Small systems theory perspective: CGC, Transport, Hydro

Raju Venugopalan
Brookhaven National Laboratory

Strange Quark Matter 2019
Discovery of the ridge in small systems

Observation of Long-Range Near-Side Angular Correlations in Proton-Proton Collisions at the LHC

Cited by 760 records
What’s the underlying QCD dynamics?

- Is it the initial state dynamics arising from rare configurations in the hadron wavefunctions?

- Or is it final state collective flow of the world’s smallest droplets?

- Or, is it some combination, where there is a smooth transition from one description to the other?

Option 1 stretches to the limit our understanding of the quark-gluon structure of the proton

Option 2 stretches to the limit the applicability of thermodynamic and hydrodynamic concepts in high energy physics
From CGC to QGP in A+A collisions

Maximally occupied gluon states

Very dense matter: occupancy $f \sim 1/\alpha_S$ and $p_T \sim Q_S$

QGP has $f \sim 1$ and $p_T \sim T \ll Q_S$

Color Glass Condensates
Overlap of Wavefns.
Glasma
sQGP - perfect fluid
Hadron Gas

For weak coupling, $\alpha_S \ll 1$ but $\alpha_S \ast f \sim 1$ -- QCD matter is strongly interacting

Real time evolution described by an ensemble average of 3+1-D classical-statistical solutions of QCD Yang-Mills equations seeded by quantum fluctuations
From CGC to QGP in A+A collisions

Classical-statistical evolution of energy-momentum tensor

\[
\langle\langle T_{\mu\nu}\rangle\rangle_{LLx+Linst.} = \int [D\rho_1][D\rho_2] W_{Y\text{beam}-Y}[\rho_1] W_{Y\text{beam}+Y}[\rho_2] \\
\times \int [da(u)] F_{\text{init}}[a] T_{LO}^{\mu\nu}[A_{\text{cl}}(\rho_1, \rho_2) + a]
\]

Distribution of color sources in the nuclei before the collision

Distribution of quantum fluctuations immediately after collision

Path integral over multiple initializations of classical Yang-Mills trajectories leads to rapid quasi-ergodic “eigenstate thermalization”

Berry; Srednicki; Rigol et al.; ...
Increasing pressure anisotropy

After some evolution when $1 < f < 1/\alpha_s$ a dual description is feasible either in terms of kinetic theory or classical-statistical dynamics ...

Numerical simulations pick out kinetic “bottom-up” thermalization scenario

CGC naturally leads to thermalization: $\tau_{\text{therm}} \to 0$ as $Q_s \to \infty$

From CGC to QGP in A+A collisions

Independent of initial momentum dist.
Self-similar evolution with universal scaling exponents

Far from equilibrium
Initial conditions
Close to equilibrium

Thermal equilibrium

Nonthermal fixed point

Berges, Boguslavski, Schlichting, RV (2014)


Baier, Mueller, Schiff, Son (2001)
Kinetic theory results when plotted as function of scaled “hydrodynamization” variable match smoothly to viscous hydro even when system is quite anisotropic.

Note however from kinetic theory analysis that regime of validity of hydro is limited for small systems: large $v_n$ coefficients already seen for quite low multiplicities.

Recent analysis with similar conclusions, Kurkela,Wiedemann,Wu, arXiv:1905.05139
From A+A to small systems: can the initial state alone describe $v_n$ data?

Basic idea: Bose and HBT enhancement of Glasma graphs (relative to mini-jet) in high multiplicity collisions

Previously, odd coefficients $v_{2n+1}$ believed to be zero in this approach; however parametrically the right order contribution (relative to $v_{2n}$) in first nontrivial correction in proton color charge density

Dumitru, et al., arXiv:5295
Dusling, RV, arXiv:1302.7018
Dumitru,Gelis,McLerran,RV, 0804.3858
Kovchegov, Wertepny, 1212.1195
Altinoluk et al., 1503.07126, 1509.03223
McLerran, Skokov, 1611.09870
Kovner, Lublinsky, Skokov, 1612.07790
Kovchegov, Skokov, 1802.08166
Can the initial state alone describe $v_n$ data in small systems?

Yang-Mills simulations (IP-Glasma model) for $v_{2,3}$ in LHC p+A collisions reasonable agreement with low pT data

Systematics of $v_n \{k\}$, with k=2,4,6,.. are also reproduced in simple initial state models

No quantitative comparisons
Can the initial state alone describe $v_n$ data in small systems?

Small system scan at RHIC

Expectations from MC Glauber+hydro models are that one sees an increasing hierarchy of $v_{2,3}$
From $p+Au$, to $d+Au$, to $^3He+Au$


Glauber+ hydro models reproduce the observed hierarchy in $v_2$ and $v_3$

The CGC (dilute-dense MSTV) model also observed the hierarchy
MSTV: Mace,Skokov,Tribedy,RV, PRL (2018)

However this was due to a unit conversion ($\hbar c$) error in the MSTV code – the hierarchy only exists at momenta $< 0.5$ GeV – MSTV does not reproduce the data
MSTV: Erratum submitted to PRL
Glauber+Hydro models also describe features of LHC data

So is the ridge due to hydro, just as in the larger systems?

As noted previously, in context of “bottom-up” thermalization, this is feasible in principle

But...
Hydro extremely sensitive to initial conditions in small systems: what’s driving what?

Bzdak, Schenke, Tribedy, RV, 1304.3403

Very little theory guidance (no dynamical model of multi-particle production)

JIMWLK evolution of model with three valence quarks - while inspired, has several ad hoc elements

Spatial fluctuations in rare events poorly constrained by theory. Somewhat constrained by HERA incoherent J/ψ’s

Possibly an opportunity for small systems
Hydro extremely sensitive to initial conditions in small systems: what’s driving what?

IP-Glasma+hydro (MUSIC)+transport (URQMD)

Significant differences between this IP-Glasma+hydro model (that fits A+A data) and Glauber+hydro models – differences in $v_3$ can be factors of 2-3. Some excess relative to data due to decorrelation of $v_2$ with rapidity (present in data but not in either model)

No $v_2\{4\}$ in PHENIX data for p+Au collisions

$v_2\{4\} > 0$ in p+A in IP-Glasma+hydro

What is the result in Glauber+hydro?
Open problems

Initial state approaches:
Glasma + kinetic theory: study relative contributions of CGC driven initial state correlations and geometry driven contributions to $v_n$ – even few scatterings can generate sizeable effects.

Example: IP-Glasma+BAMPS transport code of Greiner & Xu
Would be interesting to see similar studies by Kurkela et al.

Extension of CGC based approaches to better treat rare events:
What is the relative role of geometrical versus color charge fluctuations?
talk by Giacalone

Hadronization and hadronic rescattering – talk by Bierlich

Hydro approaches:
Large viscous corrections for small systems
Expansion parameter – Knudsen # ~ 1 - at short times

Hydrodynamic fluctuations may be of order unity at the lowest $dN/d\eta$’s where large $v_n$’s are seen – need to be quantified

See for eg., Martinez,Schafer, 1812.05279
Initial momentum anisotropy can survive and biases the final state geometry driven flow

Debate about role of nucleon vs subnucleon fluctuations

Role of jet quenching – no quenching seen in the small systems

“Shrinking the QGP” by doing symmetric and asymmetric light nuclear scans can help clarify all of these issues

Quarkonium yields and correlations in light systems can also help distinguish between initial and final state scenarios. -- talk by **Elena Ferreiro**
Summary

Purely initial state scenarios are disfavored by RHIC light system scan - results point to importance of final state effects

However, the initial shape and correlations greatly influence hydro results. Conversely, can data + hydro constrain the former?

Since CGC+kinetic theory (bottom-up)+hydro are a robust explanation of A+A, need quantitative studies of just CGC+kinetic theory – how much rescattering is sufficient?

Match to PYTHIA and hadronic afterburner?

Onia, Jets, photons add further discriminating power as do further scans of light symmetric/asymmetric nuclei at LHC and RHIC