Yellow Report

Introduction: opportunities and goals for high-density QCD at LHC

Urs Achim Wiedemann

CERN TH Department

WG5 HI: general meeting on Yellow Report overview

31 Oct 2018

General Remarks

- WG5 is part of global effort to document LHC physics opportunities throughout the approved HL-LHC era and into a potential HE-LHC era.
- Since 2010, LHC 'heavy ion programme' made many qualitative advances: i) flow/fluctuations ii) jet/ jet substructure iii) hadrochemistry iv) quarkonium (regeneration, sequential suppression) v) flavor dependence of energy loss vi)direct photons …
- The LHC discovery of collectivity in small systems gives rise to qualitatively novel working hypotheses that are experimentally accessible at HL-LHC.
- WG5 title "Future physics opportunities for high-density QCD with ions and proton beams" reflects the fact that what was conceived initially as a Pb-Pb programme has evolved in the last decade into a Pb-Pb + p-Pb + pp (+ light AA) – programme.
- Role of introduction: name the physics drivers and relate them to future measurements

Goals for the HL-LHC era

1. Characterizing the macroscopic long-wavelength QGP properties with unprecedented precision.

2. Accessing the microscopic parton dynamics underlying QGP properties.

3. Developing a unified picture of particle production from small (pp) to larger (pA and AA) systems.

4. Probing parton densities in nuclei in a broad (x,Q^2) kinematic range and searching for the possible onset of parton saturation.

We should endorse (or further discuss) the precise wording of these four explicitly stated goals.

Goal 1
Characterizing the macroscopic long-wavelength QGP properties with unprecedented precision.

Underlying theory

1. Fluid dynamic
2. Kinetic theory

Dissipative fluid dynamic description

- Based on: E-p conservation: $\partial_\mu T^{\mu\nu} = 0$

  2^{nd} law of thermodynamics: $\partial_\mu S^\mu(x) \geq 0$

- Sensitive to properties of matter that are

Lattice QCD =>

Finite Temp pQCD =>

AdS/CFT =>

calculable from first principles in quantum field theory

EOS: $\varepsilon = \varepsilon(p, n)$ and **sound velocity** $c_s = \partial p / \partial \varepsilon$

transport coefficients: shear η, bulk ζ viscosity, conductivities …

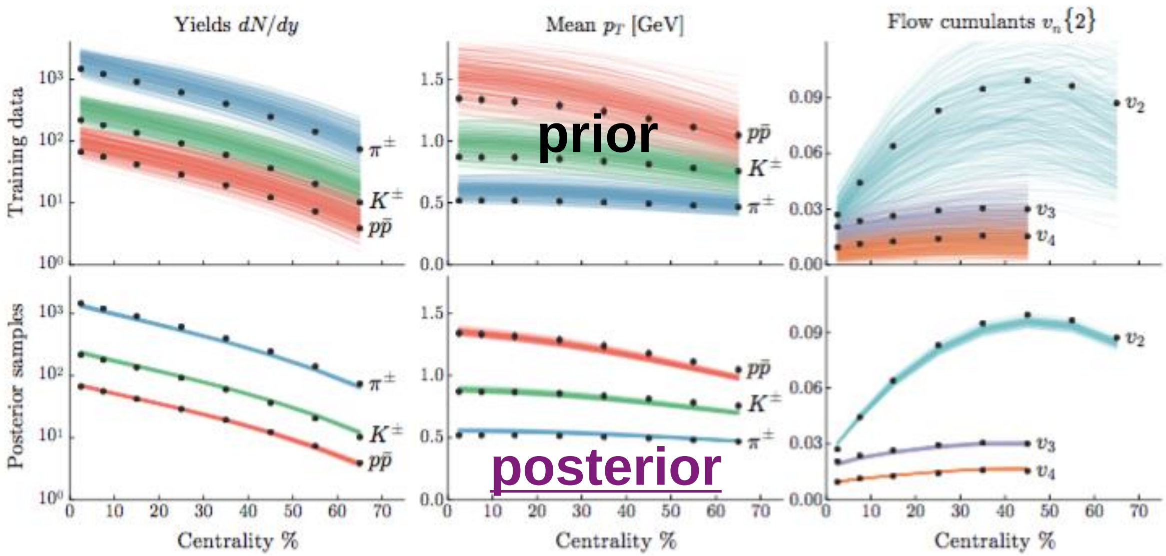
$$\eta = \lim_{\omega \to 0} \frac{1}{2\omega} \int dt\, dx\, e^{i\omega t} \left\langle \left[T^{xy}(x,t), T^{xy}(0,0) \right] \right\rangle_{eq}$$

- **relaxation times**: τ_π, τ_Π, …

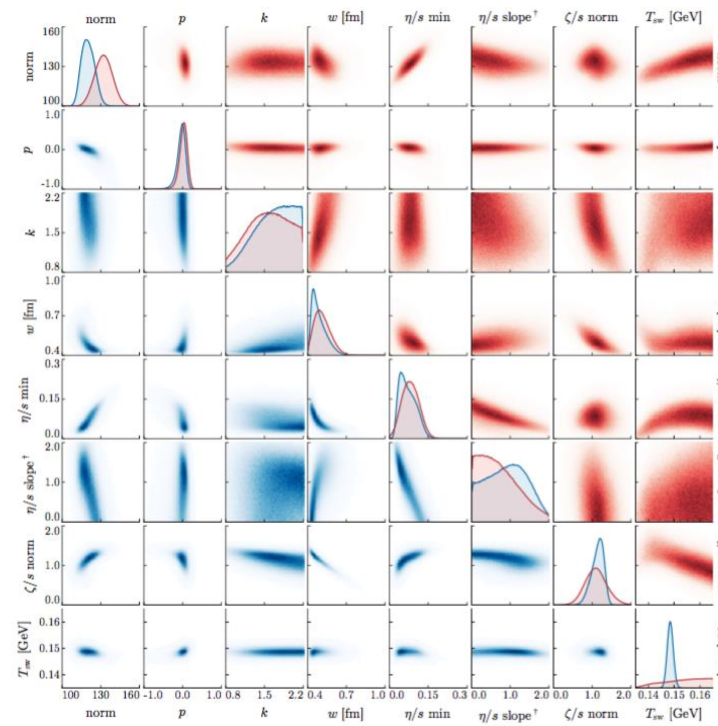
Observed collective dynamics is the main tool to access macroscopic long - wavelength (equilibrium) properties.

Fluid dynamic description

- Increased precision of ”measurements of collectivity” warranted by increased complexity of the theoretical frameworks within which these data can be analyzed: VISHNU, ECHO-QGP, MUSIC, Hirano, Romatschke, HYDJET, . . .



J.E. Bernhard et al. , arXiv:1605.03954v2, fit to ALICE data.



- Inclusion of qualitatively novel/improved measurements (such as heavy quark transport) likely to improve “global fits” of collective properties.

Kinetic theory

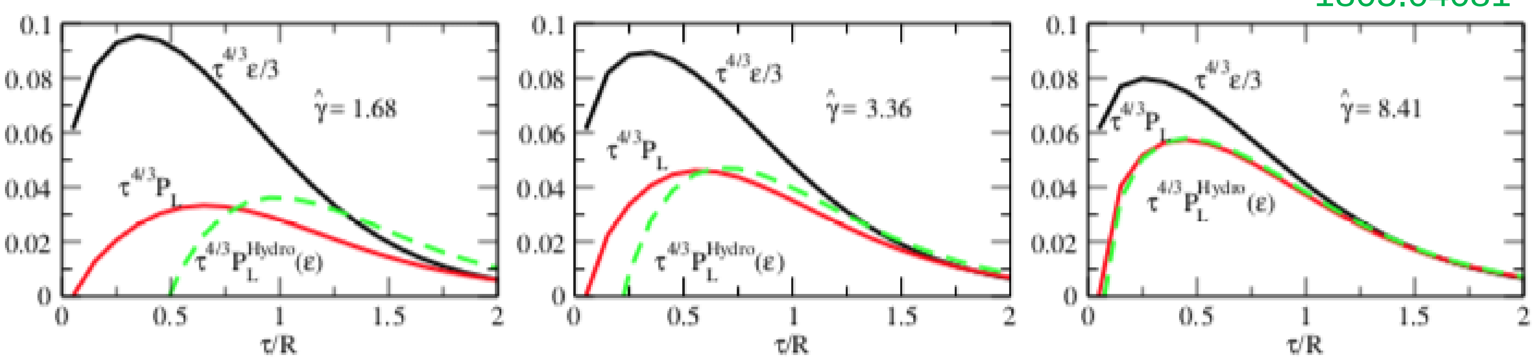
- kinetic theory based on Boltzmann transport — AMPT, BAMPS, LBT

$$\partial_t f + \vec{v}_\perp \cdot \partial_{\vec{x}_\perp} f + v_z \partial_z f = -C[f]$$

 - includes hydrodynamics as its long-wavelength limit
 - shares with hydro the same definition of QCD transport properties
 - extends dynamical description to non-hydro modes (such as particle-like excitations, free streaming effects …)

- Kinetic theory beyond its fluid dynamic limit is needed (at least) to understand early time dynamics in AA, (equilibration, hydrodynamization, anisotropic fluids…).

1805.04081



- The *definition* of QCD transport properties is the same in hydro and kinetic theory, but their *extraction from data* can depend on whether the dynamical framework includes non-hydro modes (kinetic theory vs. hydro).

$\Rightarrow$ precision in determining transport properties requires control over how close we are to the hydro limit (see goal 3).

Macroscopic QGP properties

The intro chapter of the yellow report mentions explicitly

1. Temperature
   (via thermal radiation and bottomonium dissociation)
2. QCD (phase) transition at muB~0
   (via fluctuation of conserved charges)
3. Viscosity and other QCD transport coefficients
   (with emphasis on system size dependence)
4. Heavy Quark transport coefficients
5. Searching for transport phenomena related to presence of strong electromagnetic fields
   (QCD+QED fluid dynamics = anomalous fluid dynamics)

Chapter convenors: please help to identify the subsection that relate to these points and deserved reference in the introduction!

Goal 2

Accessing the microscopic parton dynamics underlying QGP properties.

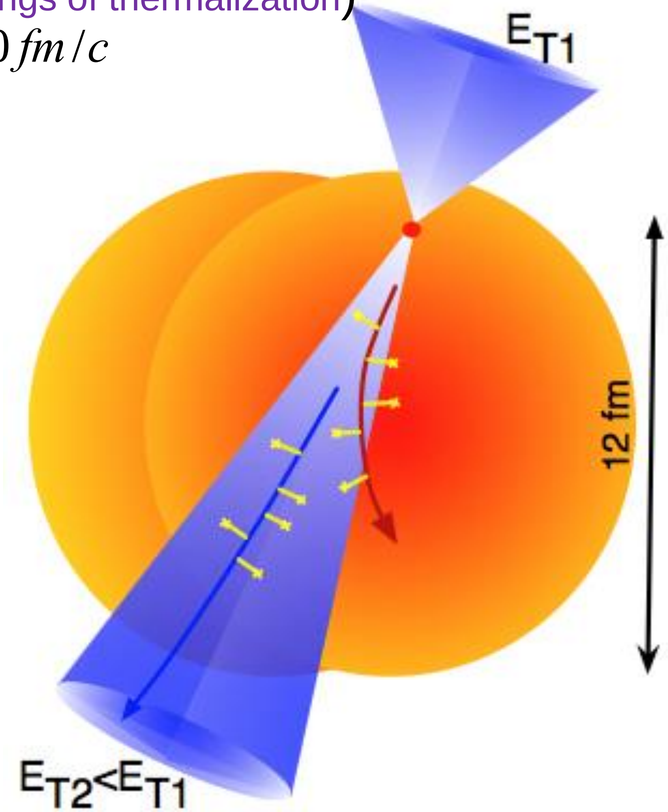
Underlying theory

1. Parton showers and their medium modifications
2. Kinetic theory

Jet quenching

What we know:

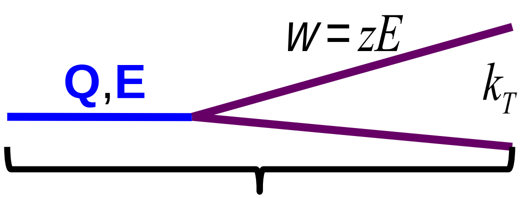
- Energy transported from hard to soft scale (inner workings of thermalization)
- Energy transported away from jet within $t_{transport} \approx 5 - 10\, fm/c$ (inner workings of isotropization)



What we expect and can test:

1. Space-time ordering of quenching

In vacuum, soft modes form **late**



$$t_f^{vac} \sim \frac{E}{Q^2} \approx \frac{\omega}{k_T^2} = \frac{1}{\theta^2 \omega}$$

In medium, expected to form **early**

$$t_f^{med} \approx \frac{\omega}{k_T^2} = \frac{\omega}{\hat{q}\, t_f^{med}} = \sqrt{\frac{\omega}{\hat{q}}}$$

(very basis of mechanism of perturbative bottom-up thermalization)

2. Jet-medium interactions

   (large angle scattering would reveal QGP constituents ..)

- Increased precision of "jet quenching measurements" warranted by increased complexity of the theoretical tools available: Q-PYTHIA/Q-HERWIG, HYDJET++/PYQUEN, MARTINI, JEWEL, hybrid model, LBT/coLBT, . . .

Accessing the inner workings of hot QCD matter

The intro chapter of the yellow report mentions explicitly

1. Constraining with jet quenching the colour field strength of the medium

   (qhat, novel HL-opportunities, boson-tagged jets, boosted tops)
2. Constraining with jet substructure the quasi-particle structure of QCD matter

   (the characterization of jet-medium interactions via recoil)
3. Bottomonium production tests color screening and serves as a thermometer

   (does this probe partake in other manifestations of collectivity?)
4. Charmonium production tests color screening and regeneration dynamics
5. Formation of hadrons and light nuclei from a dense partonic system

Chapter convenors: please help to identify the subsections that relate to these points and deserved reference in the introduction!

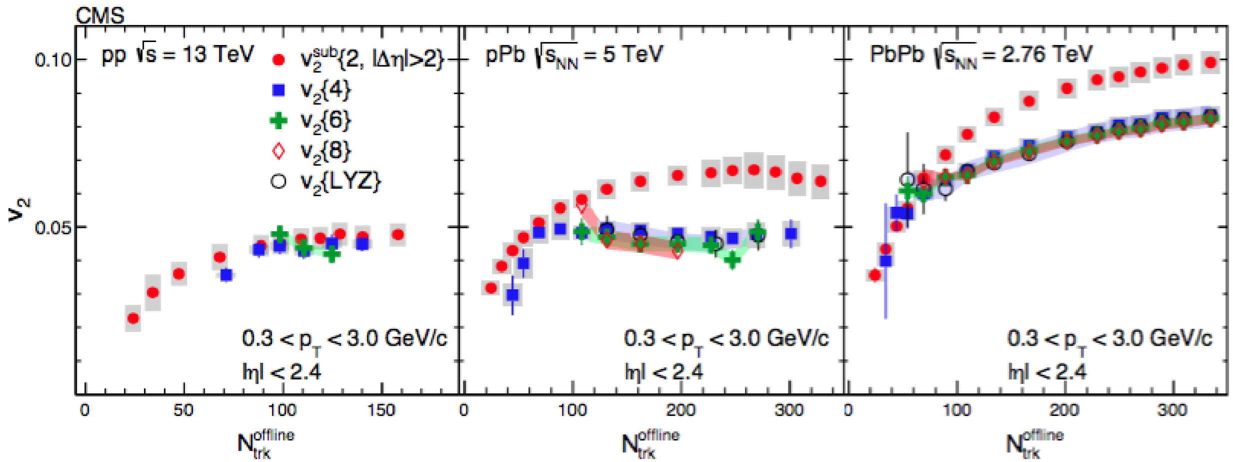
Goal 3
Developing a unified picture of particle production from small (pp) to larger (pA and AA) systems.

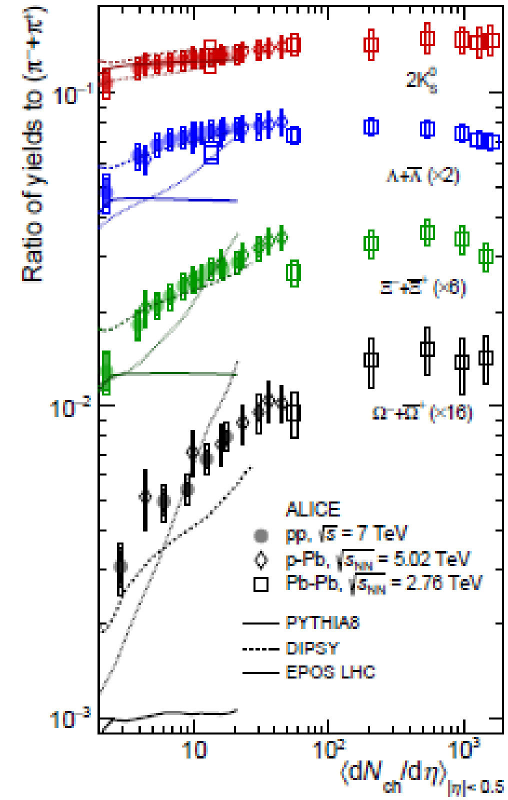
Underlying theory

1. Fluid dynamic
2. Kinetic theory

What a unified picture should explain

- In soft observables, heavy-ion like behavior seen even in the smallest systems (pp).

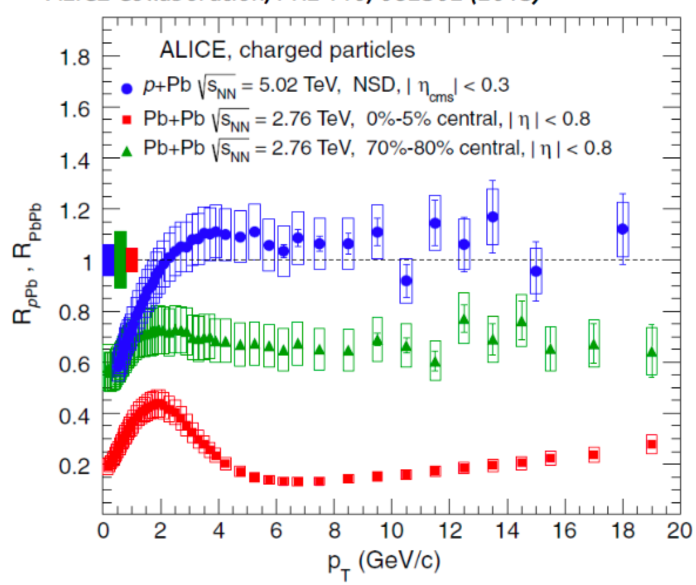




- In the hard sector, no final state interactions (FSI) visible in smaller systems (pp & pPb)

FSI at basis of both:
- hydro interpretation of v_n
- jet quenching

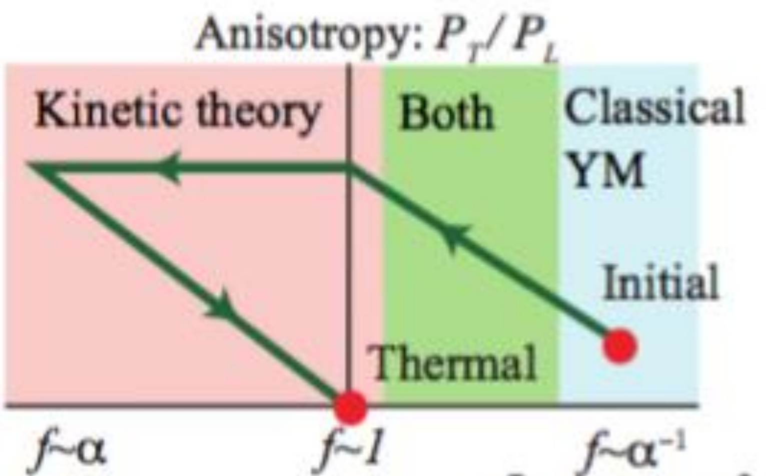
ALICE Collaboration, PRL 110, 082302 (2013)



Concepts for a unified description of soft/hard and small/large exist, e.g.

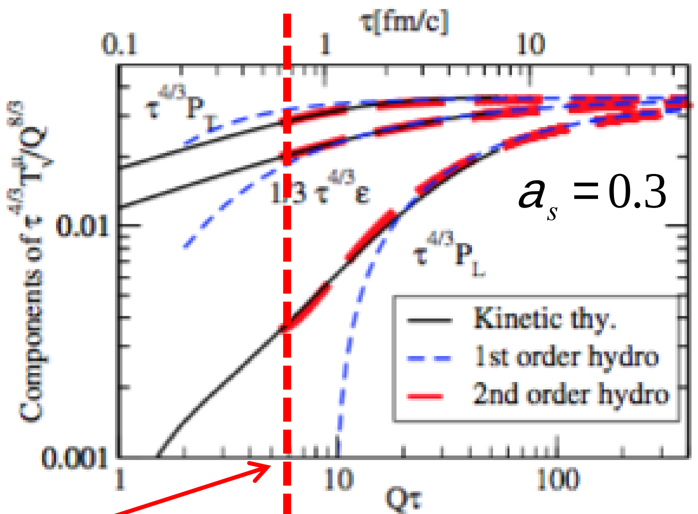
- Bottom-up thermalization formalizes relation between fluid dynamics and jet quenching

R.Baier, A.H. Mueller, D. Schiff, D.T. Son, 2001



Kurkela, arXiv:1601.03283

Kurkela&Zhu, PRL115 (2015)182301



Partonic distributions f(p) governed by **Boltzmann equation.**
We know:

- f(p) hydrodynamizes on sub-fermi time scale
- "Hydro" & "jet quenching" arise from the same collision kernels

$$\partial_t f(p,t) = -C_{2\leftrightarrow 2}[f] - C_{1\leftrightarrow 2}[f]$$

Berges, Eppelbaum, Kurkela, Moore, Schlichting, Venugopalan, …

2->2 collision kernel

LPM splitting kernel

Developing a unified picture of QCD collectivity

The intro chapter of the yellow report mentions explicitly

1. Flow measurements in pp and pA: onset of higher order correlations
   (via thermal radiation and bottomonium dissociation)
2. Flow of heavy flavor and quarkonium in smaller systems
3. Strangeness production as a function of system size
4. Searching for the onset/existence of energy loss effects in small systems
5. Searching for the onset/existence of thermal radiation in small systems

Chapter convenors: please help to identify the subsections that relate to these points and deserved reference in the introduction!

Goal 4
Probing parton densities in nuclei in a broad (x,Q^2) kinematic range and searching for the possible onset of parton saturation.

Underlying theory

1. pQCD with nuclear effects, global npdf-fits
2. pQCD in a dense (saturated) partonic system

Nuclear pdfs and search for non-linear QCD

The intro chapter of the yellow report mentions explicitly

1. Precise determination of nuclear pdfs at high Q2
   (argument for pPb and Ar-Ar,
   constraining A-dependence of npdfs)

2. Constraining nuclear pdfs at low Q2
   (mentioning quarkonia and di-jet production in UPC)

3. Access to non-linear QCD evolution at small-x
   (mentioning extended reach due to HE-LHC)

Chapter convenors: please help to identify the subsections that relate to these points and deserved reference in the introduction!

END