p_T prompt D-meson and non-prompt J/ψ R_{AA} are consistent with model calculations considering quark mass dependent energy loss. The positive v_2 values at intermediate p_T in semi-central collisions prove open heavy-flavor production azimuthal anisotropy. The similarity with charged particle v_2 in this kinematic range suggests that charm quarks participate in the system collective motion.

J/ψ production in Pb–Pb collisions is suppressed with respect to that in pp collisions scaled by the average number of nucleon-nucleon interactions. The p_T-integrated R_{AA} centrality dependence presents a flat distribution from semi-peripheral to the most central collisions, while the equivalent measurements at RHIC show an enhancement of the suppression with centrality. The production rate in Pb–Pb collisions decreases with increasing p_T, and for $p_T > 5$ GeV/c it is similar to the one measured at RHIC. These observations are interpreted considering a large suppression of charmonium in the medium, and another mechanism compensating this suppression at low p_T at the LHC. The recombination of uncorrelated heavy quark pairs appears to be a plausible scenario. Recent Υ p_T-integrated results in Pb–Pb collisions exhibit R_{AA} values smaller than the J/ψ ones, i.e. a larger suppression than J/ψ. State-of-the-art calculations are not able to reproduce these Υ measurements.

In the near future, the LHC Run-II will bring an increase of the collision energy and luminosity that should allow more precise and differential measurements. In particular, open heavy-flavor studies down to $p_T \sim 0$ and up to higher p_T will be explored, as well as the properties of quarkonia.

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