Available online at www.sciencedirect.com

ScienceDirect

Nuclear Physics A 982 (2019) 1–7

NUCLEAR PHYSICS A

www.elsevier.com/locate/nuclphysa

XXVIIth International Conference on Ultrarelativistic Nucleus-Nucleus Collisions (Quark Matter 2018)

Highlights from the ALICE experiment

A. Kalweit

CERN, EP department, Geneva

Abstract

The recent experimental breakthroughs achieved by ALICE, the world's largest heavy-ion experiment, are reported. The results cover a broad range of topics from bulk particle observables and particle chemistry to jet-medium interactions and electromagnetic probes, as well as heavy flavour and quarkonia production. The findings represent major milestones in the advancement of our understanding of the QCD matter produced in pp, p-Pb, Xe-Xe, and Pb-Pb collisions at the LHC.

Keywords: heavy-ion, ALICE overview, Xe-Xe collisions, anti-nuclei, open charm production, jets

1. Introduction

The year 2018 marks a special year in the history of the ALICE collaboration, as it is the 25th anniversary of the submission of its Letter of Intent [1]. Since then our understanding of high energy heavy-ion and high multiplicity pp collisions has dramatically evolved, thanks to impressive progress on the experimental and theory sides. In eight years of data taking ALICE has collected large data samples from pp, p-Pb, and Pb-Pb collisions, which are summarised in Table 1. The significant increase in integrated luminosity in LHC Run 2 (2015–2018) with respect to LHC Run 1 (2009–2013) allows more and more precise investigation of statistics-hungry probes. In a short pilot run in October 2017 Xe-Xe collisions were also recorded and the results were for the first time presented at this conference. This article gives an overview of the main ALICE results presented at the conference and groups them in four rough categories of observables starting from bulk particle production and particle chemistry followed by jet-medium interactions, electromagnetic probes, and finally quarkonia and heavy-flavour production.

2. Bulk particle production and particle chemistry

One of the first and most basic important measurements in a newly available collision system such as Xe-Xe is the determination of the average charged particle multiplicity density $\langle \mathrm{d}N/\mathrm{d}\eta \rangle$. Figure 1 shows $\langle \mathrm{d}N/\mathrm{d}\eta \rangle$ per participating nucleon as a function of the number of nucleons N_{part} that participate in the collision. Two scaling violations become immediately apparent in the plot: (i) the scaling with N_{part} is

https://doi.org/10.1016/j.nuclphysa.2018.10.015
0375-9474/

System	Year(s)	$\sqrt{s_{\mathrm{NN}}}$ (TeV)	L_{int}
Pb-Pb	2010-2011	2.76	≈75 μb^{-1}
	2015	5.02	≈250 μb^{-1}
	by end of 2018	5.02	≈1 nb^{-1}
Xe-Xe	2017	5.44	≈0.3 μb^{-1}
p-Pb	2013	5.02	≈15 nb^{-1}
	2016	5.02, 8.16	≈3 nb^{-1}, ≈25 nb^{-1}
pp	2009-2013	0.9, 2.76	≈200 μb^{-1}, ≈100 nb^{-1}
		7, 8	≈1.5 pb^{-1}, ≈2.5 pb^{-1}
	2015,2017	5.02	≈1.3 pb^{-1}
	2015-2017	13	≈25 pb^{-1}

Table 1. Overview of the collision systems and the integrated luminosity L_{int} that was collected by the ALICE experiment in several years of running.

broken by a factor of about two and (ii) central collisions of medium-size nuclei produce more particles per N_{part} than mid-central collisions of large nuclei at the same N_{part}. Despite often being assumed as true, the first scaling violation is already known since the RHIC data [2] and, as also shown in Fig. 1, it is well described by Glauber models based on participant quarks instead of participant nucleons as well as by several other theoretical models. The second effect, on the other hand, is currently not fully reproduced by models and is most likely linked to fluctuations in the number of produced particles which are larger in the smaller collision system. In this context, the CMS and PHOBOS collaborations observed that a better scaling behaviour is achieved when comparing events with similar fractional overlap, i.e. events with N_{part}/2A [3, 4], which could explain this behaviour.

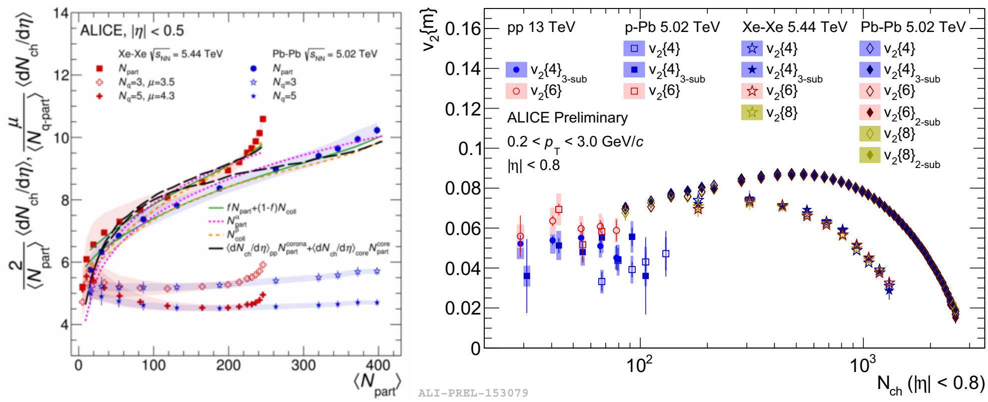

Fig. 1. (Left) ⟨dN/dη⟩ per participating nucleon as a function of the number of nucleons N_{part} that participate in the collision for Xe-Xe and Pb-Pb collisions. Also shown is ⟨dN/dη⟩ per participating quark, N_{q-part}, calculated with the effective wounded constituent quarks model [5]. The number of participant quarks N_{q-part} is normalised by the average number of participant quarks in pp collisions, μ. Figure taken from [6]. (Right) Multiplicity dependence of the elliptic flow amplitudes $v_2\{4\}$, $v_2\{6\}$ and $v_2\{8\}$ with standard, 2-subevent or 3-subevent method in 13 TeV pp, 5.02 TeV p-Pb, 5.44 TeV Xe-Xe and 5.02 TeV Pb-Pb collisions.

Figure 1 shows a comprehensive collection of measurements of the elliptic flow coefficient v_2 in various collision systems for several multiplicities and centralities. The data is extracted for higher order multi-particle cumulants in which the contributions from non-flow effects, as for instance due to mini-jets, are deliberately suppressed. Elliptic flow patterns, often ascribed to collective behaviour, are observed in all collision systems, including smaller systems such as pp and p-Pb collisions. For a more detailed investigation of the quasi-collective effects in small collision systems, a new study on identified particle v_2 was performed. At low transverse momenta ($p_T \lesssim 2$ GeV/c), a clear mass ordering is observed which is traditionally regarded as a prime signature for hydrodynamic expansion. However, recently other explanations such as initial state effects, parton escape, or hadronic re-scattering have also successfully reproduced this effect. At intermediate momenta ($2 \lesssim p_T \lesssim 8$ GeV/c), the data in small collision systems shows a baryon/meson grouping as observed in AA collisions.

As expected from the different collision geometries, a different v_2 is observed for Xe-Xe and Pb-Pb collisions at comparable multiplicities. In the hydrodynamic picture, the scaling is restored if the transverse area and eccentricity are taken into account [7]. However, consistency with the data is only found if a constituent quark Glauber model for the initial conditions is used which includes the significant non-spherical deformation of the Xe nucleus.

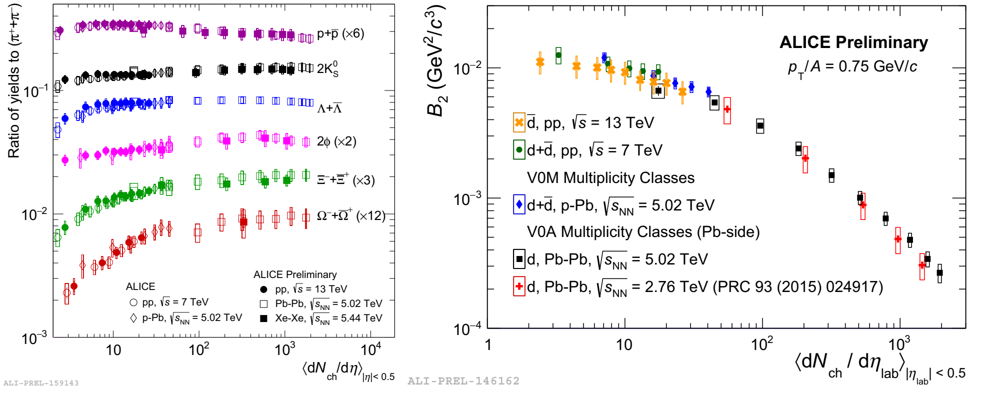

Fig. 2. (Left panel) p, K^0_S, Λ, Ξ, Ω and ϕ over π ratio *vs* multiplicity in pp 7 TeV, pp 13 TeV, p–Pb 5 TeV, Pb–Pb 5 TeV and Xe-Xe 5.44 TeV. (Right panel) Anti-deuteron coalescence parameter B_2 at fixed p_T/A = 0.75 GeV/c as a function of the average charged-particle multiplicity.

One of the most remarkable results established at the LHC is the smooth evolution of particle chemistry from small to large systems as a function of charged particle multiplicity, including an increase of strangeness production with increasing system size until grand-canonical saturation values are reached [8, 9]. Figure 2 shows that the energy and collision-system independence of this effect is now confirmed with the newly available Xe-Xe and pp $\sqrt{s}$ = 13 TeV data. In addition, an increasing trend of the ϕ-meson to pion ratio with increasing multiplicity becomes apparent in smaller collision systems which saturates in Xe-Xe and Pb-Pb collisions. This behaviour is in contrast to expectations from strangeness canonical suppression [9], highlighting the pivotal role of the ϕ in the understanding of strangeness production with thermal-statistical [9], core-corona [10], and QCD inspired Monte Carlo models [11]. As in the $\sqrt{s_{NN}}$ = 2.76 TeV collision data, also in central Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV, the data is well-described by a thermal-statistical fit based on equilibrium thermal models over seven orders of magnitude, from the abundantly produced pions to rarely produced (anti-)(hyper-)nuclei. The fit also confirms the differences seen at 2.76 TeV, namely an over-prediction of the proton yield by the models and an under-prediction of the Ξ yield. The resulting chemical freeze-out temperature of around $T_{chem} \approx 153 \pm 2$ MeV is slightly lower than the value of $T_{chem} \approx 156 \pm 2$ MeV though consistent within the respective uncertainties. The testing of true thermalisation of the system created in the collision is not only addressed by thermal-statistical fits to particle yields, but also by studying the fluctuations of conserved quantities in QCD (net baryon number, net strangeness, and net electric charge). The new ALICE data on first and second order cumulants of net-Lambda fluctuations as well as on fourth order net-proton fluctuations are consistent with the expectation from the Skellam distribution, which corresponds to the difference of two statistically independent Poisson fluctuations. Thus, they do not show any non-thermal fluctuations and appear to be driven only by conservation laws. This behaviour is expected from lattice QCD calculations in which deviations from the Skellam distribution due to pseudo-critical fluctuations are only expected for higher order cumulants ($n \geq 6$).

Some of the most intriguing results at the LHC have been achieved via the measurement of light (anti-)(hyper-)nuclei. Despite their small binding energy, their yields are in agreement with the thermal-statistical model predictions at chemical freeze-out and thus no sign of re-scattering in the hadronic phase despite the large dissociation cross-section is observed. Final-state coalescence after kinetic freeze-out could serve as explanation, but requires detailed modelling. Naive coalescence (ignoring the size of the emission volume and correlations between the nucleons) does not describe the data. In such a model, one would expect the parameter $S_3 = \frac{{}^3_\Lambda H/{}^3\mathrm{He}}{\Lambda/p} \approx 1$, but a value of around 0.6 is observed in hyper-triton measurements. Figure 2 shows the dependence of the coalescence parameter B_2 as function of multiplicity in pp, p-Pb, and Pb-Pb collisions. While a naive coalescence model would expect the same B_2 value for all multiplicities, a clear drop with increasing multiplicity is seen above a certain system size. In more advanced coalescence models this behaviour is explained by two production regimes which are distinguished by an emission volume which is either much smaller or much larger than the produced nucleus [12, 13]. The measurements are also of substantial interest outside the field of heavy-ion physics, in particular for the search of anti-matter in space [13].

3. Jet-medium interactions

ALICE recently released a constraint on jet-quenching in p-Pb collisions based on jet-hadron correlations [14]. As it turns out, jet-hadron correlations do not show a significant evolution from low to high multiplicity events in p-Pb collisions. Thus, jet quenching – if existing at all – is very small in p-Pb collisions and the out-of-cone energy transport due to jet quenching is less than 0.4 GeV/c. In our current understanding both phenomena, flow and jet quenching, arise from the same QCD interaction kernel [15]. However, as shown in Fig. 1, v_2 is still very pronounced in p-Pb collisions at multiplicities which are similar to peripheral Pb-Pb. At the same time, the nuclear modification factor R_{AA} shows a significant suppression with values of about 0.8 in peripheral (70-80%) Pb-Pb collisions. In a recent publication [16], the ALICE collaboration showed that this apparent suppression can be solely explained by selection biases, thus solving a longstanding puzzle. As shown in Fig. 3, the measurement of R_{AA} shows a significant change of behaviour for events that correspond to more peripheral collisions than the 80% most central. In fact, the R_{AA} in very peripheral collisions can be qualitatively described with a simple PYTHIA based model without nuclear modification just by event selection and geometry biases [17]. Taking into account the selection bias, the R_{AA} thus appears to be consistent with unity within uncertainties above 80% centrality and thus consistent with the results in p-Pb collisions at comparable multiplicities. The nuclear modification factor has also been measured in Xe–Xe collisions and was found to be consistent with the values observed in Pb–Pb collisions at similar multiplicities [18]. This non-trivial observation is possibly the result of complicated interplay of the geometry and path length dependences of energy loss mechanisms.

In order to achieve a more detailed understanding of the jet energy loss mechanisms in the QCD medium, the ALICE collaboration performed a series of detailed studies concerning the modification of the jet substructure, e.g. the change in the number of soft drop splittings n_{SD} when comparing Pb-Pb collisions with the vacuum (PYTHIA) reference. In this study, a jet found with the anti-k_T algorithm is re-clustered with the Cambridge-Aachen algorithm and for each splitting n_{SD} is increased by one if it fulfils the soft-drop condition [19]. Even in central heavy-ion collisions, one observes only a slight change of n_{SD} with respect to the vacuum expectation. In contrast to the expectation, the n_{SD}-distribution is found to be only slightly shifted to lower values, even though the medium response would shift splittings above the cut by adding momentum. In summary, the jet substructure remains in first order unmodified despite large energy loss in the medium for many observables which are under study.

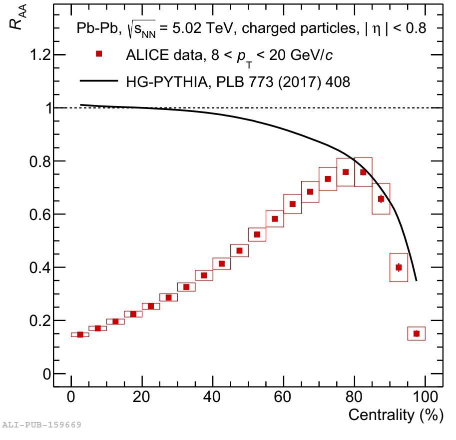

Fig. 3. Average R_{AA} for $8 < p_T < 20$ GeV/c versus centrality percentile in Pb-Pb collisions at $\sqrt{(s_{NN})} = 5.02$ TeV compared to predictions from Hijing-Glauber-PYTHIA. Vertical error bars denote statistical uncertainties, while the boxes denote the systematic uncertainties. Figure taken from [16].

At this conference, also the first ALICE results on D-meson tagged jets in pp, p-Pb, and Pb-Pb collisions were presented. In small collision systems, the measured spectra of D-meson tagged jets agree well with pQCD predictions and these measurements thus provide a well understood baseline for investigations in Pb-Pb collisions. As a matter of fact, the suppression of D-meson tagged jets in heavy-ion collisions is found to be as strong as for D-mesons itself in the region $5 < p_T < 20$ GeV/c [20].

4. Electromagnetic probes

In contrast to hadronic particles, electromagnetic probes such as photons and electrons leave the QCD medium undisturbed. Recently, ALICE released the results of the challenging measurement of the elliptic flow of direct photons $v_2^{\gamma,dir}$ [21]. While at low transverse momenta a non-zero $v_2^{\gamma,dir}$ with a similar magnitude as at RHIC energies is observed, the signal is still consistent with the hypothesis of $v_2^{\gamma,dir} = 0$ within 1.4σ. Transport and hydrodynamic models predict a slightly smaller $v_2^{\gamma,dir}$ than the measurement, but are still consistent with the data within uncertainties. In summary, there is no 'photon flow puzzle' at LHC energies within the current uncertainties. ALICE also newly addressed a long-standing issue in the field of low mass di-lepton studies, namely the question of whether an excess is present also in pp collisions. Such an excess above the cocktail prediction from known hadronic sources was observed 30 years ago in pp collisions at the ISR at $\sqrt{s} = 63$ GeV [22]. The new ALICE measurement in pp collisions at $\sqrt{s} = 13$ TeV does not rule such an excess in the mass region $0.1 < m_{ee} < 0.6$ GeV/c with the currently available statistics. The analysis of more data with lower magnetic field is currently ongoing, but also more precise measurements of the η-meson as the main contributor to the background are needed. At higher masses ($1.2 < m_{ee} < 2.5$ GeV/c), the di-electron continuum provides information on the heavy-flavour cross-section in pp collisions [23]. Since the di-electron pairs are sensitive to the the kinematic correlation of the $c\bar{c}$-pair, the extraction is model dependent and two values for the charm cross-section, one for POWHEG corresponding to $1417 \pm 184(stat.) \pm 204(syst.)\mu$b and one for PYTHIA corresponding to $974 \pm 138(stat.) \pm 140(syst.)\mu$b, were obtained. These results are the first measurement of the HF cross-sections at $\sqrt{s} = 13$ TeV.

5. Heavy flavour and quarkonia

In the quarkonia sector, new ALICE measurements in ultra-peripheral (electromagnetic) p-Pb collisions provide more and more stringent constraints on nuclear parton distribution functions (nPDFs) and saturation models. In hadronic p-Pb collisions, new results confirm a stronger suppression of the $\psi(2s)$ production compared to the J/ψ in the Pb-going direction. While these findings qualitatively clearly indicate the necessity of final state effects in p-Pb collisions, a satisfactory quantitative description is not yet achieved by any of the models. New results on the R_{pPb} of Υ should provide essential model constraints for the understanding of the Υ suppression that was observed in Pb-Pb collisions. In this context, it is worth noting that the description in the anti-shadowing region of the nPDFs is not yet optimal, i.e. an R_{pPb} of about 0.8 to 0.9 is observed in the rapidity region $-4.46 < y_{cms} < -2.96$ in data, while models predict values around 1.1 to 1.2. As previously observed in Pb-Pb collisions, the newly available Xe-Xe data also confirm the large value of R_{AA} for J/ψ with respect to the values observed at RHIC energies – probably the strongest indicator of de-confinement among all signatures of QGP formation. The values observed in Xe-Xe collisions are only slightly lower than those observed in Pb-Pb collisions. As a matter of fact, transport models [24] predict a slightly stronger suppression in Xe-Xe for a given N_{part}, which is however counterbalanced by a larger recombination effect. In summary, the results on J/ψ production in heavy-ion collisions at the LHC clearly indicate the presence of recombination as a new production mechanism which opens up with increasing beam energy and system size. Many of the measurements of open charm production profit from the large pp reference data set which was taken in November and December 2017 at the same centre-of-mass energy as the Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. In particular, the uncertainties in the R_{AA} and R_{pA} measurements of D^0 and D_s mesons are significantly reduced and thus provide much more stringent constraints on models. While a measurement of D-meson production in Xe-Xe collisions is not feasible due to the limited amount of available statistics, a measurement of the electron and muon spectra originating from decays of heavy-flavour hadrons was carried out. Thanks to the lower magnetic field of 0.2 T (instead of the nominal 0.5 T), the measurement was feasible at transverse momenta as low as $p_T = 200$ MeV.

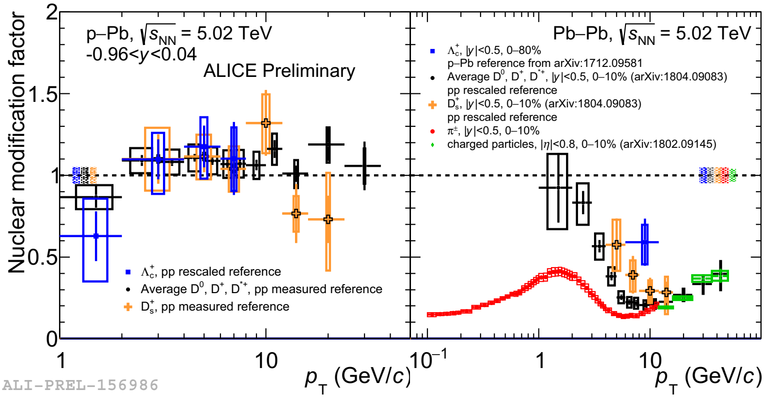

Fig. 4. Summary plot of the R_{pPb} (left panel) and R_{AA} (right panel) measurements of open charm hadrons in comparison to the R_{AA} values for charged pions and all charged hadrons.

One of the most challenging measurements which is currently carried out by the ALICE collaboration is the study of Λ_c production in pp, p-Pb, and Pb-Pb collisions making extensive use of the precise tracking and particle identification capabilities in ALICE as well as of multi-variate data analysis techniques. Surprisingly, a factor 3 to 10 times higher yield than predicted by Monte Carlo and pQCD models is found in pp and p-Pb collisions indicating that the fragmentation to heavy-flavour baryons is still not well understood. Remarkably, the Λ_c/D^0 ratio in pp and p-Pb collisions shows striking similarities to the light flavour baryon-to-meson ratios such as the proton to pion or Λ to kaon ratio possibly pointing to a common production mechanism. In Pb–Pb collisions, the Λ_c/D^0 ratio is with the current ALICE detector and currently available statistics only accessible in a single p_T ($6 < p_T < 12$ GeV/c) and centrality (0-80%) bin. With the observed value of approximately unity, which is higher than the one for pp and p-Pb collisions, the Λ_c/D^0

ratio is qualitatively in line with recombination predictions, but clearly points to the need for more statistics and more precise data as it will become available with the upgraded ALICE detector in LHC Run 3 and 4. The plethora of ALICE open charm measurements is summarised comprehensively in Fig. 4. Despite the still relatively large statistical and systematic uncertainties, the data shows globally a picture consistent with the recombination expectation. While the R_{pPb} values are consistent with each other and with unity for non-strange and strange D-mesons as well as for the Λ_c, an ordering appears in the R_{AA} for $p_{\mathrm{T}} \lesssim 10$ GeV/c: the D_s production appears enhanced with respect to the production of non-strange D-mesons as expected from a recombination production of charm quarks from a strangeness enriched QCD medium and the Λ_c production appears consistent with the expectation that baryons are more easily formed by quark coalescence than mesons from the medium at intermediate transverse momenta.

6. Summary, conclusion, and outlook

With 35 parallel talks and 99 posters, the ALICE collaboration presented a large number of detailed studies on collectivity from small to large systems and on jet-medium interactions constraining the properties of the QGP, as well as searches for evidence of deconfinement with heavy-flavour and quarkonia observables. Many more interesting results could not be mentioned in this article due to space constraints, but the interested reader is referred to the other ALICE contributions in these proceedings. Overall, impressive progress was recently achieved on many long standing topics such as the flow of direct photons, the production mechanism of anti- and hyper-nuclei, as well as the production of low mass di-leptons in pp collisions. In addition, several new avenues in ALICE are pursued, for instance the comparison of fluctuation observables to Lattice QCD or the measurement of jet substructure observables. Even after 25 years of existence, all the nice results which were presented at this Quark Matter 2018 conference merely indicate the beginning of an impressive scientific program for the next 10–15 years. Major upgrades of the Inner Tracking system, the Time Projection Chamber and the muon spectrometer will allow to collect data from Pb–Pb collisions in a continuous read-out mode at a rate of 50 kHz with an unprecedented tracking precision. The production and assembly of the new detector components is underway and their installation will start in 2019. With this upgraded detector, the ALICE experiment will continue to take data at least until 2028 with many exciting and interesting physics results on the horizon.

References

[1] N. Antoniou, et al., CERN-LHCC-93-16, CERN-LHCC-I-4.
[2] B. Alver, et al., Phys. Rev. C83 (2011) 024913.
[3] CMS Collaboration, CMS-PAS-HIN-17-006.
[4] B. Alver, et al., Phys. Rev. Lett. 102 (2009) 142301.
[5] C. Loizides, Phys. Rev. C94 (2) (2016) 024914.
[6] S. Acharya, et al., submitted to Phys. Lett. B,arXiv:1805.04432.
[7] S. Acharya, et al., accepted by Phys. Lett. B,arXiv:1805.01832.
[8] J. Adam, et al., Nature Phys. 13 (2017) 535–539.
[9] S. Acharya, et al., submitted to Phys. Rev. C,arXiv:1807.11321.
[10] J. Aichelin, K. Werner, Phys. Rev. C79 (2009) 064907.
[11] C. Bierlich, these proceedings.
[12] F. Bellini, A. P. Kalweit, arXiv:1807.05894.
[13] K. Blum, K. C. Y. Ng, R. Sato, M. Takimoto, Phys. Rev. D96 (10) (2017) 103021.
[14] S. Acharya, et al., Phys. Lett. B783 (2018) 95–113.
[15] A. Kurkela, Nucl. Phys. A956 (2016) 136–143.
[16] S. Acharya, et al., submitted to Phys. Lett. B,arXiv:1805.05212.
[17] C. Loizides, A. Morsch, Phys. Lett. B773 (2017) 408–411.
[18] S. Acharya, et al., submitted to Phys. Lett. B,arXiv:1805.04399.
[19] A. J. Larkoski, S. Marzani, G. Soyez, J. Thaler, JHEP 05 (2014) 146.
[20] B. Trzeciak, these proceedings.
[21] S. Acharya, et al., submitted to Phys. Lett. B,arXiv:1805.04403.
[22] T. Akesson, et al., Phys. Lett. B192 (1987) 463–470.
[23] S. Acharya, et al., submitted to Phys. Lett. B,arXiv:1805.04407.
[24] R. Rapp, X. Du, Private Communication.