New results and Perspectives in Heavy Ion Physics

Heavy Ion Collisions in the LHC Era

Quy Nhon, Vietnam

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Why colliding heavy nuclei at high energy ?

- Not for the purpose of studying elementary interactions

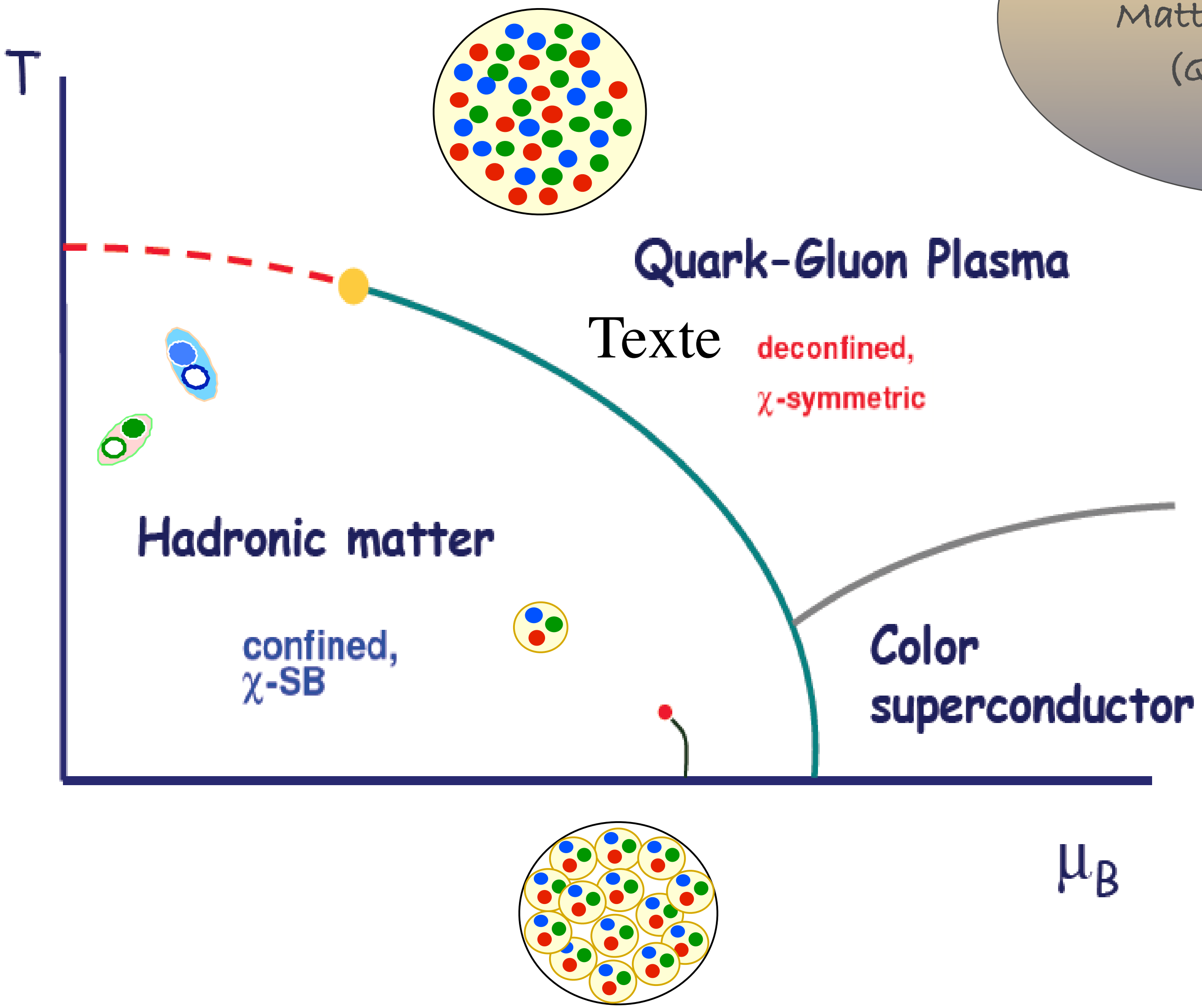
- Focus is on studying MATTER, i.e., properties of assemblies of large number of elementary constituents

- Fundamental issues of intrinsic interest (QCD phase diagram), and of relevance for astrophysics (early universe, compact stars)

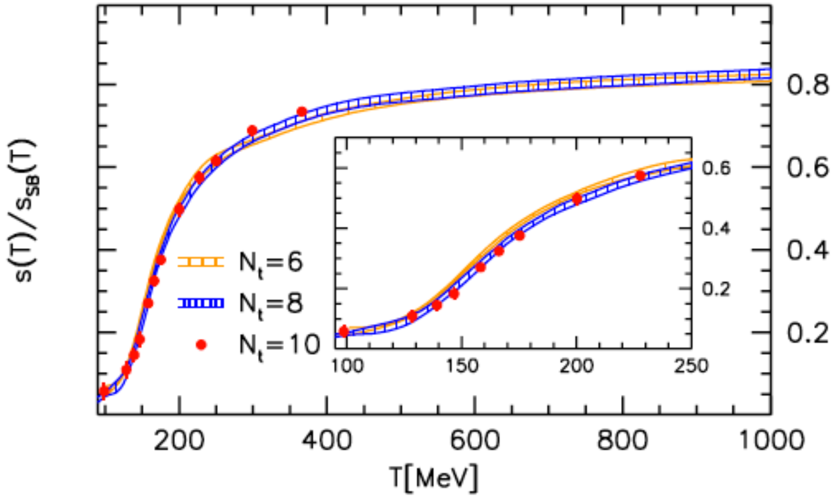
- 'Universal' character of wave functions of large nuclei at high energy (dense gluonic systems)

The QCD phase diagram

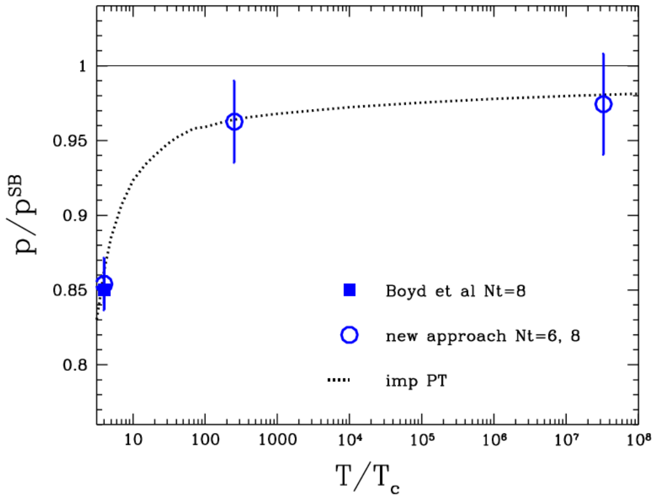
High T, n
Matter is 'simple'
(QCD A.F.)



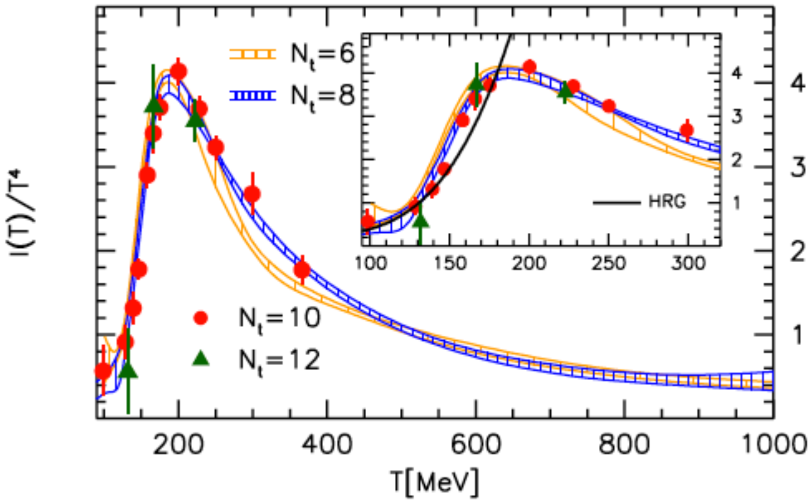
The crossover from the hadron gas to the quark-gluon plasma from lattice calculations



(Borsanyi et al, arXiv:1007.2580)



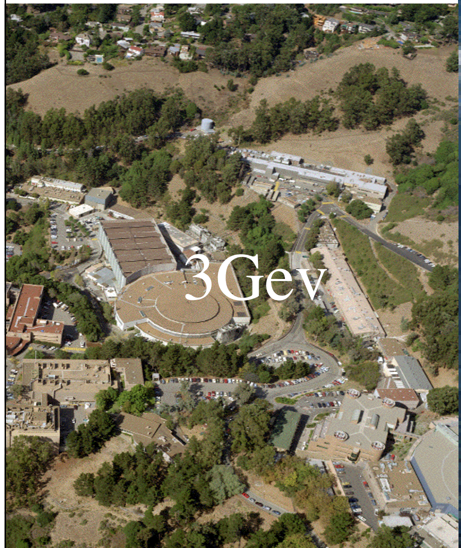
(from G. Endrodi et al, arXiv: 0710.4197)



Colliding heavy nuclei

From AGS to SPS to RHIC to LHC

Bevalac



SPS-LHC

Some historical landmarks

- 1973 Discovery of QCD asymptotic freedom. Implies that matter is simple at high temperature and density (quark-gluon plasma)

- 1986 SPS heavy ion program starts (light nuclei, O, S) $\sqrt{s_{NN}} \simeq 20$ GeV

- 1992 Au nuclei in AGS $\sqrt{s_{NN}} \simeq 5$ GeV

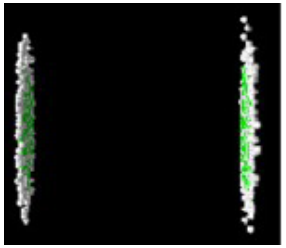
- 1996 Pb nuclei in SPS $\sqrt{s_{NN}} \simeq 17$ GeV

- 2000 First Au-Au collisions at RHIC $\sqrt{s_{NN}} \simeq 200$ GeV

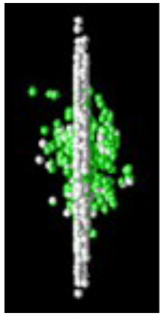
- 2010 First Pb-Pb collisions at LHC $\sqrt{s_{NN}} \simeq 2760$ GeV

The 'little bang'

Stages of nucleus-nucleus collisions

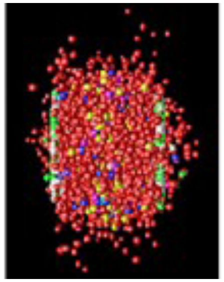


Initial conditions. Fluctuations (geometry, nucleus wave function and its parton content)

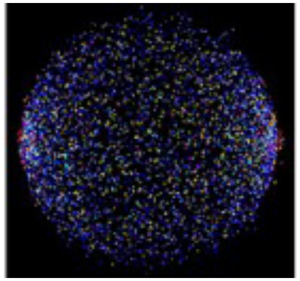


Particle (entropy) production. Involves mostly small x partons $(x = p_\perp / \sqrt{s} \sim 10^{-2} - 10^{-4} \quad \text{for} \quad p_\perp \simeq 2\text{GeV})$

One characteristic scale: saturation momentum Q_s



Thermalization. Quark-gluon plasma. Hydrodynamical expansion



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

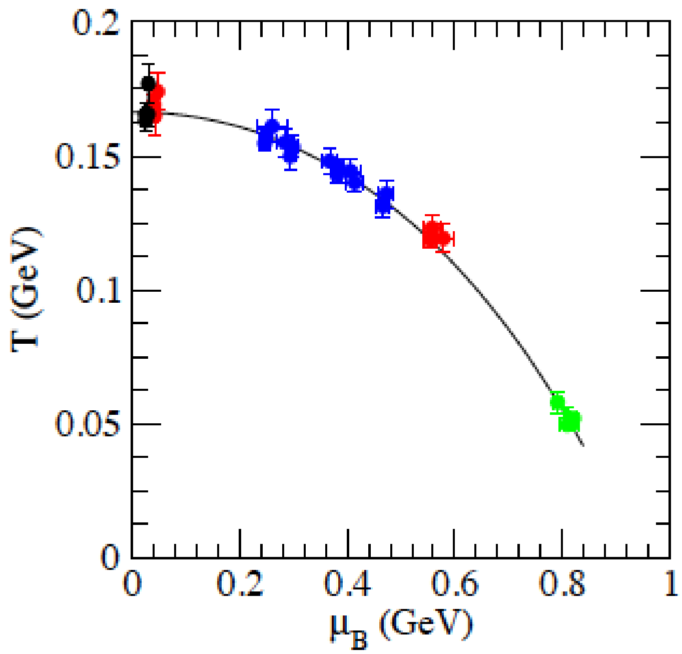
Moving backward in time

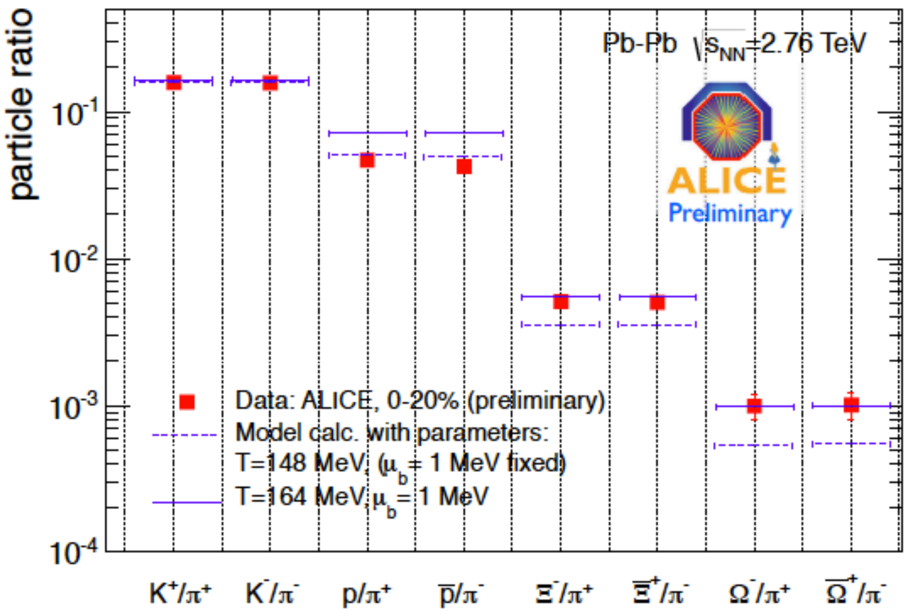
Matter at freeze-out is in chemical equilibrium

Matter at « freeze-out »

well described by statistical picture

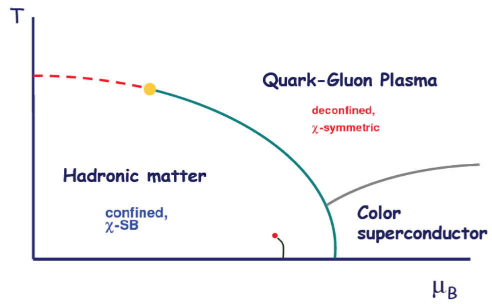
$$n \sim \frac{1}{e^{(\varepsilon_k - \mu)/T} \pm 1}$$

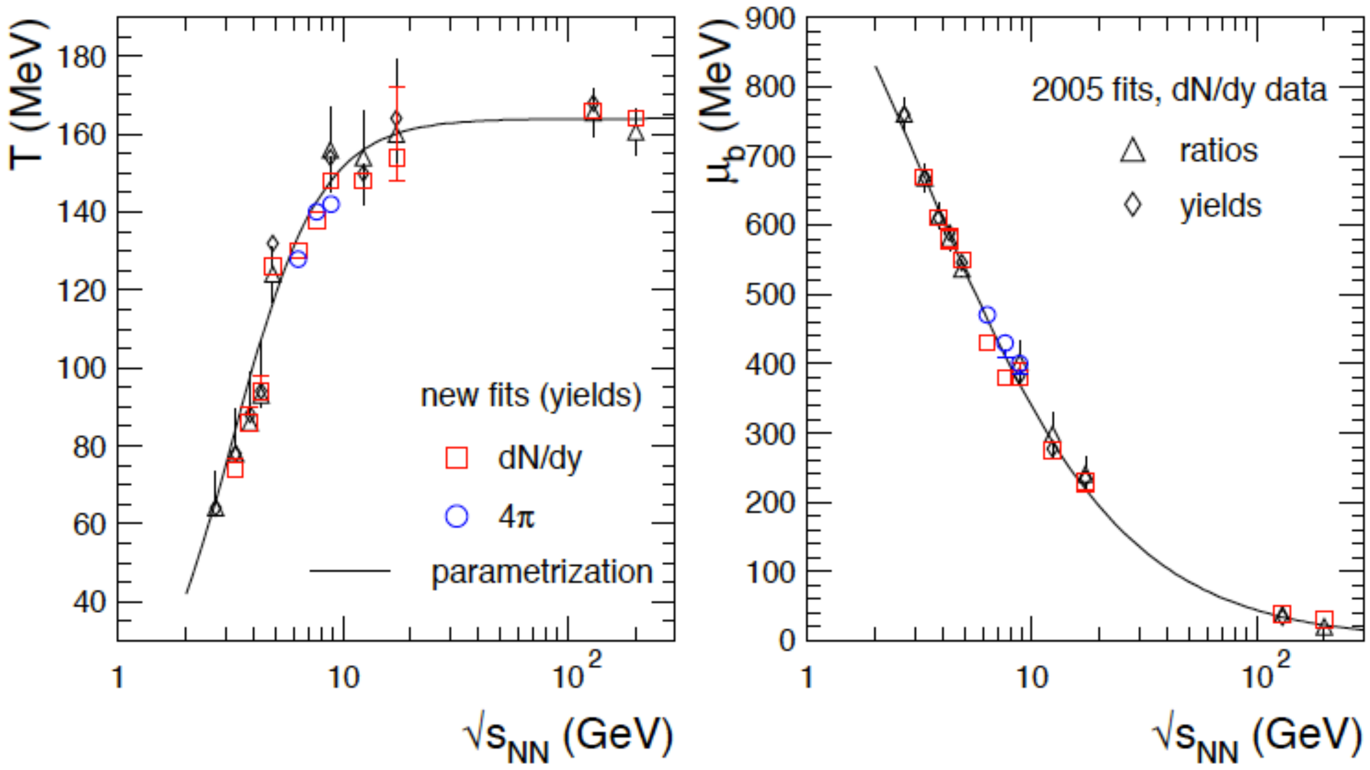




(from J. Cleymans et al, hep-ph/0511094)

Freeze-out parameters vary smoothly with collision energy

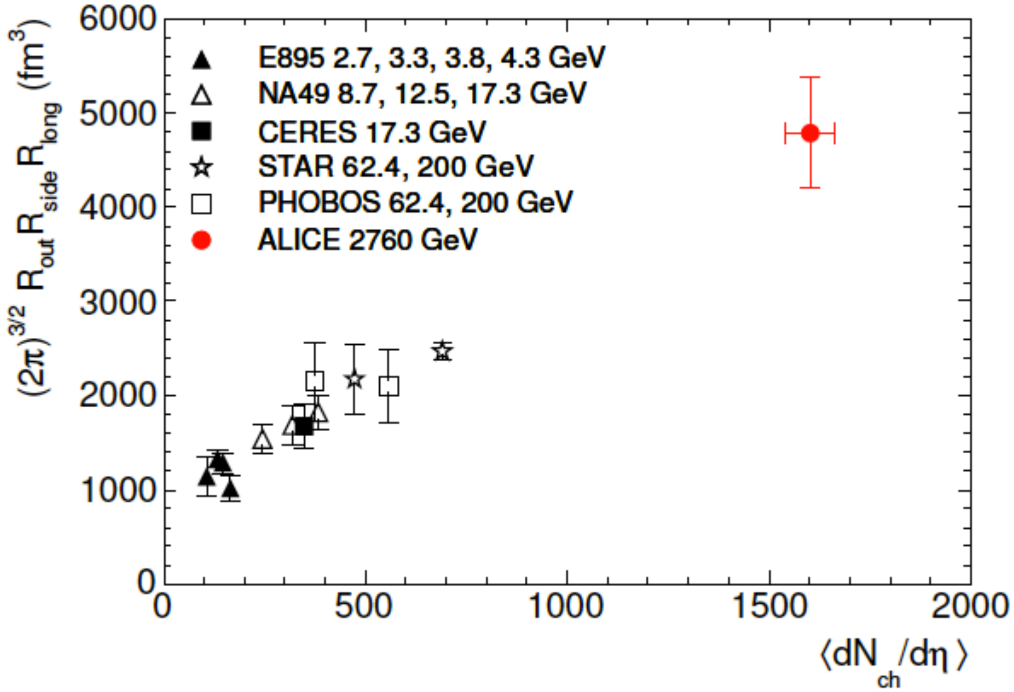


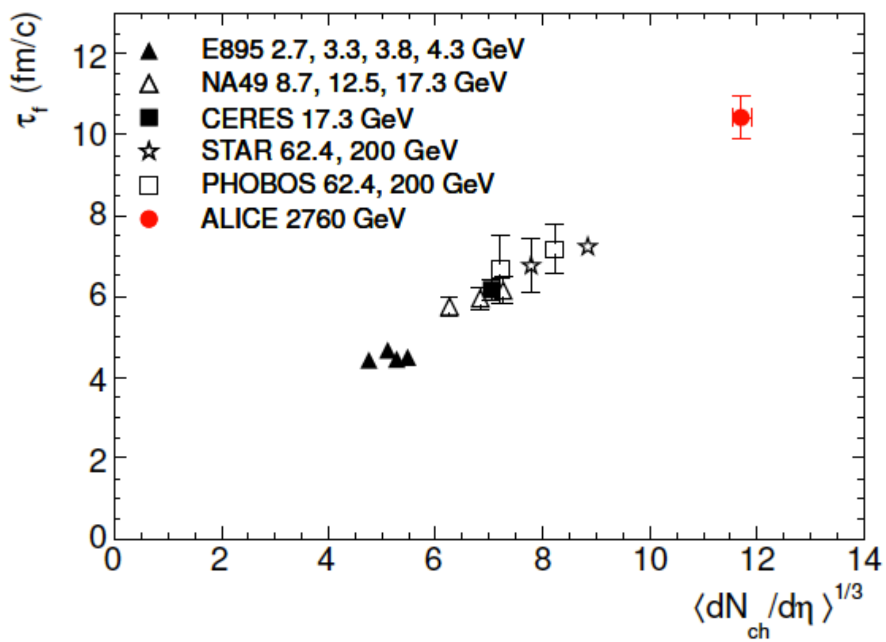


(Andronic et al., PLB 673 (2009) 142)

Freeze-out volume, time, larger at LHC

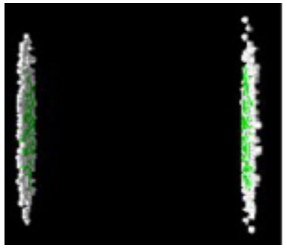
(deduced from HBT interferometry)





(ALICE, PLB696 (2011) 328)

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



$$\longleftarrow \tau_0 \longrightarrow$$

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

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

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

Moving backward in time

Matter flows like a fluid

Collective flow

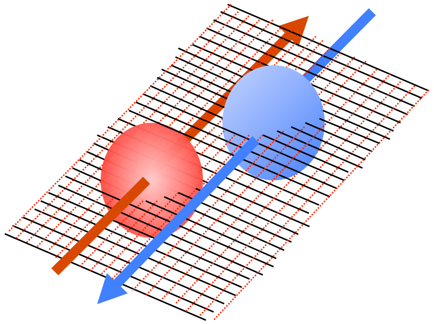
Matter flows like a fluid and is well described by hydrodynamics

Hydrodynamical flow is sensitive to viscosity, and on initial state fluctuations

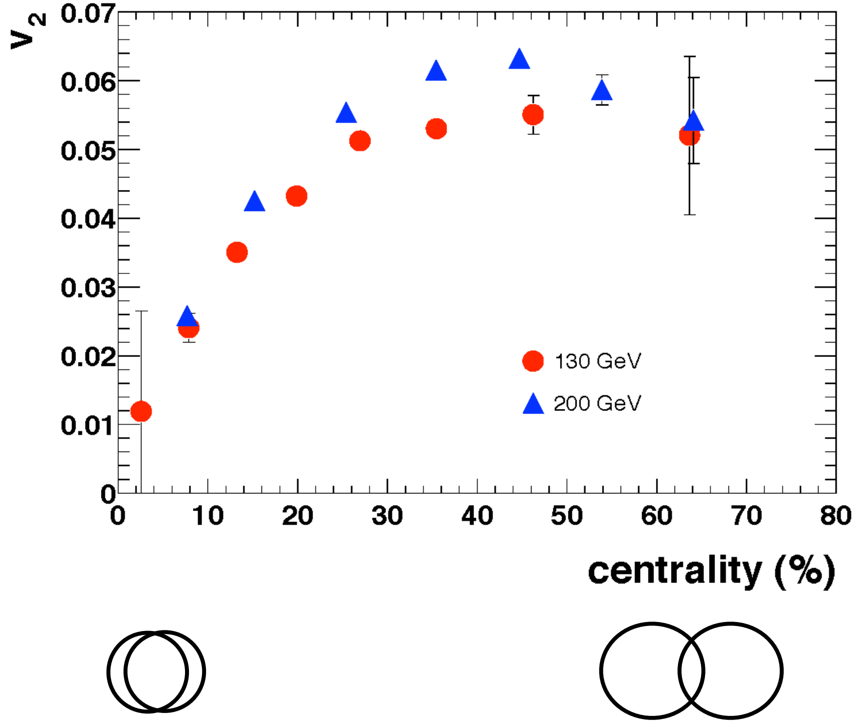
Remarkably small value of viscosity/entropy ratio, suggesting a very short mean free path, and a strong coupling

AdS/CFT correspondence provides insight into strongly coupled gauge theories and viscous hydrodynamics

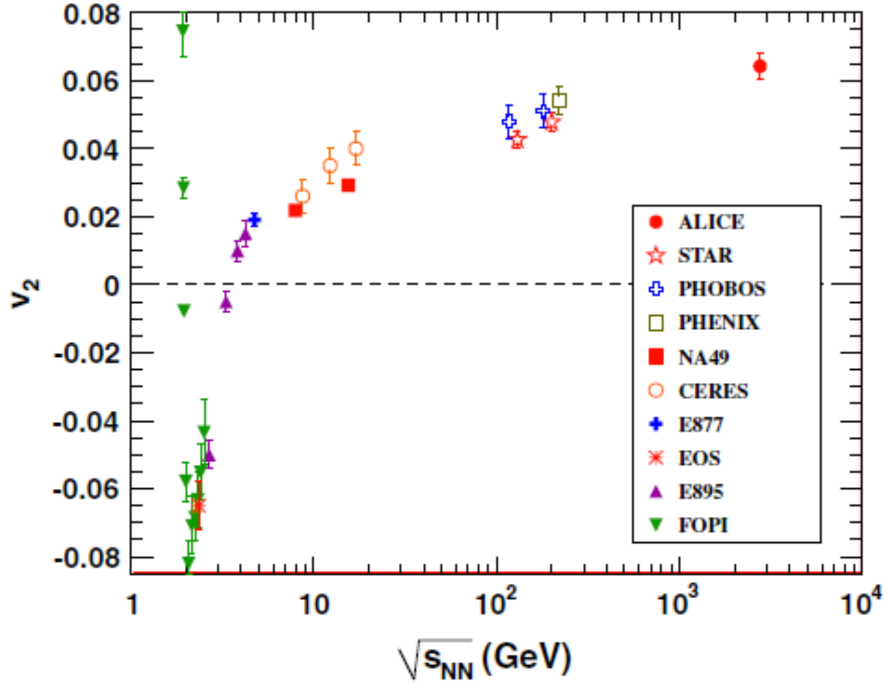
Elliptic flow



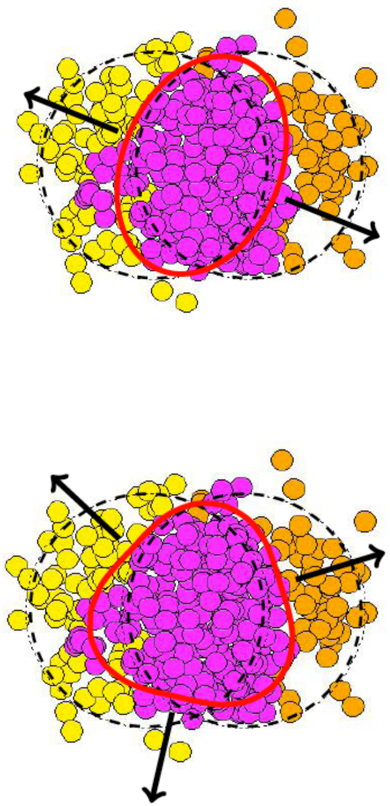
$$v_2 = \langle \cos(2\phi) \rangle$$

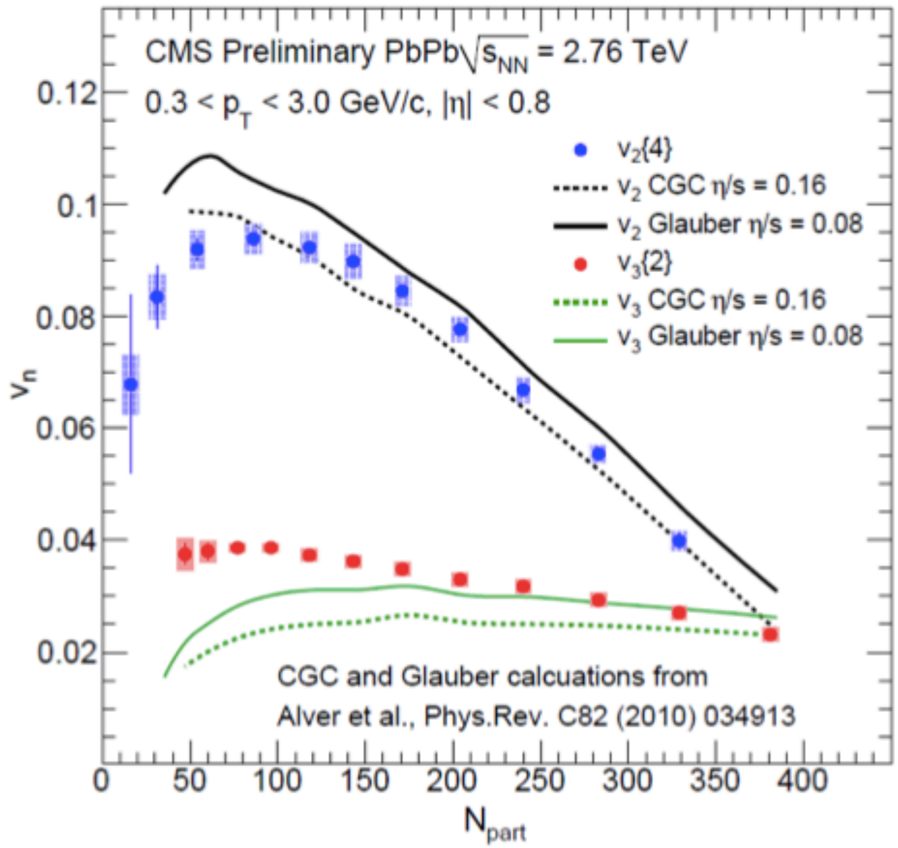


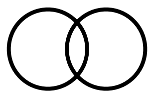
(Quark-Matter 02)



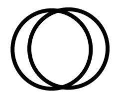
The flow is sensitive to initial nuclear density fluctuations







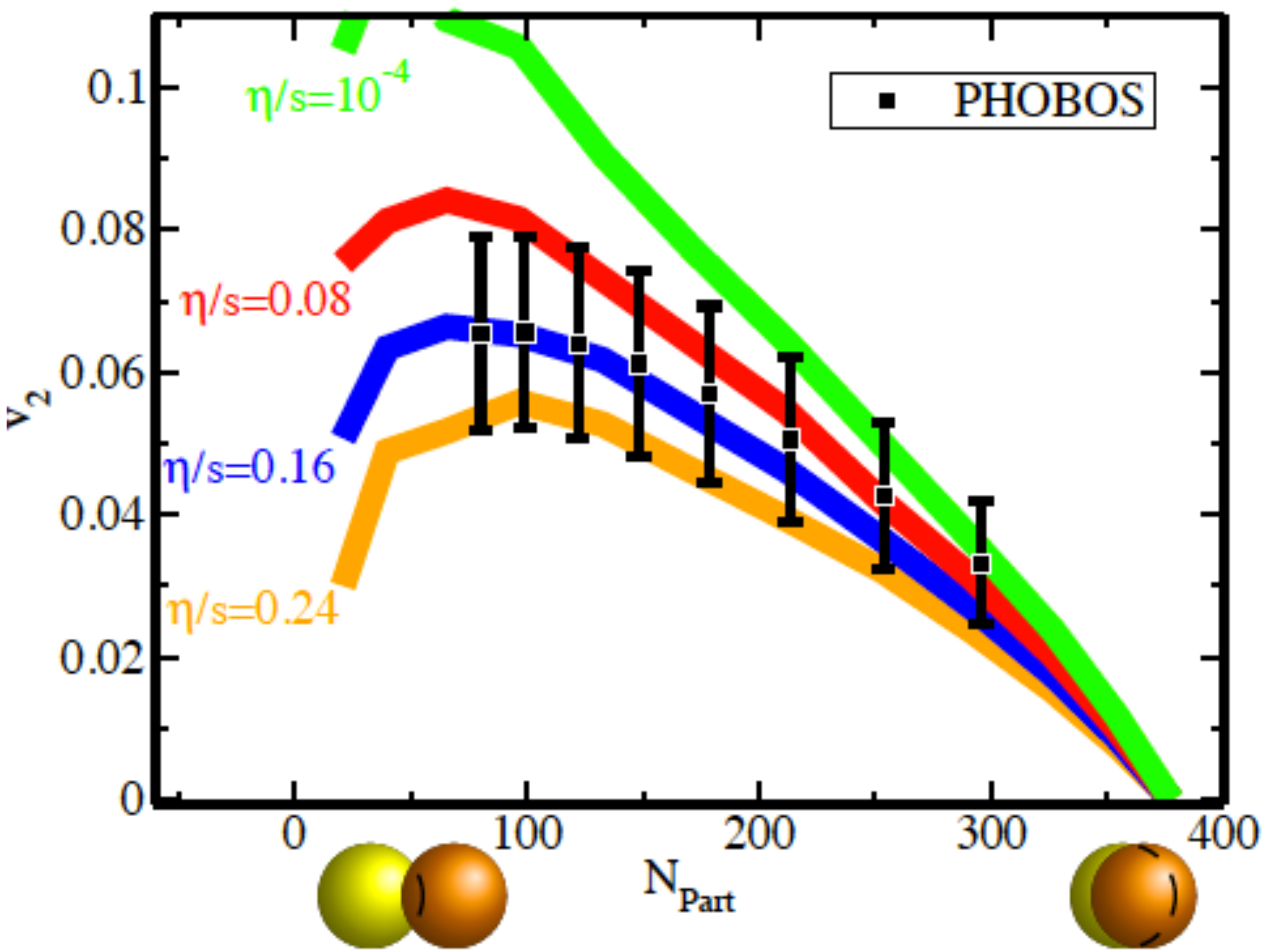
peripheral



central

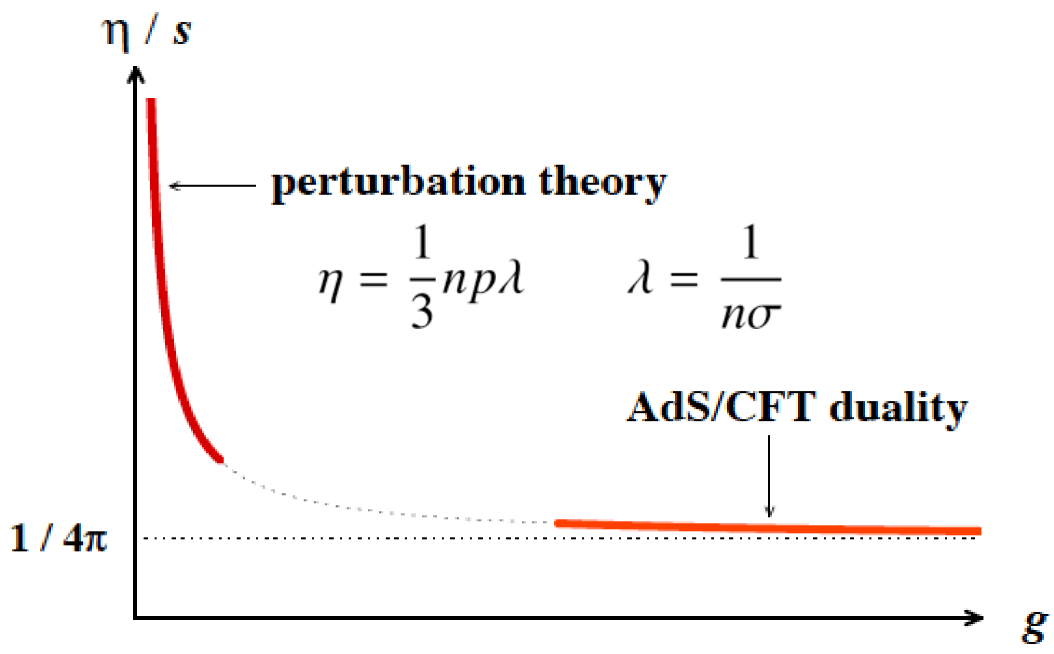
J. Velkowska,
QM2011
and
Luzum,
arXiv:1011:5173

A fluid with small (relative) viscosity



(Luzum, Romatschke (2008))

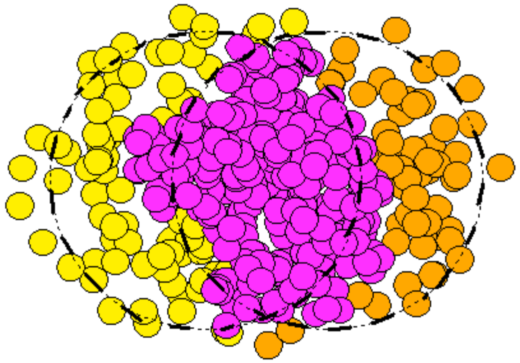
The perfect liquid

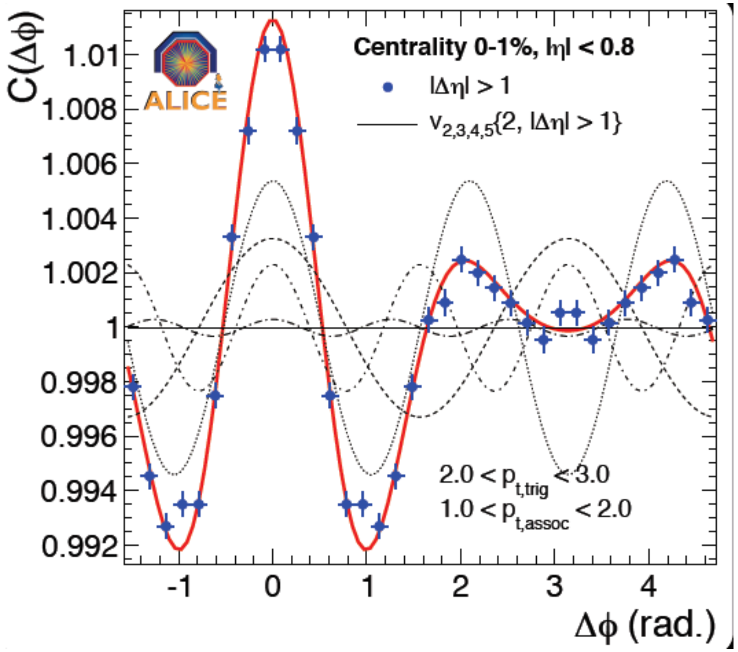


$$\frac{\eta}{s} = \frac{1}{4\pi}\frac{\hbar}{k_B}$$

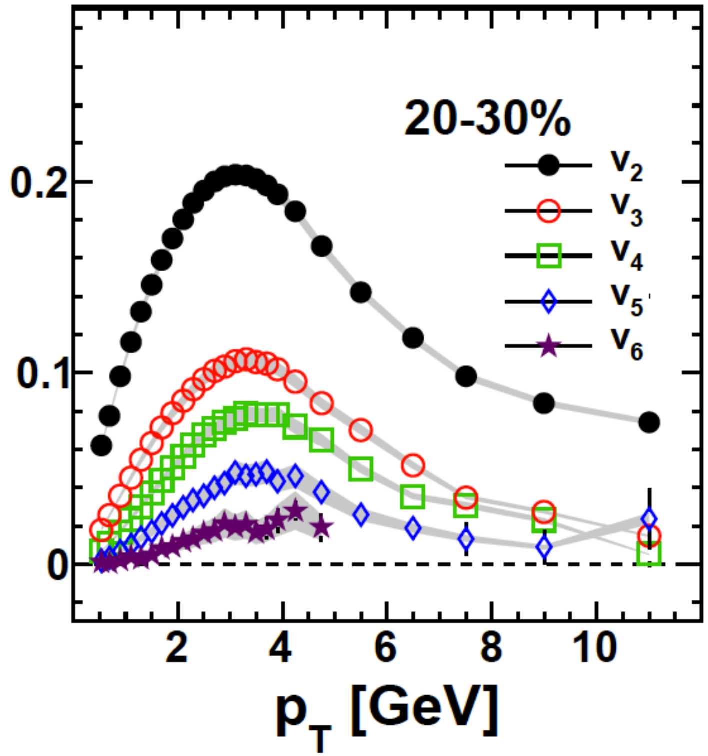
The small value of eta/s suggests a strongly coupled liquid...

Primordial fluctuations





(ALICE Collaboration PRL 107 (2011) 032301)



(Atlas coll. Quark Matter 2011)

Moving backward in time

Nuclei are made of densely packed gluons

Early stages of nucleus-nucleus collisions

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

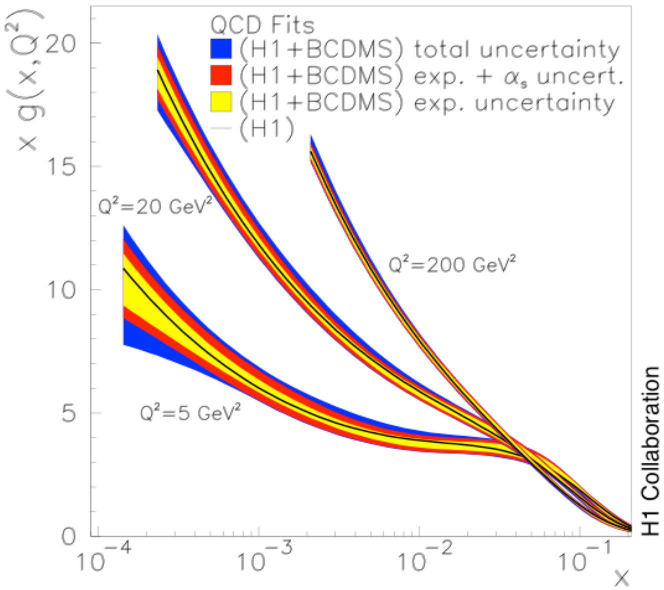
RHIC ($\sqrt{s} = 200\,\mathrm{GeV}$) $\quad x \sim 10^{-2}$

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

Probes small x components of the nuclear wave functions

Gluon density increases with energy, but the growth eventually saturates

The study of gluon saturation is an area where there has been major progress over the last decade (non linear evolution equations, color glass condensate, etc)



Saturation momentum scale

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

Large parton density at saturation

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

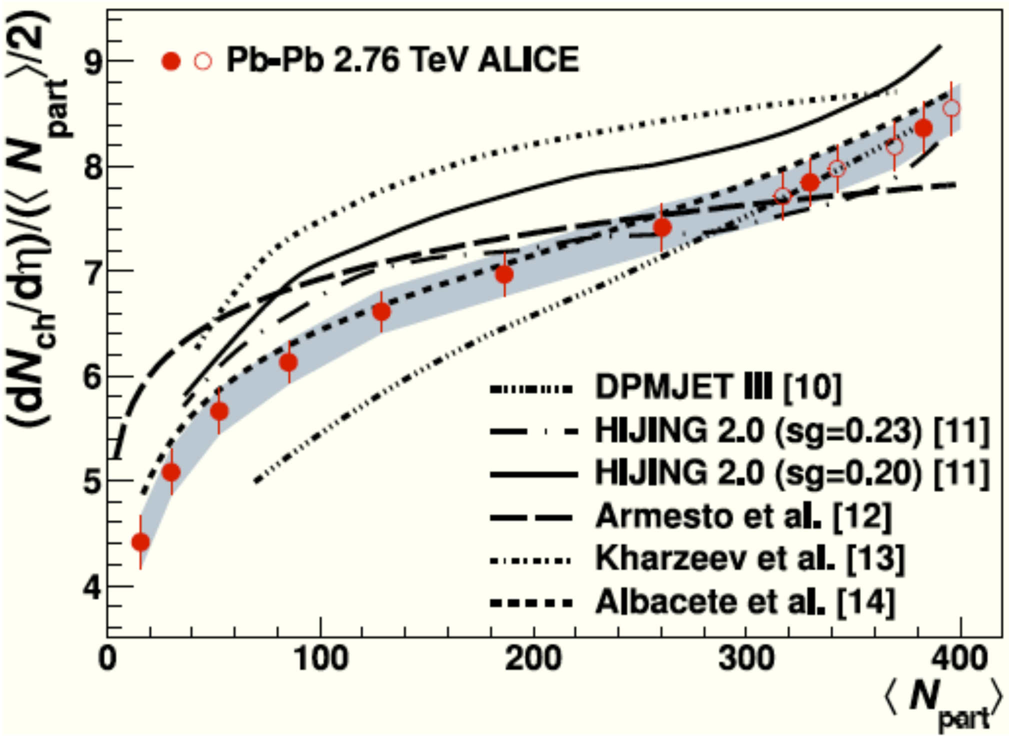
$$\frac{\pi}{Q_s^2} n \sim \frac{\pi}{\alpha_s}$$

partons with $k_T \lesssim Q_s$ are in saturated regime

partons with $k_T > Q_s$ are in dilute regime

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

Successful phenomenology at RHIC... and LHC

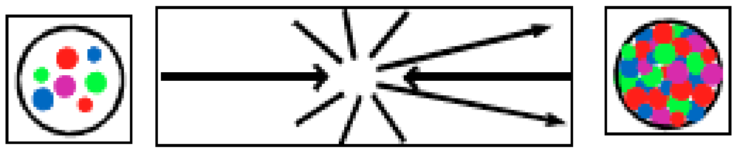


The LHC will allow for more detailed tests of the CGC picture

Di-hadron production
Azimuthal correlations at forward rapidity

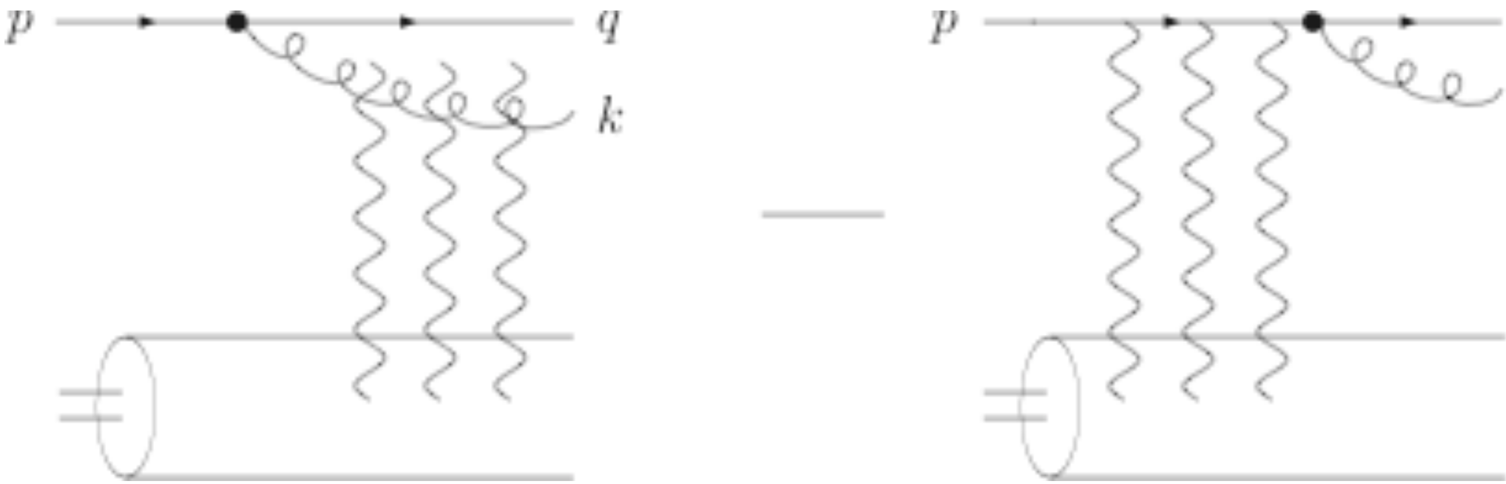
$$\mathrm{d\,Au} \to \mathrm{h_1\,h_2\,X}$$

$$x_p = \frac{k_1\, e^{y_1} + k_2\, e^{y_2}}{\sqrt{s}}$$



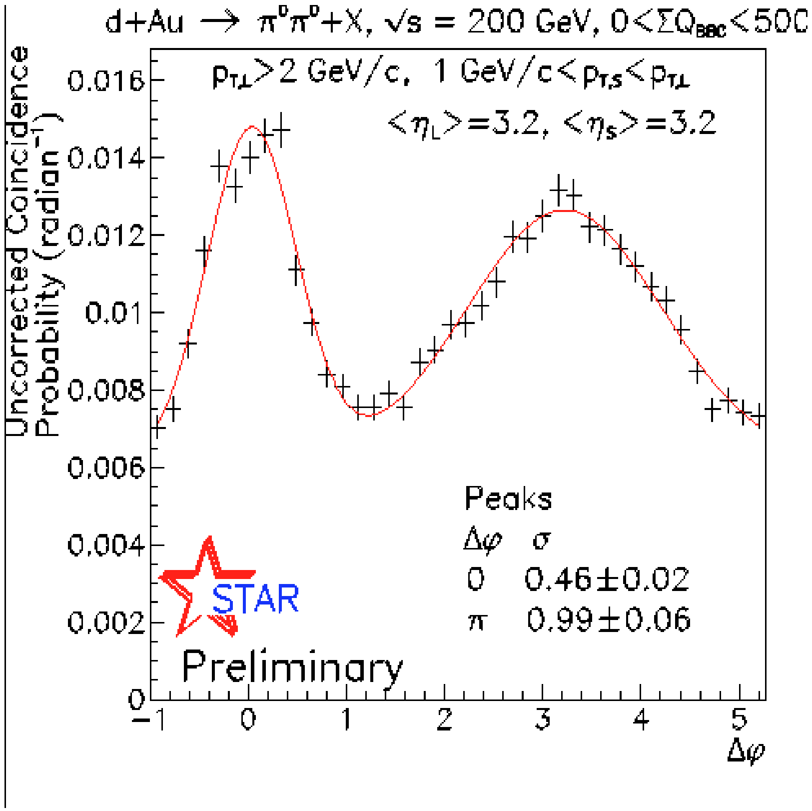
$$x_A = \frac{k_1\, e^{-y_1} + k_2\, e^{-y_2}}{\sqrt{s}}$$

$$x_p \sim 1,\; x_A \ll 1$$

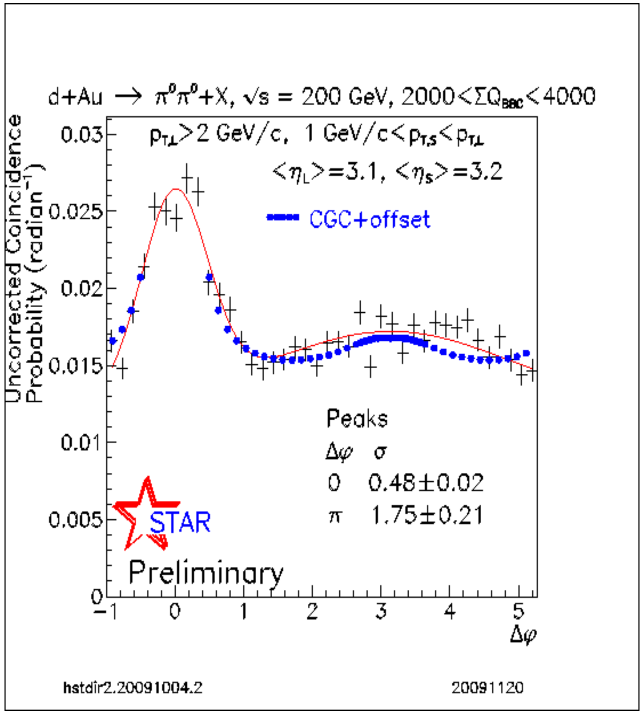


Azymuthal correlations

d+Au peripheral



d+Au central



(Albacete & Marquet RBRC wks, May 2010)

Moving backward in time

Signals from the early stages

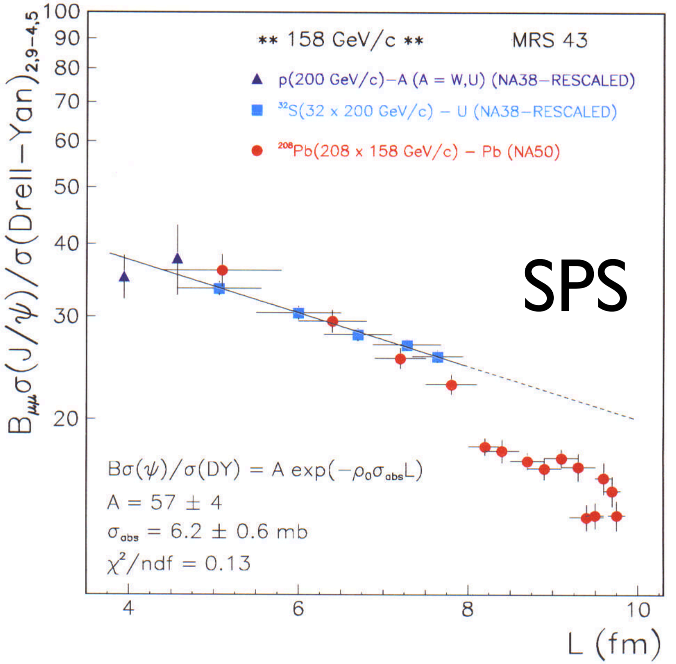
Hard probes

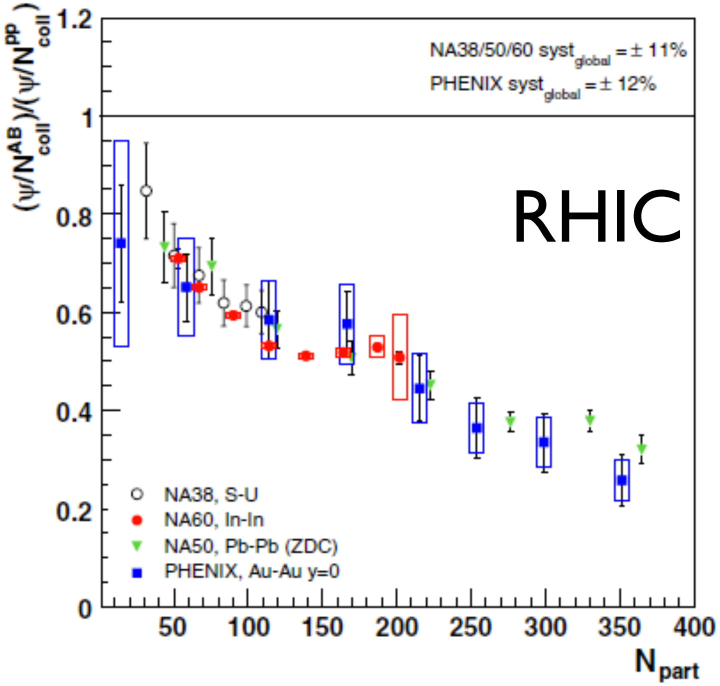
Hard processes occur on short space time scales, hence little affected by the medium. They can be calculated from pQCD

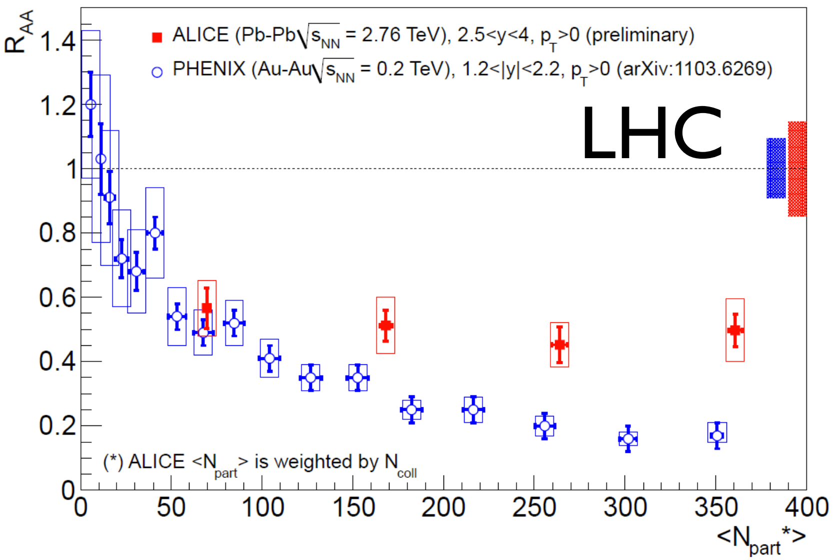
Hard probes: heavy quarks, quarkonia, photons, Z and W, jets...
Prospects for hard probes at the LHC are truly fascinating

Quarkonia bound states, beautiful idea, still unconclusive,
but new data will bring new light

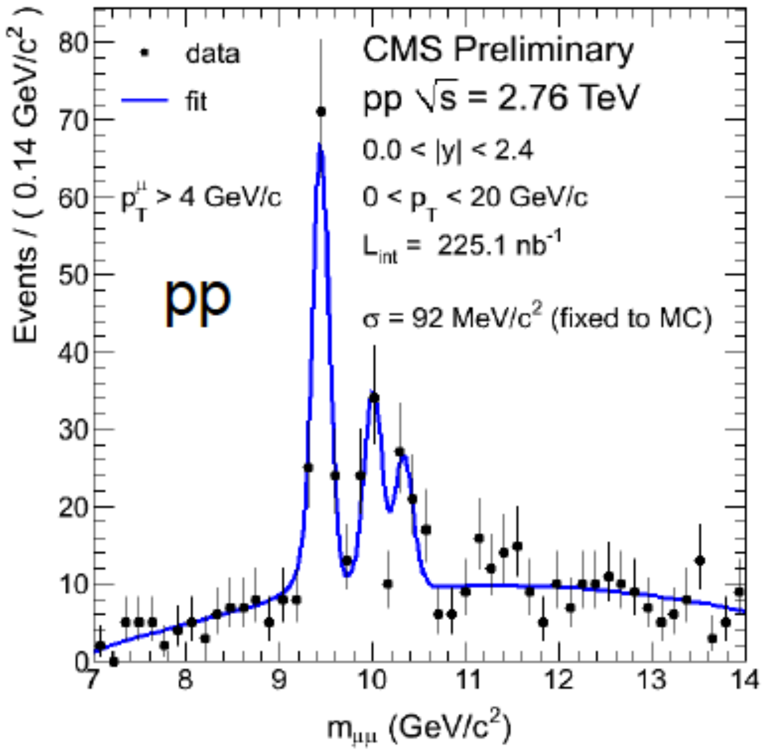
J/Ψ suppression

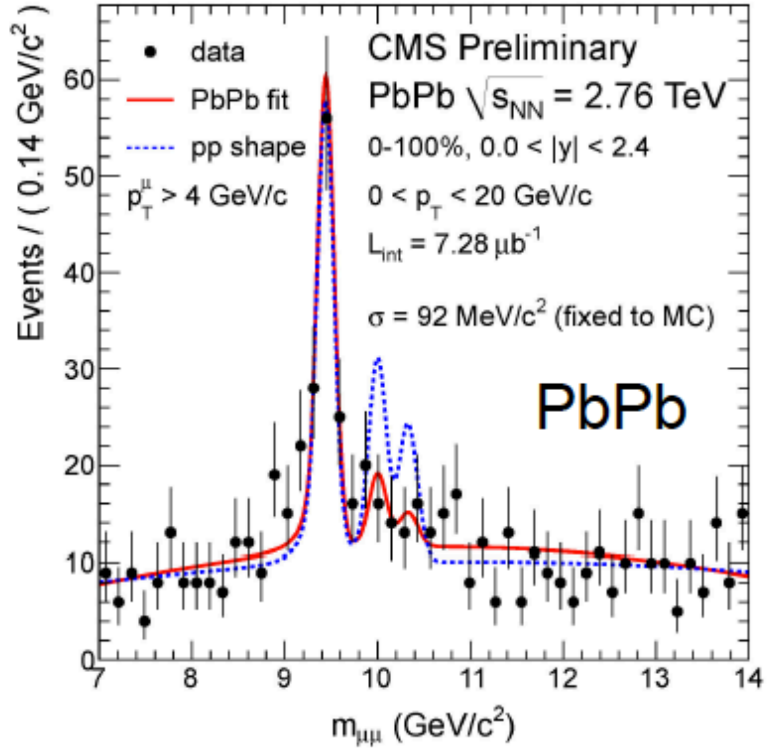






Υ suppression

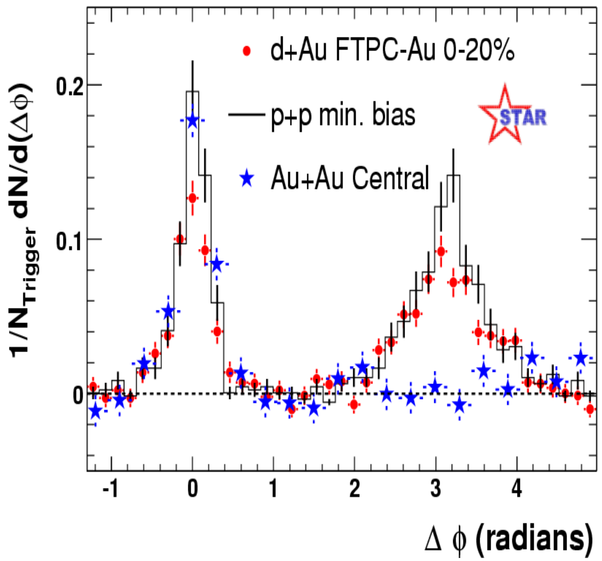




$$\Upsilon(2S+3S)/\Upsilon(1S)\big|_{pp} = 0.78^{+0.16}_{-0.14} \pm 0.02$$

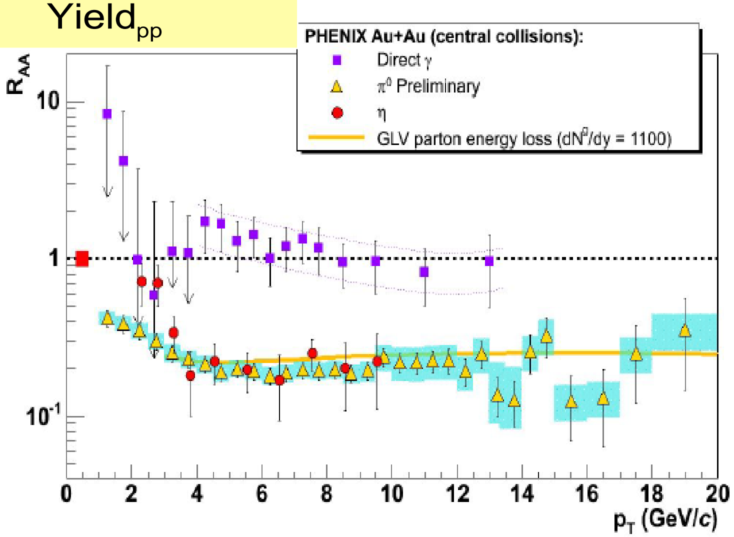
$$\Upsilon(2S+3S)/\Upsilon(1S)\big|_{PbPb} = 0.24^{+0.13}_{-0.12} \pm 0.02$$

Jet quenching

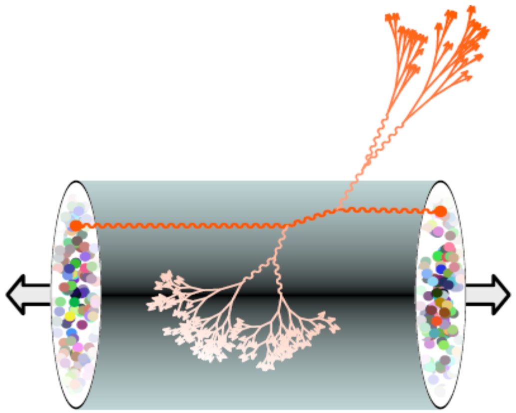


(STAR: Phys.Rev.Lett.91:072304,2003)

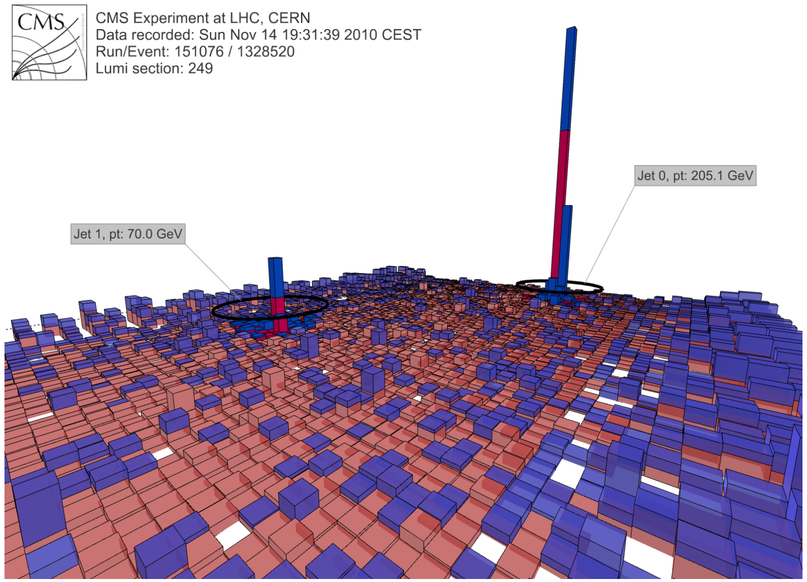
$$R_{AA} = \frac{\text{Yield}_{AuAu} / \langle N_{binary} \rangle_{AuAu}}{\text{Yield}_{pp}}$$



(from Akiba et al, NPA 774 (2006) 403)



Beautiful jet physics at the LHC



Jets are back to back (in spite of large asymmetry in energies)

Fragmentation of jets essentially unmodified

Energy distributed over many soft particles at relatively large angles

All this points to interesting in-medium QCD dynamics

Moving forward in time

Conclusions

A quark-gluon plasma is produced in ultra-relativistic heavy ion collisions, whose global properties do not seem to 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 precise (hard) probes to diagnose the QGP

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Modelling of collisions is greatly helped by the success of hydrodynamics

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The LHC is offering new precise (hard) probes to diagnose the QGP

There is exciting physics also «within» the standard model !