ALICE measures pA collisions: Collectivity in small systems?

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Abstract. Proton-nucleus collisions provide a reference for heavy ion-collisions, to study the signatures deriving from the presence of a complex nuclear structure in the initial state, which confirm that the suppression of high-\(p_T\) hadron production observed in heavy-ion collisions is a genuine effect of the hot deconfined QGP. However, several measurements of particle production in the low and intermediate momentum region indicate the presence of coherent and collective effects, already in small systems, such as the ones produced in p–Pb collisions. Measurements from proton-lead collisions at \(\sqrt{s_{NN}} = 5.02\) TeV obtained by the ALICE experiment at the CERN LHC will be presented and compared to p-p, A-A and d-A experimental results at different collision energies and to the available theoretical model predictions.

1. Introduction
In the field of heavy-ion collisions, the p–Pb physics program carried at the LHC at 5.02 TeV has developed from crucial control-experiments to study so-called cold nuclear matter (CNM) effects to an area where to find potential groundbreaking discoveries but also new challenges.

2. The control experiment
2.1. Charged Particle Multiplicity
The charged particle multiplicity density is a measure of the initial energy density and provides information on the dynamics of soft particle production and its relation to the initial collision geometry. The measurement, scaled by the mean number of participants from a Glauber model, is in line with the expectations from pp collisions. The rapidity distribution exhibits an asymmetric shape, which favors models that incorporate shadowing, while saturation models predict much steeper \(\eta\)-dependence not seen in the data [1].

2.2. Nuclear Modification Factors
The nuclear modification factor \(R_{pPb}\) tests if p–Pb collisions can be described as an incoherent superposition of \(N_{coll}\) binary collisions. The \(R_{pPb}\) measured by ALICE for charged particles [2], heavy flavor [3] and jets [4], show no deviations from unity at high-\(p_T\), as seen in figure 1. These observations combined with the binary scaling measured by CMS for direct photons and weak bosons [5–7] provide experimental evidence that the suppression observed in A-A collision [8] is a final state effect caused by parton energy loss.

ALICE also measured the \(R_{pPb}\) of \(J/\psi\) [9], which indicates a strong suppression at forward rapidity and no suppression in the backward rapidity region, in fair agreement with models

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incorporating shadowing and a mild energy loss. The impact of CNM effects, assumed to be dominated by shadowing, on heavy ion (AA) data, is calculated as the product $R_{pPb} \times R_{PbPb}$. Comparing to $R_{PbPb}$, a sizable $p_T$-dependent suppression is still visible in Pb–Pb, indicating that CNM effects are not enough to explain the high $p_T$ suppression observed in AA data, which can be therefore attributed to color screening. A hint of enhancement is visible at low $p_T$, possibly pointing to a recombination scenario.

3. Hints of collectivity?

3.1. Geometry effects

ALICE has carried out detailed studies of the centrality determination in p–Pb collisions and the possible biases induced by the event selection on the scaling of hard processes in a selected event sample [10]. In p–Pb collisions, the relatively large size of the multiplicity fluctuations induces a bias on a selection based on multiplicity, which decreases with increasing rapidity-gap between the tracking region and the estimator used for the selection. These fluctuations are partly related to qualitatively different types of collisions, e.g. hard collisions with large momentum transfers and/or multiple hard parton-parton interactions. In contrast, a centrality selection based on the energy deposited by nucleons produced in the nuclear de-excitation processes following the collision, or knocked out by wounded nucleons and measured with the ZDC in the Pb-going direction, should not induce such biases. The average number of binary nucleon-nucleon collisions for a given centrality class is obtained using the assumption that the charged-particle multiplicity measured at mid-rapidity is proportional to the number of participant nucleons.

The nuclear modification factor $Q_{pPb}$ (figure 2) calculated with mid-rapidity based multiplicity estimator (CL1) exhibits a strong multiplicity dependence. It also exhibits a negative slope in $p_T$, mostly in peripheral events, due to the jet-veto bias, as jet contribution increases with $p_T$. G-PYTHIA, a toy MC which couples Pythia to a p–Pb Glauber MC, agrees well with data for all $p_T$ in peripheral collisions and for high-$p_T$ in all multiplicity classes. This demonstrates that the proper scaling for high-$p_T$ particle production is an incoherent superposition of pp collisions, provided that the bias introduced by the centrality selection is properly taken into account. Using an unbiased selection (ZDC), the $Q_{pPb}$ are consistent with each other, and also consistent with unity for all centrality classes, as observed for MB collisions, indicating the absence of initial state effects. The Cronin enhancement, weaker at the LHC compared to RHIC energies, is stronger in central and nearly absent in peripheral collisions.

Figure 1. Transverse momentum dependence of the nuclear modification factor of charged particles measured in minimum-bias (NSD) p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in comparison to data on the nuclear modification factor $R_{PbPb}$ in central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV for charged particles, direct photon and weak bosons production.
3.2. Mean-$p_T$

To investigate particle production mechanism, we studied the first moment of the charged-particle transverse momentum spectrum, $\langle p_T \rangle$, and its correlation with the charged-particle multiplicity $N_{ch}$. An increase of $\langle p_T \rangle$ with $N_{ch}$ is observed, a feature which could be reproduced in PYTHIA only including color reconnections in the hadronization, which fuse the strings from independent parton interactions before hadronization, therefore leading to fewer, but more energetic hadrons. In Pb–Pb collisions, substantial rescattering of constituents leads to a redistribution of the particle spectrum where most particles are part of a locally thermalized medium exhibiting collective, hydrodynamic behavior, therefore leading to a moderate increase of $\langle p_T \rangle$. The p–Pb data, at low and high multiplicities, exhibit features of both pp and Pb–Pb collisions, respectively. However, the saturation of $\langle p_T \rangle$ versus $N_{ch}$ is less pronounced in p–Pb than in Pb–Pb collisions. None of the models, DPMJET, HIJING, or AMPT describes the p–Pb and Pb–Pb data, nor does the Glauber approach, indicating that $\langle p_T \rangle$ in p–Pb collisions is not a consequence of an incoherent superposition of nucleon-nucleon collisions [11].

3.3. The behavior of particles at low and intermediate $p_T$

Two-particle correlations are a powerful tool to explore particle production mechanisms in collisions of hadrons and nuclei at high energy. ALICE measured long-range correlations in p–Pb collisions. After subtracting the per-trigger yield of low from high-multiplicity events, to guarantee the suppression of short-range correlations, a double (near+away side) ridge structure emerges. The near and away side are almost identical, and identical for all event multiplicity classes, suggesting the same underlying physical origin [12].

A dense, strongly interacting system exhibiting hydrodynamic flow, such as the one formed in central A-A collisions, leads to a characteristic particle-species dependent modification of the $p_T$ spectra. Indeed, in A-A collisions, for $p_T < 2$ GeV/c, $v_2$ exhibits a particle-mass dependence as predicted by hydrodynamic model calculations (figure 3). At intermediate $p_T$ ($2 < p_T < 8$ GeV/c) the $v_2$ of mesons is smaller than that of baryons even for particle species with similar masses, which may be attributed to quark coalescence. ALICE has measured correlations of identified particles and extracted the $v_n$ flow coefficients [13]. We observe a clear non-zero flow and a mass ordering of $v_2$. In Pb–Pb $v_2$ is thought to arises from initial anisotropy of local
energy density, while the mass ordering arises from the interactions with the medium and their dependence on hadron mass. Measurements of the harmonic flow coefficient $v_3$, also known as triangular flow, indicate that initial state fluctuations modulate the overlap area, and provide additional constraints on the transport coefficients of the system (e.g. the value of the shear viscosity over entropy ratio). The $v_3$ measured in pp and p–Pb collisions are consistent for the same event multiplicity, possibly indicating the presence of global azimuthal correlations, which would be a sign of collectivity.

In the intermediate momentum region, the baryon-over-meson enhancement studied using $p/\pi$ and $\Lambda/K_S^0$, shows a clear evolution with multiplicity in p–Pb collisions (figure 3). At mid-$p_T$ the ratio increases with multiplicity, while at low-$p_T$ a corresponding depletion is observed. This behavior is reminiscent of Pb–Pb phenomenology, where this is generally understood in terms of collective flow or recombination.

3.4. The behavior of different particle species

The $p_T$ spectrum measured for identified particles in p–Pb collisions is compared to the one measured in pp collisions. The nuclear modification factor $R_{pPb}$ measured for the different particle species in the intermediate $p_T$ region shows a clear indication of mass ordering, with no enhancement for pions and kaons, and a pronounced peak visible for protons and even stronger for $\Xi$ and $\Omega$ (figure 4). The production of strange hadrons in high-energy hadronic interactions provides a key tool to investigate the properties of QCD because, unlike u and d quarks, s quarks are not present as valence quarks in the initial state, but are sufficiently light to be abundantly created in the collisions. This is even more so in a highly excited state of QCD matter, such as the one produced in A-A collisions, where a strangeness enhancement is observed with a hierarchy depending upon the number of strange quarks. ALICE studied the evolution of the yield of strange and multi-strange hadrons across collision systems. For the first time in pp and p–Pb collisions a significant enhancement of strange to non-strange hadron production is observed (figure 4). The observed enhancement follows a hierarchy with the number of strange valence quarks. The study, carried as a function of charged particle multiplicity, which is related to the energy density of the system, indicates a smooth evolution with multiplicity. No enhancement is observed for particles with no strange quark content, demonstrating that the observed effect is strangeness rather than mass related. The results are not reproduced by any of the Monte Carlo models commonly used at the LHC, suggesting that further developments are needed for a complete microscopic understanding of strangeness production and indicating the presence of a phenomenon novel in high-multiplicity pp collisions [14].

Figure 3. Left: The Fourier coefficient $v_2$ for hadrons, pions, kaons and protons as a function of $p_T$ from the correlation in the 0-20% multiplicity class after subtraction of the correlation from the 60-100% multiplicity class. Right: $p_T$-differential $\Lambda/K_S^0$ ratio for different multiplicity classes in pp at 7 TeV, p–Pb at 5.02 TeV and Pb–Pb at 2.76 TeV.
Figure 4. Left: Nuclear modification factor $R_{pPb}$ of charged particles and multi-strange baryons in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Right: $p_T$-integrated yield ratios of (multi-) strange hadrons to pions as a function of multiplicity in pp ($\sqrt{s_{NN}} = 7$ TeV), p–Pb (5.02 TeV) and Pb–Pb (2.76 TeV) collisions, compared to calculations from MC models.

4. Conclusions
As control experiment, p–Pb collisions prove that the suppression of hard probes observed in Pb–Pb collisions are genuine QGP effects. Furthermore, many intriguing surprises have emerged, suggesting that collective effects may also be present at high multiplicities in small systems.

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