Exploring sQGP and Small Systems

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Abstract

A strongly interacting Quark-Gluon Plasma (sQGP) is created in the high energy heavy ion collisions at RHIC and LHC. Our present understanding of sQGP as a very good liquid with astonishingly low viscosity is reviewed. With the arrival of the interesting results from LHC in high-energy p+p and p+A, a new endeavour to characterize the transition from these small systems to heavy ions (A+A) is now in place, since, even the small systems showed prominent similarities to heavy ions in the rising multiplicity domains. An outlook of future possibilities for better measurements is also made at the end of this brief review.

1 Introduction

We all know that the normal nuclear matter is made up of protons and neutrons, which in turn are made up of the quarks [1] and gluons [2]. The quarks and gluons are confined inside the colorless particles called hadrons and free colored particles do not occur. As explained by Quantum Chromo-Dynamics (QCD), the strong interaction is the governing interaction in the subatomic world [3, 4]. One of the important experimental observations that QCD needs to decipher, is the confinement of the quarks and gluons [5]. The confinement property is yet not fully understood, even though qualitatively we know about the hadron properties (mesons are bound states of a quark and anti-quark and baryons are bound states of 3 quarks) from the quark model [6]. The refinements of the quark model of hadrons and the development of QCD, naturally led to expectations that matter at very high densities [7, 8, 9, 10] may exist in a state of quasi-free quarks and gluons, the Quark-Gluon Plasma (QGP) [11, 12, 13].

The very early universe was different than the present times. It was too hot and dense to allow the quarks and gluons to form hadrons and was apparently filled with a

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thermalized plasma of deconfined quarks, anti-quarks, gluons and leptons, which was the primordial QGP [14]. The universe may have left the QGP phase after a few microseconds with the available quarks and gluons combining towards the formation of the mesons and baryons [15]. In our laboratories, we can probe the QGP [16, 17, 18, 19, 20, 21, 22] which is a deconfined system of quarks and gluons, by colliding heavy nuclei at relativistic energies. Such collisions, create QGP which can be characterized by colored partons as the dynamic degrees of freedom [23]. Smashing heavy ions, typically Au or Pb ions, at relativistic energies in the present accelerator facilities, such as the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC), can create the QGP. The dynamics of the early universe in terms of the “Big Bang” can be studied experimentally by relativistic nucleus-nucleus collisions at RHIC and LHC in terms of “little bangs” in the laboratory [14, 15, 23].

The main epochs [23] for such a “little bang” collision are: (1) the two nuclei which are lorentz contracted and now disk-like approach each other and collide with a very small traversal time (≪ 1 fm/c). (2) The interactions start developing when the two nuclei hit each other and after such an impact the “hard” processes [11, 24, 25, 27] i.e those which comprise of relatively large transferred momenta \( Q \gg 1 \text{ GeV} \) between the quarks, anti-quarks or gluons (partons) inside the nucleons of the two nuclei produce secondary partons with large transverse momenta \( p_T \) [26]. During these times the matter is out of equilibrium and hence will need some time to equilibrate [15]. (3) The “soft” collisions or those with small momentum exchange \( Q < 1 \text{ GeV} \) cause copious production of particles after sometime and thermalize the QGP after about 1 fm/c [28]. The QGP now expands hydrodynamically and then cools down approximately adiabatically [13, 15]. (4) The QGP then converts to a gas of hadrons and the hadrons continue to interact quasi-elastically, further accelerating the expansion and cooling the fireball until thermal freeze-out (after \( \approx 5-10 \text{ fm/c} \)) into thousands of hadrons. The unstable hadrons decay and the stable decay products fly out to the large scale detectors surrounding the interaction region. During the hadronization process the chemical composition of the hadron gas is fixed and remains basically constant afterwards [15, 23, 28].

By studying the behavior of the matter created in “little bangs” we can explore the
phase structure of the strongly interacting matter [14, 15, 23, 28]. The QGP reveals emerging collective behavior [28, 29, 30, 31] that originates from the many-body interactions in QCD. The heavy-ion experiments have explored the close to perfect fluidity aspects of QGP [32, 33, 34, 35], precisely, with varied experimental observables [36]. The new state of strongly interacting matter created in these collisions, have low shear viscosity($\eta$) to entropy density($s$) ratio, $\eta/s$, which is close to a nearly perfect fluid [15, 36, 37, 38, 39, 40, 41].

The paper is organised to start with a brief introduction of QGP and in Section 2 we have a brief survey of the different avenues of the formation and promulgation of the strongly coupled QGP. The term “strongly coupled QGP (sQGP)” was coined [32, 42] as we have realised that QGP formed in relativistic heavy ion collisions is not a weakly coupled gas but on the other hand is more a strongly coupled liquid [33, 42, 43]. The realization that QGP created at RHIC is not a weakly coupled gas but a strongly coupled liquid has aroused a significant development in this research field. In Section 3 the varied probes for this dense matter formed in our laboratories and their inferences towards the understanding of the small systems like p+p and p+A collisions are discussed. Without the critical understanding of such small systems we cannot characterize the A+A collisions. Finally, we summarise by looking into the future scope for such studies that lie ahead.

2 sQGP

The results from the relativistic heavy ion collision experiments have changed the theoretical understanding of the properties of the QCD matter. Also significant know-how has evolved regarding the deconfined QCD matter created in the central interaction volume at such high energies. Previously QGP was felt to be a weakly interacting system of quarks and gluons which might be described by perturbative QCD (pQCD). However contrary to the expectations, the experimental results from RHIC [16, 17, 18, 19], have shown that a hot, strongly interacting, nearly perfect and almost opaque relativistic liquid, also termed as the strongly coupled QGP was created in central Au+Au collisions at the top RHIC energy regime [15, 32, 33, 34].

The comparative studies of the experimental data [16, 17, 18, 19], and especially the
elliptic flow \( (v_2) \) [35], in terms of the hydrodynamic models showed the nearly perfect fluid behavior of QGP. Such inferences indicate that its properties correspond to non-perturbative, strongly interacting matter. RHIC results showed that the resulting plasma could be well described by a hydrodynamic picture of a nearly ideal liquid, which show very limited internal friction or in other words very small shear viscosity (\( \eta \)). The created medium in such relativistic collisions, can connect to the pressure gradients by flowing apparently unobstructed [36, 44, 45].

Shear viscosity, \( \eta \), is a characterizing parameter for fluids [44, 46, 47, 48] and can be defined in terms of the friction force \( F \) per unit area \( A \) produced by a shear flow with transverse flow gradient \( \nabla_y v_x \),

\[
\frac{F}{A} = \eta \nabla_y v_x.
\]

Small shear viscosity is a benchmark for a good fluid.

Shear viscosity for a weakly coupled gas can be estimated as

\[
\eta = \frac{1}{3} n p \lambda,
\]

where \( n \) is the density, \( p \) is the average momentum of the gas molecules, and \( \lambda \) is the mean free path. The mean free path can be expressed as \( \lambda = 1/(n \sigma) \) where \( \sigma \) is a preferable transport cross-section. For relativistic fluids it is more natural to normalize \( \eta \) to the entropy density \( s \) rather than the particle density \( n \).

It has been observed that good fluids are characterized by \( \eta/s \sim \hbar/k_B \) and this value is consistent with simple theoretical propositions. For all fluids, the proposed lower bound based on the results from string theory [49], is,

\[
\frac{\eta}{s} \geq \frac{\hbar}{4 \pi k_B}.
\]

A “perfect fluid” saturates around this value by dissipating the smallest possible amount of energy. A perfect fluid thus follows the laws of fluid dynamics in the largest possible domain [47, 48, 49].

The experimental results from RHIC indicate that the matter produced in nuclear reactions has a small ratio of \( \eta/s \) [37, 38]. The discovery of such a close perfect fluid nature established relativistic fluid dynamics as the new frame-work for deciphering the
bulk evolution of the system [36, 44]. The observations illustrate that QGP near $T_c$ is a strongly coupled one with the properties of a liquid with very low viscosity rather than that of a dilute gas [50, 51].

Analysis infers [41] that the averaged specific viscosity of the QGP produced in LHC collisions is quite similar to that for the dense matter created in RHIC energy domain. So, the domain in which matter produced at RHIC/LHC is, $T_c < T < 2T_c$, was renamed into a strongly coupled QGP or “sQGP” in short [35, 52, 53, 54, 55, 56, 57]. On the other hand the low value for $\eta/s$ could also result from an anomalous viscosity $\eta_A$, originating from turbulent color magnetic and electric fields dynamically produced in the expanding quark-gluon plasma [37, 51]. That is,

$$1/\eta = 1/\eta_A + 1/\eta_C,$$

where $\eta_A$ subjugates over the collisional viscosity $\eta_C$. Such arguments do not rule out a more complex structure of the gluonic component of the matter produced in the relativistic collisions [58].

At LHC energies the initial energy density (at $\tau_0 = 1$ fm/c) is about 15 GeV $fm^{-3}$ [59]. It is approximately a factor of three higher than the Au+Au collisions at the highest energy regime at RHIC. Some researchers expected that the QGP produced at the LHC would turn back to the previous picture, where quarks and gluons were more weakly coupled at higher temperature. Then the mean free path of particles in the medium and the viscosity will be significant. As a result the experimental signature will emerge as smaller flow components ($v_n$). But the ALICE elliptic flow $v_2$ results [60] have clearly shown, the opposite. The dependence of $v_2$ on transverse momentum is comparable with the RHIC measurements and ALICE has also established that radial flow grows with energy.

Understanding sQGP was a challenge which we have researched from RHIC data. However the LHC program has added a lot to our understanding, and the paramount issues in the field now include a critical search to study the evolution between p+p, p+A collisions which are known as “small systems” and heavy ion A+A collisions, with an goal to understand “the smallest drops” of the sQGP showing collective/hydrodynamics
behavior [56]. Some of these assumptions are getting tested and understood carefully both in RHIC [61] and LHC [62, 63] experiments.

At LHC since the collision energies increase, one expects a QGP which is hotter. Such favourable high energy of LHC is more evident in the area of parton energy loss analogous to the opaque nature of the sQGP where the kinematic domain exceeds that of RHIC. The significant impact of this increase of the collision energy is the huge excess of the rates of hard probes, such as jets, electro-weak particles and heavy-flavors, including the full family of quarkonia (c\bar{c} and b\bar{b} bound states) [59, 64]. With a larger in-elastic cross-section, the production of b\bar{b} pairs will increase more in LHC energies. The abundance of b\bar{b} pairs enable the possibility for bottom quark and anti-bottom quark pairs to recombine, following bottomonium state breakup, or combination after the pair forms from the open bottom states. The available high rates allow detail studies of the dense medium using the interactions of these probes with the medium constituents [64, 65, 66].

The elastic re-scattering of the heavy quarks in the sQGP is an important element for the understanding of heavy-flavor and single-electron/muon observables in heavy ion reactions at collider energies [26, 67]. The produced heavy-flavor interacts with the dense medium by exchanging energy and momentum. The ratio of the measured number of heavy-flavors in heavy ion (A+A) collisions to the expected number in the absence of nuclear or partonic matter i.e p+p collisions, is the definition of nuclear modification factor($R_{AA}$) which is suppressed at high transverse momentum [66]. The elementary degrees of freedom and basic forces at the shortest distances are understood via small systems [15]. So a clear understanding of the small systems emerge as a necessity. The small collision systems like p+p and p+A collisions at LHC energies thus needs detail study to understand the initial and final state effects in Cold Nuclear Matter(CNM), which can provide baseline for the interpretation of heavy ion (A+A) results [28, 68].

3 Small Systems

Study of QGP requires reference measurements which is provided by the small system (p+p and p+A) collisions [28, 68]. QGP is not expected to be formed in small systems as
the transverse size of the overlap region is comparable to that of a single proton [20, 69, 70, 71]. Particle production in A+A and p+A, as compared to p+p collisions, expressed as $R_{AA}$, is termed as the nuclear modification factor. It has long been formulated to understand particle production mechanisms [66]. The $R_{AA}$ of heavy-flavor is expected to be less suppressed and elliptic flow $v_2$ of heavy-flavor is felt to be smaller in comparison with the light hadrons. The experimental results from ALICE, however, show that the suppression of heavy-flavor hadrons (D-meson) at high transverse momentum ($p_T$) and its elliptic flow $v_2$ are comparable to those of the light hadrons [72, 73], which needs to be understood [74]. Hence looking into the p+A collisions is required [75], where medium absence provides necessary conditions, to isolate the nuclear effects from the initial hard-scattering processes which we often describe as CNM [76, 77, 78, 79].

Broadly the CNM effects encompass: (i) initial-state nuclear effects on the parton densities (i.e shadowing); (ii) coherent energy loss comprising of initial-state parton energy loss and final-state energy loss; and (iii) the final-state absorption by nucleons, which is expected to be negligible at LHC energies. The CNM effects like the change of the Parton Distribution Functions (PDFs) within the nucleons contained within the nuclei, as compared to the unbound nucleons can modify the interaction and production cross-sections [80]. That’s why the p+A collisions are important to decouple the effects of QGP from those of CNM, and to provide very much required input to the understanding of A+A collisions [76, 77, 78, 79]. The nuclear modification factor of charged particles from CMS experiment [81] in p+Pb collisions, in contrast to the Pb+Pb system at top LHC energies of $\sqrt{s_{NN}}=5.02$ TeV, demonstrate no suppression in the 2-10 GeV/c $p_T$ region. However we visualize a weak momentum dependence for $p_T > 10$ GeV/c in the p+Pb system, since we observe a moderate excess above unity at high $p_T$ for charged particles. Also for heavy-flavor(D-meson), the nuclear modification factor, measured by ALICE experiment [82] in p+Pb collisions at same energies, show no suppression within the uncertainties in the measured $p_T$ range of 1-24 GeV/c. The strong suppression of the D-meson yields for $p_T > 3$ GeV/c has been observed in central and semi-peripheral Pb+Pb collisions [83], whereas, for the charged particles [81] we see for $p_T < 2$ GeV/c a rising trend in both p+Pb and Pb+Pb systems. In the Pb+Pb collisions the charged particles [81] then show a significant
suppression in the 2<p_T<10 GeV/c region, and again a rising trend around 10 GeV/c to the highest p_T. The p+Pb and Pb+Pb nuclear modification factors presented in these papers [81, 82, 83], covering the light and heavy quarks respectively, provide stringent constraints on cold and hot nuclear matter effects. They also clearly establish why the CNM effects are of crucial importance for accurate interpretation of the measurements in heavy ion collisions and in turn advocate the necessity of studying the small system collisions.

But at LHC energies do we see any new features in p+p collisions? At LHC energies the particle multiplicity is high and even reach values, which are of the same order as those found in heavy ion collisions at lower energies, and as a matter of fact, they are well above the ones observed at RHIC for peripheral Cu+Cu collisions at √s_{NN} = 200 GeV [84]. When LHC started with the p+p collisions, the high-multiplicity environment revealed a “ridge” which was measured by CMS [85] while studying the long-range azimuthal correlations for 2.0 < |Δη| < 4.8. The first observation of a long-range ridge-like structure at the near-side (Δφ ≈ 0) was observed for 7 TeV p+p collisions. For the high multiplicity domain of N ≈ 90 or higher, this notable feature is clearly observed for large rapidity differences |Δη| > 2. Also in the high-multiplicity p+Pb collisions at √s_{NN}=5.02 TeV, the azimuthal correlations for 2.0 < |Δη| < 4.0 showed a qualitatively similar long-range structure at the nearside Δφ ≈ 0. Thus the long-range, near-side angular correlations in particle production emerged in p+p and subsequently in p+Pb collisions [86], which was further followed by an away-side structure, located at Δφ ≈ π and exceeding the away-side jet contribution, in p+Pb collisions [87, 88].

In a typical p+p collision, a ridge correlation is not expected because the system is too dilute to produce a fluid-like state. This paved the way to encourage the researchers to look for a detailed investigation of the existence of collective phenomena in p+p collisions which was known since long in heavy ion collisions [89]. The strong evidence for the collective nature of the long-range correlations was observed with the charged particles (light quarks) [63] by CMS experiment at √s = 13 TeV. Also the elliptic flow (v_2) coefficients for heavy-flavor decay muons was measured by ATLAS in p+p collisions at same energy [90].
Since heavy quark yields in heavy ion collisions are expected to be modified relative to minimum bias p+p collisions [66], the obvious question arises if their production rates in high-multiplicity p+p collisions at LHC energies show any effect like J/Ψ suppression [24, 25]. A stronger than linear rise of the relative production of J/Ψ as a function of multiplicity was observed for $p_T$-integrated yields and this increase is stronger for high-$p_T$ J/Ψ mesons which we see for p+p collisions at $\sqrt{s} = 13$ TeV [91]. An escalation of the relative J/Ψ and Υ yields [92, 93, 94] with the relative charged-particle multiplicity was observed in p+Pb collisions at $\sqrt{s_{NN}}=8.16$ TeV [95]. The results in p+A are very similar to the results from p+p collisions [93, 94, 96]. The rise of the J/Ψ normalized yields are comparable to the increase observed for D-mesons [97, 98] which indicate that a common mechanism may be at its origin. A plethora of new, unexpected phenomena have been observed so far in small system (p+p and p+A) collisions, which, produce remarkable similarities to heavy ion phenomenology.

4 Summary and Outlook

The more-central Au+Au collisions at RHIC, on the basis of elliptic-flow systematics, have been characterized in terms of a sQGP with small viscosity a “perfect liquid”. Crucial input to our comprehension of the sQGP were inferred from the measurements of “collective flow”, which in other words is the correlated emission of particles in azimuthal angle around the axis of the colliding beams. Conventionally, we have diagnosed the effects of the sQGP on the final-state particle production and correlations in A+A collisions, by using the relative to baseline measurements of p+p and p+A collisions, and thus assuming that in the smaller, and therefore shorter-lived systems, no QGP effects can happen. At LHC we found new things and even the small systems showed flow features in the rising multiplicity domains. With the increasing multiplicity, the p+p and p+A collisions enter the stage where the macroscopic description (thermodynamics and hydrodynamics) becomes applicable. While hydrodynamic models, when applied to p+A data, can explain many of the observed features, there are serious questions regarding their applicability [99]. Thus, a very detailed description of a broad range of signatures, in an even broader range
of systems, will be required to finally demonstrate a full understanding of these new discoveries.

Data which will be collected in Run-3 at the LHC, will be a significant addition for such studies. Better picture will be also available with the results from p+Pb collisions. Also exceptionally high-multiplicity p+p collisions are expected in Run-3 and 4 at LHC [100]. The LHC delivered nearly 30 $fb^{-1}$ by the end of 2012 and propose to reach 300 $fb^{-1}$ in its first 13-15 years of operation. The second long shutdown (LS-2) before Run-3 will consolidate the luminosity and reliability as well as the upgrading of the LHC injectors. After LS-3, the machine will be in the High Luminosity configuration. The High Luminosity LHC(HL-LHC) is an important and extremely challenging, upgrade [101]. The large p+p collision data sets expected to be collected at the HL-LHC will provide a compelling setting for these investigations [100, 102]. Such higher multiplicities will help us to bridge the gap between the p+p and heavy ion collisions, with better detector upgrades in LHC experiments [103].

References

[1] E. M. Riordan, Science 256, 1287-1293 (1992) doi:10.1126/science.256.5061.1287

[2] J. Ellis, Int. J. Mod. Phys. A 29, no.31, 1430072 (2014) doi:10.1142/S0217751X14300725 [arXiv:1409.4232 [hep-ph]].

[3] W. J. Marciano and H. Pagels, Phys. Rept. 36, 137 (1978) doi:10.1016/0370-1573(78)90208-9

[4] W. J. Marciano and H. Pagels, Nature 279, 479-483 (1979) doi:10.1038/279479a0

[5] M. Bruno, M. Caselle, M. Panero and R. Pellegrini, JHEP 03, 057 (2015) doi:10.1007/JHEP03(2015)057 [arXiv:1409.8305 [hep-lat]].

[6] J. M. Richard, [arXiv:1205.4326 [hep-ph]].

[7] J. Berges, arXiv:hep-ph/9902419.
[8] J. B. Kogut, Nucl. Phys. B Proc. Suppl. 119, 210-221 (2003) doi:10.1016/S0920-5632(03)01508-1 [arXiv:hep-lat/0208077 [hep-lat]].

[9] K. Fukushima, J. Phys. G 39, 013101 (2012) doi:10.1088/0954-3899/39/1/013101 [arXiv:1108.2939 [hep-ph]].

[10] F. Wilczek, arXiv:hep-ph/0003183.

[11] L. S. Kisslinger and D. Das, Int. J. Mod. Phys. A 31, no. 07, 1630010 (2016) doi:10.1142/S0217751X16300106 [arXiv:1411.3680 [hep-ph]].

[12] E. V. Shuryak, Phys. Rept. 61, 71 (1980).

[13] S. A. Bass, M. Gyulassy, H. Stoecker and W. Greiner, J. Phys. G 25, R1 (1999) doi:10.1088/0954-3899/25/3/013 [hep-ph/9810281].

[14] J. R. Ellis, J. Phys. Conf. Ser. 50, 8-21 (2006) doi:10.1088/1742-6596/50/1/002 [arXiv:astro-ph/0504501 [astro-ph]].

[15] U. W. Heinz, J. Phys. A 42, 214003 (2009) doi:10.1088/1751-8113/42/21/214003 [arXiv:0810.5529 [nucl-th]].

[16] J. Adams et al. [STAR Collaboration], Nucl. Phys. A 757, 102 (2005) doi:10.1016/j.nuclphysa.2005.03.085 [nucl-ex/0501009].

[17] K. Adcox et al. [PHENIX Collaboration], Nucl. Phys. A 757, 184 (2005) doi:10.1016/j.nuclphysa.2005.03.086 [nucl-ex/0410003].

[18] B. B. Back et al., Nucl. Phys. A 757, 28 (2005) doi:10.1016/j.nuclphysa.2005.03.084 [nucl-ex/0410022].

[19] I. Arsene et al. [BRAHMS Collaboration], Nucl. Phys. A 757, 1 (2005) doi:10.1016/j.nuclphysa.2005.02.130 [nucl-ex/0410020].

[20] B. B. Abelev et al. [ALICE Collaboration], Int. J. Mod. Phys. A 29, 1430044 (2014) doi:10.1142/S0217751X14300440 [arXiv:1402.4476 [nucl-ex]].

[21] G. K. Krintiras [CMS], [arXiv:2006.05556 [nucl-ex]].
REFERENCES

[22] N. Armesto and E. Scomparin, Eur. Phys. J. Plus 131, no. 3, 52 (2016) doi:10.1140/epjp/i2016-16052-4 [arXiv:1511.02151 [nucl-ex]].

[23] W. Busza, K. Rajagopal and W. van der Schee, Ann. Rev. Nucl. Part. Sci. 68, 339 (2018) doi:10.1146/annurev-nucl-101917-020852 [arXiv:1802.04801 [hep-ph]].

[24] T. Matsui and H. Satz, Phys. Lett. B 178 (1986) 416.

[25] H. Satz, Nucl. Phys. A 418, 447C (1984).

[26] M. He, R. J. Fries and R. Rapp, Phys. Lett. B 735, 445-450 (2014) doi:10.1016/j.physletb.2014.05.050 [arXiv:1401.3817 [nucl-th]].

[27] P. Foka and M. A. Janik, Rev. Phys. 1, 172-194 (2016) doi:10.1016/j.revip.2016.11.001 [arXiv:1702.07231 [hep-ex]].

[28] J. L. Nagle and W. A. Zajc, Ann. Rev. Nucl. Part. Sci. 68, 211 (2018) doi:10.1146/annurev-nucl-101916-123209 [arXiv:1801.03477 [nucl-ex]].

[29] S. A. Voloshin, A. M. Poskanzer and R. Snellings, arXiv:0809.2949 [nucl-ex]. Landolt-Bornstein 23 (2010) 293-333.

[30] R. Snellings, New J. Phys. 13, 055008 (2011) doi:10.1088/1367-2630/13/5/055008 [arXiv:1102.3010 [nucl-ex]].

[31] P. Foka and M. A. Janik, Rev. Phys. 1, 154 (2016) doi:10.1016/j.revip.2016.11.002 [arXiv:1702.07233 [hep-ex]].

[32] E. Shuryak, Prog. Part. Nucl. Phys. 53, 273-303 (2004) doi:10.1016/j.ppnp.2004.02.025 [arXiv:hep-ph/0312227 [hep-ph]].

[33] M. Gyulassy and L. McLerran, Nucl. Phys. A 750, 30-63 (2005) doi:10.1016/j.nuclphysa.2004.10.034 [arXiv:nucl-th/0405013 [nucl-th]].

[34] E. Shuryak, Prog. Part. Nucl. Phys. 62, 48 (2009) doi:10.1016/j.ppnp.2008.09.001 [arXiv:0807.3033 [hep-ph]].
[35] R. A. Lacey, Nucl. Phys. A 774, 199-214 (2006) doi:10.1016/j.nuclphysa.2006.06.041 [arXiv:nucl-ex/0510029 [nucl-ex]].

[36] F. Becattini, J. Liao and M. Lisa, [arXiv:2102.00933 [nucl-th]]. Part of the Lecture Notes in Physics book series (LNP, volume 987).

[37] R. A. Lacey, N. N. Ajitanand, J. M. Alexander, P. Chung, W. G. Holzmann, M. Issah, A. Taranenko, P. Danielewicz and H. Stoecker, Phys. Rev. Lett. 98, 092301 (2007) doi:10.1103/PhysRevLett.98.092301 [arXiv:nucl-ex/0609025 [nucl-ex]].

[38] R. A. Lacey, A. Taranenko and R. Wei, [arXiv:0905.4368 [nucl-ex]].

[39] A. Bagoly and M. Csanad, Int. J. Mod. Phys. A 31, no.28 & 29, 1645016 (2016) doi:10.1142/S0217751X16450160 [arXiv:1507.05005 [nucl-th]].

[40] J. Y. Jia, Nucl. Phys. A 834, 229C-236C (2010) doi:10.1016/j.nuclphysa.2009.12.047

[41] R. A. Lacey, A. Taranenko, N. N. Ajitanand and J. M. Alexander, Phys. Rev. C 83, 031901 (2011) doi:10.1103/PhysRevC.83.031901 [arXiv:1011.6328 [nucl-ex]].

[42] J. Liao and E. Shuryak, Phys. Rev. C 75, 054907 (2007) doi:10.1103/PhysRevC.75.054907 [arXiv:hep-ph/0611131 [hep-ph]].

[43] J. L. Nagle, Eur. Phys. J. C 49, 275-279 (2007) doi:10.1140/epjc/s10052-006-0061-1 [arXiv:nucl-th/0608070 [nucl-th]].

[44] E. Shuryak, Nucl. Phys. A 774, 387-396 (2006) doi:10.1016/j.nuclphysa.2006.06.058 [arXiv:hep-ph/0510123 [hep-ph]].

[45] M. H. Thoma, J. Phys. G 31, L7 (2005) [erratum: J. Phys. G 31, 539 (2005)] doi:10.1088/0954-3899/31/1/L02 [arXiv:hep-ph/0503154 [hep-ph]].

[46] T. Hirano and M. Gyulassy, Nucl. Phys. A 769, 71-94 (2006) doi:10.1016/j.nuclphysa.2006.02.005 [arXiv:nucl-th/0506049 [nucl-th]].

[47] T. Schäfer and D. Teaney, Rept. Prog. Phys. 72, 126001 (2009) doi:10.1088/0034-4885/72/12/126001 [arXiv:0904.3107 [hep-ph]].
REFERENCES

[48] T. Schäfer, AIP Conf. Proc. 1182, no.1, 755-758 (2009) doi:10.1063/1.3293917 [arXiv:0906.5399 [physics.flu-dyn]].

[49] P. Kovtun, D. T. Son and A. O. Starinets, Phys. Rev. Lett. 94, 111601 (2005) doi:10.1103/PhysRevLett.94.111601 [arXiv:hep-th/0405231 [hep-th]].

[50] H. Niemi, G. S. Denicol, P. Huovinen, E. Molnar and D. H. Rischke, Phys. Rev. Lett. 106, 212302 (2011) doi:10.1103/PhysRevLett.106.212302 [arXiv:1101.2442 [nucl-th]].

[51] M. Asakawa, S. A. Bass and B. Muller, Phys. Rev. Lett. 96, 252301 (2006) doi:10.1103/PhysRevLett.96.252301 [arXiv:hep-ph/0603092 [hep-ph]].

[52] H. Berrehrah, E. Bratkovskaya, W. Cassing and R. Marty, J. Phys. Conf. Ser. 612, no.1, 012050 (2015) doi:10.1088/1742-6596/612/1/012050 [arXiv:1412.1017 [hep-ph]].

[53] M. Csanad, EPJ Web Conf. 70, 00011 (2014) doi:10.1051/epjconf/2014700011 [arXiv:1208.4683 [nucl-th]].

[54] R. Rapp, D. Cabrera, V. Greco, M. Mannarelli and H. van Hees, [arXiv:0806.3341 [hep-ph]].

[55] F. Wang, Nucl. Phys. A 834, 223C-228C (2010) doi:10.1016/j.nuclphysa.2009.12.046 [arXiv:0910.2754 [nucl-ex]].

[56] E. Shuryak, Rev. Mod. Phys. 89, 035001 (2017) doi:10.1103/RevModPhys.89.035001 [arXiv:1412.8393 [hep-ph]].

[57] U. W. Heinz, [arXiv:nucl-th/0512051 [nucl-th]].

[58] J. Liao, J. Phys. Conf. Ser. 779, no.1, 012014 (2017) doi:10.1088/1742-6596/779/1/012014 [arXiv:1611.05391 [nucl-th]].

[59] B. Muller, J. Schukraft and B. Wyslouch, Ann. Rev. Nucl. Part. Sci. 62, 361-386 (2012) doi:10.1146/annurev-nucl-102711-094910 [arXiv:1202.3233 [hep-ex]].

[60] K. Aamodt et al. [ALICE], Phys. Rev. Lett. 105, 252302 (2010) doi:10.1103/PhysRevLett.105.252302 [arXiv:1011.3914 [nucl-ex]].
[61] C. Aidala et al. [PHENIX], Nature Phys. 15, no.3, 214-220 (2019) 
doi:10.1038/s41567-018-0360-0 [arXiv:1805.02973 [nucl-ex]].

[62] V. Khachatryan et al. [CMS], Phys. Rev. Lett. 115, no.1, 012301 (2015) 
doi:10.1103/PhysRevLett.115.012301 [arXiv:1502.05382 [nucl-ex]].

[63] V. Khachatryan et al. [CMS Collaboration], Phys. Lett. B 765, 193 (2017) 
doi:10.1016/j.physletb.2016.12.009 [arXiv:1606.06198 [nucl-ex]].

[64] M. Cacciari, Nuovo Cim. C 035N1, 23-28 (2012) doi:10.1393/ncc/i2012-11112-2 
[arXiv:1109.1500 [hep-ph]].

[65] D. Das and N. Dutta, Int. J. Mod. Phys. A 33, no. 16, 1850092 (2018) 
doi:10.1142/S0217751X18500926 [arXiv:1802.00414 [nucl-ex]].

[66] A. Andronic et al., Eur. Phys. J. C 76, no. 3, 107 (2016) doi:10.1140/epjc/s10052-015-3819-5 
[arXiv:1506.03981 [nucl-ex]].

[67] D. Das [ALICE Collaboration], 
Nucl. Phys. A 862-863, 223 (2011) doi:10.1016/j.nuclphysa.2011.05.044 
[arXiv:1102.2071 [nucl-ex]].

[68] D. Das, Nucl. Phys. A 1007, 122132 (2021) doi:10.1016/j.nuclphysa.2020.122132

[69] B. Abelev et al. [ALICE Collaboration], Phys. Rev. Lett. 109, 112301 (2012) 
doi:10.1103/PhysRevLett.109.112301 [arXiv:1205.6443 [hep-ex]].

[70] H. Ni [CMS Collaboration], J. Phys. Conf. Ser. 1070, no. 1, 012009 (2018). 
doi:10.1088/1742-6596/1070/1/012009

[71] D. Moreira De Godoy [ALICE Collaboration], Nucl. Phys. A 967, 636 (2017) 
doi:10.1016/j.nuclphysa.2017.05.050 [arXiv:1705.02800 [nucl-ex]].

[72] B. Abelev et al. [ALICE], JHEP 09, 112 (2012) doi:10.1007/JHEP09(2012)112 
[arXiv:1203.2160 [nucl-ex]].
[73] B. Abelev et al. [ALICE], Phys. Rev. Lett. 111, 102301 (2013) doi:10.1103/PhysRevLett.111.102301 [arXiv:1305.2707 [nucl-ex]].

[74] X. Dong, Y. J. Lee and R. Rapp, Ann. Rev. Nucl. Part. Sci. 69, 417-445 (2019) doi:10.1146/annurev-nucl-101918-023806 [arXiv:1903.07709 [nucl-ex]].

[75] S. Acharya et al. [ALICE Collaboration], Eur. Phys. J. C 78, no. 6, 466 (2018) doi:10.1140/epjc/s10052-018-5881-2 [arXiv:1802.00765 [nucl-ex]].

[76] R. Vogt, Phys. Rev. C 81, 044903 (2010) doi:10.1103/PhysRevC.81.044903 [arXiv:1003.3497 [hep-ph]].

[77] H. Fujii and K. Watanabe, Nucl. Phys. A 915, 1 (2013) doi:10.1016/j.nuclphysa.2013.06.011 [arXiv:1304.2221 [hep-ph]].

[78] R. Vogt, [arXiv:1508.01286 [hep-ph]].

[79] J. L. Albacete, F. Arleo, G. G. Barnaföldi, G. Bíró, D. d’Enterria, B. Ducloué, K. J. Eskola, E. G. Ferreiro, M. Gyulassy and S. M. Harangozó, et al. Nucl. Phys. A 972, 18-85 (2018) doi:10.1016/j.nuclphysa.2017.11.015 [arXiv:1707.09973 [hep-ph]].

[80] N. Armesto, EPJ Web Conf. 171 (2018), 11001 doi:10.1051/epjconf/201817111001

[81] V. Khachatryan et al. [CMS], JHEP 04, 039 (2017) doi:10.1007/JHEP04(2017)039 [arXiv:1611.01664 [nucl-ex]].

[82] B. B. Abelev et al. [ALICE], Phys. Rev. Lett. 113, no.23, 232301 (2014) doi:10.1103/PhysRevLett.113.232301 [arXiv:1405.3452 [nucl-ex]].

[83] J. Adam et al. [ALICE], JHEP 03, 081 (2016) doi:10.1007/JHEP03(2016)081 [arXiv:1509.06888 [nucl-ex]].

[84] B. Alver et al. [PHOBOS], Phys. Rev. C 83, 024913 (2011) doi:10.1103/PhysRevC.83.024913 [arXiv:1011.1940 [nucl-ex]].
[85] V. Khachatryan et al. [CMS], JHEP 09, 091 (2010)
doi:10.1007/JHEP09(2010)091 [arXiv:1009.4122 [hep-ex]].

[86] S. Chatrchyan et al. [CMS], Phys. Lett. B 718, 795-814 (2013)
doi:10.1016/j.physletb.2012.11.025 [arXiv:1210.5482 [nucl-ex]].

[87] B. Abelev et al. [ALICE], Phys. Lett. B 719, 29-41 (2013)
doi:10.1016/j.physletb.2013.01.012 [arXiv:1212.2001 [nucl-ex]].

[88] G. Aad et al. [ATLAS], Phys. Rev. Lett. 110, no.18, 182302 (2013)
doi:10.1103/PhysRevLett.110.182302 [arXiv:1212.5198 [hep-ex]].

[89] B. I. Abelev et al. [STAR], Phys. Rev. C 80, 064912 (2009)
doi:10.1103/PhysRevC.80.064912 [arXiv:0909.0191 [nucl-ex]].

[90] G. Aad et al. [ATLAS], Phys. Rev. Lett. 124, no.8, 082301 (2020)
doi:10.1103/PhysRevLett.124.082301 [arXiv:1909.01650 [nucl-ex]].

[91] S. Acharya et al. [ALICE], Phys. Lett. B 810, 135758 (2020)
doi:10.1016/j.physletb.2020.135758 [arXiv:2005.11123 [nucl-ex]].

[92] D. Adamová et al. [ALICE], Phys. Lett. B 776, 91-104 (2018)
doi:10.1016/j.physletb.2017.11.008 [arXiv:1704.00274 [nucl-ex]].

[93] S. Chatrchyan et al. [CMS], JHEP 04, 103 (2014) doi:10.1007/JHEP04(2014)103
[arXiv:1312.6300 [nucl-ex]].

[94] M. Aaboud et al. [ATLAS], Eur. Phys. J. C 78, no.3, 171 (2018)
doi:10.1140/epjc/s10052-018-5624-4 [arXiv:1709.03089 [nucl-ex]].

[95] S. Acharya et al. [ALICE], JHEP 09, 162 (2020) doi:10.1007/JHEP09(2020)162
[arXiv:2004.12673 [nucl-ex]].

[96] B. Abelev et al. [ALICE], Phys. Lett. B 712, 165-175 (2012)
doi:10.1016/j.physletb.2012.04.052 [arXiv:1202.2816 [hep-ex]].
[97] J. Adam et al. [ALICE], JHEP 09, 148 (2015) doi:10.1007/JHEP09(2015)148 [arXiv:1505.00664 [nucl-ex]].

[98] J. Adam et al. [ALICE], JHEP 08, 078 (2016) doi:10.1007/JHEP08(2016)078 [arXiv:1602.07240 [nucl-ex]].

[99] E. Shuryak and I. Zahed, Phys. Rev. C 88 (2013) no.4, 044915 doi:10.1103/PhysRevC.88.044915 [arXiv:1301.4470 [hep-ph]].

[100] F. Noferini [ALICE], J. Phys. Conf. Ser. 1014, no.1, 012010 (2018) doi:10.1088/1742-6596/1014/1/012010

[101] G. Apollinari, O. Brüning, T. Nakamoto and L. Rossi, doi:10.5170/CERN-2015-005.1 [arXiv:1705.08830 [physics.acc-ph]].

[102] E. Chapon, D. d'Enterria, B. Ducloue, M. G. Echevarria, P. B. Gossiaux, V. Kartvelishvili, T. Kasemets, J. P. Lansberg, R. McNulty and D. D. Price, et al. [arXiv:2012.14161 [hep-ph]].

[103] Z. Citron et al., CERN Yellow Rep. Monogr. , 1159 (2019) doi:10.23731/CYRM-2019-007.1159 [arXiv:1812.06772 [hep-ph]].