Creating QCD plasma droplets in p+p collisions at the LHC

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Review: Geometry & Correlations in Pb+Pb

[Snellings, 1102.3010]
Hydrodynamics converts geometry to flow
Main evidence for QCD matter in Pb+Pb

$\langle V_n^{2} \rangle^{1/2}$

$V_2$, $V_3$, $V_4$, $V_5$

$\rho_T < 2$ GeV: "Soft Physics"

ATLAS 20-30%, EP

narrow: $h/s(T)$
wide: $h/s = 0.2$

$\rho_T$ GeV

[57x54]0
[38x98]0.05
[45x142]0.1
[38x186]0.15
[45x230]0.2
0 0.5 1 1.5 2

$\rho_T < 2$ GeV:
"Soft Physics"

Main evidence for
QCD matter in Pb+Pb

[Gale et al., PRL110 (2013)]
Selected Soft Physics Talks at EPS-HEP ‘17

• Multi-particle flow cumulants $v_n\{m\}$ (talk by Bold)
• Flow of heavy flavor (talk by Milosevic)
• Rapidity information (talk by Alam)
• Low collision energies (talks by Lipiec, Grebieszkow, Levai)
• Collisions of light ions: $p+Pb$ and $p+p$ (talk by Bernades, ...)
• Early time-dynamics (talks by Mueller, Tanji)
• EW bosons in $Pb+Pb$ (talk by Perepelitsa)
• ALICE highlights (plenary by Floris)
Frontiers of the field: Going forward, going small

[Schenke, QM’17]
Focus of this talk: going small
Consensus: flow in Pb+Pb due to hydrodynamics

Traditional view:

- QGP in Pb+Pb
- no QGP in p+p (“baseline”)
Purely Experimental Finding

Flow similar in magnitude in all systems

[CMS, 1606.06198]
Consensus: flow in Pb+Pb due to hydrodynamics

What if there is a fluid droplet also in (min-bias) p+p?

Assuming hydro to be applicable, how would hydro signal compare to exp’ data?
One fluid to rule them all

Same fluid setup for Pb+Pb, p+Pb and p+p (same ICs, same viscosity, same numerics) *assuming hydro to be applicable*
One fluid to rule them all

Hydro in pp empirically successful
assuming hydro to be applicable

[Weller and PRL, 1701.07145]
Hydro describes (CMS) data down to min-bias p+p
Finding

Hydro successfully describes min-bias p+p experimental flow data “out of the box”

Recall: Min-bias p+p used to be reference (also for HEP!)
Recall: successful hydro description main evidence of QGP in Pb+Pb

Is there a QCD fluid droplet in p+p?

Or should we revisit the hydro paradigm for all systems???
Pb+Pb: hydrodynamics describes flow

Main evidence for QCD matter in Pb+Pb

“Large” system: $V \sim 100$ fm$^3$
Many particles: $dN/dy \sim 1000$
Flow = geometry + hydro conversion

[ATLAS 20-30%, EP]

narrow: $h/s(T)$
wide: $h/s=0.2$

$\langle v_n^2 \rangle^{1/2}$

$0.2$

$0.15$

$0.1$

$0.05$

$0$

$0.05$

$0.1$

$0.15$

$0.2$

$0$

$0.5$

$1$

$1.5$

$2$

$p_T$ [GeV]

[ATLAS 20-30%, EP]

$V_2$
$V_3$
$V_4$
$V_5$

narrow: $h/s(T)$
wide: $h/s=0.2$

[Gale et al., PRL110 (2013)]
p+p: hydrodynamics describes flow

Small system: $V \sim 1$ fm$^3$
Few particles: $dN/dy \sim 5$
Flow = fluctuations + hydro conversion

[Weller and PR, 1701.07145]
Objections to applying hydro to (min-bias) p+p

• Too few particles, cannot be collective
• System not in equilibrium (too small)
Objections to the Objection
Hydro does not apply to 5 particles

True

Irrelevant

If QCD droplet gets created in pp, dofs are QCD fields, not hadrons.
Known to have hydro behavior for strongly interacting fields without particles (e.g. AdS/CFT)

Final state particles get imprinted with hydro correlations even if 5 particles could not form correlations themselves.
Objections to applying hydro to (min-bias) p+p

• Too few particles, cannot be collective
• System not in equilibrium (too small)
Traditional QCD Phase Diagram

- Temperature T [MeV]
- Hadrons
- Quarks and Gluons
- Critical point?
- Deconfinement and chiral transition
- Neutron stars
- Color Superconductor?
- RHIC, LHC
- FAR SPS 300
Traditional QCD Phase Diagram
Heavy-Ion Experiments are Out-of-Equilibrium

Non-equilibriumness \( (x) \)

\[ T \text{ [MeV]} \]

RHIC Trajectories

QCD Liquid

Critical Point?

Hadron Gas

Neutron Stars

"Au+Au 200 GeV"
"Au+Au 62.4 GeV"
"Au+Au 39 GeV"

[1609.02820]
Finding

Even Heavy Ion Collisions are Out-Of-Equilibrium, but hydrodynamics is able to describe data

This trivially “solves” the “Early Thermalization Puzzle”: collisions simply do not thermalize. Ever.
Objections to applying hydro to (min-bias) p+p

- Too few particles, cannot be collective
- System not in equilibrium (too small)
Theory basis for applicability of hydrodynamics
Hydrodynamics requires near equilibrium ("thermalization") to be applicable.

This is the textbook requirement. Are the textbooks really correct?
Hydro as an EFT

• Hydro = EFT of long-lived, long-wavelength excitations
• EFT variables: pressure, energy density, fluid velocity
Hydro as an EFT

• Write down quantities using EFT variables and their gradients
• Energy-Momentum Tensor for relativistic fluid

\[ T^{ab} = (\epsilon + P)u^a u^b + P g^{ab} - 2\eta \nabla \langle a u^b \rangle + \ldots \]

• No thermal equilibrium or particle description needed
• Seems we need small gradients!
Gradient expansion example

• What if we had LARGE gradients?
• Example: $f(x) = e^x$, for $x \sim 1$
• $f(x) \sim 1 + x + x^2/2 + x^3/3! + x^4/4! ...$
• $f(1) \sim 1 + 1 + 1/2! + 1/3! + 1/4! = 2.70833 \sim 2.71828 = e^1$
• Works for any value of $x$ because gradient expansion converges (but may need high gradient order)
Hydro as an EFT

• What if we had LARGE gradients?
• Try to improve description by including higher orders in EFT gradient series
• E.g. Bjorken flow, go to order 240 (AdS/CFT)

\[ T(\tau) = \hat{\tau}^{-1/3} \left( 1 + \sum_{n=1}^{240} \alpha_n \hat{\tau}^{-2n/3} \right) \]

• Find: \( \alpha_n \sim n! \), gradient series diverges

[1302.0697, 1503.07514, 1603.05344, 1608.07869, 1609.04803]
Hydro as an EFT

• Gradient series diverges
• But it is Borel-summable! [Heller et al, 1302.0697]
• Borel-resumming AdS/CFT gradient series:

\[ T(\tau) = T_{\text{hydro}}(\tau) + \gamma \exp \left[ -i \int d\hat{\tau} \left( \hat{\omega}_{\text{Borel}} \hat{\tau}^{-1/3} + \sum_{n=1} \hat{\omega}_n \hat{\tau}^{-(2n+1)/3} \right) \right] + \ldots \]

• \( T_{\text{hydro}} \) is “hydrodynamic attractor solution”
• Extra pieces non-analytic in gradient expansion; this is why grad series diverges!
‘Borel-resummation’: attractor solutions far from equilibrium

- 0th order hydro
- 1st order hydro
- 2nd order hydro

- Boltzmann numerical attractor

- AdS/CFT

\[ T \]
Finding

Hydrodynamics applies as long as non-hydro modes can be neglected

No need of thermal equilibrium.
Truly new development “hydrodynamization”
Maybe time to update textbooks???

[PR, 1609.02820]

[Casalderrey-Solana, Liu, Mateos, Rajagopal, Wiedemann, 1101.0618]
Finding

Low Order Hydrodynamics coincides with Attractor Solutions for moderate Gradients

This explains why low-order hydrodynamics works quantitatively out-of-equilibrium!
One fluid to rule them all

Firm theory basis for hydro in small systems
Hydro in pp empirically sucessfull

[1701.07145]
Creating tiny droplets of QCD fluids in pp

- Firm theory basis for applying hydro to pp
- Good quantitative description of exp’ pp data using hydro
- “If it walks like a duck, and it talks like a duck, …”
- Consequence: if there is a QGP in pp, need to revisit the baseline!
- Consequence: if there is a QGP in pp, need to take into account in precision standard model tests (“new” physics, just not beyond the standard model)
Example: Higgs modification in Heavy-Ion Collisions

[D’Enterria, Loizides, QM 2017]
Frontier: Looking for QCD droplets in $e^+ e^-$

- "Old" CERN (LEP) data exists for $e^+ e^-$ collisions
- Idea: hunt for hydro signatures in old data using modern analysis techniques

Possible analysis from LEP data looking for collective effects

Jamie Nagle <jamie.nagle@colorado.edu>
to Stefan, Peter, Dennis.Perepel., Paul, Kenneth

Hello Stefan (cc Peter, Dennis, Paul, Ken),

I was given your contact information from Bill Gary (UCR) as someone who might still have access to analyzing LEP data.
Thank you!
Bonus Material
Hydro as an EFT

- Borel resummation gives Hydro part and other (“Non-Hydro”) part
- Non-hydro part:

\[
\gamma \exp \left[ -i \int d\hat{\tau} \left( \hat{\omega}_{\text{Borel}} \hat{\tau}^{-1/3} \right) \right]
\]

- \( w_{\text{Borel}} = \pm 3.1193 - 2.7471 \ i \) [Heller et al, 1302.0697]
- \( w_{\text{QNM}} = \pm 3.119 - 2.747i \) [Starinets, hep-th/0207133]
Hydro as an EFT

Quasinormal spectrum of gravitational fluctuations in the sound channel,

[Kovtun&Starinets, hep-th/0506184]
Off-equilibrium hydro

• Hydrodynamic attractor solution exists even far away from equilibrium (as long as hydro modes exist)
• Arbitrary initial conditions approach attractor via non-hydro mode decay
• Near equilibrium, attractor becomes well-known hydrodynamic gradient expansion (e.g. ‘Navier-Stokes’)
• Attractor generalizes notion of hydrodynamics to very non-equilibrium situations!
Far-from-equilibrium Hydro

- Normal hydro:
  \[ T^{ab} = (\epsilon + P)u^a u^b + P g^{ab} - 2\eta \nabla^{<a} u^b > + \ldots \]

- Far-from equilibrium hydro:
  \[ T^{ab} = (\epsilon_B + P_B) u^a u^b + P_B g^{ab} - 2\eta_B \nabla^{<a} u^b > \]

where \( \eta_B = \eta_B(|\nabla^{<a} u^b >|) \) depends on gradient strength

- For conformal system, \( \epsilon_B = 3 P_B \) even far from equilibrium!
Effective (Resummed) Viscosity

Borel-Resummed Viscosity

AdS/CFT $C_h = 0.08$
Kinetic $C_h = 0.08$
Kinetic $C_h = 0.16$
rBRSSS $C_h = 0.08$

[PR, 1704.08699]
Hydro works away from isotropy