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Recent results on Pb–Pb and p–Pb collisions from ALICE

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Abstract. ALICE (A Large Hadron Collider Experiment) at the CERN LHC is aimed at studying the hot and dense QCD matter which is formed in high-energy heavy-ion collisions. A selection of the results obtained by ALICE in lead–lead collisions will be presented; this will include collective phenomena, particle spectra and correlations, heavy flavors and jets. Results from the recent p–Pb run will be also discussed.

1 Introduction

The first run of the Large Hadron Collider (LHC) at CERN has been completed, including several data takings of pp collisions mostly at the center-of-mass energies of 7 and 8 TeV, two Pb–Pb data takings at $\sqrt{s_{NN}}$ = 2.76 TeV (with increasing luminosity) and most recently a p–Pb data taking at $\sqrt{s_{NN}}$ = 5.02 TeV. In this contribution, the main ALICE results from the Pb–Pb data takings of years 2010 and 2011 and from the p–Pb one of 2013 are presented.

2 The ALICE detector

The ALICE detector is dedicated to the study of heavy-ion collisions (Pb–Pb in Run 1, possibly also other nuclei in forthcoming runs) at the LHC, aiming at characterizing the Quark-Gluon Plasma (QGP) formed in these collisions; furthermore, pp and p–Pb collisions are studied in order to establish the baseline for QGP signals in Pb–Pb but also in their own right. ALICE features excellent tracking (down to 100 MeV/c) and particle identification in its central barrel, additional particle detection in a wide rapidity range thanks to several forward detectors, and is able to measure open heavy flavours and quarkonia in the Muon Spectrometer down to zero transverse momentum. A summary of the ALICE detector performance is given in [1].

3 Global features of Pb–Pb and p–Pb collisions

The main global features of Pb–Pb collisions in the LHC energy regime ($\sqrt{s_{NN}}$ = 2.76 TeV) have been established with the data of the first ion run in 2010. The charged multiplicity per participant pair, $(dN_{ch}/d\eta)/(0.5N_{part})$, has been measured [2] and it has been found to scale like $s_{NN}^{0.15}$, with a larger exponent compared to 0.11 for pp collisions. The size of the fireball has been measured via femtoscopy of identical charged pions [3]: the product $R_{long} \times R_{side} \times R_{out}$ is about 300 fm^3, i.e. twice

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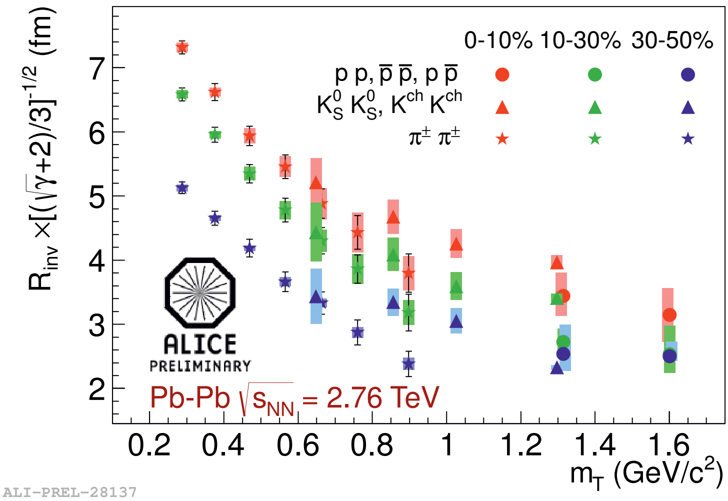

Figure 1. Invariant gaussian radius, after kinematical correction, vs. transverse mass for several identified particles in three different centrality classes of Pb–Pb collisions.

the value measured at the top RHIC energy of 0.2 TeV. The lifetime of about 10 fm/c is about 20% larger than at RHIC. The energy density reached at LHC, about 10 GeV/fm^3, is three times the one at RHIC. A preliminary measurement of the direct photons spectrum in 0-40% most central Pb-Pb collisions for 0.5-2.5 GeV/c transverse momentum yields a temperature of 304 ± 51 MeV, which is about 40% larger than the one found at RHIC.

The femtoscopic studies have been recently extended to charged and neutral kaons, protons and antiprotons, as shown in Fig. 1. The invariant radius, corrected by a kinematical factor, exhibits an approximate scaling as a function of transverse mass - as expected from an expanding source.

The charged particle η_{lab} distribution has been measured for minimum bias (non single diffractive) p–Pb collisions [4] and compared to several models. While most models are within 20% of data, we find that saturation models give a too steep dependence on η_{lab}. On the other hand, pQCD models (some version of HIJING, DPMJET) are in agreement with data. Where shadowing is included, a strong yield reduction (about 30%) is obtained.

The average transverse momentum as a function of the number of charged particles has been measured for p–Pb collisions [5] and compared to pp and Pb–Pb collisions, as shown in Fig. 2. The average p_T in p–Pb collisions follows the one of pp collisions up to $N_{ch} \approx 14$, a multiplicity corresponding to 50% of the p–Pb cross-section but only to 10% of the pp one, and shows a much stronger increase with respect to Pb–Pb collisions. The difference between pp and p–Pb at $N_{ch} > 14$ cannot be attributed to difference in collision energy (7 and 5.02 TeV respectively) as the energy dependence of the average p_T is weak. A superposition of independent pp collisions (Glauber approach), with measured p_T from pp collisions, is lower than p–Pb data: this may signal the presence of collective final state effects, color reconnection between hadronizing strings, or coherent effects between strings formed in different p–N collisions.

Di-hadron correlation results in p–Pb collisions have recently been obtained [6]. Going from low multiplicity collisions to high multiplicity ones a near–side ridge becomes evident. In order to quantify the change from low to high multiplicity, the per–trigger yield for the low multiplicity class

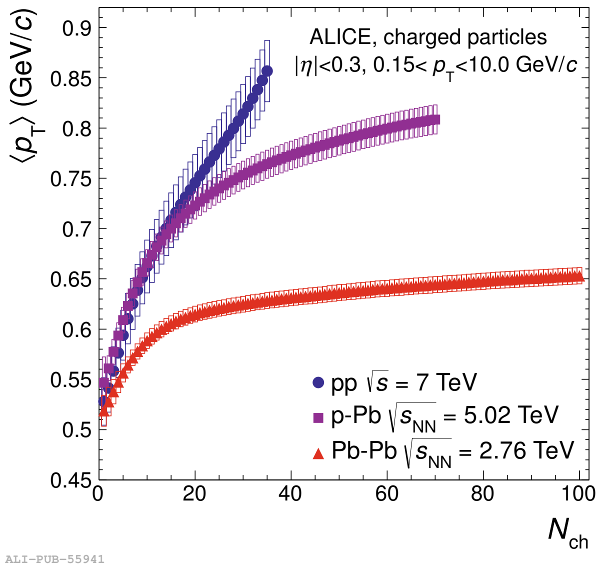

Figure 2. Average transverse momentum of charged particles vs. charged multiplicity for pp, p–Pb and Pb–Pb collisions.

(60-100%) is subtracted from the one of the high-multiplicity class (0-20%): we found that the near–side ridge is accompanied by a similar structure on the away side, whose origin is to be understood (it is not predicted by HIJING).

4 Anisotropic flow

Collective effects in heavy–ion collisions, taking place both in the QGP phase and in the hadronic gas phase, manifest themselves in the final hadrons' momentum spectra (radial flow, see next section) and in the angular distribution of produced particles with respect to the reaction plane (anisotropic flow). ALICE has obtained detailed results on anisotropic flow at LHC energies, in particular the second Fourier coefficient v_2 vs. transverse momentum has been measured in centrality classes, both for unidentified charged particles [7] and, more recently, for several particle species [8] including pions, kaons, protons and hyperons - as shown in Fig. 3. The measured v_2 for 20-40% Pb–Pb collisions shows mass ordering up to and including multi–strange baryons and is described by hydrodynamical models like e.g. VISH2+1 with Colour Glass Condensate initial conditions and 0.2 η/s (viscosity over entropy density) ratio. The scaling of v_2 with the number of constituent quarks, observed at RHIC, is not so good at LHC (but still holds within 20%).

5 Light flavour production

Identified particle spectra at low p_T in central Pb–Pb collisions [9] have been described by a superposition of collective motion and thermal motion: blast–wave fits indicate a radial flow velocity $\beta \approx 0.65$ (10% larger that at RHIC) and a kinetic freeze–out temperature $T_{kin} \approx 95$ MeV. Recently this measurement was extended up to p_T of 20 GeV/c: the nuclear modification factors for (anti–)protons,

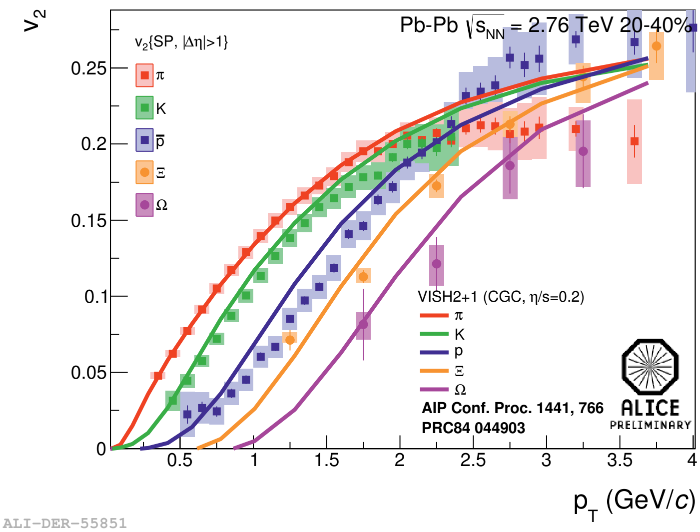

Figure 3. Anisotropic flow coefficient vs. transverse momentum for identified hadrons in 20-40% Pb–Pb collisions.

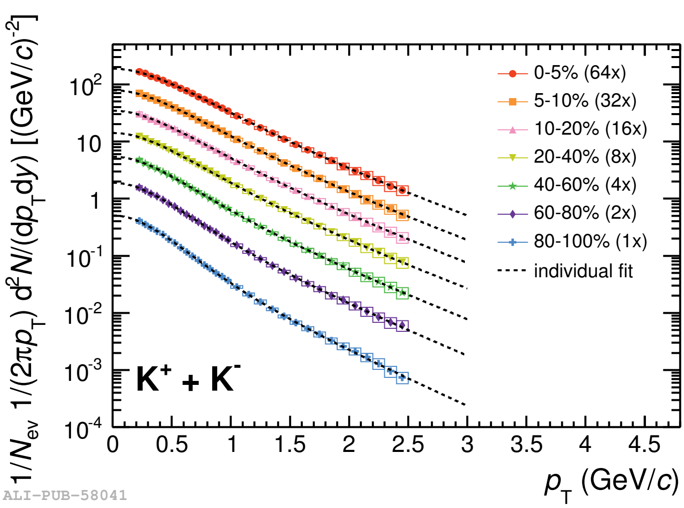

Figure 4. Spectra of charged kaons as a function of multiplicity in p–Pb collisions. Blast–wave fits are shown as well.

charged pions and kaons are all compatible above 7 GeV/c, suggesting that the medium does not affect the fragmentation strongly.

Moving to minimum bias p–Pb collisions, the nuclear modification factor for charged particles [10] is compatible with unity for p_{T} above 2-3 GeV/c and up to 20 GeV/c, indicating that binary scaling is preserved in p–Pb and that the suppression observed in Pb–Pb collisions is not an initial state effect.

Identified charged particles spectra were recently measured in p–Pb collisions [11] with a binning in percentiles of the charged multiplicity measured by the forward VZERO-A scintillator hodoscope, see e.g. Fig. 4. Spectra for long–lived hadrons can be described rather well by blast–wave fits; the average transverse momentum extracted from the spectra presents mass ordering among particle species, and the ratios of particles yields show a similar dependence on $dN_{ch}/d\eta$ in pp, p–Pb and Pb–Pb collisions at LHC energies.

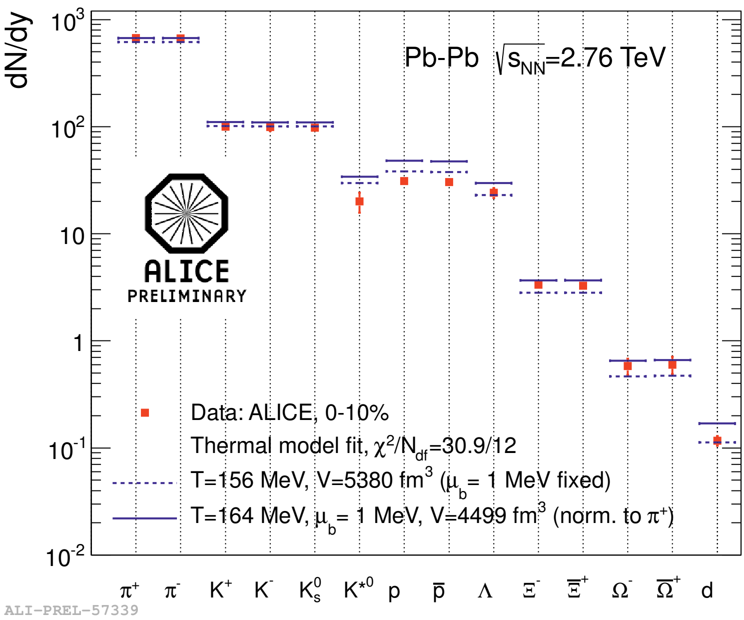

Figure 5. Hadron yields in 0-10% Pb–Pb collisions compared to thermal model.

In Pb–Pb collisions, final results on K^0_s and Λ spectra [12] as well as on hyperons [13] as a function of centrality have been recently obtained. Since strange quarks are light enough to be thermally produced in the QGP, the question naturally arises: are yields of non–strange and strange hadrons consistent with thermal production?

Yields at midrapidity in central Pb–Pb collisions for several hadrons are compared both to a thermal model prediction [14] and to a more recent fit [15] in Fig. 5. The global fit gives a freeze–out temperature of 156 MeV, lower than the prediction of 164 MeV, but misses multi–strange hadrons. Excluding protons, a better fit (not shown) gives 158 MeV, well describing hyperons. No unique chemical freeze–out temperature describes at the same time protons, Λ, Ξ and Ω yields.

An enhancement in the baryon/meson ratio at intermediate p_T, already seen at RHIC in Au–Au collisions, has been confirmed [12] for Pb–Pb collisions at LHC. Recently, very intriguing preliminary results have been obtained in p–Pb collisions, as shown in Fig. 6: at high multiplicities a behaviour has been observed which recalls hydrodynamical models which successfully describe Pb-Pb data.

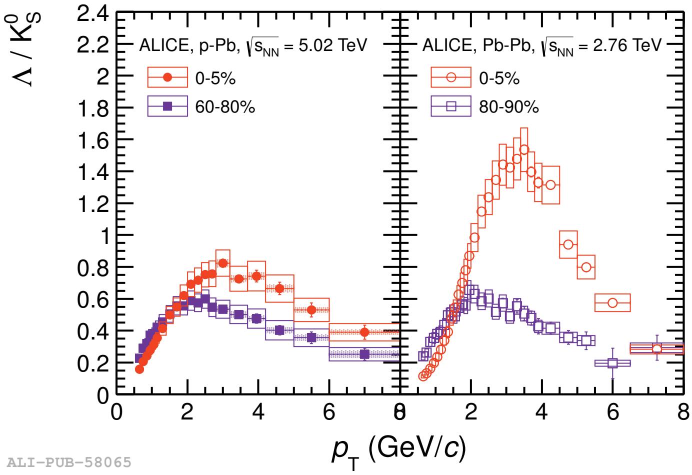

Figure 6. Λ/K^0_s ratio vs. transverse momentum in two centrality/multiplicity classes for p–Pb and Pb–Pb collisions.

6 Open heavy flavour production

Open heavy flavour hadrons are a powerful tool for studying the fate of charm and beauty quarks through the QGP phase. The nuclear modification factor R_{AA} in central Pb–Pb collisions for different charmed mesons is shown vs. p_T in Fig. 7. A strong suppression with respect to the pp reference is evident for all charmed mesons at mid–rapidity.

Additional information has been obtained by studying the nuclear suppression factor of heavy flavour decay electrons at mid–rapidity and of muons at forward rapidity: as shown in Fig. 8, a significant suppression of charm and beauty is observed in central Pb–Pb collisions. Using the CMS measurement [16] of beauty extracted from non–prompt J/ψ and comparing it to the ALICE result one can see a clear difference between charm and beauty nuclear suppression factors at LHC energies.

Another important tool for QGP studies is the anisotropic flow of hadrons containing heavy quarks. ALICE has measured a significant non–zero v_2 coefficient of anisotropic flow for D–mesons in semi-peripheral Pb–Pb collisions [17], as shown in Fig. 9. Several models which successfully describe R_{AA} vs. p_T have difficulties in describing v_2.

Cold nuclear matter effects have been investigated for D–mesons and heavy flavour leptons. The nuclear modification factor in Minimum Bias p–Pb collisions is compatible with unity both for D–mesons (see Fig. 10) and electrons from heavy flavours, and is well described by calculations based on perturbative QCD and EPS09 parton distribution functions [18]. We have thus confirmed that Pb-Pb suppression of charm is not a cold nuclear matter effect but rather a final state effect.

7 Quarkonia production

Production of different quarkonia in ion-ion collisions and their suppression relative to pp collisions constitute a fundamental tool to study the QGP characteristics. The nuclear modification factor of J/ψ vs. centrality in Pb–Pb collisions has been measured by ALICE both at forward rapidity (see Fig. 11) with dimuons and at mid–rapidity with dielectrons. Compared to earlier results obtained from

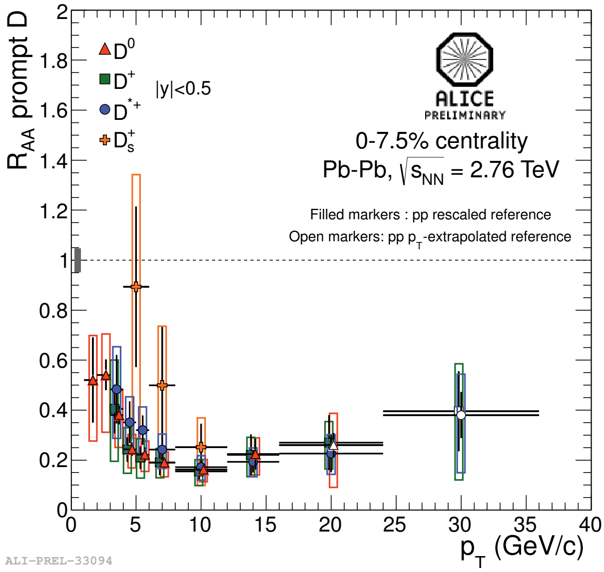

Figure 7. Nuclear modification factor vs. transverse momentum for charmed mesons in 0-7.5% central Pb–Pb collisions.

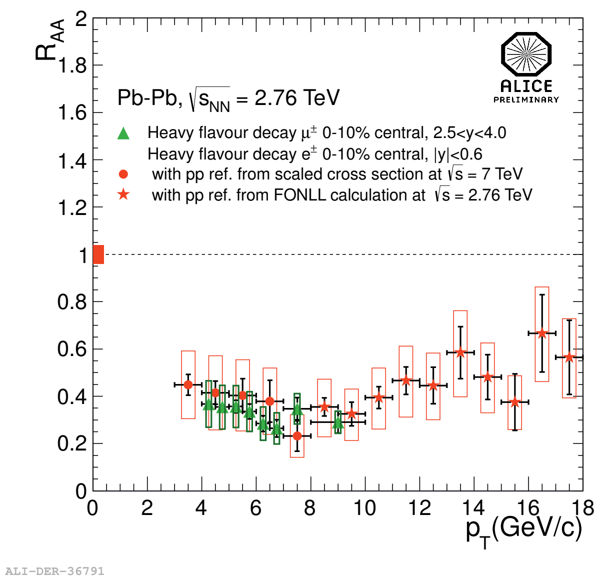

Figure 8. Nuclear modification factor vs. transverse momentum for heavy flavour electrons and muons in 0-10% central Pb–Pb collisions.

RHIC at lower energy, the suppression of charmonium is still present at LHC but it is less pronounced

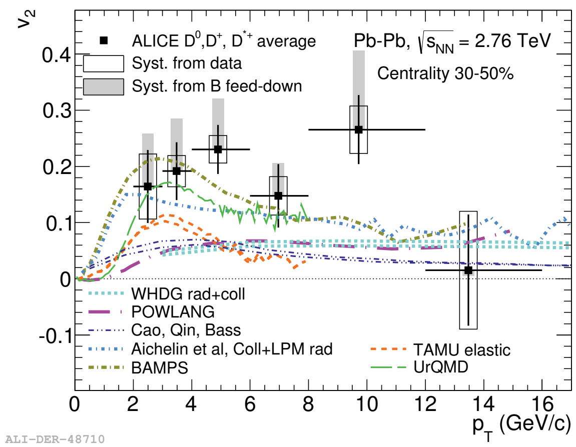

Figure 9. D–meson anisotropic flow coefficient vs. transverse momentum for 30-50% Pb–Pb collisions.

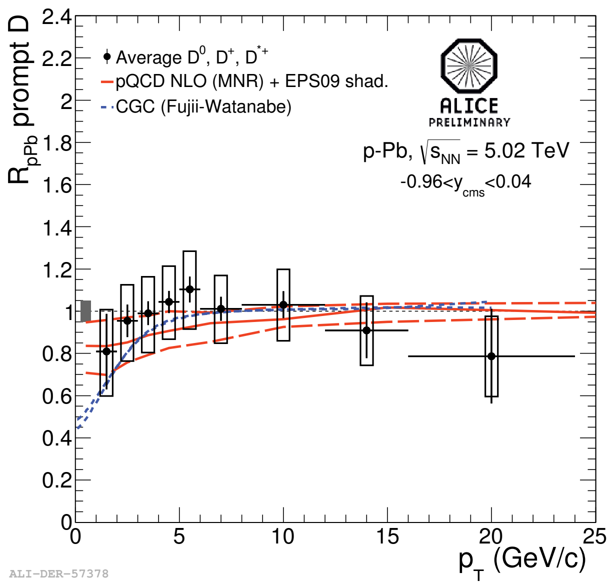

Figure 10. Nuclear modification factor for D–mesons in minimum bias p–Pb collisions.

for central collisions, a fact which may be explained by regeneration of c (anti-)quarks in the QGP (regeneration is expected to become significant only at LHC energies) or by statistical hadronization.

However, before reaching final conclusions on the Pb–Pb quarkonia observations, one has to exclude possible Cold Nuclear Matter effects and also measure the amount of shadowing in the gluon PDF. Fig. 12 shows the nuclear modification factor R_{pPb} recently obtained by ALICE [19] for two rapidity intervals, exploiting both p–Pb and Pb–p collisions. A comparison to some models including

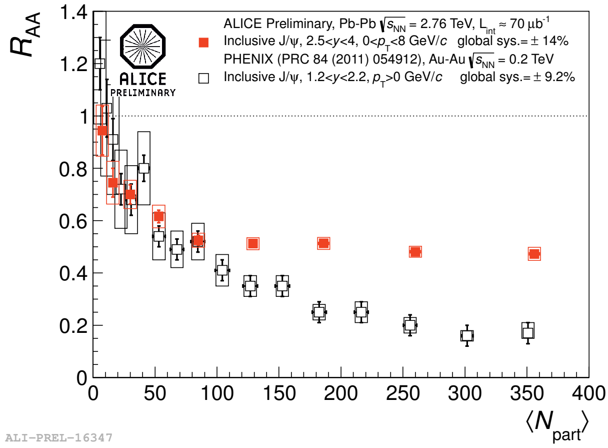

Figure 11. J/ψ nuclear modification factor vs. the average number of participant nucleons in Pb–Pb collisions at LHC compared to earlier RHIC results for Au–Au collisions.

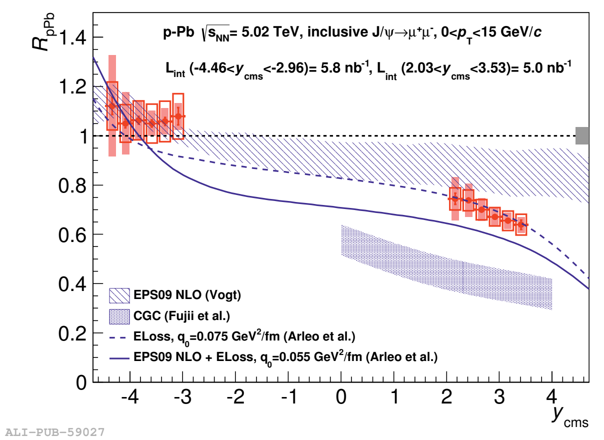

Figure 12. J/ψ nuclear modification factor vs. rapidity in p–Pb collisions at the LHC.

shadowing and initial energy loss is presented. While the rather large uncertainty in the pp reference does not allow yet for a discrimination between shadowing alone and shadowing plus initial energy loss, our data do not favour the Color Glass Condensate calculation for p–Pb collisions in the forward region. In any case, the suppression observed in Pb–Pb collisions is clearly not due to shadowing or to initial state effects. A similar result has been obtained in Pb–Pb and p–Pb collisions for the Υ mesons.

8 Conclusions

ALICE has obtained many physics results from the first two LHC Pb–Pb runs, covering: bulk particle production, soft probes, radial and anisotropic flow, correlations; high transverse momentum probes, heavy flavours and quarkonia. Strong suppression of jets and charmonium, as well as indications for charmonia regeneration, have been found in central Pb–Pb collisions. Very interesting results have been obtained from the recent p–Pb run: the nuclear modification factor R_{pPb} is consistent with unity for jets, D–mesons and Heavy Flavour Electrons, while it is below unity for quarkonia at forward rapidity, indicating that some Cold Nuclear Matter effect is present. ALICE (as well as other LHC experiments) is entering the precision measurement era for QGP, with Run 2 scheduled to provide Pb–Pb collisions at higher energy and possibly Ar–Ar collisions. Plans for a major upgrade for Run 3 are presented in another contribution [20].

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