Strongly coupled matter in heavy-ion collisions:

opportunities & challenges

Vinod ChandrA
Indian Institute of Technology

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Outline

- Introduction to strong interaction and hot nuclear matter (Quark-Gluon-Plasma: QGP)
- What have we learnt from experiments (ultra-relativistic heavy-ion collisions) ?
- Electro-Magnetic Plasmas (EMP) and QGP
- Open Questions and Challenges
- Ultra-intense lasers and fundamental HEP!

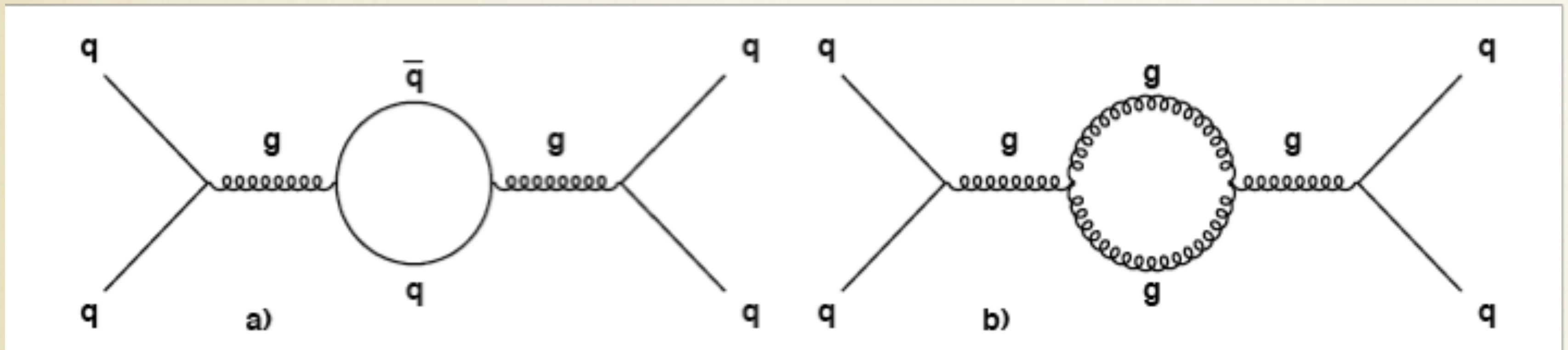
Nature at Sub nuclear scales

- Quarks/anti-quarks and gluons are the effective degrees of freedom and the nature at sub-nuclear scales is described by them and interactions among them (the strong interaction force)
- Like the photon which is the force carrier particle for the EM interaction (for that matter graviton is for the Gravitational interaction, W and Z bosons for the weak interaction) , gluon is the force carrier particle for the strong interaction force
- The underlying theoretical framework (the respective Quantum theory) of the strong interaction is the Quantum Chromodynamics (QCD)
- Unlike photons, gluons are self-interacting (non-linear interaction), this makes the strong interaction one of most complex system to understand

QCD & Strong interaction

- QCD/strong interaction has two most striking aspects
- The Asymptotic freedom : Quarks and gluons are free at shorter length scales/larger energy (momentum transfers). This leads to the Noble prize in Physics in 2004 to Gross, Politzer and Wilzeck
- The confinement: At larger length scales Quarks and anti-quarks are confined inside the hadrons. They always come in certain colorless combinations (hadrons).
- There are effectively free quarks and gluons at one extreme and hadrons at other extreme
- Therefore, their must be a way to go back and forth between these two extremes

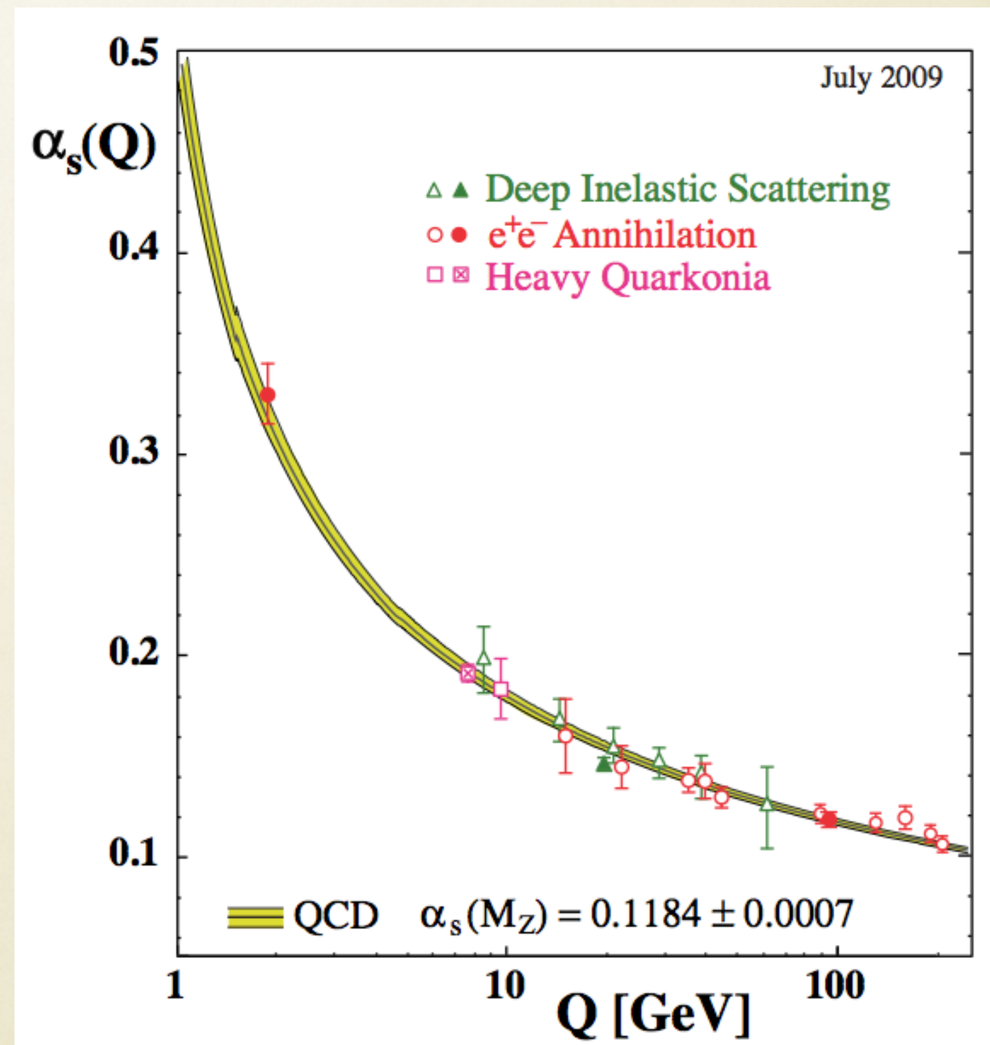
Asymptotic Freedom



$$\alpha(|q^2|) = \frac{12\pi}{(11n - 2f)\ln\left(|q^2|/\Lambda^2\right)}.$$

Noble Prize in Physics, 2004

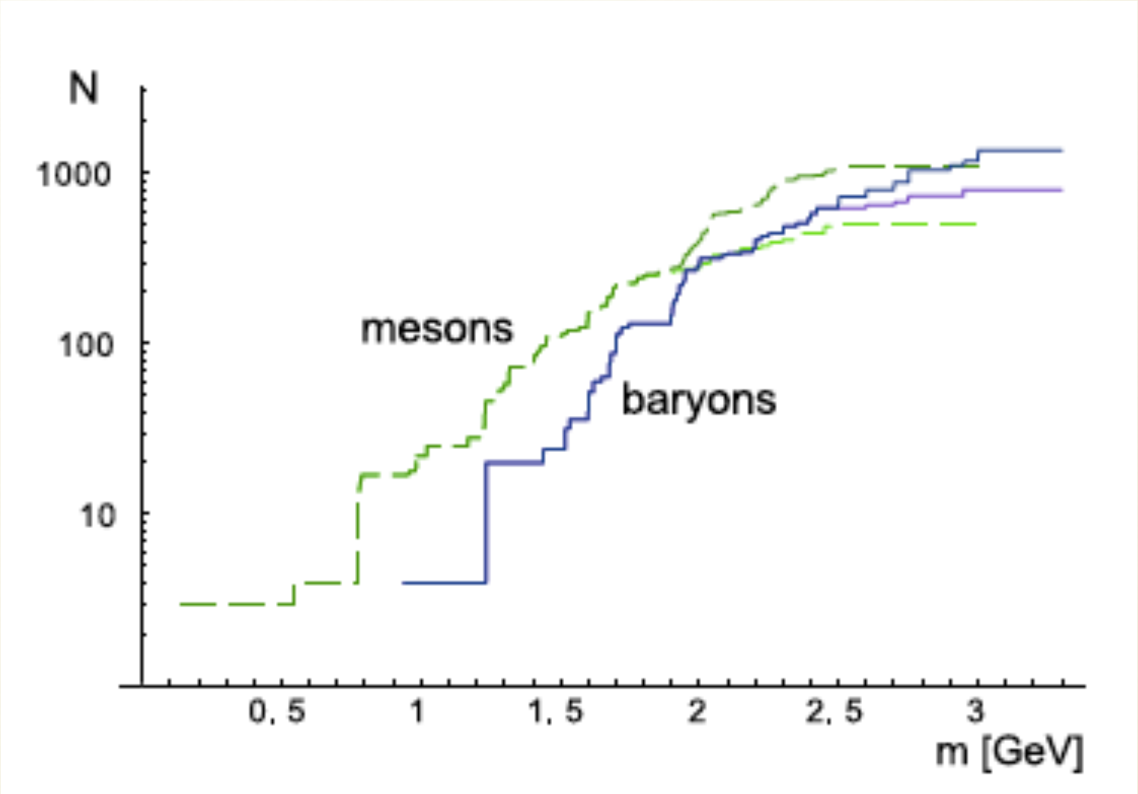
David J. Gross | H. David Politzer | Frank Wilczek



Limiting temperature for the hadrons!

$$\rho(m) = \frac{A}{m^2 + [500\text{MeV}^2]} \exp{(m/T_H)}$$

The Hagedorn temperature~170 MeV which turned out to be limiting temperature for the hadronic matter



W. Broniowski et al., Phys. Rev. D 70, 117503 (2004)

R. Hagedorn, nuovo Cim. Suppl. 3, 147 (1965).

Asymptotically free nuclear matter in experiments

Superdense Matter: Neutrons or Asymptotically Free Quarks?

J. C. Collins and M. J. Perry

Phys. Rev. Lett. **34**, 1353 – Published 26 May 1975

Exponential hadronic spectrum and quark liberation

react-empty: 71 react-empty: 72 react-empty: 73 react-empty: 74

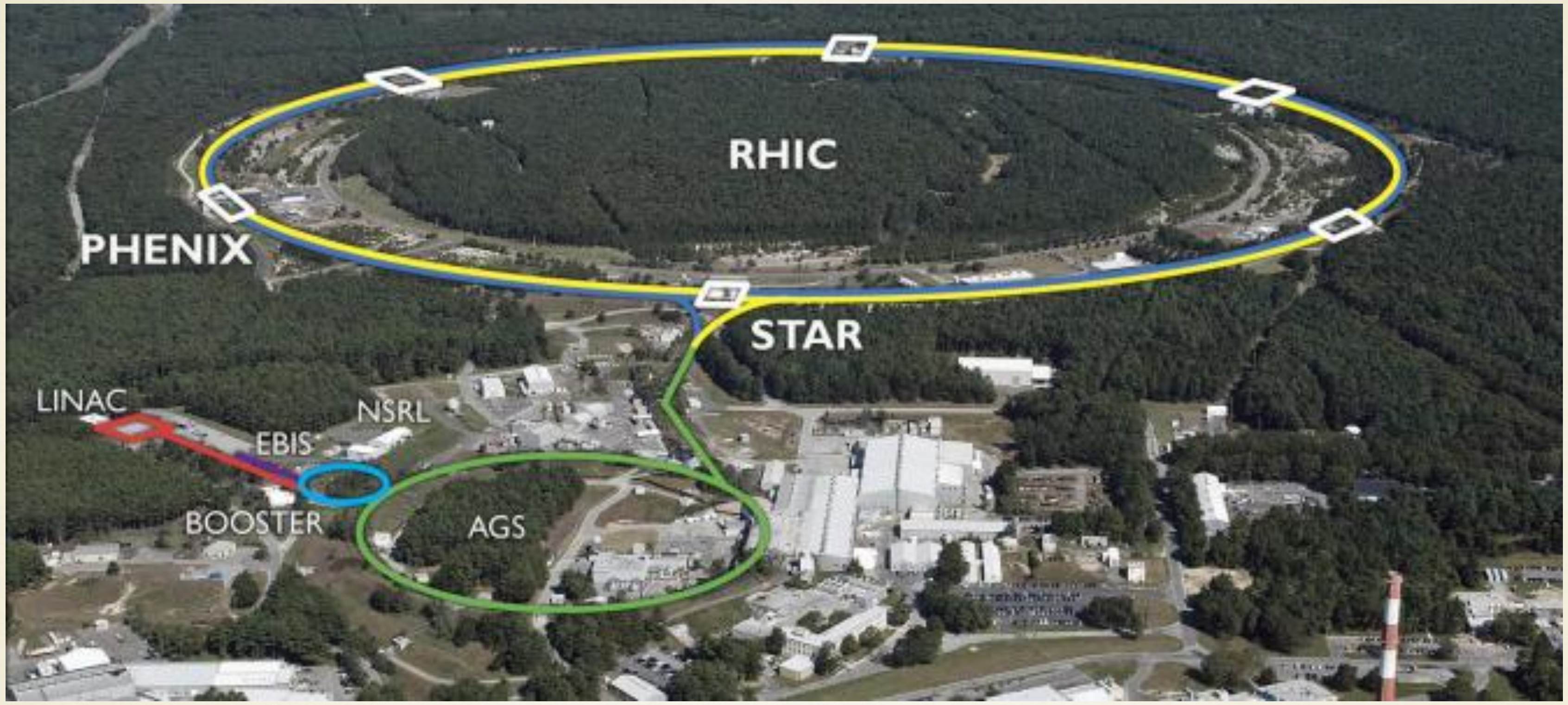
N. Cabibbo
Istituto di Fisica, Universitá di Roma, Istituto Nazionale di Fisica Nucleare, Sezione di Rome, Italy
G. Parisi
Istituto Nazionale di Fisica Nucleare, Frascati, Italy

Phys. Lett. B 59, 67 (1975).

These were two papers that provided motivation for designing heavy-ion collider experiments at BNL and later at CERN !

Hot nuclear matter

- As hadrons can not exist beyond the Hagedorn temperature, therefore there must be new state made of the quarks and gluons beyond that
- This state of the matter is commonly termed as quark-gluon plasma (QGP)
- To create the QGP in experiment we need to “squeeze” as well “heat” the normal nuclear matter
- This is achieved by colliding two heavy-nuclei such as Au-Au or Pb-Pb ultra-relativistically
- Here comes the role of world wide heavy-ion collider experiments!



RHIC, BNL

LHC, Heavy-ion Program, CERN

The quark-gluon plasma

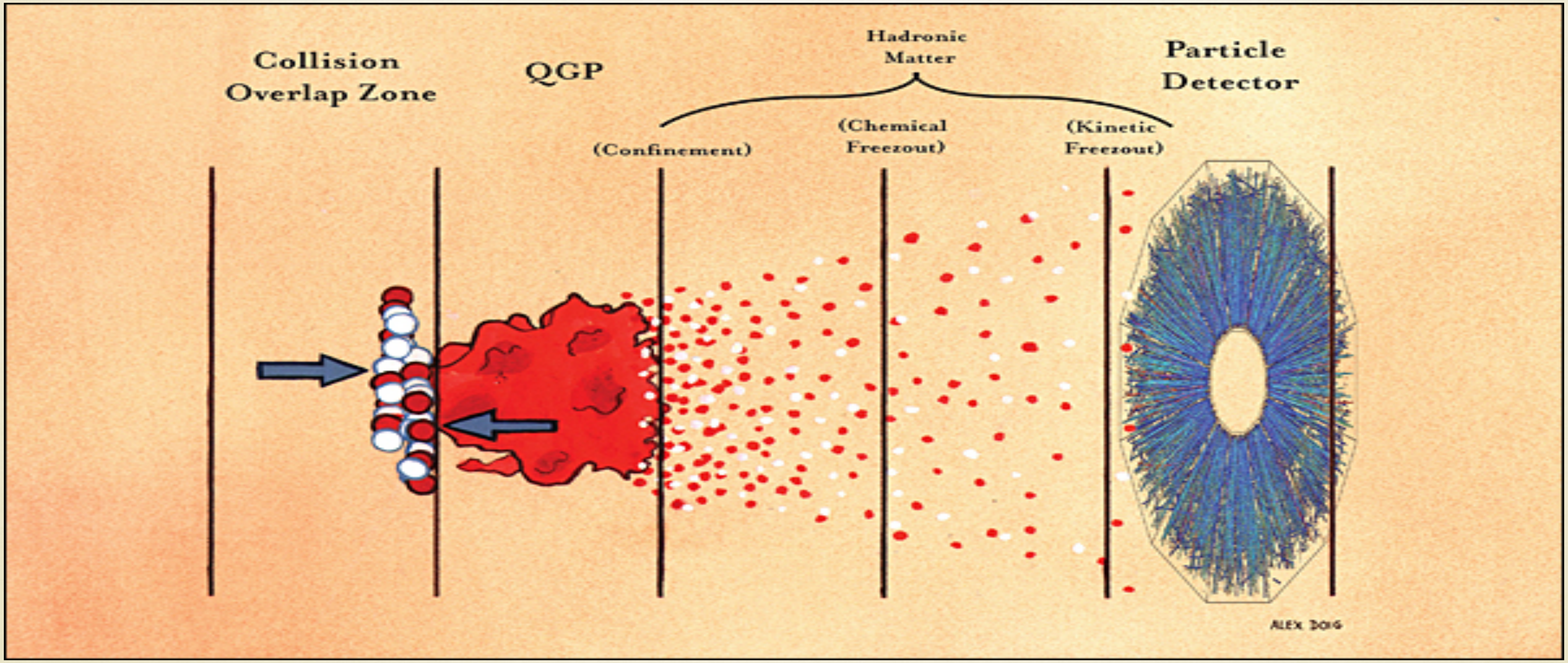
- By colliding "nuclear pancakes" of **Au-Au** or **Pb-Pb** (Lorentz contracted by~**100** at **RHIC** and now by 1400 at **LHC**) are able to create little droplets of the Big-Bang matter : the stuff that was there all around for the first few microseconds after the Big Bang.

- With the help of five detectors (PHENIX & STAR @ RHIC; ALICE, ATLAS & CMS at LHC), answers are looked about the questions on the micro-second old universe that can not be reached by any conceivable astronomical observations

- The properties of this matter turned out to be interesting—THE LIQUID QGP!

- The liquid QGP shares common features with the forms of matter that arises in condensed matter physics, black hole physics and that pose challenges that are central to each of these fields.

Space-time evolution of hot QCD matter in HIC!



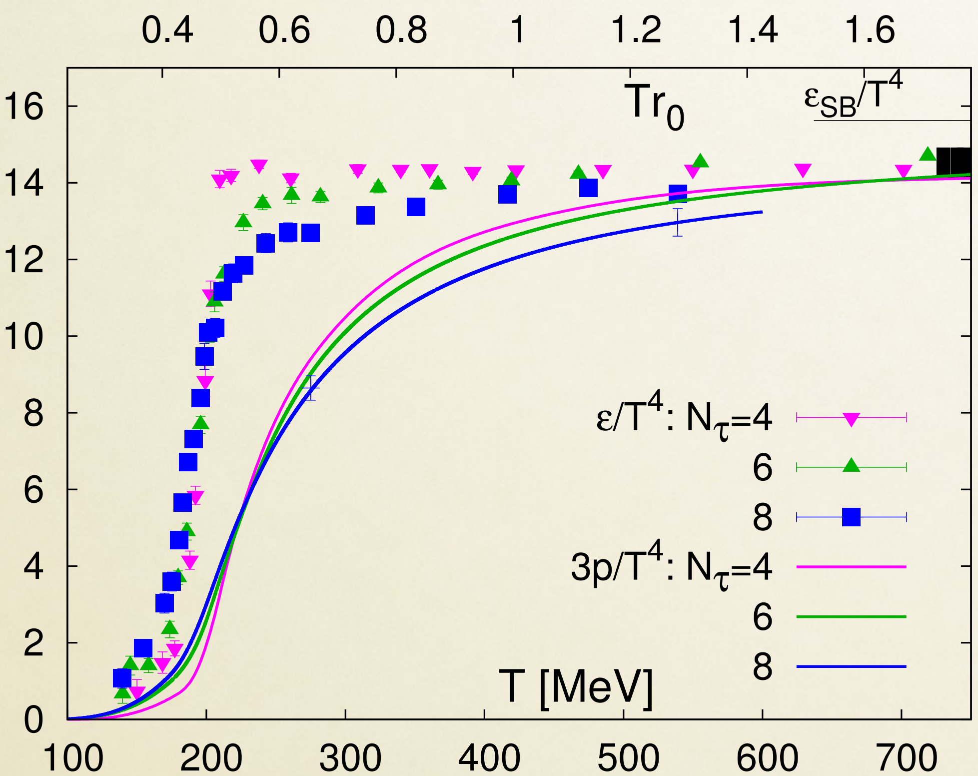
RHIC: Au-Au at 200 GeV/N

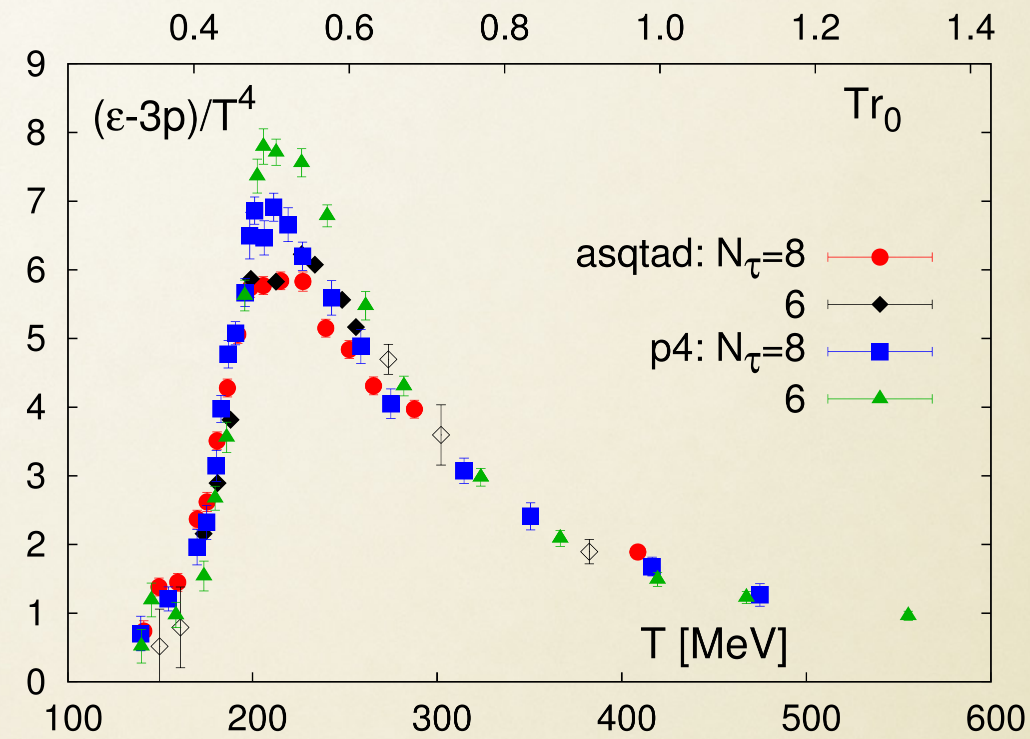
LHC: Pb-Pb at 2.76-5.5 TeV/N

T~200-400 Mev~10^{12} K

Figure: www.bnl.gov

QGP/hot QCD thermodynamics





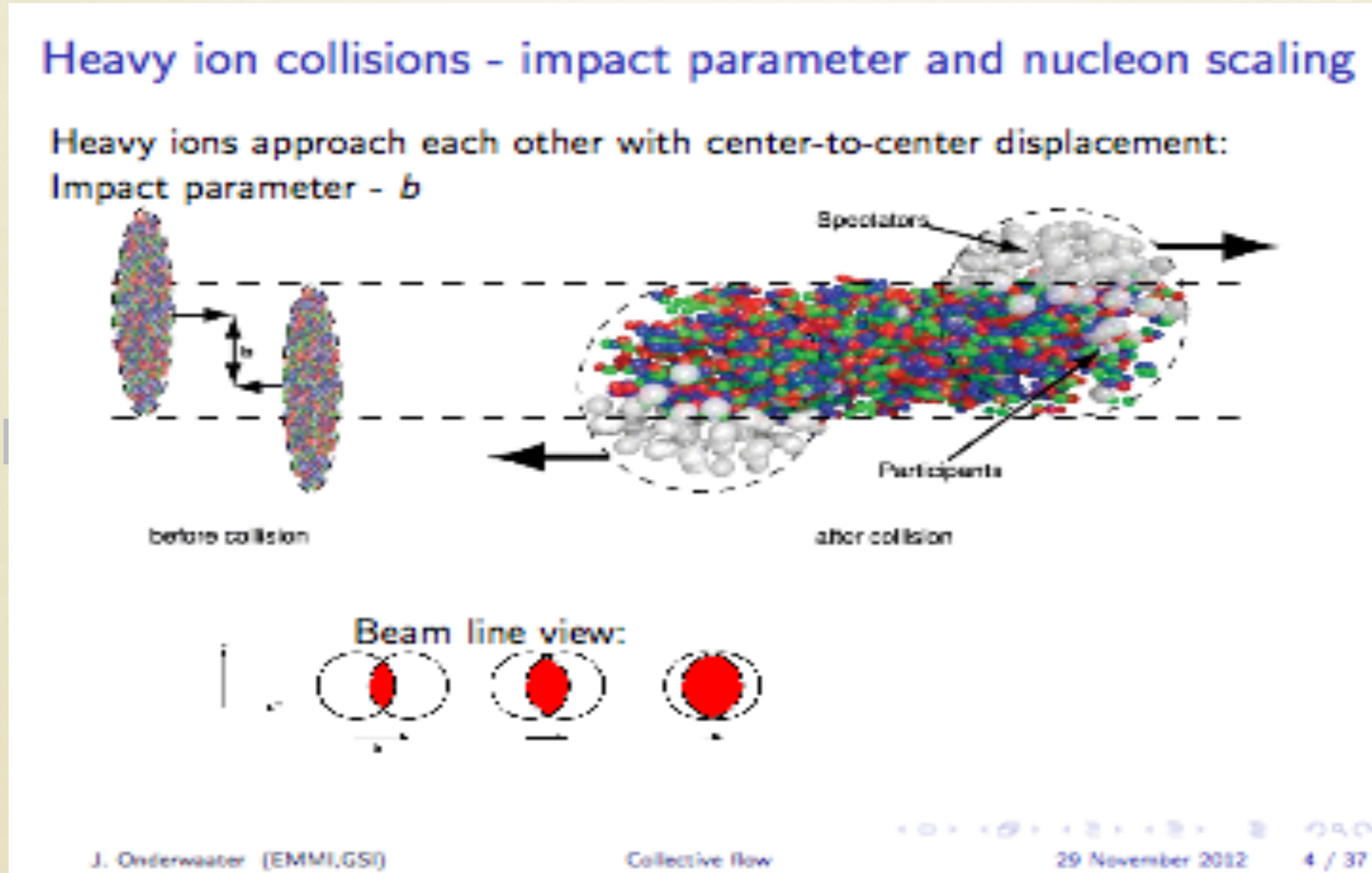
SB limit could could perhaps be achieved only asymptotically!

Bazabov et al, PRD 2009

Probing QGP in experiments

- There have been several signatures proposed for the detection of the QGP among them the most reliable ones based on the experimental observations are below
- (a) Collective behaviour and liquidity
- (b) Jet quenching and energy loss
- (c) Quarkonia suppression/dissociation, heavy-quark dynamics

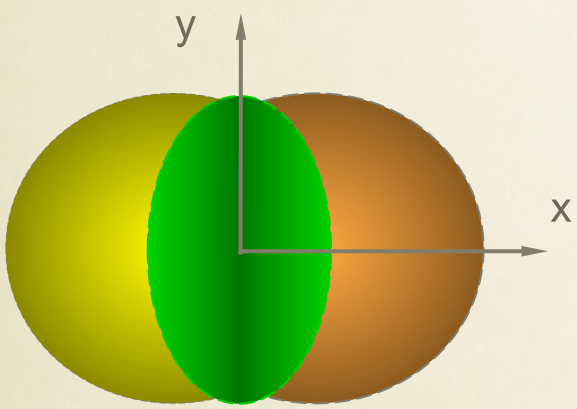
Collective behaviour



Collective flow

$$\varepsilon \equiv \frac{\langle y'^2 \rangle - \langle x'^2 \rangle}{\langle y'^2 \rangle + \langle x'^2 \rangle}$$

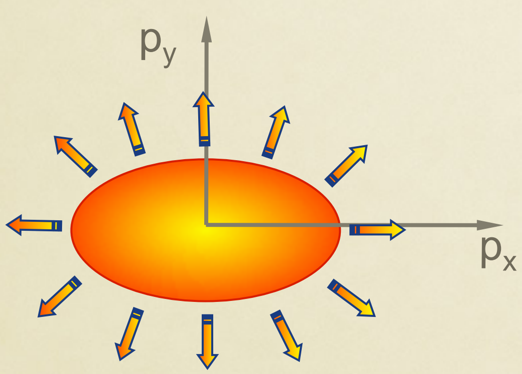
coordinate space

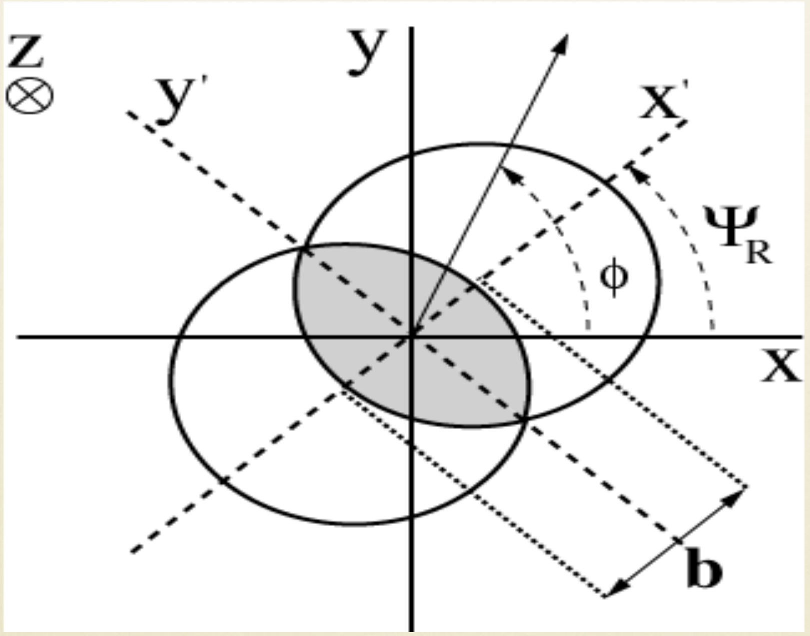


$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos\left(n\left(\phi - \Psi_r\right)\right)\right)$$

$$v_2 = \langle \cos 2(\phi - \Psi_r) \rangle, \quad \phi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

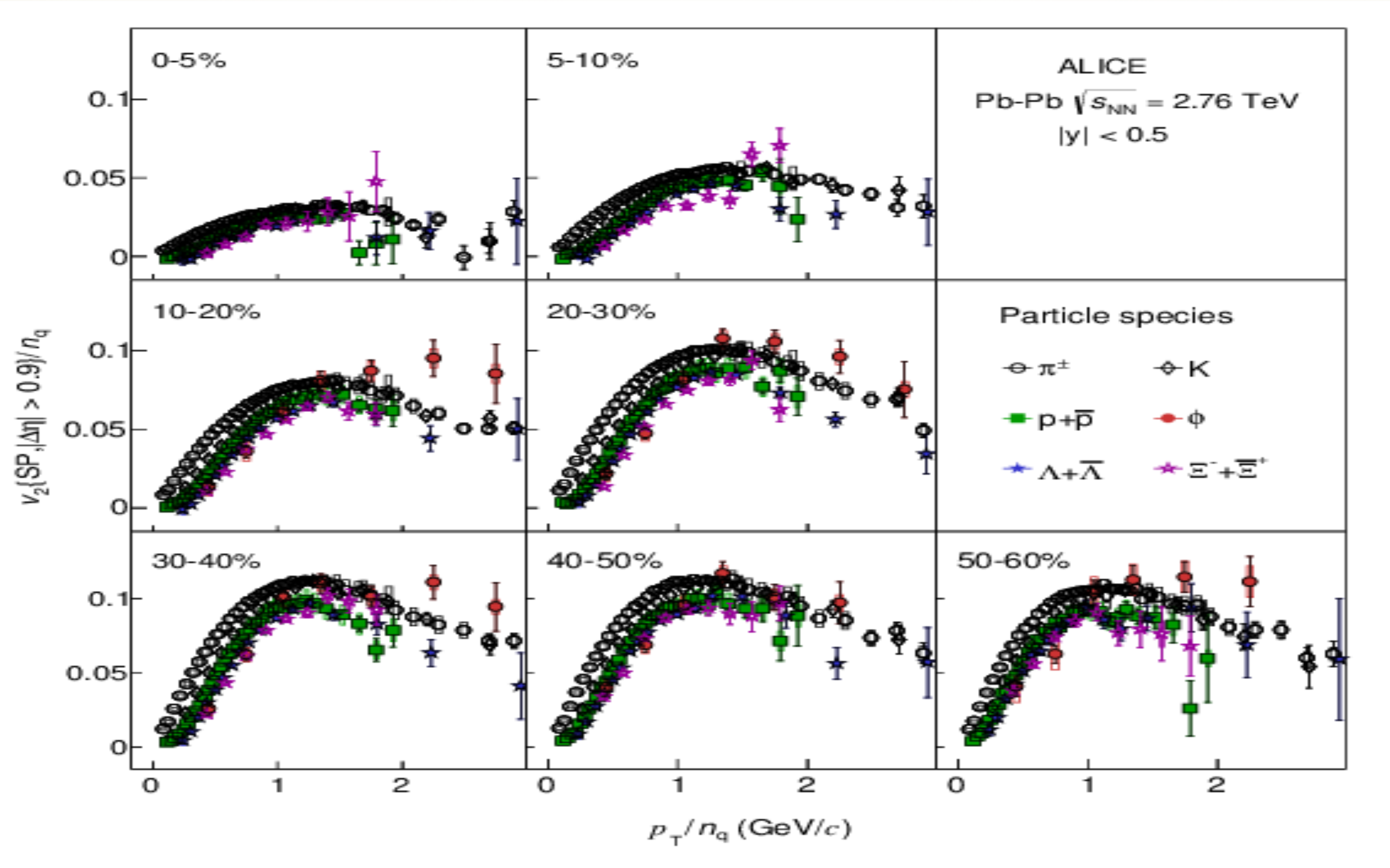
Momentum space





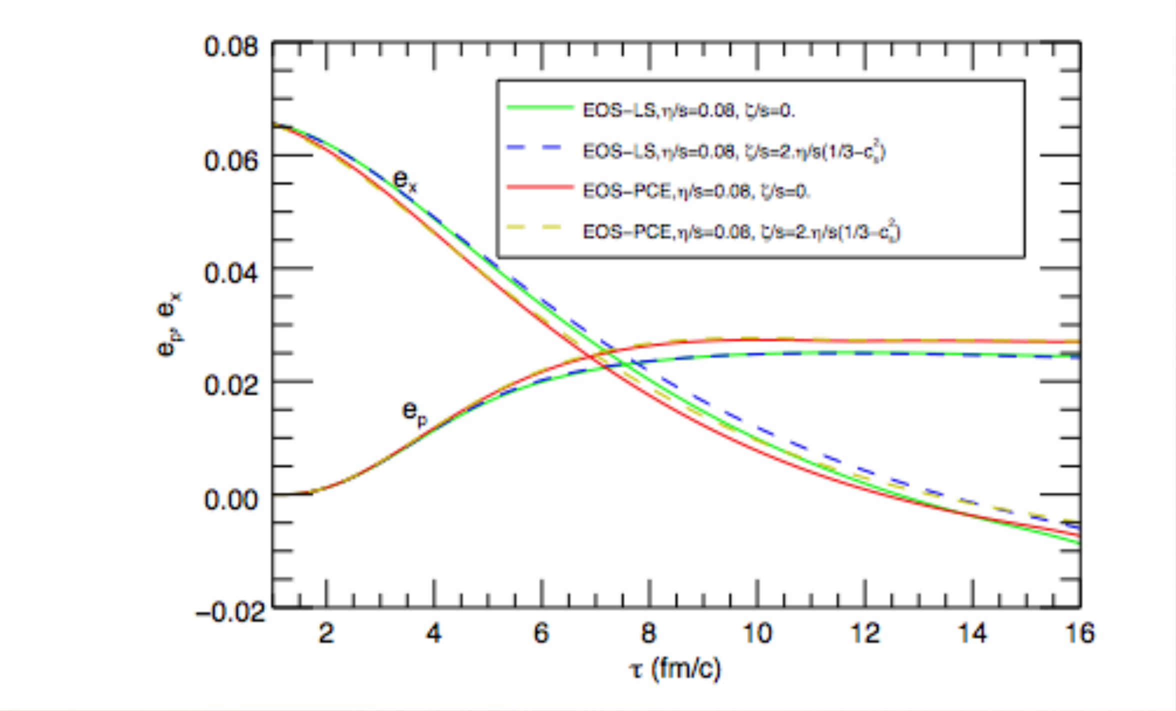
V_2: Elliptic flow

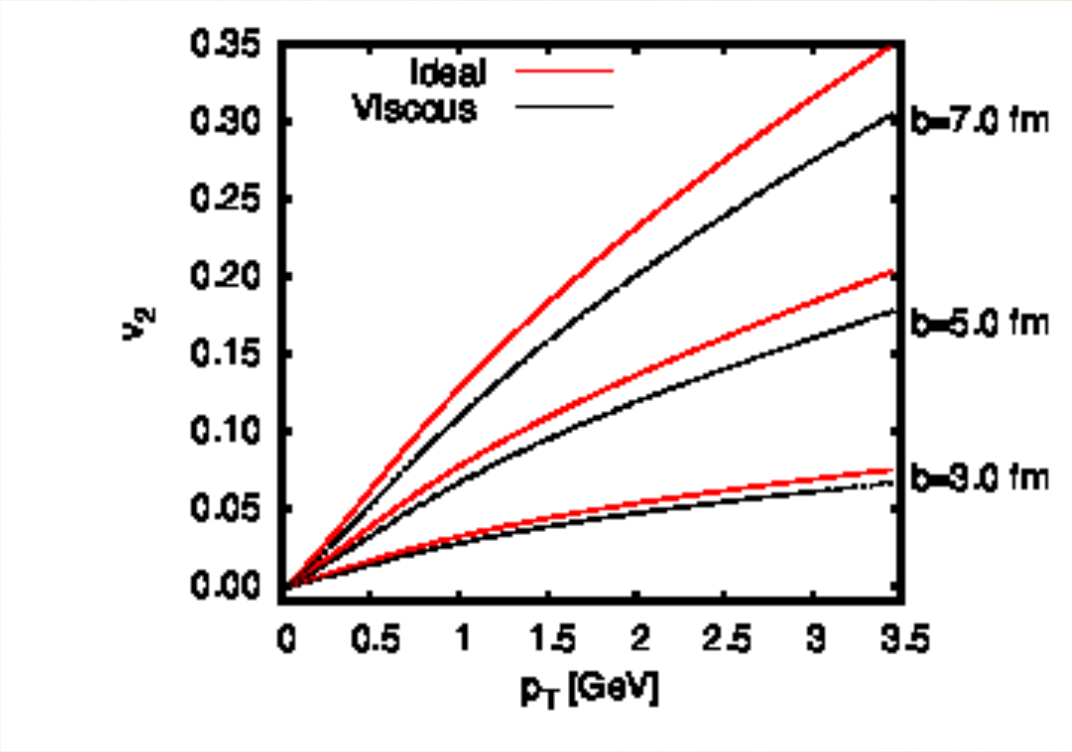
Collective flow!



ALICE collab. **JHEP 06 (2015) 190**.

Collective flow from disspative Hydro





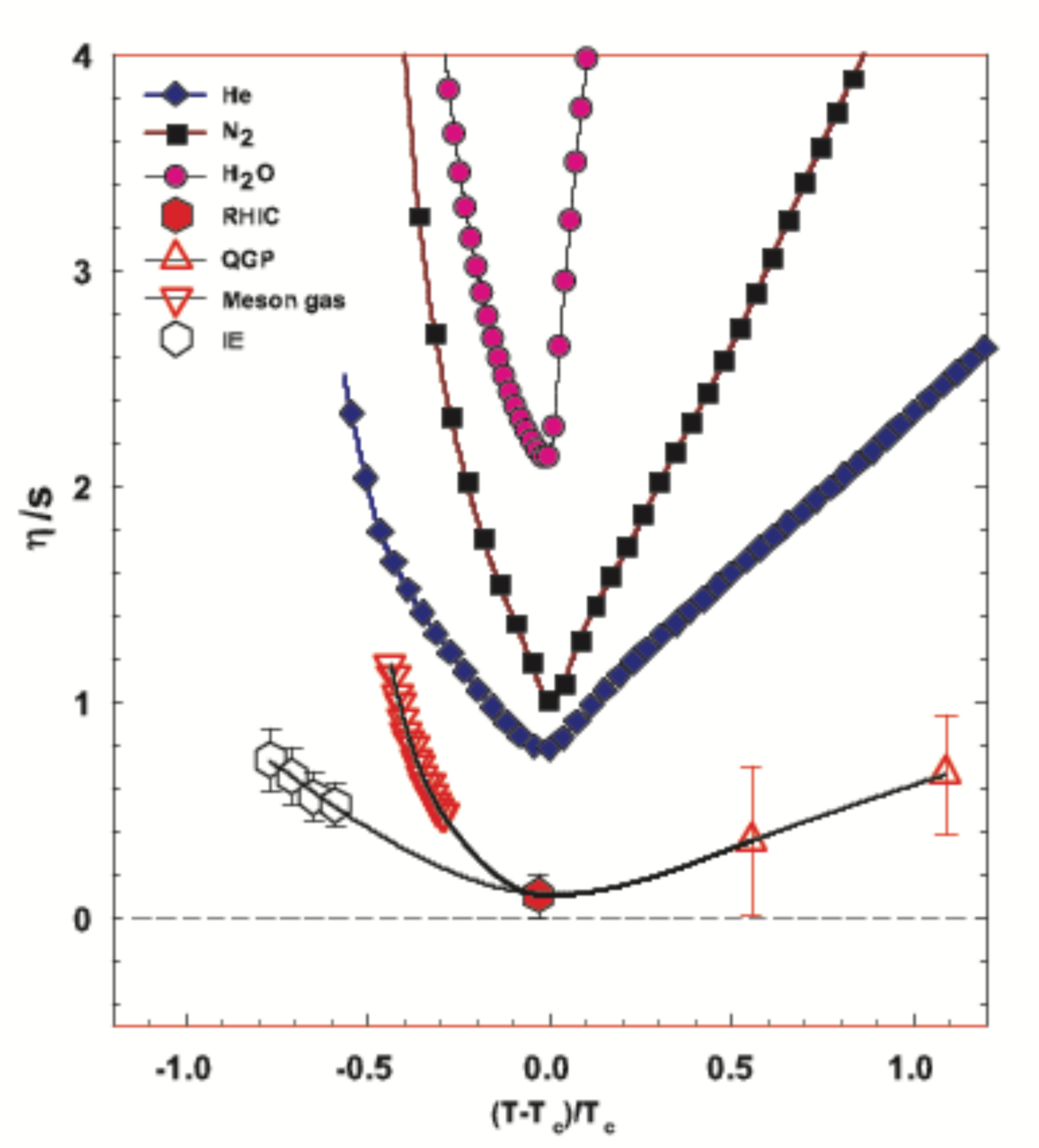
3+1 hydro simulations with ECHO QGP

L. Del Zanna, VC et al, EPJC 2015

Shear Viscosity of the QGP!

- To explain the collective flow (elliptic and higher harmonics), one needs to switch on the small shear viscosity to entropy ratio (~0.08-0.3) in the relativistic dissipative hydrodynamical simulations of the QGP
- This ratio for the QGP turned out to be smallest among almost all the known fluids in the nature!
- Although an exact quantitative estimation has to be done from the data itself by looking at all order harmonics not only the elliptic flow!
- The ongoing investigation on the determination of transport coefficients from the RHIC and LHC heavy-ion data will clarify the situation in the near future!

Comparing various liquids!



A universal bound of the specific viscosity for the strongly coupled fluids has earlier been proposed by,

Kovtun, Starinets, Son, PRL 2005

The hot QCD matter possess the smallest value!

[Except one fluid : The ultra cold fermionic atom fluid that possess comparably small value, Cao et al., Science (2010).]

Lacey *et al.*, **PRL 98, 092301 (2007).**

Understanding small η/s!

- The shear and bulk viscosities: The former accounts for the entropy production during the anisotropic expansion of the fluid at constant volume; the latter one related to the entropy production during volume expansion at constant rate
- String theory(AdS-CFT, N = 4, Super Yang-Mills): Lower bound on the η/s (~1/4π: KSS bound), Kovtun, Son, Starinets, *et al*, PRL94, 111601 (2005)
- We attempted to understand it by looking at the momentum anisotropy in expanding QGP: VC, Ravishankar, EPJC, 59 (2009), EPJC 64 (2009), PRD 84 (2011); VC, PRD 84 (2011); PRD (2012).
- Of course, there have been parallel studies based on other approaches (including lattice, unitary fermion gas). All of the studies came out to be consistent with the small shear viscosity to entropy ratio for the QGP

How hydro works

- The hot blob of matter in HIC achieves quick local thermal equilibrium (< 1 fm/c).
- Hydrodynamics is just a set of fluid conservation equations
- Initial conditions (energy/entropy distribution, EOS, transport parameters)
- These inputs needed the determination from microscopic theories
- Space time evolution through dissipative hydrodynamics
- Freeze-out and hadronic observables (hydro should smoothly connect with the kinetic theory of hadrons)

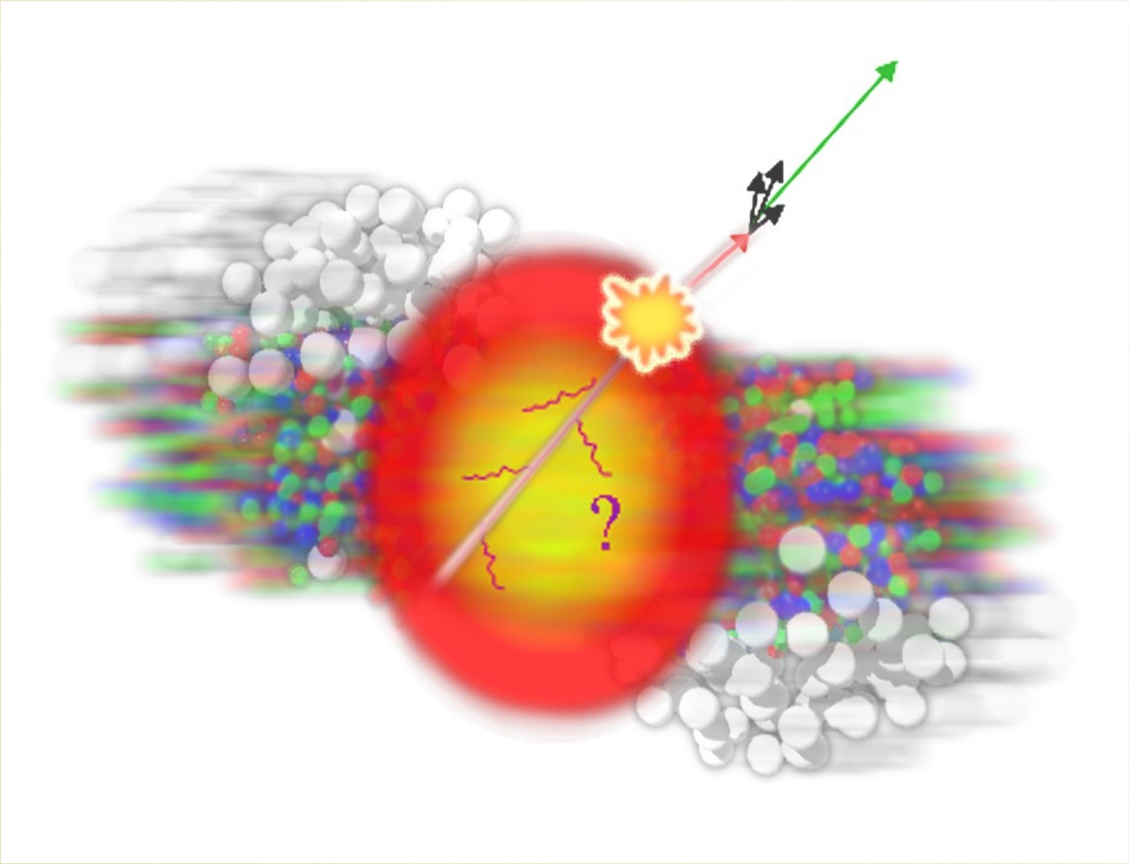
Hydro continued!

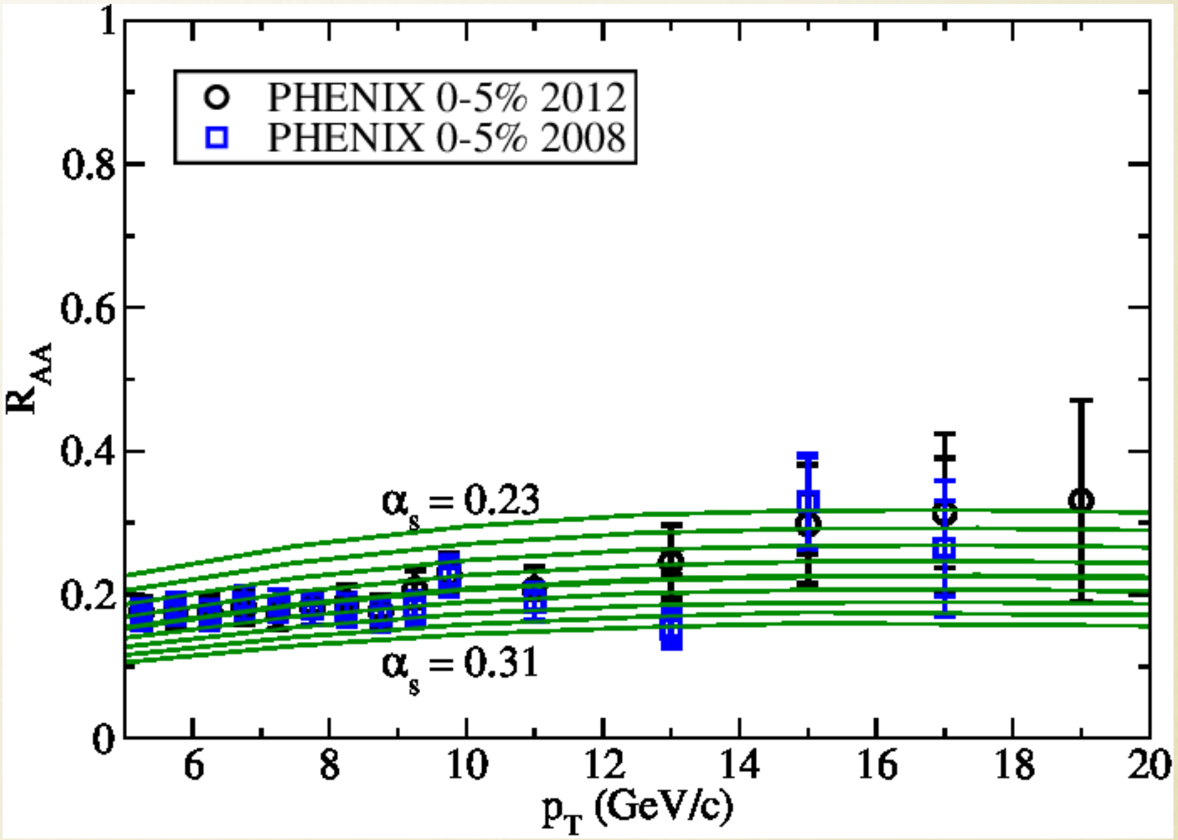
- At a later time when the system achieves complete isotropization the hydro will stop (the mean free path are now comparable to the size of the system)— Freeze-out
- At the freeze-out point the fluid cells undergo particlezation and the various hadrons come out to the detectors (depending on available energy)
- At the freeze out: hydro must connect smoothly to the statical hadronization models of the QCD to tackle the physics of hadronic systems
- This can be achieved in kinetic theory by relating the energy-momentum tensor from two sides
- In this way, the hydro evolution information along with physics of dissipation enters in hadronic observables at detectors

Hydro and Experimental observations!

- One can now compute the particle spectra and yields with the help of hadronization models (say Cooper-Frye) and and compute various flow coefficients
- Compare them against the direct observations (distribution of particles) with hadrons in the detectors
- If they agree within high order of accuracy: we claim that hydro works well
- That is indeed turns out to be true
- **Its quite remarkable that nature decides to work with quark-antiquarks and gluons like this!**

Jet Quenching



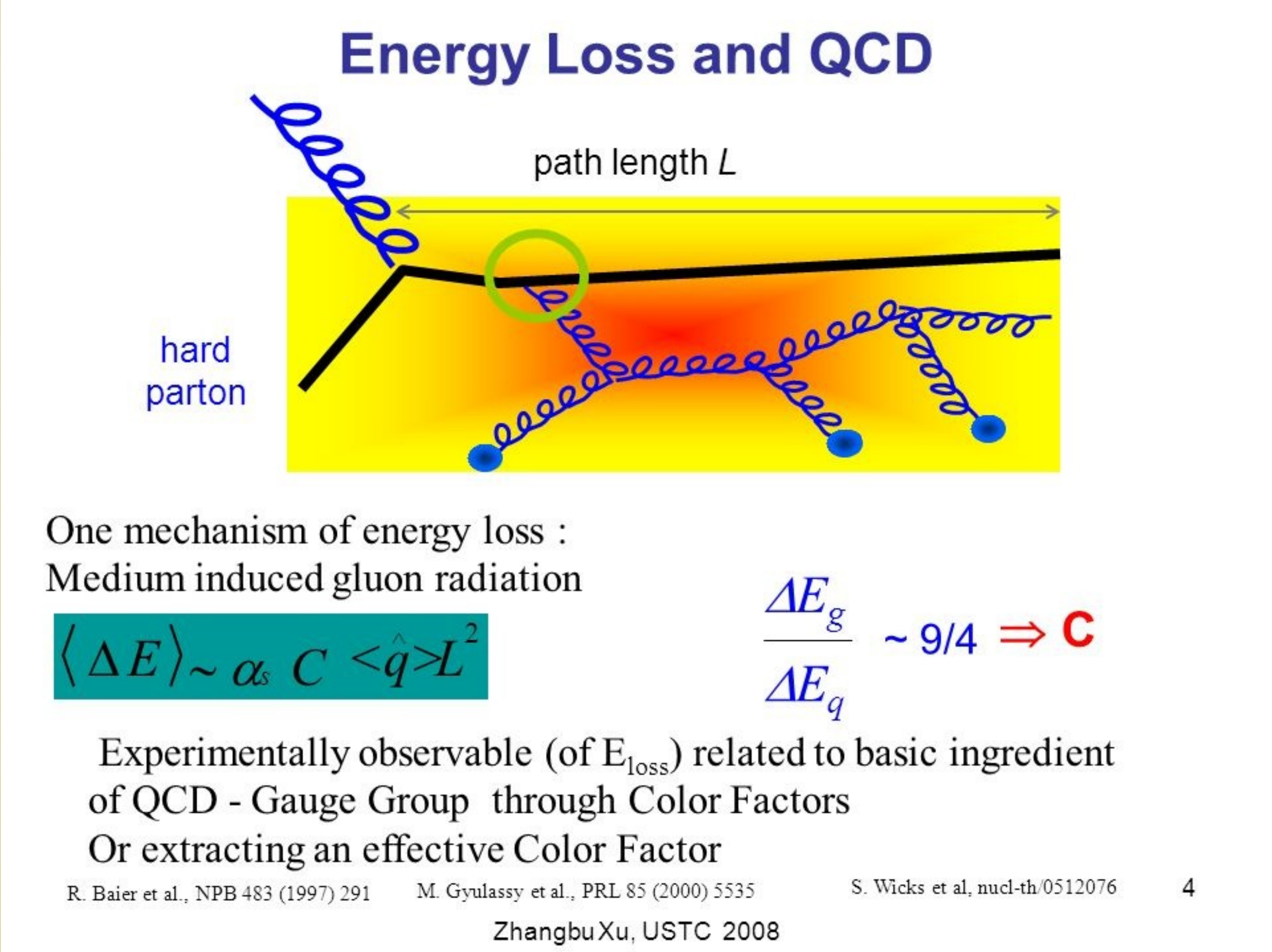


R_{AA} for neutral pion spectra at

Au-Au collisions at 200GeV/n

Burke, K. M et al. **PRC 90, 014909 (2014).**

Jet Quenching and Energy LOSS!



- The less dominant mechanism is the collisional loss. However, in the case of heavy-quark dynamics this one is also significant
- The interplay of gluonic radiation and collision loss will be a matter of immediate future investigation

RHIC vs LHC heavy ion collisions

- Temperature: RHIC, Au-Au, 200 GeV/n: T = 221 ± 19 ± 19 MeV, PHENIX, PRL 104, 132301 (2010). LHC, Pb-Pb, 2.76 TeV: T = 304 ± 51 MeV, AlICE (2013).
- Multiplicity density: Twice as large as that for central Au-Au at RHIC.
- Energy Density: three times that at RHIC (16 Gev/fm^{2}c), ALICE, PRL 106 , 032301 (2011).
- Freeze-out volume: 300 fm^3 ~ 2× at RHIC
- Life time of QGP: 10 fm/c ~ 40% larger than RHIC, ALICE, PLB 696, 328 (2011).

RHIC vs LHC!

- Collective flow: 30% increase in elliptic flow (v_2) as compared to RHIC ALICE, PRL 105, 252302 (2010).
- P_T -dependence holds as good as RHIC, suggest similar value for the η/S (0.08-0.24)
- Quark number scaling (v_2/n_q vs P_T/n_q) does not work that well at LHC (Pb-Pb at 2.76 TeV/n).
- Energy loss/jet quenching: Strong suppression at LHC $R_{AA} \sim 0.1$ at 7 GeV/c (half as at RHIC) and a rise at higher p_T ($R_{AA} \sim 0.5$)

Open Questions and theoretical challenges

- How to reach to fluid picture from quasi-particles?
- Since, at some short length scale, a quasi-particle picture of the hot QCD matter must be valid, even though on its natural length scales , it is a strongly coupled fluid
- How cab we clarify the understanding of fluids without quasi-particles, whose nature is central mystery in so many areas of science!
- Seeking the QCD critical point: there are a few promising attempt
- Chiral anomaly and chiral magnetic field and its impact
- Temperature dependence of shear and bulk viscosities from data
- Uncertainties in initial conditions and computations of transport coefficients from first principle

Learning from EM plasmas!

- The QGP reveals some obvious similarities to the well-known electromagnetic plasma, QCD describing the interactions of the quarks and gluons resembles, QED which governs interactions of charged objects.
- Thus, some lessons from EMP should be useful in the exploration of QGP. However, we have to be aware not only of similarities but of important differences between EMP and QGP
- QGP is usually relativistic or even ultrarelativistic while EMP is mostly nonrelativistic in laboratory experiments.

Learning from EM plasmas!

- Ions influence the EMP dynamics unlike Heavy-quarks in the QGP

- Unlike photons in QED, gluons not only mediate interactions among quarks and antiquarks but are self-interacting (Abelian theory for EMP and Non-abelian nature of interactions for the QGP)

- The most important common feature of EMP and QGP is the collective character of the dynamics.

EMP and QGP

- In the weakly coupled regime, the QGP plasma has similarities with the QED plasma. The Debye mass in QGP goes like g(T)T, where g(T) is QCD coupling constant
- In various laboratory experiments, EMP is embedded in an external electro- magnetic field.
- For e.g., the magnetic field is generally used to trap the plasma, and there are many interesting phenomena occurring in such a situation.
- In the case of QGP produced in relativistic heavy-ion collisions, it is hard to imagine any external chromodynamic field applied to the plasma.

EMP and QGP

- In these situation the collective mode study of the EMP helps in understanding the collective plasma modes of QGP
- This also motivate one the realise QGP as a dielectric medium and one can think of refractive index for the QGP
- The damping and growth (instabilities) of the EM fields in EMP plasma help in understanding the similar situation in QGP

Particle production!

- In has been long realised that quantum vacuum is unstable under the influence of external EM fields, Euler, Hesiserberg, Sauter, Kockel , Weisskopf, (1935-39)
- If the field strengths re strong enough (Schwinger Critical value for the electric field: $E=10^{16}$ V/cm) one can create real electron-positron pair (Intensities: $I_c = 4x\ 10^{29}$ W/cm^2)
- This sets the basic scale of field strength and intensities near which we expect to observe such non-perturbative effects
- In the presence of time dependent fields the Schwinger mechanism needs to be relooked. Ravishankar, Bhalerao PLB 1998, Ravishankar, Jain PRL (2003).
- In the intial stages of the HIC (pre-equilibrium dynamics) non-perturbative pair creation from QCD vacuum play crucial role

Probing the QFT Vacuum

- There are large magnetic fields (B~10^{19} Gauss) generated at the initial stages of the HIC although very sharply decaying. The strength is much larger the magnetic field required for sparking QED vacuum

- High intensity lasers can help in the exploration of the fundamental properties of the vacuum and particle acceleration

- QFT/QED vacuum acts like a polarized medium, the understanding of its polarizability at the non-linear order can help in understanding the theory in non-pertubative dmain

Hegelich, Mourou, J. Rafelski, EPJC (2014), TAJIMA and Homma, IJMPA (2012).

THANK YOU VERY MUCH FOR YOUR ATTENTION!