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Highlights from the ALICE experiment

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This contribution summarises the main highlights presented by the ALICE collaboration at the EPS-HEP 2017 conference. A particular emphasis is put on the recently observed similarities between results obtained in proton-proton, proton-nucleus and nucleus-nucleus collisions, and on the implications of these observations for the interpretation of hadronic collisions in general.

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1. Introduction

The main goal of experiments which study collisions of heavy nuclei at ultrarelativistic energies is to produce and characterise the high-temperature phase of strongly interacting matter. Lattice Quantum-Chromodynamics (QCD) calculations, indeed, predict at a temperature $T \gtrsim 155$ MeV the existence of a new state of matter, where quarks and gluons are not confined inside hadrons and chiral symmetry is partially restored [1]. This phase is known as "Quark Gluon-Plasma" (QGP). Collisions of lead nuclei at a centre of mass energy of several TeV are being studied at the LHC, with contributions from all four major experiments. In this contribution we report on some recent highlights from ALICE, the only LHC experiment fully dedicated to the study of heavy-ion collisions. The goal of current research is twofold: on the one hand the precise measurement of the *macroscopic* properties of the QGP, on the other hand the understanding of its *microscopic* structure and degrees of freedom, in terms of quasi-particles or excitations.

The study of the QGP requires measurements in all the colliding systems provided by the LHC. In the traditional *modus operandi* of heavy-ion experiments, the QGP is expected to be created only in (central) Lead-Lead (Pb–Pb) collisions. Proton-proton (pp) collisions provide an experimental reference with respect to which modifications induced by the presence of the QGP are measured. Proton-Lead (p–Pb) collisions have been motivated as a "control experiment", to assess the effect of the nucleus in the initial state, but where the QGP is not expected to be created. Nuclear-induced modifications of the parton distribution functions are an example of the "Cold Nuclear Matter" (CNM) effects which can be studied with with p–Pb collisions. As will be argued in the following, however, recent measurements in pp and p–Pb collisions question this traditional distinction between the three colliding systems. Phemonena which were considered to be hallmarks of heavy ion collisions are now seen also in the smaller systems, suggesting a similar underlying physical origin. The observation was initially made in rare high-multiplicity events, but it now seems to be relevant also for minimum-bias collisions. These results are leading to a more realistic description of (bulk) multiparticle production in all hadronic collisions.

2. Hadronisation, Particle Spectra and Abundances

The study of identified, and in particular strange, hadrons has traditionally had an important role in the field of heavy-ion collisions. An enhancement of strange particles in Pb–Pb relative to pp collisions was one of the first suggested signatures of deconfinement [2], and was actually observed by several experiments (see [3] and references therein). Strangeness enhancement was considered to be a hallmark of heavy-ion collisions, even if at present there is no consensus on its interpretation as a signature of deconfinement.

The ALICE experiment recently released a set of measurements on the production of strange hadrons as a function of multiplicity in the three colliding systems (pp, p–Pb, Pb–Pb) [4, 5, 6]. Figure 1 shows the ratio of several strange hadrons to pions. A smooth increase of strangeness with multiplicity across all colliding systems is seen, with the abundance of particles with higher strangeness content increasing at a faster rate. The observation of a relative strangeness increase with multiplicity in pp collisions was an unexpected result. It challenges the idea that the fragmentation parameters of QCD strings can be fixed in elementary (e^+e^-) collisions and used across

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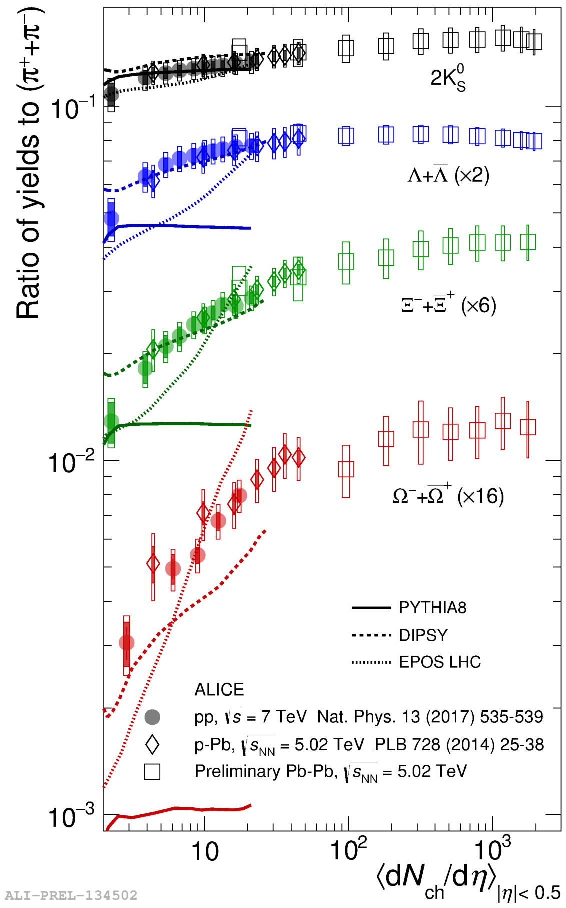

Figure 1: Ratios of strange hadrons to pions in pp, p–Pband Pb–Pb collisions (see text for details).

different colliding systems (jet universality), which is at the base of many general-purpose soft QCD models, such as PYTHIA [7]. It is interesting to notice that two of the models shown in Fig. 1 (EPOS-LHC and DIPSY) predict strangeness enhancement, albeit the data are not reproduced quantitatively. While the models differ significantly in the physics mechanisms that they implement, both seem to indicate that Multiple-Parton Interactions (MPIs) and final-state effects play an important role in the production of identified hadrons [8, 9]. These new data are also of crucial importance for the identification of the relevant strangeness enhancement scaling variable, as discussed for instance in [10, 11, 12].

New results on identified light-flavour hadron production in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV [6] and in minimum-bias pp collisions at $\sqrt{s} = 5$ and 13 TeV were also presented [5]. These new measurements represent the baseline for a precision study of hadronisation across all systems. In particular, the high-statistics data sample which is being collected in pp collisions at $\sqrt{s} = 13$ TeV (see sec. 5) will allow the study of strangeness production in a multiplicity range overlapping with Pb–Pb collisions.

The measurement of heavy-flavour hadrons is also important to understand the role of MPIs and possible final-state effects. Recent results [13, 14] show that the J/Ψ meson yield increases with event activity faster than the charged hadron yields, and that the rate of increase of heavy-

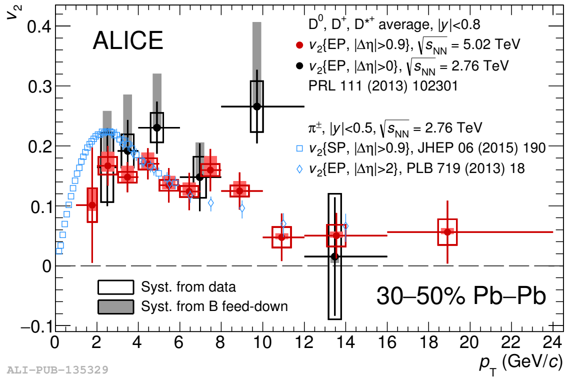

Figure 2: Nuclear modification factor R_{AA} of D mesons in semi-central Pb–Pb collisions (see text for details).

flavour is possibly non-linear. Since heavy-flavour production can be expected to scale with the number of semi-hard MPIs, while bulk particle production may be more affected by final state effects, these data provide useful constraints for a realistic description of hadronic collisions. The hadronisation of heavy flavor particles is an interesting open problem in itself. The first LHC results on mid-rapidity Λ_c^+ and Ξ_c^0 production presented at this conference show that charmed baryons are under-predicted by all available theoretical calculations by large factors (between 3 and 10) [15].

Finally, heavy-ion collisions are an excellent factory for the study of nuclei and hyper-nuclei, and allow constraining the properties and elucidating the production mechanism of compound objects in hadronic collisions. Among the many results presented at this conference [16], we emphasise new data on the production of deuteron as a function of multiplicity across all colliding systems, which hints at an intriguing non-monotonic trend, and one of the most precise measurements of the hyper-triton lifetime. These data are also essential to shed light on the nature of more exotic hadron molecule states, such as tetra-quark candidates.

3. Collective Expansion

A cornerstone in the standard interpretation of heavy-ion collision data is that, following an early thermalisation, the deconfined system expands under the effect of thermal pressure gradients. A consequence of this interpretation is that particles move in a common velocity field and are hence "blue-shifted" towards larger momenta [17], with the momentum shift being more pronounced for heavier particles. This behaviour is known as "radial flow". New high-precision measurements in RUN 2 Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV confirm the expected increase with collision centrality of the average transverse momentum of identified particles [18].

A striking observable consequence of radial flow is the evolution of the ratios of baryons over mesons as a function of p_T and centrality. For instance, the ratios proton-over-pion and Λ-over-K_S^0 reach values close to unity at intermediate $p_T \simeq 3$ GeV/c in central Pb–Pb, a factor 3-4 higher than corresponding measurements in minimum-bias pp collisions. The increase at intermediate p_T is accompanied by a corresponding decrease at low p_T. In the generally accepted interpretation, this is a consequence of the radial flow, which pushes the heavier baryons in a more pronounced way than the lighter mesons [18]. A similar increase of the baryon-over-meson ratios as a function of event activity (charged particle multiplicity) has also been reported for pp and p–Pb collisions [5]. Even if the magnitude of the effect is less pronounced in the smaller colliding systems (possibly as a consequence of the smaller multiplicity range probed), this observation raises the question whether the same interpretation in terms of collective expansion is applicable. The high statistics data collected in pp collisions at $\sqrt{s} = 5$ TeV and, in particular, $\sqrt{s} = 13$ TeV, enhanced by dedicated high-multiplicity triggers, will allow the ALICE collaboration to address this question in detail [5].

Another very non-trivial consequence of the collective expansion interpretation is the "anisotropic flow". In a non-central nuclear collision, the overlap (interaction) volume between the two nuclei is not spherically symmetric. This leads to an azimuthally asymmetric distribution of the pressure gradients, which transports the initial-state geometric anisotropy to a final state momentum-space anisotropy. The final-state momentum anisotropy can be actually measured and is commonly quantified in terms of the harmonic coefficients v_n of a Fourier series expansion of the particles momentum distributions. The v_n coefficients are one of the most-studied observables in heavy ion collisions, because they are sensitive to all phases of the system evolution: initial conditions, transport in the QGP phase, hadronisation [19]. In particular, it was recently realised that fluctuations of the gluon densities at a sub-nucleonic level may play an important role for precision studies or when performing these measurements in smaller colliding systems [20]. The ALICE experiment recently extended these studies with the RUN 2 Pb–Pb data, at a centre-of-mass energy of 5.02 TeV [21]. In particular, new results for the v_n coefficients of identified particles were reported. They show a mass ordering consistent with the collective expansion interpretation [22] Surprisingly, the phenomena have also recently been observed in pp and p–Pb collisions [23]. This raises a number of fundamental questions on the interpretation of the data. Two main classes of models are invoked to explain the observation: either the same collective expansion interpretation holds for small systems, or the correlations seen in the data are created directly in momentum-space in the initial state, as a consequence of gluon saturation [24]. The similarity between the results in pp/p–Pb and in Pb–Pb collisions raises a question on how close the system gets to thermal equilibrium. Indeed, even within the framework of the hydrodynamic models which successfully describe the data, it is found that pp collisions are out of equilibrium for most of their evolution. It is therefore apparent that hydrodynamic modelling successfully describes the data far from thermal equilibrium and this may lead to a radical change in the interpretation of heavy-ion data [25].

The study of heavy-flavour hadron collective effects can help to gain insight into the physics mechanism underlying these phenomena. Heavy flavour quarks, in fact, can only be created by hard processes in the early stages of the collisions, and propagate in the medium throughout its evolution, acting as tagged probes. The study of heavy-flavour hadrons collective effects can therefore shed light on the thermalisation process and hence on the physical origin of the "collective" effects. In particular, as shown in Fig. 2, ALICE reported at this conference new results for the p_{T}-dependece of the v_2 coefficients of D mesons in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. These data confirm the previous observation of a significant J/Ψ v_2 [26, 27, 28]. The non-zero v_2 of the J/Ψ (a $c\bar{c}$ state) indicates that the c quark actually takes part in the collective expansion. Comparing this to the v_2 of D mesons (c-light flavour states) can help to understand the hadronisation mechanism of heavy-flavour, if part of the flow is acquired by D mesons via coalecence of the c quark with light quarks from the expanding medium. The measurement of the D_s v_2 is particularly interesting in this context, since the s quarks are enhanced in heavy-ion collisions (sec. 2).

4. Hard Processes

Hard QCD processes represent a prime tool to gain information on the microscopic structure of the quark-gluon plasma. The basic idea is that preturbatively-produced partons will loose energy interacting with the hot QCD medium while propagating through it, a phenomenon known as “jet quenching”. Different parton types are expected to loose energy predominantly through different mechanisms. From this energy loss it is in principle possible to infer the microscopic properties and structure of the medium [29].

From an experimental point of view, the simplest measurement which can be done to quantify jet quenching is the “nuclear modification factor” R_{AA}, that is the ratio between a quantity measured in Pb–Pb collisions and the corresponding quantity measured in pp scaled by the effective number of nucleon-nucleon collisions, which quantify the increased effective luminosity in Pb–Pb collisions. A $R_{\mathrm{AA}} = 1$ at high p_{T} indicates negligible jet quenching effects. At low p_{T}, on the other hand, the value of R_{AA} is not related to jet quenching and energy loss, as soft processes are in general not expected to scale with the number of binary nucleon collisions.

Fully reconstructed jets were found to be strongly suppressed in Pb–Pb collisions, with $R_{\mathrm{AA}} \simeq 0.4$ [30]. New results for the R_{AA} of D mesons were presented by the ALICE collaboration [27]. These new data feature much reduced uncertainties as compared to corresponding RUN 1 results, and are important to constrain the parton and mass dependence of energy loss. Improved techniques for the tagging of jets were discussed in [31]. The R_{AA} of the J/Ψ plays a special role in the understanding of deconfinement and hadronisation. The QGP, indeed, is expected to (Debye) screen the interaction between the c and $\bar{c}$ quarks, leading to a suppression of the J/Ψ. At the same time, if many $c\bar{c}$ pairs are produced in the initial hard scattering, and a deconfined medium is formed, it is possible that an uncorrelated pair of c and $\bar{c}$ will “coalesce” at the end of the evolution to form a J/Ψ. Within this interpretation one would expect a stronger J/Ψ suppression at RHIC energies, $\sqrt{s_{\mathrm{NN}}} = 200$ GeV (where only a few $c\bar{c}$ pairs are produced per collision), than at the LHC (where hundreds of pairs per central collision are produced). This is exactly what is observed in the data [28].

A more differential way to study energy loss is to look at the internal structure of jets, using jet shapes and jet sub-structure variables. Jet shapes are constructed taking the weighted sum over the four-momenta of all jet constituents, and provide information on the parton-to-jet fragmentation, on modifications to the intra-jet energy distribution (e.g. broadening or collimation), and on the parton-type dependence of energy loss (e.g. quark/gluon differences). The picture emerging from several jet shapes measurements in pp, p–Pb and Pb–Pb collision is that of very similar shapes in pp and nuclear collisions, with a hint for slightly more collimated jets [30, 32]. As an example, the first measurement of the jet mass in Pb–Pb collisions in three p_{T} bins is compared in Fig. 3 with several theoretical models [30, 33].

Finally, the observation of similarities in hadron production and correlation (collective) effects discussed in sec. 2 and sec. 3 raises the obvious question of whether jet quenching effects are also present in small systems. No clear hints have been observed in pp or p–Pb collisions so far [14, 34, 32], but this remains a very active area of investigation. It is important to notice that hard processes in p–Pb and Pb–Pb collisions could also be modified by initial state effects, such as nuclear modifications of the parton distribution functions. Ultra-peripheral Pb–Pb collisions,

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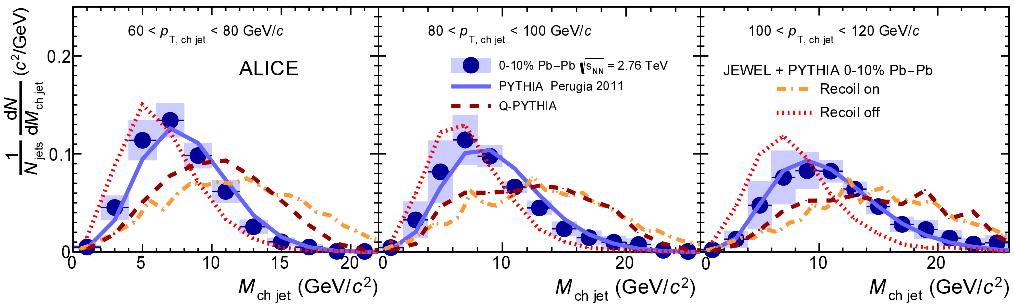

Figure 3: Mass distribution of charged jets in three transverse momentum bins, in central Pb–Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV (see text for details).

that is collisions where the impact parameter is larger than twice the Pb radius, can be used as an alternative method to constrain initial state effects. In these processes, a photon produced by the strong electro-magnetic field of the "projectile" nucleus interacts with the "target" one. The LHC is hence effectively used as a $\gamma-$Nucleus collider and the nucleus is examined with a clean probe. Recent results indicate moderated shadowing [35].

For a complete review of the hard probes results presented at EPS-HEP, see [36].

5. Data Taking and Upgrade Programme

The RUN 2 data harvesting of the ALICE experiment is well in progress. Among the highlights expected for the upcoming data taking periods are the collection of a large sample of pp data at the reference energy (1 pb^{-1} at $\sqrt{s}$ = 5.02 TeV), the completion of the high-multiplicity data taking in pp collisions at 13 TeV (2.5 billion of high-multiplicity events are expected by the end of RUN 2) and the central data taking in Pb–Pb collisions (200 million events).

ALICE has also an ambitious upgrade program, which will be deployed during the second long shutdown (2019-2020) and will begin operation in RUN 3 (2021). The main goal of the program is the study of rare and low p_T observables [37], in particular heavy-flavours, low-mass dielectrons [38] and nuclei. These observables cannot be triggered, and require the implementation of a new data taking strategy, based on the continuous readout of the detector, with data reduction via (semi)online reconstruction [39]. The status of the main detector upgrades was discussed in three contributions at EPS-HEP 2017 [40, 41, 42].

6. Summary and Outlook

In summary, many recent results show striking similarities between pp, p–Pb and Pb–Pb collisions, for observables which were considered to be hallmarks of heavy-ion collisions. This is leading to a paradigm shift in the description of hadronic collisions and challenges accepted models of soft QCD processes (for what concerns the universality of fragmentation) and of the quark-gluon plasma (for what concerns the degree of thermal equilibrium reached by the system). All things considered, these data may be indicating the formation of precursor phenomena or even of the quark-gluon plasma in small colliding systems.

The new RUN 2 results in Pb–Pb collisions confirm the trends observed in RUN 1 with increased statistical accuracy, and are leading to a precise characterisation of high-energy nuclear collisions.

These studies require good tracking over a wide p_{T} region and first-rate particle identification. The already excellent ALICE capabilities in this respect will be further improved with the upcoming detector upgrade, which will allow to collect high-luminosity Pb–Pb data with a significantly expanded tracking performance.

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