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Experimental and Theoretical Insights into Deconfined Matter Formation in High-Multiplicity PP Collisions

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Abstract

The complex dynamics of heavy-ion interactions and the search for deconfined quark-gluon matter have long been studied via proton-proton (pp) collisions, which have served as an important standard. Exciting collective behaviors in small systems have been discovered in recent experiments at the Large Hadron Collider (LHC), particularly in pp collisions and high-multiplicity events. The possible formation of a deconfined state of matter—quark-gluon plasma (QGP)—in proton-proton collisions at ultra relativistic energy is thoroughly investigated in this paper from both theoretical and practical viewpoints. Observables such as the existence of more multi-strange hadrons than pions, collective flow patterns, chemical freeze-out temperatures comparable to heavy-ion systems, and long-range ridge-like correlations point to QGP-like behavior in these collisions. We study theoretical frameworks, such hydrodynamic and color glass condensate models, that try to explain these events and how these signals challenge the traditional separation of small and huge systems. The goal of the study is to provide better understanding of partonic collectivity in compact systems and of the possibility of QGP droplet production in high-multiplicity pp events at the LHC.

Keywords: *Quark–Gluon Plasma, High-multiplicity events, Deconfined matter, Collective phenomena, Strange particle enhancement.*

Introduction

Research into deconfined matter synthesis, or QGP production, is a major area of modern high-energy nuclear and particle physics. The release of quarks and gluons from hadrons is a characteristic of this deconfined phase of matter, which is traditionally thot to be generated only in ultra-relativistic heavy-ion collisions, namely with lead (Pb-Pb) or gold (Au-Au) nuclei at facilities like the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC). The energies and temperatures produced by these collisions are far greater than those required for deconfinement according to Quantum Chromodynamics (QCD). Upcoming experimental findings have shown surprising collective phenomena in systems with few collisions, such as proton-nucleus (pA) and proton-proton (pp) interactions with high multiplicity. These results suggest that light-ion settings are not the only possible ones where deconfined or QGP-like matter might arise. Experimentally, data from ALICE, CMS, and ATLAS, among other LHC collaborations, have shown interesting features in high-multiplicity proton-proton collisions, such as long-range angular correlations (the "ridge" phenomenon), increased strangeness production, and collective flow behavior similar to larger systems. The presence of a medium with collective properties comparable to a QGP is suggested by these occurrences, which are not seen in tiny systems. For instance, the observation of hydrodynamic-like flow patterns in proton-proton collisions with 7–13 TeV center-of-mass energy demonstrates that thermalization and collective expansion may be seen in tiny, short-lived systems. Moreover, femtosecond studies of particle correlations show that source sizes and lifetimes grow with event multiplicity, which is consistent with medium-like behavior theory. The question of whether QGP-type signals may be produced by other processes, including color reconnection, string overlap, or gluon saturation effects, or by deconfinement in tiny systems, has been revived by these experimental findings. Theoretical progress has been made in the understanding and modeling of these unexpected findings. In order to test the limits of collective behavior, hydrodynamic models that properly represent flow processes in heavy-ion collisions have been downsized for use with tiny systems. Applying these models to high-multiplicity pp events surprisingly reproduces important experimental patterns, suggesting that even a tiny system may display collective behavior if local thermalization occurs. Different theoretical frameworks provide different interpretations, tho.

A method that avoids thermalization, the color glass condensate (CGC) method attributes long-range correlations to interactions between initial-state gluon fields. Certain collective-like properties may be reproduced by means of final-state effects and parton dynamics in microscopic models like PYTHIA and EPOS, which include color reconnection or multiple parton interactions (MPI). Thus, the clarification of the production of deconfined matter in small systems is still a hotly debated and unsolved problem.

The study of unbound matter in high-multiplicity proton-proton collisions is now an exciting and challenging new area of research in Quantum Chromodynamics, thanks to the merging of experimental results and theoretical models. The main challenge is to distinguish genuine indications of Quark-Gluon Plasma (QGP) production from events caused by complex initial-state effects or hadronic interactions. We want to use new observables that are sensitive to early-stage dynamics, study how collective observables scale with system size and event multiplicity, and improve theoretical frameworks to include both thermal and non-thermal causes in future work. The difference between confined and deconfined QCD matter in tiny systems is becoming more blurry as computational modeling and experimental precision increase. It follows that the variables governing the change from hadronic to partonic phases of matter, as well as the fundamental character of strong interactions, will be better understood.

Review of Related Studies

Acharya, Susmita et al., (2025). This study uses data from the ALICE experiment at the CERN LHC to analyze the inclusive forward J/ψ output in pp collisions at ∢s = 13 TeV as a function of forward charged-particle multiplicity. Our results are expressed as a comparison of values obtained from inelastic collisions involving at least one charged particle in the pseudorapidity range $|\eta| < 1$, using relative J/ψ yields and relative charged-particle multiplicities. In the forward speed area ($2.5 < y < 4$), we may determine the nature of the J /φ mesons by observing their decay into μ + μ − pairs. In the area where the J/ψ rapidity occurs, which is also the forward pseudorapidity range, the relative multiplicity is determined. In relation to multiplicity, the results show that J/ψ yields increase at a steeper-than-linear rate. Previous measurements and theoretical model calculations are compared with them. Mishra, A. et al., (2021). Our analysis of the transverse momentum spectra of charged particles in proton-proton (pp) and lead-lead (Pb-Pb) collisions at LHC energies, using the Color String Percolation Model (CSPM) developed by the ALICE Collaboration, reveals the temperature extraction. In order to determine the degrees of freedom (DOF), the dimensionless quantity ε/T4 may be obtained by using the observed energy density ε and temperature T. The value here is DOFπ2/30. The two-step pattern in the growth of DOF, an indication of deconfinement, is seen for the first time for both Pb-Pb and pp collisions above the hadronization temperature of around 210 MeV. In Pb-Pb collisions, there is an abrupt increase to the ideal gas value of around 47, which corresponds to three quark flavors.

Varga, Zoltán et al., (2019). In proton-proton collisions, we use Monte Carlo event generators to study the multiplicity dependence of jet structures. We forecast topologies of multiplicity-differential jets and show that charged hadron event multiplicity significantly determines jet form, which may be used as a precise way to empirically differentiate between similarly successful simulation tunes. Based on the discovery of large jet shape changes in high-multiplicity events at high pT, we also provide a way to prove the presence and size of multiple-parton interactions (MPI) or color reconnection (CR). It may be easier to understand the interaction between the jet particles and the underlying event (UE) if multiplicity-dependent jet structure observables are used across distinct pT windows. We provide a distinctive jet size measure that is independent of multiplicity and use a simple model to help with its physical interpretation. Adam, Jaroslav et al., (2017). A phase transition occurs in nuclear matter when quarks and gluons are unbound at sufficiently high temperatures and energy densities. A phase known as Quark-Gluon Plasma (QGP) exists at this point [1]. In laboratory settings, this extreme kind of strongly-interacting QCD (Quantum Chromo-Dynamics) matter is produced by high-energy heavy-nuclei collisions, which lead to an increase in the production of odd hadrons [2-6]. The significance of strangeness enhancement, which was first proposed as an indication of QGP generation in nuclear collisions [7], becomes much more apparent for multi-strange baryons. Several heavy-ion physics features have been seen in high-multiplicity proton-proton (pp) collisions [8, 9]. Nevertheless, there is no evidence of a rise in the production of multi-strange particles at this time. It has never been seen before that high-multiplicity pp collisions exhibit strangeness amplification. In regard to pions, the integrated yields of strange and multi-strange particles increase considerably as the charged-particle multiplicity of the event increases. The results show that the phenomenon is linked to the system that was created in the collision, which is in great accord with previous research on p-Pb collisions [10, 11]. The strangeness creation in high-multiplicity events reaches values similar to those in Pb-Pb collisions, which produce a QGP. The production of multi-strange hadrons is enhanced in proton-proton collisions with high multiplicity.

Glazek, Stanislaw & Kubiczek, Patryk. (2016). Anisotropy coefficients in the initial collision state of matter in high-energy, high-multiplicity proton-proton contact events are determined in the Monte Carlo Glauber model using a few-body proton picture. In the renormalization group technique for effective particles, this picture should be derivable from QCD. We make an educated guess as to the ridge-like correlations in the last hadronic state, assuming they are proportionate to the anisotropy in the initial collision state. Our best estimates lead us to believe that the p-p ridge effect amplitude can be described by a small set of singular few-body proton configurations, the exact nature of which may vary with multiplicity.

Space–Time Evolution and Freeze-Out Processes in Heavy-Ion Collisions

Hadronic and heavy-ion collision space-time evolutions (Figure 1) are complex phenomena with different degrees of freedom in different space-time coordinates. The system is complex, making it difficult to describe all of its changes with a single explanation. Following the heavy-ion collisions, the system undergoes a series of phases: the pre-equilibrium, deconfined QGP, and mixed phases, the last of which may exhibit symptoms of a first-order phase transition. Composite hadrons are formed from primordial partonic matter after this process of hadronization. The transition from quasi-gaseous phase (QGP) to hadron gas is possible at this point, which is why it is called the crucial temperature (Tc). Particle ratios remain constant throughout time because the system's chemical composition is frozen (inelastic collisions end). It is caused by the system's baryochemical potential (μB) and chemical freeze-out temperature (Tch). Because it assumes the system is an ideal gas and disregards interactions, a statistical hadron gas model is applicable at this stage. Moving near the detectors, the particles in their ultimate condition cause the systems mean free path to expand beyond its size. This indicates that collisions between the particles occur seldom. The system's transverse momentum distribution has stabilized (elastic collisions have ended) at this stage. Our phenomenon here is called kinetic freeze-out. A Boltzmann distribution, with invariant yield as a function of transverse momentum, is often fitted to particle spectra in order to get an equilibrium distribution. The effective temperature of the system as a particle exits is the inverse slope parameter. One obtains the total by applying the Boltzmann-Gibbs blast-wave model to the low-pT spectrum (usually below 3 GeV/c).

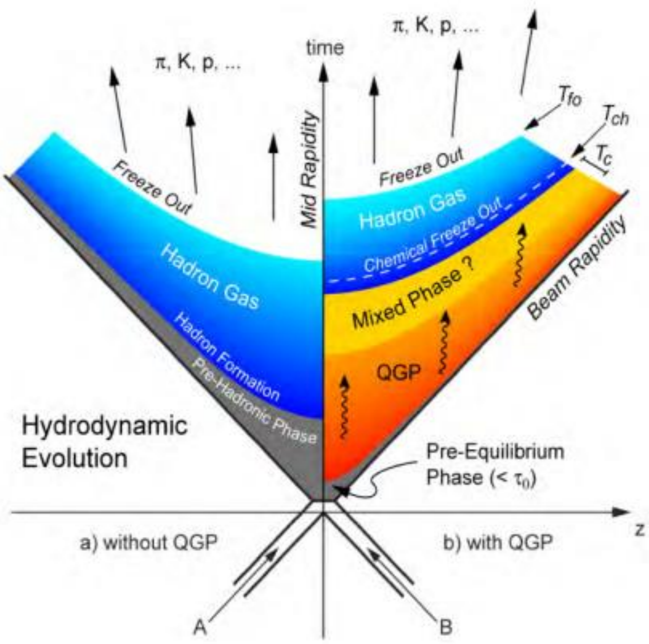

Figure 1: A possible space-time Minkowski diagram in hadronic collisions, compared with heavy-ion collisions.

The radial velocity of the particle. You may look at it from two angles. One scenario involves obtaining a common radial flow velocity and thermal temperature by performing a single freezeout (formally a simultaneous fit) on all the detected particle spectra. On the other hand, hydrodynamic behavior is shown in a differential (mass-dependent) freeze-out scenario by the early exit of heavy particles from the system with decreased radial flow velocities. Particles, both weird and ordinary, may freeze solid in different contexts. Both the hard and soft physics domains make up the whole pT-spectrum. While pQCD is used to describe the hard domain, statistical models are used to describe the non-perturbative soft domain.

The system's space-time development in hadronic (pp) collisions is a newly formed yet understudied field of physics. According to the current theory, hadronic collisions cause the system to go via a pre-hadronic phase, hadrons (a gas consisting of hadrons), and finally freeze out (as seen in Figure 1). However, the paths for progress in hadronic physics have been lately solidified by scientists who have accepted the idea of a similar spacetime framework to that of a heavy-ion collision, especially at LHC energies. These novel aspects of LHC hadronic collisions will be discussed in the sections that follow.

Experimental Signatures and Observables of Quark–Gluon Plasma

Due to QGP's short lifespan of 10-23 seconds, the signatures are indirect. Following are a few of the most important indicators of QGP. Any basic book on QGP may provide you with extra information. It should be emphasized that as we delve into new energy frontier research areas, some of the concepts underlying QGP signatures will evolve, and new findings will bring with them new signatures.

a) Strangeness enhancement

U and d quarks, the fundamental particles of nucleons, are the building pieces of protons and heavy ions. Composite things, like as hadrons composed of strange quarks, may only be created in a realistic partonic medium via hadronization or by particles generating inelastic interactions. Nevertheless, in order to arrive at a reasonable conclusion, we often compare the out-of-the-ordinary improved experimental data to a hadron gas scenario at a certain collision energy. When the temperature of the system is higher than the mass of a strange quark ($m_s \gg m_{(u,d)}$) in an equilibrated QGP, strange quarks and anti-quarks may be produced in enormous numbers via several mechanisms that promote strangeness. Flavor production, gluon splitting, and flavor excitation are the three processes involved. In the final state, there are more multi-strange particles than pions, which increases the strangeness. This is considered a characteristic of QGP. Strangeness increase has been seen experimentally during heavy-ion collisions at CERN SPS, RHIC, and LHC energies.

b) Suppression of J/ψ

The state J/ψ is characterized by the combination of charm and anti-charm quarks. The presence of additional quarks, anti-quarks, and gluons in a QGP medium makes it unlikely that a charm quark can approach its corresponding counterpart in order to establish a bound state. Color Debye screening describes this. This is analogous to the QED Debye screening that is used to prevent electric charges in an electromagnetic plasma. Additionally, in a QGP phase—a deconfined medium operating at very high temperatures—the string tension between charm and anti-charm quarks vanishes. The combined impact of both of these causes a decrease in the yield of J/φ. Conversely, open charms (D0, D±, Ds, etc.) have larger yields due to the fact that orphan charm quarks may combine with neighboring light flavors. One sign of QGP is the reduction of J/φ. It is possible for suppression and regeneration/recombination to go to war when the collision energy is high enough to produce a large number of charm and anti-charm quarks in the system. In order to produce additional J/ψ, quarkonia in higher states might disintegrate or decay. This is the reason why the reduction of J/φ is smaller in the LHC heavy-ion collisions compared to the RHIC heavy-ion collisions.

c) Suppression of high-pT particles (jet quenching)

The generation of high-pT particles from the first partonic interactions in hadronic or nuclear collisions at relativistic energy serves as an indirect probe of a hypothetical deconfined medium. Very high transverse momenta quarks and gluons are produced from the typical partonic scatterings ($g + g \rightarrow g + g$, $q + q \rightarrow q + q$). The quarks and gluons disintegrate into several bound particles, often arranged in a cone-shaped region called a "jet." For understanding the first phases of a collision, hard partons are useful since they are formed early on (formation time $\tau \sim 1/pT$, where pT is the momentum component in the direction perpendicular to the beam). The energy of these high-pT partons and jets is drained as they traverse dense media. The distance traveled determines the quantity of energy dissipated. If you make a parton or jet at the fireball's edge, it will lose less energy if it departs straight than if you make one in the center of the medium. A nuclear modification factor (RAA) is described as an observable that is reliant on pT and is created by:

$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{Yield_{AA}}{Yield_{pp}}$$

With each nucleus-nucleus collision, on average, this many binary nucleon-nucleon collisions occur. Approximations derived from the Glauber model provide this result. In the absence of medium effects, RAA would be equal to one if the nucleus-nucleus collision were just a superposition of nucleon-nucleon collisions. The CMS experiment conducted at the LHC confirms the anticipated lack of nuclear suppression for direct photons and the mediating particles of weak interactions, W± and Z0. However, the level of suppression is around four to five times larger for charged particles with a high pT (identified). While QGP is not anticipated to occur in dAu or pPb collisions, RAA is less than 1 in Au-Au or Pb-Pb collisions. There seems to be no cold nuclear matter (CNM) impact at high-pT, as shown by the absence of suppression in dAu or pPb collisions. This finding suggests that hard-scattered partons undergo energy loss as they move throughout the dense and hot medium, and this suppression is seen as a consequence of the end state. Jet quenching via dihadron angular correlation was shown convincingly in the STAR experiment at RHIC. The azimuthal angle between a high-pT particle and its accompanying particles was measured for pp, dAu, and Au-Au collisions, where $4 < pT\ trig < 6$ GeV/c. On the other hand, pp and dAu collisions did not exhibit an away-side jet suppression ($\Delta\phi \sim \pi$), while Au-Au collisions did. This shown that when heavy ions collide, a dense and heated medium is formed, which causes the away-side partons to lose energy as they pass thru. Consequently, low-pT particles are produced.

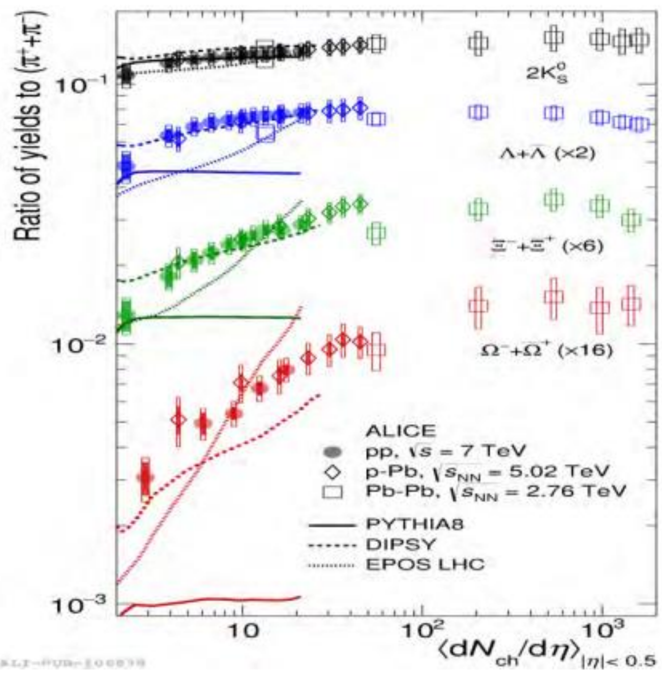

Figure 2: Transverse momentum integrated yield ratios of strange and multi strange hadrons to pions as a function of mid-rapidity charged particle density.
The measurements in pp collisions at √s = 7 TeV are compared with the results from p-Pb and Pb-Pb collisions and with theoretical MC models. This shows heavy-ion-like strangeness enhancement in high-multiplicity pp collisions.

Conclusion

Experimental and theoretical insights into the anticipated formation of deconfined matter in high-multiplicity proton-proton (pp) collisions at the Large Hadron Collider (LHC) are thoroughly reviewed in this work. From its inception as a standard for heavy-ion collisions, pp collisions have shown intriguing collective behaviors and QGP-like features that challenge traditional ideas about the system size and energy density requirements for deconfinement. Under severe circumstances, small systems may exhibit partonic collectivity and hydrodynamic behavior, according to observations such as an increase in the production of multi-strange hadrons, long-range ridge correlations, and freeze-out temperatures comparable to those in heavy-ion systems.

Supported by hydrodynamic and color-glass-condensate models, theoretic explanations show that even small and dense regions may have localized thermalization and flow-like properties. Our understanding of the transition from the confined to the deconfined state of QCD matter may be further enhanced by these findings. The key problem, however, is the difficulty of distinguishing between effects in the initial state and collectivity in the end state. To confirm the existence of QGP droplets in proton-proton collisions and to redefine the differences between small and large collision systems, future studies must combine precise experimental data with sophisticated theoretical models. Research of this nature ultimately aids in our understanding of the fundamental properties of highly interacting matter and the lab-replicable circumstances of the early universe.

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Conflicts of interest
The authors declare that there are no conflicts of interest regarding the publication of this paper.

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