Ultra-Relativistic Heavy-Ion Collisions and Quark-Gluon Plasma

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2nd Jagiellonian Symposium on
Fundamental and Applied Subatomic Physics
Krakow, Poland

4-9 June 2017

IISER PUNE

Outline

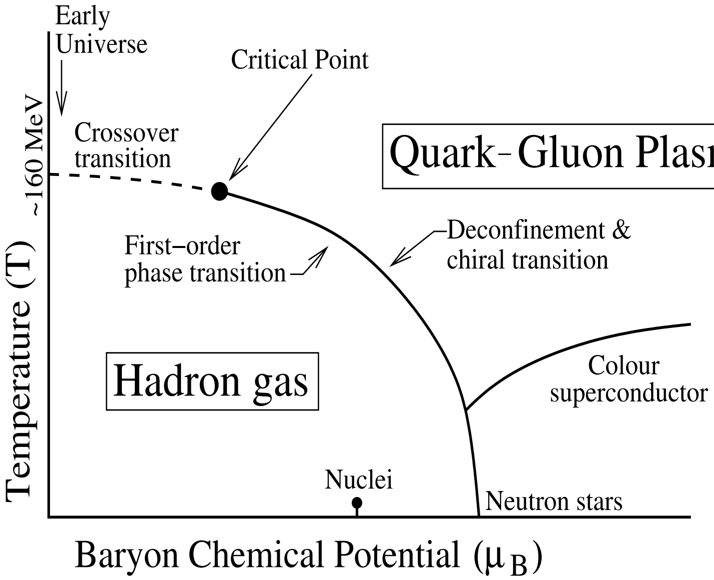
- Overview of this Field
- Recent Advances — Experimental, Theoretical
- Take-Home Message / Open Questions

Fundamental Questions

This field addresses some fundamental questions regarding QCD:

- Nature of equilibration processes in QCD
- Collectivity (especially in small systems) as an emergent phenomenon in QCD
- How to experimentally probe the physical degrees of freedom relevant in the QCD transition region

QCD Phase Diagram (schematic)



THE BIG IDEA IS TO MAP OUT THE QCD PHASE DIAGRAM QUALITATIVELY and QUANTITATIVELY, and also STUDY QCD NON-EQLBM (TRANSPORT) PROPERTIES.

RELATIVISTIC HEAVY-ION COLLISIONS IS THE ONLY AVAILABLE LABORATORY TOOL.

Various Stages

- Collision of two Lorentz-contracted nuclei (or two CGC plates)
- Deposition of kinetic energy & formation of a fireball (or Glasma)
- Liberation of partons from the strong chromofields (or Decoherence)
- Approx. local thermalization of partons: Formation of QGP
- Hydrodynamic expansion, cooling, dilution. QCD EoS.
- Particlization — Kinetic theory
- Chemical freezeout: inelastic processes stop
- Kinetic freezeout: elastic scatterings stop. Free streaming.
- Detection of particles — Extraction of QGP properties

Wealth of Data

- Initial-State Variables: beam energy, beam species, centrality of collision
- Final-State Variables: particle species, transverse momentum, rapidity or pseudo-rapidity
- Observables (differential or integrated): charged particle multiplicity, p_T spectra, anisotropic transverse flows for $n = 1 - 6$, strangeness enhancement, J/ψ suppression, Υ suppression, BE correlations, jet quenching, 2-,3- and multi-particle correlations, γ and $\ell\ell$ spectra, ...

Any model has to agree with this body of data

Standard Model of URHICs

- Initial state: Glauber model / Colour-Glass Condensate-based model
- Pre-equilibrium evolution: AMPT or classical Yang-Mills eqs
- Intermediate evolution: Rel. 2nd-order hydro $\oplus$ lattice QCD EoS
- End evolution: Rel. Boltzmann dynamics leading to a freeze-out
- Final state: Detailed measurements (single-particle inclusive, two- & multi-particle correlations, etc.) are available.

Aim: To achieve a quantitative understanding of the thermodynamic and transport properties of QGP, e.g., its EoS, transport coeffs, etc.

Major hurdle

Event-by-event fluctuations

(not just in the initial state)

Sources of Event-by-Event Fluctuations

- Initial-state fl.: Quantum fl. in the distributions of N's in $\Psi_{nucleus}$. In addition, fl. in the colour charge distributions inside a N. Hence, e-by-e fl. in $\epsilon_i(x, y)$ and $\mathbf{v}_i(x, y)$ at nucleonic and sub-nucleonic scales.
- Hydrodynamic fl.: Due to finite particle no. in a given coarse-grained fluid cell. Local thermal noise or fl. in $\epsilon(x, y)$ and $\mathbf{v}(x, y)$. Deterministic vs stochastic hydrodynamics.
- Fl. induced by hard processes: Jet prod. is a random process. Hard partons propagating in the medium impart energy to the medium in a random manner.
- Freezeout fl.: Finite particle no. effects during and after the freezeout (or particlization of the fluid).

Hence every event is different!

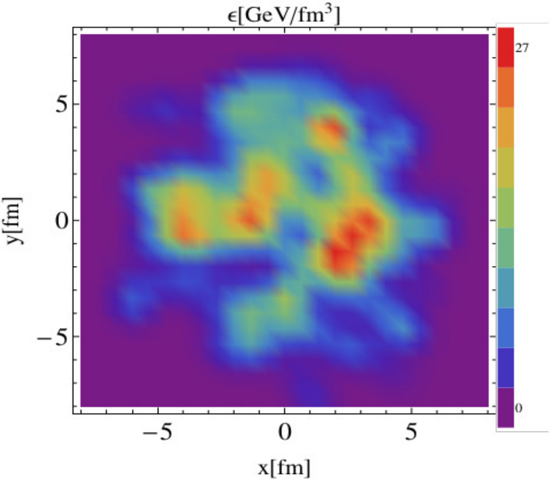


Fig. from Ollitrault & Gardim, 1210.8345

Initial energy density in the transverse plane at $z = 0$ in a simulated random central Pb-Pb collision at 2.76 TeV.

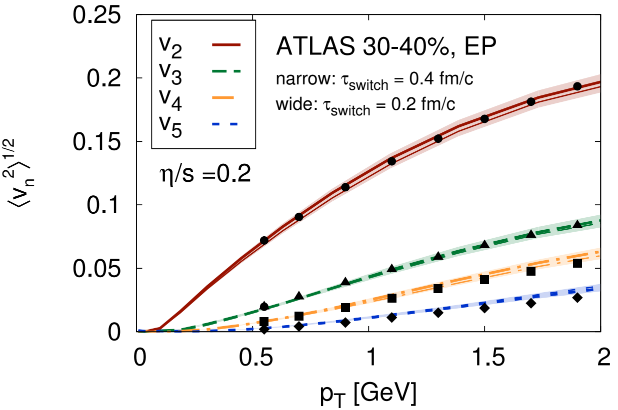
Final-state flow pattern is the collective hydrodynamic response to the initial conditions fluctuating event by event.

HYDRO† PLAYS A CENTRAL ROLE IN UNDERSTANDING THE SOFT SECTOR OF RELATIVISTIC HEAVY-ION COLLISIONS.

† Relativistic, dissipative, causal (second-order) hydrodynamics

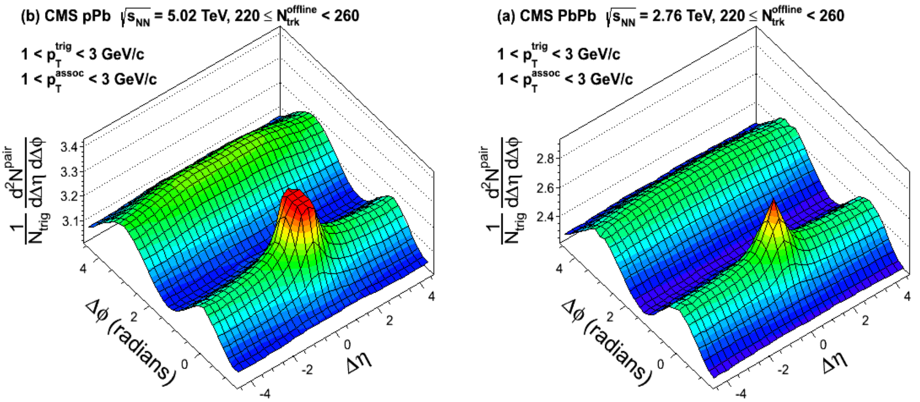
Some Successes of Hydrodynamics Picture ...

Extraction of Shear Viscosity ... Gale et al PRL (2013)



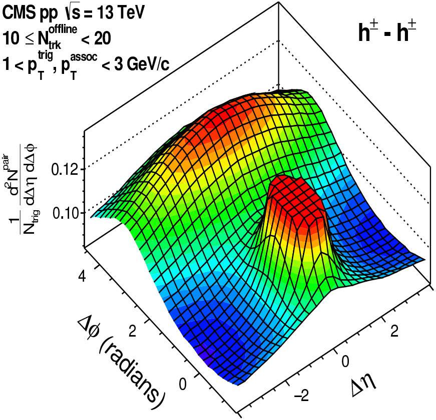
Basic idea: $v_n(perfect\ fluid) > v_n(viscous\ fluid)$
IF one has a good control on $v_n(perfect\ fluid)$, one can adjust η/s to fit the data on v_n, and thus extract η/s

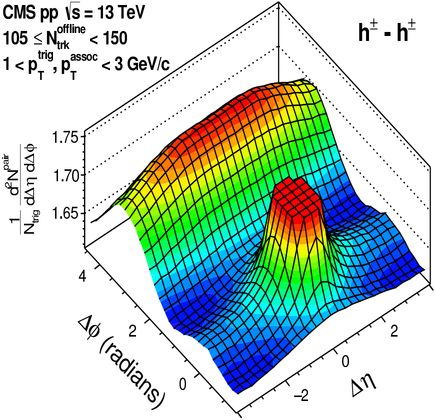
Ridges in *pPb* and *PbPb* collisions at LHC



Phys. Lett. B 724 (2013) 213

CMS Collab, arXiv:1606.06198





Ridge: One of the key experimental pieces of evidence for the strong collective behaviour comparable to a fluid.

Quark-Gluon Plasma is

the smallest, hottest, densest, and most perfect

fluid ever produced in the laboratory

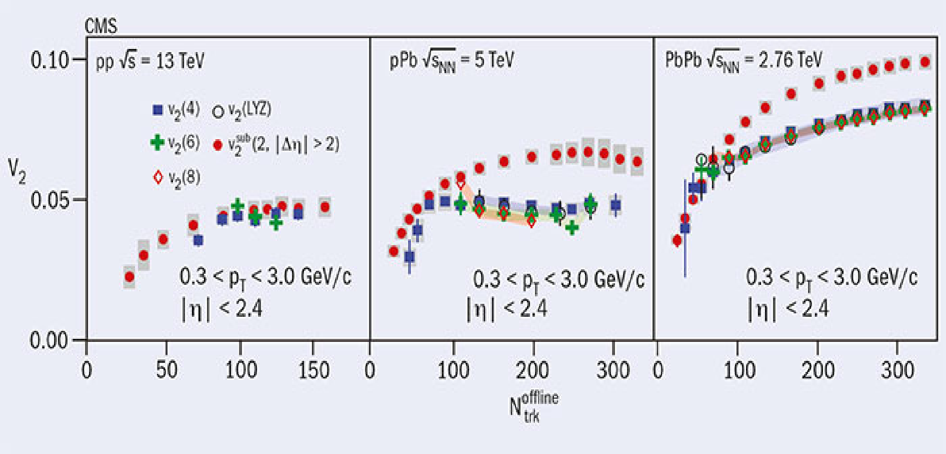
- Smallest: $R \sim 10$ fm
- Hottest: $T \sim 200$ MeV $\sim 2 \times 10^{12}$ K
  (T at the core of the sun $\sim 1.6 \times 10^{7}$ K)
- Life-time: $\sim 3 \times 10^{-23}$ sec
- Most perfect: Even more so than liquid helium

Some Recent ($\sim$ 5-6 years) Developments

- Collectivity in small systems
- Longitudinal dynamics
- Event-plane correlators
- Stochastic hydrodynamics
- Anisotropic hydrodynamics (Krakow)
- New flow analysis method

Collectivity in Small Systems

Elliptic Flow (for charged particles) in pp, pPb, PbPb



CMS Collab, arXiv:1606.06198

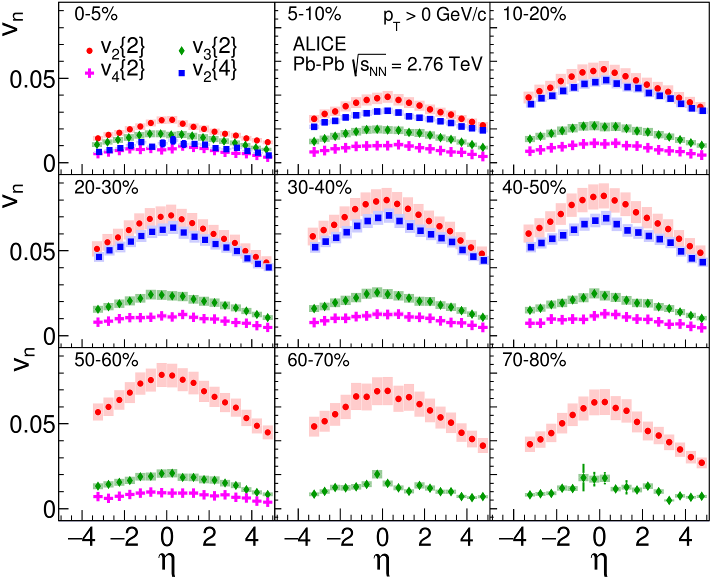
Evidence for collectivity in *pp* collisions at the LHC,

First extraction of v_2 in *pp* collisions using multi-particle correlations.

Longitudinal Dynamics

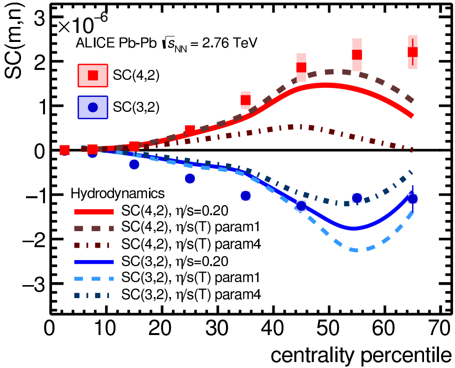
Longitudinal dynamics of the fireball formed in HE collisions:

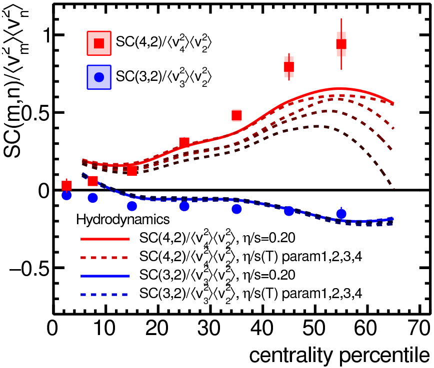
- Forward-backward rapidity correlations $\longrightarrow$ Mechanism of particle production in HE AA and pA collisions
- Event-plane decorrelation and factorization breakdown for particles of different η were demonstrated recently
- η dependence of v_n $\longrightarrow$ Mechanism underlying collectivity: hydrodynamics or saturation?


0-5%
$v_2\{2\}$
$v_3\{2\}$
$v_4\{2\}$
$v_2\{4\}$
5-10%
p_T > 0 GeV/c
ALICE
Pb-Pb $\sqrt{s_{NN}}$ = 2.76 TeV
10-20%
20-30%
30-40%
40-50%
50-60%
60-70%
70-80%
v_n
0.05
0
−4 −2 0 2 4
η

Origin of Longitudinal Correlations

- Fluctuations in multiplicity $dN/d\eta$ e-by-e. Not just statistical but also due to $N_{part}(proj) \neq N_{part}(tgt)$.
- Fluctuations in anisotropic flow $v_n(\eta)$ e-by-e. Not just statistical but also due to $\Psi_n(proj) \neq \Psi_n(tgt)$.
- Symmetry, if any, arises after event averaging.
- $dN/d\eta$ and $v_n(\eta)$ need to be treated on equal footing





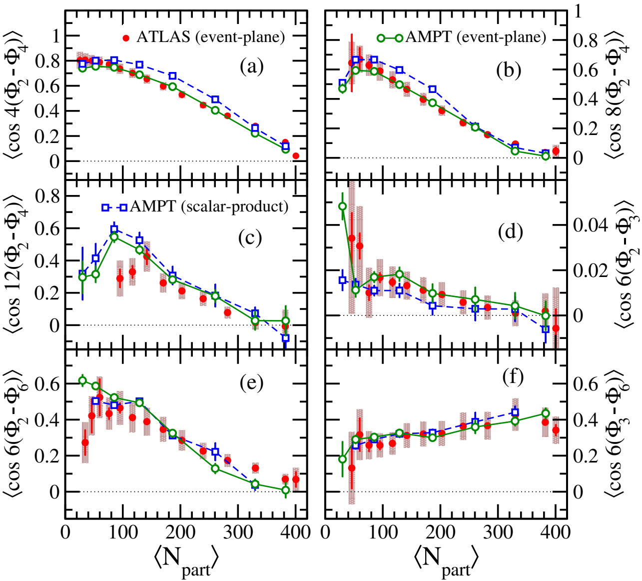
$$SC(m,n) = < v_m^2 \; v_n^2 > - < v_m^2 >< v_n^2 >$$

Symmetric Cumulants = Standard Candles (old name) = Correlations between the amplitudes of anisotropic flow in diff. Fourier harmonics

Event-Plane Correlators

- Pair correlations (or the anisotropic flow v_n extracted from them) are by now reasonably well understood.
- Event-plane correlations: correlations among event planes (Ψ_n) corresponding to different harmonics.
- Represent higher-order correlations, involving at least three particles.
- They bring in a large number of new observables with a promise to provide new, detailed insight into the hydrodynamic response & the initial-state phenomena.
- They open a new direction in heavy-ion physics.
- ATLAS @ LHC (2013): Two- and three-plane correlators. Predictions exist for four-pl correlators.

Two-Event-Plane Correlators ... Pb-Pb, 2.76 TeV, PRC (2013)

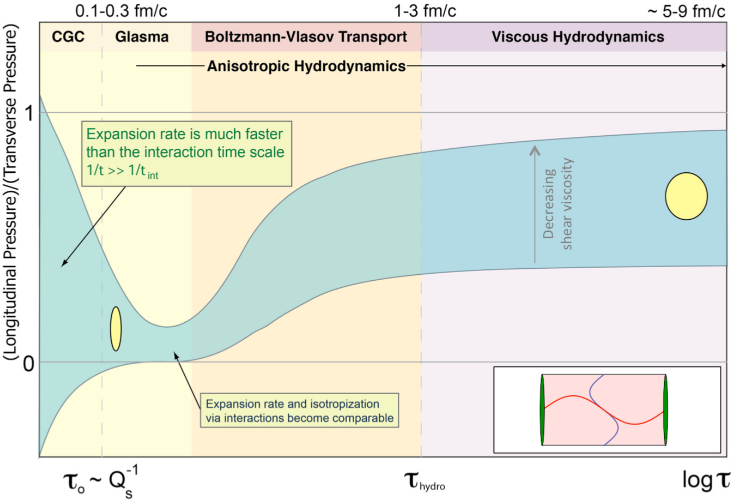


Stochastic Hydrodynamics

- Hydrodyn. fluct. is not a new idea, but their relativistic theory is: Kapusta, Müller, Stephanov, PRC 2012.
- Hydrodyn. fluct. arise due to finite particle no. fluct. in a given coarse-grained fluid cell. This leads to local thermal noise or fluct. in $\epsilon(x, y)$ and $\mathbf{v}(x, y)$. Effect is intrinsic to hydrodyn.
- Fluctuation-Dissipation Theorem: Viscosity controls the magnitude of hydro fluct. This provides another handle on η/s.
- $T^{\mu\nu} = T^{\mu\nu}_{perfect} + \Delta T^{\mu\nu} + S^{\mu\nu}, \quad J^{\mu} = J^{\mu}_{perfect} + \Delta J^{\mu} + I^{\mu}$, $\partial_\mu T^{\mu\nu} = 0 = \partial_\mu J^{\mu}$: Stochastic (rather than deterministic) hydro.
- Are there any observable effects? Correlations across large $\Delta\eta$?

ANISOTROPIC HYDRODYNAMICS (aHydro)

Evolution of Pressure Anisotropy ... M. Strickland, 1410.5786



Yellow ellipses: shape of the momentum-space distribution with x-axis: longitudinal direction, y-axis: transverse direction.

Anisotropic Hydrodynamics (aHydro)

- Originally proposed in 2010: Florkowski and Ryblewski 1007.0130, Martinez and Strickland 1007.0889
- Very early times: sizable pressure anisotropy in LRF
- Sizable momentum-space anisotropy ($p_L^2 << p_T^2$) in parton $f(x, p)$
- Better to reorganize hydrodynamic expansion by taking into account large momentum anisotropy at leading order non-perturbatively, instead of as a perturbative correction to an isotropic $f(x, p)$
- This extends applicability of hydrodynamics to situations far from isotropic thermal equilibrium
- Recent Progress in aHydro: 1610.10055 and 1611.05056

Principal Component Analysis of Event-by-Event Fluctuations

RSB, Jean-Yves Ollitrault (Saclay), Subrata Pal (TIFR), Derek Teaney (Stony Brook), *PRL* 114 (2015) 152301

A New Flow Analysis Method (contd.)

Analysis of anisotropic flow v_n

- Methods currently in use (event-plane, cumulants, ..): devised before the importance of flow fluctuations was recognized
- New method: extraction of flow fluct. directly from data on 2-particle correls; uses all the information
- Based on Principal Component Analysis (PCA) — applied to the 2-particle correlation matrix, $\langle \cos n\Delta\phi \rangle$
- Leading eigenmode $\longleftrightarrow$ usual v_2, v_3
  Subleading modes of v_2, v_3 revealed for the 1st time

Other Recent Developments ...

- Critical Point search in RHIC Beam Energy Scan:
  Overview STAR, EPJ Web Conf. 95 (2015) 01009
- Rel. Hydrodynamics $\longrightarrow$ Rel Magneto-hydrodynamics:
  F. Becattini et al, arXiv:1609.03042
- Multi-dimensional parameter optimization program that uses sophisticated Bayesian techniques:
  S.A. Bass et al, arXiv:1502.00339, 1605.03954
- Alternative (non-fluid-dynamic) explanations of apparent collectivity: Discussion in arXiv:1604.03310
- Heavy ions at the Future Circular Collider (FCC):
  CERN Yellow Report, arXiv:1605.01389

Take-Home Message / Open Questions

- All data so far are consistent with the formation of Quark-Gluon Plasma, and we are in the midst of trying to determine its equilibrium and transport properties accurately.
- Data provide a strong support to hydrodynamics as the appropriate effective theory for rhics. But the Standard Model still incomplete.
- Dichotomy between strong and weak coupling descriptions of hot QCD matter.
- How does a weakly-coupled colour-glass condensate become a strongly-coupled fluid?
- Collectivity in small systems. Size of the smallest QCD droplet?
- QCD Phase Diagram still remains largely unknown. Critical Point?
- LHC: High luminosity era. NICA: Fixed target expt to start in 2017. CBM@FAIR: Data taking to start in 2022. EIC? So this exciting field is going to remain very active for a decade at least.

THANK YOU