# Heavy Ion Theory

## Overview

12th VIENNA CENTRAL EUROPEAN SEMINAR
ON PARTICLE PHYSICS AND QUANTUM FIELD THEORY

PHYSICS AT LHC - RUN 2

Vienna, Dec. 2, 2016

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# Why colliding heavy nuclei at high energy ?

Fundamental issues

- Extreme states of matter. Of intrinsic interest (QCD phase diagram, deconfinement, chiral symmetry restoration, etc), and of relevance for astrophysics (early universe, compact stars)

- 'Universal' character of hadronic wave functions at high energy (dense gluonic systems, saturation, color glass condensate)

- QCD dynamics in "high density" environment

# A multifaceted field

Dense hot matter

Astrophysics (compact stars)

Cosmology (early universe)

Fundamental aspects of strong interactions (soft interactions, confinement, chiral symmetry)

## Heavy ions

Quantum field theory

Many-body physics

Statistical physics

# A field driven by experiments

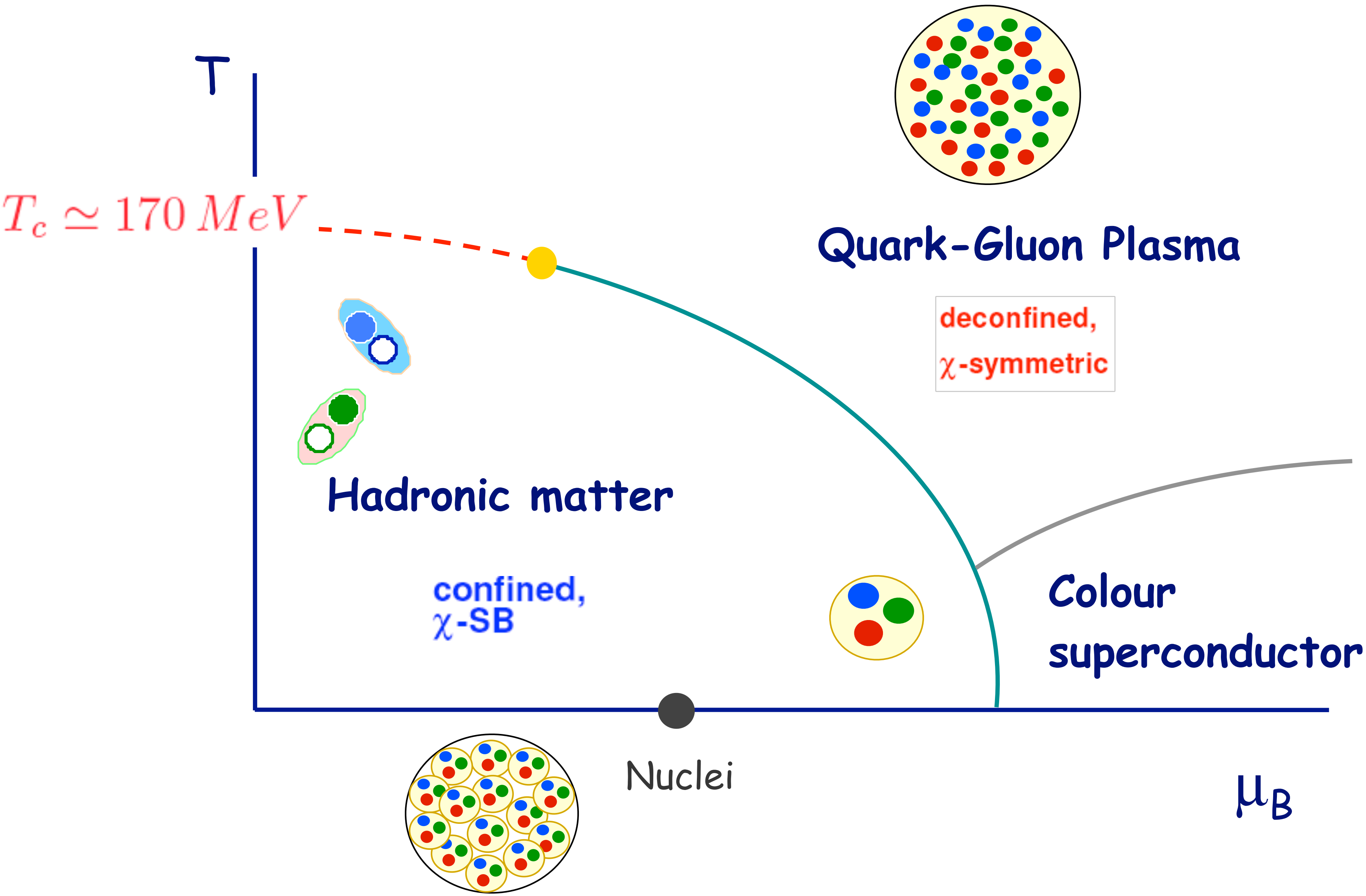
Complexity of heavy ion collisions -> Plethora of models

However, many observables, and accurate measurements
(particle species, collision energy, size of colliding systems, etc)
-> we are getting a good control of what is going on

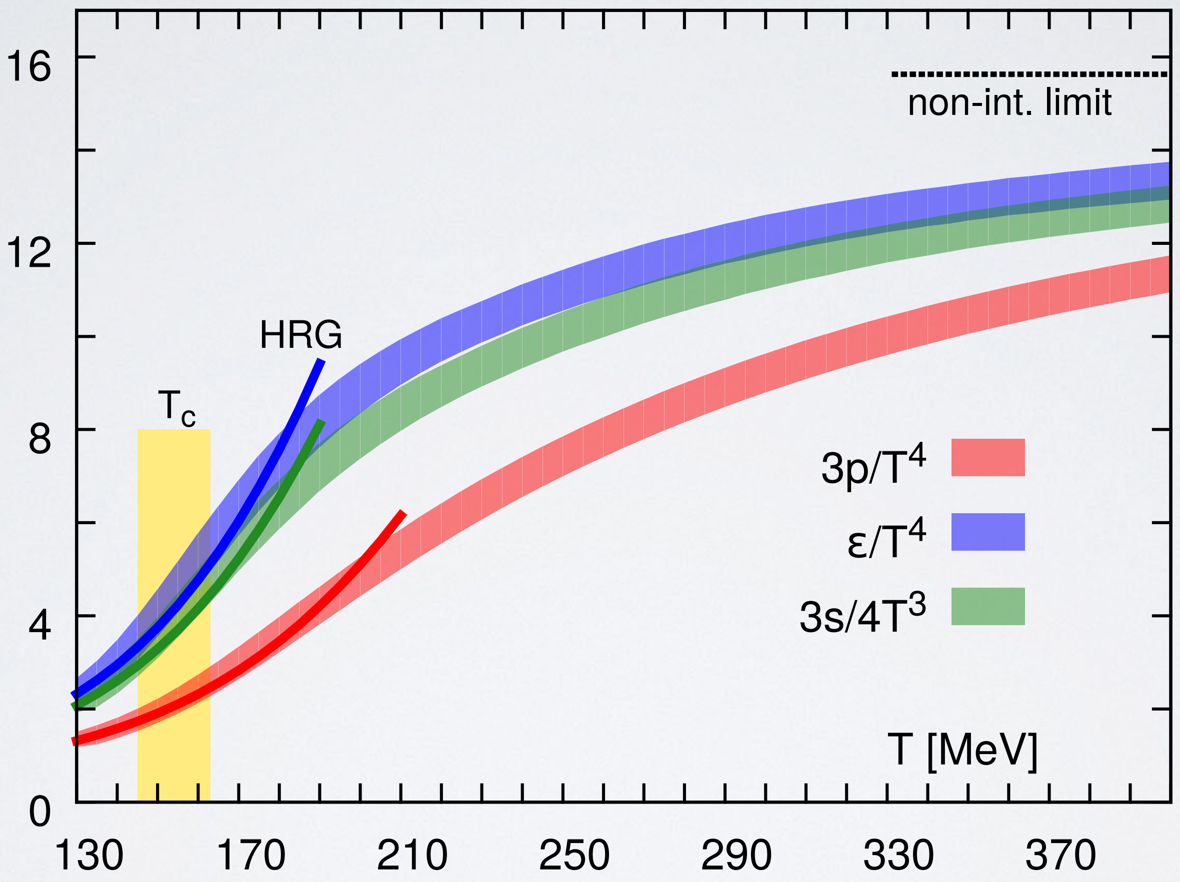
Unexpected phenomena have been discovered

This talk: focus on (some) important theoretical issues without going into the detailed comparison of models with experiments

# The QCD phase diagram

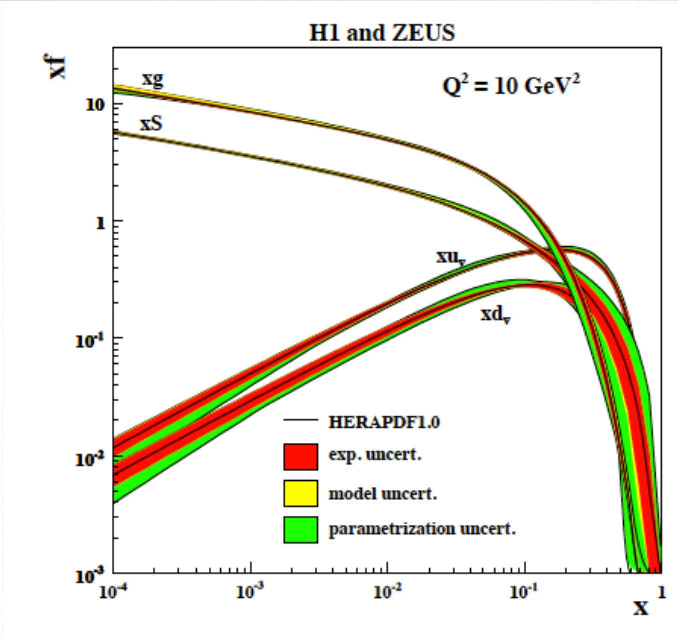


# Crossover from hadrons to quarks and gluons




[1407.6387 Hot QCD collaboration]

# High density partonic systems



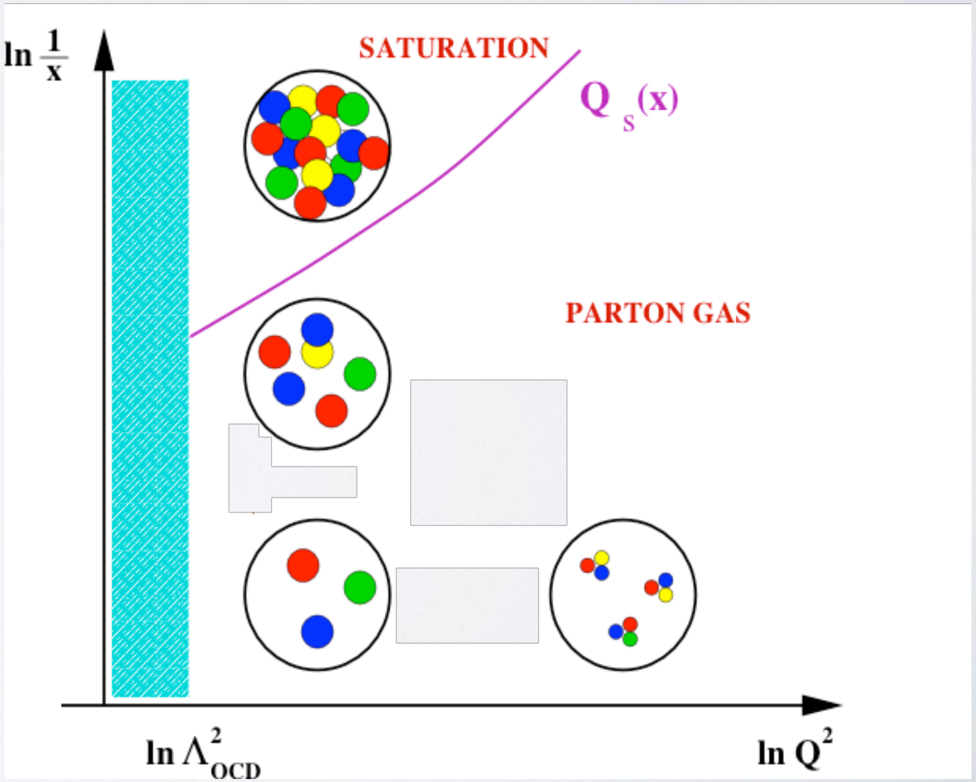

**Bulk of particle production** ( $p_T \lesssim 2$ **GeV** )

RHIC ( $\sqrt{s} = 200$ GeV) $x \sim 10^{-2}$

LHC ( $\sqrt{s} = 5.5$ TeV) $x \sim 4 \times 10^{-4}$

Saturation momentum

$$Q_s^2 \approx \alpha_s \frac{xG(x, Q^2)}{\pi R^2}$$

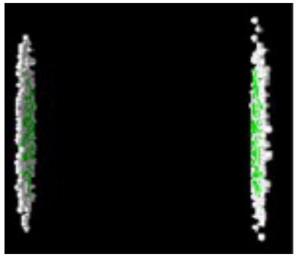



Large occupation numbers

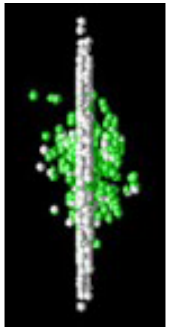
$$\frac{xG(x, Q^2)}{\pi R^2 Q_s^2} \sim \frac{1}{\alpha_s}$$

# Colliding heavy nuclei

# Stages of nucleus-nucleus collisions

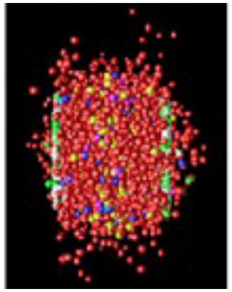


Initial conditions. Fluctuations (of various origins)

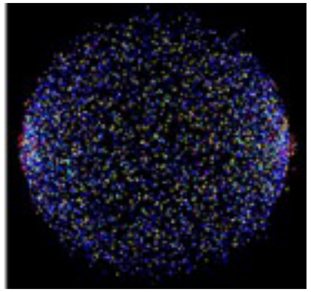


Particle (entropy) production. Involves mostly small x partons $(x = p_\perp / \sqrt{s} \sim 10^{-2} - 10^{-4} \quad \text{for} \quad p_\perp \simeq 2\text{GeV})$

One characteristic scale: saturation momentum $Q_s$



Quark-gluon plasma.
Thermalization.
Hydrodynamical expansion



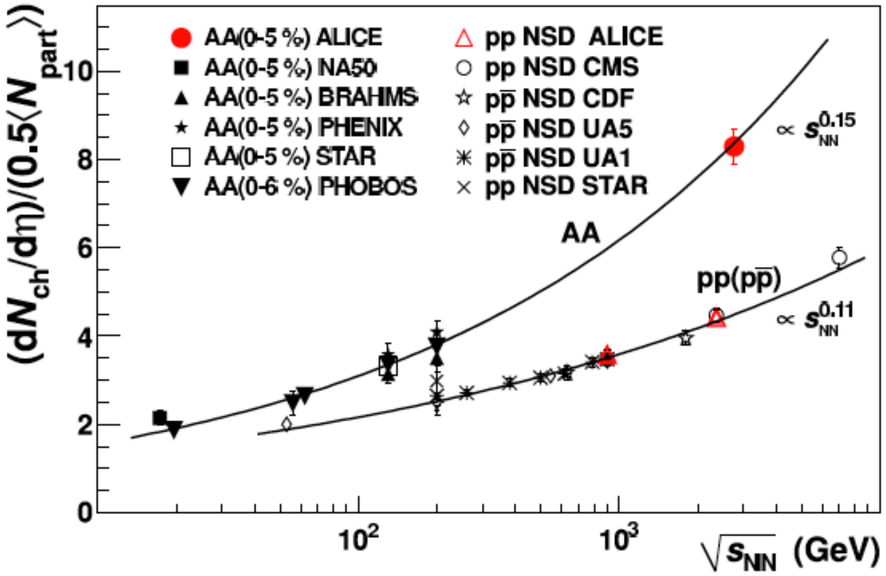
Hadronization in apparent chemical equilibrium.
Hadronic cascade till freeze-out.

# Moving backward in time

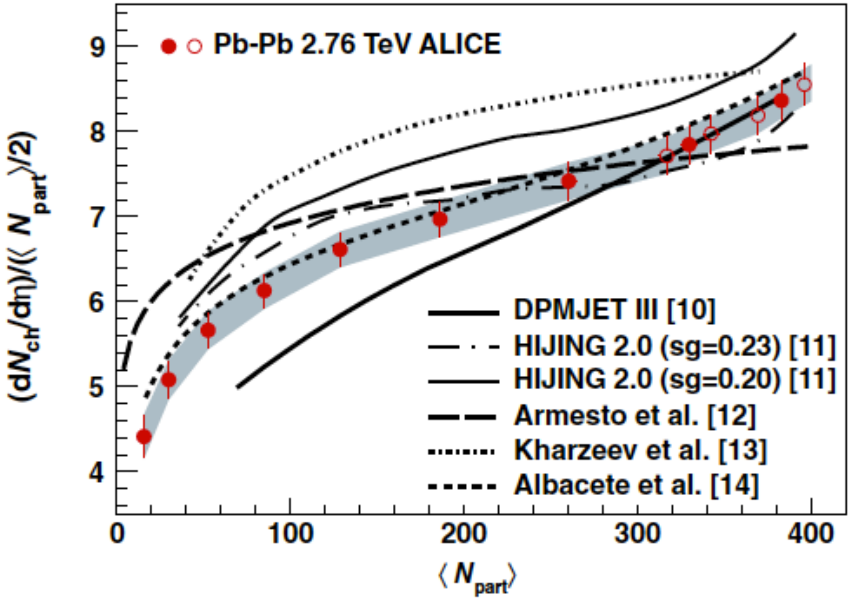
Conditions are reached for the formation of a quark-gluon plasma

Matter at freeze-out is in chemical equilibrium

# Counting particles



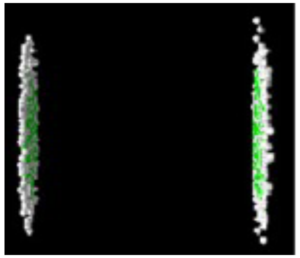

ALICE PRL 105 (2010)




ALICE PRL 106 (2011)

Compatible with theoretical expectations, but large (theoretical) uncertainties remain...

The conditions for the formation of a quark-gluon plasma are reached in the early stages of the collisions



$\longleftarrow \tau_0 \longrightarrow$

order of magnitude estimate

$$\frac{dN_{ch}}{d\eta} \simeq 1600$$

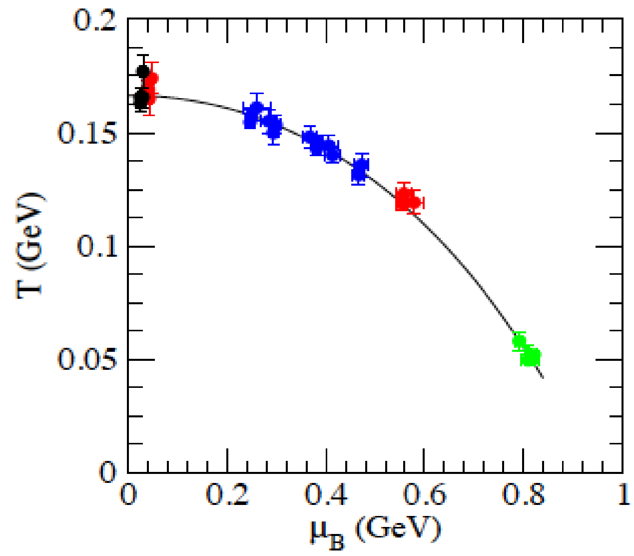
$$\epsilon\,\tau_0 \simeq 15\mathrm{GeV/fm}^2$$

$$T_0 \simeq 300\,\mathrm{MeV}$$

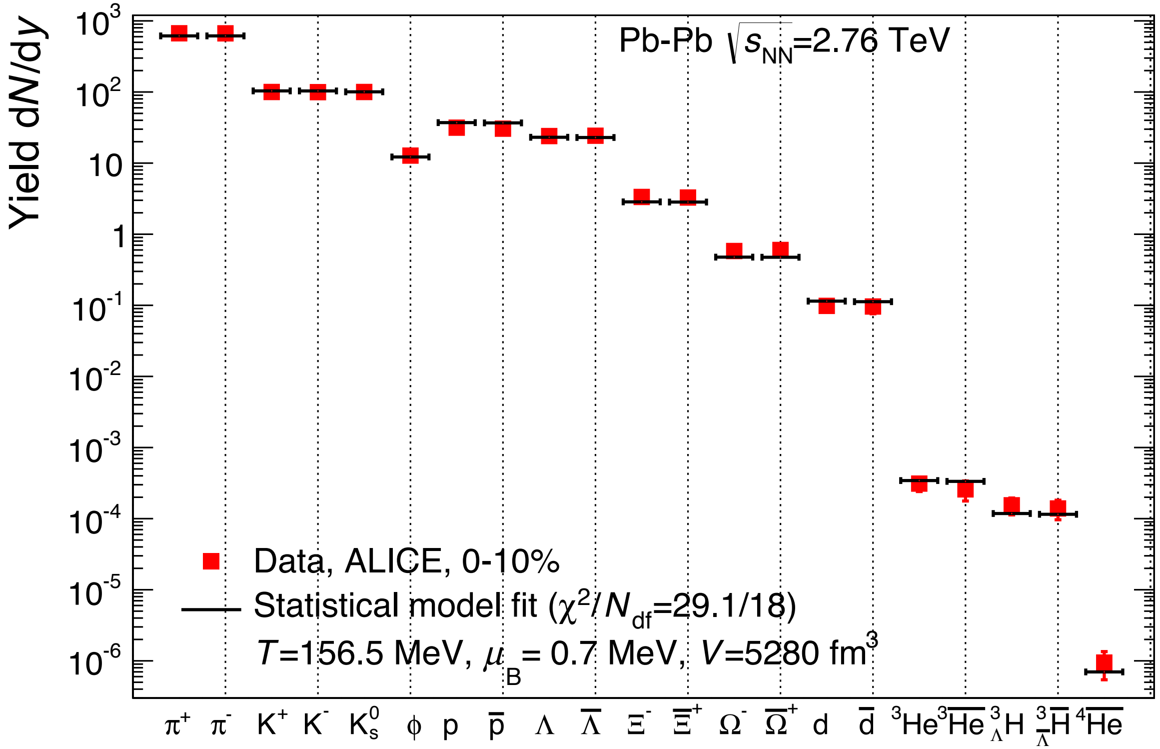
# Matter at freeze-out

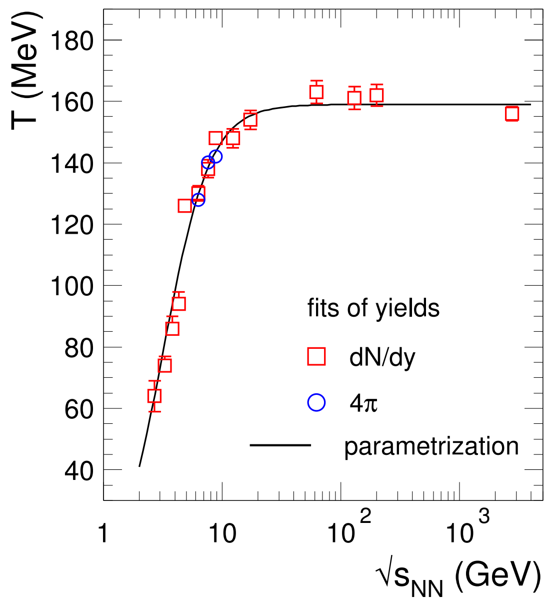
**well described by a statistical picture**

$$n \sim \frac{1}{e^{(\varepsilon_k - \mu)/T} \pm 1}$$




(from J. Cleymans et al, hep-ph/0511094)



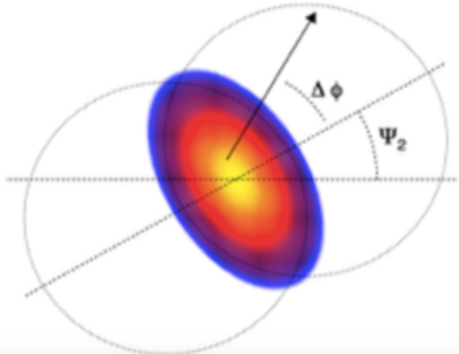

(from A. Andronic, SQM2016)

# Moving backward in time

Matter flows like a fluid

The quark-gluon plasma as a nearly perfect fluid

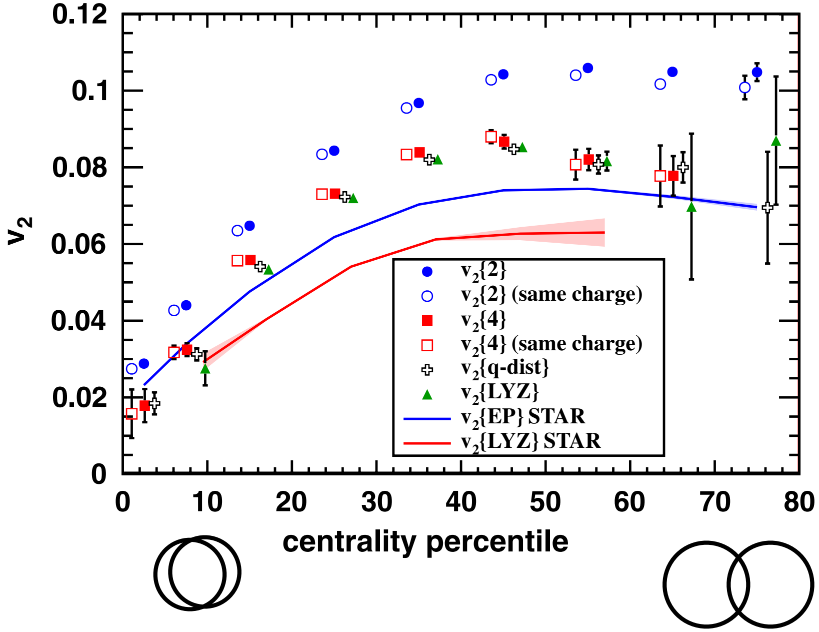
# Azimuthal anisotropy




$$\frac{dN}{d\phi} = \sum_n V_n e^{-in\phi}$$

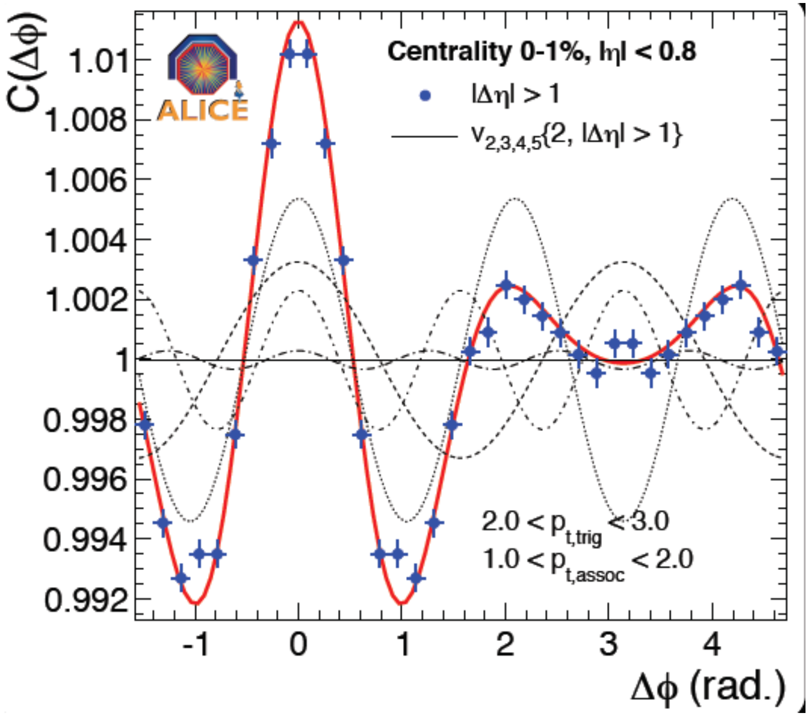
$V_2$ = elliptic flow

[ALICE PRL 105 (2010)]




central

peripheral



# Collective flow

Matter flows like a fluid and is well described by relativistic hydrodynamics

$$\partial_\mu T^{\mu\nu} = 0 \qquad \partial_\mu j^\mu = 0$$

Description in terms of a few local fields

energy density $\varepsilon(x)$

energy density $P(x)$

energy density $n_B(x)$

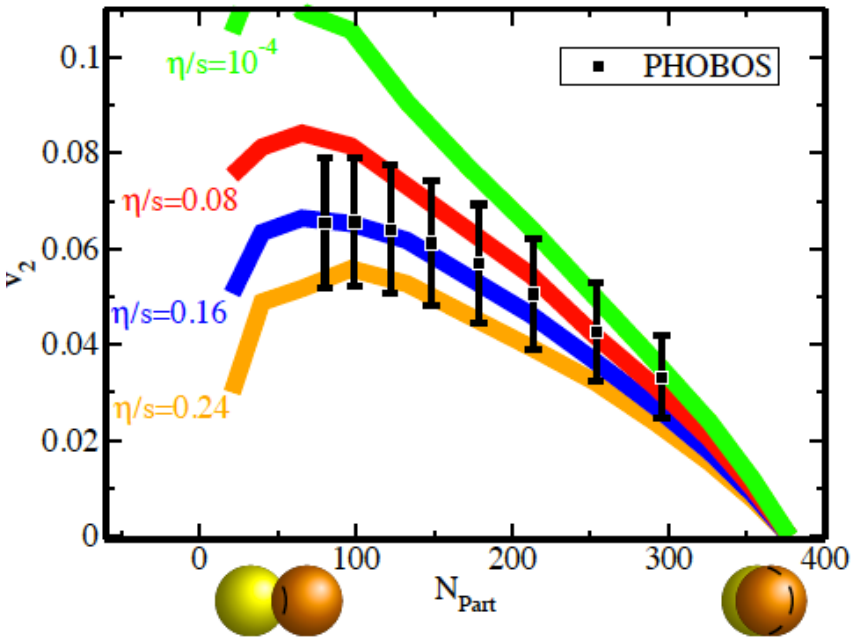
Effective theory for long wavelength modes

**This description works amazingly well !**

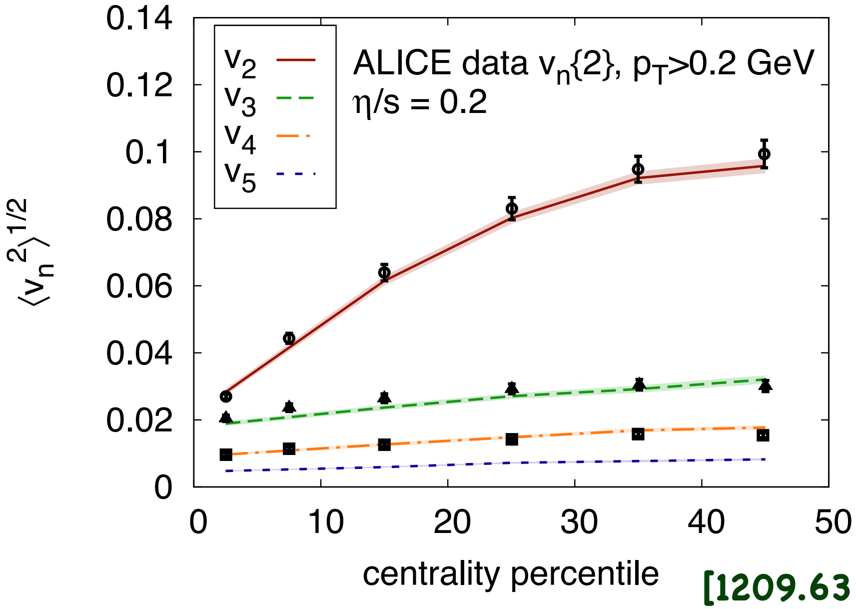
**even in situations where, a priori, it should not ...**

# The perfect liquid

Viscous corrections are small

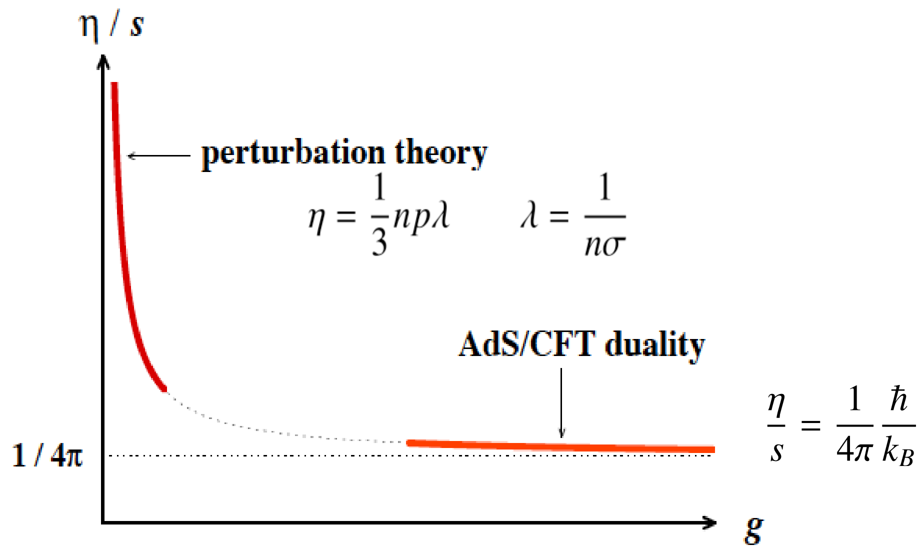



(Luzum, Romatschke, 2007)

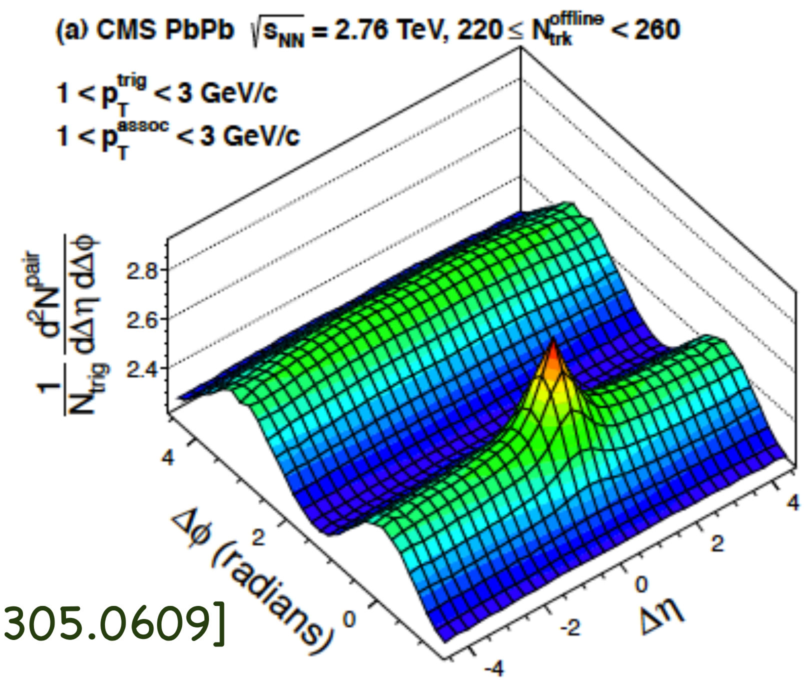



[1209.6330]

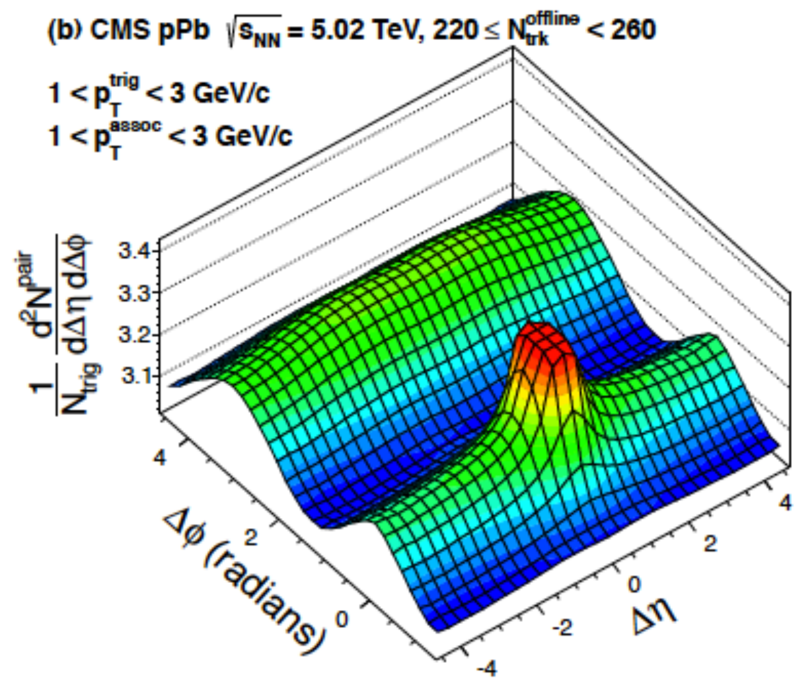
The small value of eta/s suggests
a strongly coupled liquid...



# Surprising p-Pb collisions

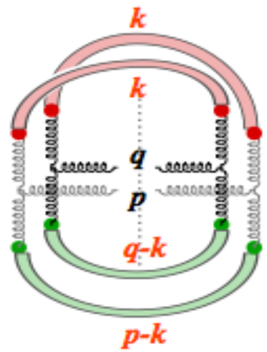



[arXiv: 1305.0609]




Is it hydrodynamics ?

Or evidence for CGC ?




Dumitru, Dusling, Gelis, Jalilian-Marian, Lappi, Venugopalan : 1009.5295

Dusling, Venugopalan:1211.3701

# So, why does hydro work so well

- How does the hot dense systems of gluons that are freed very early in the collisions turn into a liquid with low relative viscosity ?

  [will be discussed shortly]

- How small can the system be for hydro still to make sense ?

  Topic of hot debate !

Standard point of view (kinetic)

$$\tau_{\rm hydro} \gg \tau_{\rm micro} \sim 1/T$$

$$R \gg \ell_{\rm micro} \sim 1/T$$

AdS/CFT (strong coupling)

$$\tau_{\rm hydro} \lesssim 1/T$$

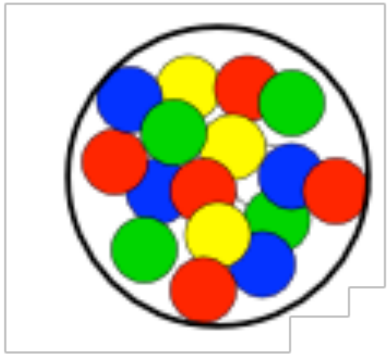
$$R \lesssim 1/T$$

# Moving backward in time

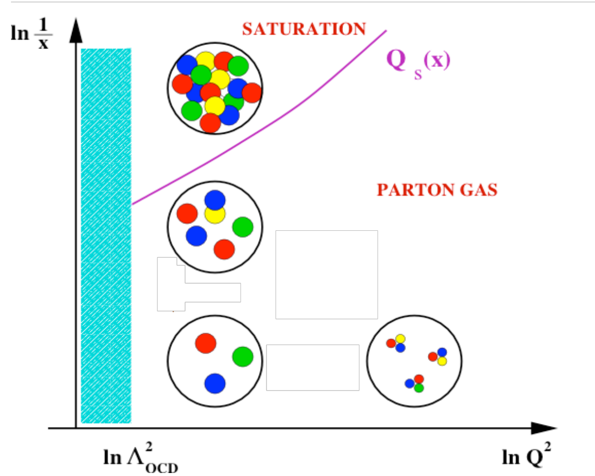
Nuclei are made of densely packed gluons

How does fluid behavior emerge ?

# Saturated gluon systems



$$Q_s^2 \approx \alpha_s \frac{xG(x,Q^2)}{\pi R^2}$$

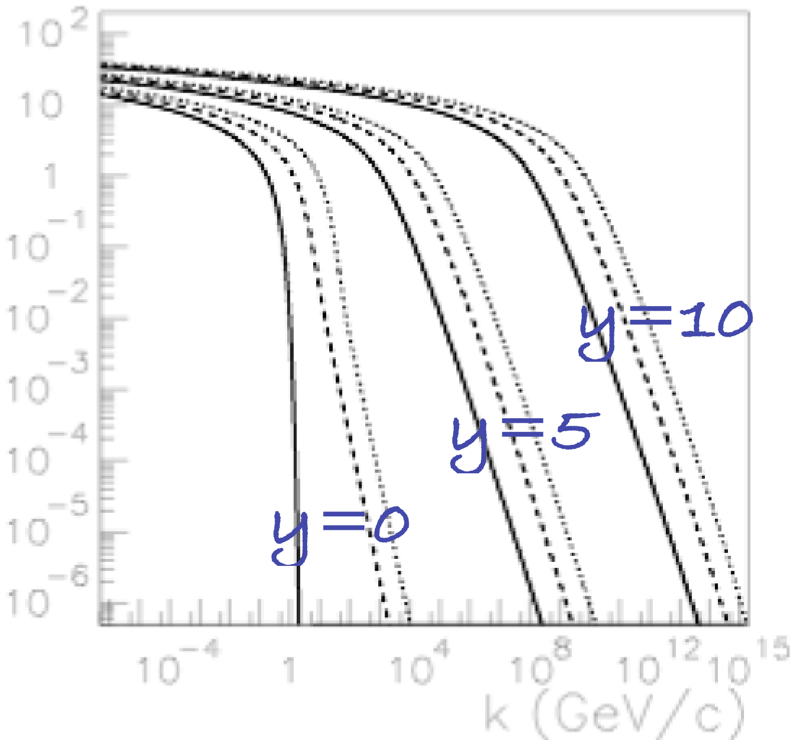



**At saturation, occupation numbers are large**

$$\frac{xG(x,Q^2)}{\pi R^2 Q_s^2} \sim \frac{1}{\alpha_s}$$

Most partons taking part in collision have $k_T \sim Q_s$

$$f_A(k_\perp \ll Q_s) \approx \frac{1}{\alpha N_c} \ln \frac{Q_s^2}{k_\perp^2}$$



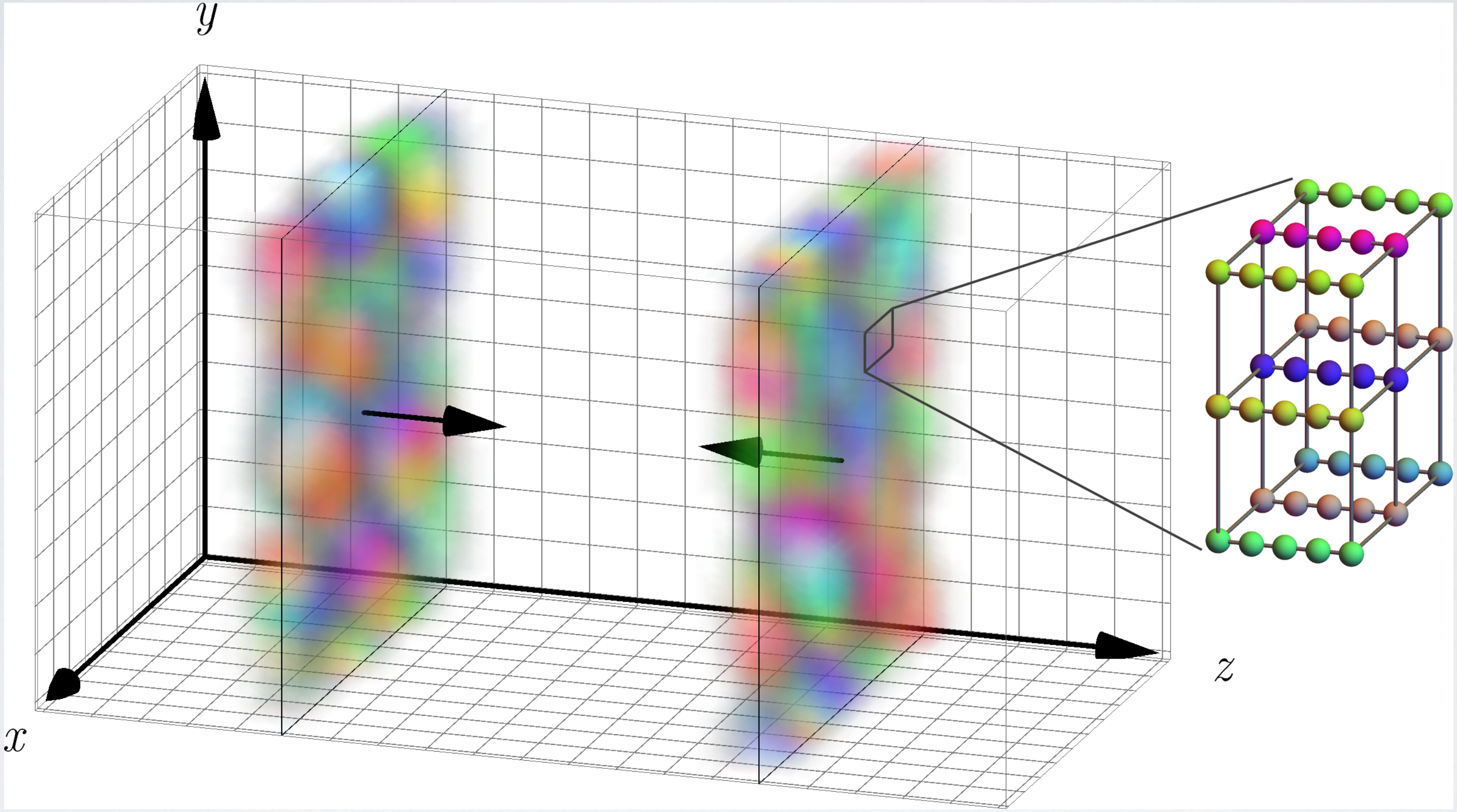

$$Q_s^2(x,A) \simeq Q_0^2 \, A^{1/3} \left(\frac{x_0}{x}\right)^\lambda$$

$$\lambda = 0.2 \div 0.3$$

[For a recent (pedagogical) review see 1607.04448]

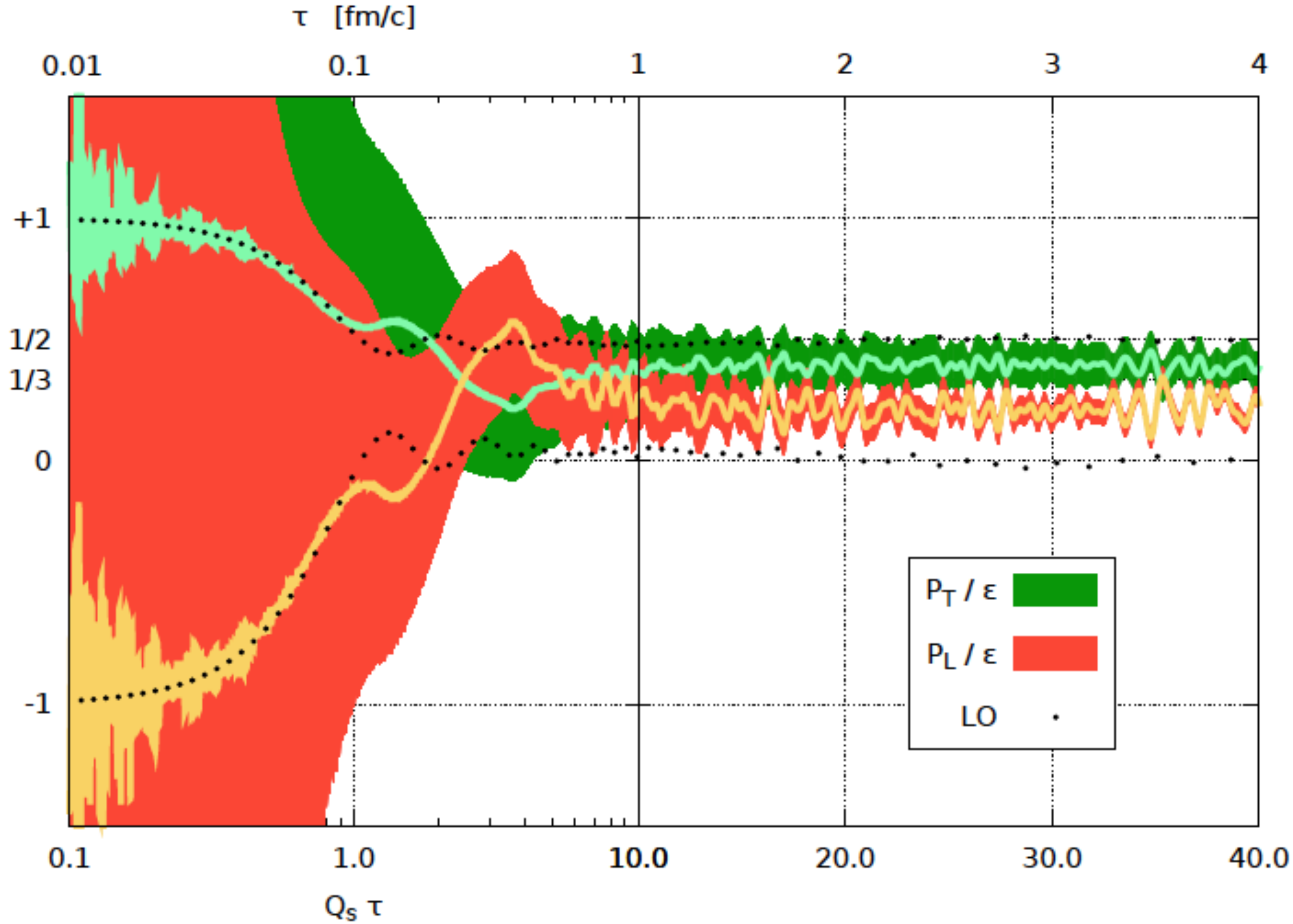
$$f_A(k_\perp \gg Q_s) \approx \frac{1}{\alpha N_c} \frac{Q_s^2}{k_\perp^2}$$

# Simulation of classical Yang-Mills equations with random distribution of color charges



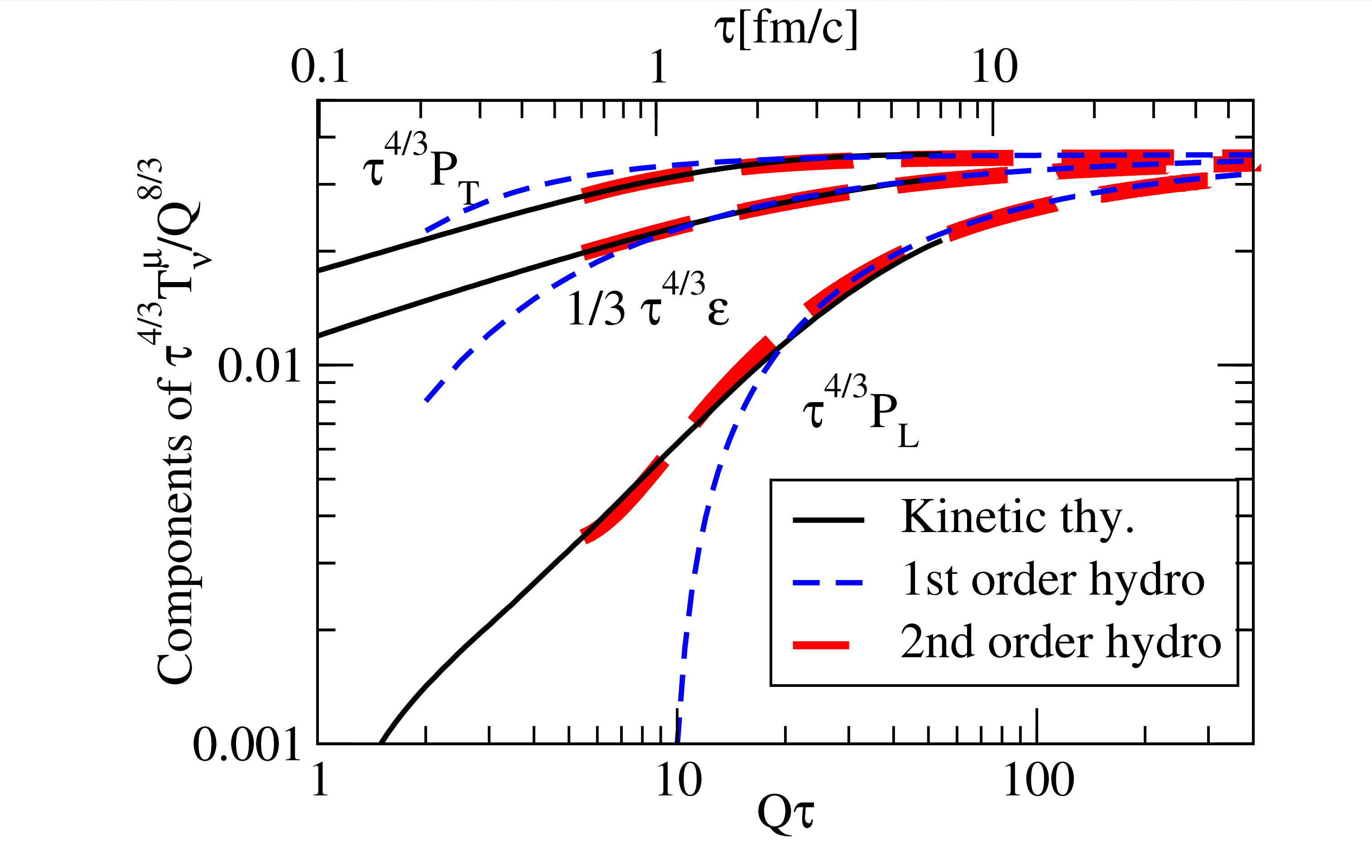

[D. Gelfand, A. Ipp, D. Müller, 1605.07184]

# Statistical-classical field simulations




T. Epelbaum and F. Gelis, PRL (2013)

# Microscopic understanding of how liquid behavior emerges




[A. Kurkela and Y. Zhu, PRL 115,182301]

# Moving backward in time

## Signals from the early stages

### Hard probes

# Hard probes

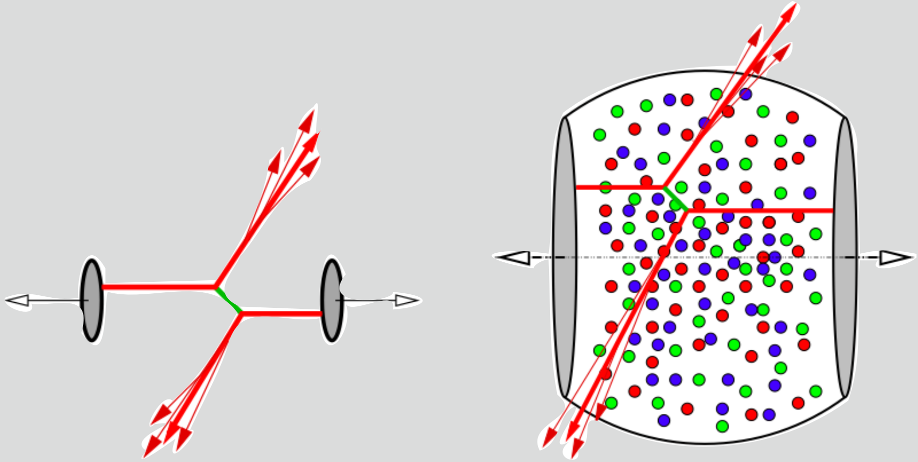
Hard probes are produced on short space time scales, and their production rate can be calculated from pQCD

Hard probes are like test particles. The study of their propagation provides much information about the medium in which they propagate.

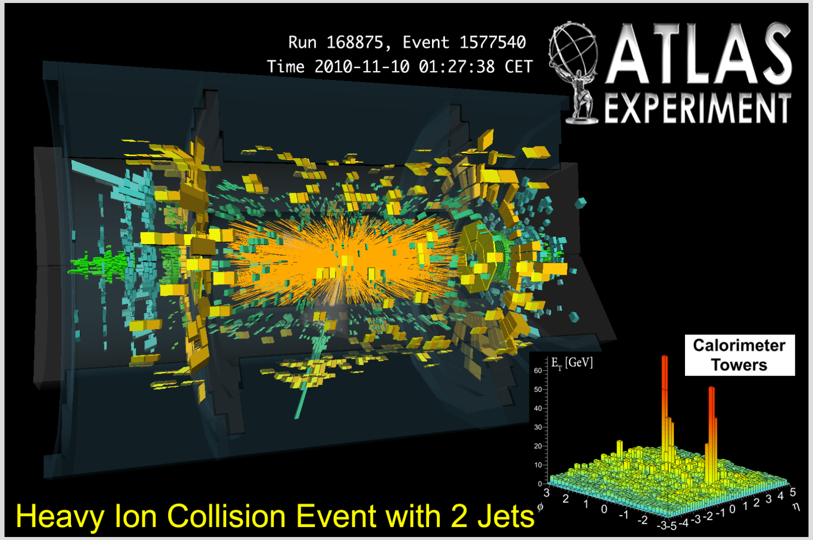
Examples of hard probes: heavy quarks, quarkonia, photons, Z and W, jets...

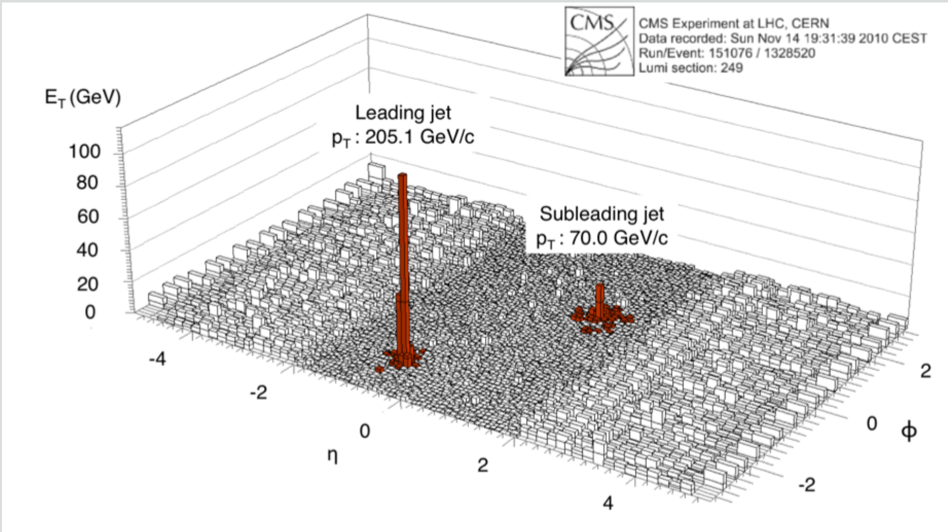
Prospects for hard probes at the LHC are truly fascinating. But our theoretical tools to exploit them still need to be further developed.

# Jets in a quark-gluon plasma



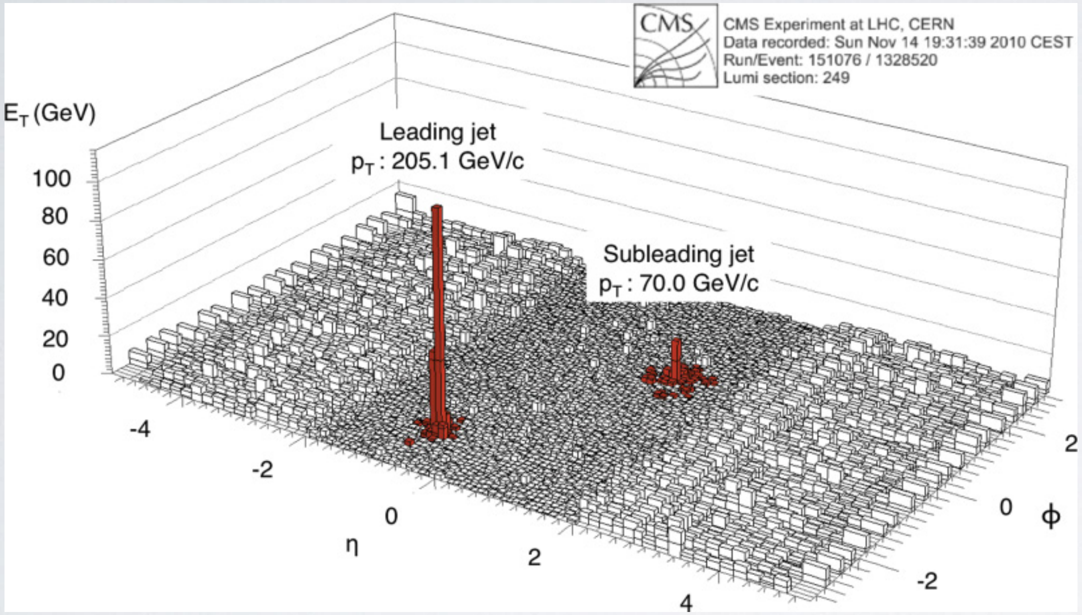
**Jets are quenched due to interactions with the QGP**

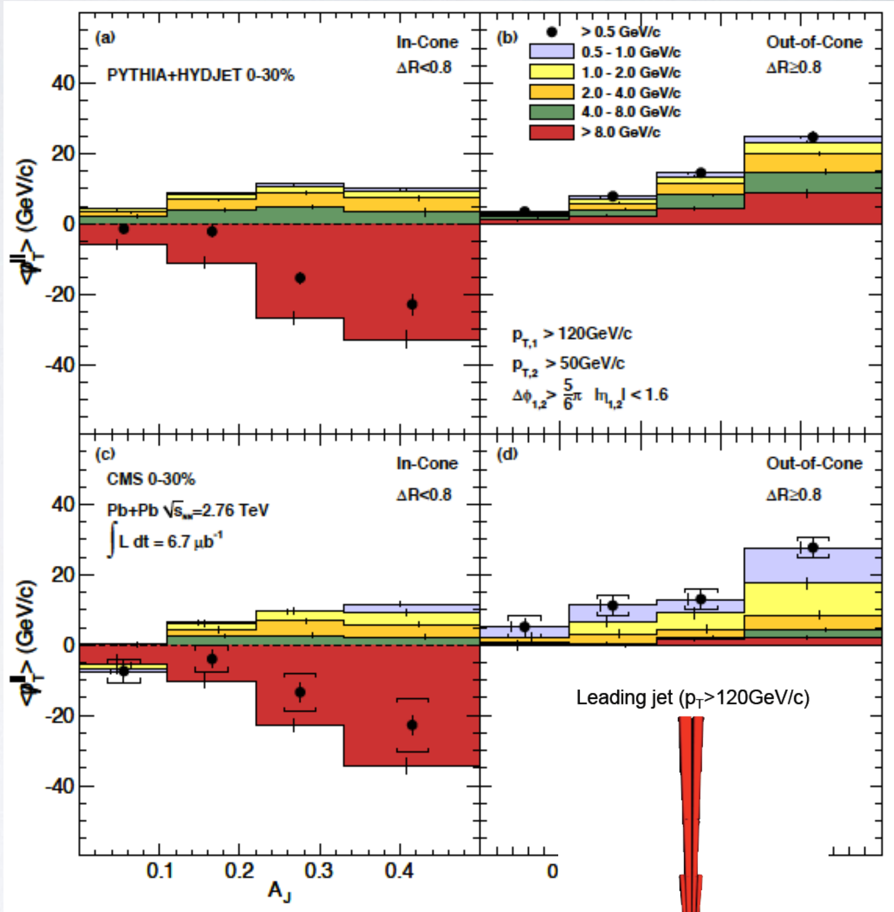


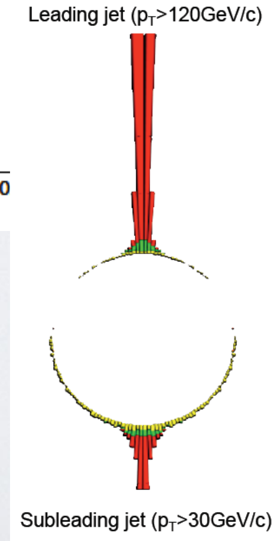



# Di-jet asymmetry

## there is more to it than just 'quenching'...



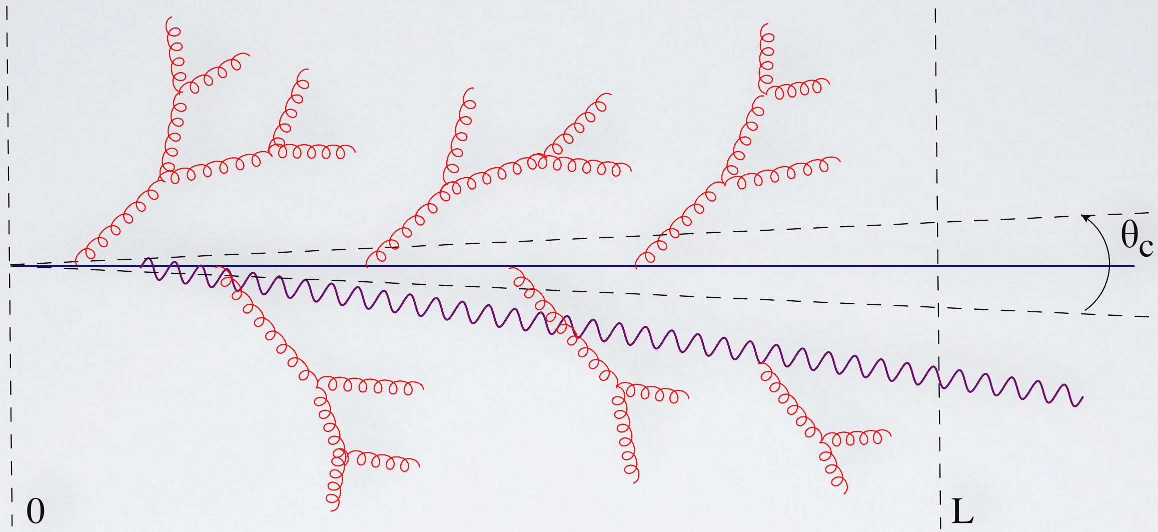

Missing energy is associated with additional **radiation of many soft quanta at large angles**

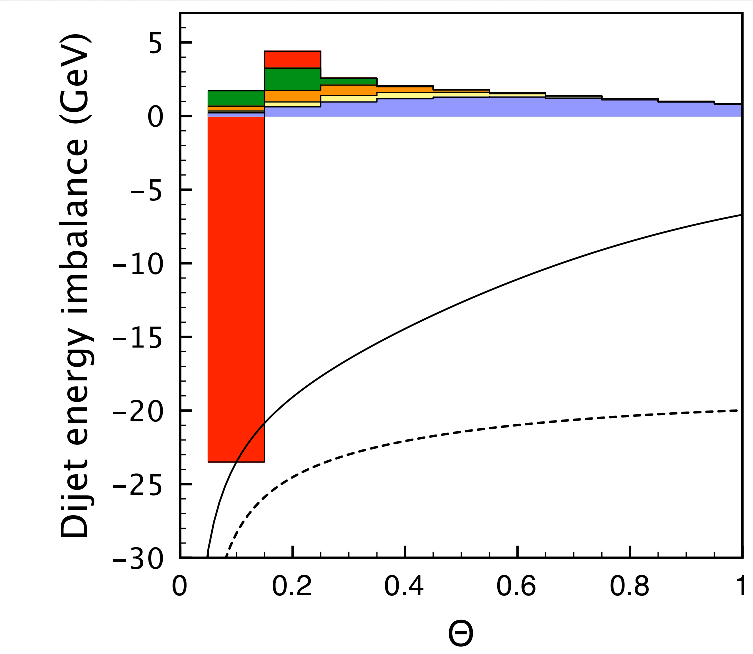
$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

This reflects a **genuine feature of the in-medium QCD cascade.**

(for recent review, see arXiv: 1503.05958)

# The angular structure is a generic property of the in-medium QCD cascade




red: 8-100 GeV
green: 4-8 GeV
yellow; 1-2 GeV
blue: 0-1 GeV

[arXiv:1407.0326]

# Melting of quarkonia

A very nice idea....

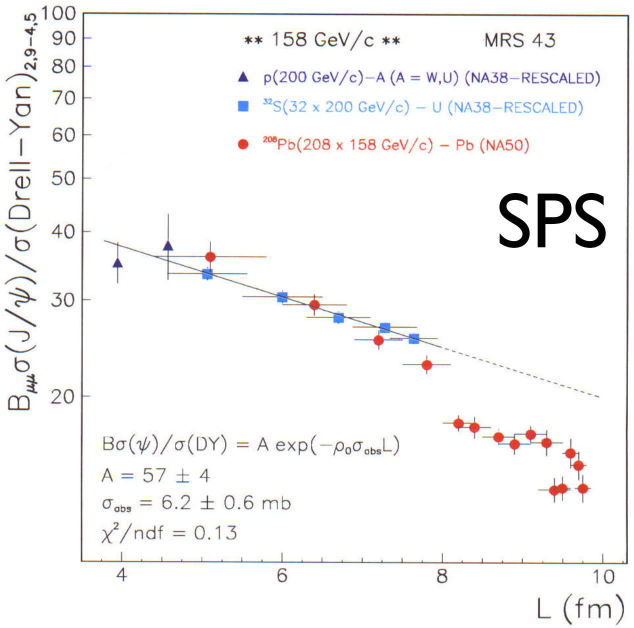
a considerable experimental effort

but a very difficult many-body problem !

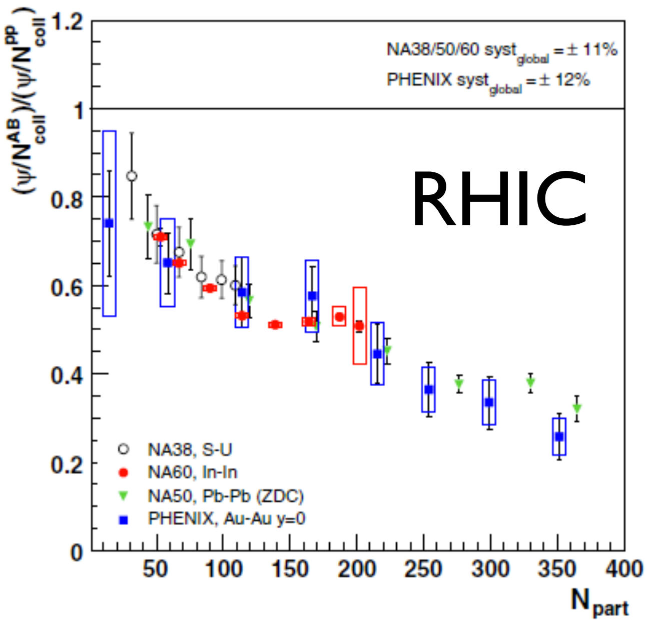
$$V_{\text{eff}}(r_1 - r_2) = -\frac{g^2}{4\pi}\left[m_D + \frac{e^{-m_D r}}{r}\right] - i\frac{g^2 T}{4\pi}\phi(m_D r)$$

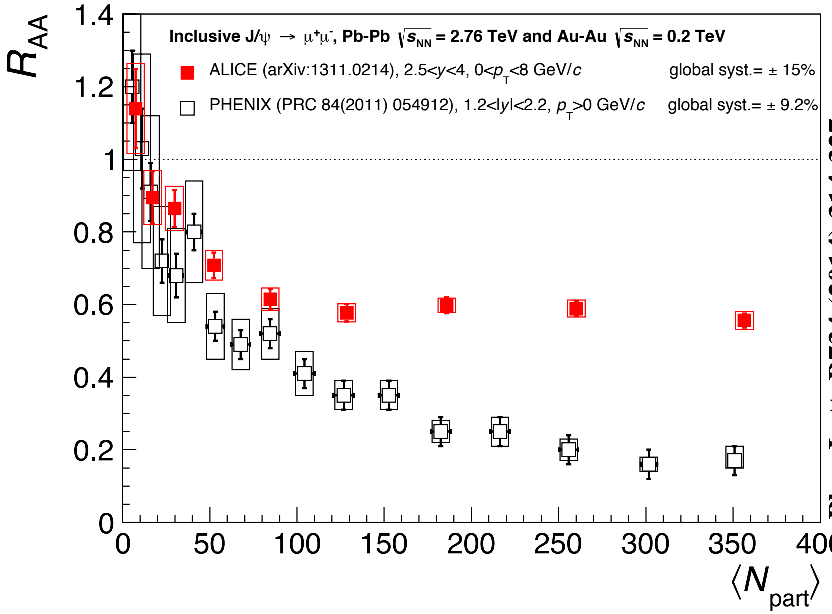
# $J/\Psi$ suppression

## A long story....




'anomalous' suppression

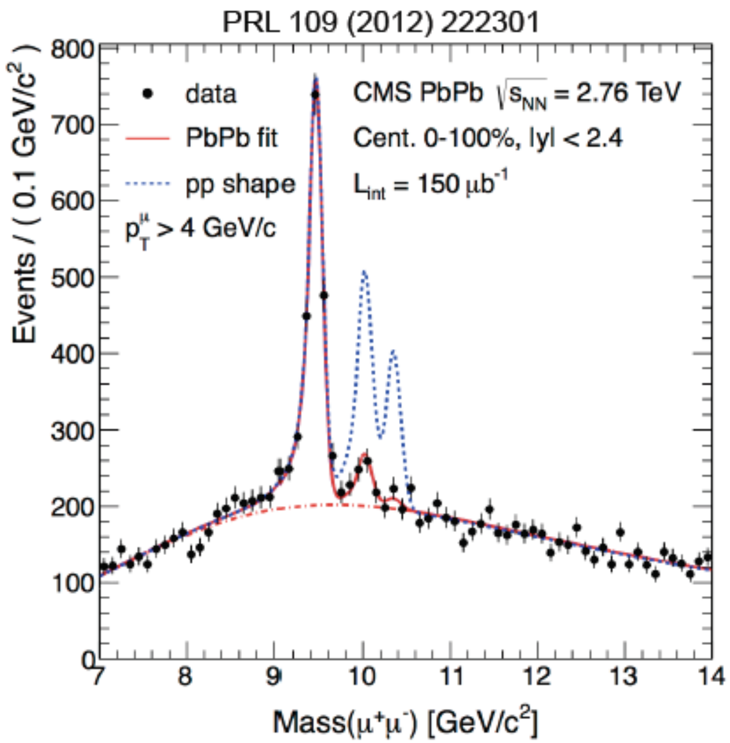



Phys.Lett. B734 (2014) 314-327

suppression / regeneration

# Υ suppression




excited states are more 'fragile'....

It remains a theoretical challenge to understand the details of what is going on, but progress are being made, and the quality of the data justifies further theoretical efforts.

# Conclusions

A quark-gluon plasma is produced in ultra-relativistic heavy ion collisions, whose global properties do not change much between RHIC and LHC (a liquid with low relative viscosity)

We have began to study the properties of this quark-gluon plasma

Modelling of collisions is greatly helped by the success of hydrodynamics

Early stages of the collisions may be amenable to first principle calculations

The LHC is offering new and precise probes to diagnose the QGP, and new phenomena are being discovered

Much, much more remains to be learned !

The field has never been so exciting as now !