Overview of ALICE Results

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Abstract. Recent results from the ALICE Collaboration are presented and discussed. Special emphasis is given to measurements relevant for strangeness and open and hidden heavy flavor physics.

1. Introduction
The main goal of ultra-relativistic heavy-ion collisions is the study of the deconfined phase of QCD matter, known as the Quark-Gluon Plasma (QGP). Current research aims at precisely determining properties of the QGP. In particular, a significant effort is being dedicated to the determination of its transport properties (such as shear and bulk viscosity), to the understanding of its microscopic structure (what are the relevant degrees of freedom?) and the mechanism of hadronization. Flavor plays a crucial role in this program, as extensively discussed during this conference.

The recent observations in pp and pA collisions of features traditionally associated with the formation of a deconfined phase, highlights the importance of studying the energy and system-size dependence of the relevant observables, rather than simply focusing on the largest system at the highest center of mass energy.

In this work, recent results from the ALICE collaboration are reviewed, focusing on the measurements presented at this conference, with particular emphasis on strangeness and heavy flavor measurements.

The ALICE apparatus is composed of a central barrel, covering $|\eta| < 0.8$ for full-length tracks and providing tracking and particle identification in the transverse momentum region $p_T \gtrsim 0.1 \text{ GeV}/c$. The first two layers of the central barrel are made of silicon pixel detectors (SPD) and can be used to reconstruct short track segments pointing to a common origin (tracklets). The central barrel is complemented by a forward muon arm, covering $-4.0 < \eta < -2.5$. A detailed description of the ALICE apparatus can be found in [1].

2. Flow and bulk properties
One of the main surprises from the first pA data taken at the LHC was the observation of long-range structures in two-particle correlation measurements (the so-called ridges) [2, 3, 4, 5, 6]. These structures, in fact, are typically associated with collective flow effects, and indeed hydrodynamic models could give a satisfactory description of the data (see e.g. [7]). At the same time, alternative explanations based in particular on saturation physics (e.g. color-glass condensate [8]) could qualitatively account for the effects seen in the data.
These measurements have recently been extended significantly in $\Delta \eta$, with the measurement of correlations between muons observed at large rapidities in the muon arm and tracklets reconstructed at mid-rapidity in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [9, 10]. The LHC provided p–Pb collisions in two configurations, with Pb nuclei circulating either clockwise or counterclockwise. This allowed the study of muons both in the Pb-going and p-going directions, with the correlation measurements covering the range $1.5 < |\Delta \eta| < 5$. Figure 1 shows the elliptic flow coefficient $v_2$, obtained subtracting the correlation function measured in low multiplicity collisions from the one in high multiplicity collisions, to reduce the contribution of jet fragments correlations ($v_2^2 \{2\text{PC}, \text{sub}\}$) [10]. The $v_2^2 \{2\text{PC}, \text{sub}\}$ is about 16% higher in the Pb-going direction, as one would qualitatively expect in case of hydrodynamic flow [11]. The measurement is also compared to a corresponding AMPT [12] calculation. The $v_2^2 \{2\text{PC}, \text{sub}\}$ in the data is significantly higher than in the simulation for $p_T > 2$ GeV/c. In this $p_T$ range, the production of muons is dominated by heavy flavor decays, which have zero $v_2$ in AMPT. This result could indicate a finite $v_2$ of heavy flavor particles or significantly different parent distributions in data and AMPT.

Other observables traditionally associated with radial flow are the ratios between baryon and mesons, such as $p/\pi$ and $\Lambda/K_0^0$, which show a strong enhancement (up to a factor $\sim 5$) in central Pb–Pb collisions. A similar enhancement was also observed in high multiplicity pA collisions [13, 14]. The ALICE collaboration has shown that, in the 0-5% most central Pb–Pb collisions, the main factor driving these ratios is the different mass of the particles: the ratio $\phi/p$ was indeed found to be flat out to $p_T \sim 5$ GeV/c [15, 16]. In a new measurement presented at this conference [17], it was shown that the ratio $\Lambda/K_0^0$ is consistent with the one measured in pp collisions for particles associated with a reconstructed jet (Fig. 2). This poses a challenge for models which describe the enhancement via the recombination of semi-hard quarks from jet fragmentation with thermal partons from the medium.

3. Energy loss
The detailed study of high-$p_T$ partons energy loss and energy redistribution provides a tool to identify the microscopic nature of the QGP.
The ALICE experiment has recently published results on a new observable $\Delta_{\text{recoil}}$, built from hadron-jet correlations subtracting the contributions of random associations on a statistical basis, see [17, 18] for a detailed discussion. This allows the study of jet modifications out to larger radii (up to 0.5 in the resolution parameter $R$) and down to lower jet momenta ($\langle p_T \rangle_{\text{jet},\text{ch}} = 20$ GeV) than previous measurements. This variable was also used to study the angular distribution of the recoil jets. The results do not show any evidence for intra-jet broadening, no evidence of medium-induced acoplanarity and no signal for large-angle (Molière) parton-medium scattering: they are consistent with a largely homogeneous medium.

The study of the particle-species dependence of the energy loss is a powerful tool to differentiate different energy loss models. Species-dependent effects could be caused by in-medium modifications of jet fragmentation and are expected to arise as a consequence of the mass dependence of energy loss. In general, due to color factors, gluons are expected to lose more energy than heavy quarks and light quarks, due to the “dead cone” effect, are expected to lose more energy than heavy quarks. Quarks and gluons, however, are not directly accessible experimentally and the simplest way to study these effects is the “nuclear modification factor” $R_{AA}$ for different particle species.

The ALICE experiment has performed an exhaustive study of identified-particles $R_{AA}$, both in the light and in the heavy quark sector. In the light flavor sector, no difference between different particle species has been observed above $p_T > 10$ GeV/c, establishing the baseline for heavy flavor studies [19]. Below this $p_T$ threshold, mass-dependent bulk effects become important.

The $R_{AA}$ for D mesons is found to be in agreement with that of the pions in Fig. 3 [20, 21]. At the momenta depicted in the figure ($p_T > 8$ GeV/c), the charm quark behaves essentially as a light quark, while pions are expected to originate mostly from gluons at LHC energies. Considering hadrons $R_{AA}$ as a proxy for the corresponding parton (quark or gluon) $R_{AA}$, one would naively expect pions to be more suppressed than D mesons. The agreement observed in Fig. 3 can however be understood as being due to an interplay of parton energy loss and the

**Figure 2.** $\Lambda/K_S^0$ ratio inside jets.

**Figure 3.** $R_{AA}$ of D mesons, pions and non-prompt $J/\psi$. 

\[ R_{AA} = \frac{N_{\text{coll}}/N_{\text{coll}}}{N_{\text{disc}}/N_{\text{disc}}} \]

\[ N_{\text{coll}} = N_{\text{coll}}/N_{\text{coll}} + N_{\text{coll}}/N_{\text{coll}} \]

\[ N_{\text{disc}} = N_{\text{disc}}/N_{\text{disc}} + N_{\text{disc}}/N_{\text{disc}} \]
effect of fragmentation functions (see e.g. [22]).

The same figure also shows the CMS measurement of the $R_{AA}$ of non-prompt $J/\psi$ [23], which originate from the decay of B mesons. The difference between non-prompt $J/\psi$ and D mesons is the first clear indication of mass-dependent energy loss. These measurements have also been recently extended, with the ALICE study of low $p_T$ non prompt $J/\psi$ [24] and of the $D^+_s$ meson [25]. The latter is of particular interest because of the interplay with strangeness enhancement and could be sensitive to recombination effects.

4. Study of possible nuclear modifications at High-$p_T$ in pA

The observation of collective-like effects in pA collisions (suggestive of the formation of a thermalized medium) and the ample evidence for energy loss and high-$p_T$ suppression in Pb–Pb collisions lead to the natural question of whether high-$p_T$ energy loss can also be observed in small systems.

A number of early publications did not find any indication for such effects in minimum-bias p–Pb collisions. The $R_{pPb}$ was found to be consistent with unity for charged hadrons [26, 27], jets [28], D mesons [29] and heavy flavor decay leptons [30]. Other correlations and jet measurements [31] also indicate result consistent with proton-proton collisions.

A natural extension is the study of high multiplicity p-Pb collisions, which is however complex due to the difficulty in defining a reliable measurement of “centrality”. While centrality has a clear and non-ambiguous geometrical interpretation in Pb–Pb collisions, multiplicity dependent studies in small systems are sensitive to local multiplicity fluctuations and the relatively low multiplicity leads to large non-trivial biases for the centrality selection. The nuclear modification factor is called in this case $Q_{pPb}$ to highlight that it is potentially affected by dynamical biases. These become stronger when the regions used for the measurements and to define the centrality classes are overlapping or close in phase space. They can be quantitatively understood in a simulation in which $n$ Pythia collisions are superimposed, based on the number of binary collisions sampled from a Glauber Monte Carlo [32, 33]. To minimize their effect, the ALICE collaboration employed a hybrid approach [32, 33], in which the multiplicity classes are selected using the neutron Zero Degree Calorimeter in the Pb-going direction (ZN, the ALICE detector farther away from mid-rapidity). The number of binary collisions is then calculated with several assumptions for scaling properties of particle production: i) assuming that $dN_{ch}/d\eta$ at mid-rapidity scales with the number of participants, ii) assuming that the multiplicity in the Pb-going direction scales with the number of wounded target nucleons or iii) assuming that particle production at high $p_T$ scales with the number of binary collisions. The three assumptions give consistent results. As an example, the $Q_{pPb}$ of charged particles, computed with the first two assumptions is shown in Fig. 4. It is consistent with unity for $p_T \gtrsim 10$ GeV/c.

5. Cold Nuclear Matter effects

The traditional motivation for the study of pA collision is to provide a reference for Pb–Pb measurements and assess the so-called “Cold Nuclear Matter” (CNM) effects, that is effects related to the presence of the nucleus, but not associated to the formation of a deconfined medium. Examples of CNM effects include, for instance, nuclear modifications of the parton distribution functions or the effect of hadronic co-movers.

While recent results indicate phenomena beyond CNM in pA collisions (Sec. 2), it remains of central importance for the interpretation of heavy-ion collisions results to understand CNM effects. Figure 5 shows the $R_{pPb}$ of the $J/\psi$ and of the $\Psi(2S)$ as a function of rapidity, $y$ [34, 35]. The $R_{pPb}$ of the $J/\psi$ is consistent with unity at backward rapidity (the Pb-going direction), and suppressed at mid- and forward rapidity (the p-going direction). This trend can be explained by models which include nuclear modifications of the parton distribution functions (shadowing), with a contribution from energy loss. This is studied in more details in Fig. 6, which shows
Figure 4. $Q_{pPb}$ for charged particles, as a function of centrality, obtained in bins of ZN energy, with $N_{\text{coll}}$ computed assuming a that the $dN_{\text{ch}}/d\eta$ at mid-rapidity scales with the number of participant (left) or assuming that the multiplicity in the Pb-going direction scales with the number of wounded target nucleons (right).

the $Q_{pPb}$ of the $J/\psi$ as a function of the number of binary collisions (obtained with the hybrid method described in Sec. 4) [36]. Shadowing is necessary to describe the multiplicity dependence of the data, especially at backward rapidity.

Figure 6 also depicts the $R_{pPb}$ of the $\Psi(2S)$, which shows a different trend as compared to that of $J/\psi$, being similarly suppressed at backward and forward rapidities. This trend is somewhat surprising, as initial state effects should not differentiate between the two charmonium states. It can be understood in models which incorporate the effect of hadronic co-movers. While the effect of co-movers is expected to be stronger in the Pb-going direction, the effect of shadowing is stronger in the p-going direction. The two contributions seem to balance each other. At the same time, it should be noted that the co-movers model would predict a flatter-than-measured multiplicity dependence of the $J/\psi$ $Q_{pPb}$ (Fig. 6).

An alternative way of studying shadowing effects and the initial-state nuclear wave function is through “ultra peripheral collisions.” With this term, we refer to inelastic collisions where the impact parameter is larger than twice the nuclear radius. In these collisions, the scattering process is initiated by the photons produced in the strong electric field of the nuclei (“photo-production”). Models including moderate shadowing give a good description of the data on photo-production of vector mesons. Recent results are discussed in [37]. The ALICE collaboration has also recently reported an excess of $J/\psi$ production at low $p_T$ in peripheral Pb–Pb events: this could be the first indication of $J/\psi$ photo-production in collisions with impact parameter smaller than twice the nuclear radius [38] (i.e. with a finite nuclear overlap).

6. Hadrons and the hadronic phase

The ALICE experiment recently reported new results on the enhancement of strange particles at the LHC. Figure 7 shows the ratios $\Xi/\pi$ (left) and $\Omega/\pi$ (right) measured in pp, p–Pb and Pb–Pb collisions [14]. The two ratios are seen to increase as a function of multiplicity in p–Pb reaching, for the highest measured multiplicities, values comparable to central (peripheral)
Pb–Pb collisions in the case of the Ξ (Ω). This could be interpreted as a release of canonical suppression in p–Pb collisions, even if the quality of a grand canonical fit of high multiplicity p–Pb collisions is rather poor ($\chi^2/ndf \sim 5$) [14].

On the other hand, a grand canonical fit in central Pb–Pb collisions yields fair agreement with the data, although some tensions are still observed ($\chi^2/ndf \sim 2$) [39]. In particular the measured proton yield is lower than predicted by the model (protons would prefer a lower temperature), while strange baryons are in general higher (would point to a larger temperature). These tensions have been extensively debated in the literature, and several explanations have been proposed, including an incomplete hadron spectrum [40, 41], sequential freeze-out [42, 43, 44] and interactions in the hadronic phase [45] (for a review, see [46, 47]).

Other measurements reported at this conference will allow to better constrain the effect of the hadronic phase, including one-dimensional femptoscopic radii of identified particles [48] and resonance production as a function of centrality [15]. These result suggests that at least elastic scattering in the hadronic phase is playing a relevant role. The same hadronic-cascade model
used to describe these data (UrQMD) predicts a significant suppression of baryons, because of baryon-antibaryon annihilation. However, this point is not yet established, for instance because of the lack of some inverse reactions in the model. Moreover, it is not yet clear how the presence of significant inelastic processes in the hadronic phase can be reconciled with the fact that loosely bound objects such as light (anti-)nuclei and hypertritons survive the hadronic phase, being produced with a rate consistent with the equilibrium thermal model calculations [49].

These studies of particle abundances also provide a baseline for exotica searches. In particular, the ALICE experiment searched for ΛΛ and Λn bound states in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, placing upper limits $\gtrsim 4$ times smaller than the yield expected from the thermal models [49], when lifetimes consistent with theoretical expectations are assumed for the dibaryons, namely not exceeding $10^{-8}$ s.

7. Outlook

The ALICE collaboration is completing the campaign of analysis based on the data collected during the first run of the LHC. Additional results presented at this conference, but not covered in this summary include dilepton production [50, 51], W meson production [52] and D meson production as a function of multiplicity in pp and p–Pb collisions [53]. These new results are posing stringent constraints on the modelling of the hydrodynamic evolution of the system created in heavy-ion collisions, of its microscopic structure, of the initial state configuration and of the late stage of evolution. At the same time, the study of small systems has been extended with more differential measurements, in order to investigate the possible formation of a collective medium.

The LHC resumed the operations for the second data taking run recently, with the first pp collisions at $\sqrt{s} = 13$ TeV taking place at the beginning of June. A Pb–Pb run at $\sqrt{s_{NN}} = 5$ TeV will follow, pushing the energy frontier of heavy-ion collisions. At the same time, the ALICE experiment is preparing for a significant upgrade for the high luminosity measurements, foreseen in run four [54, 55].

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