HIGHLIGHTS FROM THE ALICE EXPERIMENT*

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Since the last Quark Matter conference in Wuhan in 2019, the ALICE Collaboration has produced a remarkable number of new results, studying all colliding systems available at the LHC. This document contains only a partial collection of the wealth of results presented at the 2022 edition of Quark Matter in Kraków.

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1. Introduction

In recent years, the ALICE Collaboration has widened its field of investigation, profiting from the versatility of the Large Hadron Collider. As a consequence, this will be only an incomplete summary of the dozens of new results presented by the ALICE Collaboration at the Quark Matter 2022 conference in Kraków. Given the diverse nature of the results, this summary document is organised in four sections: the first one dedicated to the study of the properties and the evolution of heavy-ion collisions (Section 2), Section 3 is about small systems and hadronisation, Section 4 is dedicated to the interactions among hadrons, and finally, in Section 5 the first results from the upgraded ALICE detector using data from the October 2021 LHC beam test are shown.

2. Properties and evolution of a heavy-ion collision

Using different observables, the ALICE experiment is probing all the stages of the evolution of heavy-ion collisions. One example of how to investigate the initial configuration of the colliding nuclei is the measurement of the event-by-event correlation between the elliptic flow v_2 and the average transverse momentum, $\rho(v_2^2, [p_{\mathrm{T}}])$. Figure 1 shows this correlation as a function of centrality in both Pb–Pb and Xe–Xe collisions, compared with

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models that demonstrate how, while keeping the same description of the later stages of the collision, the $\rho(v_2^2, [p_{\mathrm{T}}])$ is able to distinguish between different initial conditions. As detailed in [1], there is no model that gives a quantitative description of the data, however, there is a slightly better agreement with models using IP-Glasma initial conditions that predicts the correct sign of the correlation across all centralities.

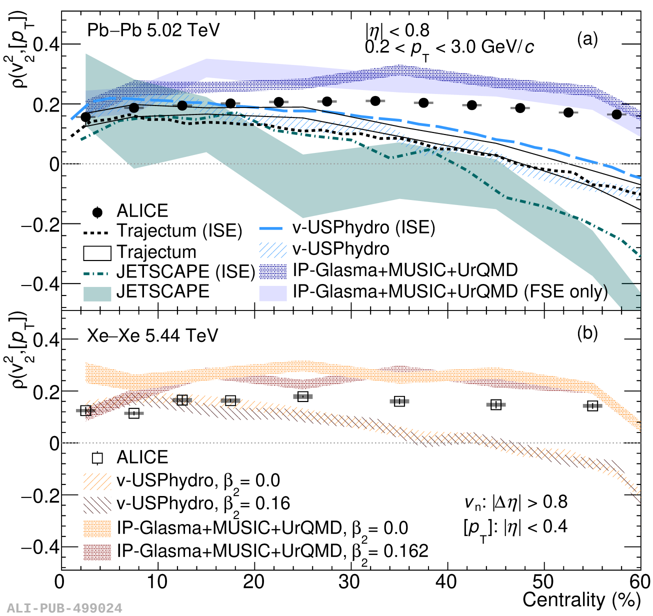
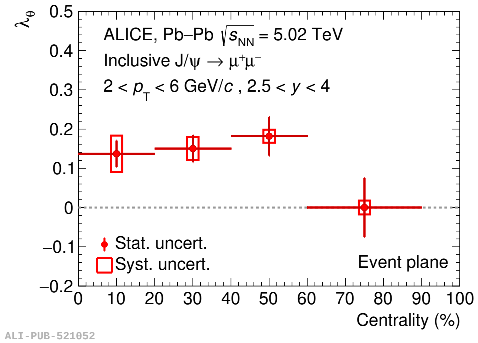


Fig. 1. Centrality dependence of $\rho(v_2^2, [p_{\mathrm{T}}])$ in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV (top) and Xe–Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV (bottom). The statistical (systematic) uncertainties are shown as vertical bars (filled boxes). Initial-state estimations (ISE) are represented by lines, while IPGlasma+MUSIC+UrQMD [2], v-USPhydro [3], Trajectum [4], and JETSCAPE [5] hydrodynamic model calculations are shown with bands. Figure from Ref. [1].

At the very early stages of collisions, intense electromagnetic interactions take place between the colliding nuclei. In recent years, several measurements of the spin alignment of vector mesons have been carried out to study this phenomenon. Most recently, ALICE measured the J/Ψ polarisation with respect to the event plane in Pb–Pb collisions [6]. As shown in Fig. 2 (left), there is evidence of the polarisation of inclusive J/Ψ with respect to the event plane at low p_{T}. This effect is significant up to semicentral collisions, while there is a vanishing polarisation at larger momenta. Here, model calculations are needed to establish the sensitivity of this observable to the medium vorticity and the initial magnetic field.



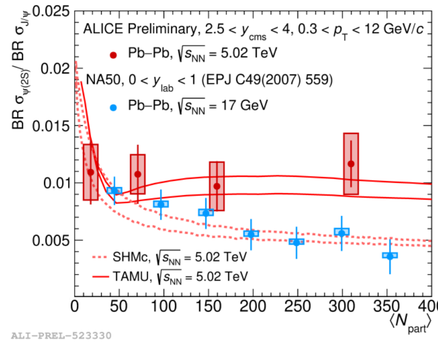


Fig. 2. Left: The J/Ψ polarisation angle with respect to the event plane as a function of the collision centrality. Bars and boxes represent statistical and systematic uncertainties, respectively. Figure from Ref. [6]. Right: The ratio of the $\Psi(2S)$ and J/Ψ cross sections measured by ALICE in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Results are shown as a function of the number of participant nucleons and no correction for the branching ratios was applied. Data are compared to predictions from the TAMU [7] and SHMc [8] models. Results from the SPS NA50 experiment for Pb–Pb collisions at $\sqrt{s_{NN}} = 17.3$ GeV in $0 < y < 1$ [9] are also shown.

This is only one example of how ALICE uses charmonium production to characterise the evolution of heavy-ion collisions. Another example is the first measurement of $\Psi(2S)$ in Pb–Pb collisions down to zero p_{T} and in the rapidity region of $2.5 < y < 4$. As shown in Fig. 2 (right), a suppression by a factor of ~ 2 of the $\Psi(2S)$ with respect to the J/Ψ is observed, with no significant centrality dependence within the uncertainties. The comparison to transport [7] and statistical models [8] shows qualitative agreement, however, transport models better reproduce the measurements for central events.

A different approach to study the interaction of quarks in the QGP phase is the study of the modification of jet shapes in heavy-ion collisions. Recently, ALICE reported on how the population of jets changes in Pb–Pb collisions with respect to *pp* collisions when looking at distribution of the angle of the first hard splitting, having a narrower distribution in Pb–Pb with respect to *pp* [10]. This indicates that the jet core is more collimated in Pb–Pb than in *pp* collisions. Such a focusing effect could also explain the difference between the measured nuclear modification factor R_{AA} for jets with a large resolution parameter ($R = 0.6$) and the R_{AA} for narrower jets ($R = 0.2$) shown in Fig. 3. Indeed, the ratio between these two nuclear modification factors suggests that broader jets are more suppressed with respect to more focused jets.

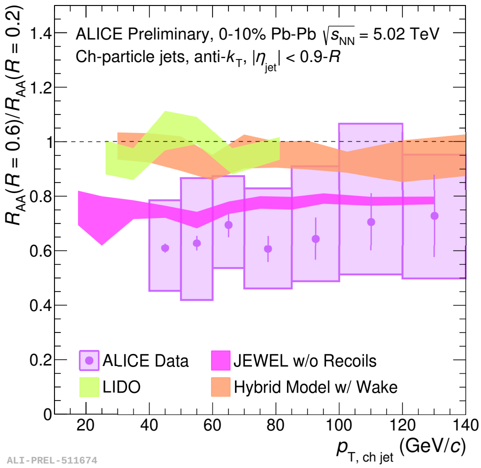


Fig. 3. Nuclear modification factor of jets with resolution parameter $R = 0.6$ divided by that of jets with $R = 0.2$ as a function of the jet transverse momentum.

The large system created in heavy-ion collisions is not only suitable for the characterisation of the QGP, but it can be used to study the antinucleosynthesis process in hadronic collisions. In particular, even after the large number of new measurements of antinuclei production in different colliding systems, it is still not clear what is the nucleosynthesis model at play in

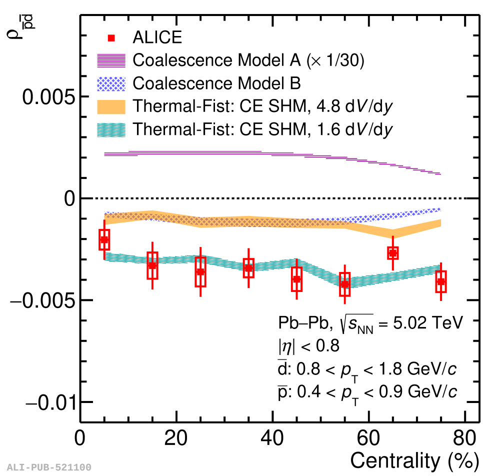


Fig. 4. The Pearson correlation between the measured $\bar{p}$ and $\bar{d}$ as a function of collision centrality in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Measured correlations are compared with estimations from the CE version of the SHM for two different baryon number conservation volumes and from a coalescence model. Figure from Ref. [11].

hadronic collisions. Indeed, both coalescence and statistical hadronisation models give very similar predictions for the average production yields in heavy-ion collisions [12]. The ALICE Collaboration uses the event-by-event fluctuations of the number of antinuclei produced in Pb–Pb collision and the Pearson correlation with the number of antiproton produced ($\rho_{\bar{p}\bar{d}}$) to distinguish between the coalescence and the statistical hadronisation model. Figure 4 shows $\rho_{\bar{p}\bar{d}}$ and how it compares to the expectations of simple coalescence [12] and the statistical hadronisation model [13]. The coalescence model is shown to be sensitive to the initial correlation among nucleons created in the collision, and only a fully uncorrelated configuration gives the correct sign of the $\rho_{\bar{p}\bar{d}}$. In the case of the SHM, the magnitude of the correlation can be explained by introducing a correlation volume $V_{\mathrm{c}} = 1.6\,\mathrm{d}V/\mathrm{d}y$ that does not fit other observables such as proton yields and event-by-event fluctuations [11]. This measurement requires some model extensions to understand light nuclei and other light flavour hadrons within the same framework.

3. Small systems and hadronisation

Since the discovery of the strangeness enhancement and of the double ridge structure in *pp* and *p*–Pb collisions, ALICE has put a lot of effort towards understanding which other typical heavy-ion observables are actually present in small systems. At this conference, the measurement of the v_2 of identified particles, fully corrected to account for non-flow effects, has been presented. The measurements have been carried out in both *pp* collisions at $\sqrt{s} = 13$ TeV and in *p*–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. As shown in Fig. 5, in both *pp* and *p*–Pb collision, a clear mass scaling is present for $p_{\mathrm{T}} < 2$ GeV/c. However, at larger transverse momenta, the data suggest

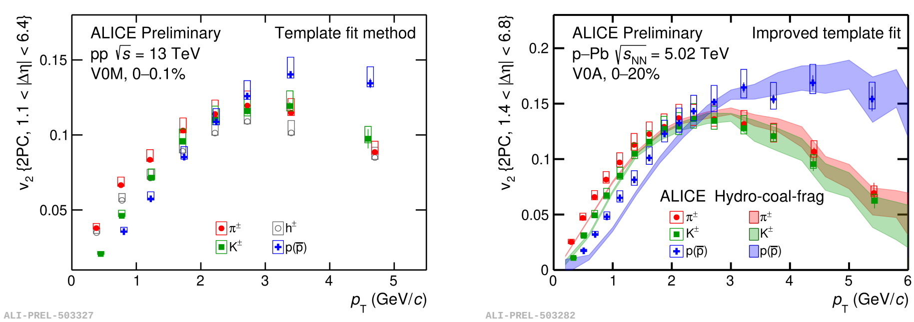


Fig. 5. (Colour on-line) Measured v_2 of charged pions (red dots), charged kaons (green squares), and protons (blue crosses) in *pp* collisions at $\sqrt{s} = 13$ TeV (left) and *p*–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV (right). The measurements in *p*–Pb collisions are compared with the predictions from a hydro model including both fragmentation and quark coalescence.

the presence of a scaling with the number of valence quarks of the hadrons. This is indicative of the presence of a quark coalescence mechanism in the hadronisation of the rapidly expanding fireball. This claim is further substantiated by the comparison with theoretical models: only hydrodynamical models including both quark fragmentation and quark coalescence are able to describe the observed flow for the different particle species in p–Pb collisions.

4. Hadron–hadron interactions

The study of femtoscopic correlations among hadrons produced in small colliding systems is a fundamental tool to complement our knowledge of the hadron–hadron interactions coming from scattering experiments. This method is not only used to explore regions of the phase space that would not be possible to measure with scattering experiments, but for short-lived particles devising such experiments would be impossible, hence femtoscopy is the only way to study their interactions with other hadrons. This is the case for charmed mesons, whose typical average lifetimes are of the order of 10^{-13} s. Recently, the ALICE Collaboration measured the correlation function between charged D mesons and protons, finding that the data are compatible with the Coulomb interaction within 2σ [14]. In this conference, new results on the correlation functions between charged D mesons and charged pions have been presented. By studying separately the correlation functions for the like-sign and opposite-sign pairs, as shown in Fig. 6, and simultaneously fitting them with an interaction model derived from lattice QCD, it is possible to extract for the first time the strong interaction scattering parameters of the interaction among charmed and light flavoured

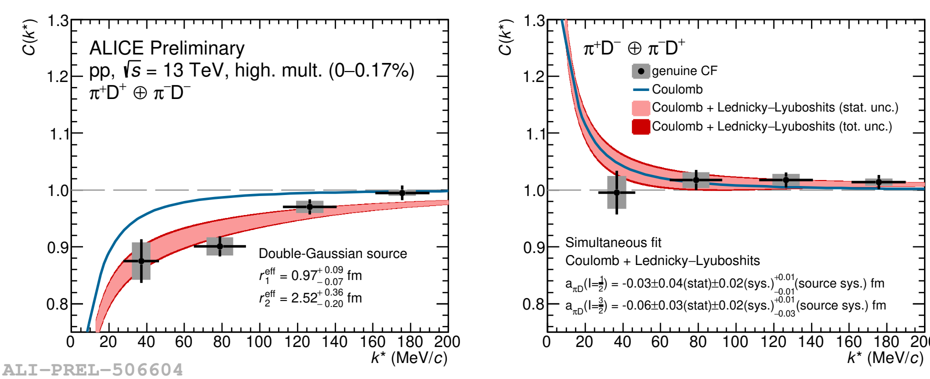


Fig. 6. (Colour on-line) Correlation functions for the same-charge D–π pairs (left) and the opposite-charge D–π pairs (right). The measured correlation functions are compared with the expectations from the Coulomb interaction only (blue/black line), and from the Coulomb and Strong interactions (red/grey line).

hadrons. This represents a significant step forward in the investigation of charmed hadron interactions and it has interesting applications for understanding the (non)interaction of D mesons with the surrounding particles in the hadronic rescattering phase.

5. The start of LHC Run 3

In July of this year, the LHC started its third physics run. Even before its start, on a few occasions some beam tests were performed for the benefit of the experiments in order to test their upgraded detectors. For the ALICE Collaboration, this has been an occasion to test its new apparatus: during the LHC shutdown, a completely new Inner Tracking System has been installed, the trigger detectors have been replaced as well, the readout chambers of the TPC have been changed to GEM detectors, and the readout of all detectors has been updated to allow the experiment to run in a triggerless mode. Such a large change in the configuration of the apparatus requires an extended physics performance validation. The first confirmation of the detector performance is the measurement of the charged-particle density in pseudorapidity ($\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$). The first measurement of $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ in pp collisions at $\sqrt{s} = 0.9$ TeV using the new ALICE apparatus is shown in Fig. 7. The new measurement is compatible within uncertainties with the analysis performed during the first runs of the LHC [15], giving confidence to the commissioning progress of the new ALICE apparatus.

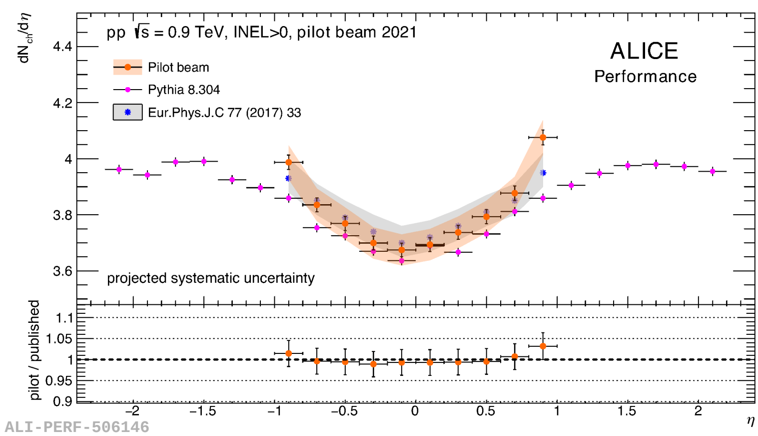


Fig. 7. (Colour on-line) Charged particle production as a function of pseudorapidity measured in pp collisions at $\sqrt{s} = 0.9$ TeV. The measurement performed with the new detector is shown as orange/light grey dots and it is compared with the measurement published during LHC Run 1 (blue/black points) and the expectations from PYTHIA 8 (purple/small grey dots). The lower panel shows the ratio between the new measurement and the published one.

REFERENCES

[1] ALICE Collaboration (S. Acharya *et al.*), *Phys. Lett. B* **834**, 137393 (2022).

[2] B. Schenke, C. Shen, D. Teaney, *Phys. Rev. C* **102**, 034905 (2020).

[3] G. Giacalone, F.G. Gardim, J. Noronha-Hostler, J.-Y. Ollitrault, *Phys. Rev. C* **103**, 024909 (2021).

[4] G. Nijs, W. van der Schee, U. Gürsoy, R. Snellings, *Phys. Rev. Lett.* **126**, 202301 (2021).

[5] D. Everett *et al.*, *Phys. Rev. Lett.* **126**, 242301 (2021).

[6] ALICE Collaboration, `arXiv:2204.10171 [nucl-ex]`.

[7] X. Du, R. Rapp, *Nucl. Phys. A* **943**, 147 (2015).

[8] A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel, *Nature* **561**, 321 (2018).

[9] NA50 Collaboration (B. Alessandro *et al.*), *Eur. Phys. J. C* **49**, 559 (2007).

[10] ALICE Collaboration (S. Acharya *et al.*), *Phys. Rev. Lett.* **128**, 102001 (2022).

[11] ALICE Collaboration, `arXiv:2204.10166 [nucl-ex]`.

[12] Z. Fecková, J. Steinheimer, B. Tomášik, M. Bleicher, *Phys. Rev. C* **93**, 054906 (2016).

[13] V. Vovchenko, H. Stoecker, *Comput. Phys. Commun.* **244**, 295 (2019).

[14] ALICE Collaboration (S. Acharya *et al.*), `arXiv:2201.05352 [nucl-ex]`.

[15] ALICE Collaboration (J. Adam *et al.*), *Eur. Phys. J. C* **77**, 33 (2017).