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

F. Becattini (University of Florence and INFN)

SOMMARIO

- Termodinamica delle interazioni forti
- Collisioni di ioni pesanti
- Termometri adronici
- Modello idrodinamico
- Attività in Italia
- Conclusioni

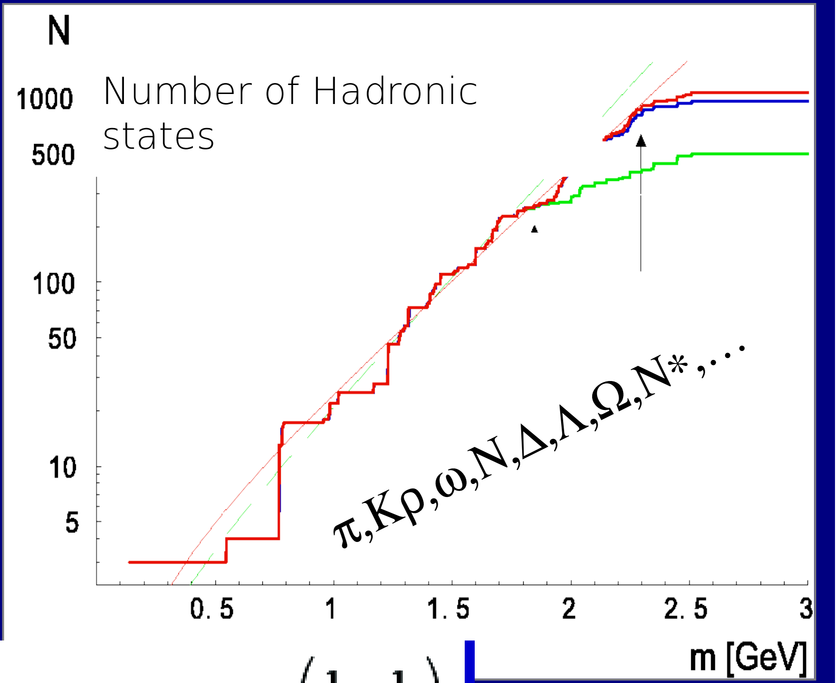
Termodinamica dell'interazione nucleare forte

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

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

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

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

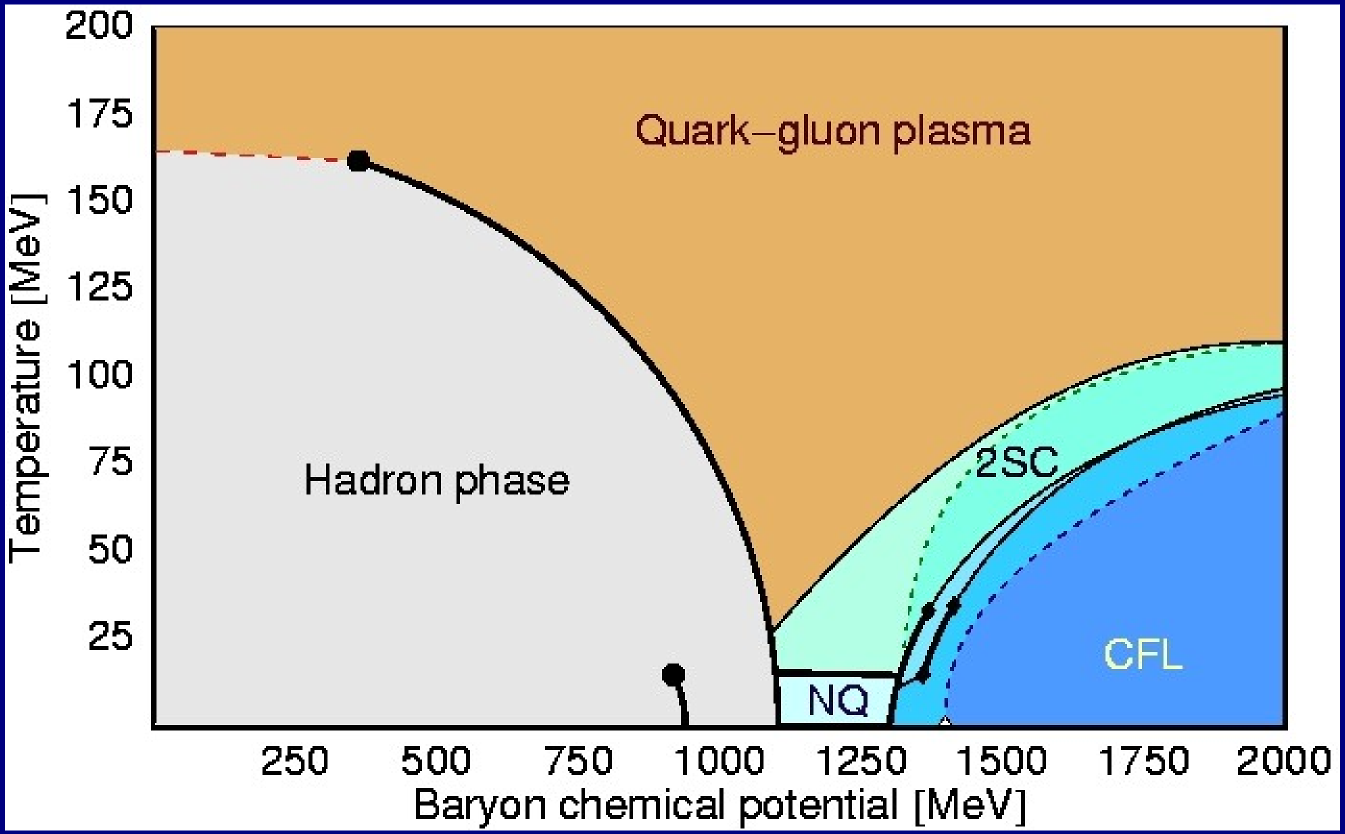
Integral diverges for $T \to T_0$:
hadronic matter cannot have a $T > T_0$

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

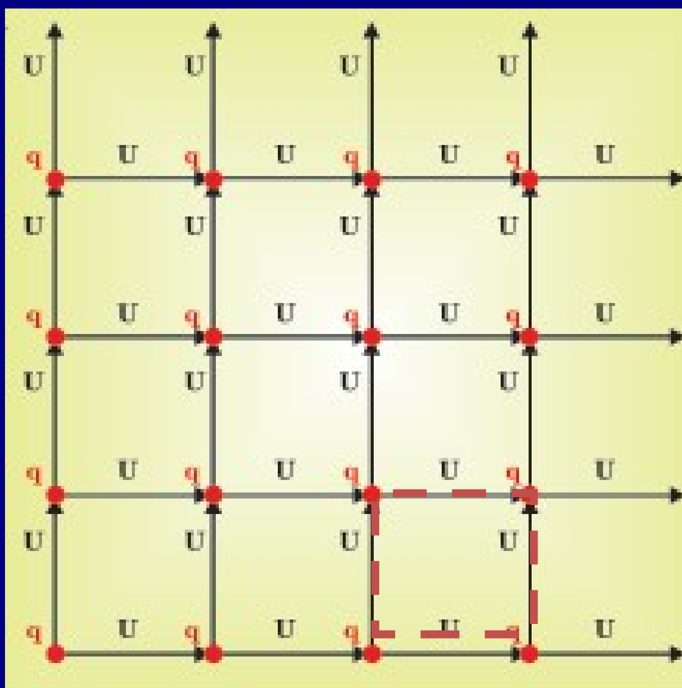
Diagramma di fase della materia fortemente interagente



Cromodinamica quantistica numerica

(vedi talk di M.P. Lombardo)

Goal: solving QCD on a grid of points in space and time with size $(Ns)^3 x Nt$



Partition function

$$Z = \int D A_\mu^a(x) D\overline{\psi}(x) D\psi(x) e^{i\int_0^\beta d\tau \int d^3x L[A,\overline{\psi},\psi]}$$

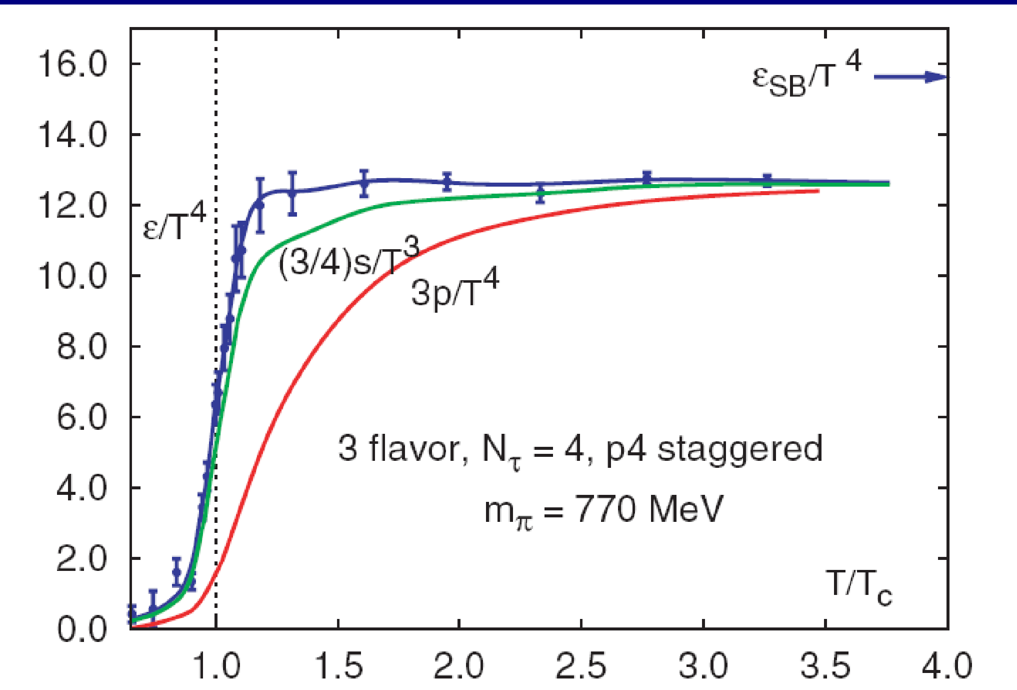
$$i\tau \rightarrow 1/T = \beta$$

Physical size : L = Ns x a,   Time → Temperature: T = 1/(Nt x a)

$$U(n, n+\hat{\mu}) = \exp\left(i g t^a A_\mu^a(n)\right)$$

- Only thermodynamical observables (EoS, susceptibility, …)
- No real time dynamical processes!
- Cannot be directly used at finite baryon density (sign problem, no neutron star aargh!!)
- Only very recently, calculations for physical quark masses became feasible!

Wuppertal-Budapest collaboration, QM2012 talk

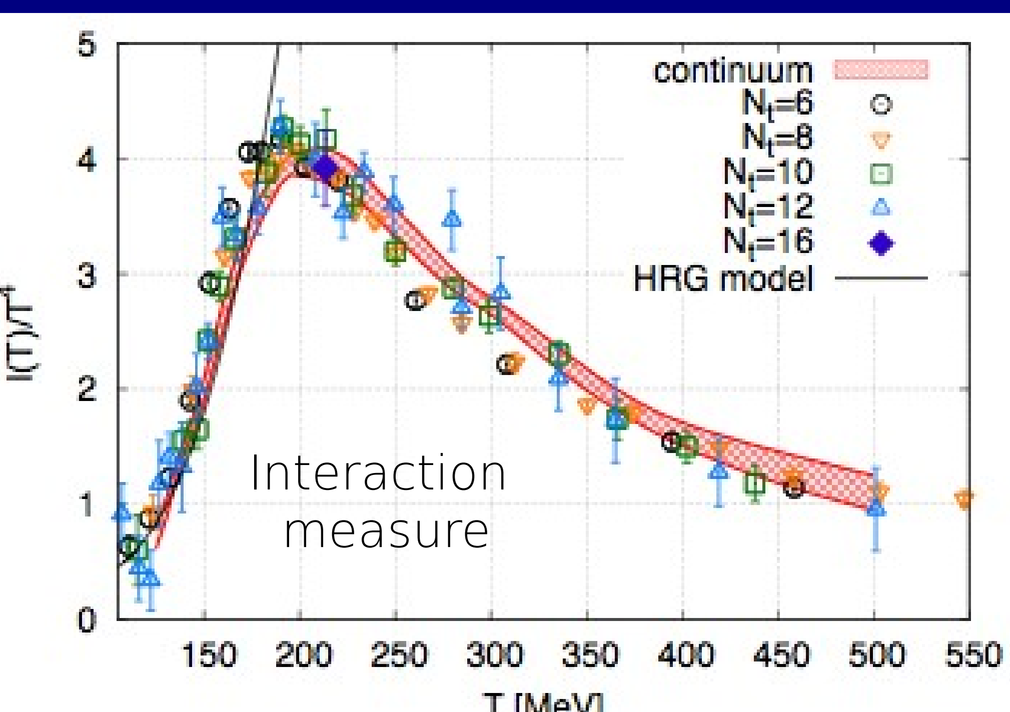


Reference: a gas of non-interacting massless Particle (Stefan-Boltzmann law)

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

$$\varepsilon_c \approx 0.7\, GeV / fm^3$$

$$T_c \cong 160\, MeV$$



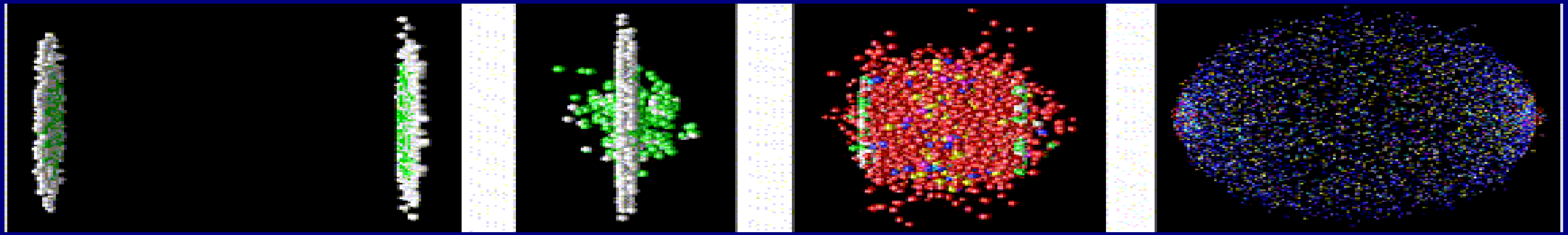
No interaction means (for a massless gas)

$$I = T^{\mu}_{\mu} = \rho - 3p = 0$$

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

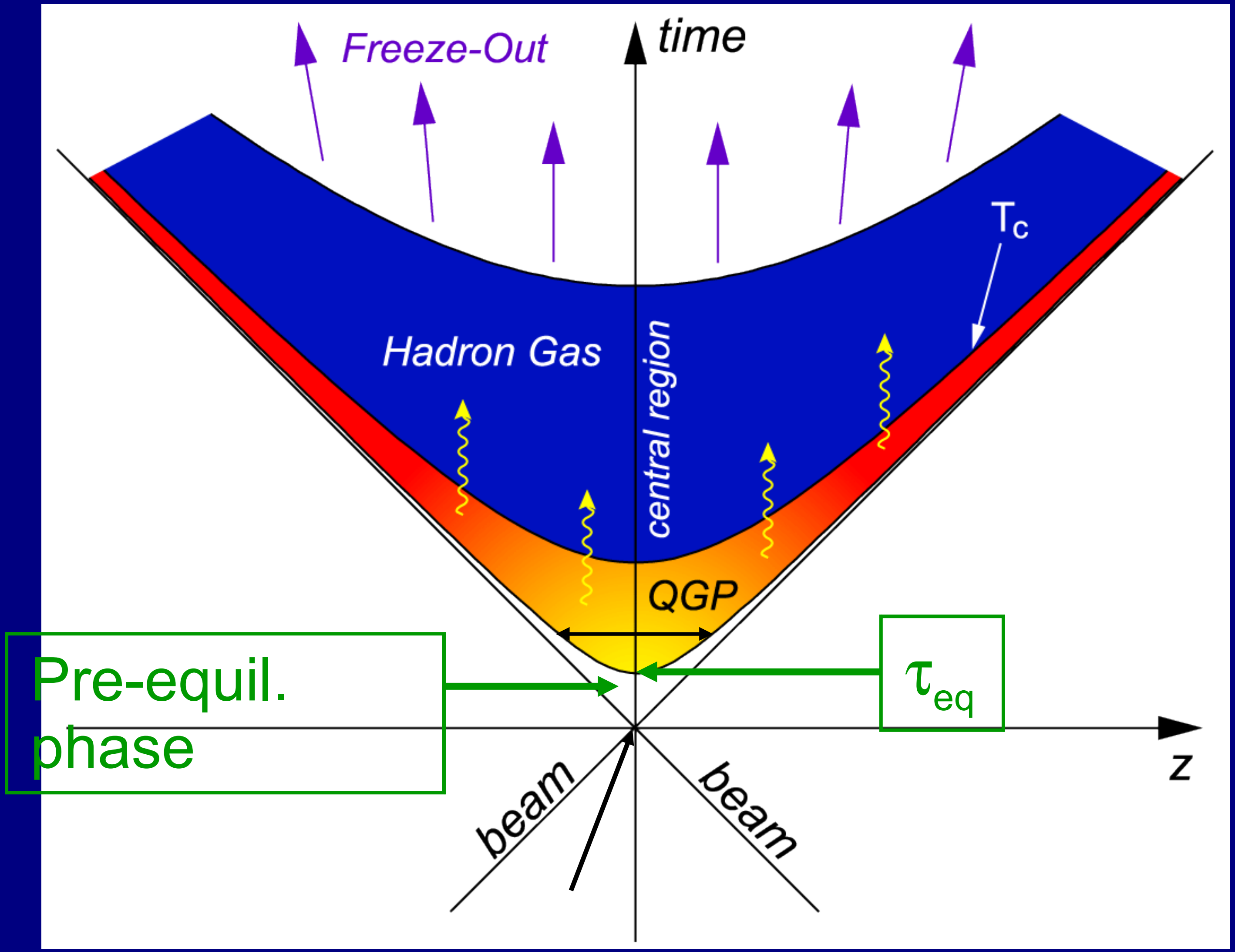
T > Tc ceases to be a hadron gas
but it is not a gas of weakly interacting quarks and gluons up to very high T

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

Space time sketch of the nuclear collision process



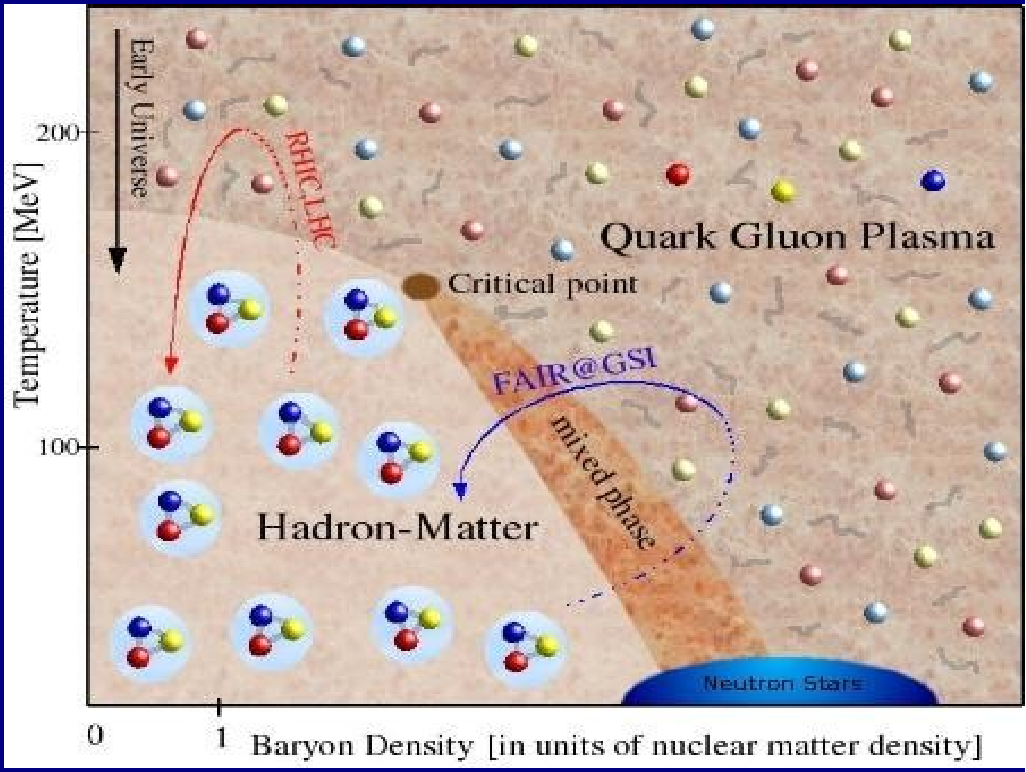
Probing the Quark Gluon Plasma

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

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

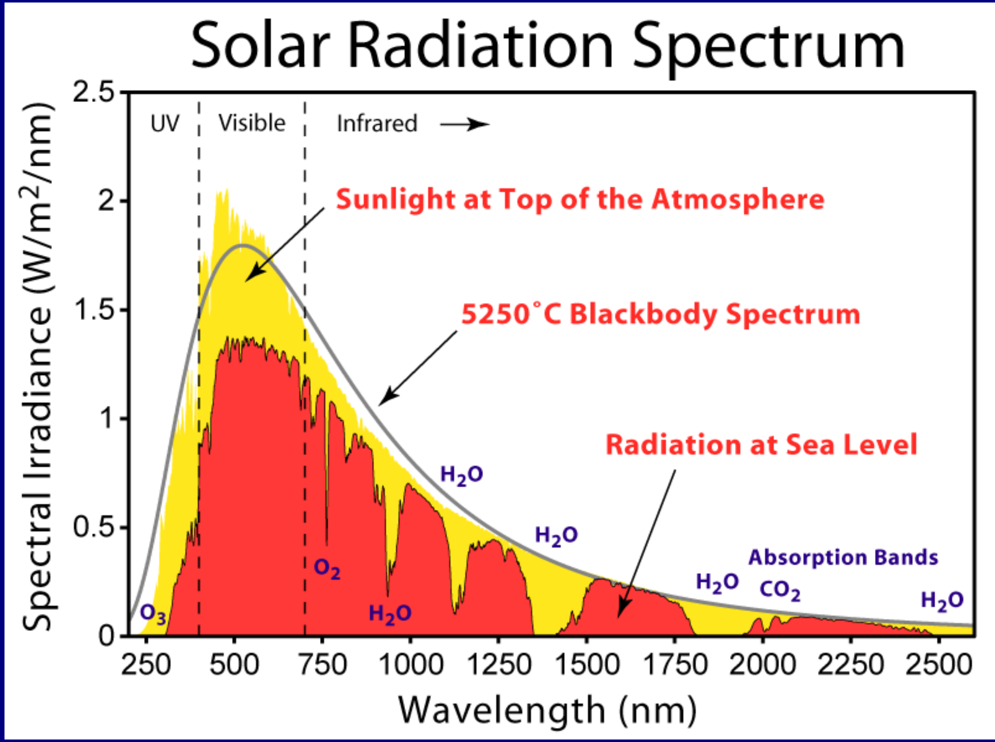
- Hadron radiation
- Electromagnetic radiation
- Hard probes: heavy quarks and quarkonia, jets, hard photons etc.

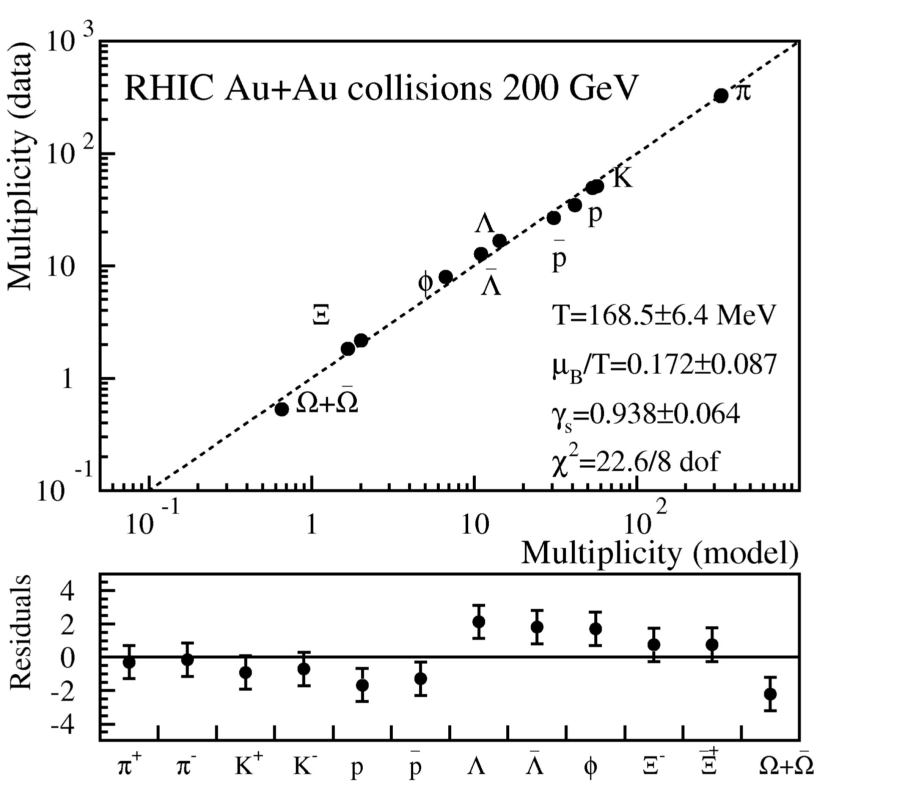
Common feature: early production, "calculable" in perturbative QCD, easily comparable to pp and pA



Hadron radiation

Provides direct information about the hadronization stage of the plasma.
With hadronic multiplicities one can determine the thermodynamical state at the stage when hadrons cease inelastic interactions and decouple (chemical freeze-out)

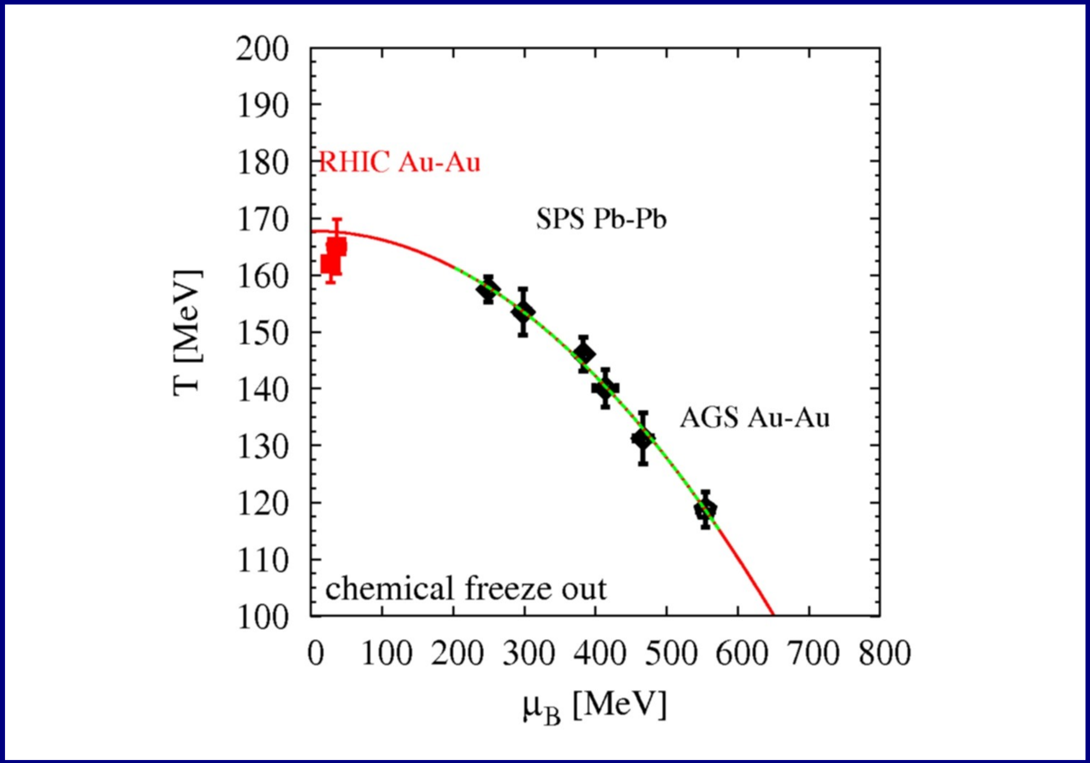




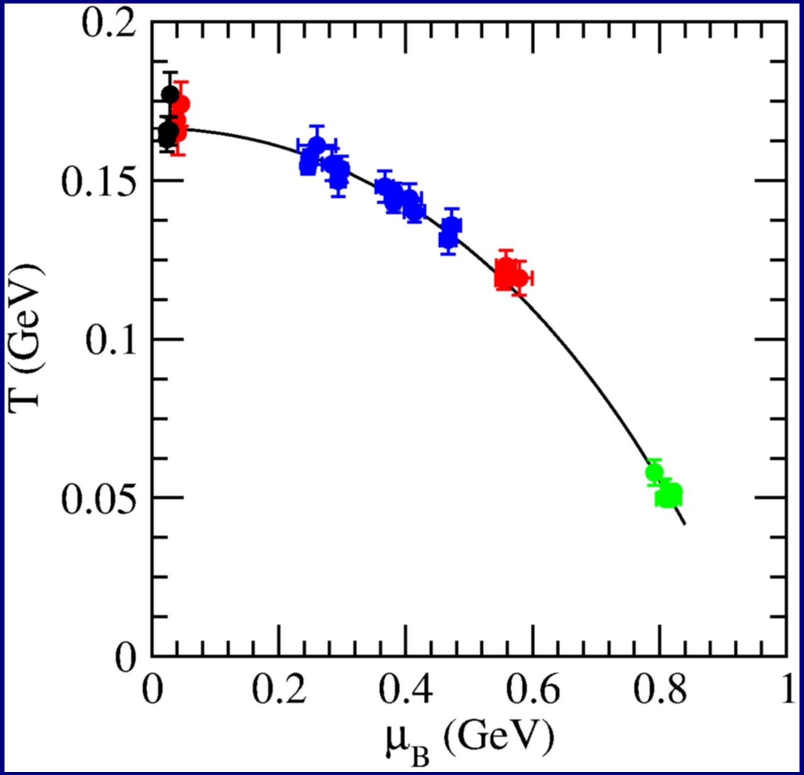
F. B., J. Manninen, Phys. Rev. C 78 (2008) 054901

$$\langle n_j \rangle = \frac{(2S_j+1)V}{2\pi^2} m_j^2 T \gamma_S^{n_{sj}} K_2(m/T) e^{\sum_i \mu_i q_j^i / T}$$

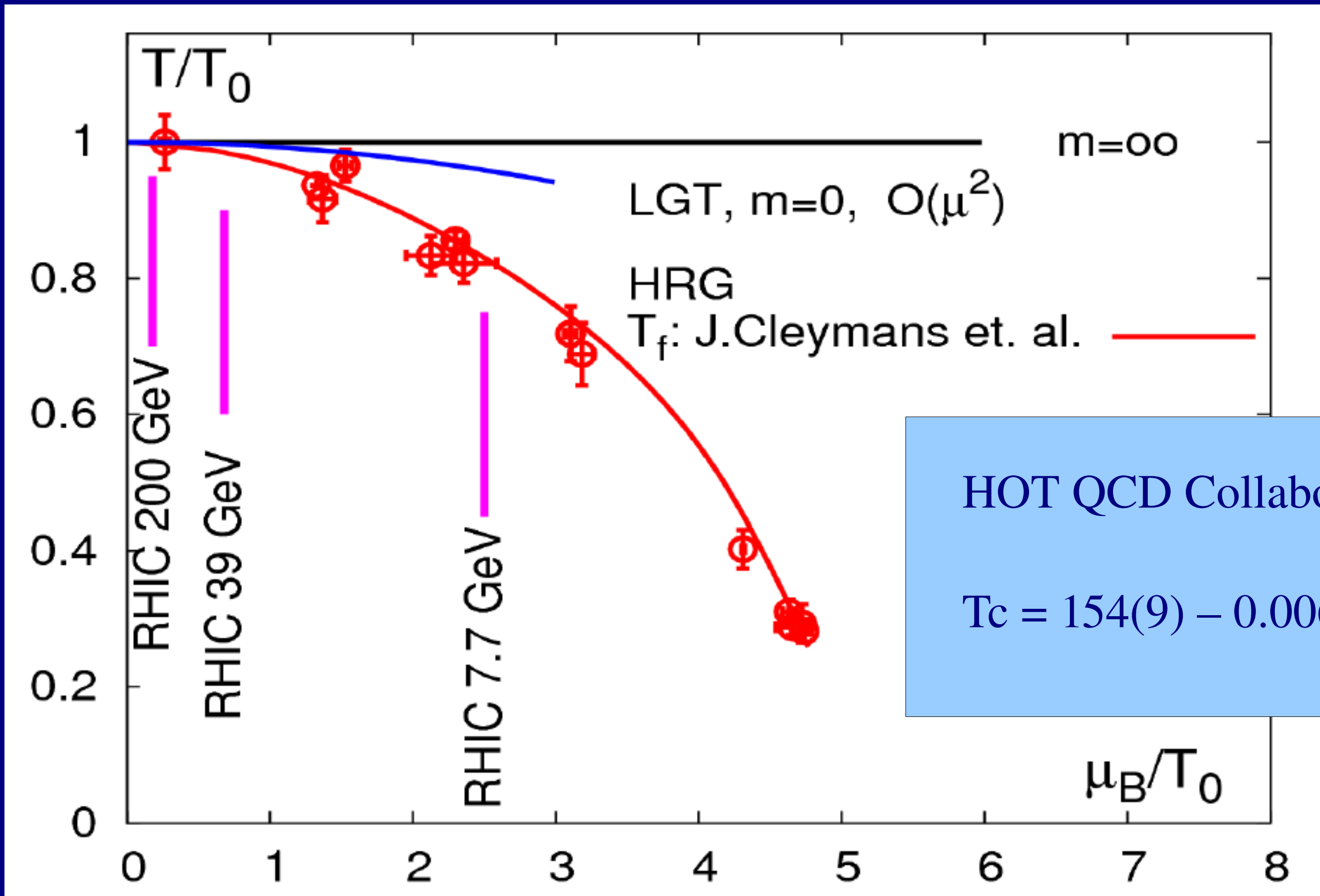
F. B., J. Manninen, Phys. Rev. C 78 (2008) 054901



J. Cleymans et al. Phys.Rev. C73 (2006) 034905



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)



Chemical freeze-out line steeper than the extrapolated QCD line

HOT QCD Collaboration (F. Karsch, Wroclaw 2013)

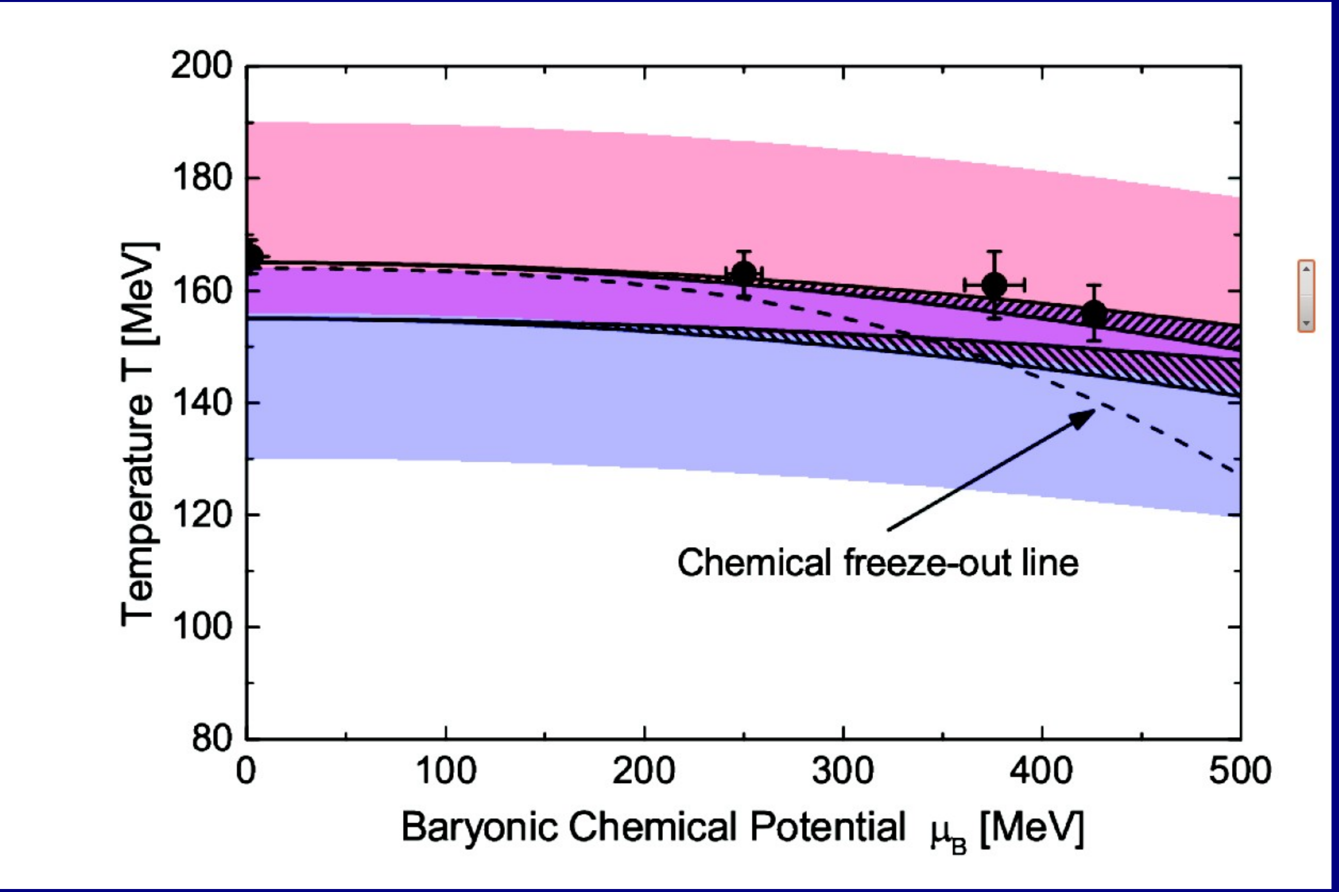
$T_c = 154(9) - 0.0066(7)\,(\mu/T)^2$ MeV

Because of post-hadronization inelastic rescattering, chemical freeze-out may not coincide with hadronization (strictly speaking: latest chemical equilibrium point)

Reconstruction of the hadronization point and comparison with lattice QCD

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

F.B., M. Bleicher et al., Phys. Rev. Lett. 111, 082302 (2013)



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)

See also: *The critical line of two-flavor QCD at finite isospin or baryon densities from imaginary chemical potentials.* P. Cea, L. Cosmai, M. D'Elia, A. Papa, F. Sanfilippo, Phys.Rev. D85 (2012) 094512

Il Quark Gluon Plasma come liquido quasi-perfettodel

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

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*.

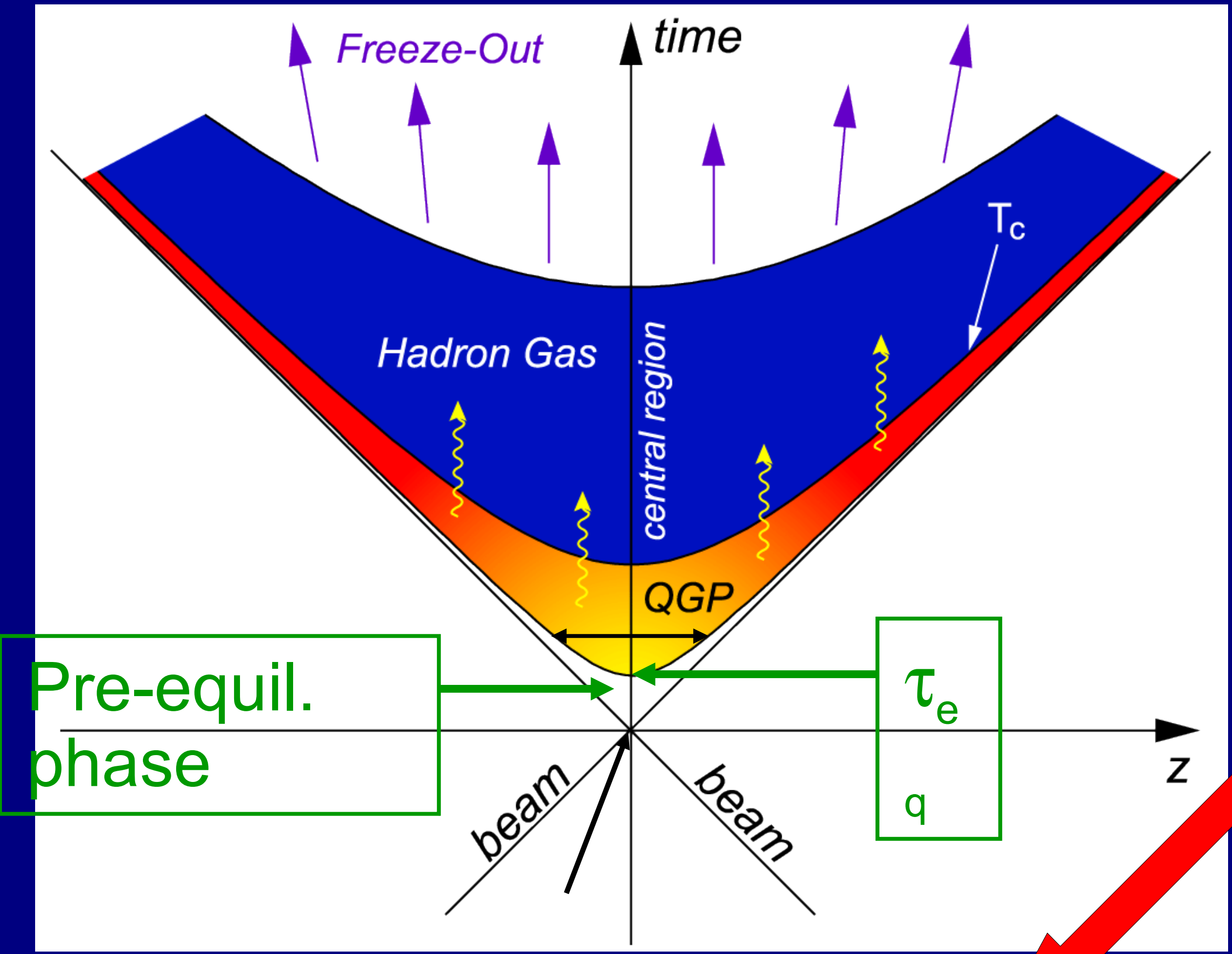
"Once again, the physics research sponsored by the Department of Energy is producing historic results," said Secretary of Energy Samuel Bodman, a trained chemical engineer. "The DOE is the principal federal funder of basic research in the physical sciences, including nuclear and high-energy physics. 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

Relativistic hydrodynamical model



$$\begin{cases} \partial_\mu T^{\mu\nu}(x) = 0 \\ \partial_\mu j^\mu_B(x) = 0 \end{cases}$$

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

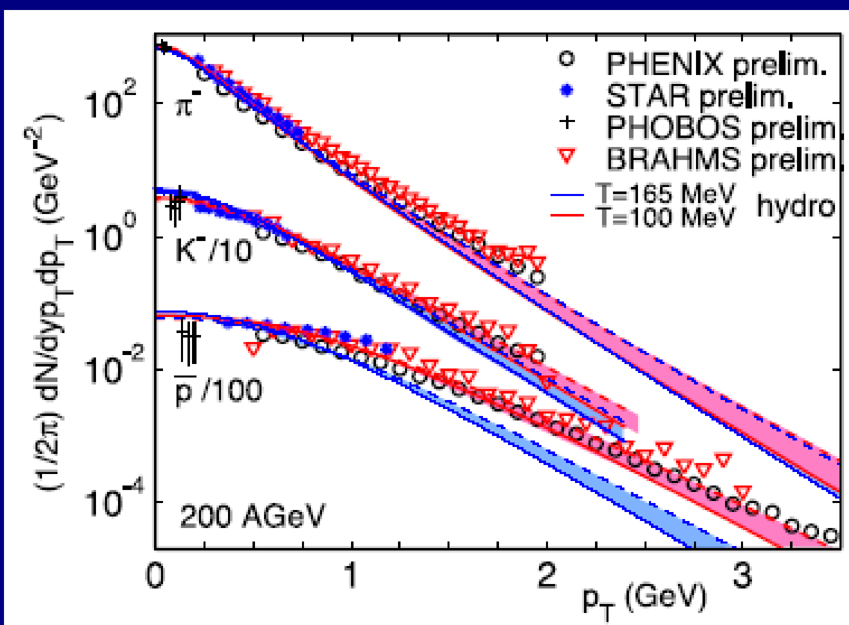
Assumptions:

- Local thermodynamical equilibrium at chemical decoupling (Cooper-Frye distribution)
- Lattice QCD Equation of State
- Ideal fluid (now viscous 2nd order in gradients)
- Bjorken longitudinal solution v_z=z/t (2+1) (lately 3+1 D)
- Initial conditions: may differ

“Measuring” the initial temperature of the plasma with hydrodynamical model

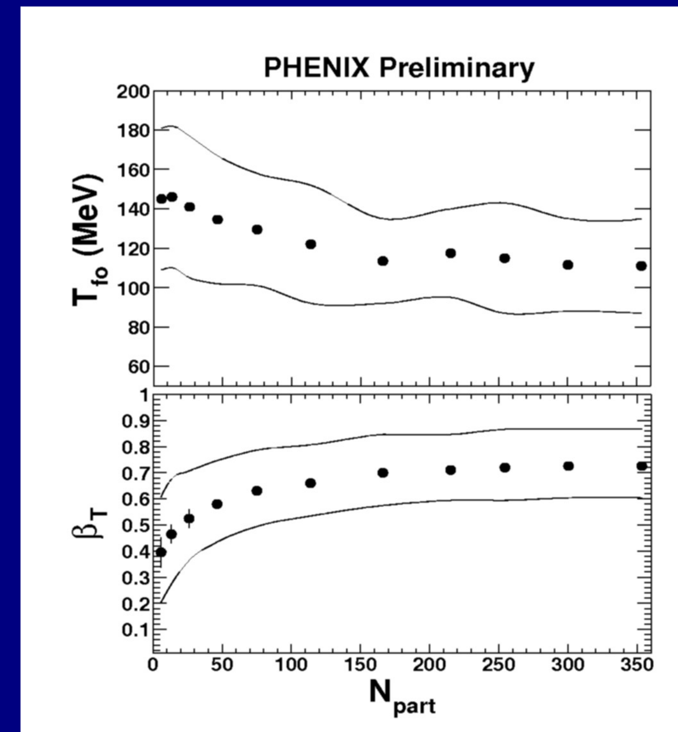
(Huovinen, Kolb, Heinz, Hirano, Romatschke, Teaney,..)

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



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

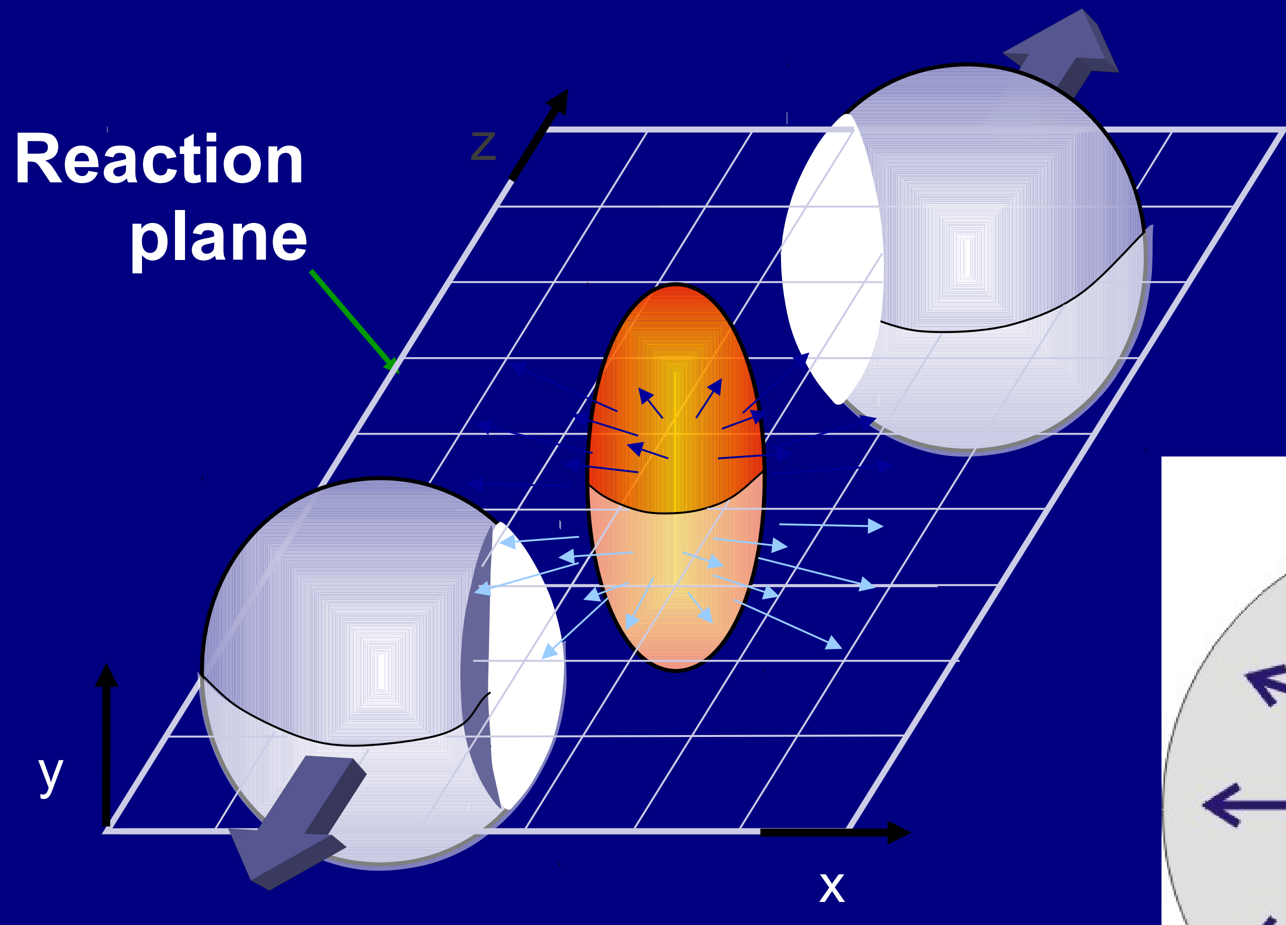
$$T_{eff} \approx T_{dec} + \frac{1}{2} m \langle u_T^2 \rangle$$

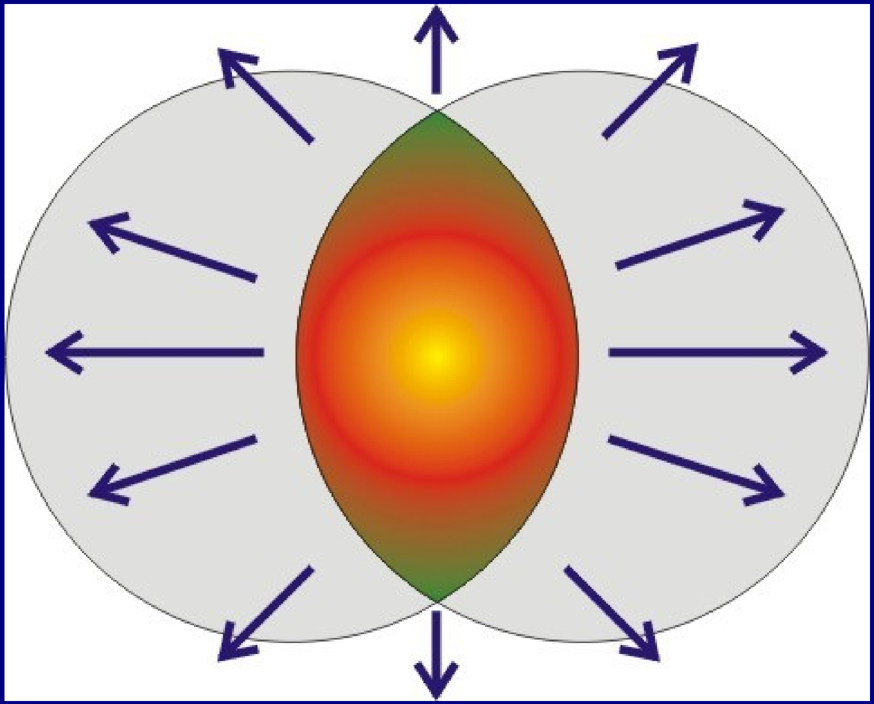


	SPS	RHIC 1	RHIC 2
$\sqrt{s_{\mathrm{NN}}}$ (GeV)	17	130	200
s_{eq} (fm^{-3})	43	95	110
T_{eq} (MeV)	257	340	360
τ_{eq} (fm/c)	0.8	0.6	0.6

Fitted parameters. The initial T is correlated to the initial equilibration time.

Elliptic flow in peripheral collisions



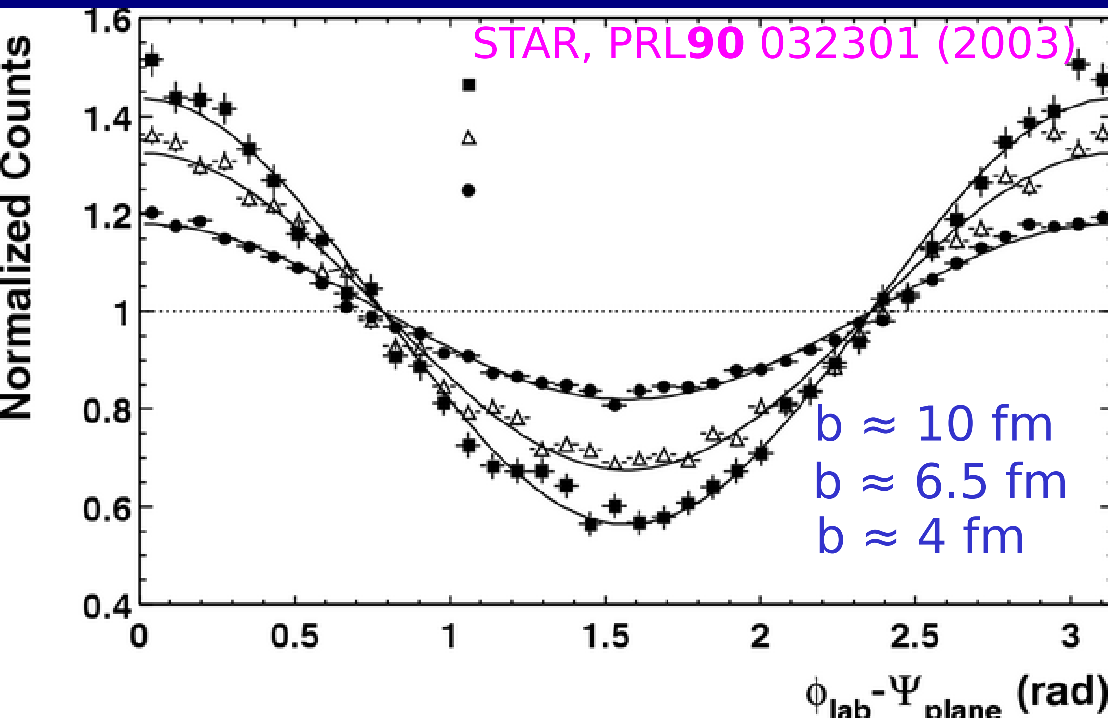


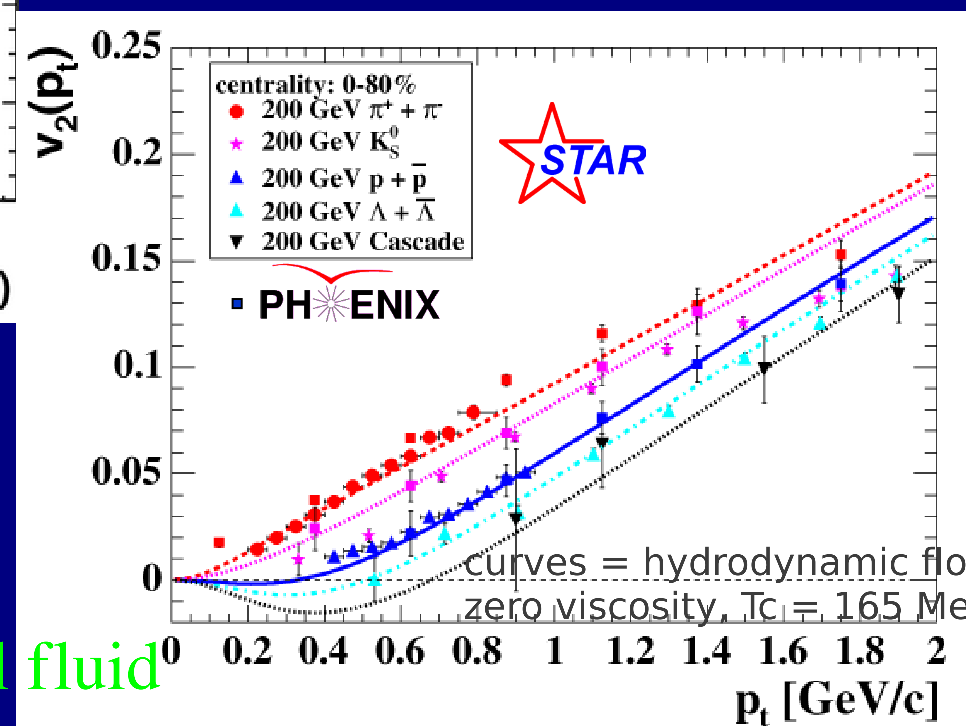
Anisotropic pressure gradient: if there is collective flow, particles get a larger momentum on the reaction plane!

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

Elliptic flow coefficient v_2

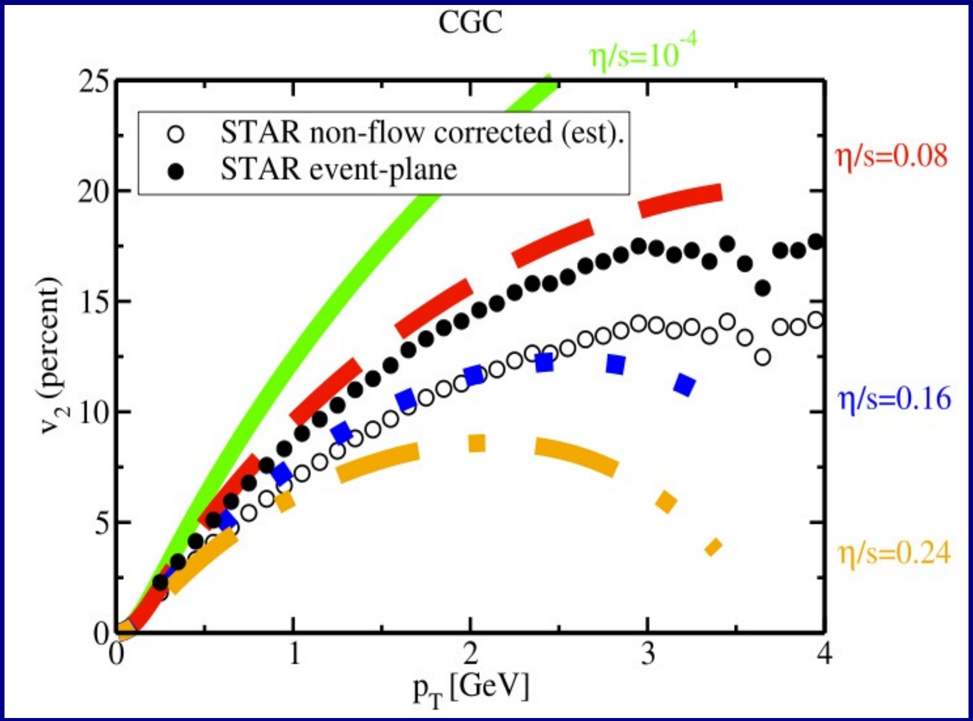
$$\frac{dN_i}{dy\,p_\perp dp_\perp\,d\varphi_p}(b) = \frac{1}{2\pi}\frac{dN_i}{dy\,p_\perp dp_\perp}(b)\left(1 + 2\,v_2^i(p_\perp,b)\cos(2\varphi_p) + \ldots\right).$$

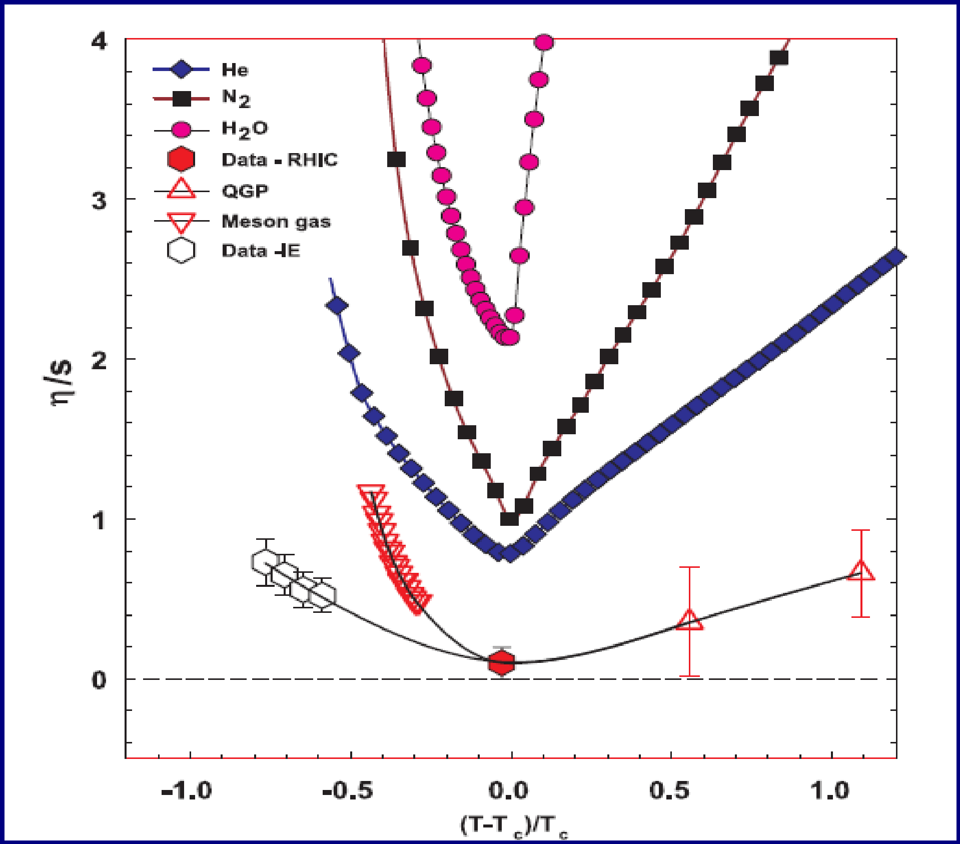




v_2 in good agreement with quasi-ideal fluid

Elliptic flow is sensitive to the viscosity of the QGP





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

Sommario delle determinazioni di viscosità a RHIC e LHC (Heinz, RANP 2013)

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

Shear viscosity in strongly interacting conformal quantum field theory (from AdS/CFT correspondance)

Kovtun, Son, Starinets PRL 94, 111601 (2005)

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

Conjecture: 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 $\eta/s \gtrsim \hbar$

What does low viscosity mean?

From kinetic theory:

$$\eta = \frac{1}{3}\rho v_T \lambda = \frac{1}{3} m n v_T \lambda = \frac{1}{3} n p_T \lambda$$

In relativistic fluid:

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

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 $\tau_{\rm qp} \sim (5\eta/s)(1/T) \gg 1/T$.]
- 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;...

Il QGP e' un sistema di campi quantistici in interazione, ma puo' essere ancora definito come un fluido.

Perche' possa esserlo e' solo necessario che la tipica scala microscopica (per es. definita dalla distanza di correlazione di grandezze come le varie correnti o il tensore degli sforzi $\lambda << L$ (λ/L = numero di Knudsen).

Fluidodinamica senza teoria cinetica

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

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

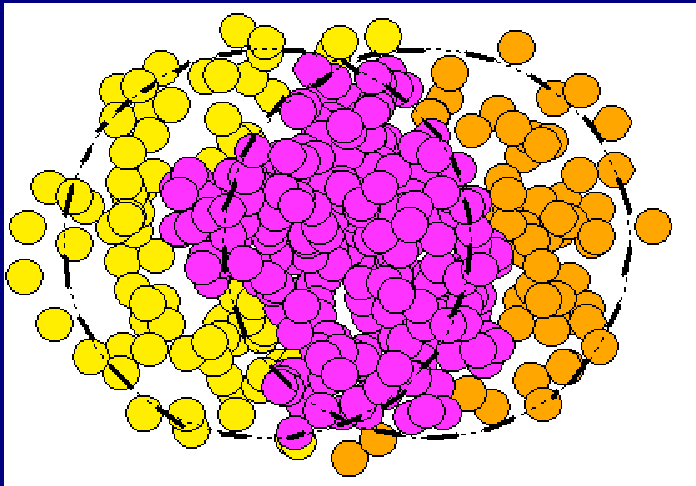
Operatore stazionario di Zubarev

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

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

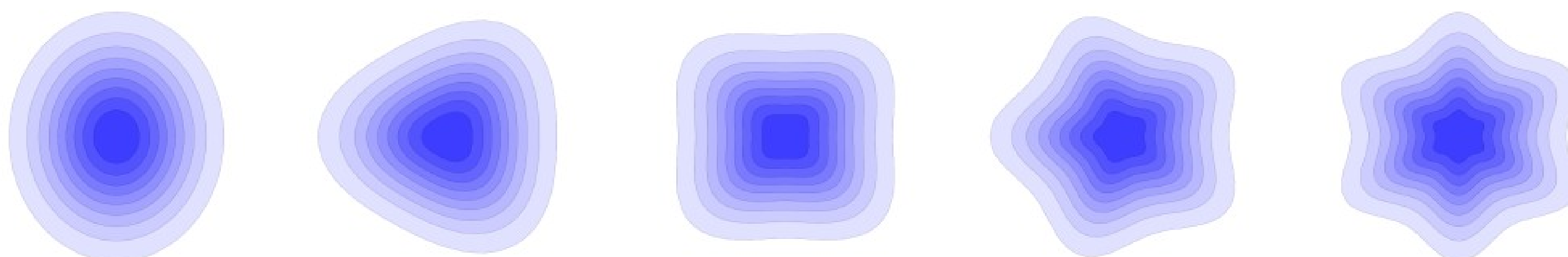
La scala miscroscopica emerge dalla distanza di correlazione del tensore degli sforzi e deve essere molto minore della distanza su cui variano significativamente i campi β e ξ

Recent developments from LHC experiments: from averages to event-by-event hydrodynamics



Si studiano le componenti armoniche n>2 nello spettro azimutale degli adroni

When including fluctuations, all moments appear:



$n = 2$ $\quad$ $n = 3$ $\quad$ $n = 4$ $\quad$ $n = 5$ $\quad$ $n = 6$

also v_1 and $n > 6$

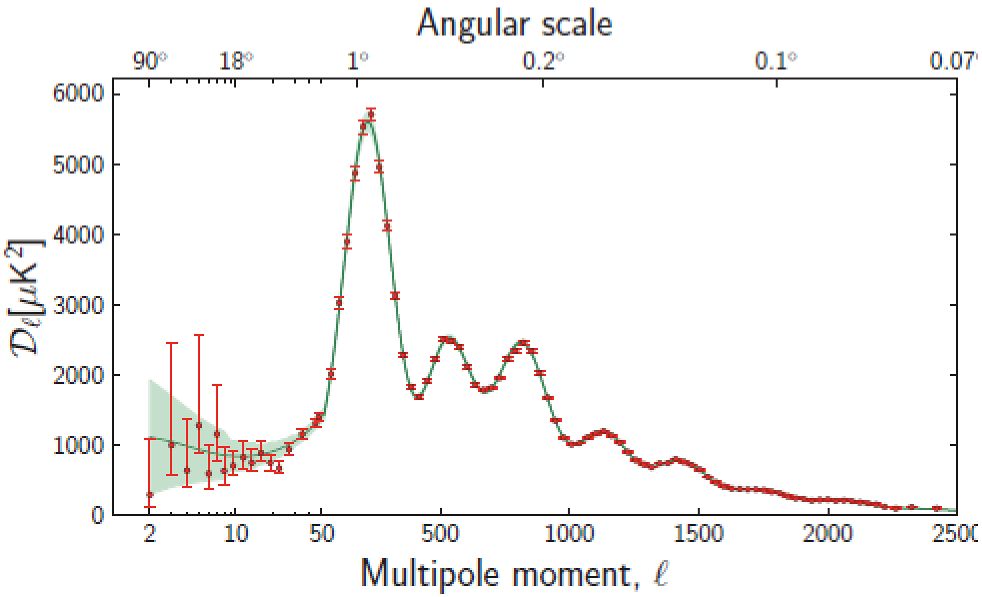
Compute $v_n = \langle \cos[n(\phi - \psi_n)] \rangle$

Big vs. Little Bang: The fluctuation power spectrum

Mishra, Mohapatra, Saumia, Srivastava, PRC77 (2008) 064902 and C81 (2010) 034903

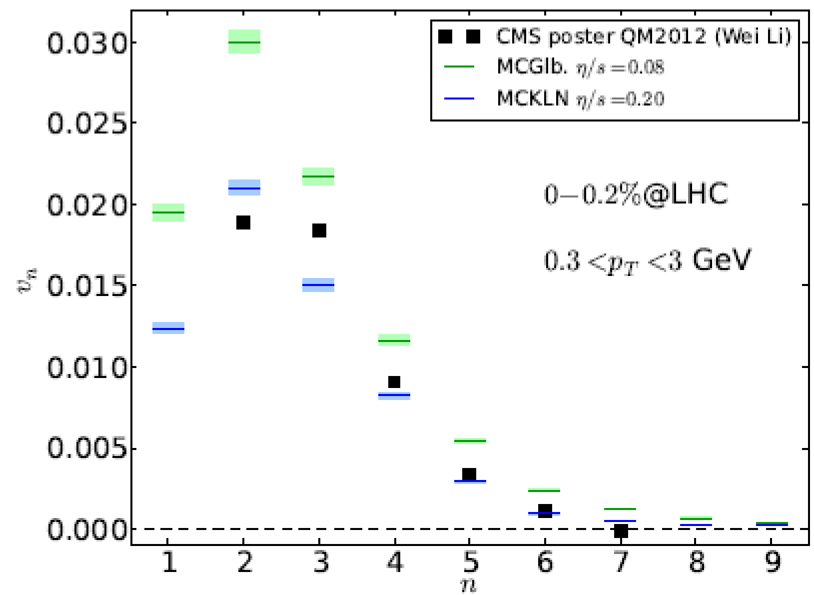
Mocsy & Sorensen, NPA855 (2011) 241, PLB705 (2011) 71

Big Bang temperature power spectrum (Planck 2013)



Flow power spectrum for ultracentral PbPb Little Bangs

(Data: CMS, Quark Matter 2012; Theory: OSU 2013)



Higher flow harmonics get suppressed by shear viscosity

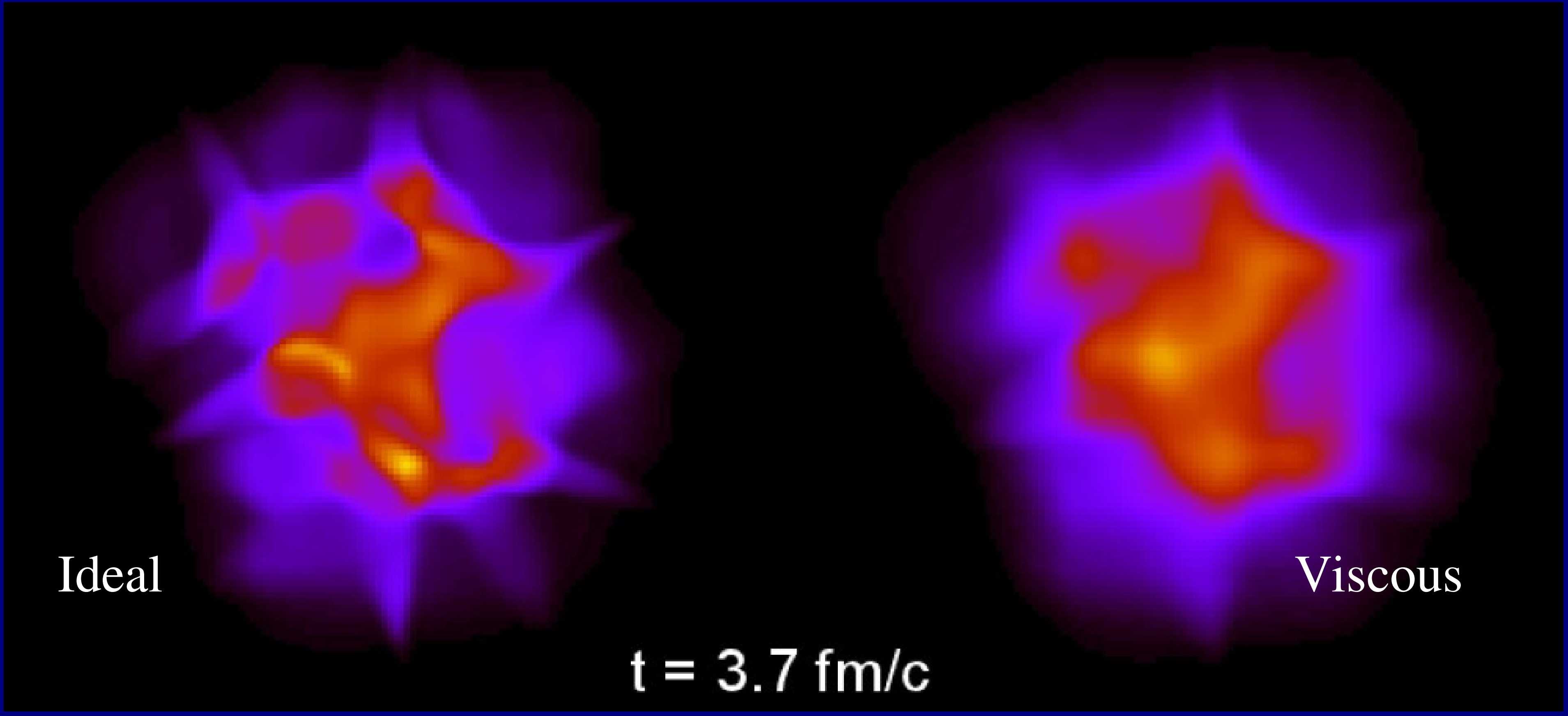
A detailed study of fluctuations is a powerful discriminator between models!

Viscosity smoothens fluctuations and affect more higher harmonics

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

In questo lavoro assumono sempre più importanza i codici numerici di fluidodinamica relativistica.

Stato dell'arte: 3+1 D con implementazione della teoria di Israel-Stewart
e fluttuazioni di stato iniziale.



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

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

Eur. Phys. J. C (2013) 73:2524
DOI 10.1140/epjc/s10052-013-2524-5

THE EUROPEAN PHYSICAL JOURNAL C

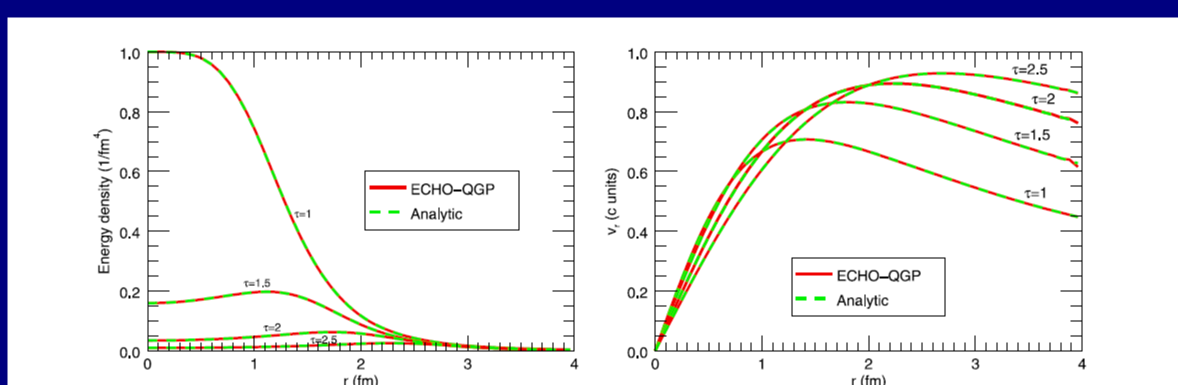
Regular Article - Theoretical Physics

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)



Un breve sommario dell'attività in Italia

Ampio spettro di argomenti nel campo di questa fisica sia per quanto riguarda la fenomenologia che la teoria:

- Produzione di stranezza (Firenze)
- Soppressione della J/psi (Torino)
- Cromodinamica su reticolo (Torino)
- Modelli effettivi del quark-gluon plasma (Catania, Torino)
- Fenomenologia dei quarks pesanti nel plasma (A. Beraudo, Catania)
- Jet quenching nel plasma (Catania)
- Fenomenologia delle collisioni pp di alta energia (Firenze, Trieste)
- Materia nucleare ad alta densita' e oggetti stellari compatti (Catania, Ferrara, Firenze, Torino Politecnico)
- Polarizzazione nel quark-gluon plasma (Firenze, vedi talk di E. Grossi)

Vedi talks di Ruggieri, Puglisi, Grossi, Rolando, Lavagno, Alba, Scardina

Conclusioni

- There is little doubt that QGP has been produced in relativistic heavy ion collisions

- Many observations point to a system which is hotter than Tc and strongly interacting (low viscosity), in accordance with QCD. The study of its properties is ongoing at LHC

- Search of the QCD critical point and the onset of deconfinement at lower energies

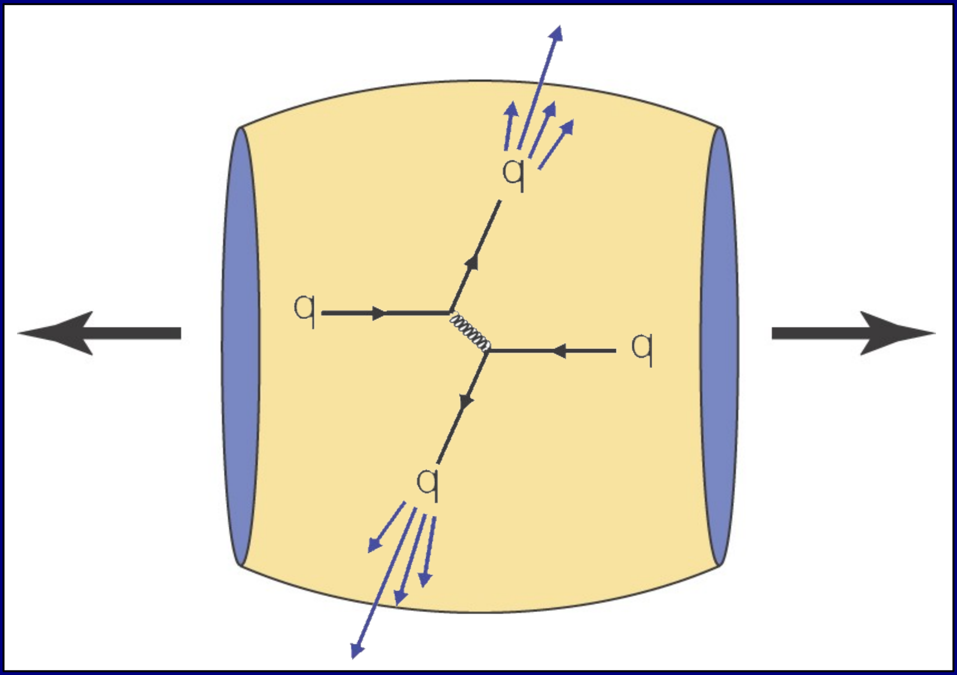
- Relativistic heavy ion collisions have been a very effective laboratory for advanced theoretical subjects: not only QCD, but also relativistic statistical mechanics, relativistic hydrodynamics and kinetics

- Hopefully, there will be useful results for relativistic astrophysics and cosmology

Jets as a probe of the plasma

Nucleus-nucleus collisions

- hard initial scattering
- scattered partons probe traversed hot and dense medium
- 'jet tomography'



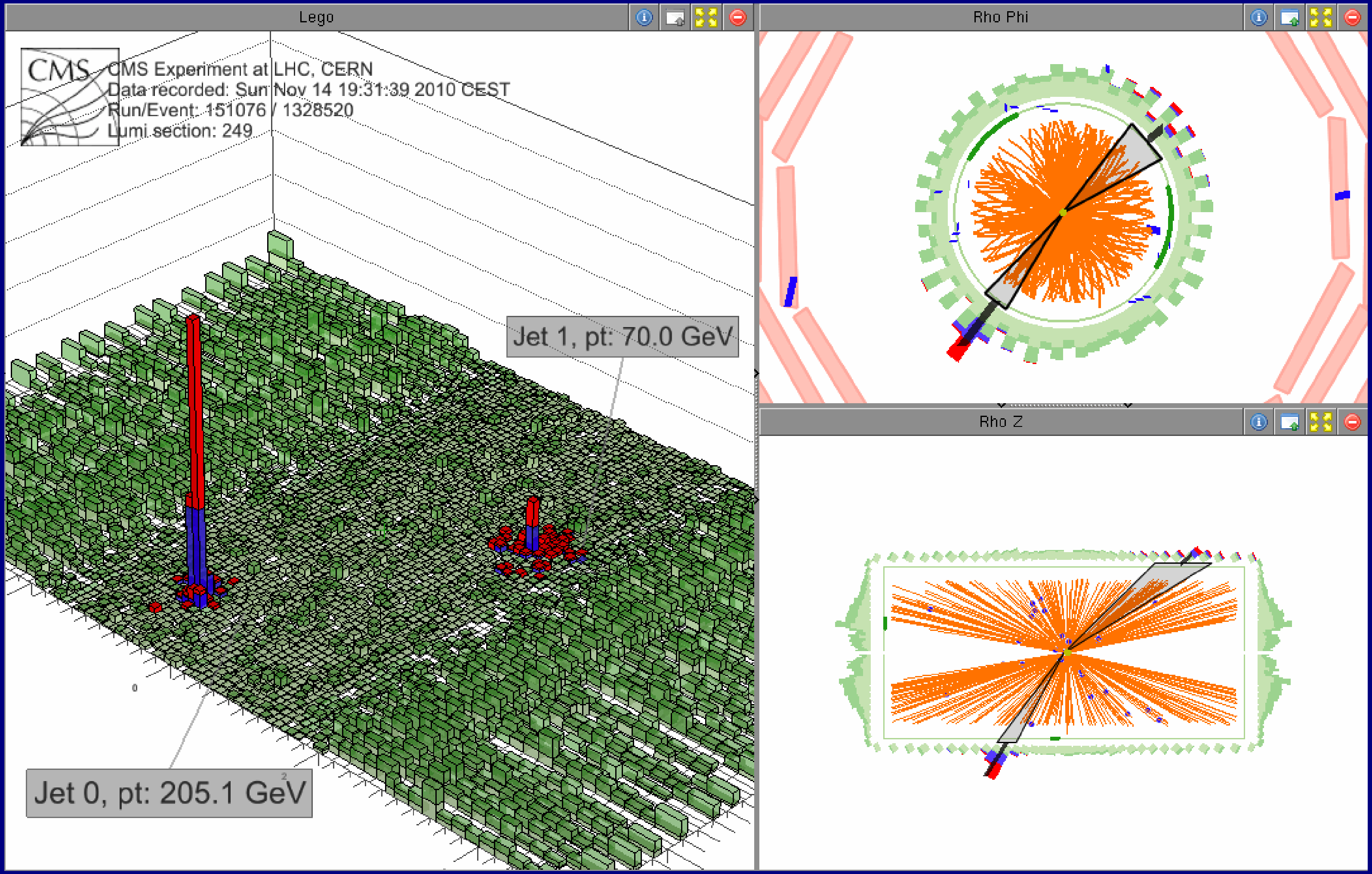
- Initial parton-parton scattering with large momentum transfer

- 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



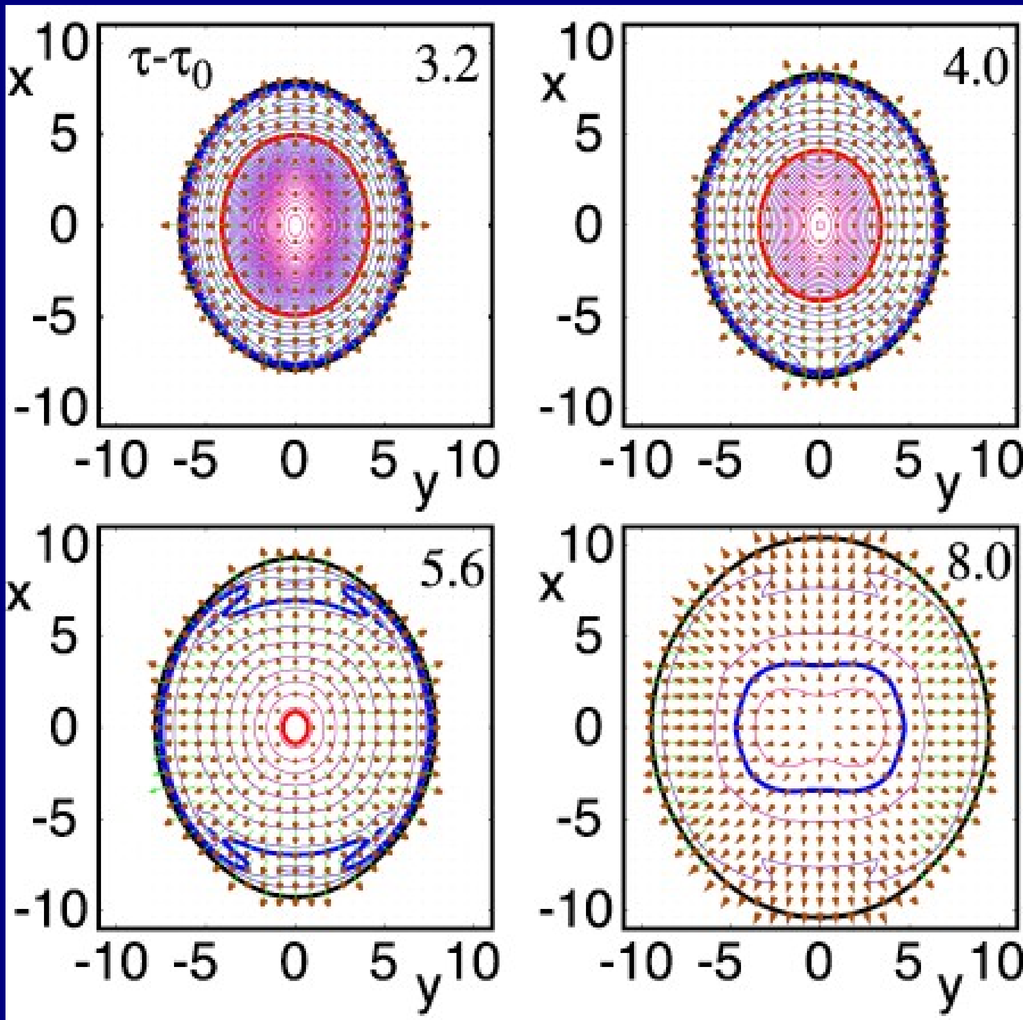
-

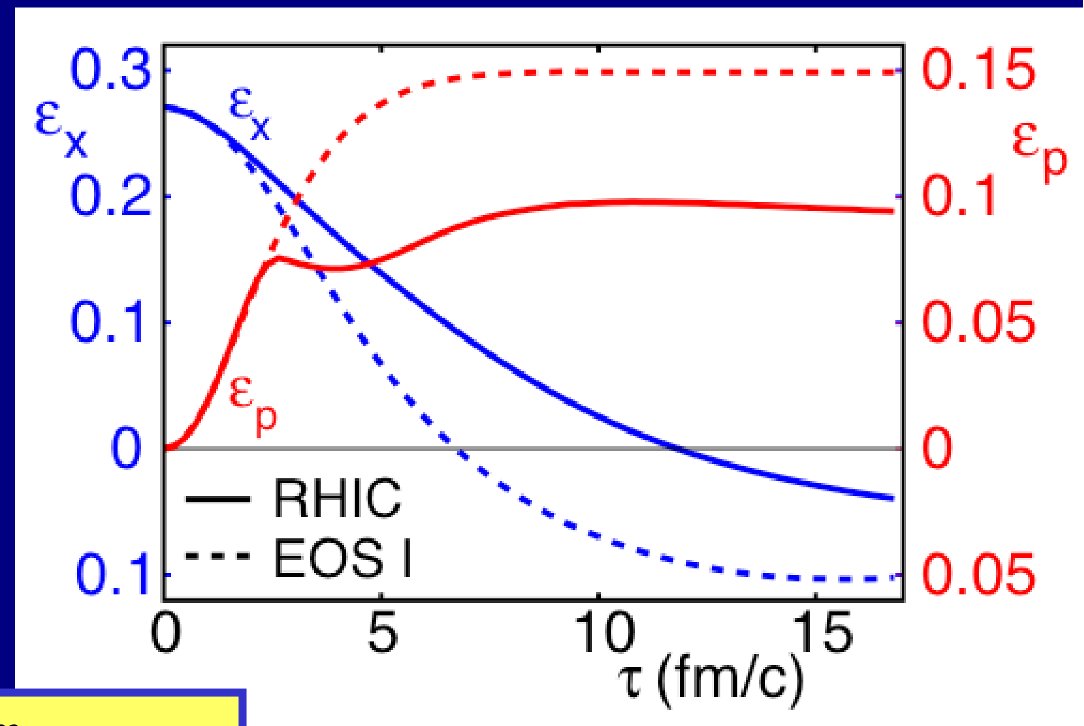
→ recoiling jet strongly quenched!

CMS: arXiv:1102.1957

Anisotropia di impulso

$$\epsilon_p = \frac{\langle T^{xx} - T^{yy} \rangle}{\langle T^{xx} + T^{yy} \rangle}$$





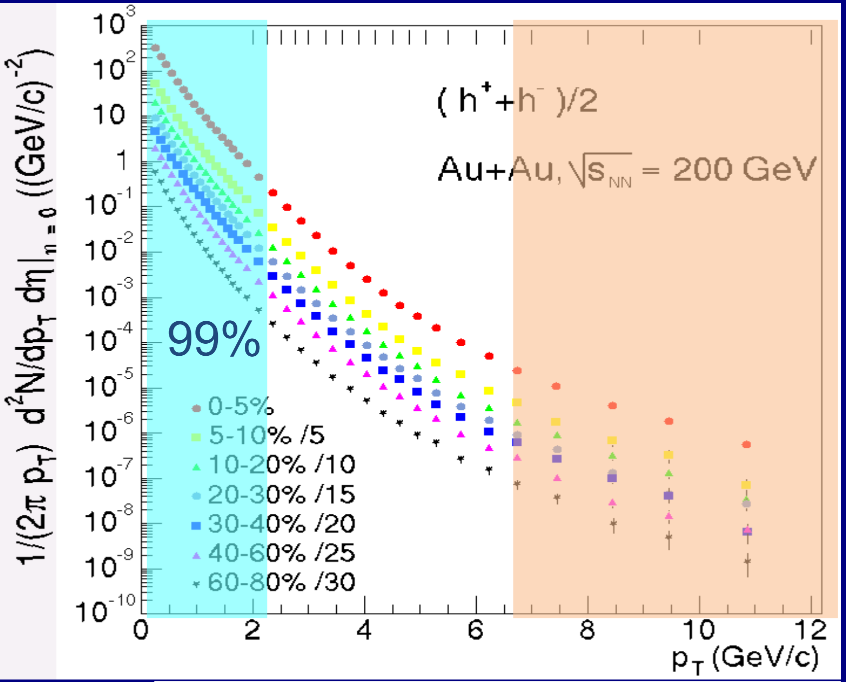
Spacial anisotropy gets converted into momentum anisotropy provided that:

- 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 ~ΛQCD,T)
driven by *non perturbative QCD*

dron yields, collective modes of the bulk,
angeness enhancement, fluctuations,
rmal radiation, dilepton enhancement

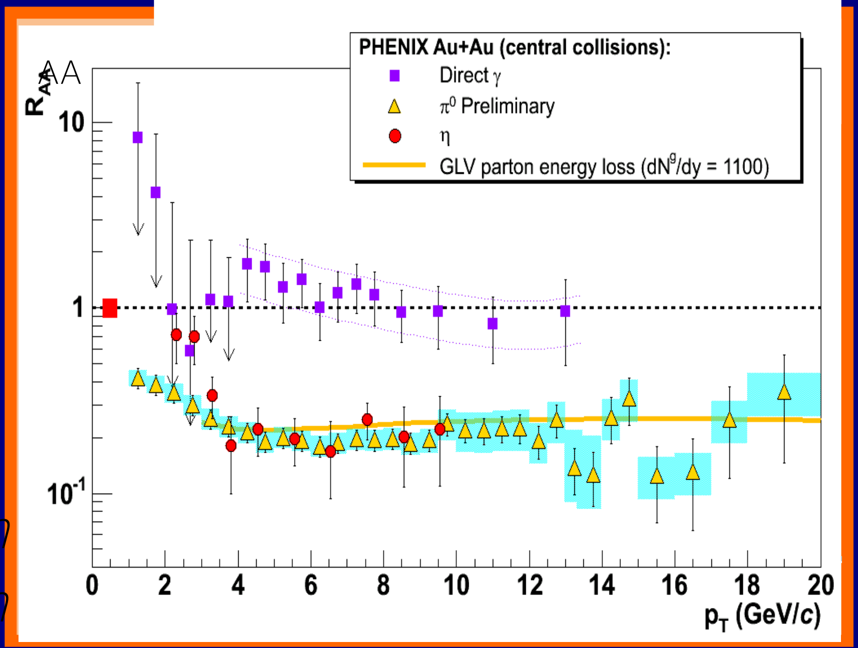


HARD (pT >>> ΛQCD)
Early production, pQCD applicable,
Baseline pp, pA

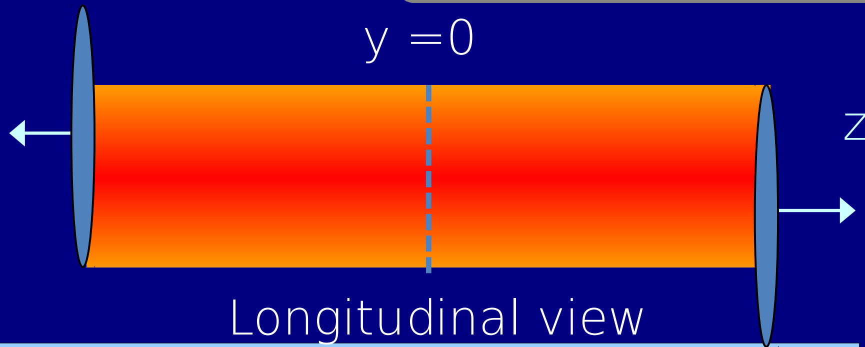
quenching, heavy quarks, quarkonia,
rd photons (W,Z)

Nuclear modification factor

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



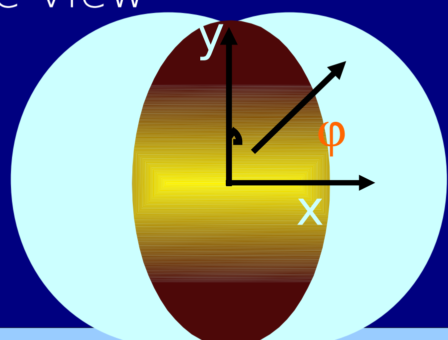
Some typical definitions



Longitudinal view

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

Transverse view

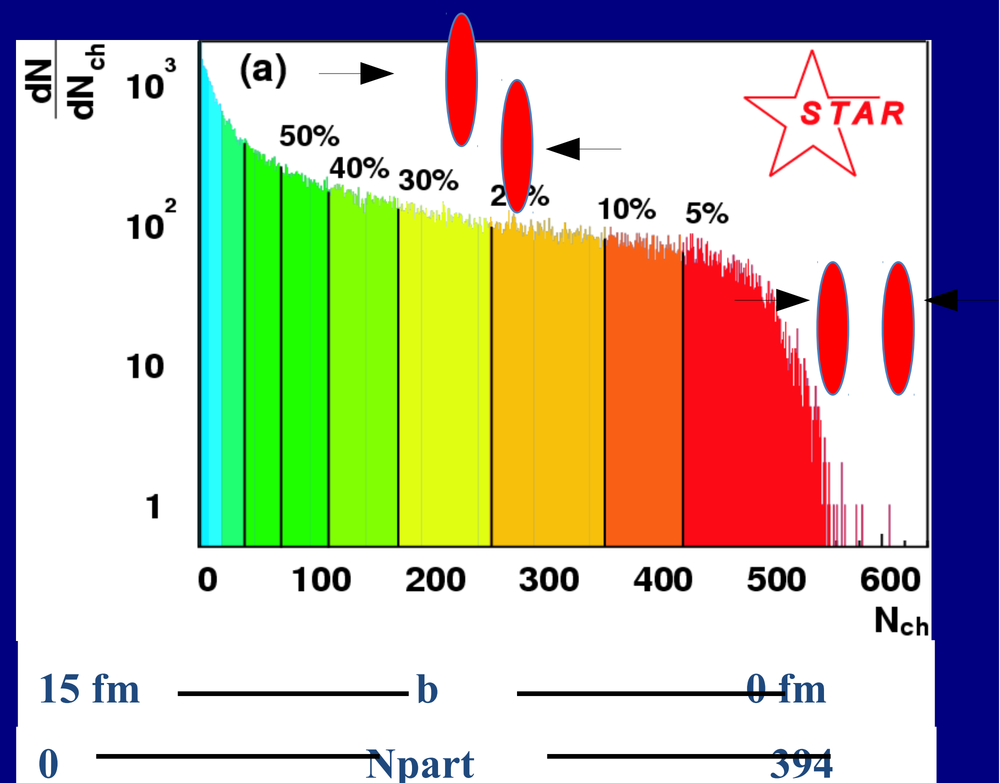


$$p^\mu = \left(E, p_x, p_y, p_z\right)$$

In terms of pT and y

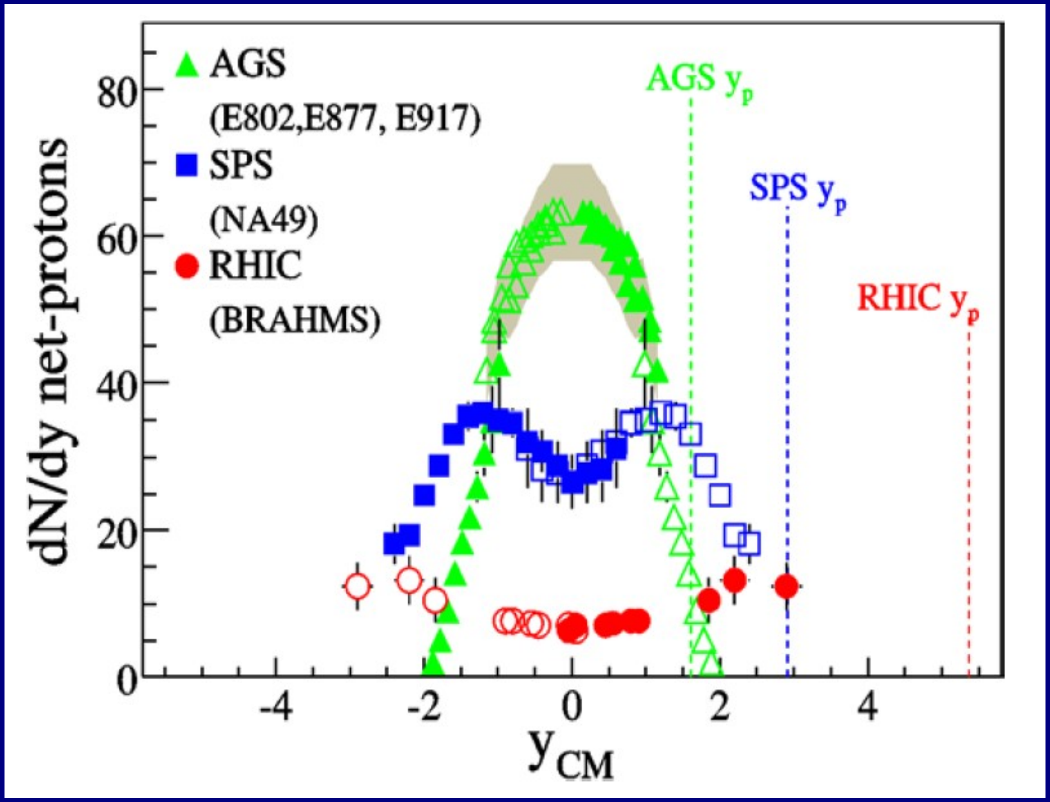
$$p^\mu = \left(m_T \cosh y, p_T, m_T \sinh y\right)$$

Centrality of the collisions

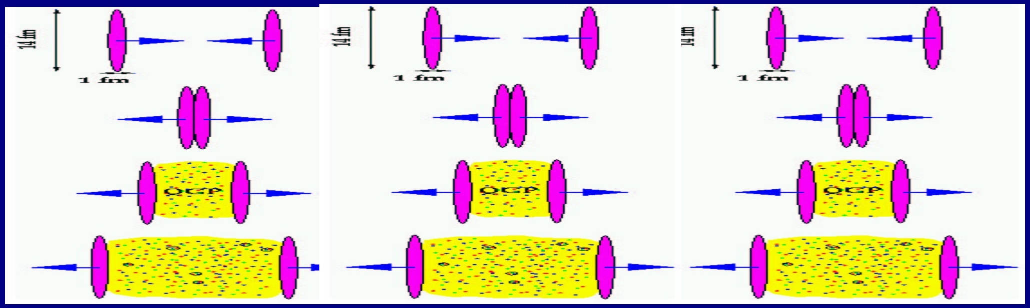


$$m_T = \sqrt{p_T^2 + m^2}$$

Increasing the energy...

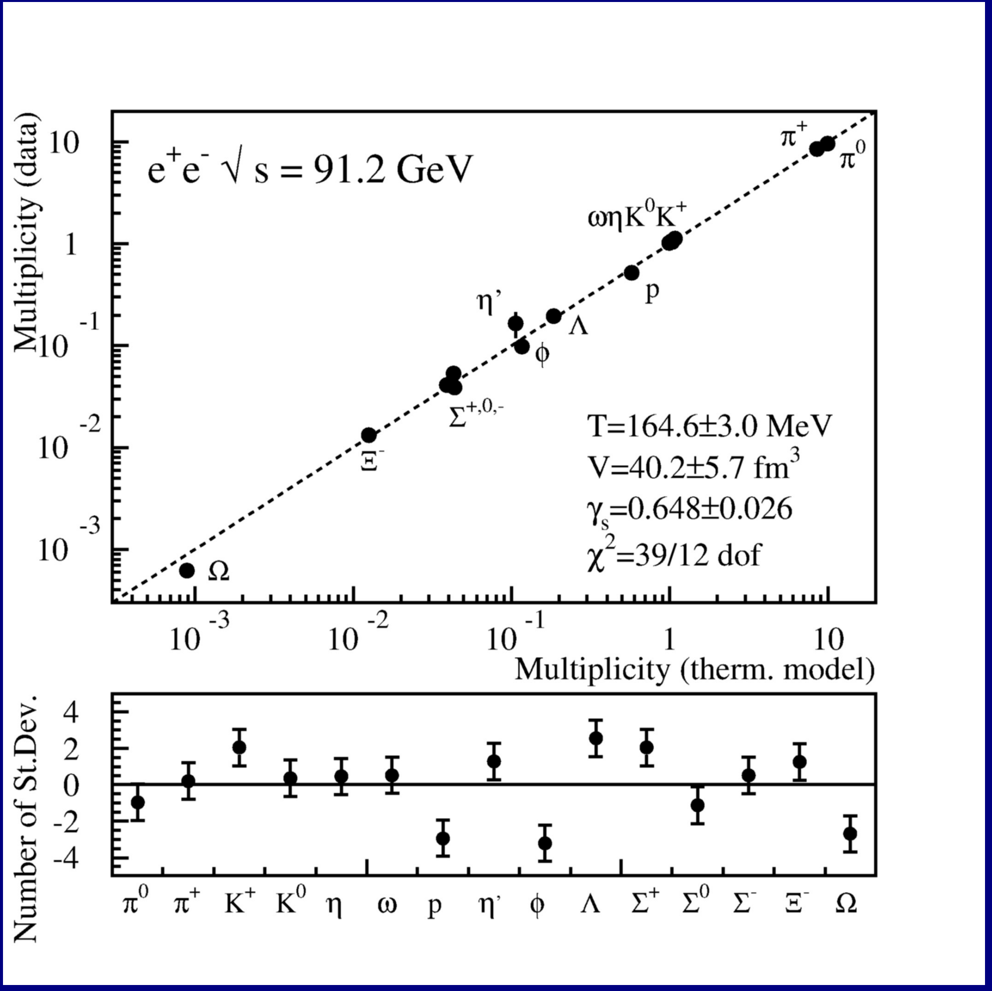


Baryon stopping decreases, but a larger energy density is achieved
(hotter, denser, longer)



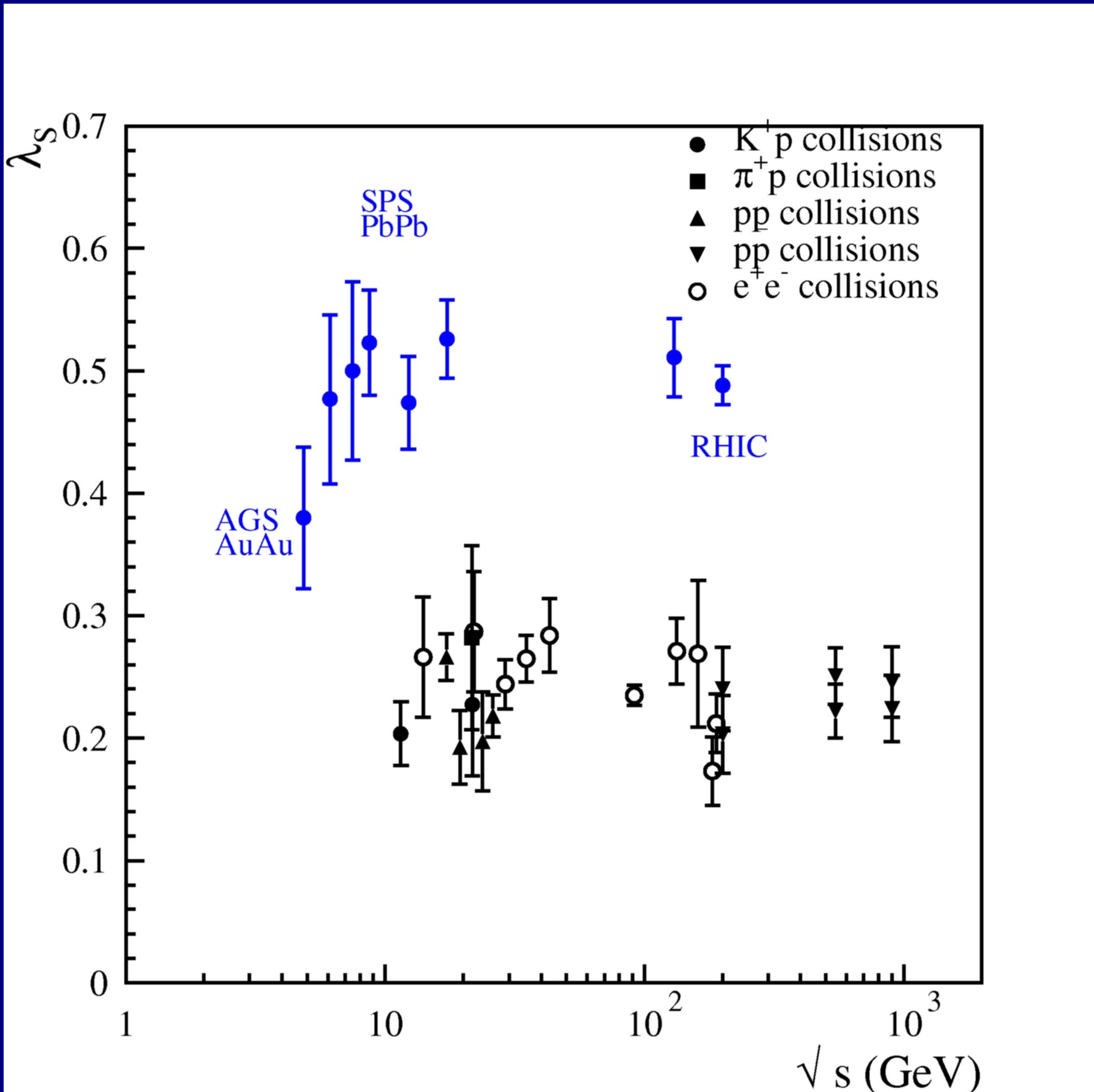
Have we overcome the critical T?

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



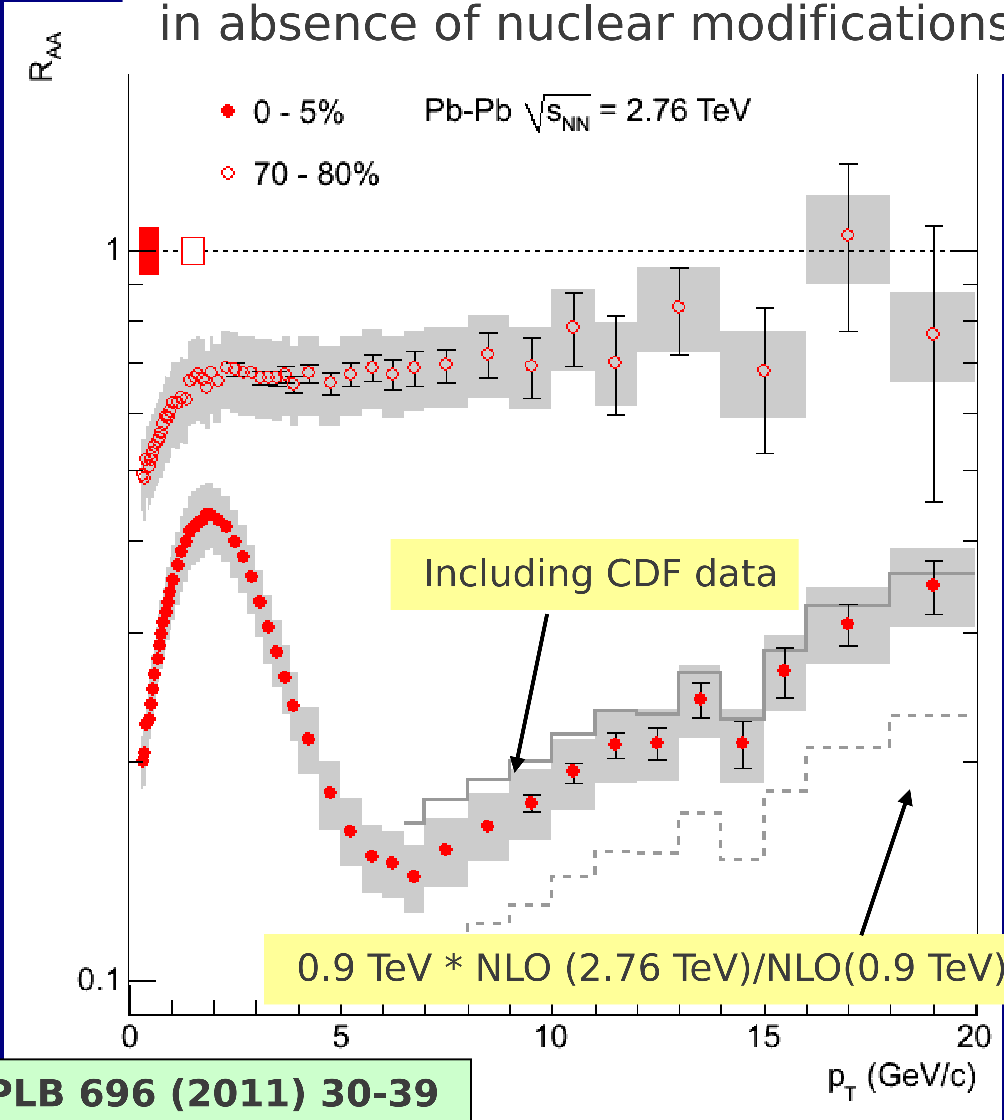
$$\lambda_S = 2\frac{\langle s\bar{s}\rangle}{\langle u\bar{u} + d\bar{d}\rangle}$$

Suppression of high-p_T hadrons (not so for γ)

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

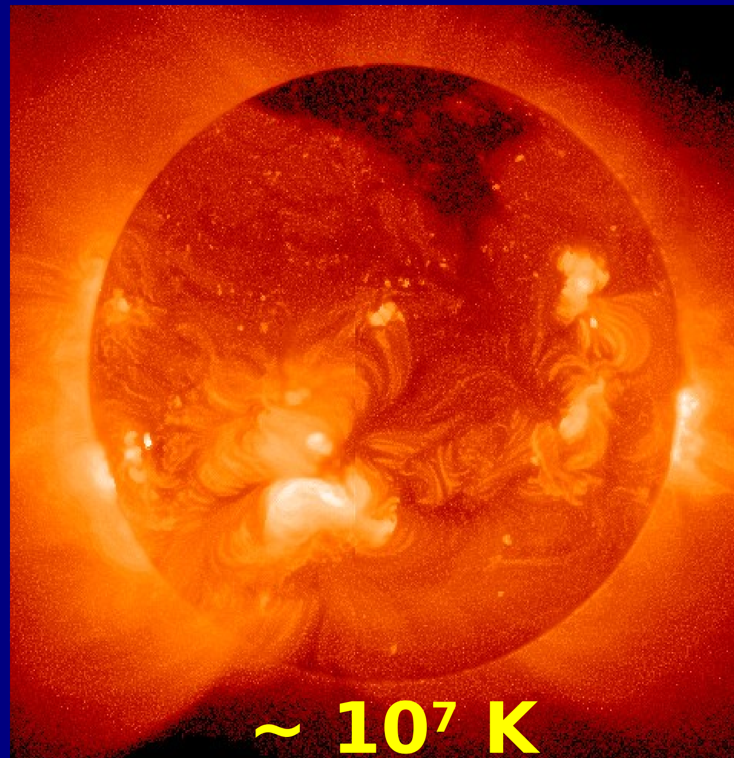
R_{AA} = 1 for hard QCD processes in absence of nuclear modifications

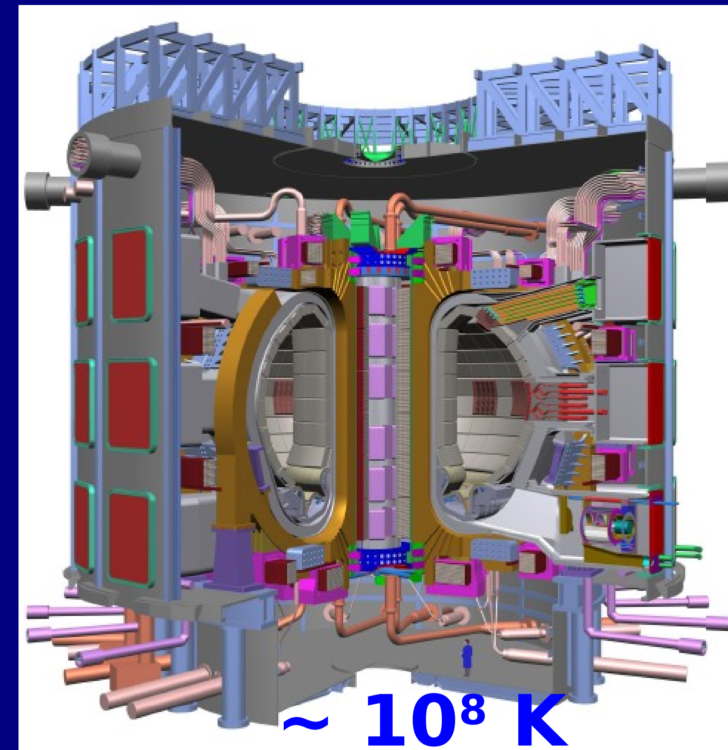
- Due to energy loss of partons, there is a strong suppression of high pt hadrons
- Even larger at LHC than @ RHIC
- Nuclear modification factor $R_{AA}(p_T)$ for charged particles produced in 0-5% centrality range
  - minimum (~ 0.14) for p_T ~ 6-7 GeV/c
  - then slow increase at high p_T

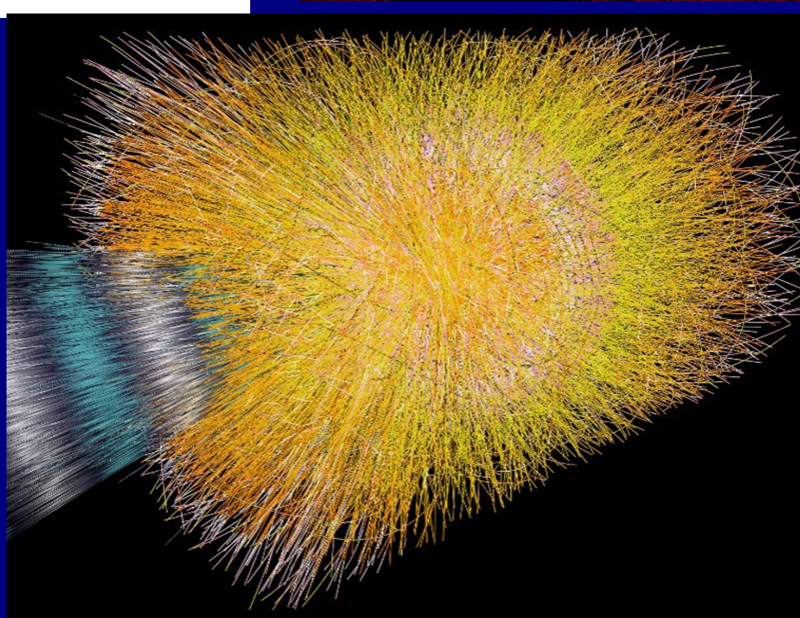


PLB 696 (2011) 30-39

The largest temperature ever achieved on Earth ($> 2 \times 10^{12}$ K)

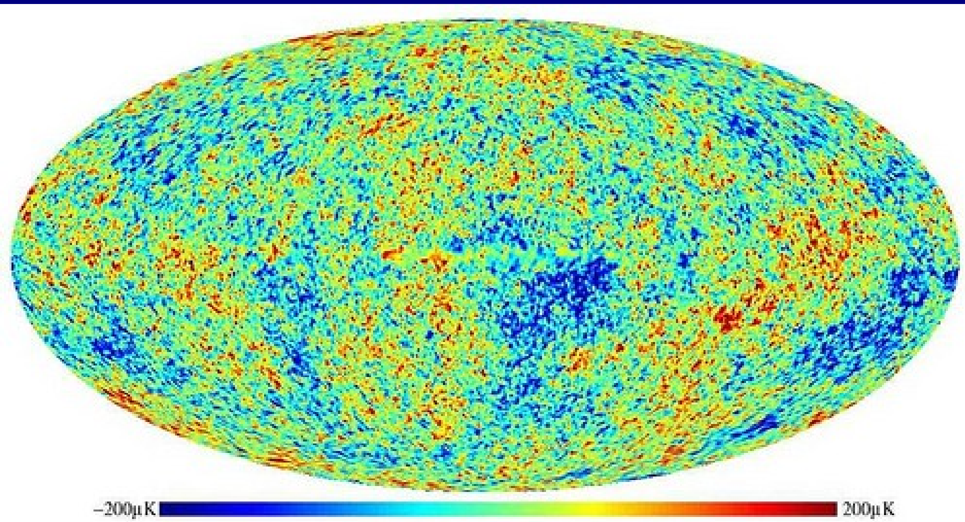


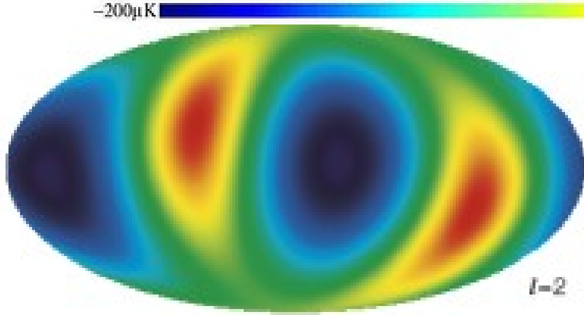


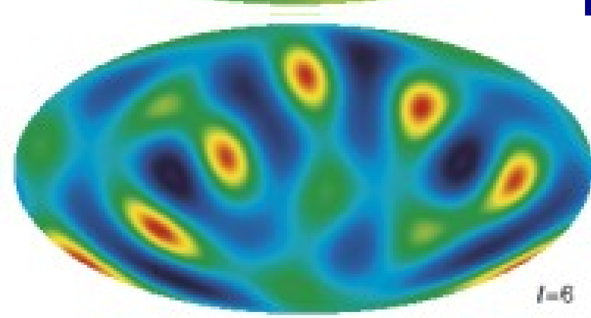


$\sim 5\ 10^{12}$ K !

High harmonics fluctuations reminds the CMB fluctuations...



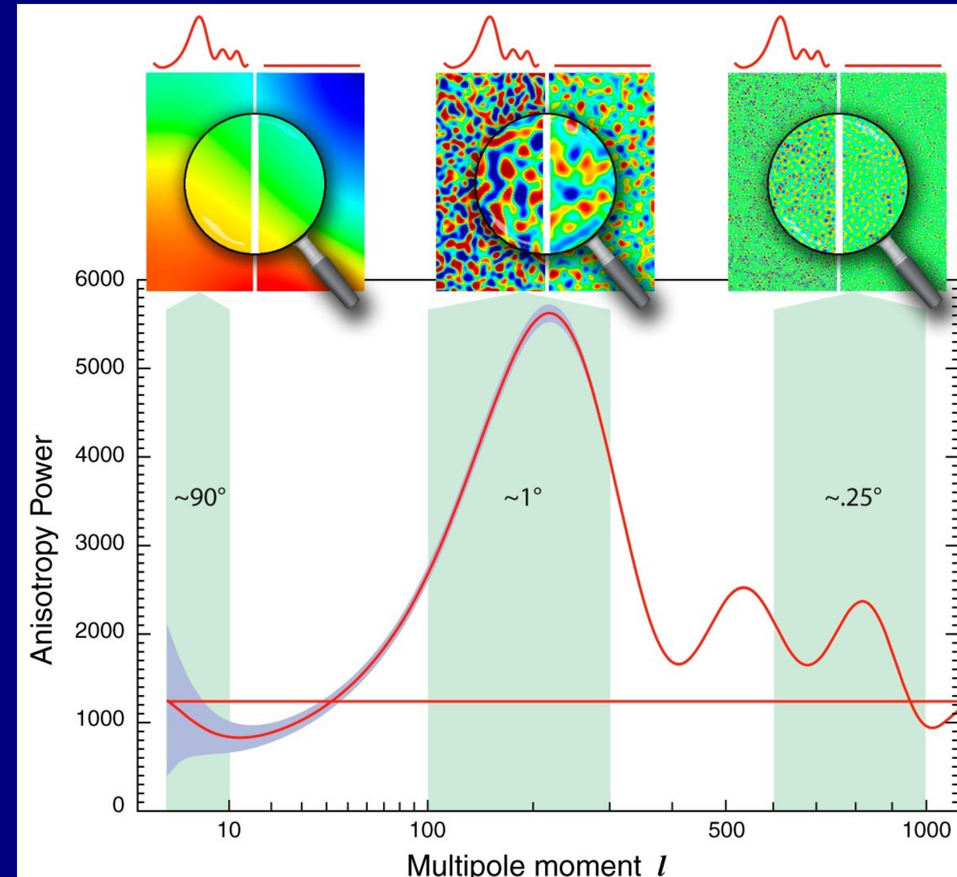




$$\frac{\Delta T}{T} \sim 10^{-5}$$

$$l_{maximum} \approx 210$$

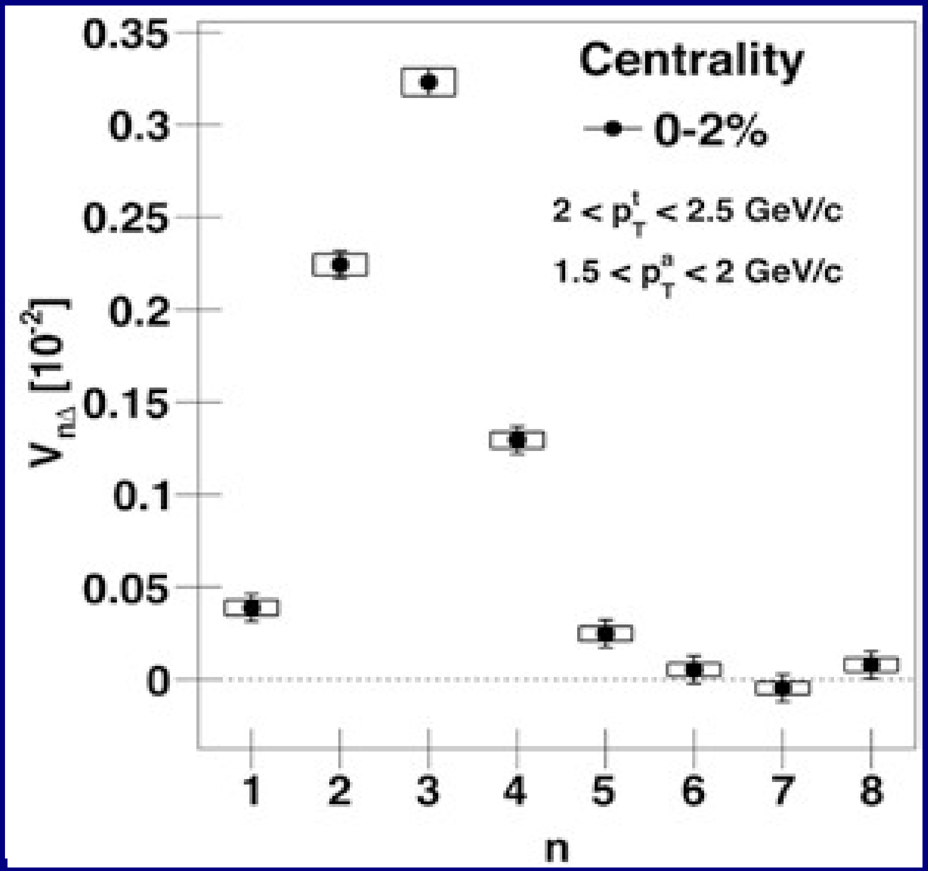
$$\delta\phi \sim 2\pi / l_{maximum} \sim 1^{o}$$



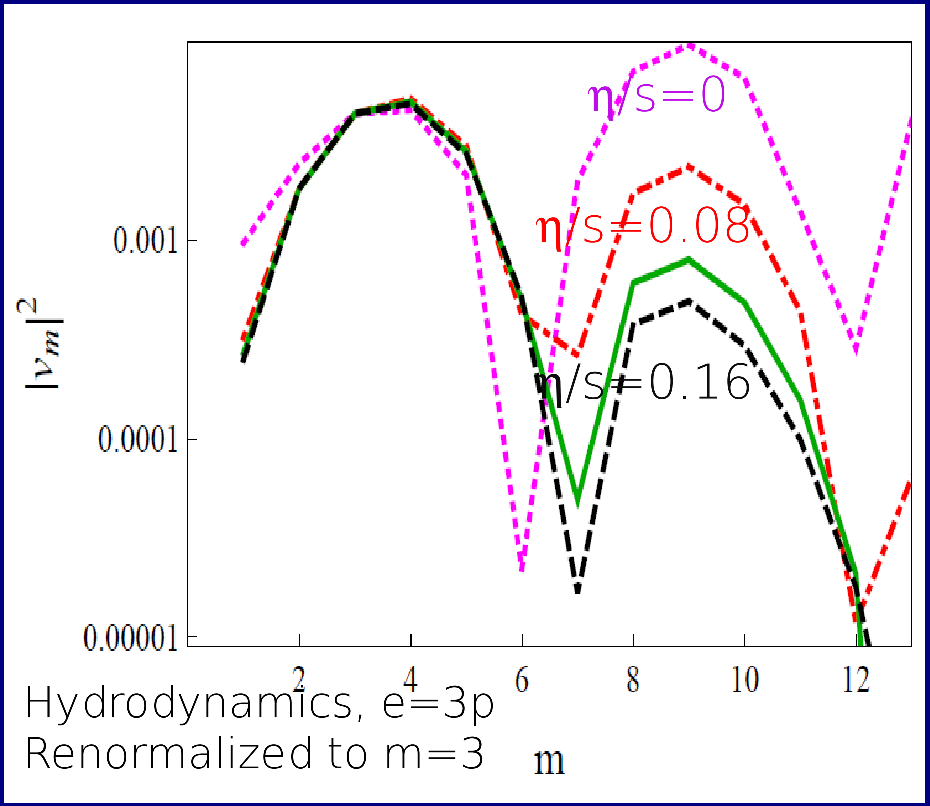
Freeze-out τ ~ 380.000 y's (QGP ~ 10^{-22} s)
Sound horizon R ~ Mps (QGP ~ 6 fm)

Of course n=200 is not possible to be seen for a hadron system with R ~ 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