

QGP droplet formation in small asymmetric collision systems

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Abstract. The journal Nature recently published a letter titled "Creating small circular, elliptical, and triangular droplets of quark-gluon plasma" [1]. The basis for that claim is a combination of measured Fourier amplitudes v_2 and v_3 from collision systems p -Au, d -Au and h -Au (helion h is the nucleus of atom ${}^3\text{He}$), Glauber Monte Carlo estimates of initial-state transverse collision geometries for those systems and hydrodynamic Monte Carlo descriptions of the v_n data. Apparent correspondence between hydrodynamic model v_n trends and data trends is interpreted as confirmation of "collectivity" occurring in the small collision systems, further interpreted to indicate QGP formation. QGP formation in small systems runs counter to pre-RHIC theoretical assumptions that QGP formation should require large collision systems (e.g. central A-A collisions). There is currently available a broad context of experimental data from p - p , A-A and p -Pb collisions at the RHIC and LHC against which the validity of the Nature letter claims may be evaluated. This talk provides a summary of such results and their implications.

[1] Nature Phys. 15, no. 3, 214 (2019).

1 Introduction

A recent letter published in the journal Nature reports observation of "short-lived QGP droplets" in 200 GeV p -Au, d -Au and h -Au (h representing the helion nucleus of ${}^3\text{He}$) [1]. The claimed observation is based on a combination of Glauber Monte Carlo estimates of initial conditions (IC), hydrodynamic theory evolution from the IC to the hadronic final state and comparison of theory results with measurements of azimuth Fourier components $v_2(p_T)$ and $v_3(p_T)$. The letter concludes: "...hydrodynamical models which include QGP formation provide a simultaneous and quantitative description of the data in three systems." The overall argument is based on five critical assumptions that have been challenged in Ref. [2]. In this presentation I confront the five assumptions with evidence from a broad array of published data that contradict them. The context for comparison is the two-component (soft + hard) model (TCM) of hadron production in high-energy nuclear collisions. A third component inferred from measurements of a *nonjet* (NJ) azimuth quadrupole structure is also introduced.

2 Is a perfect liquid formed in A-A collisions?

Arguments in favor are based on azimuthal asymmetries (v_2 , v_3 etc.) and jet quenching (R_{AA} high- p_T suppression) as common manifestations of a dense and flowing QCD medium or QGP

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in A-A collisions. Reference [1] argues by analogy that if some or all of those phenomena are observed in small asymmetric collision systems then QGP may be formed there as well.

Figure 1 (left) shows identified-hadron (PID) $v_2(p_t)$ for pions, kaons and Lambdas from 200 GeV Au-Au collisions. The conventional wisdom is that *mass ordering* at lower p_t indicates the presence of radial flow. However, a simple sequence of transformations takes those data from the first to the second panel [3]. Resulting *quadrupole spectra* for three species plotted in the boost frame fall on the same Lévy distribution with slope parameter $T = 92$ MeV. The transformations assume a fixed boost $\Delta y_{t0} = 0.6$ from lab to boost frame. That result falsifies the notion that most hadrons experience Hubble expansion of a bulk medium. The small minority of hadrons “carrying” the NJ quadrupole have a very different spectrum structure and experience a fixed boost corresponding to an expanding thin shell.

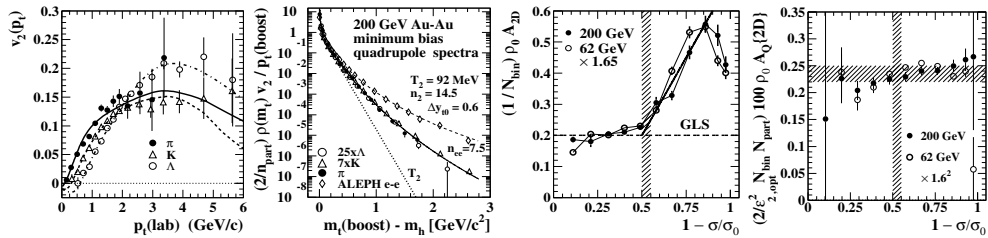


Figure 1. Left: PID $v_2(p_t)$ data on $p_t(\text{lab})$ and corresponding quadrupole spectra on $m_t(\text{boost})$ from 200 GeV Au-Au collisions [3]. Right: Centrality trends for jet quenching and v_2 from 200 GeV Au-Au [4].

Figure 1 (right) shows a comparison (based on 200 GeV Au-Au 2D angular correlations) between jet modification (third) exhibiting a *sharp transition* near 50% centrality (hatched band) and the NJ quadrupole trend (fourth) showing no deviation from a fixed trend from peripheral to central collisions [4]. If there were a common dense QCD medium or QGP, with onset near the sharp transition as suggested by jet modification, it is reasonable to expect that elliptic flow as manifested by v_2 data should show a corresponding marked change in its centrality trend, but no correspondence is observed. In other analysis the jet contribution to p_t spectra is described accurately by pQCD for all Au-Au centrality, albeit fragmentation functions are modified in more-central collisions [5, 6]. That combination, consistent with other evidence, casts strong doubts on formation of a “perfect liquid” in A-A collisions.

3 Is a Monte Carlo Glauber valid for x-A collision geometry?

The hydrodynamic model utilized in Ref. [1] requires estimation of the IC (i.e. the initial transverse geometry) for small asymmetric x -A collision systems. It is assumed that the Glauber Monte Carlo (MC) provides meaningful estimates of the IC for such systems. That assumption can be strongly questioned based on analysis of ensemble-mean \bar{p}_t data from 5 TeV p -Pb collisions.

Figure 2 (left) compares MC Glauber estimates to TCM estimates for nucleon participant-pair number $N_{part}/2$ (first) and ensemble-mean \bar{p}_t (second) vs mean charge density $\bar{\rho}_0 = n_{ch}/\Delta\eta$ from 5 TeV p -Pb collisions [7, 8]. MC Glauber estimates are based on the assumption that p -N collisions within p -Pb collisions are on average equivalent to isolated non-single-diffractive (NSD) p - p collisions. In contrast, TCM estimates are based on an analysis of \bar{p}_t data which indicates that p -N mean multiplicities vary strongly with p -Pb centrality. The MC Glauber estimates (solid points) dramatically fail to describe \bar{p}_t data (open squares) in the second panel whereas the TCM description (solid curve) describes the data accurately.

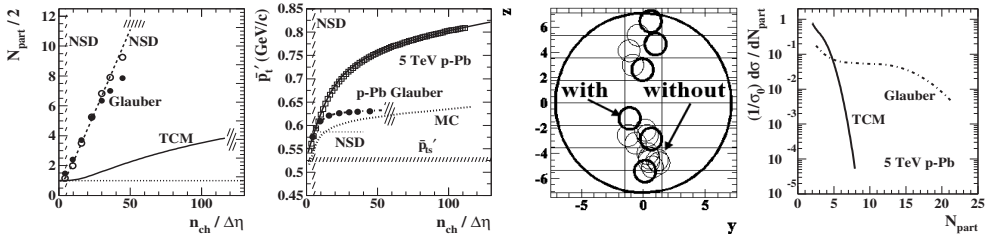


Figure 2. TCM vs Glauber geometry for 5 TeV p -Pb collisions. Left: Estimates of $N_{part}/2$ and \bar{p}_t vs mean charge density $\bar{\rho}_0 = n_{ch}/\Delta\eta$ [7, 8]. Right: Monte Carlo Glauber simulation of p -Pb collisions [9].

Figure 2 (right) provides an explanation for the discrepancy. The third panel shows a Glauber MC simulation of a central p -Pb collision. The total number of small circles denotes the number of geometric *encounters* of the projectile proton with target nucleons. The bold circles denote actual p -N *collisions* allowed by an “exclusivity” condition: the projectile proton can interact with only *one nucleon at a time* [9]. The MC Glauber *with* exclusivity (labeled TCM in fourth panel) is consistent with \bar{p}_t data and other aspects of p -Pb data. The MC Glauber *without* exclusivity produces severely biased IC estimates for x -A collisions.

4 Do A-B p_t spectra provide evidence for radial flow?

Radial flow is conventionally inferred from p_t spectra by qualitative observations of increasing spectrum “hardening” (increased slope parameter) with increasing collision centrality and hadron mass, and by quantitative application to spectra of a blast-wave fit model with parameters T_{kin} and β_t , the latter interpreted as a quantitative measure of radial flow.

Figure 3 (left) shows a TCM analysis of proton spectra from 200 GeV Au-Au collisions [6]. The first panel shows the full spectra while the second panel shows the extracted spectrum hard components (complete minimum-bias jet contribution). The spectra show no evidence for radial flow (boost or translation of the spectrum soft component on y_t leading to *suppression* at lower y_t). The hard components (second panel) indicate *suppression* at higher y_t (consistent with R_{AA} and “jet quenching”) but substantial *enhancement* near $y_t \approx 3.5$ compared to the TCM references (dotted). The hard components below $y_t = 3$ show no change with centrality. These Au-Au proton spectra thus provide no evidence for radial flow.

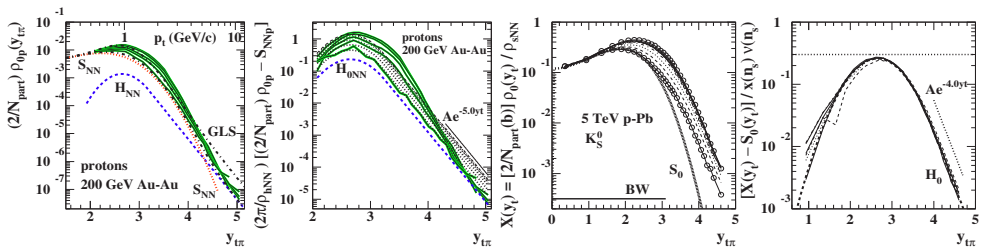


Figure 3. Left: Proton y_t (transverse rapidity $y_{tr} = \ln[(p_t + m_{tr})/m_\pi]$) spectrum TCM for 200 GeV Au-Au collisions [6]. Right: K_s^0 y_t spectrum TCM for 5 TeV p -Pb collisions [7].

Figure 3 (right) shows K_s^0 spectra from 5 TeV p -Pb collisions extending down to zero momentum (full spectra and jet-related hard components respectively) [7]. If significant radial

flow played a role there should be substantial suppression at lower p_t as a consequence of spectra boosted (translated to the right) on y_t . These spectra show no evidence for radial flow. The spectra above 0.5 GeV/c ($y_t = 2$) are dominated by the minimum-bias jet contribution, and the jet contribution (fourth) shows no evidence for jet modification (changes in shape).

5 Do Fourier amplitudes v_n measure flows?

Fourier amplitudes v_n inferred from two-particle angular correlations can be derived from direct model fits to full 2D angular correlations or from Fourier fits to 1D azimuth projections of 2D angular correlations. In the latter case there is the possibility that certain jet-related structures when projected will contribute substantially to inferred v_n as a “nonflow” bias.

Figure 4 (left) shows 2D angular correlations from high-multiplicity 200 GeV p - p collisions (first) and an inferred NJ quadrupole amplitude vs multiplicity soft component $\bar{\rho}_s$ (second) [5]. The quadrupole amplitude (\propto number of correlated pairs) increases $\propto \bar{\rho}_s^3$ accurately over a thousand-fold amplitude increase. Referring to participant low- x gluons with $N_{part} \propto \bar{\rho}_s$ and $N_{bin} \propto \bar{\rho}_s^2$ (dijet production) the p - p quadrupole then varies as $\propto N_{part}N_{bin}$.

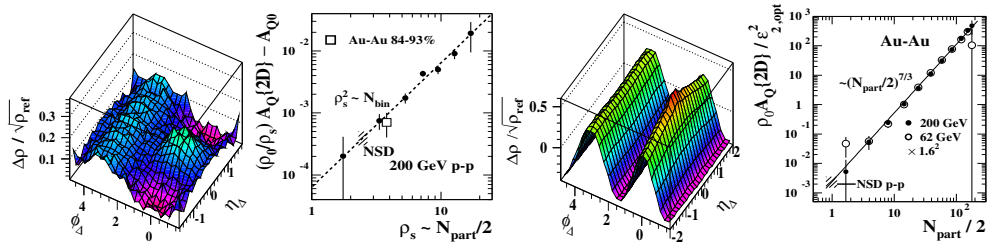


Figure 4. Left: NJ quadrupole n_{ch} trend for 200 GeV p - p collisions [5]. Right: NJ quadrupole centrality trend for 200 GeV Au-Au collisions [10, 11].

Figure 4 (right) shows 2D angular correlations from mid-central 200 GeV Au-Au collisions, dominated by the NJ quadrupole, and the centrality trend for the quadrupole amplitude (divided by ϵ_{opt}^2) vs nucleon participant pairs $N_{part}/2$ [10, 11]. The solid line is consistent with the amplitude trend $\propto N_{part}N_{bin}\epsilon_{opt}^2$. In both cases quadrupole amplitudes are inferred by model fits to 2D angular correlations that exclude any significant jet contribution. The simple p - p and Au-Au trends appear to be closely related, and there is no evidence for response to high densities and QGP formation. The p - p $\bar{\rho}_s^3$ trend suggests that the quadrupole arises from a three-gluon interaction and is not a manifestation of hydrodynamic expansion (flows).

Figure 5 (left) shows $v_2\{\text{EP}\}$ (event-plane method) data (open circles) from more-central 200 GeV Au-Au collisions compared with $v_2\{\text{SS}\}$ derived from the same-side 2D jet peak (solid triangles) [11]. $v_2\{2D\}$ NJ quadrupole data (solid points) are also inferred from 2D model fits. In more-central Au-Au collisions $v_2\{\text{EP}\}$ data are dominated by or entirely determined by jets – i.e. as a Fourier component of the SS 2D jet peak projected onto 1D azimuth.

Figure 5 (right) shows quadrupole amplitude $B_Q\{2D\}$ derived from $v_2\{2D\}$ data for 200 GeV Au-Au collisions vs transverse rapidity y_t (third) and quadrupole spectra in the lab frame inferred from those data (fourth, see Fig. 1, left) [11]. The quadrupole spectrum shapes and the source boost $\Delta y_{t0} \approx 0.6$ derived from $v_2\{2D\}$ data are independent of Au-Au centrality even for peripheral collisions. There is no evidence for the presence of a dense QCD medium.

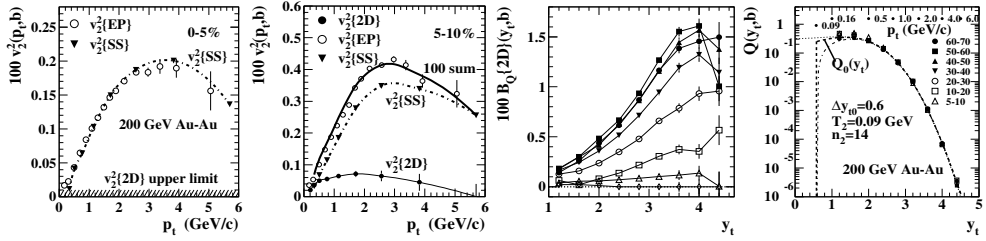


Figure 5. Left: $v_2^2\{EP\}(p_t)$ trend for 200 GeV Au-Au collisions. Right: $v_2^2\{2D\}(p_t)$ trend for 200 GeV Au-Au collisions.

6 Do hydrodynamic models have any relation to real A-B collisions?

The apparent success of hydrodynamic models in describing spectra and angular-correlation data from an array of A-B collisions has been viewed as convincing evidence for QGP formation. Hydrodynamic descriptions of x -A data as reported in Ref. [1] are invoked to buttress claims of QGP-droplet formation in those collision systems. However, such interpretations can be questioned.

Figure 6 (left) shows hydrodynamic theory (solid curves) [12] compared to a pion spectrum from 0-5% central 2.76 TeV Pb-Pb collisions (open circles). In the first panel, on linear p_t , the apparent agreement between theory and data at higher p_t is emphasized. However, in the second panel, on logarithmic y_{tr} , the large discrepancy below $y_t = 2$ ($p_t = 0.5$ GeV/c) falsifies the hydrodynamic model. Strong suppression at lower p_t is expected from a hydrodynamic model (arising from a source boost distribution) but is not observed in data. hydrodynamic theory in effect accommodates the large jet contribution H_{NN} (TCM hard component) peaked near $y_t = 2.7$ ($p_t \approx 1$ GeV/c) [2].

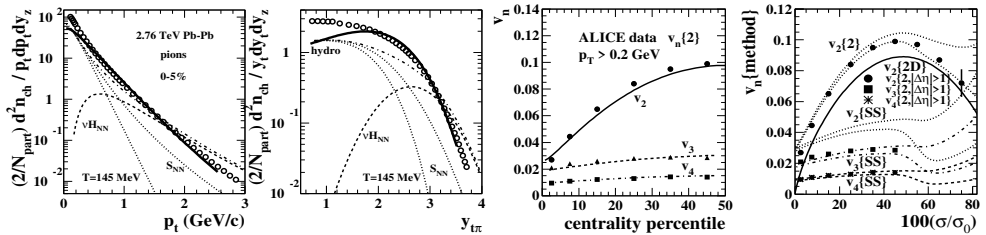


Figure 6. Left: Hydrodynamic theory compared to pion spectrum data from 2.76 TeV Pb-Pb collisions [2, 12]. Right: Hydrodynamic theory compared to $v_2(b)$ centrality data from 2.76 TeV Pb-Pb collisions [12, 13].

Figure 6 (right) shows hydrodynamic theory (curves in third panel) [12] compared to v_n data vs centrality from 2.76 TeV Pb-Pb collisions (points). The hydrodynamic curves appear to describe the data well. However, the fourth panel shows an alternative description of the same ALICE data (albeit with additional points that are missing from the hydrodynamic treatment) [13]. The dotted, dashed and dash-dotted curves in the fourth panel are *predictions* for v_n derived from jet features inferred from model fits to 2D angular correlations [10]. The solid curve represents the NJ quadrupole feature obtained from the same fits. The step up in jet-related trends from peripheral to central collisions (near $\sigma/\sigma_0 \approx 0.5$) corresponds to the “sharp transition” in jet structure occurring in Fig. 1 (third panel) that relates to “jet

quenching.” Especially for v_3 and v_4 the hydrodynamic model accommodates only jet-related correlation structure. One can conclude from these examples that at least some current hydrodynamic models are sufficiently complex and variable to accommodate data that may have no relation to flows. They are not predictive.

7 Summary

Sections 2-6 respond to five critical assumptions (expressed here in the form of questions) that form the basis for argument in a recent Nature letter introduced to claim formation of QGP droplets in small asymmetric x -A collisions. The evidence invoked for QGP formation in small collision systems presents a problem with two possible resolutions: (a) QGP formation is apparently a universal phenomenon in high-energy nuclear collisions, requiring novel theoretical approaches in response, or (b) certain “signatures” conventionally associated with QGP formation in A-A collisions are misinterpreted in any collision system and hydrodynamic descriptions of certain data features do not necessarily correspond to a flow mechanism, may actually be accommodating minimum-bias jet contributions. Experimental evidence presented in this talk responding to the five assumptions calls into question identification of certain data features with QGP formation and challenges hydrodynamic theory descriptions of data that have been interpreted to confirm the presents of flows.

The two-component (soft + hard) model (TCM) of hadron production provides a simple alternative description of hadron production in high-energy nuclear collisions that is consistent with basic QCD and with a broad array of jet measurements. The TCM offers methods and results that enable accurate distinctions among jet contributions (hard) and nonjet contributions (soft) to yields, spectra and two-particle correlations. In p - p and p -A collisions the TCM provides an exhaustive description of data with no need for exceptional mechanisms (e.g. no flows or jet quenching). In A-A collisions the TCM provides a stable and predictive *reference* against which deviations from linear superposition (e.g. jet modification) can be assessed quantitatively. A third, nonjet quadrupole, component with simple trends in p - p and A-A collisions appears to arise from an elementary QCD process (few-gluon interactions).

References

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