Quark Gluon Plasma

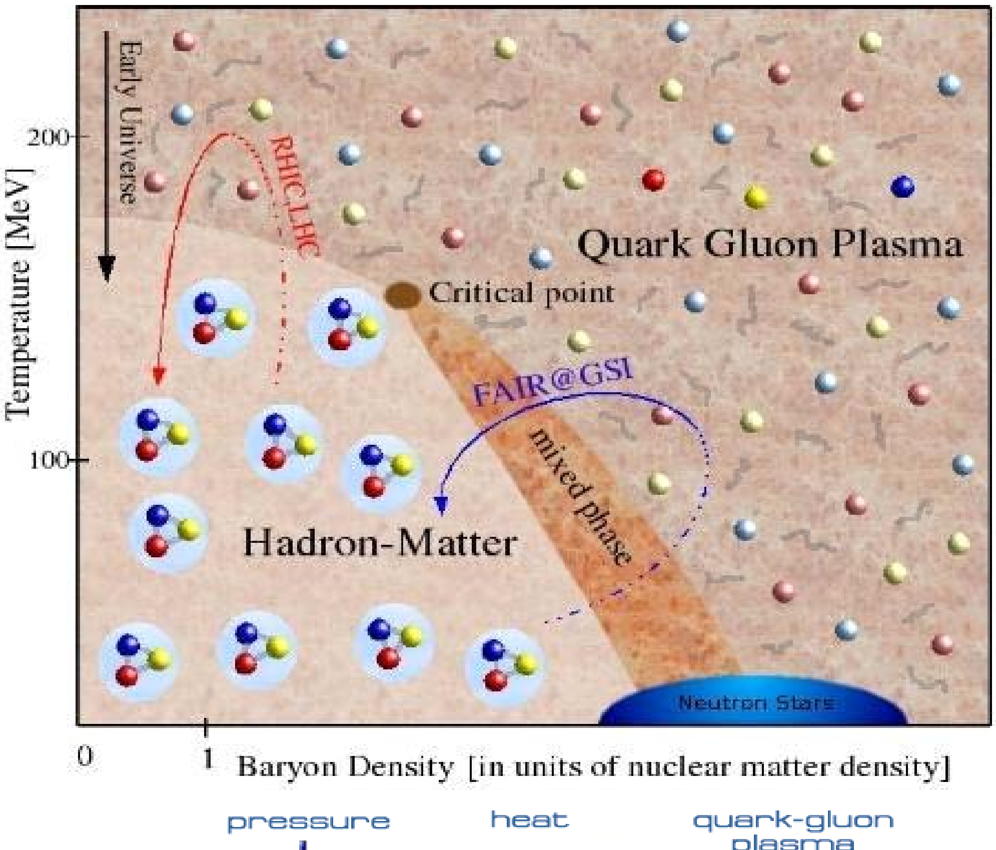
Y. Akiba (RIKEN Nishina Center)

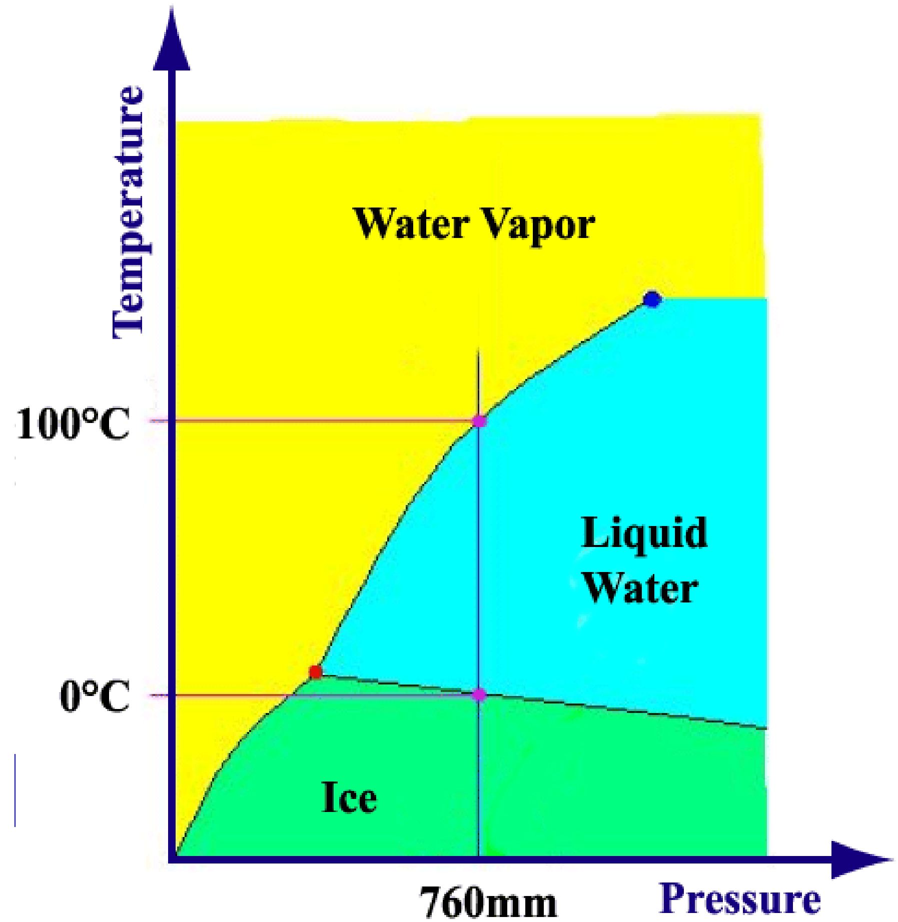
Qukars to Universe in Computational Science

December 14, 2012

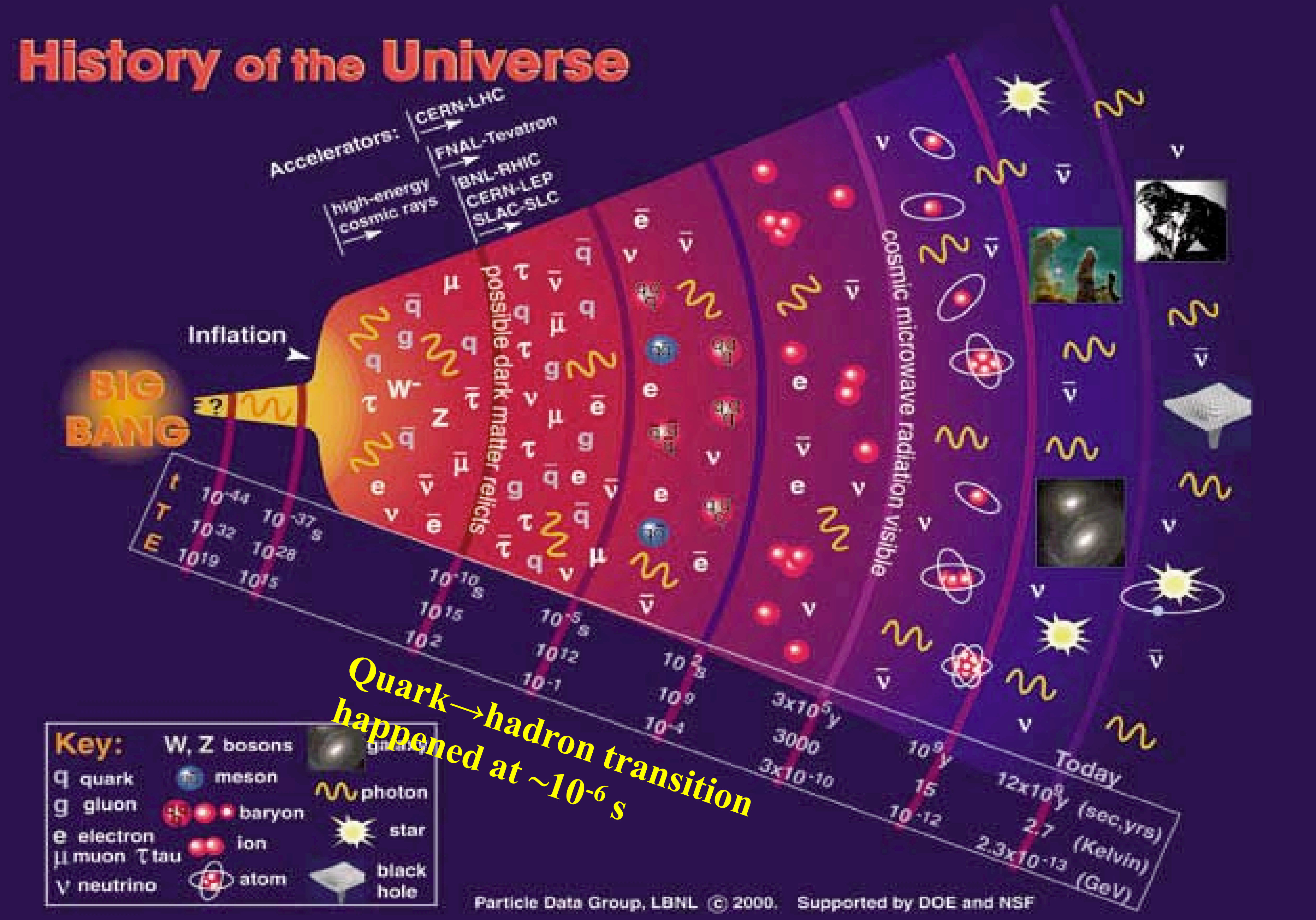
QCD Phase Transition

- The colliding nuclei at high energies would melt protons and neutrons into a collection of quarks and gluons





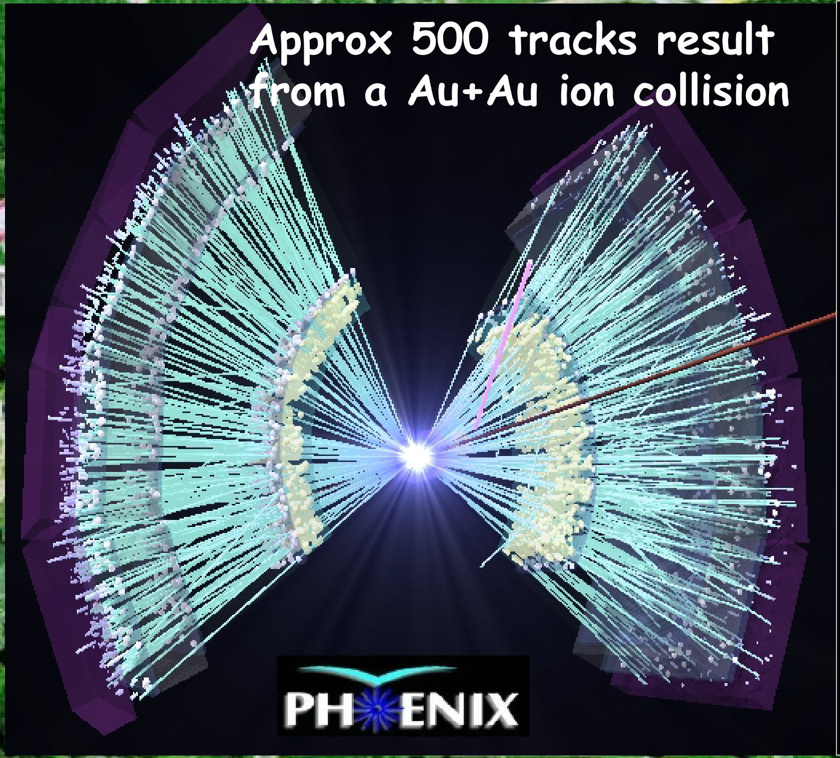
This is the only phase transition that occurred in the early universe that can be recreated in the lab

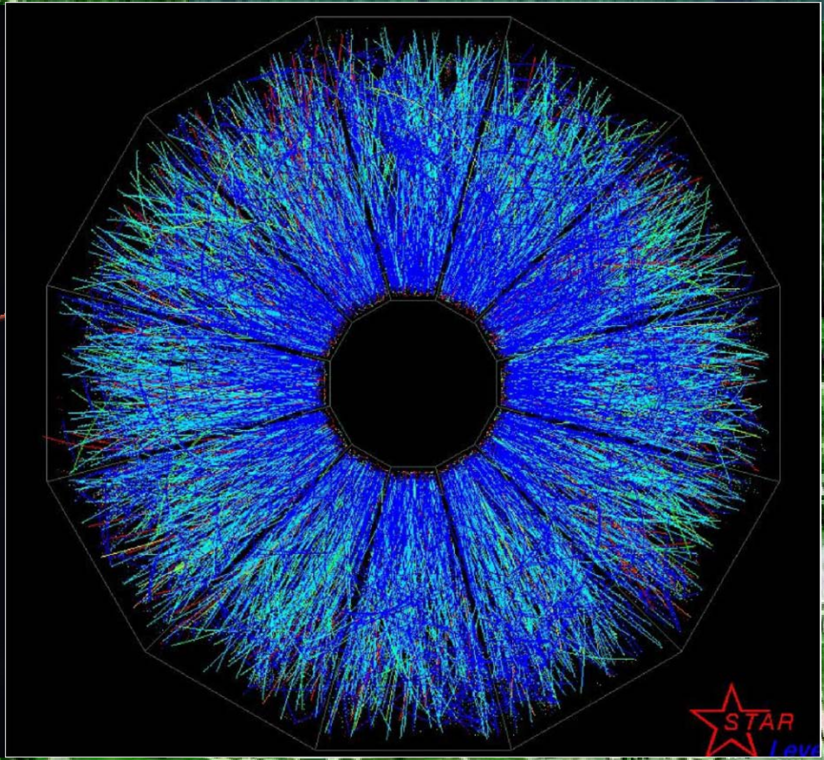


Quark→hadron transition happened at ~10^{-6} s

RHIC at BNL

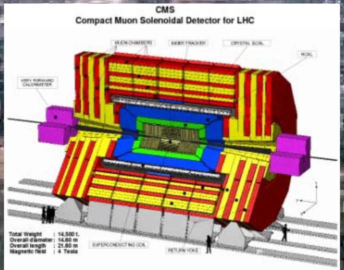
p+p at √s=510 GeV max
Au+Au at √s=200 GeV max
Started at Year 2000
collided various beams
pp, dAu, CuCu, CuAu
AuAu, UU



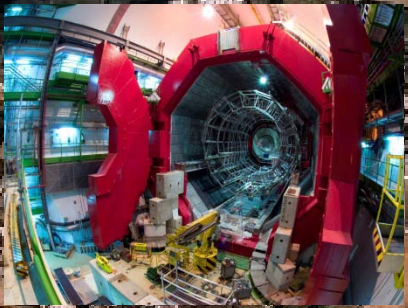


LHC at CERN

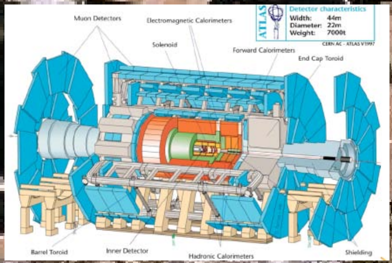
p+p at √s=7, 8 TeV
Pb+Pb at √s=2.76 TeV
heavy ion running: 4 physics weeks/year
First Pb+Pb in 2010



CMS

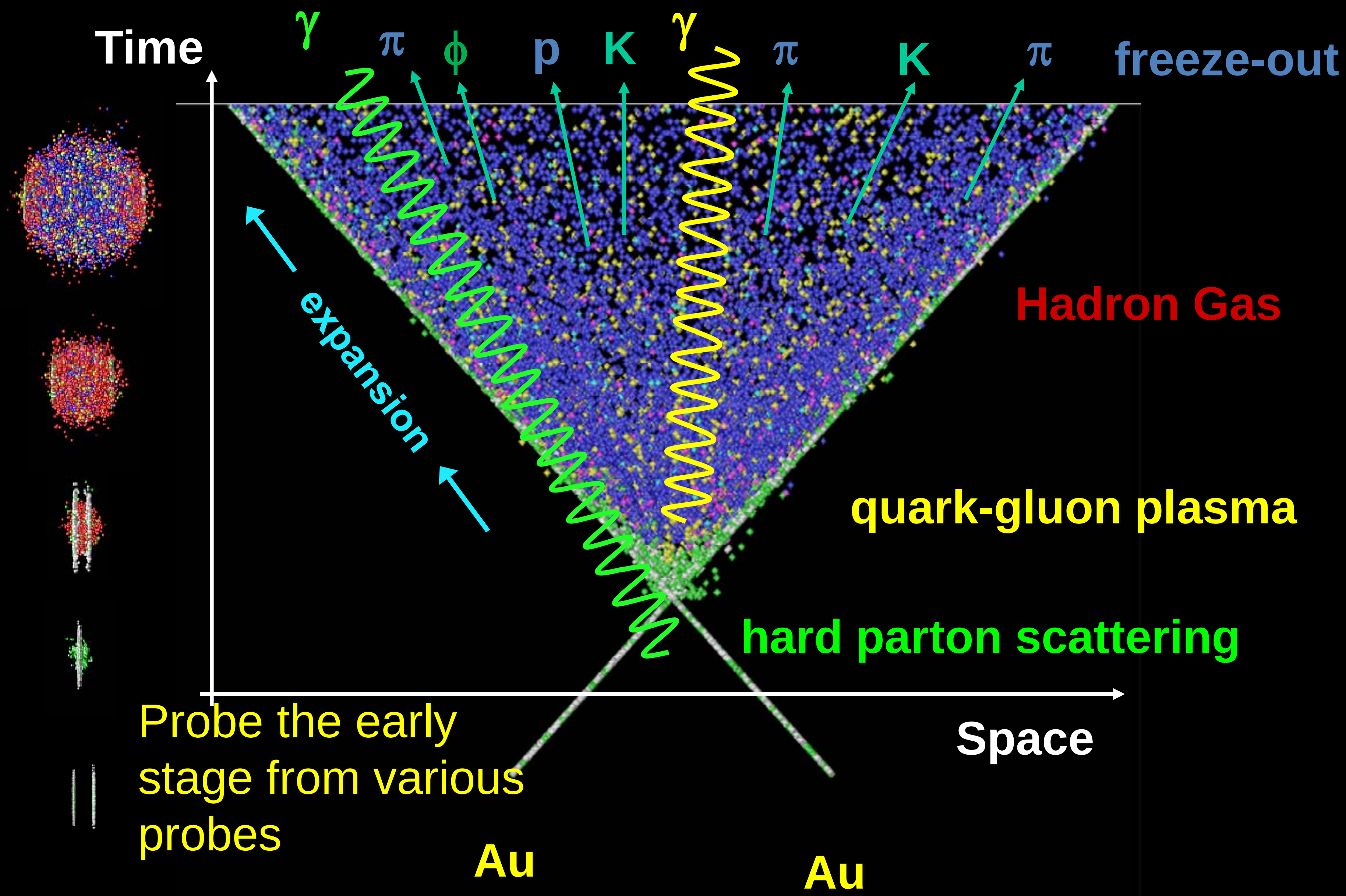


ALICE



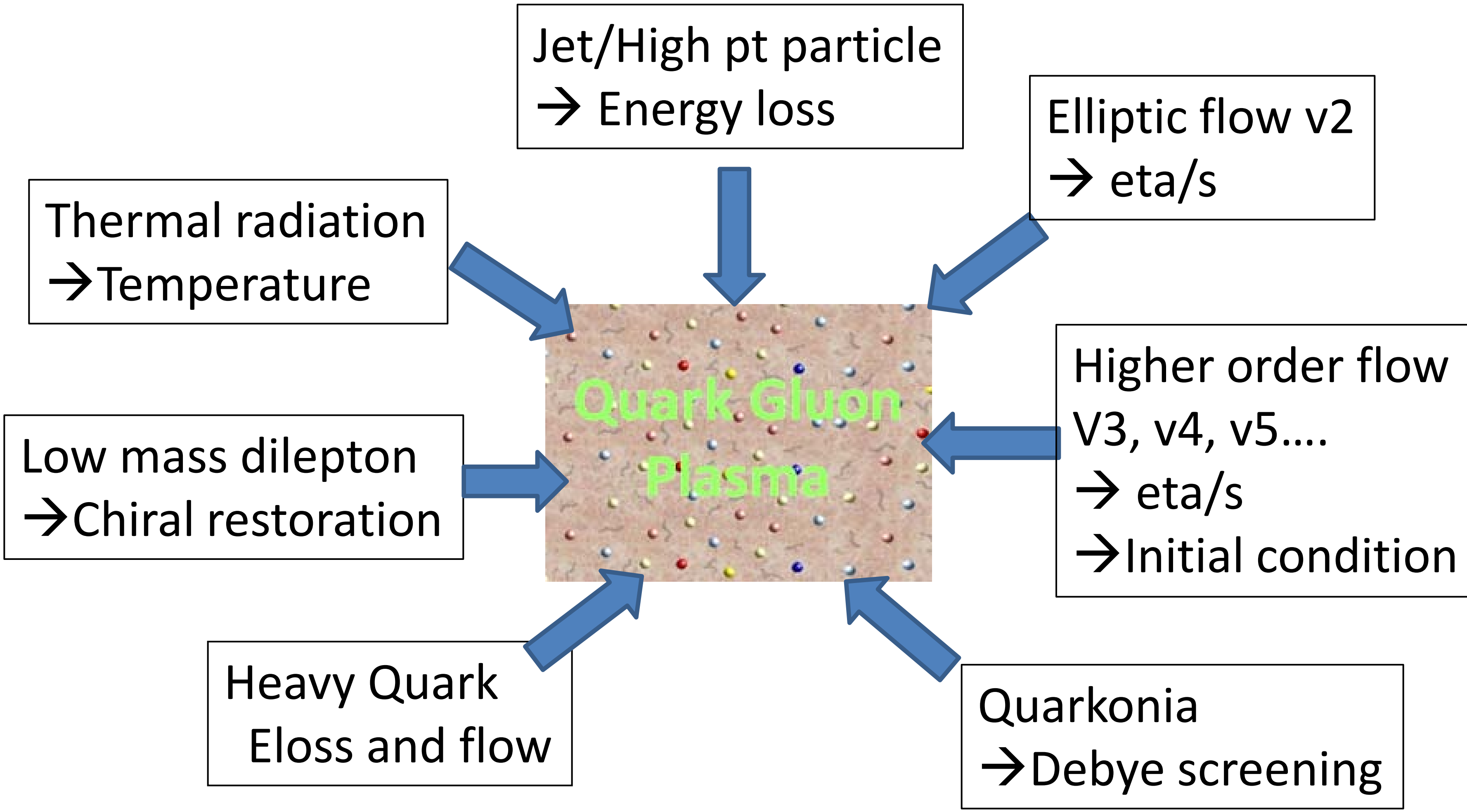
ATLAS

Probe of Nuclear Collisions



Probe the early stage from various probes

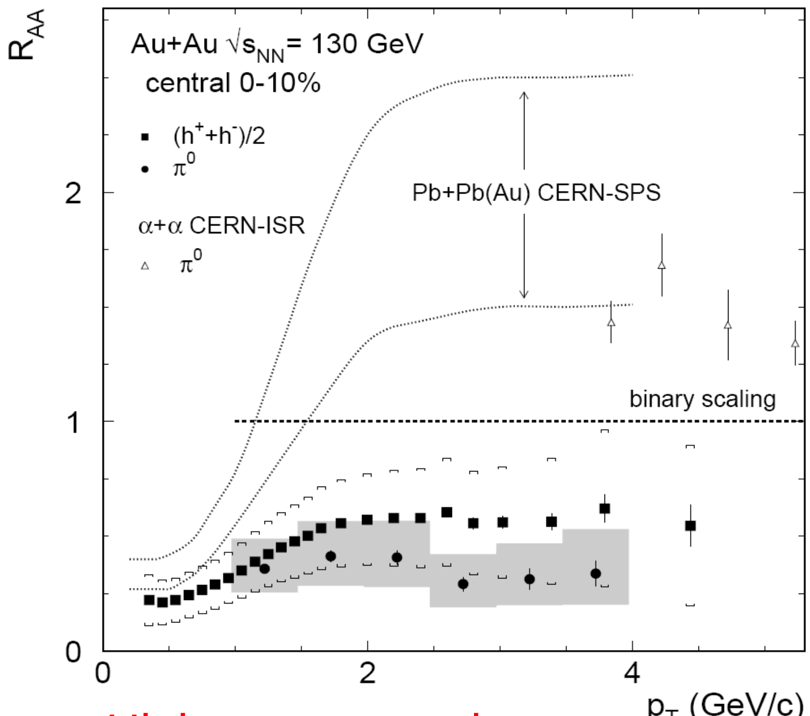
Probing QGP



- Systematic study with different condition (T, μ) with various probe is required to *quantitatively understand properties of QGP*
- Both RHIC and LHC is needed to provide *large leverage* in conditions and dynamic range of hard probes (p_T, mass, etc).

RHIC's Two Major Discoveries

PHENIX PRL88,022301(2002)

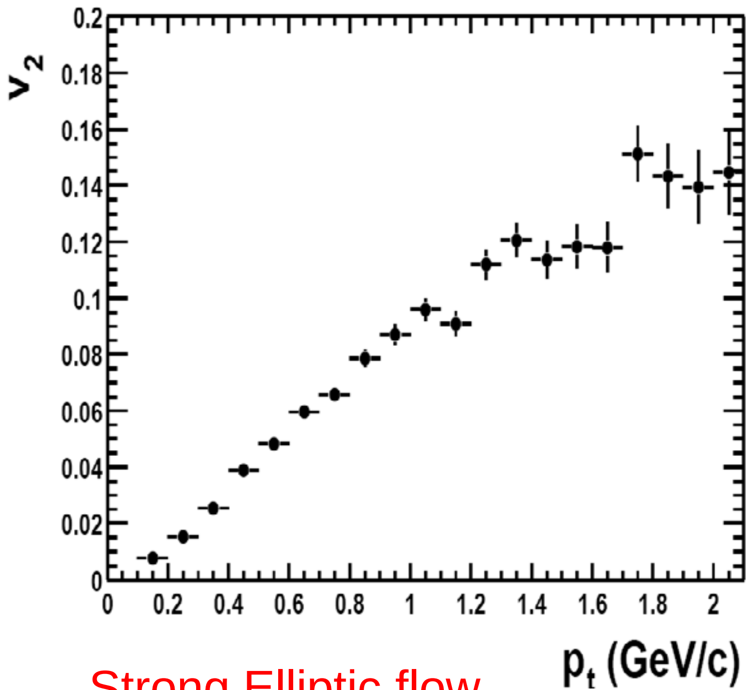


High p_T suppression

→Energy loss of quark/gluon

→Very dense matter

STAR PRL86,402 (2001)



Strong Elliptic flow

→Agree with ideal hydrodynamics

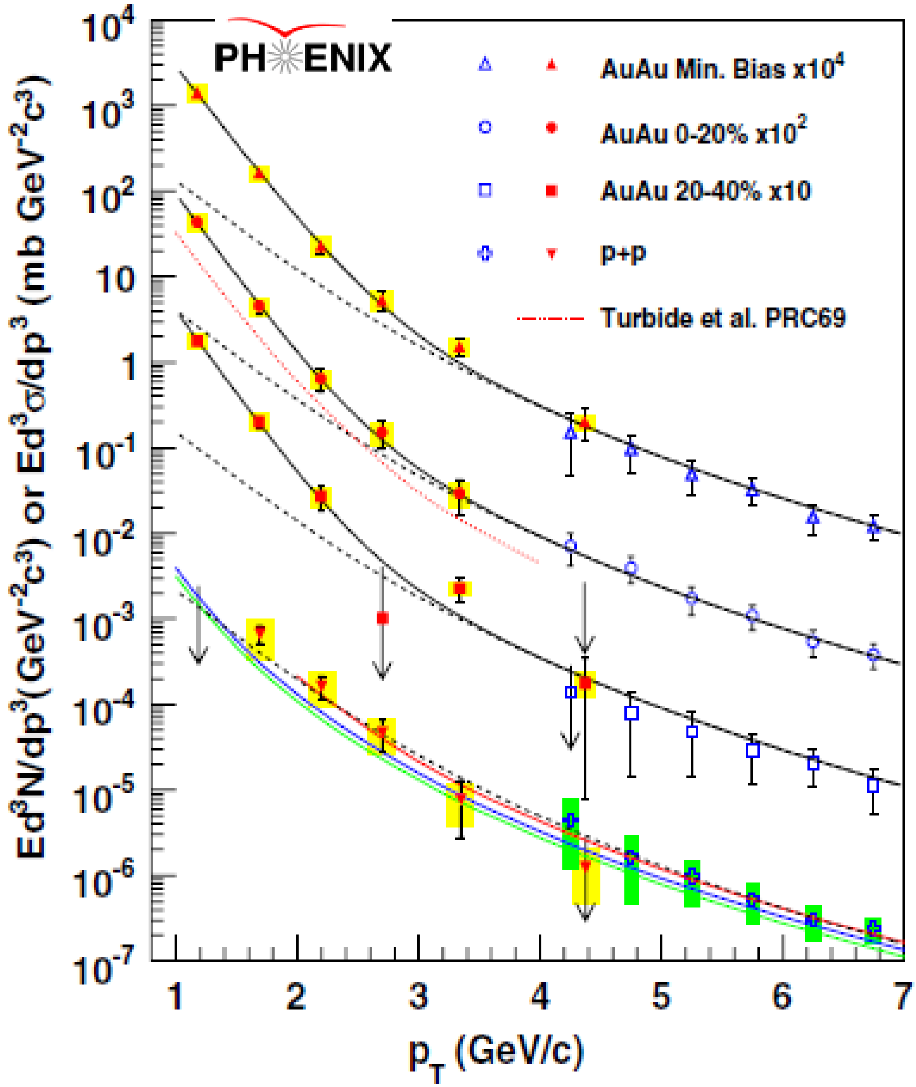
→Low viscosity/entropy (η/s)

Dense and low viscosity fluid is formed in nuclear collisions at RHIC

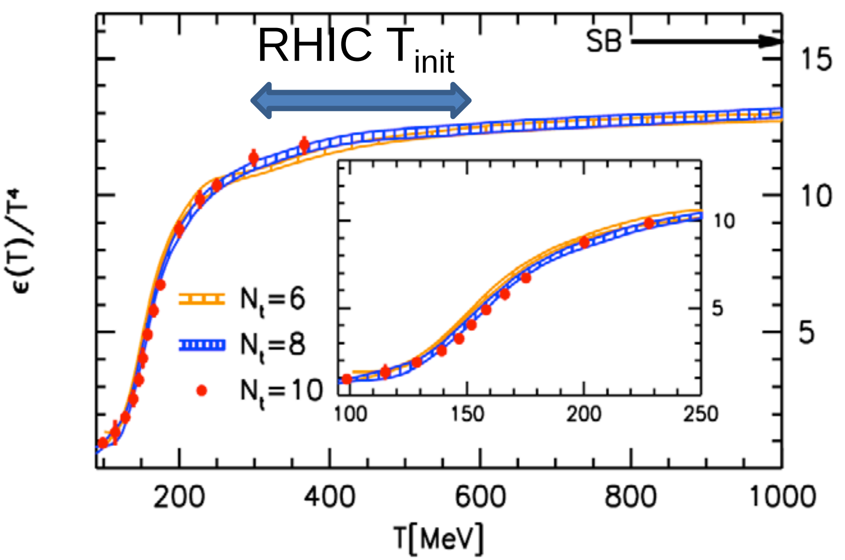
These results are confirmed by LHC at higher energy

Initial temperature via photons

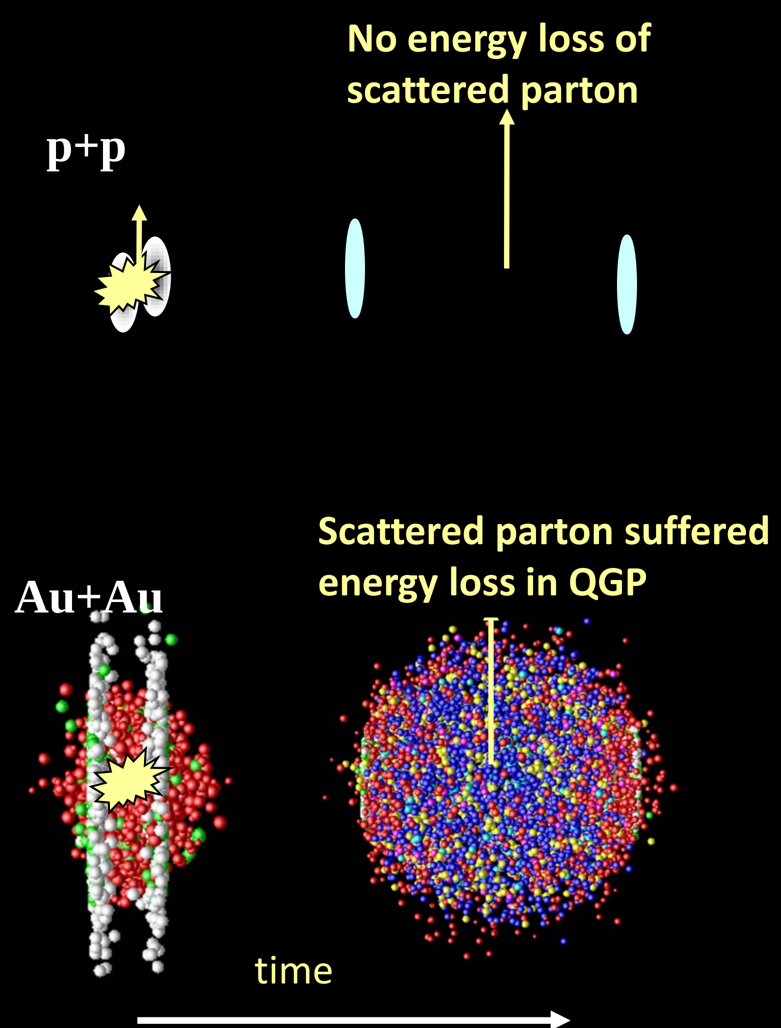
PHENIX PRL104, 132391 (2010)

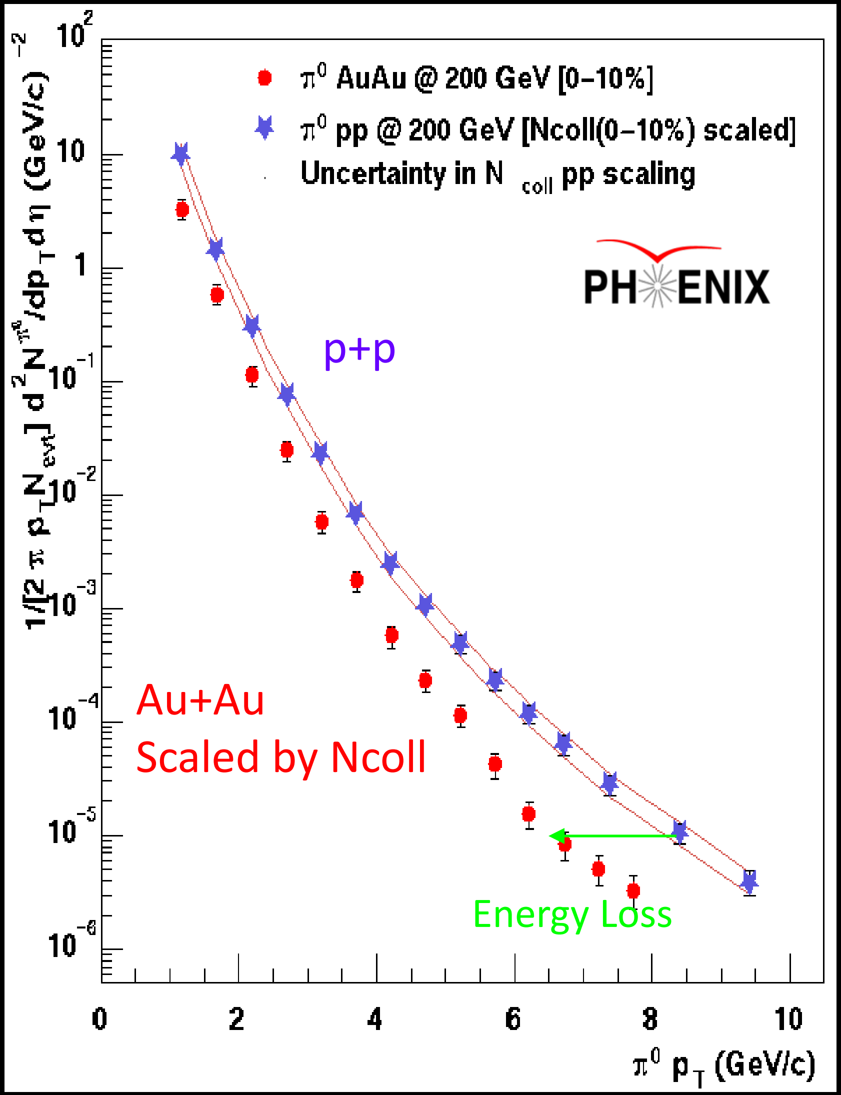


- Large enhancement of direct photons at low p_T at RHIC
- Consistent with thermal radiation with initial temperature of 300-600 MeV



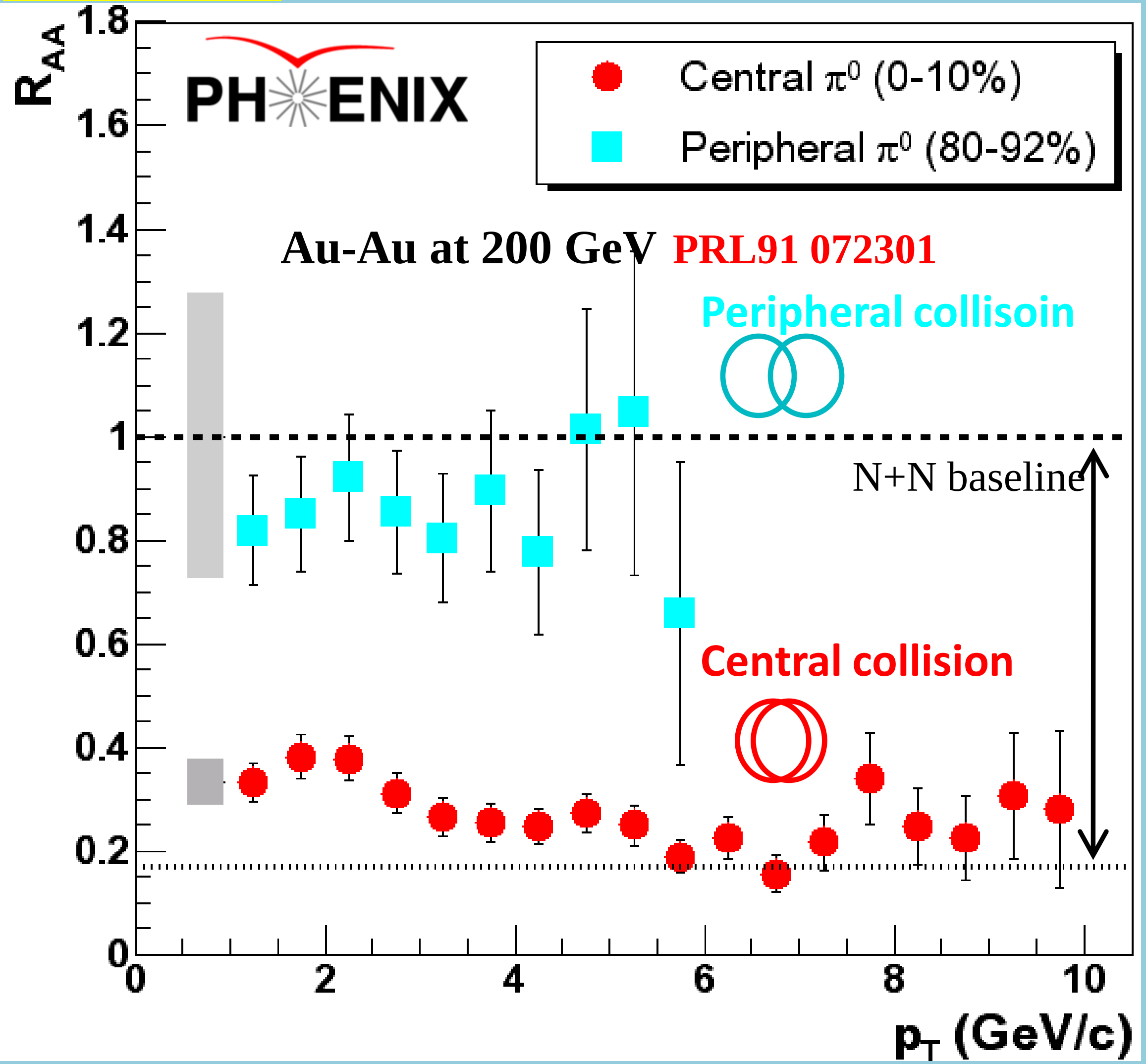
High pT hadron suppression





Strong suppression of high p_T pi0

2002 data.



Nuclear Modification factor

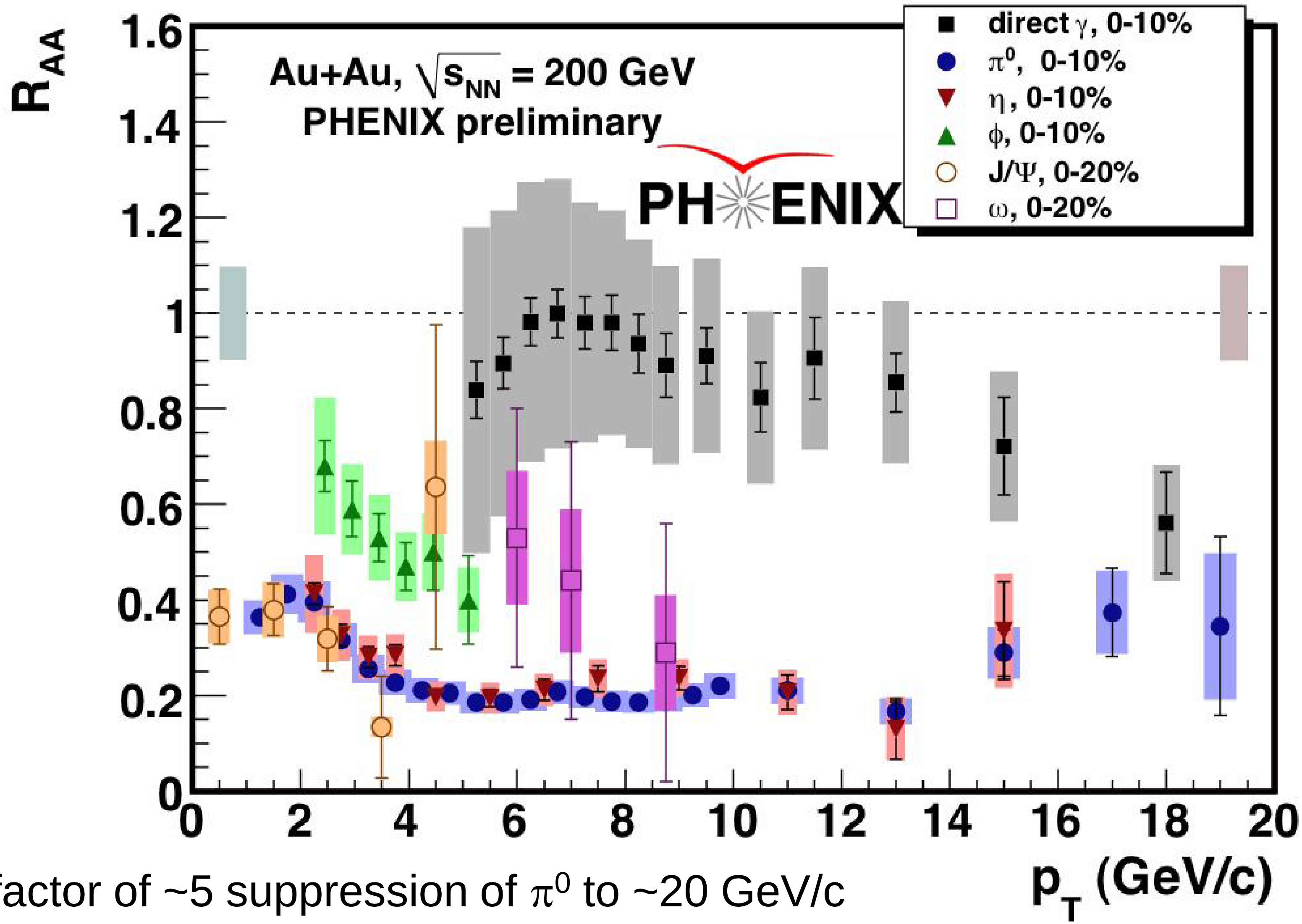
$$R_{AA} = \frac{Yield_{AuAu} / \langle N_{binary} \rangle_{AuAu}}{Yield_{pp}}$$

Suppression/enhancement factor relative to binary collisions

A facor of five suppression at 10 GeV/c

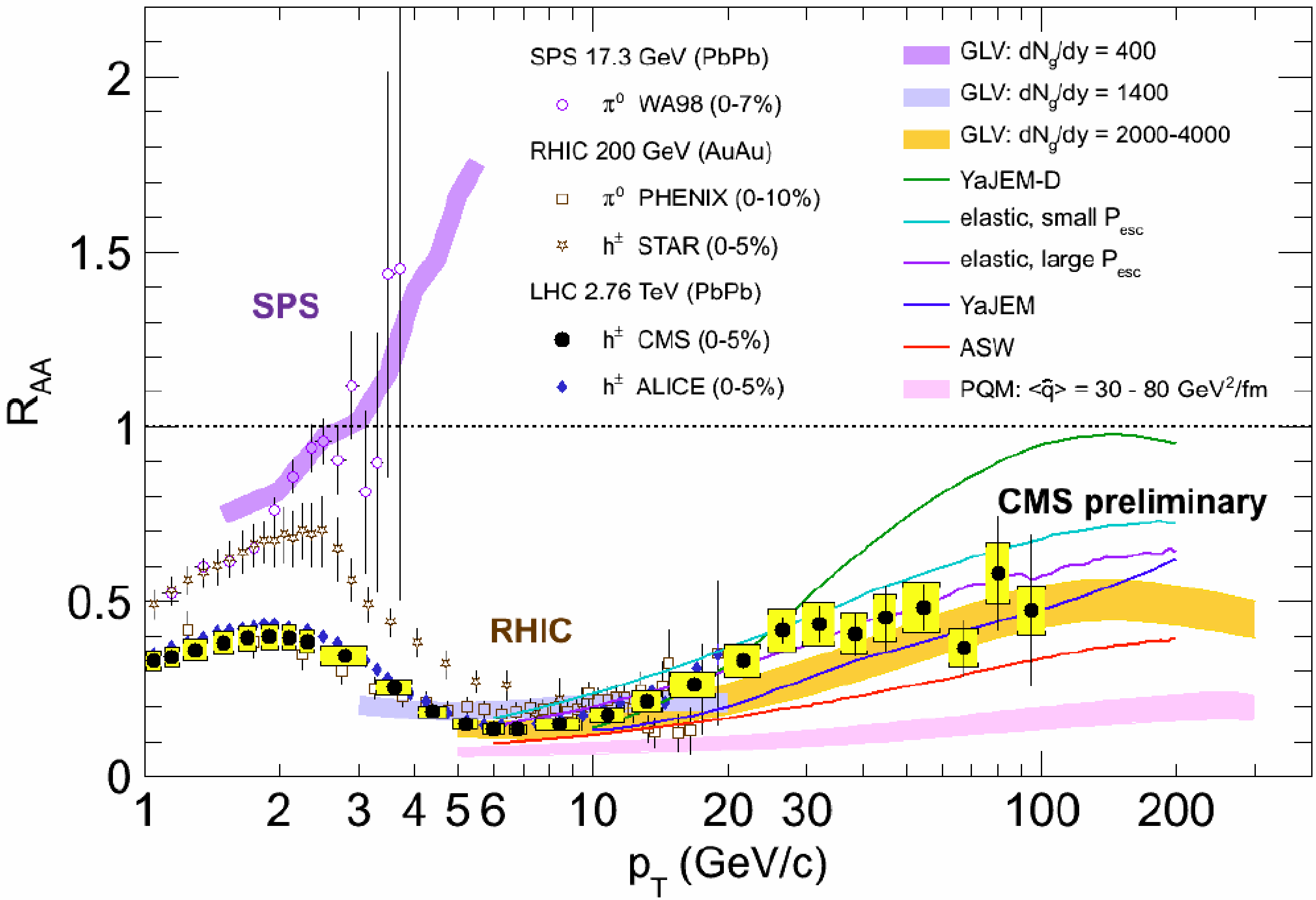
→Scattered paron suffer a large energy loss in QGP

R_{AA} of various particles



- A factor of ~5 suppression of π^0 to ~20 GeV/c
- Same suppression for pi0 and eta
- Ncoll scaling for direct γ

LHC extends R_{AA} to ~100 GeV/c

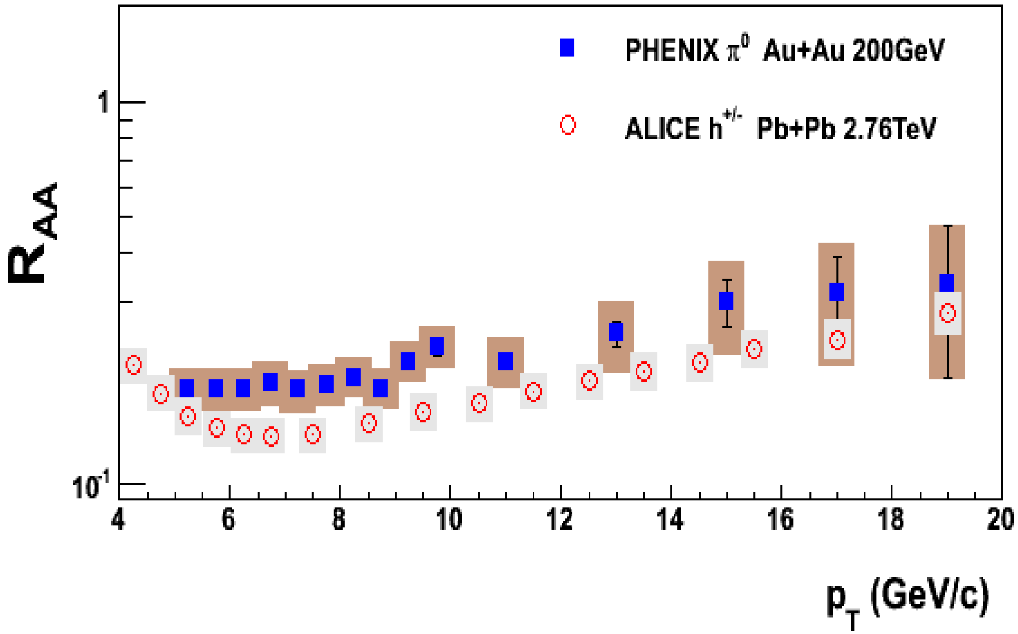


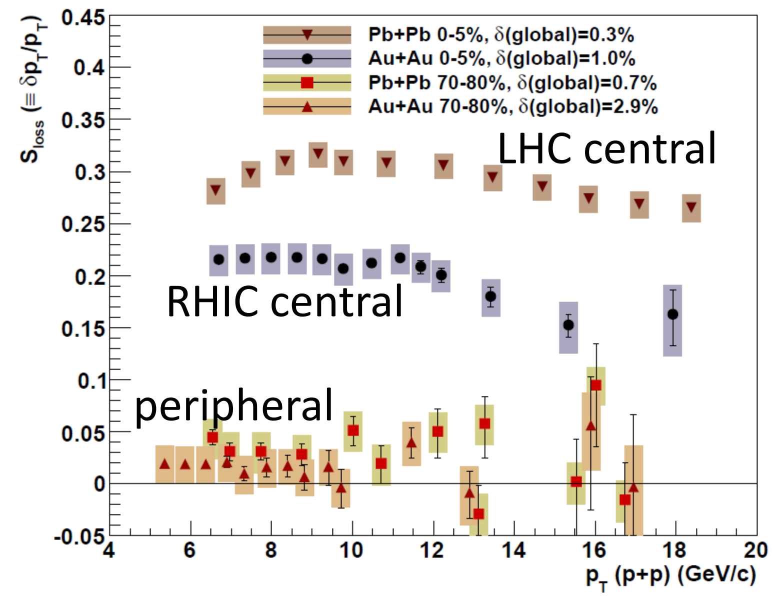
Strong constraint on the parton energy loss models

Rise to RAA ~ 0.5 at pT~30-40 GeV/c and stay constant (?)

Energy loss at RHIC and LHC

PHENIX arXiv:1208.2254 **ALICE PLB696,301(2011)**



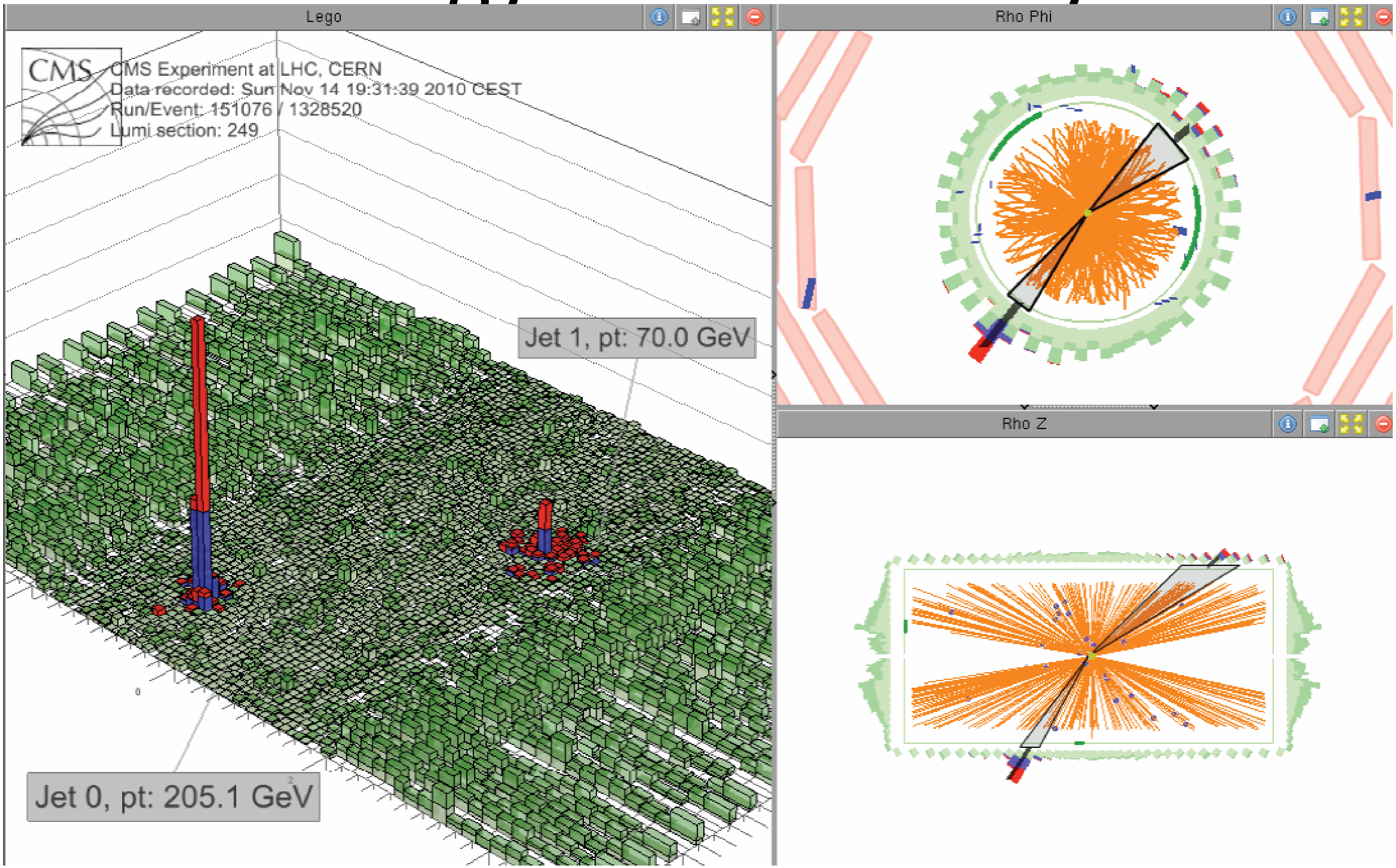


Fractional energy loss deduced from R_{AA}

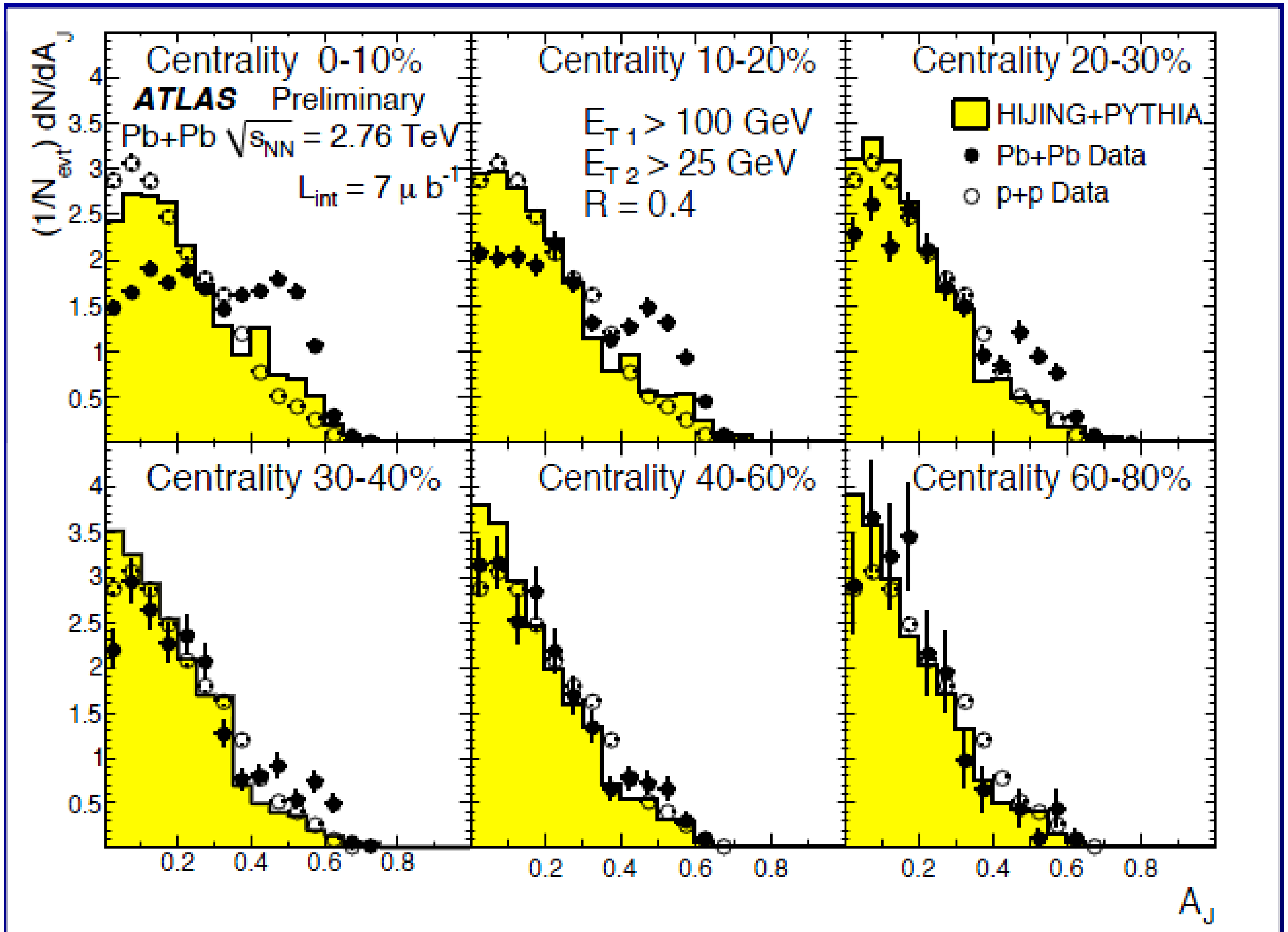
- R_{AA} increase at high p_T at RHIC and LHC
- R_{AA}(LHC)<R_{AA}(RHIC) at the same p_T, indicating stronger energy loss
- Fractional energy loss deduced from R_{AA} is higher at LHC

→ Started to see difference in medium property at RHIC and LHC

Jet energy loss is directly seen



Jet Energy asymmetry



$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}$$

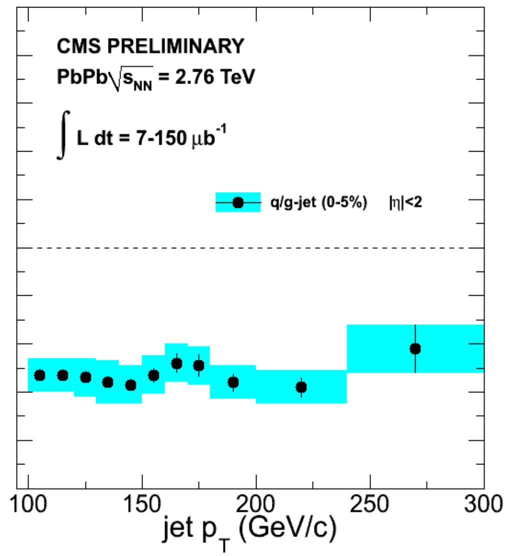
E_{T1}: E_T of Jet 1

E_{T2}: E_T of Jet 2

- A large jet ET asymmetry → direct evidence of Jet energy loss in QGP

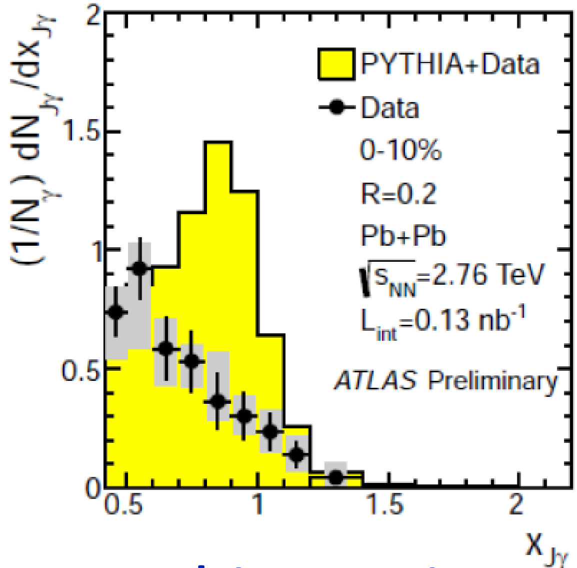
Jet measurements at LHC

CMS QM2012



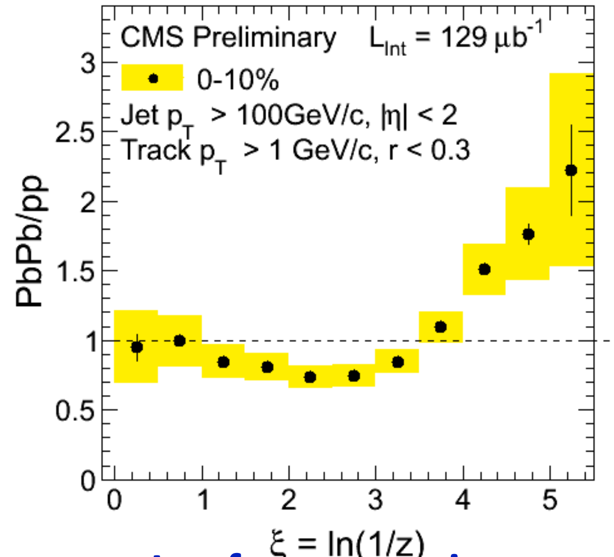
Jet R_{AA}

ATLAS QM2012



γ-Jet asymmetry

CMS QM2012

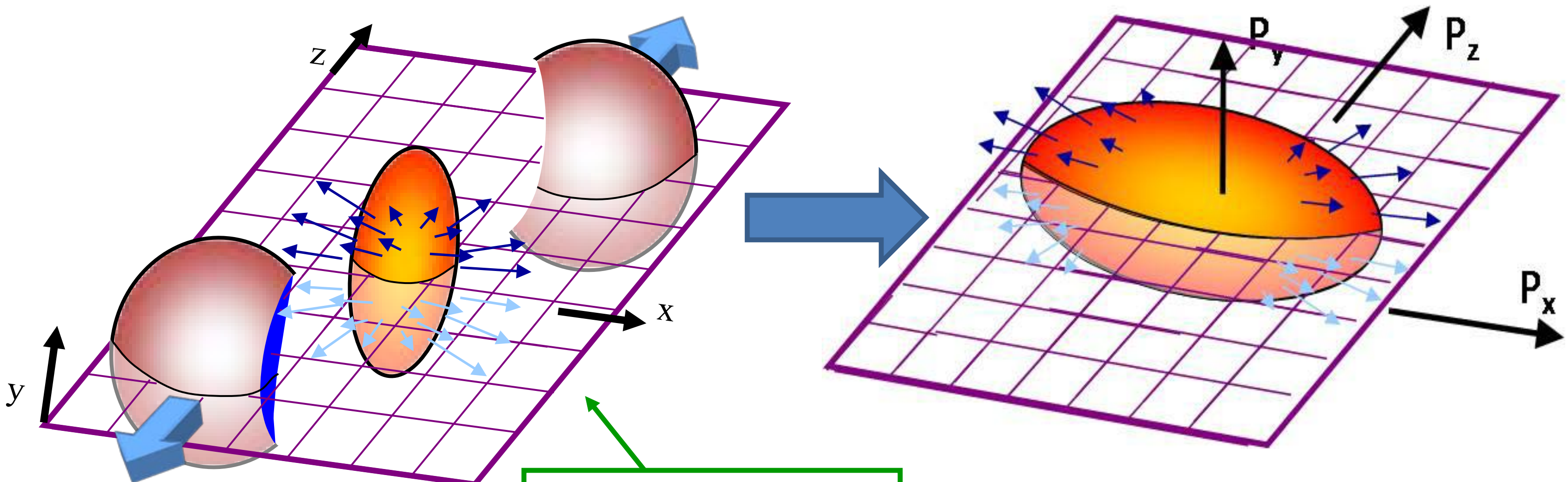


Jet fragmentation

- LHC demonstrated that direct jet measurement in heavy ion collision is possible.
- Rich data on reconstructed jets at LHC from ATLAS and CMS
  - R_{AA}, v_2, Jet-Jet, γ-Jet, Z/W-jet, Jet fragmentation, etc

Elliptic Flow

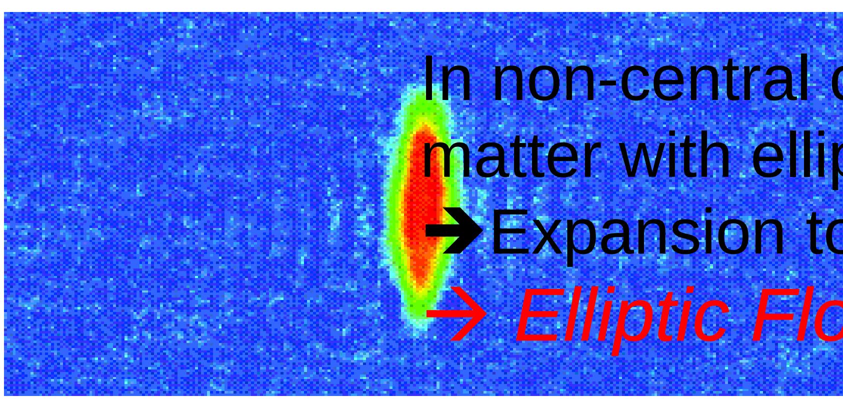
Non Central collision



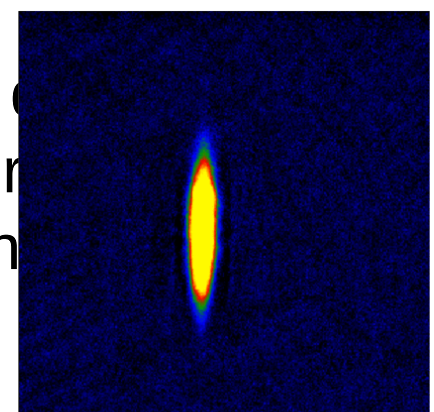
Reaction Plane

strongly-coupled
small η/s

Weakly-coupled
large η/s



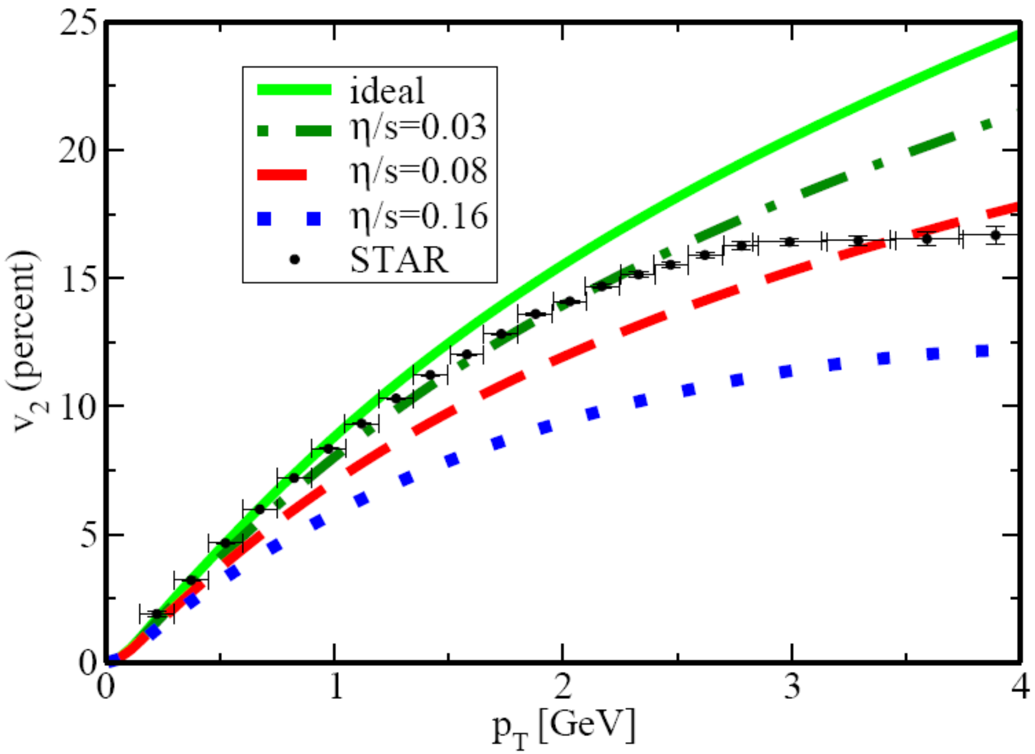
In non-central collisions, high d
matter with elliptic shape is for
➔Expansion towards reaction
→ *Elliptic Flow*



Comparison with viscous hydro

- Behavior of the fluid is governed by the sheer viscosity (η) to entropy density (s) ratio η/s
- Recent theoretical work with non-zero viscosity suggests that very small $\eta/s \sim 0.1$ is required to explain RHIC v_2 data
- Matter formed at RHIC is almost *perfect fluid*.

P. Romatschke and U. Romatschke、PRL99,172301(2007)

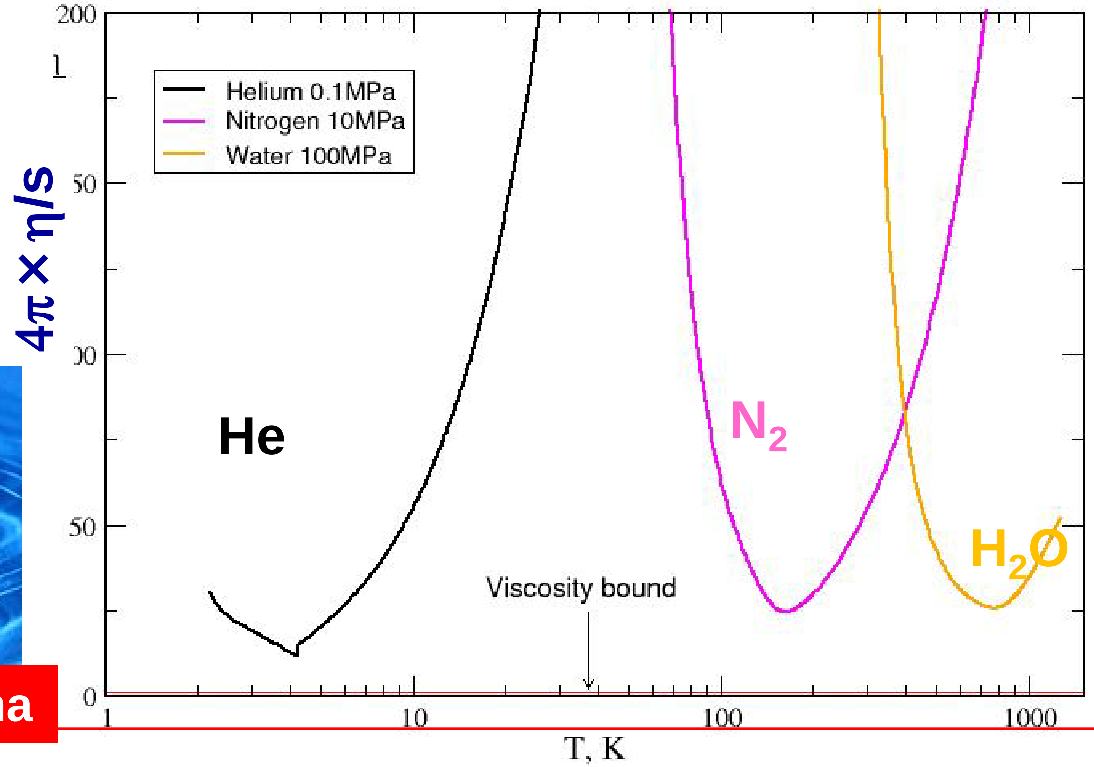


(Almost) perfect liquid

v2 data from RHIC indicates that the high density matter formed at RHIC has very small η/s.

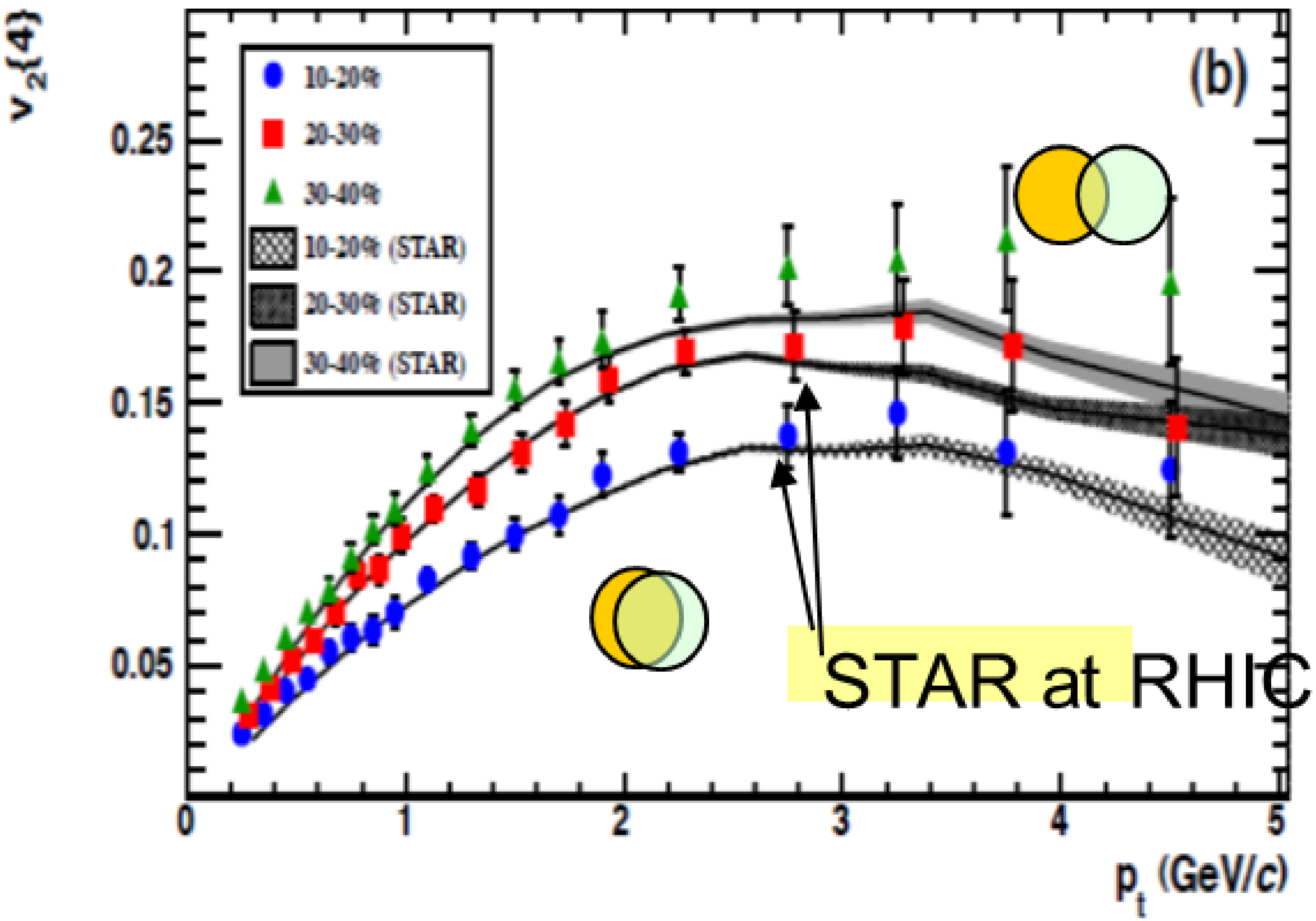
The value, $\eta/s \sim 0.1$, is 1/10 of all known matter, and it is close to the lower bound $1/4\pi$ conjectured by AdS/CFT model

Quark Gluon Plasma



10^{12} ^{0}C

Elliptic Flow at LHC : similar to RHIC



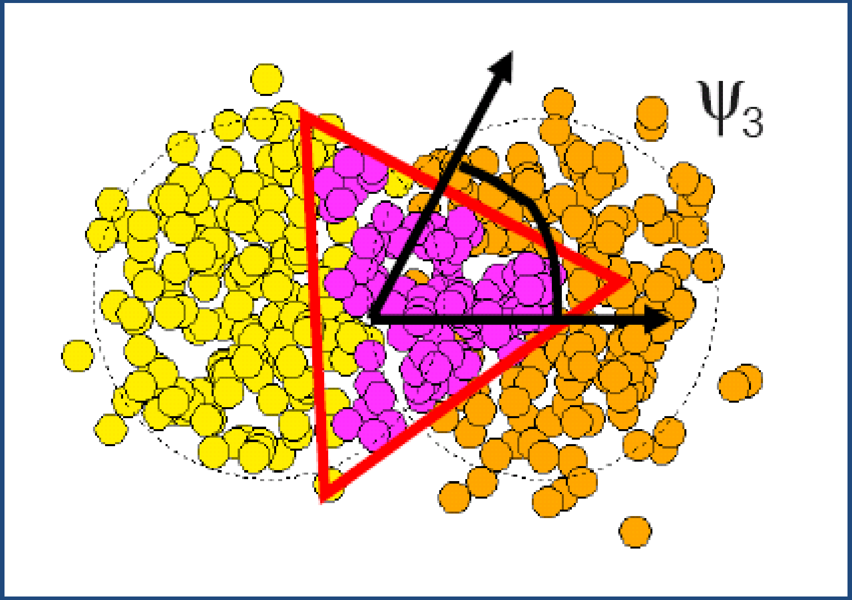
V2 measured by ALICE = v2 measuread by STAR
→ eta/s of QGP at LHC is also very small
Is there difference in eta/s?

Triangular flow v3

$$\frac{dN}{d\phi} \propto 1 + \sum_n 2\mathrm{v}_\mathrm{n} \cos n\left(\phi - \Psi_n\right)$$

Elliptic flow v2 is the 2nd order Fourier component of azimuthal distribution
There are higher order componets v3, v4, v5….

Odd order componets v3, v5, etc relative to reaction plane is zero due to symmetry



Event-by-Event Fluctuation of initial geometry cause v_3 and higher odd order components.

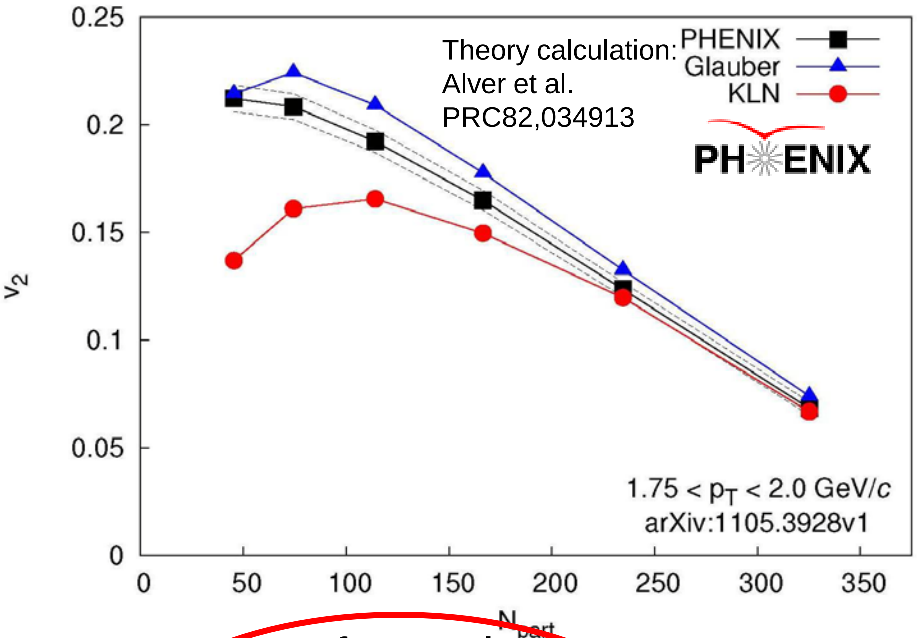
Initial geometry 3rd order component ε_3 causes 3rd order flow v3

V3 is a good probe of initial condition

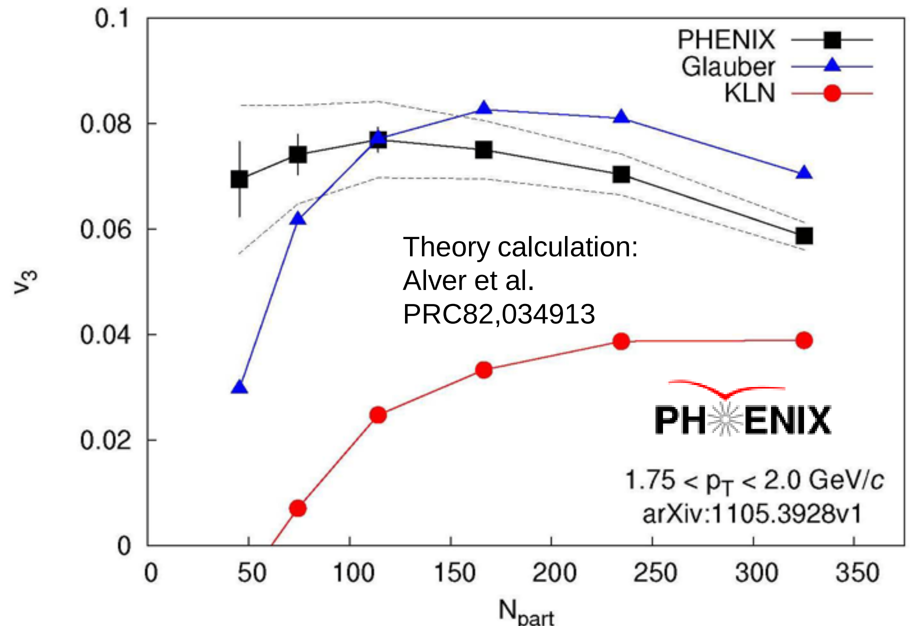
v_3 disentangles initial state and η/s

PRL107,252301

v_2 described by Glauber and CGC



v_3 described only by Glauber



Lappi, Venugopalan, PRC74, 054905
Drescher, Nara, PRC76, 041903

favored

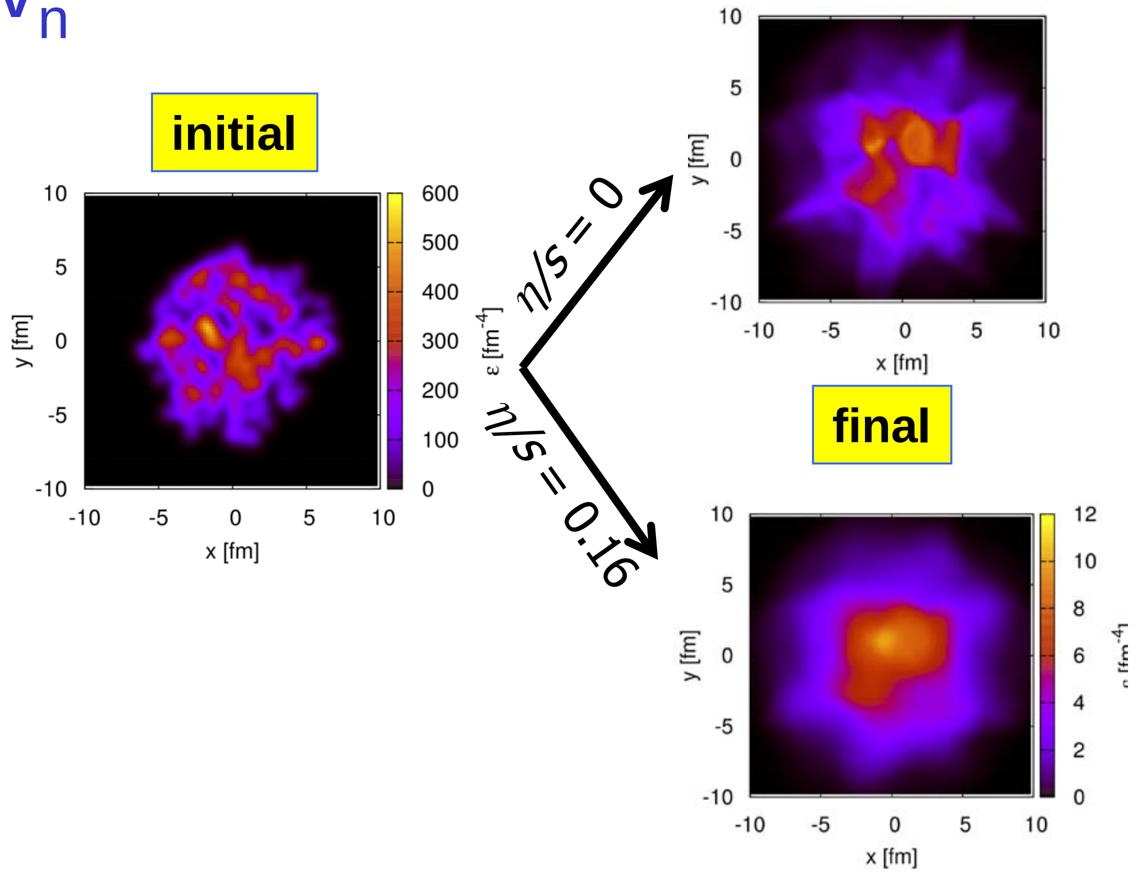
- Glauber
  - Glauber initial state
  - $\eta/s = 1/4\pi$

← Two models →

- MC-KLN
  - CGC initial state
  - $\eta/s = 2/4\pi$

Higher Order Flow and eta/s

- Higher order flows v3, v4, etc are sensitive to viscosity η/s
- Finite η/s makes the final state smoother → reduce higher v_n

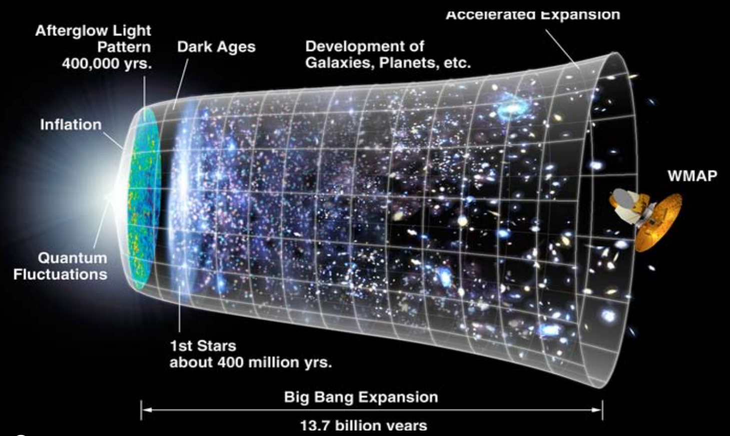


•B. Schenke, S. Jeon, C. Gale, Phys. Rev. C82, 014903 (2010); Phys.Rev.Lett.106, 042301 (2011)

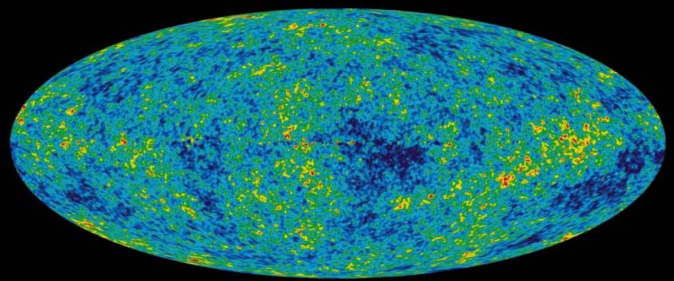
•B.Schenke, P.Tribedy, R.Venugopalan, Phys.Rev.Lett. 108, 252301 (2012)

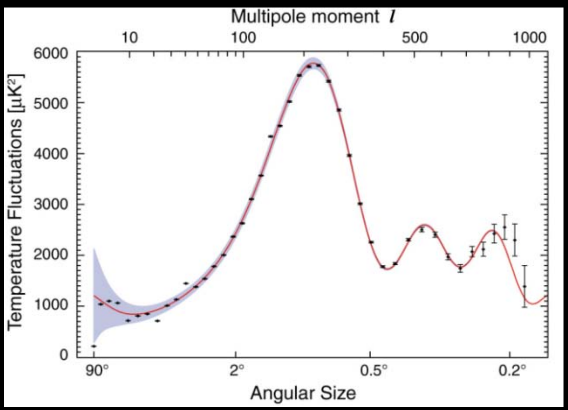
The Big Bang vs the Little Bangs

The Universe



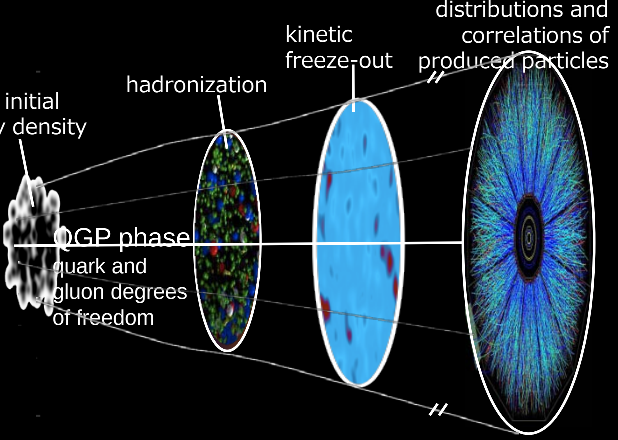
Cr

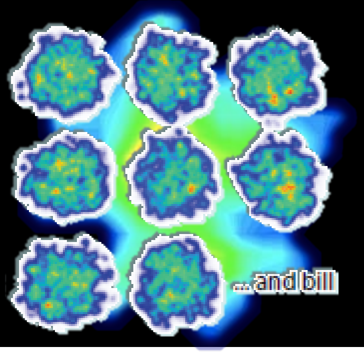


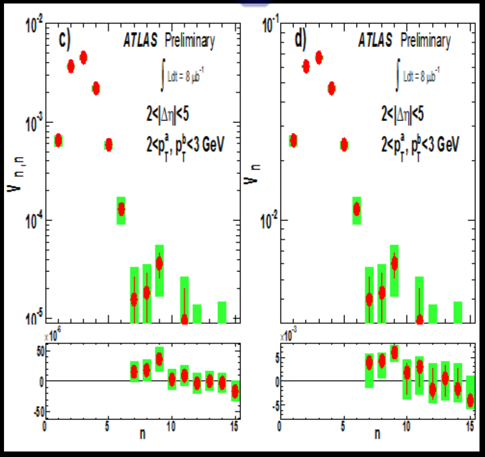


WMAP

HIC







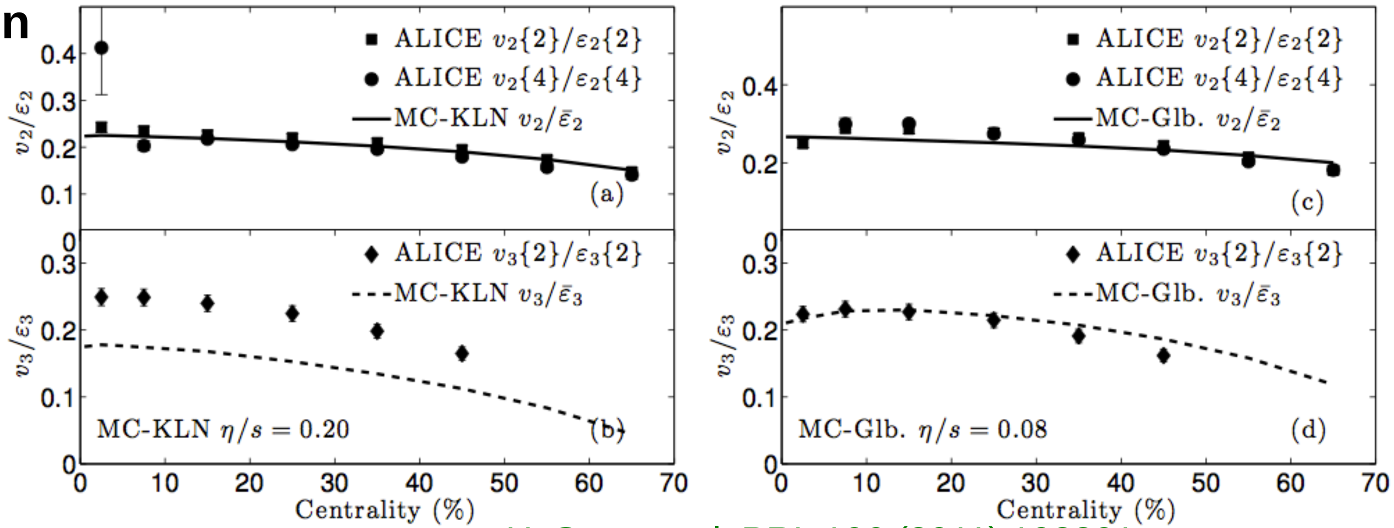
What we conclude from fluid dynamics

- Recent data & recent analyses yield tight constraints

$$1 \le 4\pi(\eta/s) \le 2$$

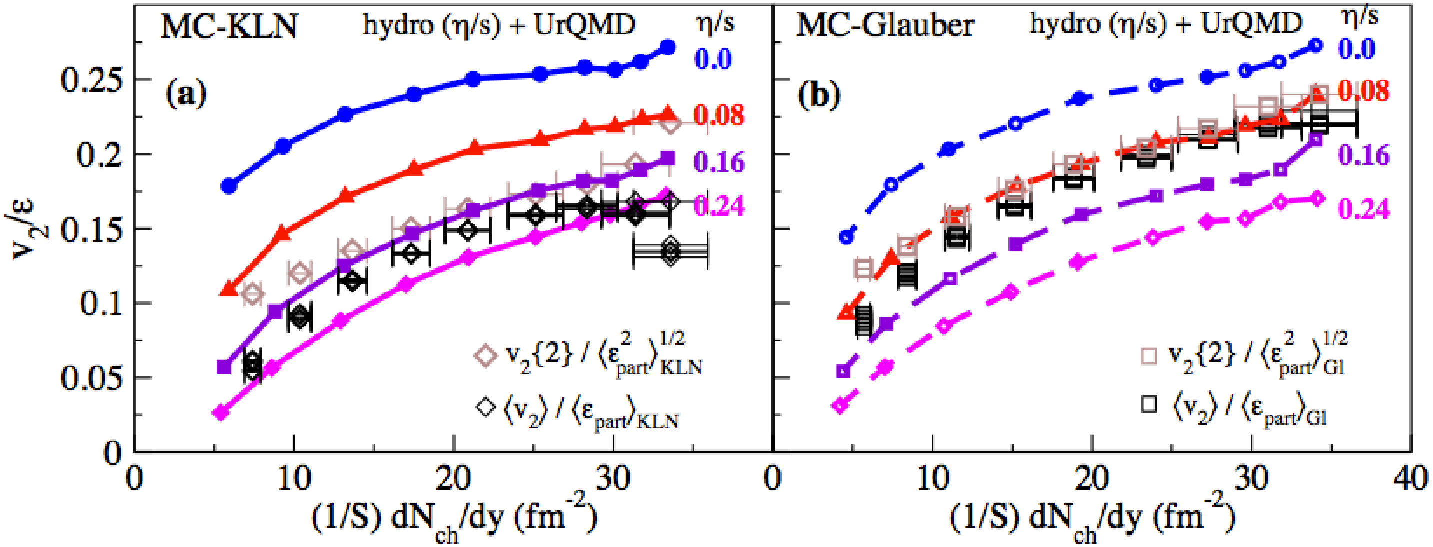
Slide by Wiedermann

LHC

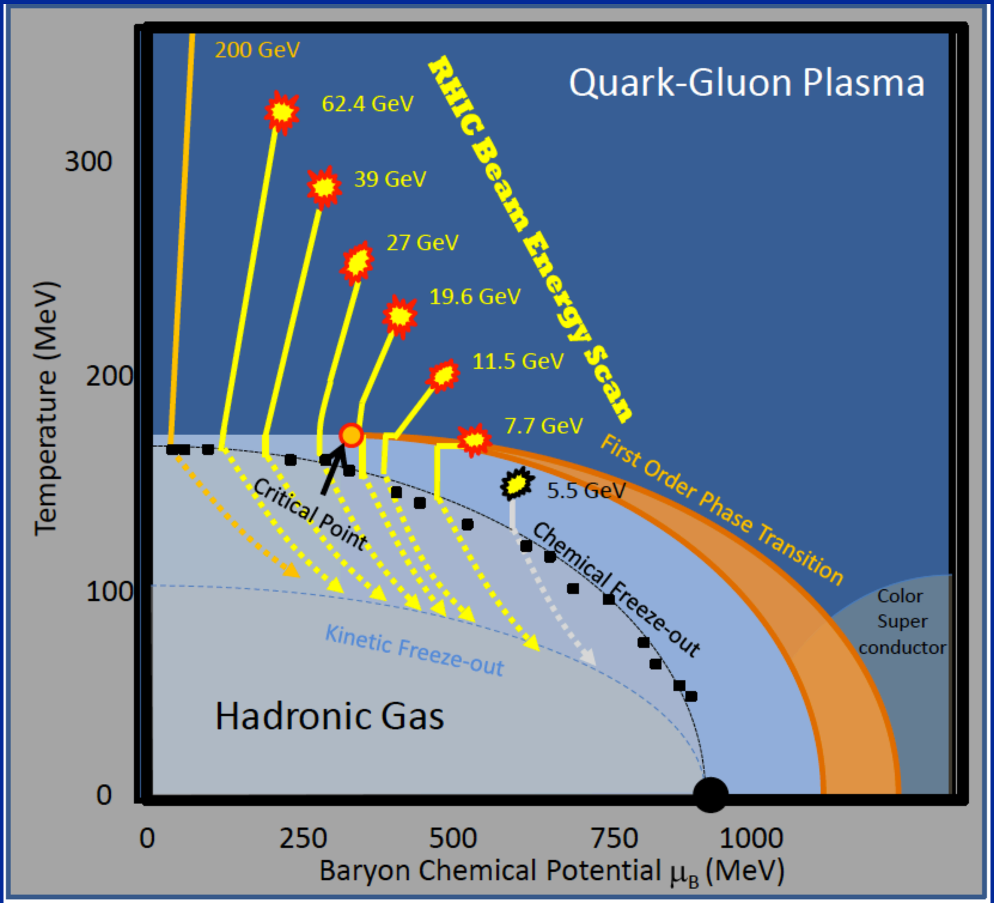


H. Song et al. PRL 106 (2011) 192301
Z. Qiu et al., Phys.Lett.B 707 (2012) 151

RHIC



Beam Energy Scan : Search for critical point



0) Turn-off of sQGP signatures

1) Search for the signals of phase boundary

2) Search for the QCD critical point

BES Phase-I

Year	$\sqrt{s_{NN}}$ (GeV)	Events (10^6)
2010	39	130
2011	27	70
2011	19.6	36
2010	11.5	12
2010	7.7	5

What I didn’t covered

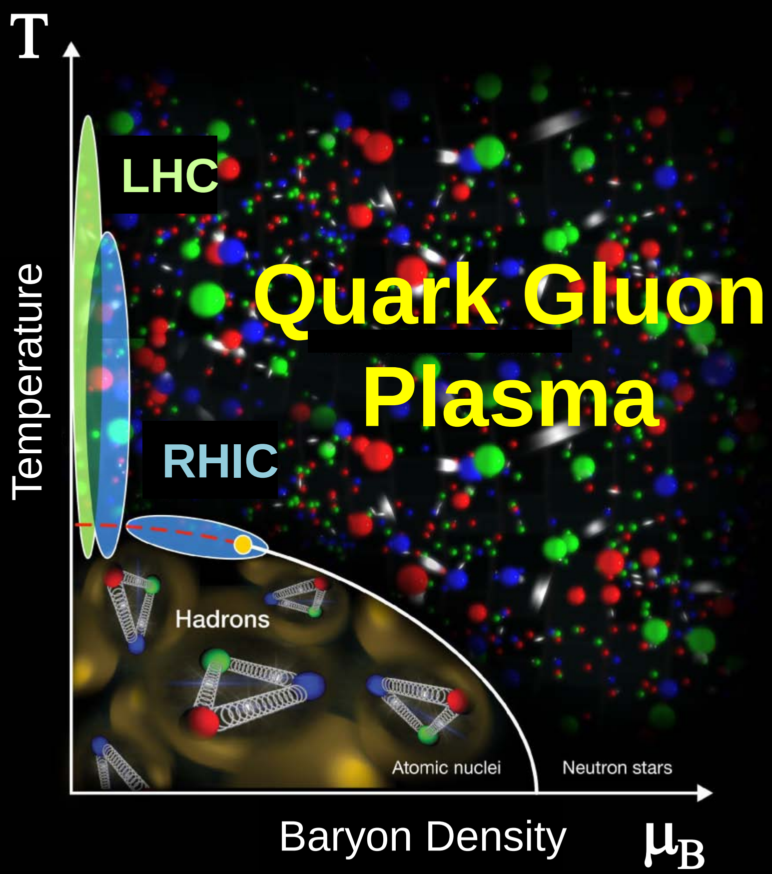
- Hadron spectra and yield
- Heavy quark probe
  - Energy loss
  - Flow
- Quarkonia (J/Psi, Upsilon)
- Low mass lepton pairs
- Direct photon v2
- Chiral magnetic effect
- Fluctuations
- and more…

Computation for QGP physics

Quantitative study of QGP property requires comparison of the data and precise theory calculations

- Relativistic Hydrodynamics
  - Full 3D with viscosity
  - event-by-event calculation to take into account fluctuations of the initial condition
- QGP properties from Lattice QCD
  - Tc
  - Critical Point
  - EOS
  - eta/s
  - Heavy quark potential at finite Tc
  - conductivity in QGP
  - EM emission rate

Summary



- New phase of matter, QGP, is discovered at RHIC and is confirmed at LHC
- QGP is characterized by
  - Near perfect fluidity
  - Strong energy loss of parton
- This is the only "Phase transition" of quantum field realized at laboratory
- Quantitative study of its properties at RHIC and LHC