

# SQM2013: Experimental Summary

**Andrea Dainese**

INFN – Sezione di Padova, via Marzolo 8, I-35131 Padova, Italy

E-mail: [andrea.dainese@pd.infn.it](mailto:andrea.dainese@pd.infn.it)

**Abstract.** We present an overview of the new experimental results from heavy-ion collisions discussed at the Strangeness in Quark Matter 2013 conference.

## 1. Introduction

The SQM2013 conference was held in Birmingham on July 22–27, 2013. This was the first major conference in the field of heavy-ion physics after the run with proton–lead collisions at a centre-of-mass energy  $\sqrt{s_{NN}} = 5.02$  TeV per nucleon–nucleon pair, which took place at the LHC in January–February 2013. Therefore, the new results from this run were among the most awaited for. On one hand, the measurement of heavy flavour, quarkonia and jet production in this collision system provides a control experiment to assess the role of initial-state effects on the probes of the hot and dense medium formed in nucleus–nucleus collisions. On the other hand, the unexpected observations in the sector of bulk particle production in high-multiplicity pp and p–Pb (from the first pilot run) events at the LHC raised high expectations for the outcome of more detailed studies. New results from d–Au collisions at RHIC were presented as well, providing an essential complement to the observations at the LHC.

For nucleus–nucleus collisions, the LHC and RHIC Collaborations presented new results, in particular on strangeness and heavy-flavour production, from the Pb–Pb run of 2011 at  $\sqrt{s_{NN}} = 2.76$  TeV, from the Au–Au runs of 2010–2011 at  $\sqrt{s_{NN}} = 200$  GeV and from the beam energy scan with Au–Au at  $\sqrt{s_{NN}}$  in the range 7.7–39 GeV. A summary of the status and main open questions before SQM2013 can be found in Refs. [1–3].

The paper is organized as follows: Section 2 presents the results from nucleus–nucleus collisions on strangeness, open heavy flavour and quarkonia; Section 3 presents the results from the measurement of hard probes production in proton–nucleus collisions; Section 4 presents the new observations in high-multiplicity p–Pb collisions at the LHC and at RHIC.

## 2. Nucleus–Nucleus Collisions: New Results on Strangeness and Heavy Flavour

### *Strangeness*

The ALICE Collaboration presented the final results on the enhancement of hyperons ( $\Lambda$ ,  $\Xi$ , and  $\Omega$ ) in Pb–Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV with respect to pp collisions at the same energy [4, 5]. The enhancement of the per-participant yield in Pb–Pb relative to pp increases with the strangeness content and towards more central collisions, up to a factor of about six for the triply-strange  $\Omega$ . In comparison with lower energy results from NA57 at the SPS and STAR at RHIC, the enhancement is found to be decreasing for increasing  $\sqrt{s_{NN}}$ . For example, the  $\Omega$  enhancement at SPS energy is of a factor of about twenty in central collisions. This



energy dependence is due to the pp reference: the hyperon/ $\pi$  ratios show no evident energy dependence in AA collisions and a strong dependence in pp(p–Be) collisions, which is usually attributed to increasing strangeness canonical suppression towards smaller values of  $\sqrt{s}$ . Overall, the experimental data are consistent with a scenario in which the bulk of strange hadrons are formed from a partonic system with a large abundance of strange quarks.

Final results from the ALICE experiment were also presented for the  $\Lambda/K_S^0$  ratio in Pb–Pb collisions, as a function  $p_T$  and centrality [4, 6]. The baryon/meson enhancement in central collisions with respect to peripheral collisions is of a factor of about two and it is consistent with the value measured by STAR at top RHIC energy. The STAR Collaboration presented the results of this measurement from the beam energy scan: the enhancement is visible starting from  $\sqrt{s_{NN}} = 19.6$  GeV (consistently with the observation by NA57 at the top SPS energy of about 17 GeV) and not evident at 11.5 and 7.7 GeV. The peak of the  $\Lambda/K_S^0$  ratio in central collisions is at about 2.5 GeV/ $c$  at energies 19.6–200 GeV and 3.5 GeV/ $c$  at 2.76 TeV. Models including parton recombination, which was the first explanation put forward when the effect was observed at RHIC, describe the LHC data only qualitatively. Models including only radial flow, where the effect is related to the particle mass and not to its quark composition, also provide a good description. Therefore, the role of recombination in this effect is still not clarified. The  $\phi$  meson could provide important additional information, because it is a meson and has mass similar to that of the  $p$  and  $\Lambda$  baryons. However, preliminary results from ALICE and final result from PHENIX at RHIC show that the  $\phi$  nuclear modification factor  $R_{AA}$  has intermediate value between those of light mesons ( $\pi$ ,  $K$ ) and those of baryons ( $p$ ,  $\Lambda$ ) [4, 7, 8]. This suggests that both effects, radial flow and recombination, may play a role.

### *Open Heavy Flavour*

The long-standing question about the quark mass dependence of parton energy loss is on the way of finding a clear answer in the LHC data. The ALICE Collaboration presented a new comparison of  $D$  meson  $R_{AA}$  as a function of centrality with the measurement of non-prompt  $J/\psi$  from  $B$  decay by the CMS Collaboration [9–11]. The new  $D$  meson data in the interval  $8 < p_T < 16$  GeV/ $c$  (corresponding to average  $p_T$  of about 10–11 GeV/ $c$ ) show a suppression in central collisions larger by a factor of two with respect to  $J/\psi$  with  $p_T > 6.5$  GeV/ $c$  (corresponding to approximately the same average  $p_T$  for  $B$  mesons). Considering the uncertainties of the two measurements, in central collisions, the difference between charm and beauty is observed with a significance of more than  $3\sigma$ . This is the first observation of a hadron species dependence of energy-loss induced suppression at such large  $p_T$ . Comparison with models of radiative energy loss indicates that the measurements are consistent with the predicted quark mass dependence.

The comparison of  $D$  mesons and pions, presented by ALICE as a function of  $p_T$  and centrality, shows comparable suppression. A hint is seen that the suppression may be larger for pions at low  $p_T$  in central collisions, although with the present uncertainties it is not possible to draw a firm conclusion [9, 10]. These observations can be described by calculations in which radiative energy loss depends on the parton colour charge and the larger energy loss of gluons with respect to quarks is to some extent counterbalanced by the harder fragmentation of  $c \rightarrow D$  with respect to  $g \rightarrow \pi$  [12].

The STAR experiment presented preliminary spectra of heavy-flavour decay electrons in Au–Au collisions at  $\sqrt{s_{NN}} = 62.4$  GeV [13]. Lacking pp reference data at this energy from RHIC, the spectra were compared with binary scaled spectra from  $p\bar{p}$  at the ISR and with binary scaled perturbative QCD calculations: surprisingly, no suppression is observed in Au–Au with respect to this references. It would be important to have reference pp runs at RHIC at lower energies, in order to study the onset of the jet quenching effects, not only for heavy flavour.

New results on heavy-flavour azimuthal anisotropy  $v_2$  at the LHC were presented by the ALICE Collaboration [9, 10, 14]. The final results for  $D$  mesons show average  $v_2$  values of about

$0.21 \pm 0.04$  in the interval  $2 < p_T < 6$  GeV/ $c$ . The new preliminary results on heavy-flavour decay muon  $v_2$  at forward rapidity indicate  $v_2 > 0$  in the interval  $3 < p_T < 6$  GeV/ $c$ , consistent with the measurements with electrons at central rapidity. These results suggest that charm quarks participate in the collective expansion of the medium. A similar conclusion was obtained from the PHENIX and STAR measurements at top RHIC energy.

The silicon tracker upgrades of the PHENIX and STAR detectors (already partially installed) and of the ALICE detector (planned for 2018) will give a strong boost to the heavy flavour measurements [15–17]. Precise studies of  $R_{AA}$  and  $v_2$  separately for charm and beauty hadrons and investigation of charm hadronization mechanisms in heavy-ion collisions via baryon/meson and  $D_s$  measurements will become accessible.

### *Quarkonia*

A new piece was added to the puzzle of  $J/\psi$  production and suppression in nucleus–nucleus collisions: STAR preliminary measurements of  $R_{AA}$  at high  $p_T$  ( $> 5$  GeV/ $c$ ) show a lower suppression than at low  $p_T$ , consistently in all centrality classes. Therefore, the  $p_T$  dependence of the  $J/\psi$   $R_{AA}$  is opposite at RHIC and LHC: at RHIC the suppression decreases for increasing  $p_T$ , while at the LHC it increases for increasing  $p_T$  [13, 18, 19]. This pattern is consistent with the predictions of kinetic transport models including melting and regeneration.

The comparison of  $J/\psi$  and  $\Upsilon$  suppression provides additional insight in the relative contributions of the melting and regeneration effects. ALICE presented new preliminary results on  $\Upsilon(1S)$   $R_{AA}$  at  $p_T > 0$  and  $2.5 < y < 4$ , which show a suppression of a factor of about two in minimum-bias Pb–Pb collisions [18, 20]. The measurement complements at forward rapidity the results from the CMS Collaboration (presented in [11]): taken together, these data show no evident dependence of the  $\Upsilon(1S)$   $R_{AA}$  on rapidity. On the other hand, ALICE observed a rapidity dependence for the  $J/\psi$   $R_{AA}$ , with increasing suppression towards large  $y$ . This difference between  $\Upsilon(1S)$  and  $J/\psi$  is consistent with a significant role of regeneration for the latter. Indeed, this mechanism is expected to contribute to the  $J/\psi$  yield proportionally to  $(dN_{c\bar{c}}/dy)^2$ , thus more at central than at forward rapidity.

### **3. Proton–Nucleus Collisions: Control Experiment for Hard Probes**

The main goal of proton–nucleus collisions in the heavy-ion physics programmes at RHIC and LHC is the study of initial state and cold nuclear matter effects. On one hand, it is necessary to quantify the modification in the production of hard partons determined by the fact of having nucleons (within nuclei) instead of protons in the initial state of the hard scattering processes. This is a crucial control experiment to disentangle, in the case of nucleus–nucleus collisions, the modifications that are induced by the presence of a hot and dense QCD medium in the final state. On the other hand, the study of initial state effects is highly interesting *per se*, in the context of high-density gluon dynamics and saturation at small parton fractional momentum (Bjorken  $x$ ).

For the  $R_{pA}$  measurements at the LHC, an interpolated pp reference was used, since there are no reference pp data at  $\sqrt{s} = 5.02$  TeV.

### *High $p_T$ and Jets*

The nuclear modification factor  $R_{pA}$  of charged particles in minimum-bias p–Pb collisions at the LHC, measured by ALICE up to  $p_T = 20$  GeV/ $c$ , is consistent with unity in the range  $2 < p_T < 20$  GeV/ $c$ , with a central value at about 1.1 and uncertainties of about  $\pm 10\%$  [21]. This suggests that particle production at medium-high  $p_T$  is dominated by hard scattering processes and approximately scales with the number of binary collisions in this  $p_T$  range.

Therefore, the large suppression observed in central Pb–Pb collisions (up to a factor of seven at 6–10 GeV/ $c$ ) is an effect of the hot medium in the final state. Another method to verify

binary scaling of hard scattering processes in nucleus–nucleus collisions is the measurement of high- $p_T$  photons,  $W \rightarrow \ell \nu_\ell$  and  $Z \rightarrow \ell^+ \ell^-$ , that are produced in hard scattering processes and do not interact with the QCD medium. The CMS Collaboration presented new preliminary results on  $Z \rightarrow ee$  and  $Z \rightarrow \mu\mu$   $R_{AA}$  in Pb–Pb collisions, using new reference data from the high luminosity pp run at 2.76 TeV from February this year. The results show that  $R_{AA}$  is consistent with unity, in line with the previous measurements with  $\gamma$ ,  $W$  and  $Z$  (see [22] and references therein).

The outcome of the control experiment with p–Pb at the LHC is the same also for jet production. In minimum-bias collisions ALICE measures a charged-jet  $R_{pA}$  consistent with unity in the range  $20 < p_T < 100$  GeV/ $c$  [23], with uncertainty of about  $\pm 20\%$ . CMS presented measurements of the di-jet momentum imbalance  $p_{T,2}/p_{T,1}$  for  $p_{T,1} > 120$  GeV/ $c$  and  $p_{T,2} > 30$  GeV/ $c$  [24]: the distributions of this variable for p–Pb collisions in various multiplicity classes are fully consistent with the pp case. These results indicate that the large  $R_{AA}$  suppression of up to a factor of four and the large di-jet imbalance observed in central Pb–Pb collisions are produced by jet quenching in the final state.

### *Open Heavy Flavour*

The ALICE Collaboration reported on the measurement of  $D$  mesons ( $D^0$ ,  $D^+$ ,  $D^{*+}$ ,  $D_s^+$ ) and heavy-flavour decay electrons in minimum-bias p–Pb collisions at central rapidity [9, 25, 26]. The  $D$  meson  $R_{pA}$ , measured in the interval  $1 < p_T < 24$  GeV/ $c$ , and the electron  $R_{pA}$ , 0.5–12 GeV/ $c$ , show consistency with unity within the experimental uncertainties. Theoretical predictions based on next-to-leading order perturbative QCD supplemented with nuclear modified parton distribution function and based on the Colour Glass Condensate framework are both consistent with the data. At very low  $p_T$ , both calculations predict a suppression, by 20% and 40% for the central value, respectively, due to initial-state saturation effects that reduce the effective partonic flux. While the data are not precise enough to be sensitive to effects of this level (few 10%), they clearly indicate that, like for light-flavour particles, the strong suppression of  $D$  mesons and heavy-flavour decay electrons in central Pb–Pb collisions is due to heavy-quark energy loss.

It is interesting to note that the electron  $R_{pA}$  at the LHC has a central value of 1.4 at low  $p_T$  (with large uncertainties of 30–40%), which is similar to that of the same measurement in d–Au collisions at RHIC, where the PHENIX experiment measured a larger  $R_{dA}$  for heavy-flavour decay electrons than for pions [15]. This observation at RHIC is intriguing, especially when taken together with the enhancement measured for heavy-flavour decay muons at backward rapidity (corresponding to large  $x$  values in the Au nucleus): both  $R_{dA}$  values seem to be larger than the expectations based on nuclear modification of the parton distribution functions (anti-shadowing). It will be, therefore, very interesting to see a measurement of electrons with reduced systematic uncertainties from ALICE and the corresponding measurement for backward rapidity muons.

### *Quarkonia*

The production of  $J/\psi$  and  $\Upsilon(1S)$  in minimum-bias p–Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV was reported by the ALICE (both particles) and LHCb ( $J/\psi$ ) experiments using the di-muon decay channel [18, 27, 28]. Both experiments measure di-muons at forward rapidity and for  $p_T > 0$ . Using p–Pb and Pb–p collisions they could cover both the backward and forward rapidity regions, probing large and small Bjorken  $x$  values in the Pb, respectively. The  $J/\psi$   $R_{pA}$  from both experiments is consistent with unity in the backward region (large  $x$ ) and shows a suppression of about 30% in the forward region (small  $x$ ). The  $\Upsilon$   $R_{pA}$  is consistent with the  $J/\psi$   $R_{pA}$ . Both measurements are described reasonably well by perturbative calculations with nuclear shadowing. The prediction of the Colour Glass Condensate, available only for  $J/\psi$  and only

for the forward region (small  $x$ ) underestimates the value of  $R_{pA}$ . For  $J/\psi$ , ALICE presented also a measurement of yield in the forward region divided by yield in the backward region, as a function of  $p_T$ , which has better accuracy than  $R_{pA}$ , because no pp reference is required. The pattern of the data, with a pronounced suppression at low  $p_T$  and a consistency with unity at high  $p_T$ , is not well reproduced by the calculations.

The PHENIX Collaboration presented final results on  $R_{dA}$  of  $J/\psi$  and  $\psi'$  as a function of centrality in d–Au collisions at 200 GeV [15]. While the  $J/\psi$  shows a roughly constant and moderate suppression of about 20%, the  $\psi'$  suppression increases towards more central collisions reaching down to  $R_{pA} \approx 0.2$ –0.4. That is: it is 2–3 times more suppressed than the  $J/\psi$ . Since the initial-state effects related to shadowing should be the same for the two states, this observation indicates strong final-state effects for the more-loosely-bound  $\psi'$ . The nature of these final-state effects is not clear: cold nuclear matter energy loss, hadronic rescattering, ... It will be interesting to see the result of the  $\psi'$  measurement in p–Pb collisions at the LHC, which is essential for the interpretation of the  $J/\psi$  and  $\psi'$  comparison in Pb–Pb collisions.

#### *Centrality Determination and Binary Scaling in p–Pb at the LHC*

The measurements of the p–Pb nuclear modification factors presented at the conference were obtained using minimum-bias collisions. In this case, the general conclusion is that hard process scale according to the number of binary collisions for  $p_T$  larger than a few GeV/c. The next step is to extend the comparison with binary-scaled pp reference to p–Pb collisions in various multiplicity classes. This is especially interesting in view of the effects observed in high-multiplicity events, which will be discussed in the next Section.

The intrinsic challenge of this measurement was discussed by the ALICE Collaboration [21]. In the minimum-bias case the binary scaling variable, e.g. the average number of binary collisions, is well-defined as  $\langle N_{\text{coll}} \rangle = A \sigma_{\text{inel}}^{\text{pp}} / \sigma_{\text{inel}}^{\text{pA}}$ . At variance, when considering centrality classes, defined in terms of the particle multiplicity or energy measured in a given pseudo-rapidity ( $\eta$ ) range, a model of particle production and the collision geometry is needed to define the average number of binary collisions. In the case of pA collisions the correlation between the measured multiplicity and the geometrical collision variables is very loose. This is due to the small dynamical range of the geometrical variables (e.g. the number of participants reaches barely 30 in p–Pb, to be compared with more than 400 in Pb–Pb) and to the local multiplicity bias associated with jets and long-range correlations. Consequently, there is a large overlap in terms of, e.g., distribution of binary collisions for centrality classes defined in terms of multiplicity. In addition, it was shown that the hard probes bias the determination of the binary scaling variable, if the centrality classes are defined using multiplicity measured at less than five  $\eta$  units from the region where the hard probes themselves are measured [21]. It is now under detailed scrutiny whether the usage of centrality estimators with a larger  $\eta$  gap offers a solution to reduce the bias at an acceptable level, for example below the intrinsic systematic uncertainties of the measurement.

#### **4. Proton–Nucleus Collisions: Hints of Collectivity in High-Multiplicity Events?**

The measurements of particle production and correlations in high-multiplicity p–Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV have produced the most unexpected and intriguing results not only of the pA programme, but probably of the entire heavy-ion programme at the LHC. The news in this sector, including for the first time identified particles, were among the highlights of the conference.

##### *Correlations*

Two-particle correlations in azimuthal angle  $\varphi$  and pseudo-rapidity are measured by constructing the two-dimensional distribution of  $\Delta\varphi$  vs.  $\Delta\eta$  for all charged particles (called ‘associated’ particles) in a given  $p_T^{\text{assoc}}$  range with respect to a ‘trigger’ particle with given  $p_T^{\text{trigger}}$ , where

generally  $p_T^{\text{trigger}} > p_T^{\text{assoc}}$ . In nucleus–nucleus collisions the two-particle correlation distribution for typical  $p_T$  ranges of 2–4 GeV/ $c$  for trigger particles and 1–2 GeV/ $c$  for associated particles exhibits a double-ridge structure, with the two ridges extended over several units in  $\Delta\eta$  and described by a dominant second-order harmonic in  $\Delta\phi$ , quantified by the  $v_2$  coefficient. This structure is well consistent with hydro-dynamical collective expansion of a hot and dense system.

Shortly after the pilot p–Pb run in September 2012, two-particle correlation measurements in high-multiplicity events have revealed, in a rapid sequence: first, an extended  $\Delta\eta$  ridge in the (near-side) region of  $\Delta\phi \sim 0$ , observed by the CMS Collaboration [31]; then, a corresponding away-side ( $\Delta\phi \sim \pi$ ) ridge of similar size, observed by the ALICE Collaboration by subtracting the distribution of low-multiplicity events from that of high-multiplicity events [21, 29, 34, 35]. The latter observation was shortly after confirmed by the ATLAS Collaboration [30, 32]. This subtraction technique is an empirical way of eliminating the correlations with the trigger particle originating from hard scattering processes (i.e. jets), in order to emphasize the underlying long-distance correlations. The resulting double-ridge resembles the structure that, in nucleus–nucleus collisions, is interpreted in terms of collective effects induced by an expanding medium. A Fourier analysis showed values of  $v_2$  comparable to those measured in Pb–Pb collisions with similar multiplicity [29–31]. Results from a similar analysis by the PHENIX Collaboration showed that the effect is present also in high-multiplicity d–Au collisions at  $\sqrt{s_{\text{NN}}} = 200$  GeV, with corresponding  $v_2$  values even larger than observed at the LHC [33], which could result from the larger initial eccentricity of deuteron-induced with respect to proton-induced interactions. These first observations were described by models with an hydro-dynamical treatment of the final state of p–Pb collisions [36, 37], as well as by calculations based on the Colour Glass Condensate framework, where multi-gluon process in the saturated initial state can give rise to correlations in the final state [38]. It was pointed out that also colour reconnection among strings in the parton shower as implemented in the latest version of the PYTHIA generator can induce multi-particle correlations in the final state [39, 40].

An important additional piece of information was provided by the ALICE Collaboration with the measurement of the two-particle correlation using identified associated particles [34, 35]. In particular, the double-ridge was observed for pions, kaons and protons and the corresponding  $v_2$  coefficients were extracted, as a function of  $p_T$  up to 4 GeV/ $c$ . The data show a clear indication of mass ordering, in particular in the comparison for pions and protons, with  $v_2^p < v_2^\pi$  for  $p_T < 1.5$  GeV/ $c$  and  $v_2^p > v_2^\pi$  for  $2.5 < p_T < 4$  GeV/ $c$ . The same mass ordering is observed in Pb–Pb collisions, and it is interpreted in terms for collective radial and elliptic flow. Models with collective effects in pA collisions have predicted this feature [37].

### *Light-Flavour Particle $p_T$ Spectra*

As discussed in Section 2, the baryon-over-meson ratios as a function of  $p_T$  exhibit an enhancement in central with respect to peripheral nucleus–nucleus collisions, which can be described in terms of radial flow or in terms of parton recombination.

The ALICE Collaboration presented new measurements of  $\pi$ ,  $K$ ,  $p$  and  $\Lambda$  in p–Pb collisions in various multiplicity classes [4, 35, 41]. The  $(p+\bar{p})/(\pi^++\pi^-)$  and the  $(\Lambda+\bar{\Lambda})/K_S^0$  ratios in the 20% highest multiplicity events in comparison with the 60–80% multiplicity class show a pattern that is reminiscent of the corresponding Pb–Pb data. In particular, both baryon-over-meson ratios appear to be higher in high multiplicity than in low multiplicity events for  $p_T > 2$  GeV/ $c$ . The  $p/\pi$  measurement extends only to 3 GeV/ $c$ , while the  $\Lambda/K$  extends to 8 GeV/ $c$  and shows that at this  $p_T$  the ratio is independent of event multiplicity, as also observed in Pb–Pb collisions. The  $\Lambda/K$  ratio was also measured in pp collisions at  $\sqrt{s} = 7$  TeV as a function of  $p_T$  and event multiplicity. It is interesting to note that, in a given  $p_T$  and multiplicity interval, the ratio has similar values for different colliding systems and energies. This might indicate that the same physical mechanisms are at play in different systems. Detailed comparison with models should

allow for drawing a more definite conclusion.

The PHENIX Collaboration presented the  $p/\pi^+$  and  $\bar{p}/\pi^-$  ratios in various centrality classes in d–Au collisions at  $\sqrt{s_{NN}} = 200$  GeV [8]. These data show a very similar pattern as seen at LHC energy: in central collisions both ratios are clearly higher than for peripheral collisions, in the interval  $1.5 < p_T < 4$  GeV/ $c$ . Like for the case of two-particle correlations, the data look qualitatively similar at RHIC and LHC energies.

A complementary approach for investigating the change of  $p_T$  spectra with the event multiplicity is the measurement of average  $p_T$  ( $\langle p_T \rangle$ ) vs. multiplicity. The CMS Collaboration presented new results on this analysis for identified pions, kaons and protons in pp collisions at and p–Pb collisions [42]. In pp collisions,  $\langle p_T \rangle$  increases roughly linearly with multiplicity. The increase is steeper for protons than for pions and kaons. In p–Pb low-multiplicity collisions,  $\langle p_T \rangle$  is the same as in pp at the same multiplicity. In high-multiplicity p–Pb, the growth of  $\langle p_T \rangle$  is less steep than in pp at the same multiplicity. The multiplicity dependence of average  $p_T$  was measured for charged particles by the ALICE Collaboration for pp, p–Pb and Pb–Pb collisions and compared with several models [21, 41]. In pp and p–Pb collisions, the increase of  $\langle p_T \rangle$  with multiplicity is much stronger than that measured in Pb–Pb collisions. For pp collisions, this behaviour is described by the PYTHIA model of hadronizing strings when multiple-parton interactions and final-state colour reconnection are included [39]. Using the pp measurement, the expectation for p–Pb and Pb–Pb under the assumption that they are an incoherent superposition of nucleon–nucleon collisions was derived. Both the Pb–Pb and the p–Pb data show a  $\langle p_T \rangle$  significantly larger than this expectation. In Pb–Pb, this is generally attributed mostly to radial flow. It is still an open question whether a similar effect is at play also in p–Pb, adding to initial-state effects, like intrinsic partonic transverse momentum ( $k_T$ ) broadening.

## 5. Conclusions and Outlook

A wealth of new and exciting experimental results were presented at the conference. At the high energy frontier, the first run period of the LHC indicates that some of the long-standing questions are on the way to find a clear answer (for example the fate of quarkonia in the medium and the mass dependence of energy loss), while new and unexpected perspectives were opened by the possible hints of collectivity in high-multiplicity proton–nucleus collisions. The RHIC experiments continue to produce new results at impressive pace, and the complementarity of the two colliders is a unique richness for the field. Just to quote one example, the parallel study of high multiplicity proton(deuteron)–nucleus collisions at such different energies is providing key information and strong constraints for theoretical interpretations.

A selection of the highlights of the conference is summarized in the following. The production of  $D$  mesons ( $p_T > 1$  GeV/ $c$ ) and jets ( $p_T > 20$  GeV/ $c$ ) in minimum-bias p–Pb collisions at the LHC does not exhibit significant deviations from binary scaling and also the di-jet momentum imbalance is similar to the pp case. This implies that the strong modifications observed in nucleus–nucleus collisions are mainly induced by in-medium parton energy loss. A quark mass dependence of the latter is suggested by the comparison, in Pb–Pb at the LHC, of hadrons originating from  $c$  and  $b$  quarks, which manifest the only observed hadron-species dependence of  $R_{AA}$  for  $p_T > 8$  GeV/ $c$ . The production of quarkonia in p–Pb collisions at the LHC shows only modest deviations from binary scaling, roughly consistent with the expected initial-state effects. Remarkably, a clear suppression is seen for  $\psi'$  particles in d–Au at RHIC. These data represent crucial constraints for the interpretation of the nucleus–nucleus measurements in terms of quarkonium melting and regeneration. In high-multiplicity proton–nucleus collisions, the main highlights were the measurements with identified particles at the LHC. These exhibit multiple qualitative similarities with the nucleus–nucleus case: namely, the hadron mass ordering of the azimuthal anisotropy modulation (in particular for  $v_2^\pi$  and  $v_2^p$ ), the baryon-over-meson ( $p/\pi$  and  $\Lambda/K$ ) enhancement (also observed at RHIC), and the dependence on hadron mass and on

event multiplicity of mean  $p_T$ . These similarities are suggestive of a similarity in the underlying physical mechanisms in nucleus–nucleus and high-multiplicity proton–nucleus (and maybe even pp) collisions. Further studies—including the challenging centrality-dependent pA nuclear modification factor and systematic multiplicity-dependent measurements in pp— will allow us to address the question whether these mechanisms are related to multi-parton correlations in the initial or in the final state of the collision, or to the formation of a high-density final state.

This and other questions promise to keep the field very lively for more than a decade ahead of us. The RHIC experiments are being upgraded and new projects are proposed for the future. The extension of the LHC heavy programme till the mid 2020s was recently endorsed and very substantial detector upgrades are planned. The low energy and high baryon density frontier will be explored as well in the next decade, with the continuation of the SPS programme and the new facilities FAIR and NICA [43–46].

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### References

- [1] Caines H, these proceedings
- [2] Hippolyte B, these proceedings
- [3] Granier de Cassagnac R, these proceedings
- [4] Barnby L (ALICE Collaboration), these proceedings
- [5] Colella D (ALICE Collaboration), these proceedings
- [6] Hanratty L (ALICE Collaboration), these proceedings
- [7] Knospe A G (ALICE Collaboration), these proceedings
- [8] Belmont R (PHENIX Collaboration), these proceedings
- [9] Stocco D (ALICE Collaboration), these proceedings
- [10] Bruna E (ALICE Collaboration), these proceedings
- [11] Jo M (CMS Collaboration), these proceedings
- [12] Djordjevic M, these proceedings
- [13] Kikola D (STAR Collaboration), these proceedings
- [14] Zhang X (ALICE Collaboration), these proceedings
- [15] Jouan D (PHENIX Collaboration), these proceedings
- [16] Qiu H (STAR Collaboration), these proceedings
- [17] Terrevoli C (ALICE Collaboration), these proceedings
- [18] Bruno G E (ALICE Collaboration), these proceedings
- [19] Valencia Palomo L (ALICE Collaboration), these proceedings
- [20] Khan P (ALICE Collaboration), these proceedings
- [21] Morsch A (ALICE Collaboration), these proceedings
- [22] Gardner M (CMS Collaboration), these proceedings
- [23] Verweij M (ALICE Collaboration), these proceedings
- [24] Stephans G (CMS Collaboration), these proceedings
- [25] Luparello G (ALICE Collaboration), these proceedings
- [26] Heide M (ALICE Collaboration), these proceedings
- [27] Lakomov I (ALICE Collaboration), these proceedings
- [28] Zhong L (LHCb Collaboration), these proceedings
- [29] ALICE Collaboration 2013 *Phys. Lett. B* **719** 29
- [30] ATLAS Collaboration 2013 *Phys. Rev. Lett.* **110** 182302
- [31] CMS Collaboration 2013 *Phys. Lett. B* **724** 213
- [32] Trzupek A (ATLAS Collaboration), these proceedings
- [33] PHENIX Collaboration, arXiv:1303.1794
- [34] Christakoglou P (ALICE Collaboration), these proceedings
- [35] Milano L (ALICE Collaboration), these proceedings



- [36] Bozek P, these proceedings
- [37] Werner K, these proceedings
- [38] Dusling K and Venugopalan R 2013 *Phys. Rev. D* **87** 094034
- [39] Sjostrand T, Mrenna S and Skands P Z 2008 *Comput. Phys. Commun.* **178** 852
- [40] Ortiz A *et al* 2013 *Phys. Rev. Lett.* **111** 042001
- [41] Anielski J (ALICE Collaboration), these proceedings
- [42] Appelt E A (CMS Collaboration), these proceedings
- [43] Fodor Z (NA61/SHINE Collaboration), these proceedings
- [44] Ali Y (NA61/SHINE Collaboration), these proceedings
- [45] Schmidt H R (CBM Collaboration), these proceedings
- [46] Sorin A (NICA/MPD Collaboration), these proceedings