

Existence of a second phase transition in A-A collisions at energies available at the CERN Large Hadron Collider: A physical interpretation

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The observed fluid behavior of the matter produced in heavy ion and pp collisions implies that the strings stretched between the constituents of the projectile and target should have a hard core giving rise to a repulsion between them. It is shown that in these collisions there are two critical string densities, one corresponding to the well-studied percolation of strings and another to the percolation of the hard core of the strings. These two critical densities are related to two critical temperatures, one $T \approx 160$ MeV would correspond to the restoration of chiral symmetry and partial deconfinement and a second transition $T \approx 220$ MeV form the fluid behavior of quantum chromodynamics matter strongly interacting to a quasi free gas of quarks and gluons. This argument is supported by the recently published results on the sudden increase in the degrees of freedom above the deconfinement temperature in pp and A-A collisions [Mishra *et al.*, [Nucl. Phys. A](#) **1046**, 122865 (2024)].

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I. INTRODUCTION

It is commonly accepted that lattice quantum chromodynamics (LQCD) results [1] showing a smooth crossover in the properties of the thermal interacting matter at the temperature $T \approx 155$ MeV, going from confined matter to deconfined matter. This temperature coincides with the corresponding to the restoration of chiral symmetry.

On the other hand, the experimental results from the BNL Relativistic Heavy Ion Collider (RHIC) [2–5] and CERN Large Hadron Collider (LHC) [6] indicates that a strongly interacting fluid medium is formed with extremely low shear viscosity over entropy density ratio η/s in line with the results from the anti-de Sitter/Conformal field theory holographic dual [7].

However, the physics of thermal QCD transition is not quite settled and there are several questions which should be addressed. In particular, the current accepted scenario offers limited room for describing the change from a weakly interacting hadron resonance gas to strongly interacting near perfect fluid, as well as how transition takes place from this state to a free gas of quarks and gluons. In the literature there are several approaches pointing out new phases at low baryon density.

In this paper we explore the possible signatures of this new phase and how it could be accommodated in the phenomenological models, particularly in the color string percolation model (CSPM) which describes rightly most of the RHIC and LHC experimental data [8]. In the CSPM the cross over transition from hadronic phase to quarks and gluons phase at temperature $T \approx 160$ MeV corresponds to the critical string percolation. At this point a cluster of overlapping strings is formed crossing the transverse surface of the collision.

The strings as chromoelectric superconductor repel each other analogous to the interaction between vortex lines in a superconductor (Meissner effect) meaning that the strings have a hard core whose size is determined by the London penetration depth which depends on the string tension [9]. The existence of repulsion between strings and subsequently the existence of a hard core in the strings is also required by the radial distribution of the color strings in the transverse collision surface. In fact, the radial distribution of sources of a fluid can not be periodic as in the case of a solid neither flat as in the case of a gas but some minimum and maximum like a hard core [10].

The size of the hard core provide us with a new scale. The percolation of these hard core of the strings, crossing the transverse collision surface, corresponds to a second critical string density and consequently to a second critical temperature, marking the transition from a fluid of quarks and gluons strongly interacting to a gas of free quarks and gluons.

In our earlier work the equation of state was obtained as shown in Fig. 1 [11]. In this figure the energy density is obtained using the well known Bjorken formula. The experimental data of the ALICE Collaboration for the multiplicities dN/dy and the p_t distribution in the range $0.15 < p_t < 2$

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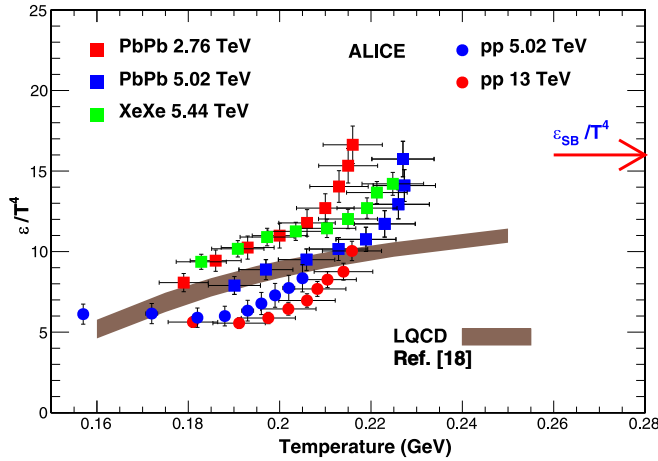


FIG. 1. Dimensionless quantity ε/T^4 as a function of temperature from CSPM using ALICE data [11]. The LQCD calculations are from HotQCD Collaboration (brown band) [18].

GeV is used to compute the dependence on the energy and centrality. The temperature is obtained by analyzing the p_t spectrum using the CSPM methodology. A sudden rise of ε/T^4 is seen at temperature $T \approx 220$ MeV [11].

The plan of the paper is as follows. We start summarizing briefly some theoretical proposals of a new phase transition, namely, the different behavior of Dirac spectrum in three different regions, the center vortex evidence of a second temperature above the crossover temperature, the existence of a stringy fluid phase transition based on chiral spin symmetry, and the difference dependence on the power of N_c of the energy, entropy densities of a confined hadron gas, a stringy fluid and a liberated gluon gas.

In the next sections we introduce the color string percolation model (CSPM) and present a new phase transition from a fluid to a free gas of quarks and gluons. Finally the conclusions are presented.

II. THEORETICAL PROPOSALS

A. Behavior of the Dirac spectrum

A new thermal phase of QCD has been proposed, the infrared phase based in the analysis of the behavior of the Dirac spectrum [12–17]. In quenched QCD increasing the temperature the properties of a thermal state remain similar to the zero temperature vacuum, until the scale of thermal agitation becomes comparable to the scale of broken scale invariance, i.e. gluon condensate. This is characterized by the crossover temperature T_a . Beyond this temperature the properties of the medium change rapidly toward the restoration of the scale invariance at a well defined infrared temperature $T_{ir} > T_a$. In the range $T_{ir} < T < T_{uv}$ (IR phase), the gauge fields are scale invariant at distances larger than $\frac{1}{T}$. The infrared invariance appears due to the interaction that is still strong at long distances. For $T > T_{uv}$ (UV phase), the field fluctuations of the IR phase disappear and the notion of the IR scale invariance becomes trivial.

The infrared temperature T_{ir} coincides with the critical temperature of the Polyakov line first order transition in quenched QCD. $T_{ir} \approx 200$ –250 MeV. The crossover temperature, $T_a \approx 155$ MeV, is simply a characteristic temperature of the onset of changes toward the IR scale. Chiral symmetry remains spontaneously broken for the range of temperatures $T_a < T < T_{ir}$. Only after crossing such anomalous phase does the system become both deconfined and chirally symmetric. The lattice studies of the Dirac spectrum show that as the temperature cross T_{ir} the Dirac spectral function (the number of eigenmodes λ per unit of volume and spectral interval) changes from extremely flat in the infrared (λ close to zero) to follow a $1/\lambda$ curve [14,15]. At $T \approx 200$ MeV well above the established region, the anomalous phase fully develop with a clear peak and a large depletion at intermediate scales. This behavior is also seen not only in quenched QCD but also in the presence of light dynamical quarks. In this scheme it is argued that this IR phase is not detected by the lattice studies due to insufficient large volumes [15].

B. Center vortex evidence for a second finite-temperature QCD transition

Center vortices are regions of the gauge fields that carry magnetic flux quantized according to the center of SU(3). The center vortex structure is temporal and spatial slices of the lattice reveal that vortex percolation persists through the chiral transition and ceases at a temperature that is approximate twice the chiral transition temperature T_c . This implies that confinement is retained through temperatures up to T around $2T_c$, pointing toward a second transition corresponding to deconfinement. The loss of percolation is quantified by the vortex cluster event, providing a clear signal for the confinement transition [19].

C. Stringy fluid

In addition to the hadron gas and the quark gluon plasma phases, it was proposed the existence of a stringy fluid phase based on the chiral spin symmetry. At temperatures below the pseudocritical temperature $T_c \approx 155$ MeV the QCD matter is hadron gas with spontaneously broken chiral symmetry. Within the window $T_c - 3T_c$ the hot QCD is represented by stringy fluid with restored chiral and approximate chiral spin symmetries. Above $\approx 3T_c$ the chiral symmetry disappears and one observes a smooth transition to partonic degrees of freedom, i.e., to a quark-gluon plasma [20–23].

D. A new perspective on thermal transition in QCD

Another proposal is the partial deconfinement which implies an intermediate phase in which color degree of freedom split into the confined and deconfined sectors [24–26]. The partially deconfined phase is dual to the small black hole that lies between large black hole and the graviton gas. The transition to partial deconfinement would corresponds to the standard cross over. From partial to complete deconfinement would be accompanied by additional transition of the energy

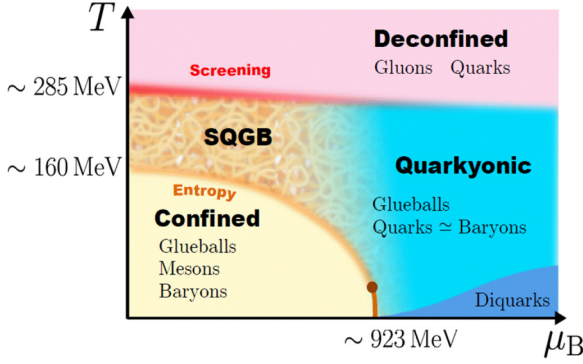


FIG. 2. New and realistic phase diagram for $N_c = 3$ including a window of the SQGB regime [27].

density. The three phases are characterized by the behavior of the function embedded in the phases of the Polyakov line.

E. New state of matter between the hadronic phase and the quark-gluon plasma?

The energy density, pressure and entropy density in the stringy fluid scale as N_c which is in contrast to the independence of N_c of a gas of color confined hadrons and to the N_c^2 scaling of the liberated gluons. Therefore, as the temperature increases, matter should first go through a region where the energy density is independent of N_c and then transit to a partially deconfined phase with the energy density of the order $\mathcal{O}(N_c)$, and should eventually reach a fully deconfined phase with gluons that lift the energy density of the order of $\mathcal{O}(N_c^2)$. The proposed phase diagram would be like Fig. 2 where the intermediate phase is denoted by SQGB (spaghetti of quarks with globalls) [27–29].

Thermodynamics quantities have been evaluated using a string based model for the density of states. The obtained equation of state is shown in Fig. 3 (green square). The experimental energy points (CSPM) in Fig. 3 are same as in Fig. 1.

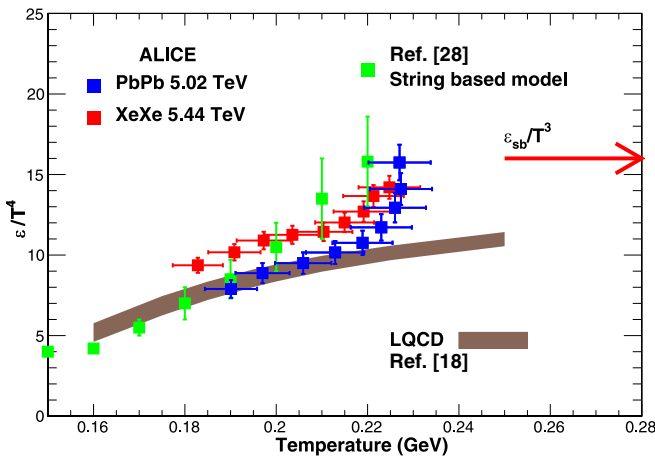


FIG. 3. Dimensionless quantity ε/T^4 as a function of temperature from CSPM (using ALICE data) are shown as blue and red boxes [11]. LQCD calculation from HotQCD Collaboration are shown as brown band [18] while String model results as green box [28].

It is observed that experimental ε/T^4 is in agreement with lattice results [18] up to the temperature $T < 200$ MeV and a departure from it above $T \approx 200$ MeV. The CSPM result sees a clear increase of ε/T^4 above $T \approx 200$ MeV.

There are more examples of nontrivial behavior above T_c , for instance, the spectral peak of the heavy quarkonium remains above T_c [30–32]. A partially confined/deconfined new phase has also been found in a model with the adjoint Polyakov loop [33].

F. String models

The above-mentioned proposals are different and therefore also their details as well as the values of temperature transitions and the nature and order of the transition. We will focus in common general aspects of all of them as the increase of the degrees of freedom and correspondingly of the entropy and energy densities and the existence of two temperatures and the corresponding two scales.

Most of the models describing the RHIC and LHC data, such as PYTHIA [34], EPOS [35], AMPT [36], HIJING [37], and color string percolation (CSPM) [8], are based on the formation of strings stretched between projectiles and target. In the glasma picture of color glass condensate, also are formed strings (color ropes) which are in correspondence with the clusters of strings of the CSPM [38,39]. Further discussions are focused on CSPM and interpretation of the results as shown in Fig. 1.

III. COLOR STRING PERCOLATION MODEL

Multiparticle production is currently described in terms of color strings stretched between the projectile and the target, which decay into new strings and subsequently hadronize to produce the observed hadrons [8]. Color strings may be viewed as small areas in the transverse plane filled with color field created by colliding partons. In terms of gluon color field they can be considered as the color flux tubes stretched between the colliding partons. The mechanism of particle creation is the Schwinger QED₂ mechanism and is due to the color string breaking [40,41]. With growing energy and size of the colliding system, the number of strings grows, and they start to overlap, forming clusters, in the transverse plane very much similar to disks in two dimensional percolation theory [42,43]. At a certain critical density, a macroscopic cluster appears that marks the percolation phase transition. This is the color string percolation model (CSPM) [8]. The interaction between strings occurs when they overlap and the general result, due to the SU(3) random summation of charges, is a reduction in multiplicity and an increase in the string tension, hence an increase in the average transverse momentum squared, $\langle p_T^2 \rangle$. We assume that a cluster of n strings that occupies an area of S_n behaves as a single color source with a higher color field $\vec{Q}_n$ corresponding to the vectorial sum of the color charges of each individual string $\vec{Q}_1$. The resulting color field covers the area of the cluster. As $\vec{Q}_n = \sum_1^n \vec{Q}_1$, and the individual string colors may be oriented in an arbitrary manner respective to each other, the average $\vec{Q}_{1i}\vec{Q}_{1j}$ is zero, and $\vec{Q}_n^2 = n\vec{Q}_1^2$.

Knowing the color charge $\bar{Q}_n$ one can obtain the multiplicity μ and the mean transverse momentum squared $\langle p_t^2 \rangle$ of the particles produced by a cluster of n strings [44]

$$\mu_n = \sqrt{\frac{nS_n}{S_1}} \mu_0; \quad \langle p_t^2 \rangle = \sqrt{\frac{nS_1}{S_n}} \langle p_t^2 \rangle_1, \quad (1)$$

where μ_0 and $\langle p_t^2 \rangle_1$ are the mean multiplicity and $\langle p_t^2 \rangle$ of particles produced from a single string with a transverse area $S_1 = \pi r_0^2$. In the thermodynamic limit, one obtains an analytic expression [44,45]

$$\left\langle \frac{nS_1}{S_n} \right\rangle = \frac{\xi}{1 - e^{-\xi}} \equiv \frac{1}{F(\xi)^2}; \quad F(\xi) = \sqrt{\frac{1 - e^{-\xi}}{\xi}}, \quad (2)$$

where $F(\xi)$ is the color suppression factor. $\xi = \frac{N_S S_1}{S_N}$ is the percolation density parameter assumed to be finite when both the number of strings N_S and total interaction area S_N are large. Equation (1) can be written as $\mu_n = F(\xi) \mu_0$ and $\langle p_t^2 \rangle_n = \langle p_t^2 \rangle_1 / F(\xi)$. The critical cluster which spans S_N , appears for $\xi_c \geq 1.2$ [43].

The decay of Lund type string follows a Gaussian p_T distribution, whose width is proportional to the string tension x :

$$\frac{dn}{dp_T^2} \sim \exp(-\pi p_T^2 / x^2). \quad (3)$$

The Gaussian fluctuations of the string tension give rise to a thermal distribution [46]

$$\frac{dn}{dp_T^2} \sim \sqrt{\frac{2}{\langle x^2 \rangle}} \int_0^\infty dx \exp\left(-\frac{x^2}{2\langle x^2 \rangle}\right) \exp\left(-\pi \frac{p_T^2}{x^2}\right), \quad (4)$$

$$\frac{dn}{dp_t^2} \sim \exp\left(-p_t \sqrt{\frac{2\pi}{\langle x^2 \rangle}}\right) \quad (5)$$

with $\langle x^2 \rangle = \pi \langle p_t^2 \rangle_1 / F(\xi)$.

The initial temperature is expressed as

$$T(\xi) = \sqrt{\frac{\langle p_t^2 \rangle_1}{2F(\xi)}}. \quad (6)$$

This temperature can be regarded as a local one associated to the transverse momentum distribution of particles produced in the fragmentation of a cluster of strings. However, above the critical string percolation, the cluster is extended all over most of the transverse surface of the collision and thus, the local temperature can be considered as a global temperature.

The color string percolation model describes rightly most of the experimental RHIC and LHC data, including rapidity and transverse momentum distributions, multiplicity distributions, long range correlations, ridge structure, p_t correlations, and azimuthal distributions [8]. The mechanism to describe these distributions is loss of momentum of a parton produced in the fragmentation of a cluster. This is due to the interaction with the color field of the rest of strings of the collision surface in the way to get out the collision surface. This mechanism predicted the scaling law $v_2 \propto p_t^{2/3}$. Also describes rightly the hierarchy of V_n for small systems [47–51].

Second phase transition in the CSPM

As the area covered by the strings is $[1 - \exp(-\xi)]S_\perp$, the mean distance between strings d is given by

$$d = \left[\frac{N}{[1 - \exp(-\xi)]S_\perp} \right]^{-1/2} = F(\xi) \sqrt{\pi} r_0, \quad (7)$$

which at the critical percolation density $\xi_c = 1.2$, $d = 1.34 r_0$. This means that the overlapping of strings is very peripheral at this density, covering only the edges (corona) of the strings. At this density using Eq. (6), $T \approx 160$ MeV corresponding to the hadronization temperature and a partial deconfinement because the string structure is not destroyed, even though the color field is extended over almost the whole collision surface. From the point of view of statistical mechanics the formed medium can form a fluid (such as it has been observed) only if the color sources, in our case strings, have a hard core. If not, the radial distribution of the color sources either obeys the periodic structure of a solid or the flat distribution corresponding to a free gas [10]. The size of this hard core h provide us with a new scale. In order to penetrate the hard core the overlapping strings should be larger, in such a way that $d = 2h < r_0$. For reasonable values of $h \approx 0.4 - 0.5 r_0$ (half of the radius of the string), we have $F(\xi) \approx 0.45 - 0.50$ corresponding to the temperature of 210–220 MeV according to Eq. (6). It is worth to ask for the string density needed to obtain percolation of the hard core of the strings. The corresponding ξ will be larger than the critical string percolation $\xi_c = 1.2$ by the factor $(r_0/h)^2$ which for reasonable values of h around $r_0/2$ gives 4. As the temperature is proportional to $\xi^{1/4}$ we have $T = 1.414 T_c$ as T_c is around 155 MeV, T is 220 MeV, similar value of the temperature obtained before, as it should be. The repulsion of strings have been studied previously in phenomenological models [52,53]. In the Lund-Pythia model “stringshoving” is introduced to improve the agreement with some data concerning the elliptic flow and heavy flavor production in pp and $A-A$ collisions [53]. In the case of high string densities, each string have in its neighbor strings in all azimuthal directions in such a way that the net effect of the repulsion would be zero or negligible. However at low multiplicities in pp and in peripheral $A-A$ collisions at low p_t the repulsion can produce negative elliptic flow v_2 contrary to hydrodinamical models [54].

The value of $T \approx 220$ MeV for the temperature can be taken with caution due to the uncertainties, mainly coming from the value of the size of the hard core, taken as half of the string transverse size. Some evaluations of penetration depth would favor a smaller core giving rise to higher T . Most of the proposals mentioned before obtain $T = 285 - 300$ MeV. It is well known that quenched QCD has a first order phase transition at $T = 285$ MeV. However the value of $T \approx 220$ MeV is not only obtained as percolation of hard cores but also corresponds to the sudden rise of the ε/T^4 of Figs. 1 and 3.

We have been concerned with the CSPM but most of the string models should incorporate some of the effects discussed here. In particular the glasma picture of the color glass condensate (CGC) that can be related to the CSPM. In particular the size of the color flux tube is proportional to $1/Q_s$, determining the particle correlations. The color flux

tube size increases as the energy or centrality increases, becoming smaller without any bound. If flux tubes of glasma have hard core, the size of the flux tube can not be smaller than the size of the hard core.

Above $T = 220$ MeV we expect that some of the signatures of the fluid found above $T = 160$ MeV to disappear. In particular the elliptic flow and rest of the harmonics or long range rapidity correlations should diminish, although some other effects not related with collective motion can give contribution to those observable. The fact this new phase transition is not supported by the LQCD, can be due to a insufficient large volume as it is mentioned in the reference [15] or to the lack of an exact confinement order parameter in spite of several unsuccessful theoretical attempts [55–58].

IV. CONCLUSIONS

We explore the possibility to accommodate in the CSPM the new phase transition proposed in theoretical approaches. The strings are color conductors and repel the color field of other strings, meaning that they have a hard core. This structure is also required for the radial distribution of the color string sources in the transverse plane of the collision. In the fluid phase, this distribution cannot be periodic (case of a

solid) neither flat (case of a gas) but something like a hard core. A second critical density arises when the hard core of the strings cross the transverse surface of the collision, which means the percolation of the hard core of the strings. This critical string density corresponds a critical temperature of $T \approx 220$ MeV, which marks the beginning of the transition from a stringy fluid to a free gas of deconfined quarks and gluons. This temperature coincides with the value of the sudden rise of ε/T^4 evaluated from the ALICE data [11] and also with the sudden rise of a string based model [28].

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DATA AVAILABILITY

There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

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- [1] Y. Aoki, G. Endrődi, Z. Fodor, S. D. Katz, and K. K. Szabó, The order of the quantum chromodynamics transition predicted by the standard model of particle physics, *Nature (London)* **443**, 675 (2006).
 - [2] I. Arsene, I. G. Bearden, D. Beavis, C. Besliu, B. Budick, H. Bøggild, C. Chasman, C. H. Christensen, P. Christiansen, J. Cibor, R. Debbe, E. Enger, J. J. Gaardhøje, M. Germinario, O. Hansen, A. Holm, A. K. Holme, K. Hagel, H. Ito, E. Jakobsen, *et al.* (BRAHMS Collaboration), Quark–gluon plasma and color glass condensate at RHIC? The perspective from the BRAHMS experiment, *Nucl. Phys. A* **757**, 1 (2005).
 - [3] B. B. Back, M. D. Baker, M. Ballintijn, D. S. Barton, B. Becker, R. R. Betts, A. A. Bickley, R. Bindel, A. Budzanowski, W. Busza, A. Carroll, Z. Chai, M. P. Decowski, E. García, T. Gburek, N. K. George, K. Gulbrandsen, S. Gushue, C. Halliwell, J. Hamblen, *et al.* (PHOBOS Collaboration), The PHOBOS perspective on discoveries at RHIC, *Nucl. Phys. A* **757**, 28 (2005).
 - [4] J. Adams, M. M. Aggarwal, Z. Ahammed, J. Amonett, B. D. Anderson, D. Arkhipkin, G. S. Averichev, S. K. Badyal, Y. Bai, J. Balewski, O. Barannikova, L. S. Barnby, J. Baudot, S. Bekele, V. V. Belaga, A. Bellingeri-Laurikainen, R. Bellwied, J. Berger, B. I. Bezverkhny, S. Bharadwaj, *et al.* (STAR Collaboration), Experimental and theoretical challenges in the search for the quark–gluon plasma: The STAR Collaboration’s critical assessment of the evidence from RHIC collisions, *Nucl. Phys. A* **757**, 102 (2005).
 - [5] K. Adcox, S. S. Adler, S. Afanasiev, C. Aidala, N. N. Ajitanand, Y. Akiba, A. Al-Jamel, J. Alexander, R. Amirikas, K. Aoki, L. Aphecetche, Y. Arai, R. Armendariz, S. H. Aronson, R. Averbeck, T. C. Awes, R. Azmoun, V. Babintsev, A. Baldissieri, K. N. Barish, *et al.* (PHENIX Collaboration), Formation of dense partonic matter in relativistic nucleus–nucleus collisions at RHIC: Experimental evaluation by the PHENIX Collaboration, *Nucl. Phys. A* **757**, 184 (2005).
 - [6] B. Müller, J. Schukraft, and B. Wyslouch, First results from Pb+Pb collisions at the LHC, *Annu. Rev. Nucl. Part. Sci.* **62**, 361 (2012).
 - [7] G. Policastro, D. T. Son, and A. O. Starinets, Shear viscosity of strongly coupled $N = 4$ supersymmetric Yang–Mills plasma, *Phys. Rev. Lett.* **87**, 081601 (2001).
 - [8] M. A. Braun, J. Dias de Deus, A. S. Hirsch, C. Pajares, R. P. Scharenberg, and B. K. Srivastava, De-confinement and clustering of color sources in nuclear collisions, *Phys. Rep.* **599**, 1 (2015).
 - [9] P. Cea, L. Cosmai, F. Cuteri, and A. Papa, Flux tubes in the SU(3) vacuum: London penetration depth and coherence length, *Phys. Rev. D* **89**, 094505 (2014).
 - [10] J. E. Ramírez, B. Díaz, and C. Pajares, Interacting color strings as the origin of the liquid behavior of the quark–gluon plasma, *Phys. Rev. D* **103**, 094029 (2021).
 - [11] A. N. Mishra, G. Paić, C. Pajares, R. P. Scharenberg, and B. K. Srivastava, Exploring the QGP phase above the deconfinement temperature in pp and A–A collisions at LHC energies, *Nucl. Phys. A* **1046**, 122865 (2024).
 - [12] A. Alexandru and I. Horváth, Spontaneous chiral symmetry breaking as condensation of dynamical chirality, *Phys. Lett. B* **722**, 160 (2013).
 - [13] A. Alexandru and I. Horváth, Chiral symmetry breaking and chiral polarization: Tests for finite temperature and many flavors, *Nucl. Phys. B* **891**, 1 (2015).
 - [14] A. Alexandru and I. Horváth, Possible new phase of thermal QCD, *Phys. Rev. D* **100**, 094507 (2019).
 - [15] A. Alexandru and I. Horváth, Unusual features of QCD low-energy modes in the infrared phase, *Phys. Rev. Lett.* **127**, 052303 (2021).

- [16] A. Alexandru, I. Horváth, and N. Bhattacharyya, Localized modes in the IR phase of QCD, *Phys. Rev. D* **109**, 014501 (2024).
- [17] X. L. Meng, P. Sun, *et al.* (χ QCD and CLQCD Collaboration), Separation of infrared and bulk in thermal QCD, *J. High Energy Phys.* **12** (2024) 101.
- [18] A. Bazavov, T. Bhattacharya, C. DeTar, H.-T. Ding, S. Gottlieb, R. Gupta, P. Hegde, U.M. Heller, F. Karsch, E. Laermann, L. Levkova, S. Mukherjee, P. Petreczky, C. Schmidt, C. Schroeder, R.A. Soltz, W. Soeldner, R. Sugar, M. Wagner, and P. Vranas, (HotQCD Collaboration), Equation of state in $(2+1)$ -flavor QCD, *Phys. Rev. D* **90**, 094503 (2014).
- [19] J. A. Mickley, C. Allton, R. Bignell, and D. Leinweber, Center vortex evidence for a second finite-temperature QCD transition, *Phys. Rev. D* **111**, 034508 (2025).
- [20] L. Ya Glozman, Three regimes of QCD, *Int. J. Mod. Phys. A* **36**, 2044031 (2021).
- [21] L. Ya Glozman, O. Philipsen, and R. D. Pisarski, Chiral spin symmetry and the QCD phase diagram, *Eur. Phys. J. A* **58**, 247 (2022).
- [22] L. Ya Glozman, Chiral spin symmetry and hot/dense QCD, *Prog. Part. Nucl. Phys.* **131**, 104049 (2023).
- [23] O. Philipsen, Emergent chiral spin symmetry, non-perturbative dynamics and thermoparticles in hot QCD, *Eur. Phys. J. A* **62**, 54 (2026).
- [24] H. Watanabe, G. Bergner, N. Bodendorfer, S. S. Funai, M. Hanada, E. Rinaldi, A. Schäfer, and P. Vranas, Partial deconfinement at strong coupling on the lattice, *J. High Energy Phys.* **02** (2021) 004.
- [25] M. Hanada and H. Watanabe, Partial deconfinement: A brief overview, *Eur. Phys. J. Spec. Top.* **232**, 333 (2023).
- [26] M. Hanada and H. Watanabe, On thermal transition in QCD, *Prog. Theor. Exp. Phys.* **2024**, 043B02 (2024).
- [27] Y. Fujimoto, K. Fukushima, Y. Hidaka, and L. McLerran, New state of matter between the hadronic phase and the quark-gluon plasma? *Phys. Rev. D* **112**, 074006 (2025).
- [28] M. Marczenko, G. Kovács, L. McLerran, and K. Redlich, String-based model with Hagedorn temperature of $T_H \sim 300$ MeV describes the spectrum of mesons and glueballs, *Phys. Rev. D* **112**, 096010 (2025).
- [29] L. McLerran, Two lectures on the phase diagram of QCD, *Acta Phys. Pol. B* **57**, 4-A2 (2026).
- [30] M. Asakawa and T. Hatsuda, J/ψ and η_c in the deconfined plasma from lattice QCD, *Phys. Rev. Lett.* **92**, 012001 (2004).
- [31] Y. Burnier and A. Rothkopf, Bayesian approach to spectral function reconstruction for Euclidean quantum field theories, *Phys. Rev. Lett.* **111**, 182003 (2013).
- [32] D. Bala, O. Kaczmarek, P. Lowdon, O. Philipsen, and T. Ueding, Pseudo-scalar meson spectral properties in the chiral crossover region of QCD, *J. High Energy Phys.* **05** (2024) 332.
- [33] J. C. Myers and M. C. Ogilvie, New phases of $SU(3)$ and $SU(4)$ at finite temperature, *Phys. Rev. D* **77**, 125030 (2008).
- [34] C. Bierlich *et al.*, A comprehensive guide to the physics and usage of PYTHIA 8.3, *SciPost Phys. Codeb.* **2022**, 8 (2022).
- [35] K. Werner, T. Hirano, I. Karpenko, T. Pierog, S. Porteboeuf, M. Bleicher, and S. Haussler, Gribov-Regge theory, partons, remnants, strings – and the EPOS model for hadronic interactions, *Nucl. Phys. B Proc. Suppl.* **196**, 36 (2009).
- [36] Z.-W. Lin, C. M. Ko, B.-A. Li, B. Zhang, and S. Pal, Multiphase transport model for relativistic heavy ion collisions, *Phys. Rev. C* **72**, 064901 (2005).
- [37] X. N. Wang and M. Gyulassy, Hijing: A Monte Carlo model for multiple jet production in pp , pA , and AA collisions, *Phys. Rev. D* **44**, 3501 (1991).
- [38] L. McLerran and R. Venugopalan, Computing quark and gluon distribution functions for very large nuclei, *Phys. Rev. D* **49**, 2233 (1994).
- [39] J. D. Dias de Deus and C. Pajares, String percolation and the glasma, *Phys. Lett. B* **695**, 211 (2011).
- [40] J. Schwinger, On gauge invariance and vacuum polarization, *Phys. Rev.* **82**, 664 (1951).
- [41] C. Y. Wong, *Introduction to High Energy Heavy Ion Collisions* (Singapore World Scientific, Singapore, 1994).
- [42] M. B. Isichenko, Percolation, statistical topography, and transport in random media, *Rev. Mod. Phys.* **64**, 961 (1992).
- [43] H. Satz, *Extreme States of Matter in Strong Interaction Physics*, Lecture Notes in Physics Vol. 945 (Springer International Publishing AG, Berlin, 2018).
- [44] M. A. Braun, F. del Moral, and C. Pajares, Percolation of strings and the relativistic energy data on multiplicity and transverse momentum distributions, *Phys. Rev. C* **65**, 024907 (2002).
- [45] M. A. Braun and C. Pajares, Implications of color-string percolation on multiplicities, correlations, and the transverse momentum, *Eur. Phys. J. C* **16**, 349 (2000).
- [46] A. Bialas, Fluctuations of the string tension and transverse mass distribution, *Phys. Lett. B* **466**, 301 (1999).
- [47] M. A. Braun, C. Pajares, and V. V. Vechernin, Anisotropic flows from colour strings: Monte Carlo simulations, *Nucl. Phys. A* **906**, 14 (2013).
- [48] M. A. Braun, C. Pajares, and V. V. Vechernin, Ridge from strings, *Eur. Phys. J. A* **51**, 44 (2015).
- [49] C. Andrés, M. Braun, and C. Pajares, Energy loss as the origin of a universal scaling law of the elliptic flow, *Eur. Phys. J. A* **53**, 41 (2017).
- [50] M. A. Braun and C. Pajares, Elliptic and triangular flows in dAu collisions at 200 GeV in the fusing color string model, *Eur. Phys. J. A* **56**, 41 (2020).
- [51] M. A. Braun and C. Pajares, Flow coefficients in O-O, Al-Al, and Cu-Cu collisions at 200 GeV in the fusing color string model, *Phys. Rev. C* **103**, 054902 (2021).
- [52] I. Altsybeev and G. Feofilov, Azimuthal flows in hadron collisions from quark-gluon string repulsion, *EPJ Web Conf.* **125**, 04011 (2016).
- [53] C. Bierlich, G. Gustafson, and L. Lönnblad, Collectivity without plasma in hadronic collisions, *Phys. Lett. B* **779**, 58 (2018).
- [54] C. Bierlich, P. Christiansen, G. Gustafson, L. Lönnblad, R. Törnkqvist, and K. Zapp, Going against the flow: Revealing the QCD degrees of freedom in hadronic collisions, *Phys. Lett. B* **874**, 140216 (2026).
- [55] C. DeTar and L. McLerran, Order parameters for the confinement-deconfinement phase transition in $SU(N)$ gauge theories with quarks, *Phys. Lett. B* **119**, 171 (1982).
- [56] N. Weiss, How to distinguish a confining from a deconfining phase in gauge theories with fermions, *Phys. Rev. D* **35**, 2495 (1987).
- [57] M. Faber, O. Borisenko, and G. Zinovjev, Triality in QCD at zero and finite temperature: A new direction, *Nucl. Phys. B* **444**, 563 (1995).
- [58] M. Ghanbarpour and L. von Smekal, Quarks and triality in a finite volume, *Phys. Rev. D* **106**, 054513 (2022).