Overview of results from ALICE

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Abstract. ALICE is a dedicated experiment for measurements of heavy-ion collisions at the Large Hadron Collider (LHC). A wealth of experimental data recorded in 2010, 2011 and 2012 suggests that a strongly interacting de-confined medium is created in collisions of lead ions at a centre-of-mass energy $\sqrt{s_{\rm NN}} = 2.76$ TeV. In order to quantify the properties of this hot and dense matter, measurements were performed in smaller systems, such as proton-proton and proton-lead, where effects related to the medium are expected to be negligible. We present an overview of recent measurements of particle production and particle correlations in proton-proton, Pb–Pb and p–Pb collisions at the LHC by ALICE Collaboration.

1. Identified particle production

Recent ALICE results on the inclusive particle production from different collision systems can be found in [1, 2, 3] for pp collisions, in [4] for p–Pb collisions and in [5, 6, 7] (and ref. therein) for Pb–Pb collisions. Figure 1 shows the integrated yields of various hadrons per unit rapidity in most central Pb–Pb collisions. The particle yields are compared to a simultaneous fit (to all particles except K*) of a thermal equilibrium (statistical hadronization) model defined with three parameters: the volume of the fireball V, baryochemical potential μ_b and temperature T. The fit to ALICE data with the fixed V for Pb–Pb collisions and $\mu_b = 1$ results in T of 156 MeV. We note the tension in the fit results between protons and multi-strange baryons as well as much heavier, deuterons. There are several potential explanations for such a tension: additional late stage baryon-antibaryon annihilation (specifically p–$\bar{\rm p}$), sequential freeze-out of different quark flavors, non-equilibrium freeze-out conditions, or incomplete knowledge of the baryon resonance spectrum. For a more in-depth discussion on the particle production see [8] and references therein.

Modifications of particle production in heavy-ion collisions can be established by studying the nuclear modification factor $R_{\rm AA}$. $R_{\rm AA}$ is defined as the ratio of yields in heavy-ion collisions to yields measured in pp collisions scaled with appropriate number of binary nucleon-nucleon collisions. The $R_{\rm AA}$ in the absence of nuclear or medium effects is by construction unity at high transverse momenta where hard processes dominate. The particular shape differences of $R_{\rm AA}$ shown in Fig. 2 between baryons and mesons are a consequence of the interplay between the shapes of the particle $p_{\rm T}$ distributions, the collective flow (both depending on particle mass), jet quenching phenomena (sensitive to parton type), and possible novel hadronization phenomena such as parton recombination. One easily identifies the similarities of the curves for two groups of particles: baryons and mesons. The two special cases are the Ω baryon for which the large $R_{\rm AA}$ values can be related to the suppressed strangeness production in pp collisions, and the ϕ meson for which $R_{\rm AA}$ at $p_{\rm T}$ below 2 GeV/c resembles the suppression of baryons, whereas for

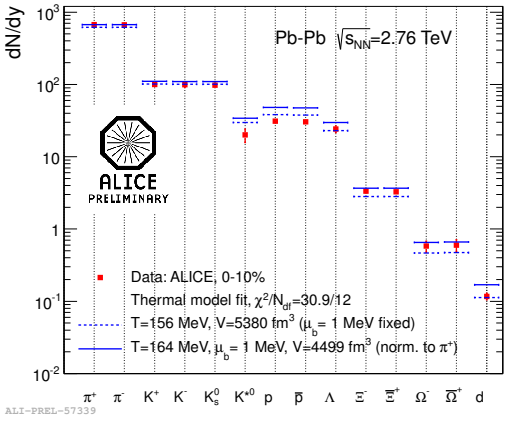

Figure 1. Identified particle abundances in most central heavy-ion collisions compared to a thermal model fits.

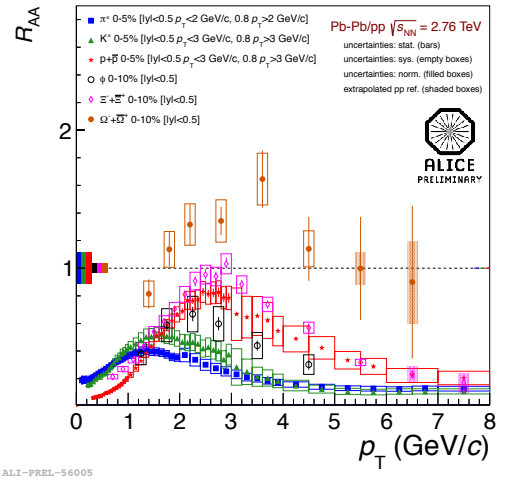

Figure 2. Nuclear modification factor for identified particles in most central Pb–Pb collisions.

$p_{\rm T} > 2$ GeV/c deviates from both, mesons and baryons. For an overview of measurements of short lived resonances see [9, 10].

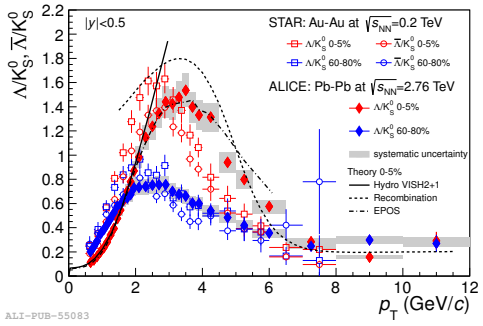

Figure 3. Ratio of Λ baryons to K^0_s mesons as a function of the transverse momentum in most central and peripheral heavy-ion collisions at RHIC and at the LHC [6].

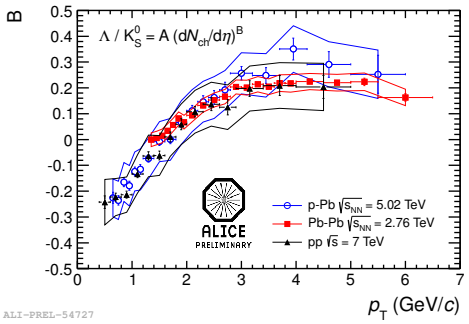

Figure 4. Exponent B calculated from the Λ/K^0_S ratio as a function of transverse momentum for three collision systems: pp p–Pb and Pb–Pbat the LHC [4].

Concurrently, the $p_{\rm T}$ dependence of the baryon to meson ratio in heavy-ion collisions is likewise sensitive to the various dynamical phenomena of particle production (collective expansion of the system, parton recombination into hadrons, and jet fragmentation and hadronization). Figure 3 shows the measurements performed at RHIC and at the LHC of the Λ/K^0_S ratio in most-central and peripheral collisions. For the most central collisions at the LHC the ratio reaches its maximum at larger momenta than at RHIC. This observation is consistent with an expectation of stronger radial flow at higher energies. The ratio declines in the 3-6 GeV/c interval, where its shape, in some models is ascribed to parton recombination effects, reaching values of about 0.2 measured in peripheral collisions and driven by jet fragmentation

processes. Moreover, the baryon to meson ratio for a given momentum bin shows a power law behavior with respect to the particle multiplicity density, such that a simple functional form can be fitted with $\Lambda/\mathrm{K}^0_s = A(\mathrm{d}N_{ch}/\mathrm{d}\eta)^B$, where A and B are free parameters. Figure 4 shows remarkable similarity of the extracted exponent between pp, p–Pb and Pb–Pb systems. The importance of this finding, hinting at a possibly common mechanism driving the baryon to meson ratio, remains to be fully understood [4].

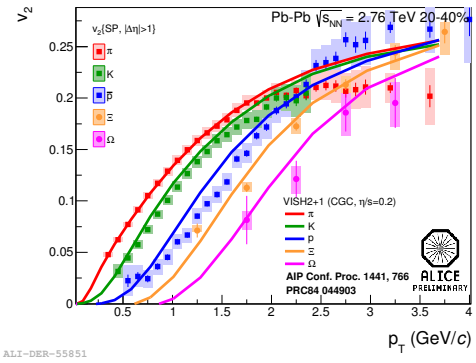

Figure 5. Elliptic flow coefficient (v_2) for various particle species as a function of transverse momentum for semi-central heavy-ion collisions at the LHC. The measurements are compared to hydrodynamical predictions (see [11] and references therein).

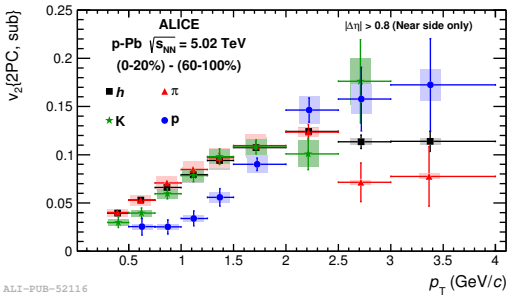

Figure 6. The v_2 coefficient extracted from two-particle correlations in most violent (highest multiplicity) p–Pb collisions for unidentified hadrons, pions, kaons and protons [13].

The collective behavior of the created matter within high-energy heavy-ion collisions is quantified by the second Fourier coefficient (v_2) of the azimuthal angular distribution of measured particles. The initial spatial anisotropy of the system of two nuclei colliding with non-zero impact parameter is transformed into a final state momentum anisotropy by interactions between the particles of the hot medium. Figure 5 shows good agreement between the measurements of v_2 for pions, kaons, protons and hydrodynamical modeling of the plasma. Similar agreement is seen also for heavier particles, such as Ξ and Ω, obeying the particular hydrodynamical prediction of mass ordering in the reported dependence of v_2 on transverse momenta of particles. More results on v_2 and higher harmonics measured with ALICE are reported in [11]. Furthermore, a striking observation has been made by analyzing the highest multiplicity p–Pb collisions and decomposing the two-particle azimuthal correlations into the single particle Fourier coefficients. For unidentified particles a positive v_2 coefficient has been found [12] for the event class of $0-20\%$ of the multiplicity distribution selected by the VZERO–A multiplicity detector ($2.8 < \eta^{\mathrm{VZERO-A}}_{\mathrm{det}} < 5.1$). The recent analysis of these two-particle correlations with emphasis on the particle identification (see Fig. 6) has revealed that a similar mass ordering as seen in Pb–Pb collisions also holds for the highest multiplicity p–Pb collisions [13].

2. Hard probes

Hard scatterings occurring early within high energy heavy-ion collisions are utilized to study the properties of the hot and dense medium. Partons, including heavy-quarks, are expected to loose energy within the medium depending on the traversed path length and the medium density. The parton energy loss is manifested by suppression of particle and jet yields measured in heavy-ion

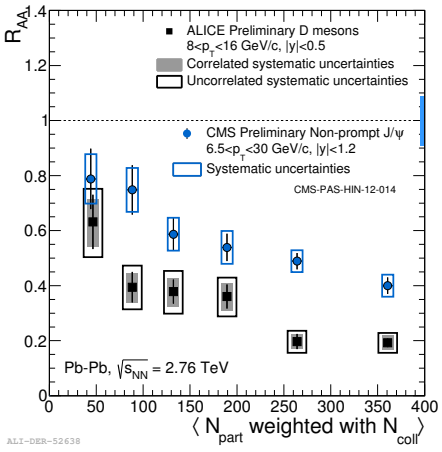

Figure 7. Nuclear modification factor for selected p_{T} ranges of D-meson and J/ψ from B-meson decays as a function of the average number of participating nucleons (see text for details) from ALICE and CMS at the LHC [17].

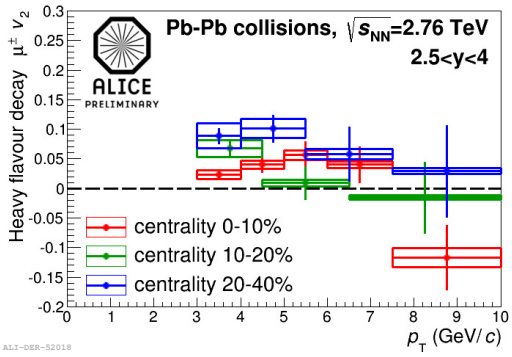

Figure 8. Elliptic flow coefficient (v_2) measured for heavy-flavor decay muons at forward rapidities in three centrality bins of Pb–Pb collisions at the LHC [18].

collisions as compared to pp collisions [14]. ALICE measurements on D-meson production in pp collisions are reported in [15], and the strong suppression of D-meson production in heavy-ion collisions is reported in [16]. Figure 7 shows the R_{AA} of D-mesons measured with ALICE together with non-prompt J/ψ preliminary results measured with CMS. The p_{T} range of the J/ψ has been chosen such that the p_{T} range of B-meson (parent in case of J/ψ) match the D-meson p_{T} range (see [17] for details). The observation that $R_{\mathrm{AA}}^{\mathrm{D}} < R_{\mathrm{AA}}^{\mathrm{non-prompt\ J/\psi}}$ is consistent with the predicted mass ordering in the energy-loss (larger loss for lighter quarks) within the hot plasma created in heavy-ion collisions. Furthermore, the measurement of elliptic flow (v_2) of heavy-flavor decay muons at large rapidities shown in Fig. 8 [18] is consistent with the substantial interaction of heavy quarks within the medium. Similar observations of positive heavy-flavor v_2 have been previously reported by ALICE for D-mesons in [19], and [20] for heavy-flavor decay electrons at mid-rapidity. The measurements of the R_{AA} together with the flow measurements are an essential input to modeling of the heavy-quark in-medium energy-loss.

In order to assess the importance of *cold nuclear matter effects* for the strong suppression of the hard probes observed in heavy-ion collisions, up to now, ALICE measured the nuclear modification factor in minimum-bias p–Pb collisions for charged particles [21], D-mesons (see Fig. 9 and [22]), heavy-flavor decay electrons [23], and jets reconstructed with charged particles [24] (see Fig. 10). In all cases R_{pPb} is consistent with unity within the uncertainties present in the current measurements strongly suggesting that the suppression seen in heavy-ion collisions must be related to final state interaction of the particles and jets with the hot and dense plasma. For more on p–Pb results and on the feasibility for reporting multiplicity differential nuclear modification factors see [25].

3. Quarkonia

ALICE has measured the production of quarkonia in pp, p–Pb and Pb–Pb collisions at the LHC. The suppression of J/ψ production at forward rapidities ($2.5 < y < 4.0$) in heavy-ion collisions

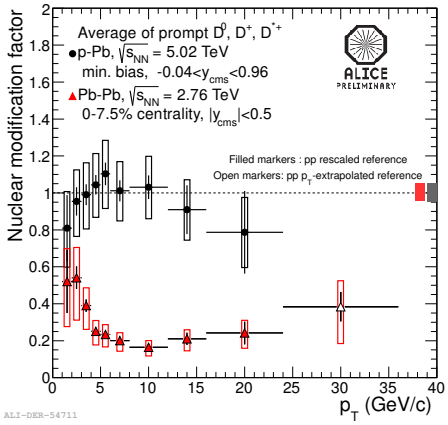

Figure 9. Comparison of the nuclear modification factor for D-mesons in heavy-ion and proton-lead collisions at the LHC.

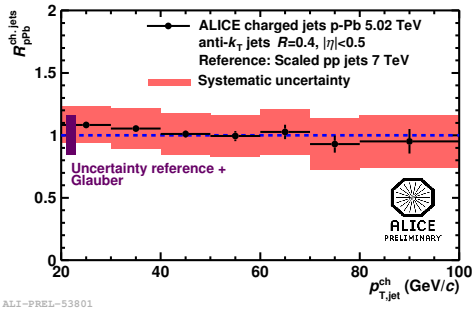

Figure 10. Nuclear modification factor for anti-k_T jets with $R = 0.4$ reconstructed from charged particles in minimum-bias proton-lead collisions at the LHC.

as a function of average number of participating nucleons has been reported by ALICE in [26] and is shown in Fig. 11 together with the $R_{\rm AA}$ of Υ(1S) [27]. The suppression pattern as a function of collision centrality reaches values of about 0.5 and remains constant over a wide range of centralities up to the most central events. Together with observation of the positive v_2 in the semi-central collisions this result suggests that the (re-)combination of $c\bar{c}$ pairs in the plasma or at the phase boundary plays a sizable role in the J/ψ production. The $R_{\rm AA}$ of both J/ψ and $\Upsilon(1S)$ have been measured for down to zero transverse momentum. Within the uncertainties a similar suppression of $\Upsilon(1S)$ as for inclusive J/ψ is observed. The suppression is stronger for central than semi-peripheral collisions. Together with the measurement from CMS performed for $|y| < 2.4$, no rapidity dependence of the Υ(1S) suppression is observed within the large rapidity range probed by the two experiments (for details see [28] and ref. therein).

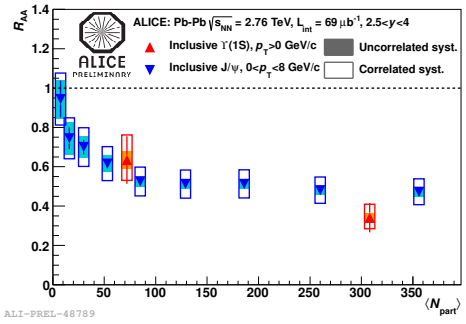

Figure 11. Nuclear modification factor for J/ψ and Υ as a function of the average number of participating nucleons in Pb–Pb collisions at the LHC.

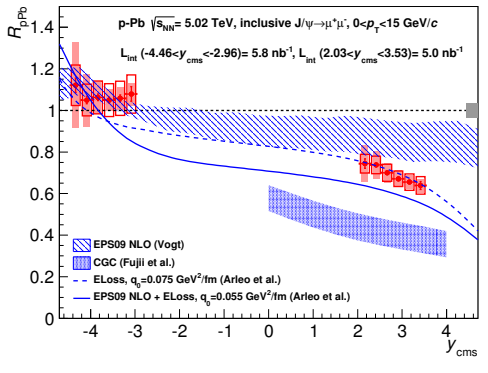

Figure 12. Nuclear modification factor for J/ψ as a function of center-of-mass rapidity in minimum bias proton-lead collisions at the LHC. The $R_{\rm pPb}$ is compared a theoretical models (see [29] for details).

To investigate *cold nuclear matter effects* relevant for quarkonium production (parton shadowing, gluon saturation, parton energy loss or final state break-up), ALICE studied proton-nucleus interactions. The nuclear modification factor $R_{\rm pPb}$ for the J/ψ [29] as a function of the quarkonium rapidity y_{cms} is shown in Fig. 12. The results are compared with theory predictions, based on a pure nuclear shadowing scenario, as well as partonic energy loss, either in addition to shadowing or as the only nuclear effect. Within the uncertainties, the model based on nuclear shadowing is in fair agreement with the data. Models including a contribution from parton energy loss are likewise in fair agreement with the data, while the prediction based on Color Glass Condensate model underestimate the results. A more complete overview of the quarkonia results has been given in [27]. For more results and discussions on quarkonia (including Υ(1S)) production in pp, p–Pb and Pb–Pb collisions see [28, 30, 31, 32] and references therein.

4. More ALICE highlights

This writeup presents a selected list of measurements performed with ALICE. The reader is encouraged to get familiar with ALICE measurements of low-mass di-leptons [33], on the search for exotic hyper-matter and nuclei [34], production of hyper nuclei in heavy-ion collisions [35], and particle production in ultra-peripheral collisions [36].

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