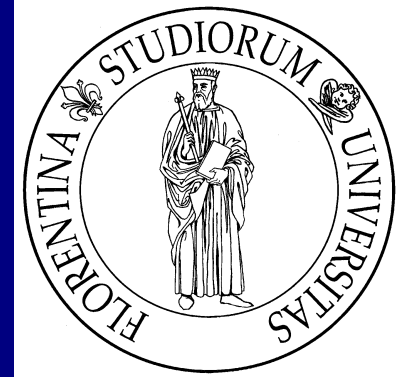# Quark-Gluon Plasma and Relativistic Heavy Ion Collisions in the LCH era

F. Becattini (University of Florence and INFN)

OUTLINE

- QCD thermodynamics
- Hadronic thermometers
- The hydrodynamical model
- Outlook

IFAE, L'Aquila, 10 Aprile 2014

Strong interaction thermodynamics

• Hagedorn (1965): density of hadronic states dN/dm grows exponentially

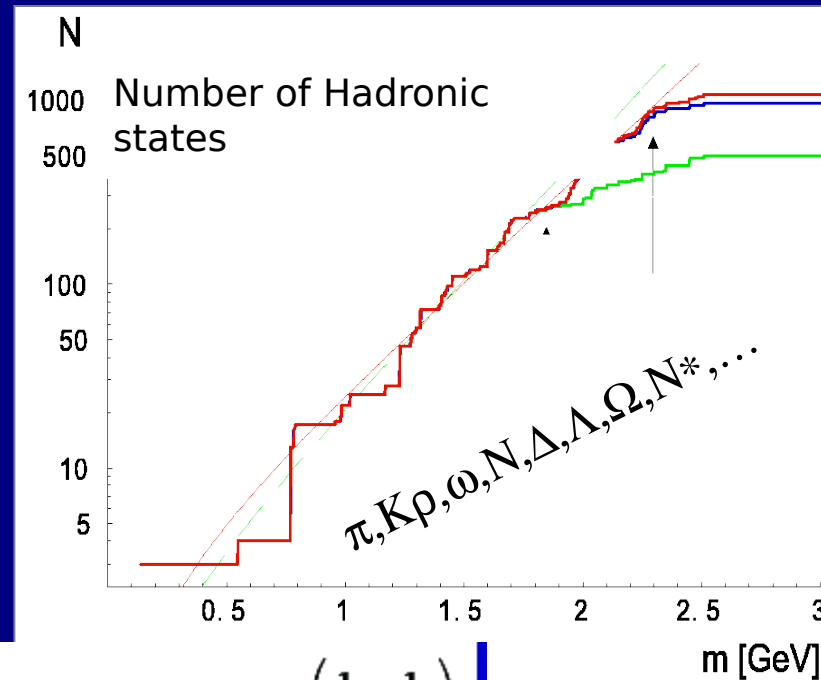$$\rho(m) = Cm^{\alpha}e^{m/T_0}$$

T_0 estimated to be 160 MeV

T_0 is called Hagedorn *limiting temperature for an hadronic system*

Partition function for a gas of hadrons, with m>~T

N

1000 Number of Hadronic
500   states

100

50

10

5

0.5 1 1.5 2 2.5 3

m [GeV]

$\pi, K\rho, \omega, N, \Delta, \Lambda, \Omega, N^*, \dots$

$$\log Z(T,V) \propto \int_{m_0}^{\infty} dm\ m^{3/2}\ \rho(m)e^{-\frac{m}{T}} \propto \int_{m_0}^{\infty} dm\ m^{\alpha+3/2}\ e^{-m\left(\frac{1}{T}-\frac{1}{T_0}\right)}$$

Integral diverges for T->T_0:
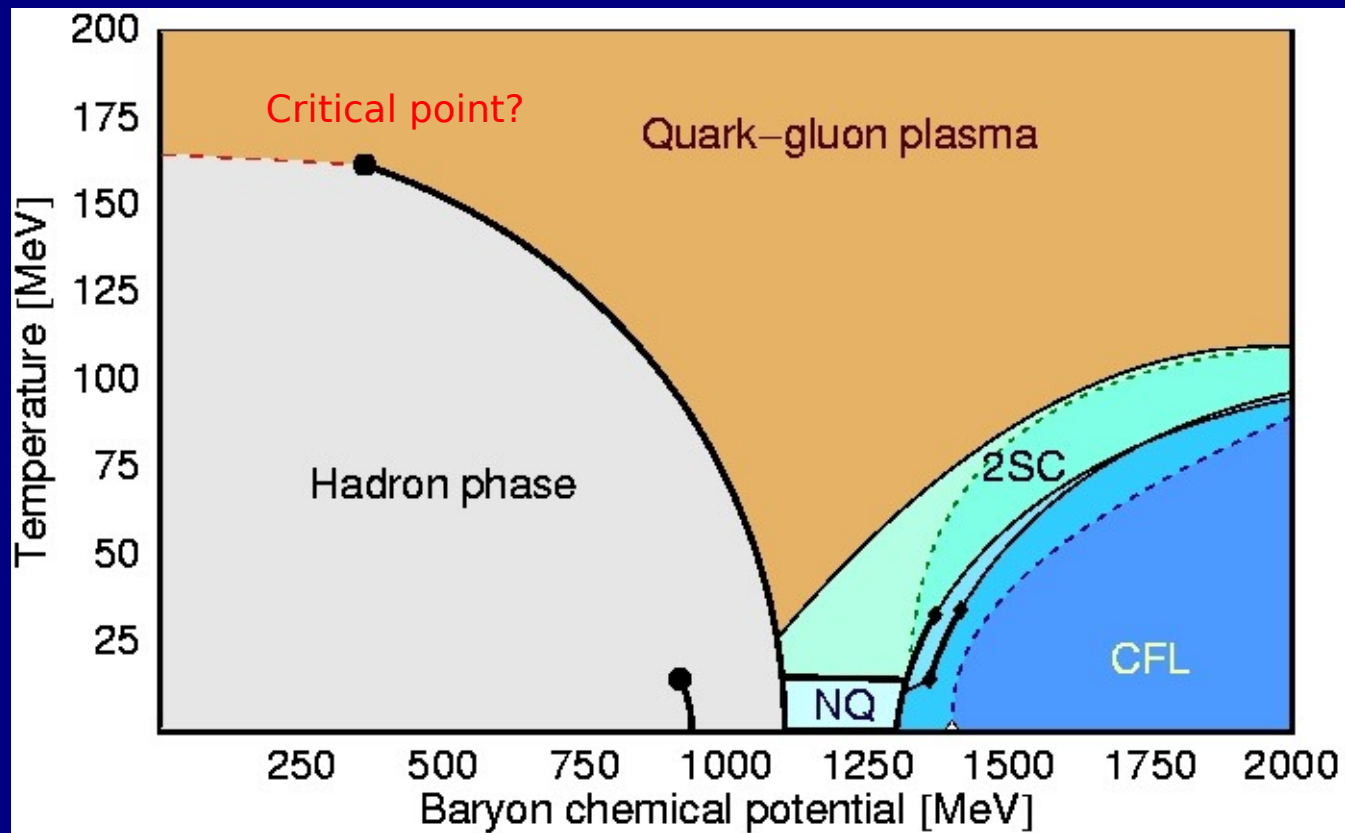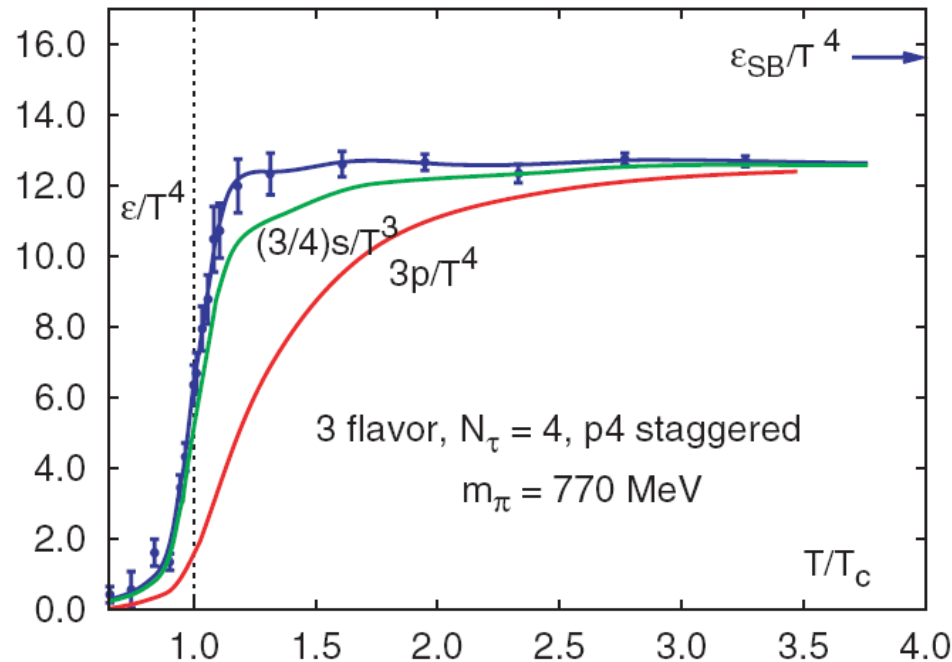hadronic matter cannot have a T>T_0

Cabibbo-Parisi (1975) – one year after Gross –Wilczek paper:

Divergency of the partition function has to be associated with
a phase transition of hadronic matter to quark-gluon matter
+ asymptotic freedom at large T -> weakly quark gluon gas

QCD phase diagram

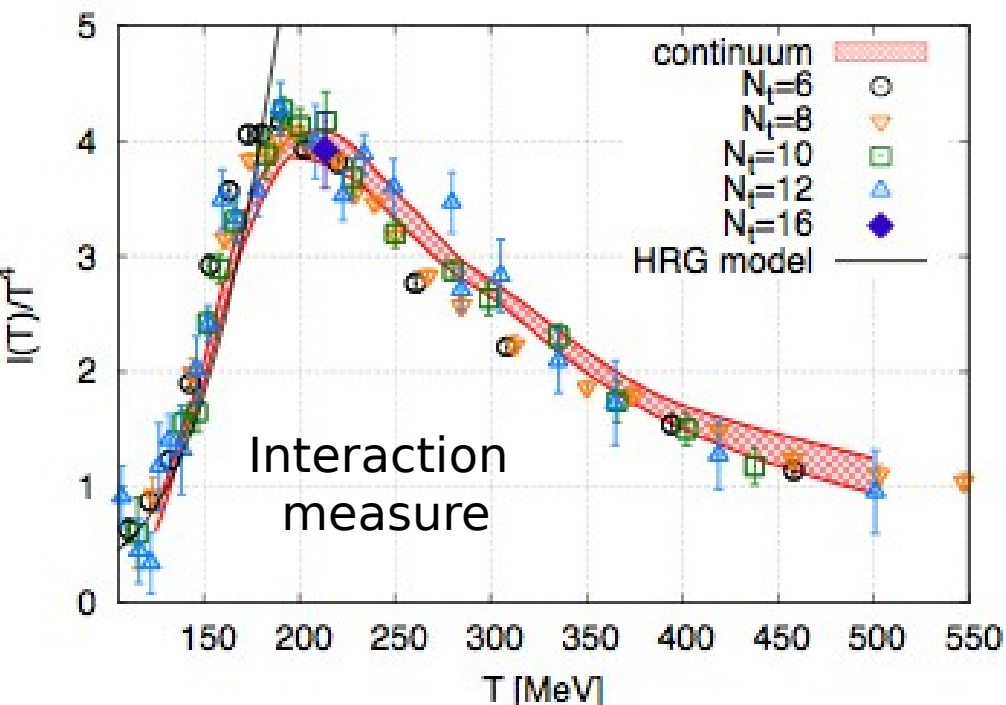Reference: a gas of non-interacting massless Particle (Stefan-Boltzmann law)

$$\frac{\varepsilon_{SB}}{T^4} = \frac{\pi^2}{30}\left[\frac{7}{8}d_{q+\bar{q}} + d_g\right]$$

$$\varepsilon_c \approx 0.7\,GeV\,/\,fm^3$$
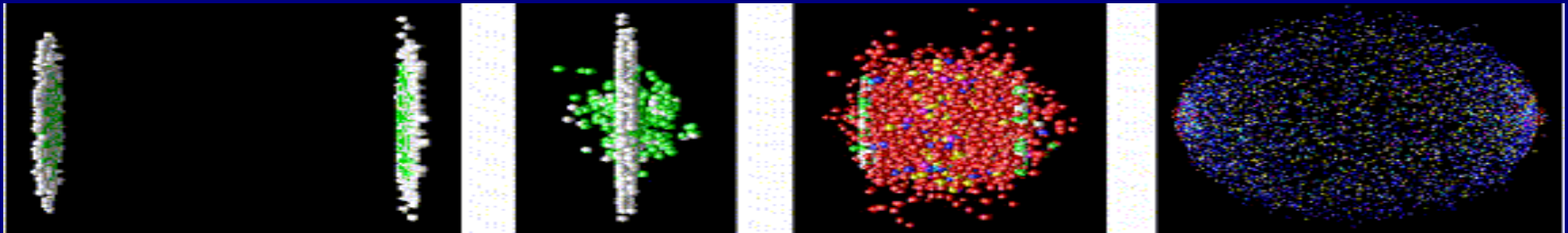
$$T_c \cong 160\,MeV$$

No interaction means (for a massless gas)

$$l = T^\mu_{\ \mu} = \rho\text{-}3p = 0$$

but in fact $l = O(\rho)$!

T > Tc ceases to be a hadron gas but it is not a gas of weakly interacting quarks and gluons up to very high T

How to produce a matter
with $\rho \gg 1$ GeV/fm^3
# lasting for t > 1 fm/c
in a volume much larger than a hadron?

| Accelerator	Lab	$\sqrt{s}_{NN}$	Nuclei
SPS (90's)	CERN	6-18	Pb-Pb
RHIC (00-..	RHIC	7.7-200	Au-Au
LHC (09-..)	CERN	2750	Pb-Pb

Probing the Quark Gluon Plasma

The plasma is a transient and rapidly decays. This situation is dramatically different from the idealized (steady) situation of lattice QCD calculations.

Several possible probes at our disposal, that can be clustered in three groups

- Hadron radiation

- Electromagnetic radiation

- Hard probes: heavy quarks and quarkonia, jets, hard photons etc.
Common feature: early production, "calculable" in perturbative QCD, easily comparable to pp and pA
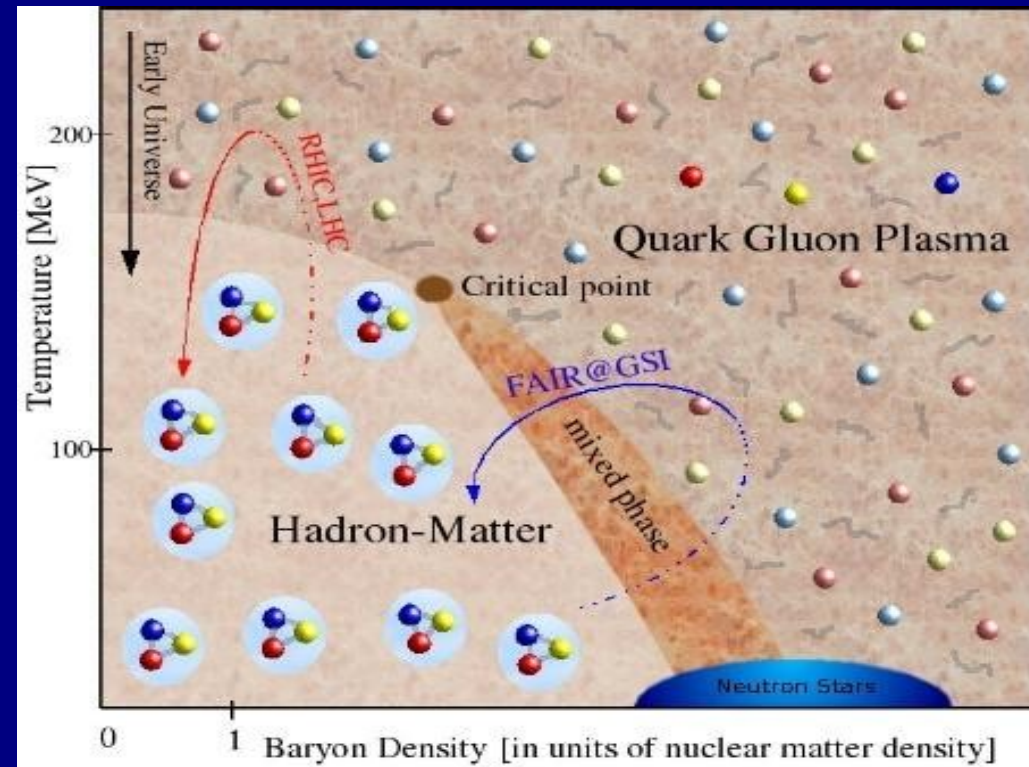
Relativistic hydrodynamical model
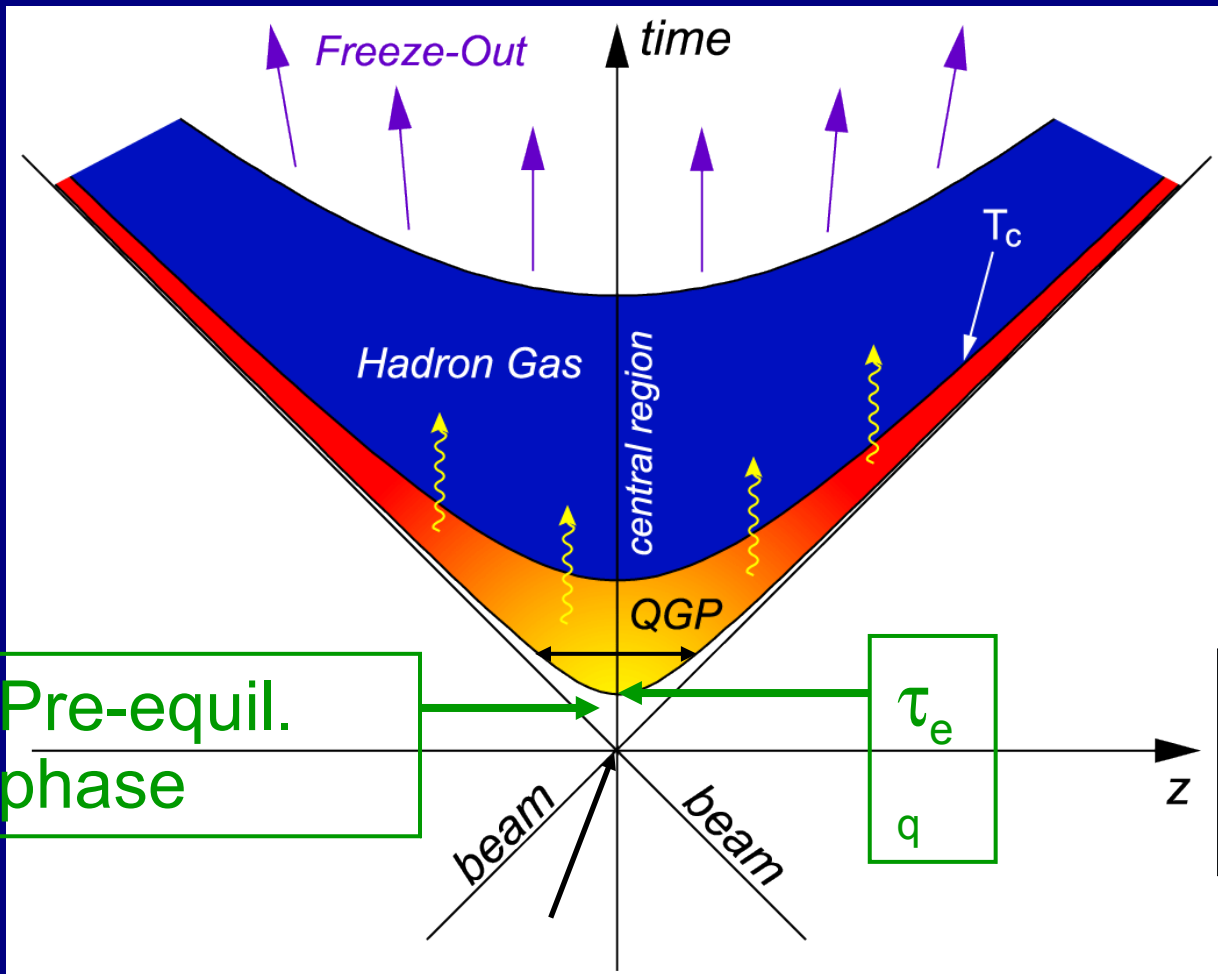
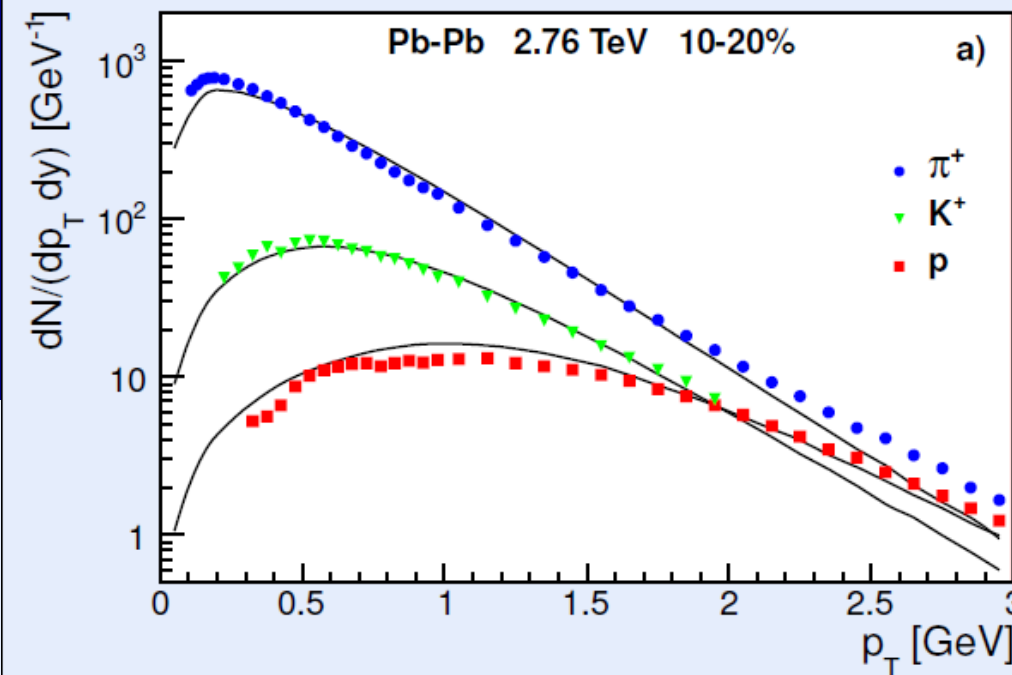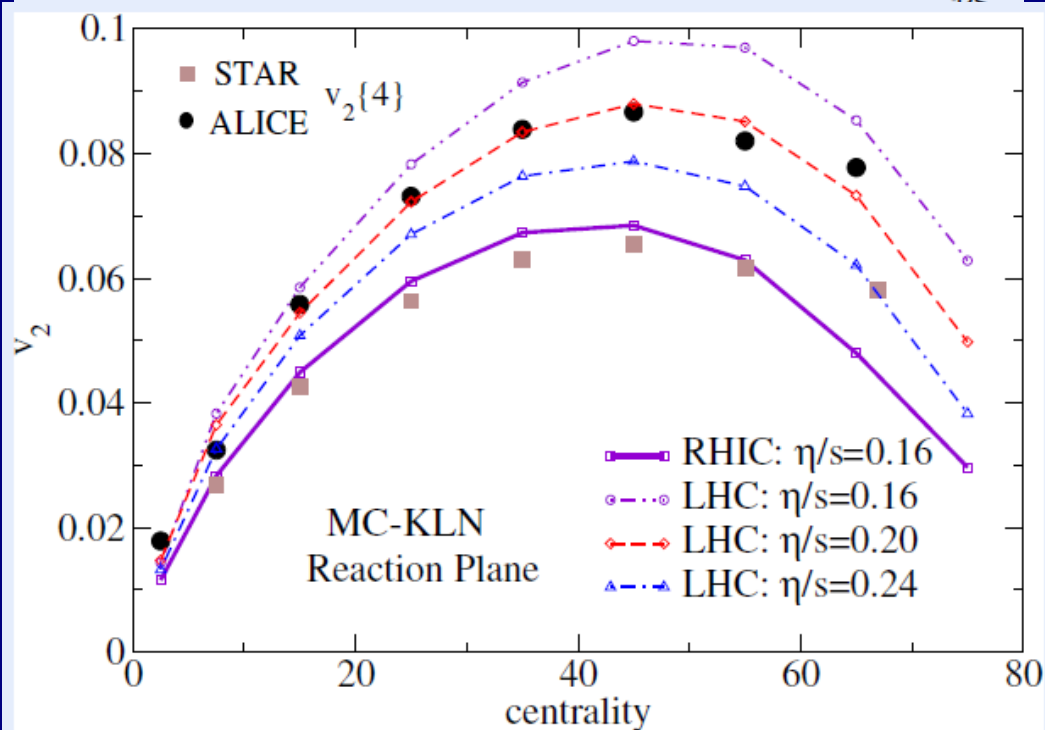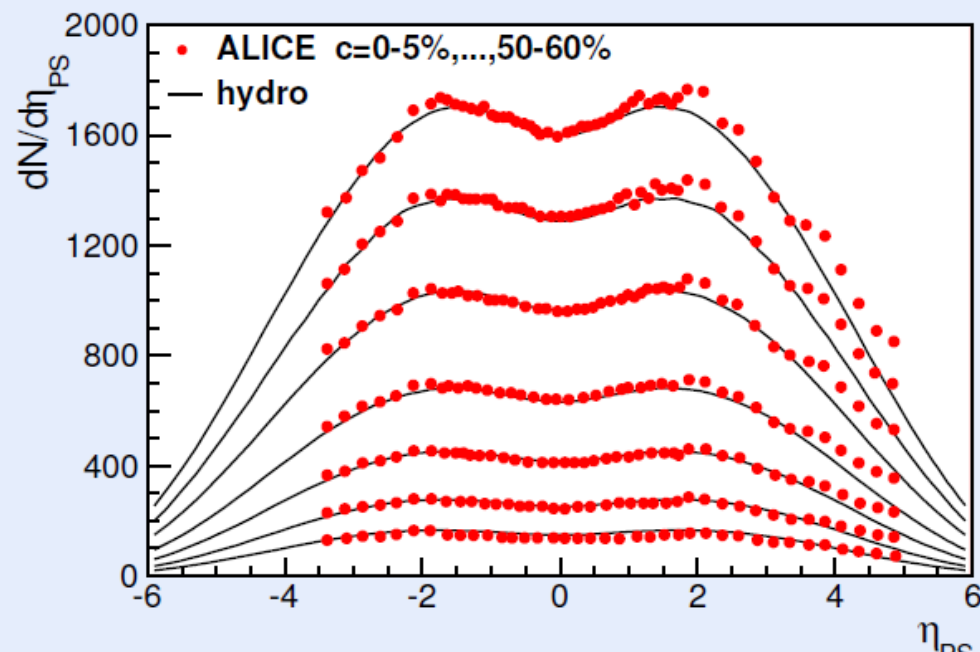$$\begin{cases} \partial_\mu T^{\mu\nu}(x) = 0 \\ \partial_\mu j_B^\mu(x) = 0 \end{cases}$$

Generate particles with:

$$\varepsilon \frac{dn}{d^3 p} = \int d\Sigma_\mu p^\mu \frac{1}{e^{\beta \cdot p} \pm 1}$$

Hydrodynamics requires *local thermodynamical equilibrium*. This implies a formidable reduction of the degrees of freedom in the dynamical problem: from the full problem of interacting quantum fields to the evolution of few functions: *u(x), T(x), μ(x)*
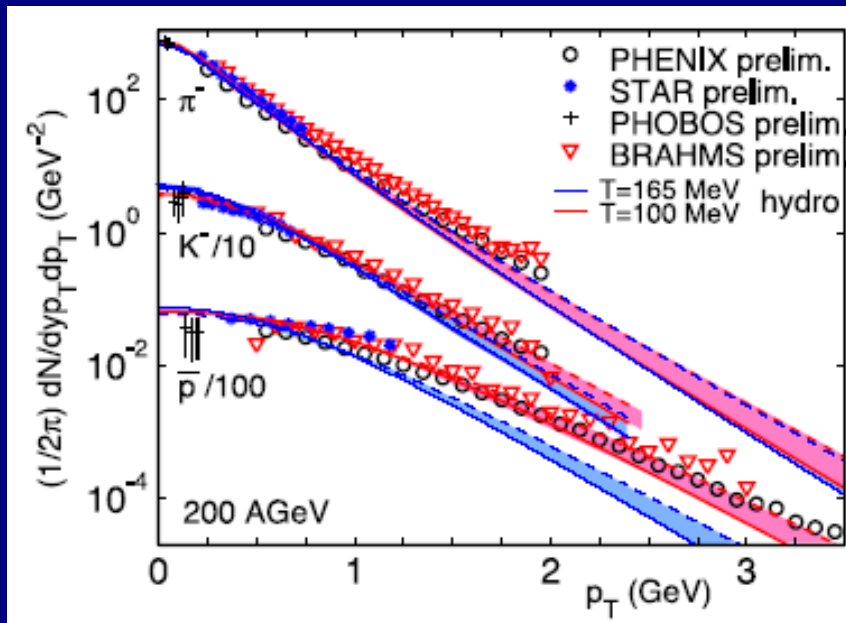
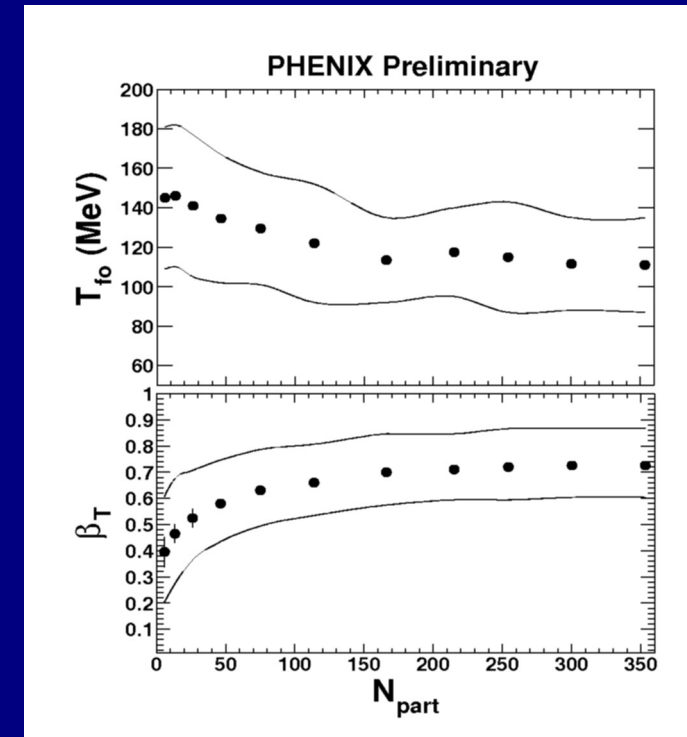# Hydrodynamical model is very succesfull

"Measuring" the initial temperature of the plasma with hydrodynamical model

The idea is to determine the initial conditions
from the observed final spectra (in the transverse plane)

$$\frac{dN}{dp_T} \approx e^{-m_T/T_{eff}}$$

$$T_{eff} \approx T_{dec} + \frac{1}{2}m\langle u_T^2 \rangle$$

PHENIX Preliminary

	SPS	RHIC 1	RHIC 2
$\sqrt{s_{NN}}$ (GeV)	17	130	200
s_{eq} (fm^{-3})	43	95	110
T_{eq} (MeV)	257	340	360
τ_{eq} (fm/c)	0.8	0.6	0.6

Fitted parameters (U Heinz et al.).
The initial T is correlated
to the initial equilibration time.

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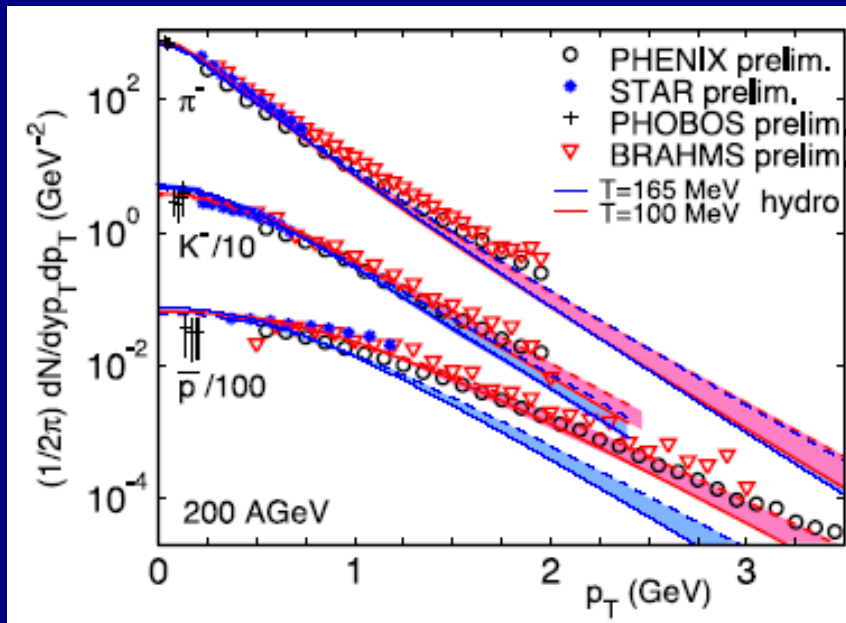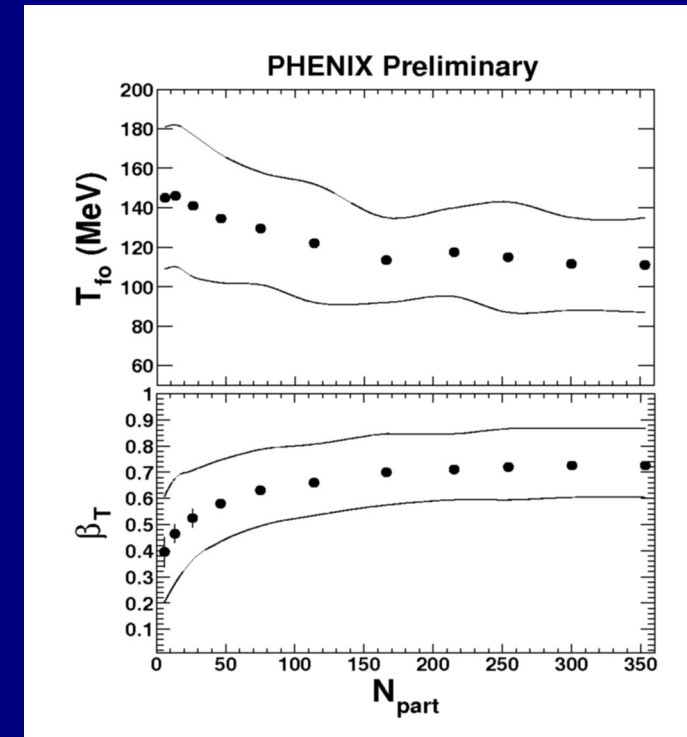$$T_{eff} \approx T_{dec} + \frac{1}{2}m\langle u_T^2 \rangle$$

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The initial T is correlated
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With hadronic multiplicities one can determine the thermodynamical state at the stage when hadrons cease inelastic interactions and decouple (chemical freeze-out)

$$\langle n_j \rangle = \frac{(2S_j + 1)V}{2\pi^2} m_j^2 T \gamma_S^{n_{sj}} K_2(m/T) e^{\sum_i \mu_i q_j^i / T}$$
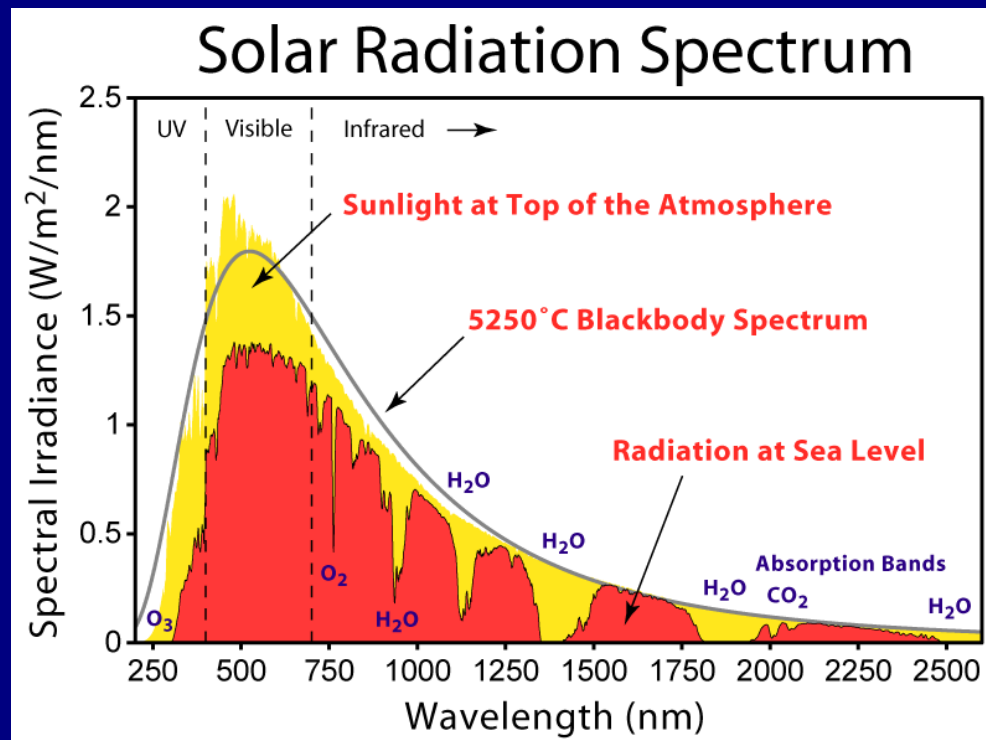
J. Cleymans et al. Phys.Rev. C73 (2006) 034905

Solar Radiation Spectrum
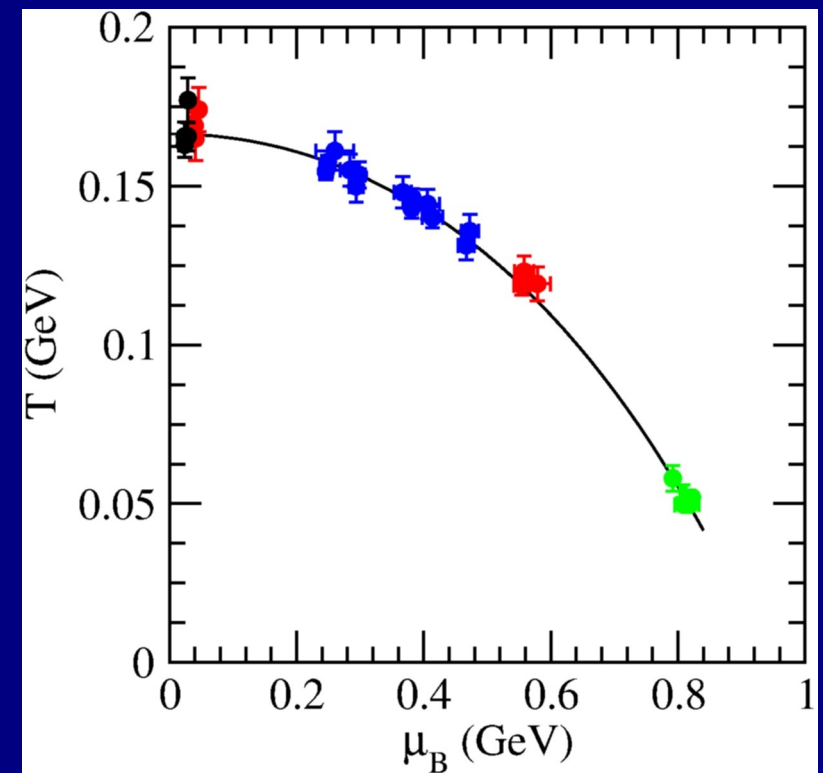
The temperature at the chemical freeze-out at RHIC is that of a hadronic black-body and it is the largest ever measured on Earth (~ 2 10^{12} K)

Reconstruction of the hadronization point and comparison with lattice QCD

Rescattering corrections imply an upward shift of the c.f.o. temperature

Chemical freeze-out line
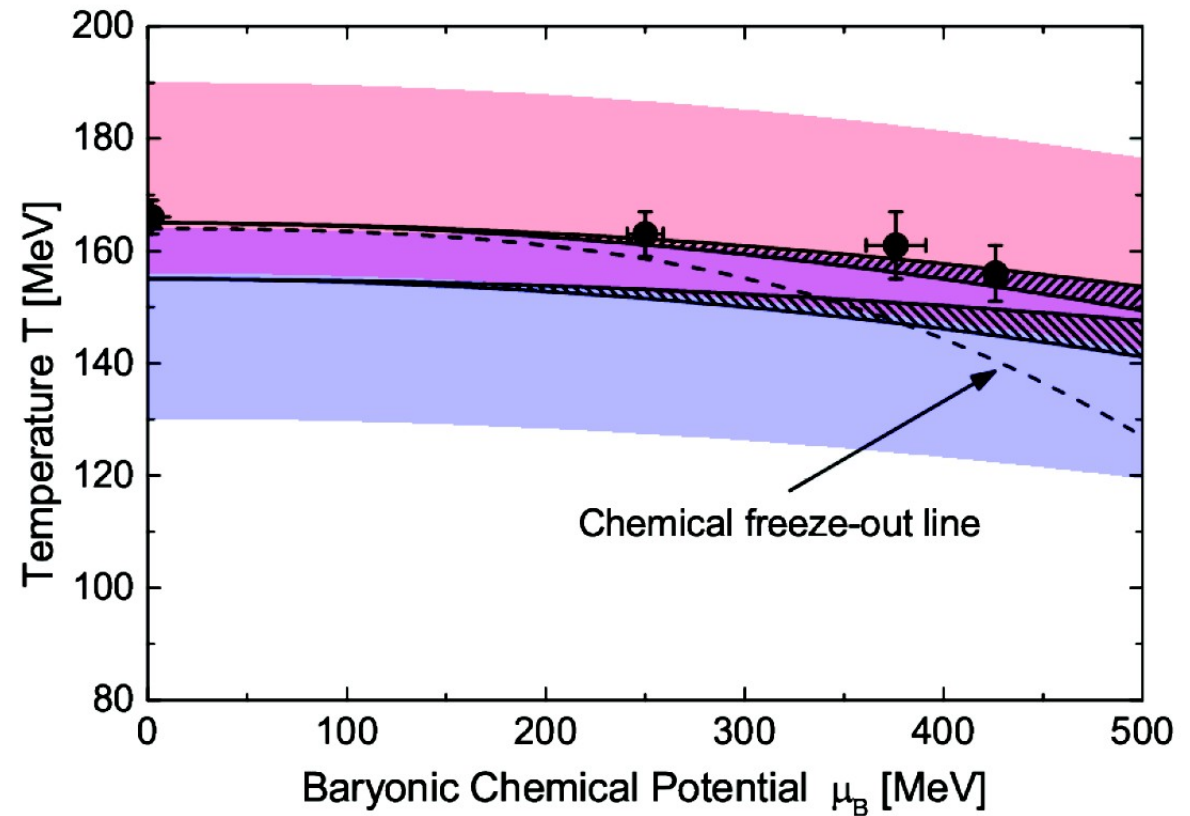
Lattice calculations from
F. Karsch, J. Phys. G 38, 124098 (2011); S. Borsanyi et al., ibidem 124101
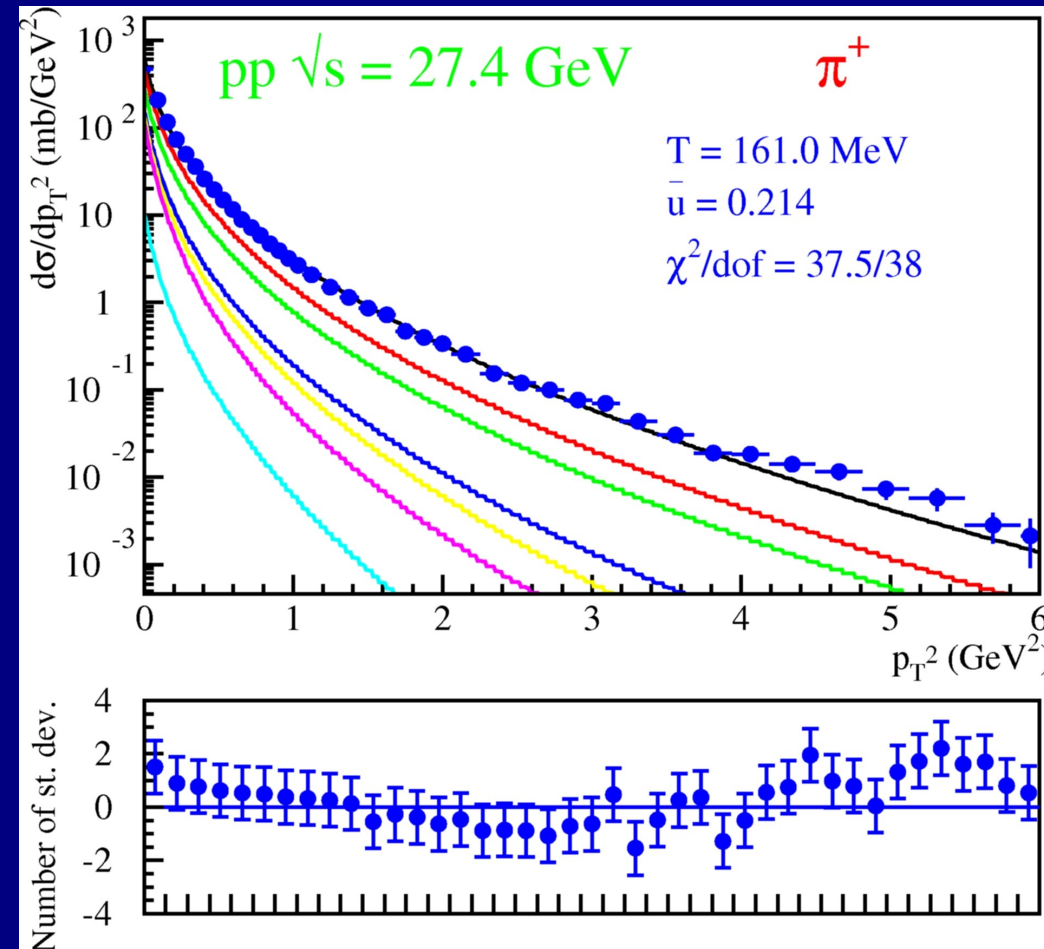G. Endrodi, Z. Fodor, S. D. Katz and K. K. Szabo, JHEP 1104, 001 (2011)
P. Cea, L. Cosmai, M. D'Elia, A. Papa, F. Sanfilippo, Phys.Rev. D85 (2012) 094512

Thermal distributions are ubiquitous in relativistic heavy ion collisions and in strong interactions (in the soft regime) in general.
It seems to be a feature of QCD in the non-perturbative regime. Why?

F. B., P. Castorina, J. Manninen, H. Satz, Eur. Phys. J. C 56 (2008) 493
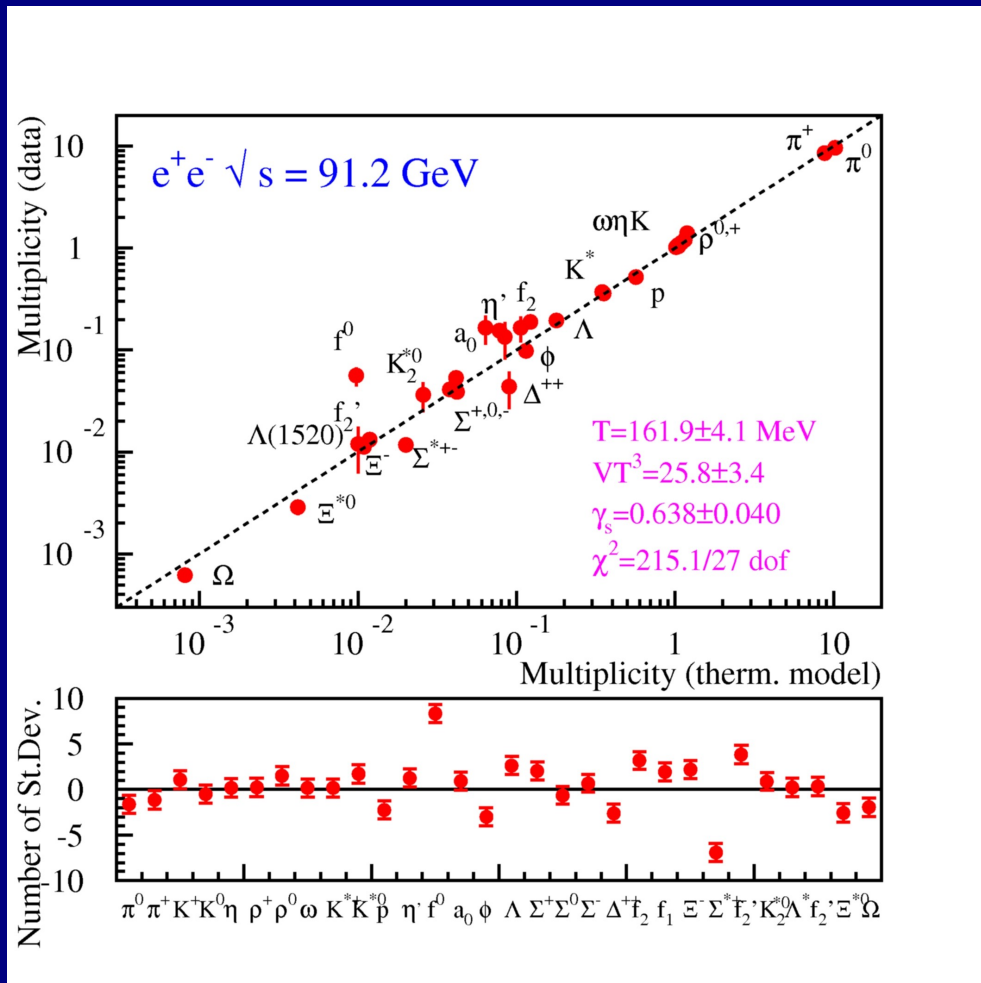
F. B., G. Passaleva, Eur. Phys. J. C 23 (2002) 551

Quark Gluon Plasma as a quasi-ideal fluid

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Contacts: Karen McNulty Walsh, (631) 344-8350 or Mona S. Rowe, (631) 344-5056

Print-friendly   E-mail Article

RHIC Scientists Serve Up "Perfect" Liquid

New state of matter more remarkable than predicted -- raising many new questions

April 18, 2005

TAMPA, FL -- The four detector groups conducting research at the Relativistic Heavy Ion Collider (RHIC) -- a giant atom "smasher" located at the U.S. Department of Energy's Brookhaven National Laboratory -- say they've created a new state of hot, dense matter out of the quarks and gluons that are the basic particles of atomic nuclei, but it is a state quite different and even more remarkable than had been predicted. In peer-reviewed papers summarizing the first three years of RHIC findings, the scientists say that instead of behaving like a gas of free quarks and gluons, as was expected, the matter created in RHIC's heavy ion collisions appears to be more like a *liquid*.

"Once again, the physics research sponsored by the Department of Energy is producing historic results," said Secretary of Energy Samuel Bodman, a trained chemical engineer. "The DOE is the principal federal funder of basic research in the physical sciences, including nuclear and high-energy physics. With today's announcement we see that investment paying off."

"The truly stunning finding at RHIC that the new state of matter created in the collisions of gold ions is more like a liquid than a gas gives us a profound insight into the earliest moments of the universe," said Dr. Raymond L. Orbach, Director of the DOE Office of Science.

Also of great interest to many following progress at RHIC is the emerging connection between the collider's results and calculations using the methods of string theory, an approach that attempts to explain fundamental properties of the universe using 10 dimensions instead of the usual three spatial dimensions plus time.

Secretary of Energy
Samuel Bodman

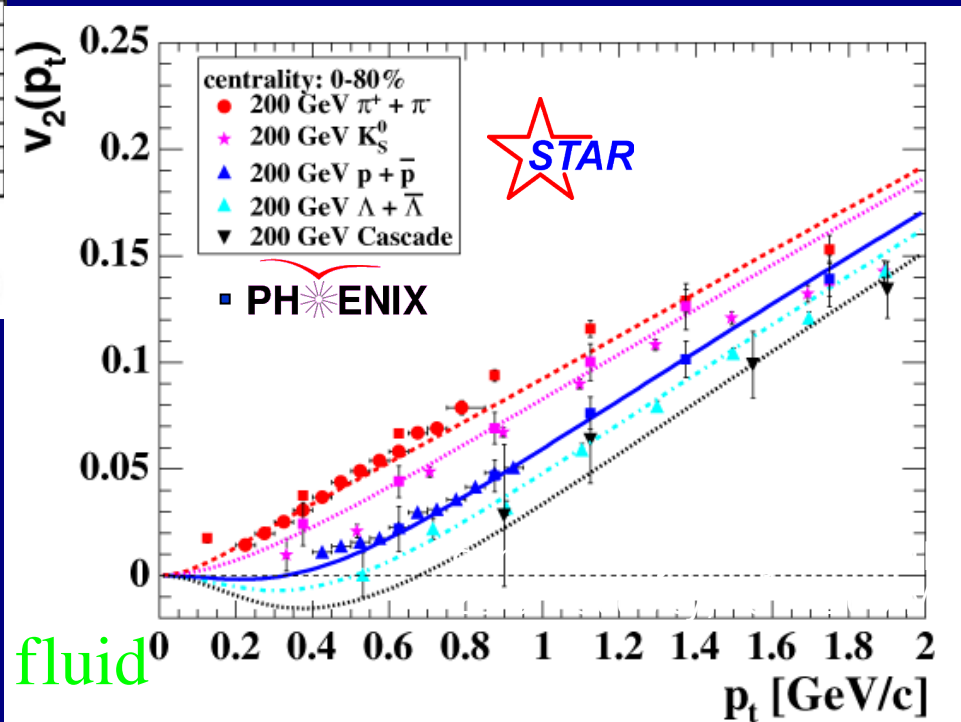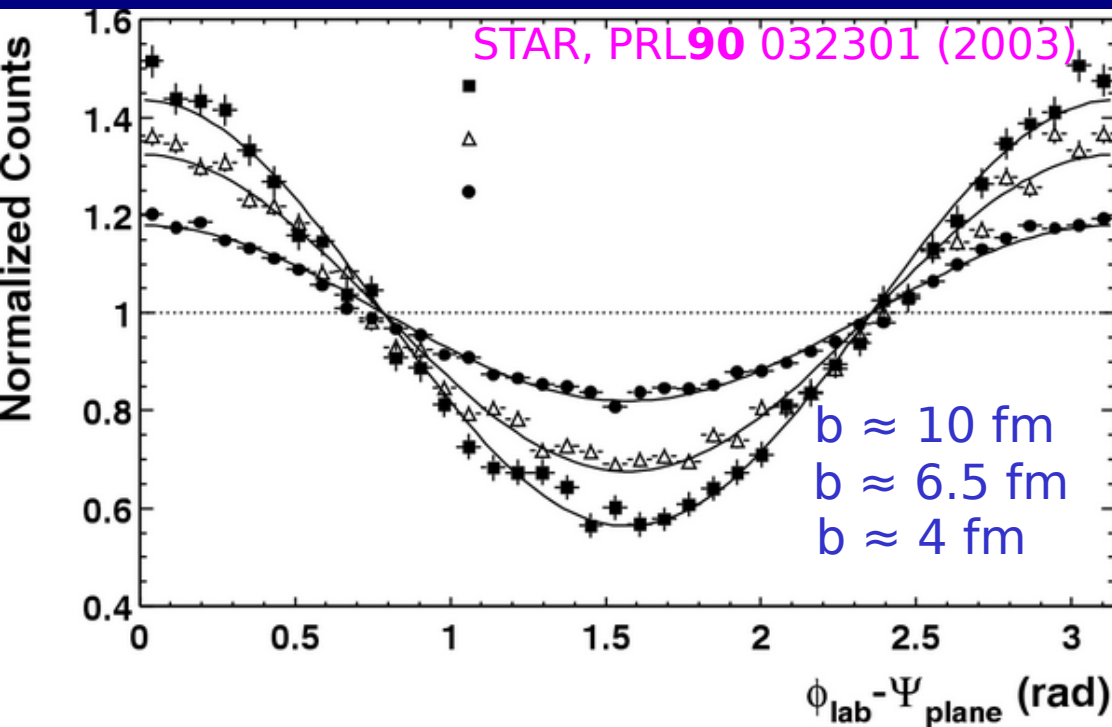# Elliptic flow in peripheral collisions

Reaction plane

z

y

x
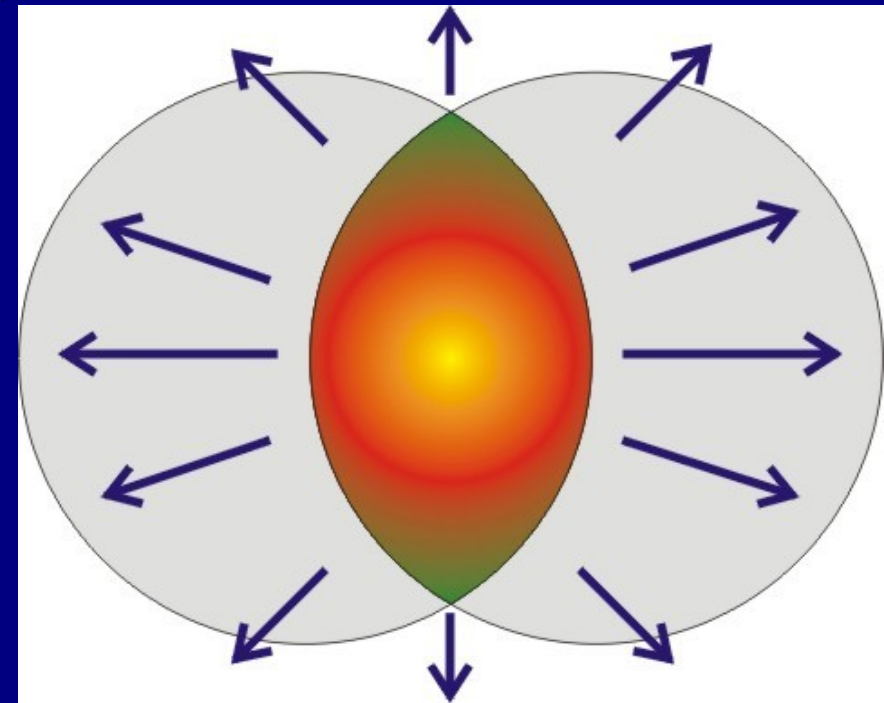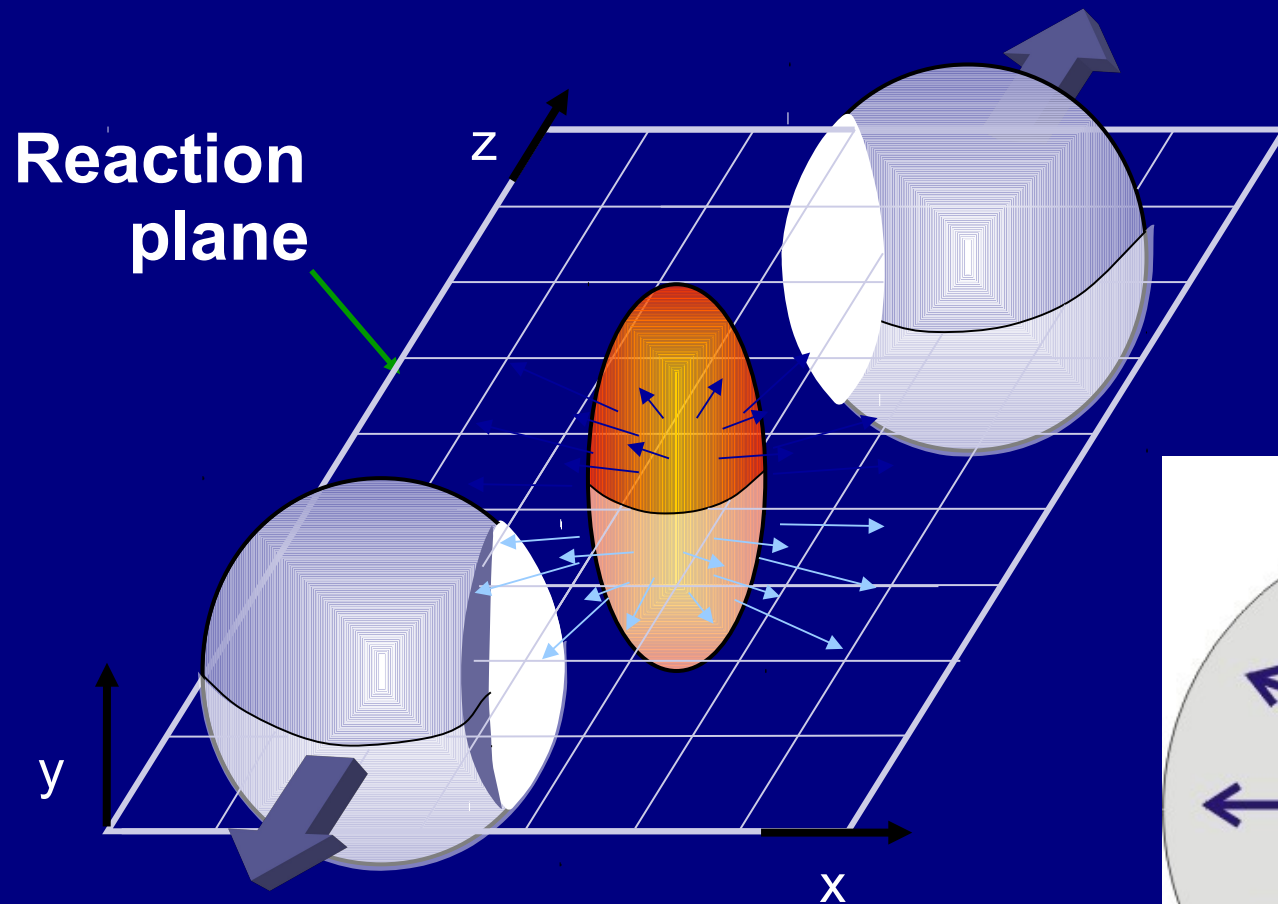
Anisotropic pressure gradient: if there is collective flow, particles get a larger momentum on the reaction plane!

$$\frac{dN_i}{dy\, p_\perp dp_\perp\, d\varphi_p}(b) = \frac{1}{2\pi} \frac{dN_i}{dy\, p_\perp dp_\perp}(b)\left(1 + 2\, v_2^i(p_\perp, b)\cos(2\varphi_p) + \dots\right).$$
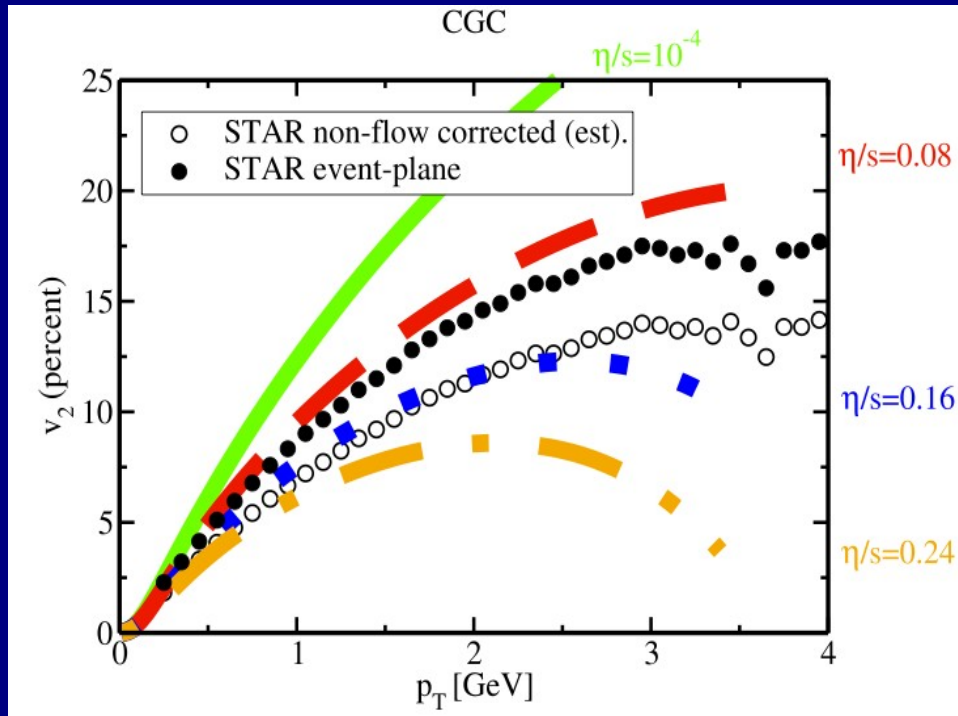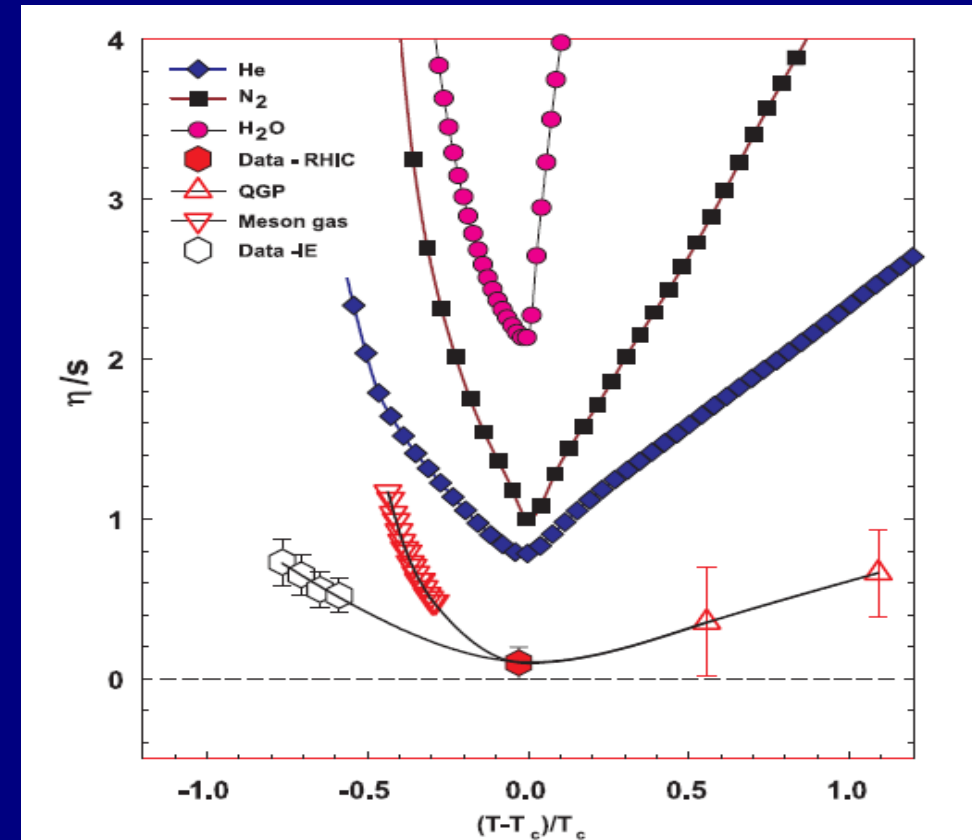
Elliptic flow coefficient v_2

$$\frac{dN_i}{dy\, p_\perp dp_\perp\, d\varphi_p}(b) = \frac{1}{2\pi} \frac{dN_i}{dy\, p_\perp dp_\perp}(b)\left(1 + 2\, v_2^i(p_\perp, b)\cos(2\varphi_p) + \dots\right).$$

STAR, PRL**90** 032301 (2003)

$b \approx 10$ fm
$b \approx 6.5$ fm
$b \approx 4$ fm

centrality: 0-80%
- 200 GeV $\pi^+ + \pi^-$
- 200 GeV K_S^0
- 200 GeV $p + \bar{p}$
- 200 GeV $\Lambda + \bar{\Lambda}$
- 200 GeV Cascade

STAR

PH✳ENIX

v_2 in good agreement with quasi-ideal fluid

Elliptic flow is sensitive to the viscosity of the QGP

P. Romatschke

Very low values of viscosity, or better: η/s ratio

Summary of viscosity "measurements" at RHIC and LHC (U. Heinz, RANP 2013)

$$(\eta/s)_{QGP}(T_c < T < 2T_c) = \frac{2}{4\pi} \pm 50\%$$

What does low viscosity mean?

From kinetic theory:

$$\eta = \frac{1}{3}\rho v_T \lambda = \frac{1}{3}mnv_T\lambda = \frac{1}{3}np_T\lambda$$

In relativistic fluid:

$$n \sim s \qquad \qquad \frac{\eta}{s} \sim p_T\lambda$$

Low values of η/s imply that the thermal wavelenght is comparable to the mean free path: a particulate description of this fluid is inconsistent

Gas at STP:

$$n = 2.7 \times 10^{25}m^{-3} \qquad \sigma \approx 10^{-19}m^2$$
$$\rightarrow \lambda \approx 400nm \gg d = (1/n)^{1/3} = 3nm \gg \lambda_T \approx 5pm$$

Water:

$$n = 3.410^{28}m^{-3} \qquad \sigma \approx 10^{-19}m^2$$
$$\rightarrow \lambda \approx 0.3nm \approx d = (1/n)^{1/3} = 0.31nm \gg \lambda_T \approx 5pm$$

QGP is so strongly interacting near Tc that a particle cannot travel a wavelenght without colliding!

Beyond Quasiparticles

- QGP at RHIC & LHC, unitary Fermi "gas", gauge theory plasmas with holographic descriptions are all strongly coupled fluids with no apparent quasiparticles.

- In QGP, with η/s as small as it is, there can be no 'transport peak', meaning no self-consistent description in terms of quark- and gluon-quasiparticles. [Q.p. description self consistent if $\tau_{qp} \sim (5\eta/s)(1/T) \gg 1/T$.]

- Other "fluids" with no quasiparticle description include: the "strange metals" (including high-T_c superconductors above T_c); quantum spin liquids; matter at quantum critical points;...

K. Rajagopal

QGP near Tc is not a kinetic system, it is a system of strongly interacting quantum fields, still it is a fluid.

Microscopic scale << macroscopic size: $\lambda \ll L$.

Hydrodynamics without kinetic theory

$$T^{\mu\nu}(x) = \text{tr}(\widehat{\rho}\,\widehat{T}^{\mu\nu}(x))$$

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

Zubarev non-equilibrium stationary density operator (for close-to-local equilibrium evolution):

$$\widehat{\rho} = \frac{1}{Z}\exp\left[-\lim_{\varepsilon\to 0}\varepsilon\int_{-\infty}^{t'}\mathrm{d}t\,\mathrm{e}^{\varepsilon(t-t')}\int \mathrm{d}^3 x\,(\widehat{T}^{0,\nu}(x)\beta_\nu(x) - j^0(x)\xi(x))\right]$$

$$\beta = \frac{1}{T}u \qquad \xi = \mu/T$$

It contains a microscopic length, which is not properly a mean free path, rather a correlation distance for quantum fields, particularly of stress-energy tensor components.

Recent developments from LHC experiments: from averages to event-by-event hydrodynamics
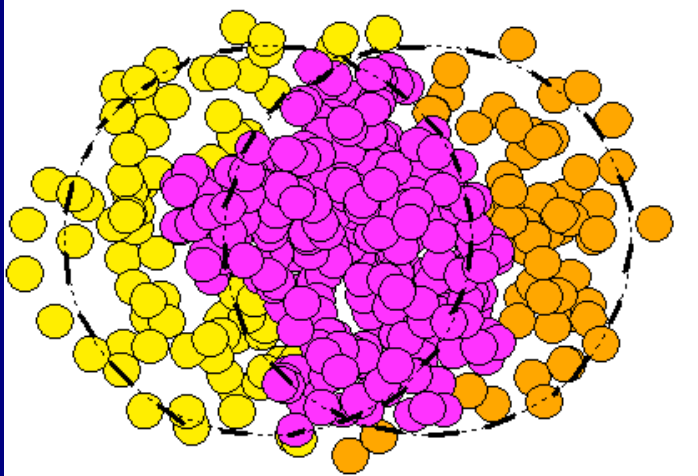
Higher harmonics in the azimuthal spectrum of
Particles in the transverse plane

When including fluctuations, all moments appear:
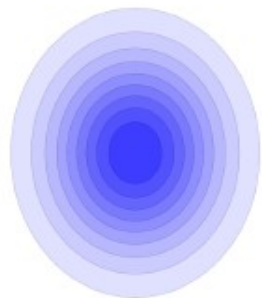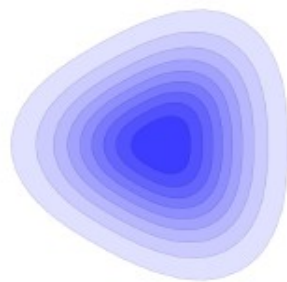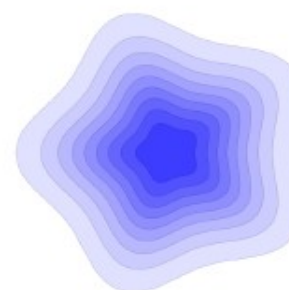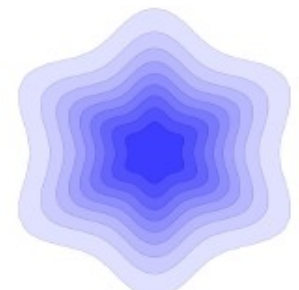
$n = 2$ $n = 3$ $n = 4$ $n = 5$ $n = 6$

also v_1 and $n > 6$

Compute $v_n = \langle \cos[n(\phi - \psi_n)] \rangle$

Viscosity smoothens fluctuations and affect more higher harmonics

$$(\eta/s)_{\mathrm{QGP}}(T_c < T < 2T_c) = \frac{2}{4\pi} \pm 50\%$$

Numerical codes are getting more important and more performing.
State of the art: 3+1 D with viscous corrections in the Israel-Stewart framework plus
initial state fluctuations (among others: ECHO-QGP, Firenze-Ferrara-Torino collaboration).

Ideal

Viscous

t = 3.7 fm/c
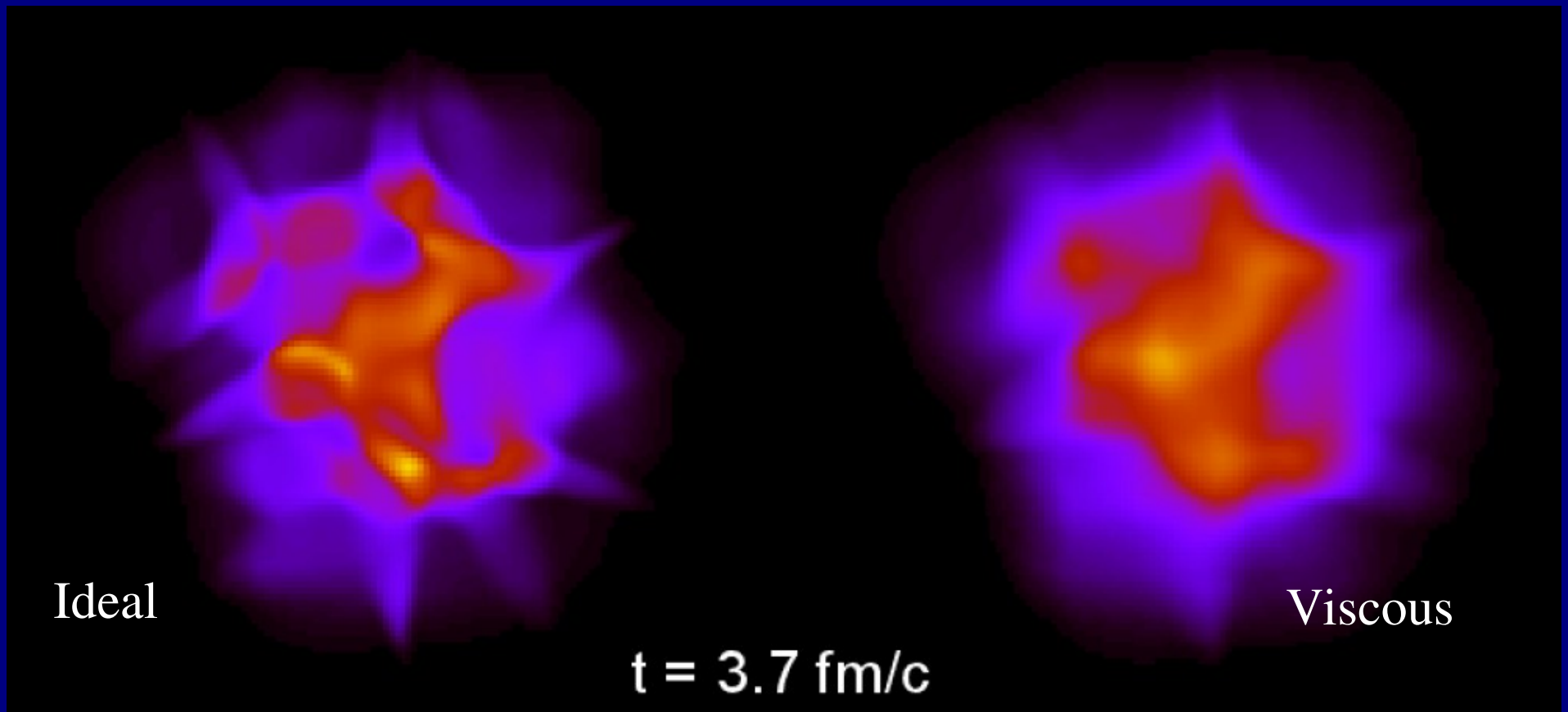
Anisotropies in the azimuthal plane in relativistic heavy ion collisions: extraction of the QCD transport coefficients

Analogous to CMB anisotropies

t = 3.7 fm/c

PLANCK

ALICE

Centrality
0-2%

$2 < p_T^t < 2.5$ GeV/c

$1.5 < p_T^a < 2$ GeV/c
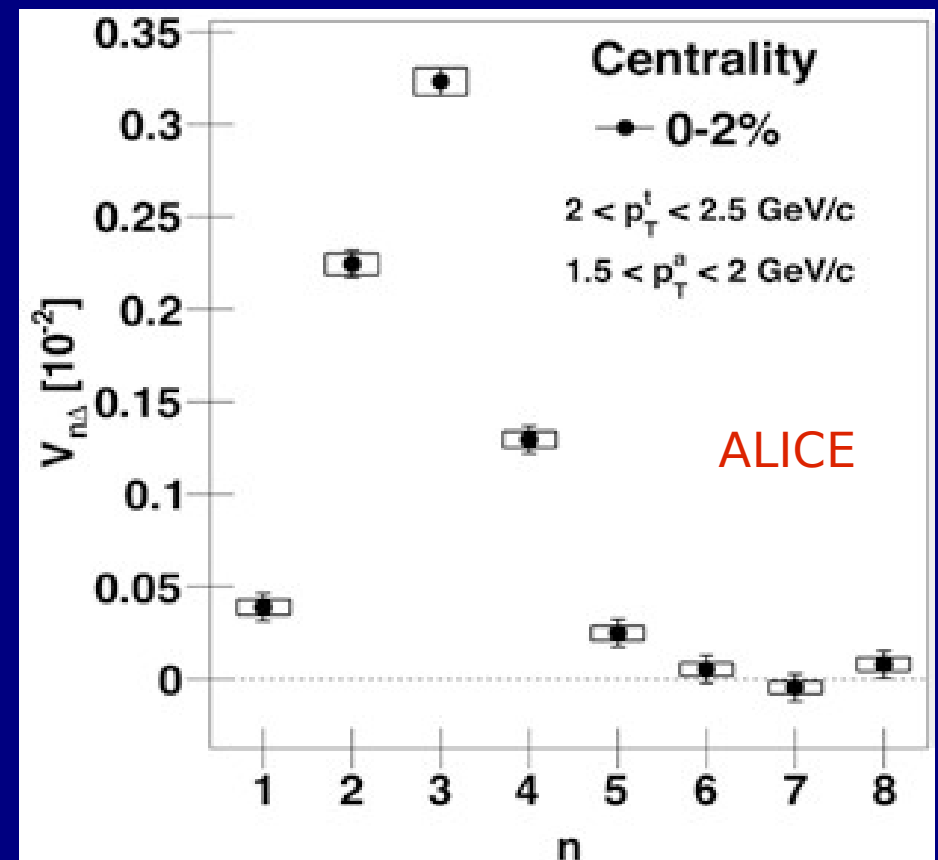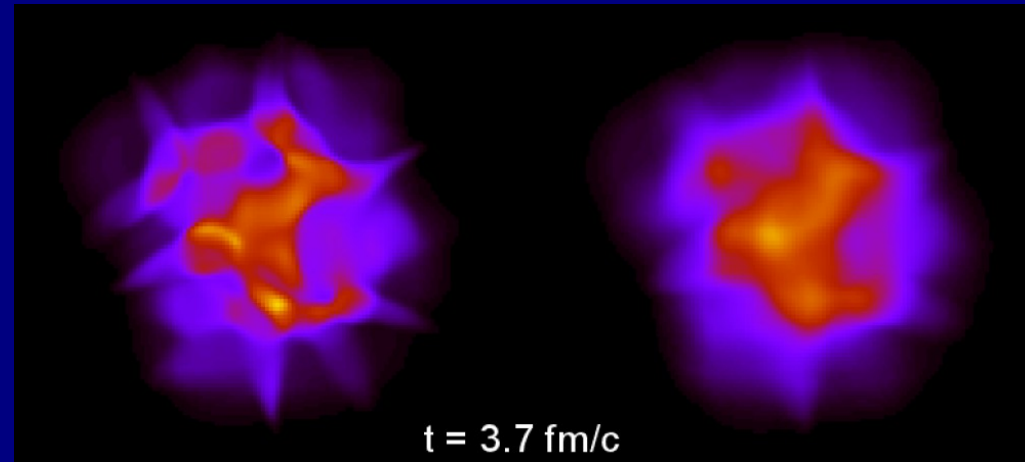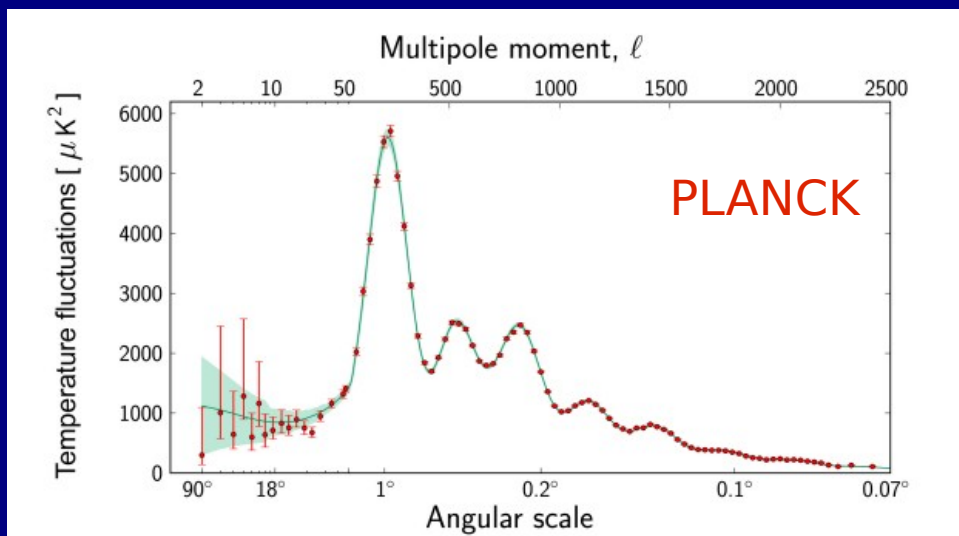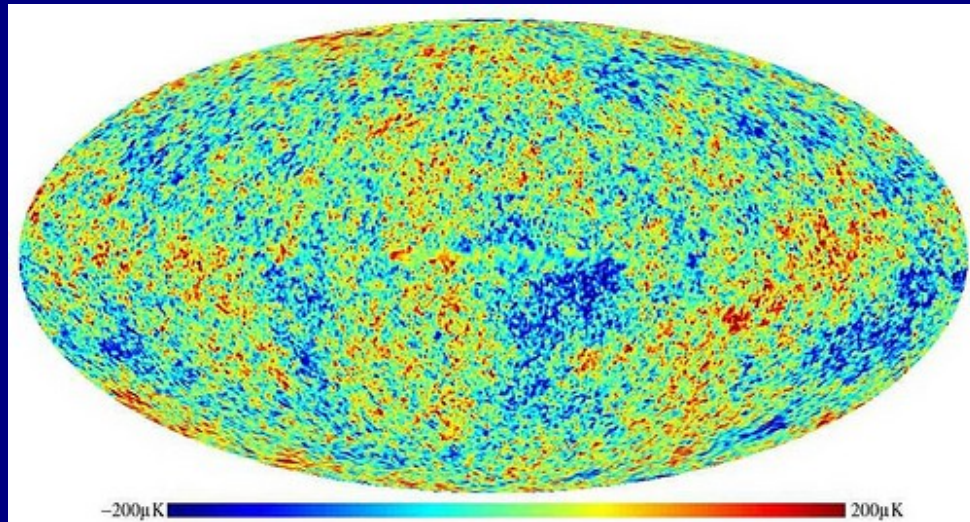
Outlook

- There is little doubt that QGP has been produced in relativistic heavy ion collisions. The study of its properties is ongoing at the LHC.

- The dynamical QGP evolution can be described in terms of relativistic thermodynamics and hydrodynamics. This allows to test specific predictions of QCD thermodynamics, such as equation of state, transport coefficients etc.

- Why are the thermal distributions observed at all in strong interactions in high energy collisions?

- Search of more features of QCD phase diagram at lower energy: critical point ?

- Relativistic heavy ion collisions have been a very effective laboratory for many physics subjects: not only QCD, but also relativistic statistical mechanics, relativistic hydrodynamics and kinetics

ECHO-QGP: codice di idrodinamica relativistica dissipativa della comunità italiana

Collaborazione Firenze-Ferrara-Torino entro RM31-SIM e PRIN2009(2011)

Relativistic viscous hydrodynamics for heavy-ion collisions with ECHO-QGP

L. Del Zanna[1,2,3,a], V. Chandra[2], G. Inghirami[1,2], V. Rolando[4,5], A. Beraudo[6], A. De Pace[7], G. Pagliara[4,5], A. Drago[4,5], F. Becattini[1,2,8]

Evoluzione di ECHO codice numerico 3+1 D ideale GR per plasmi astrofisici
(L. Del Zanna et al.)

Include 3+1D Israel-Stewart con fluttuazioni di stato iniziale e produzione di particelle (vedi talk di Valentina Rolando)
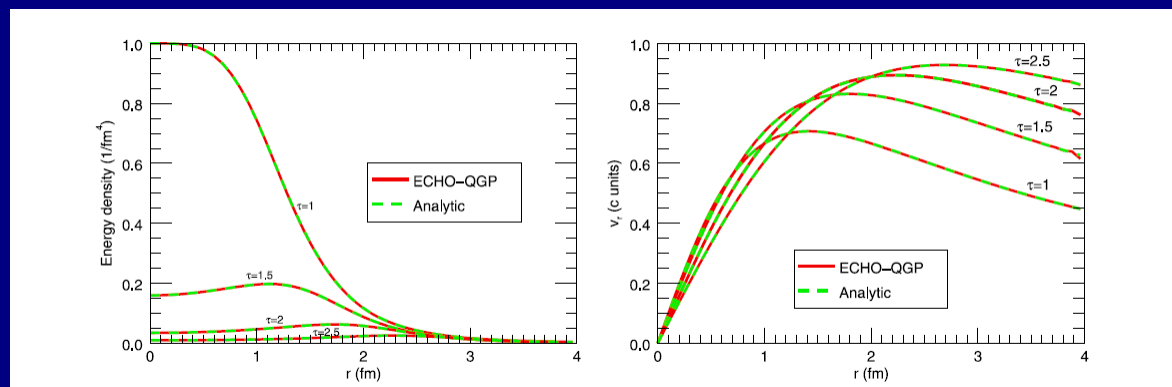
Shear viscosity in strongly interacting conformal quantum field theory (from AdS/CFT correspondance)

$$\frac{\eta}{s} = \frac{\hbar}{4\pi}$$

<u>Conjecture:</u> it is a universal quantum bound which is reached for the maximal coupling

$$\eta \sim \rho v \ell, \qquad s \sim n = \frac{\rho}{m}$$

$$\frac{\eta}{s} \sim m v \ell \sim \hbar \frac{\text{mean free path}}{\text{de Broglie wavelength}}$$

Quasiparticles: de Broglie wavelength $\lesssim$ mean free path

Therefore $\eta/s \gtrsim \hbar$

Jets as a probe of the plasma

Nucleus-nucleus collisions

- hard initial scattering
- scattered partons probe traversed hot

   and dense medium
- 'jet tomography'

- Initial parton-parton scattering with

large momentum transfer

 - Unlike in vacuum, quarks and gluons lose energy (brehmsstrahlung and collisions) before hadronizing
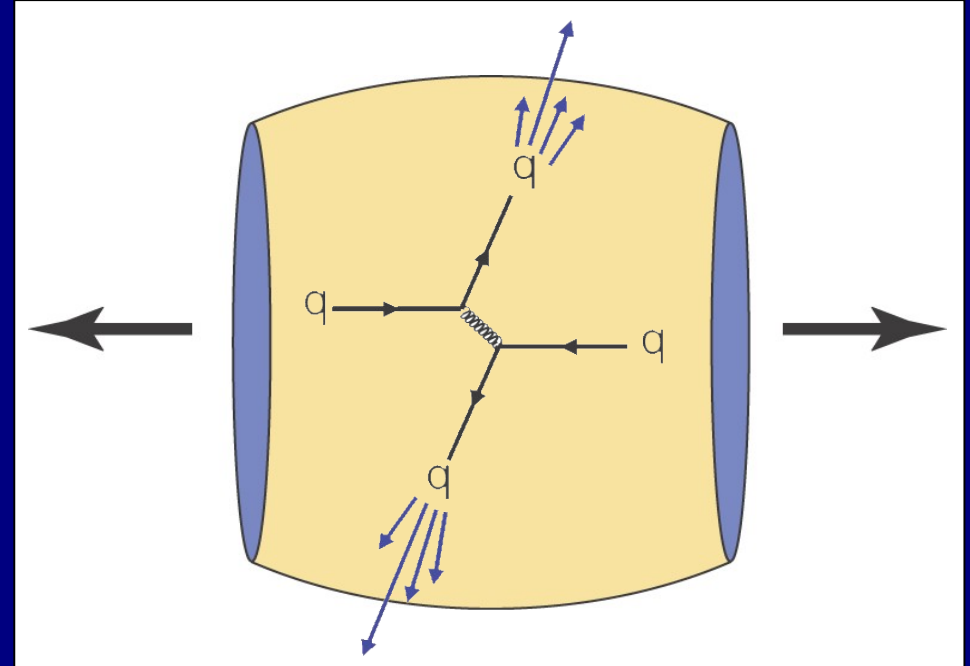
Theoretical task: to calculate energy distribution of hard partons traversing a length L within the medium

Di-jet imbalance

- Pb-Pb events with large di-jet imbalance observed at the LHC
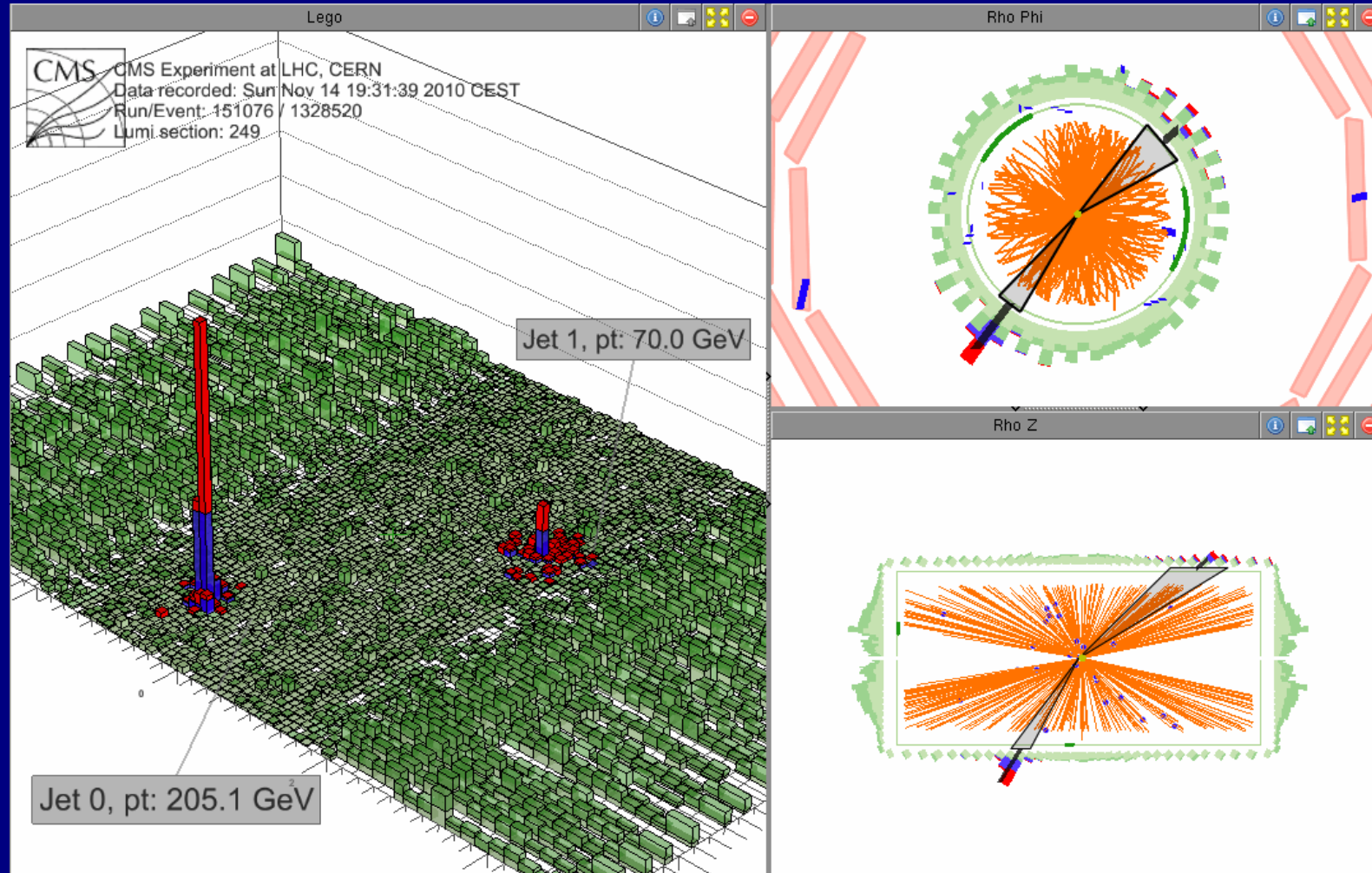
-
→ recoiling jet strongly quenched!

Anisotropia di impulso

$$\epsilon_p = \frac{\langle T^{xx} - T^{yy} \rangle}{\langle T^{xx} + T^{yy} \rangle}$$
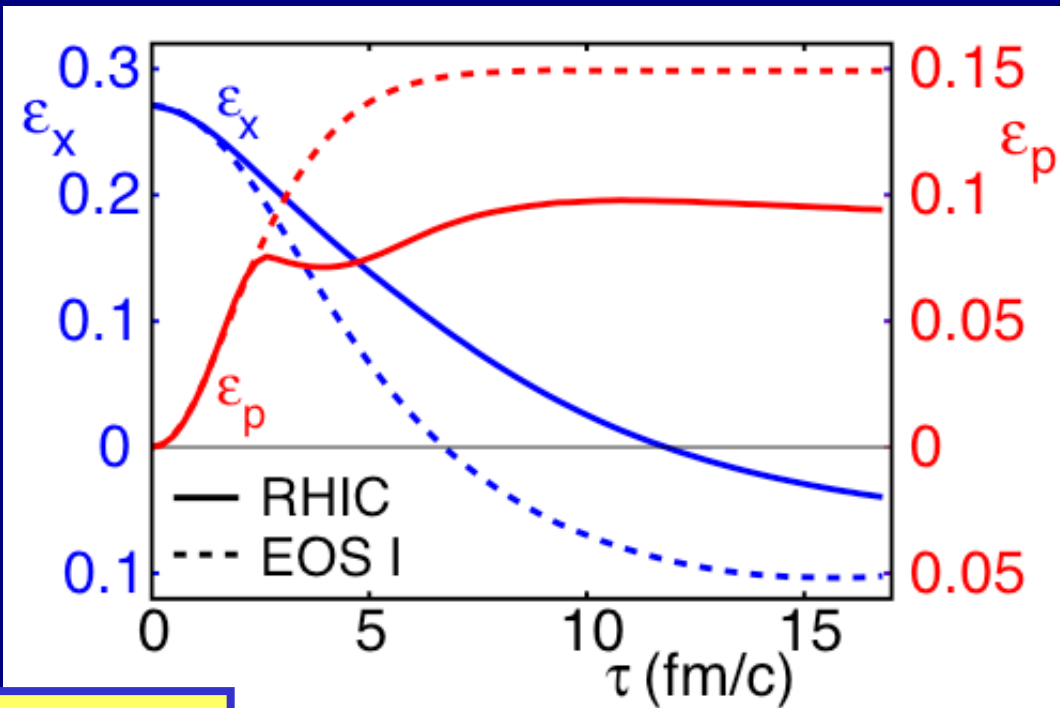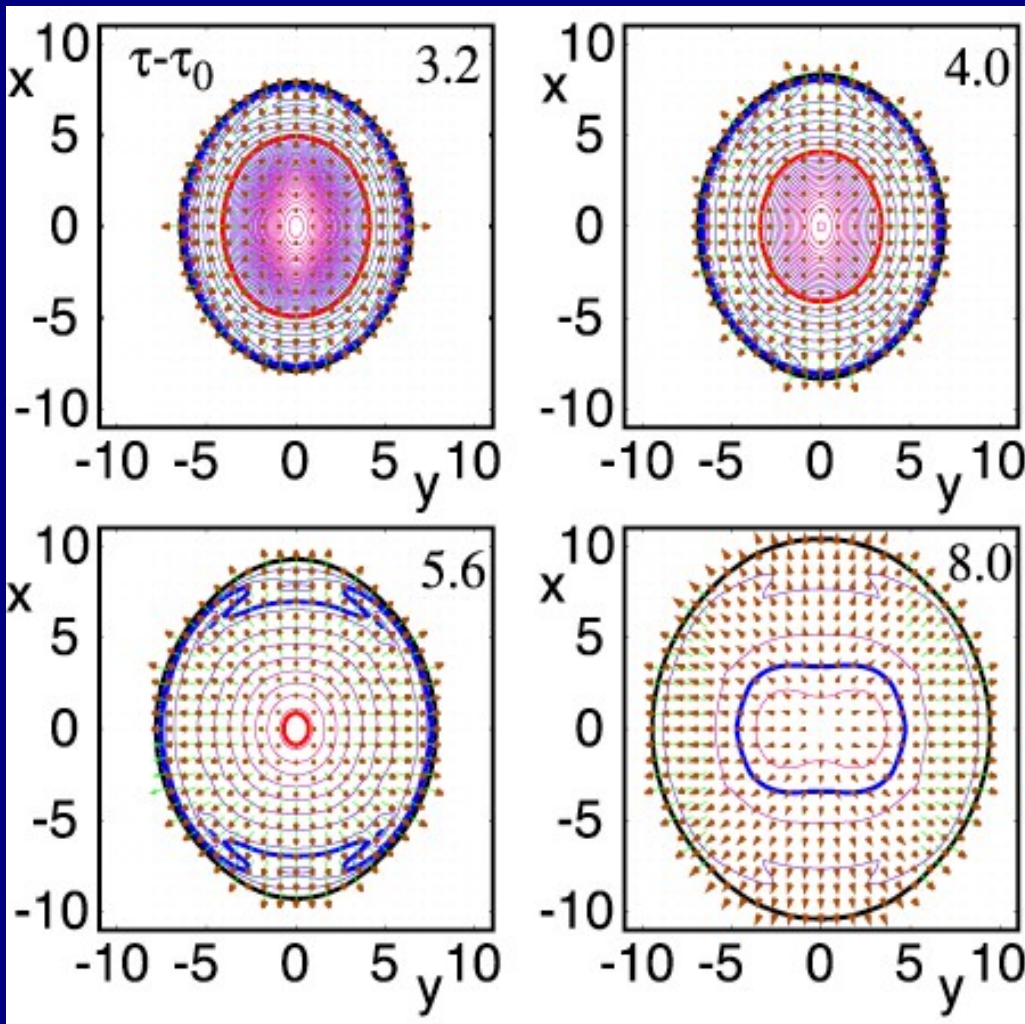
Spacial anisotropy gets converted into momentum anisotropy provided that:
- Thermalization occurs while the system is still almond-shaped
- This requires short times (~ 1 fm/c) when the system is still in the QGP phase

Soft and Hard probes

SOFT (pT $\sim \Lambda$QCD,T)
driven by *non perturbative QCD*

dron yields, <u>collective modes of the bulk</u>,
ngeness enhancement, fluctuations,
rmal radiation, dilepton enhancement

HARD (pT >>> ΛQCD)
Early production, pQCD applicable,
Baseline pp, pA

quenching, <u>heavy quarks</u>, quarkonia,
rd photons (W,Z)

Nuclear modification factor

$$R_{AA}(p_T) = \frac{d^2 N^{AA}/dp_T}{N_{coll}\, d^2 N^{NN}/dp_T} = \frac{medium}{vacuum}$$
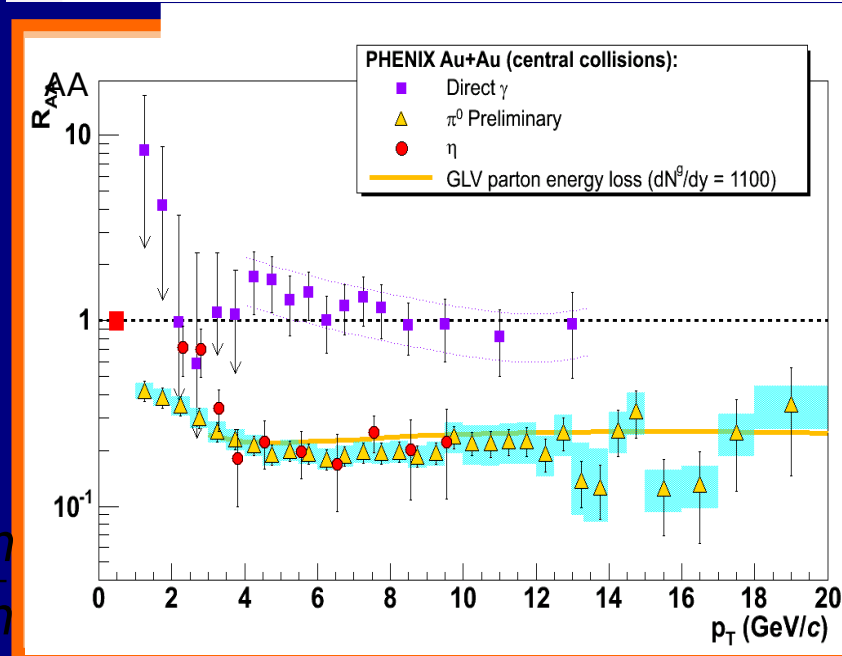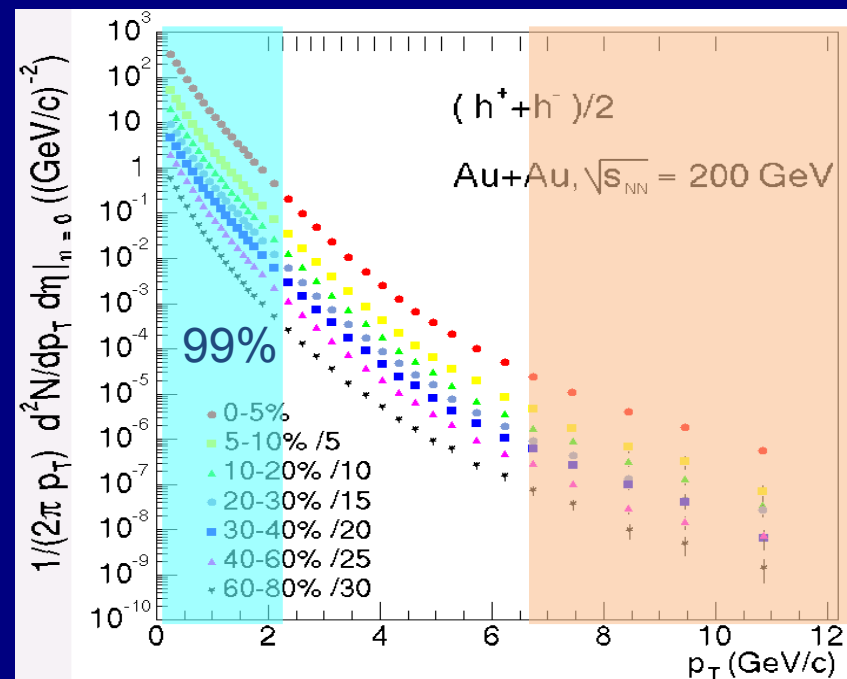
Some typical definitions

Longitudinal view

y = 0

z
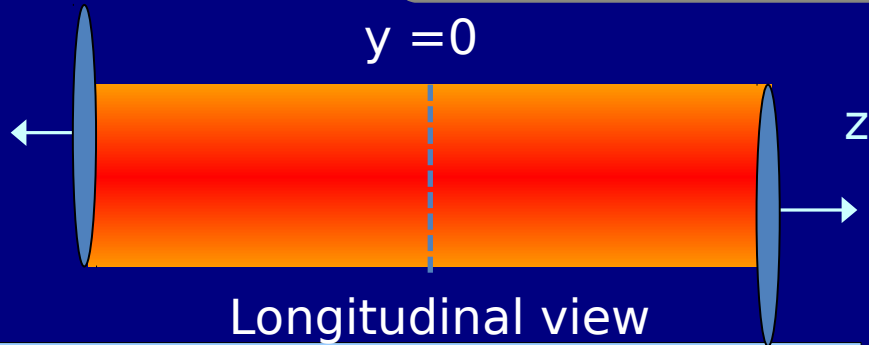
$$y_z = \tanh^{-1}\beta = \frac{1}{2}\ln\frac{E+p_z}{E-p_z} \approx v_z$$

Transverse view

y

φ

x
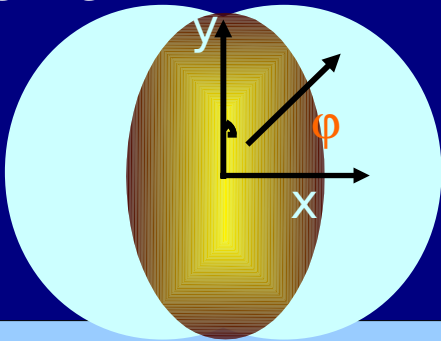
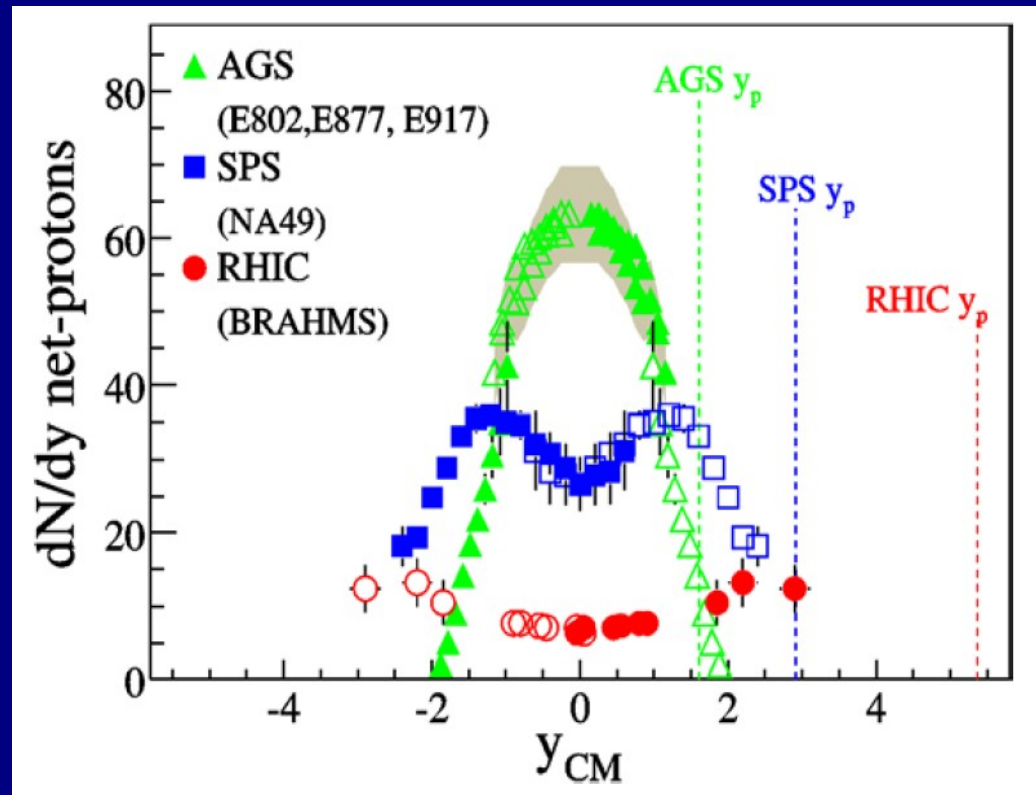$$p^\mu = \left(E, p_x, p_y, p_z\right)$$

In terms of pT and y

$$p^\mu = \left(m_T\cosh y, p_T, m_T\sinh y\right)$$

Centrality of the collisions

$\frac{dN}{dN_{ch}}$ 10^3 (a)

50%

40% 30%   20%   10%   5%

STAR

10^2

10

1

0   100   200   300   400   500   600 N_{ch}

15 fm ——————— b ——————— 0 fm

0 ——————— Npart ——————— 394
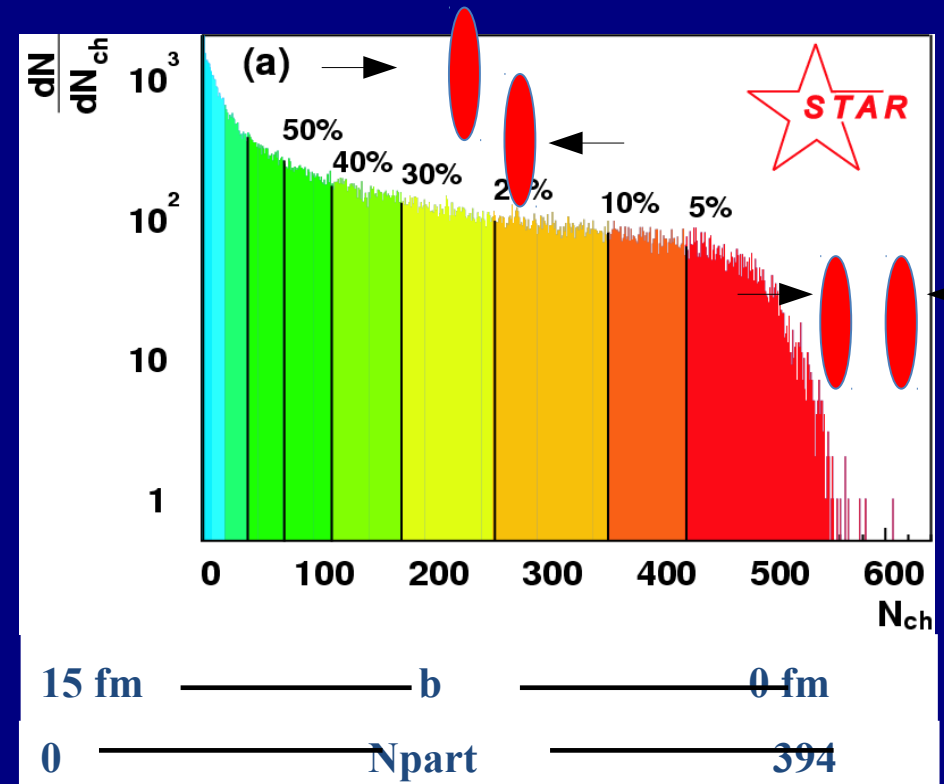
$$m_T = \sqrt{p_T^2 + m^2}$$

Increasing the energy...

Baryon stopping decreases, but a larger energy density is achieved
(hotter, denser, longer)
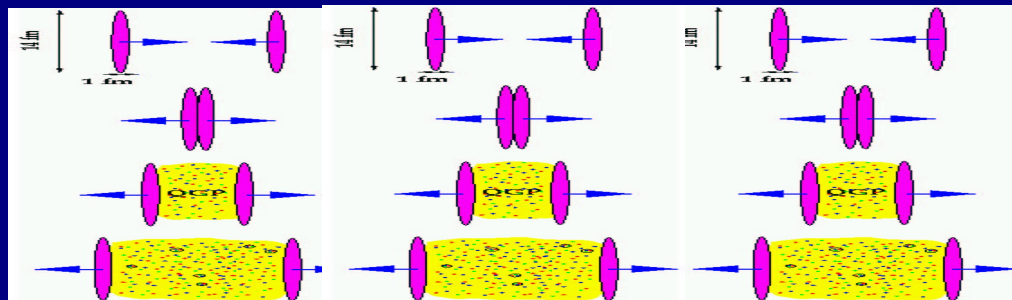
Have we overcome the critical T?

Same observation as in elementary collisions. Statistical equilibrium as an Intrinsic feature of QCD at the soft scale, i.e. hadronization (F.B., U. Heinz, R. Stock, H. Satz et al)
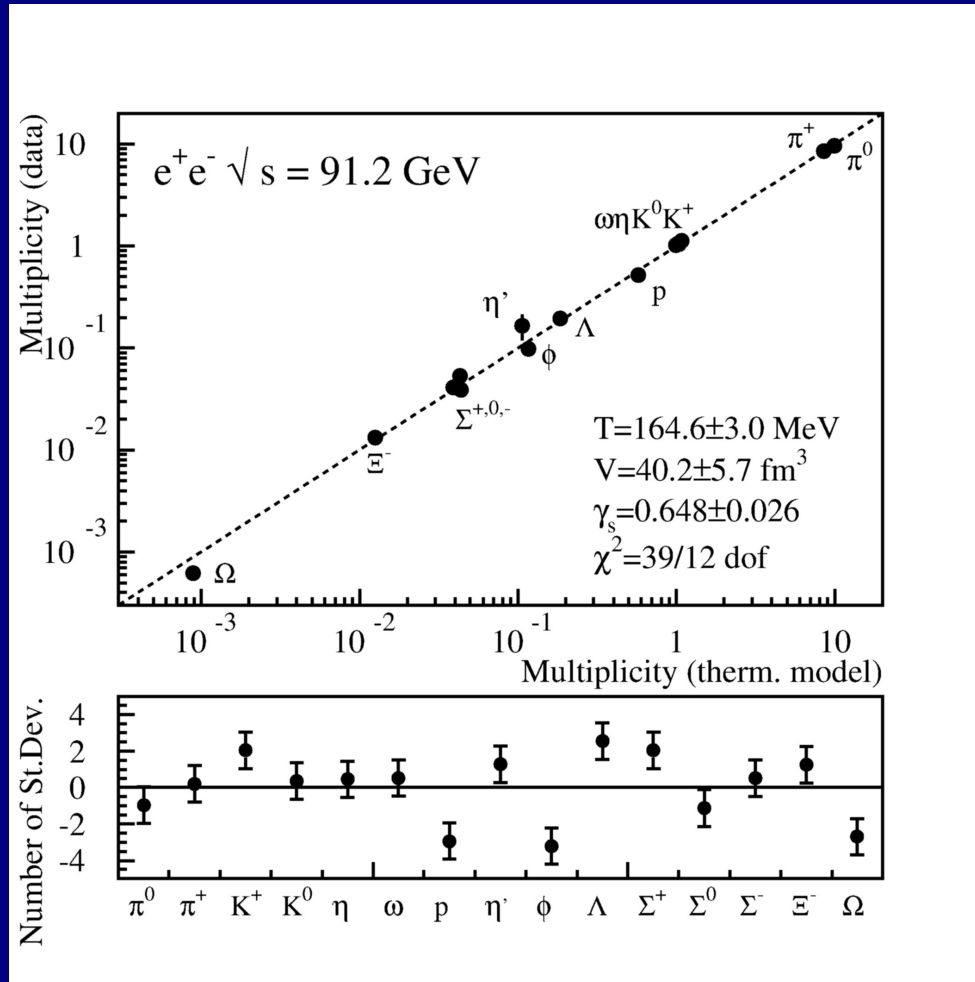
In order to show that Tc has been overcome, i.e. that a QGP has been produced, we need to go to other observables

Strangeness enhancement: Wroblewski ratio
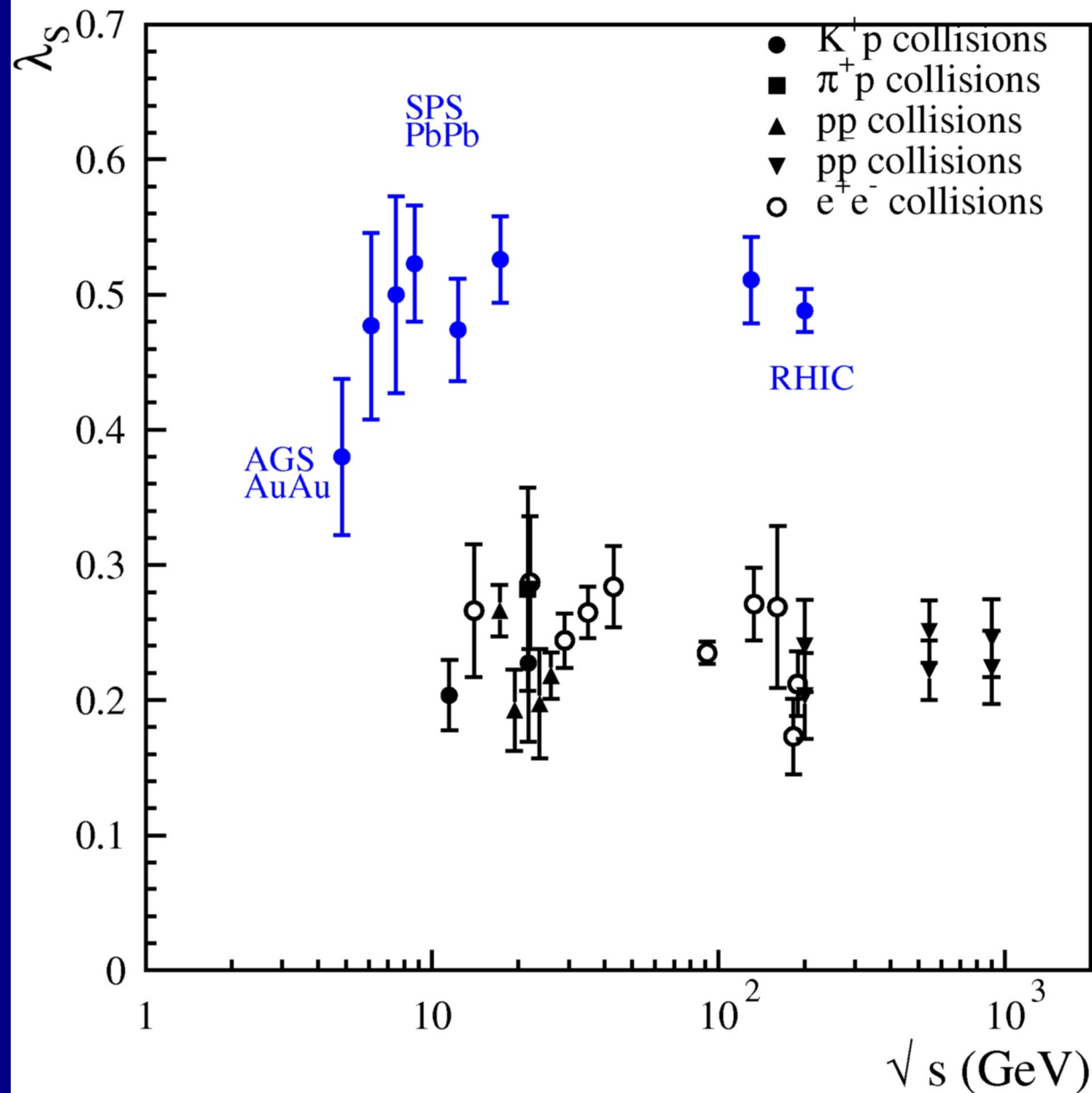
$$\lambda_S = 2 \frac{\langle s\bar{s} \rangle}{\langle u\bar{u} + d\bar{d} \rangle}$$
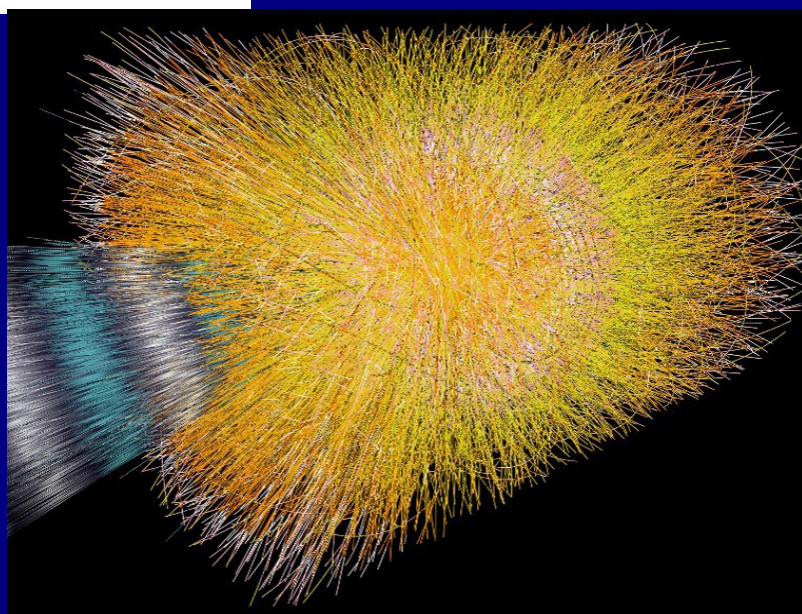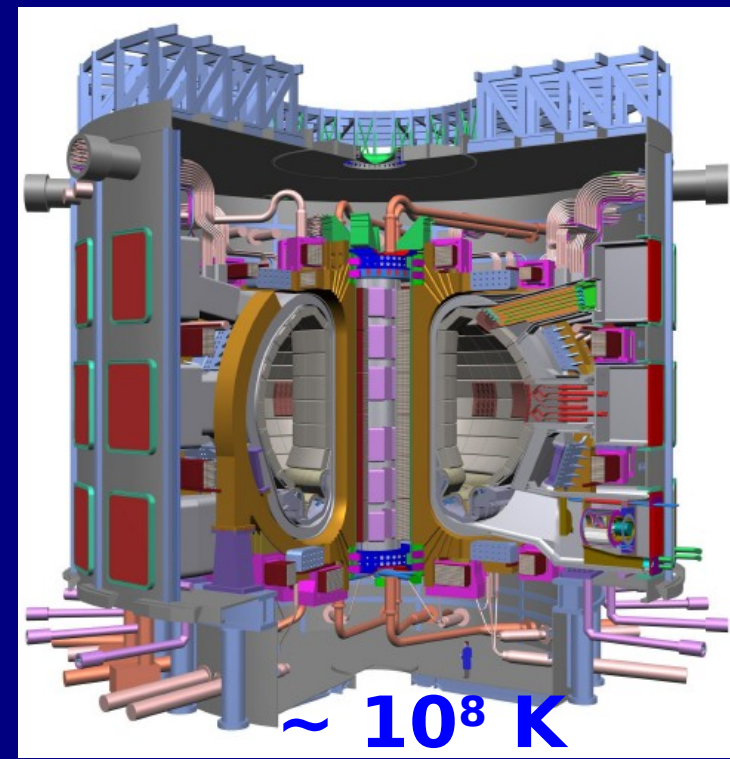
Suppression of high-p$_T$ hadrons (not so for γ)

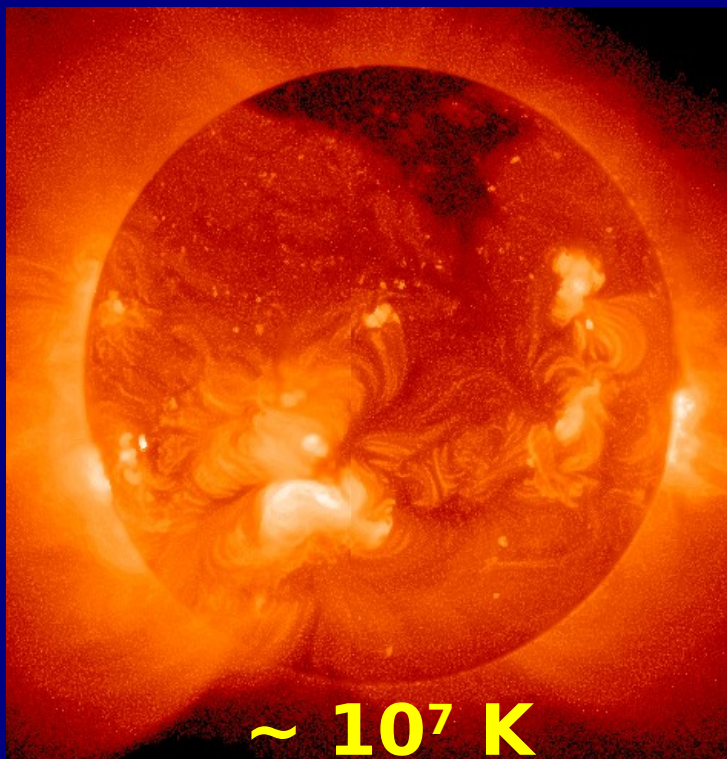$$R_{\mathrm{AA}}(p_T) = \frac{\mathrm{Yield}_{\mathrm{AA}}(p_T)}{\langle Nbin \rangle_{\mathrm{AA}} \, \mathrm{Yield}_{\mathrm{pp}}(p_T)}$$

- Due to energy loss of partons, there is a strong suppression of high pt hadrons

- Even larger at LHC than @ RHIC

- Nuclear modification factor R$_{AA}$(p$_T$) for charged particles produced in 0-5% centrality range

  – minimum (~ 0.14) for p$_T$ ~ 6-7 GeV/c

  – then slow increase at high p$_T$

Including CDF data

0.9 TeV * NLO (2.76 TeV)/NLO(0.9 TeV)

R$_{AA}$

- 0 - 5%
- 70 - 80%

Pb-Pb $\sqrt{s_{NN}}$ = 2.76 TeV

p$_T$ (GeV/c)
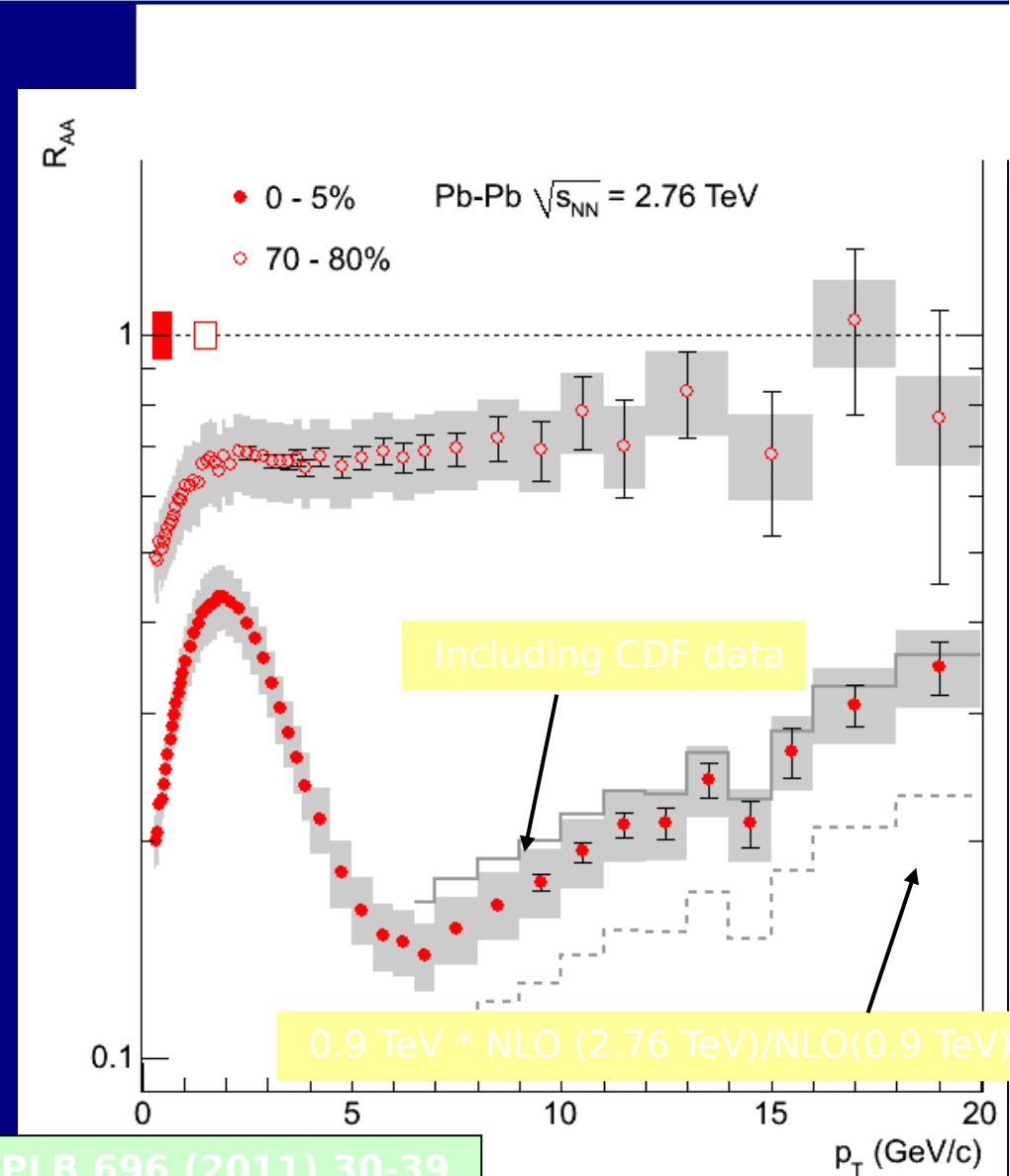
The largest temperature ever achieved on Earth
(> 2 x 10^{12} K)

~ 10^3 K

~ 10^7 K

~ 10^8 K

~ 5 10^{12} K !
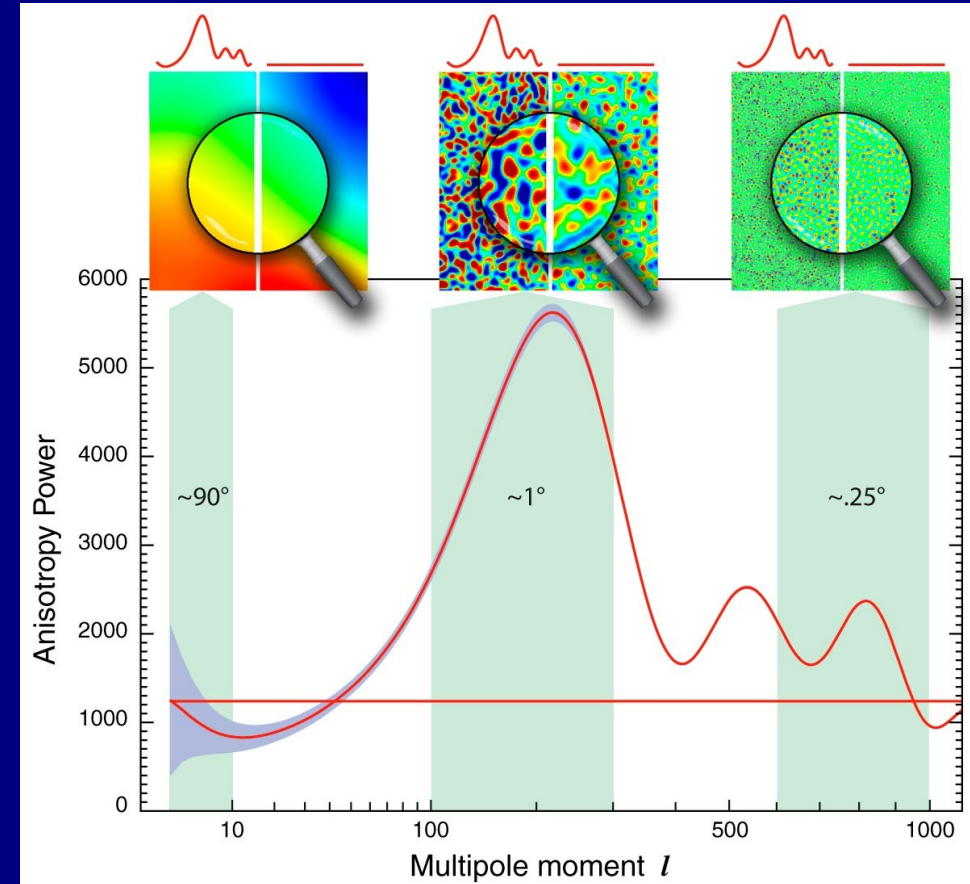
High harmonics fluctuations reminds the CMB fluctuations…
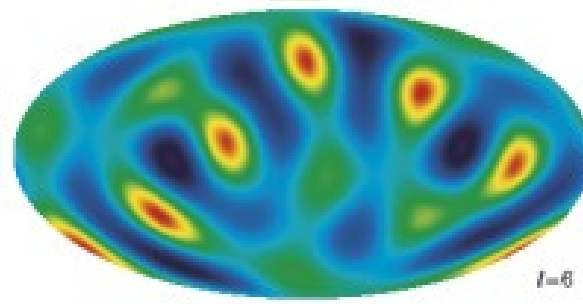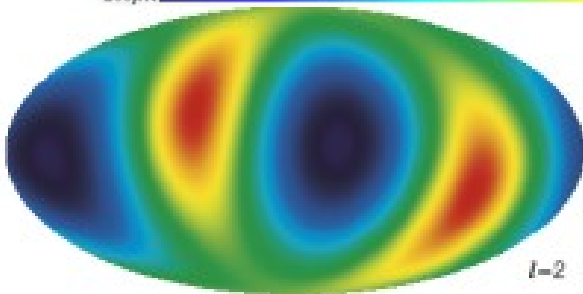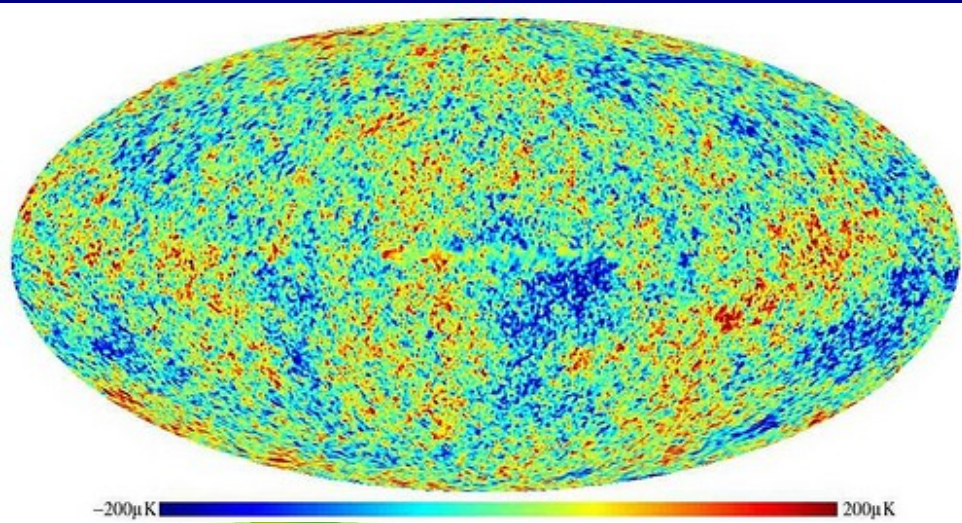
$$\frac{\Delta T}{T} \sim 10^{-5}$$

$$l_{maximum} \approx 210$$

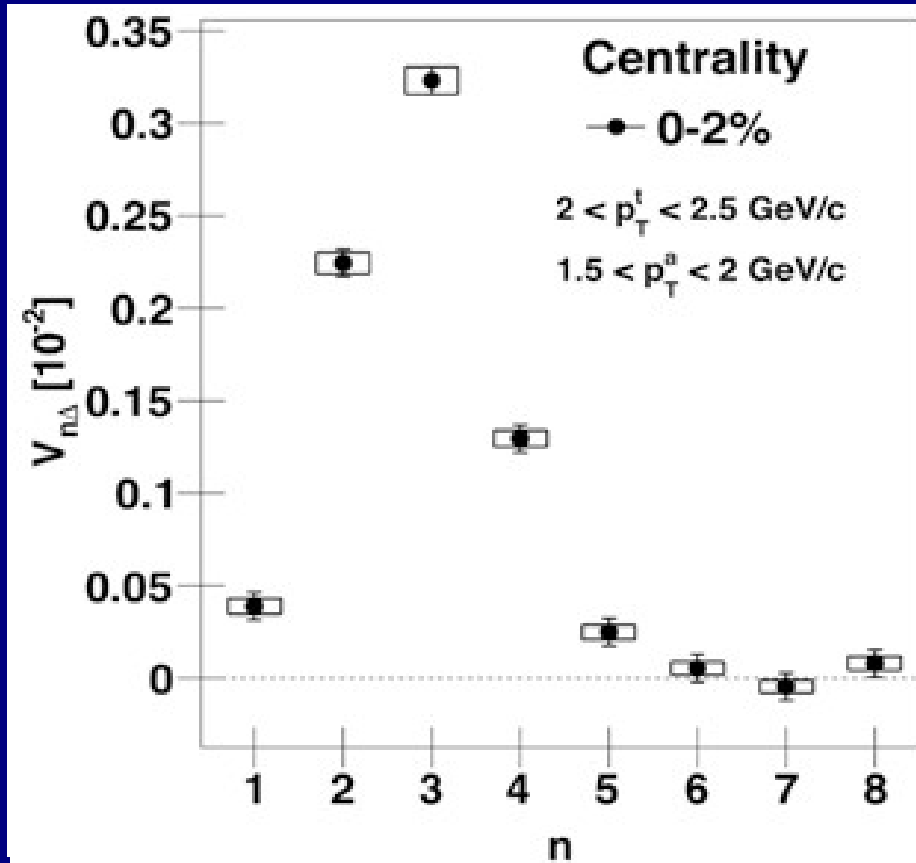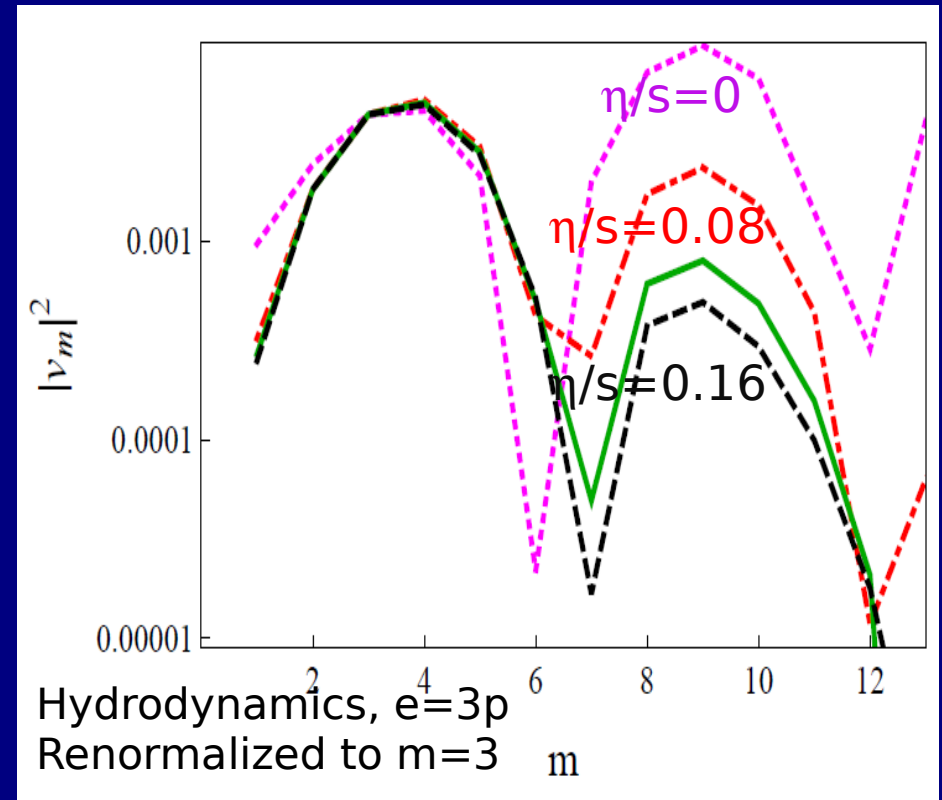$$\delta\phi \sim 2\pi/l_{maximum} \sim 1^o$$

Freeze-out $\tau \sim 380.000$ y's (QGP $\sim 10^{-22}$ s)
Sound horizon R $\sim$ Mps   (QGP ~ 6 fm)

Of course n=200 is not possible to be seen for a hadron system
with R $\sim$ 10 fm

A recent ALICE measurement

A first schematic calculation

Staig & Shuryak, PRC (2011)

None of the models reproduce the correct shapes:
- No peak at n=3
- Too large for n> 6

A promising new challenge -> new findings and knoweledge