Heavy Ion Experimental 1

Introduction to the Experiments
Bulk Properties of the QGP

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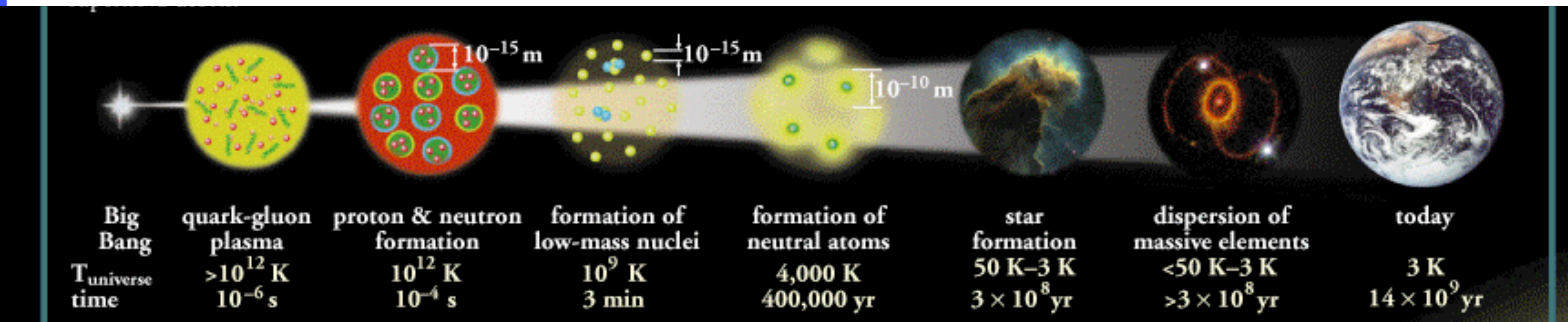
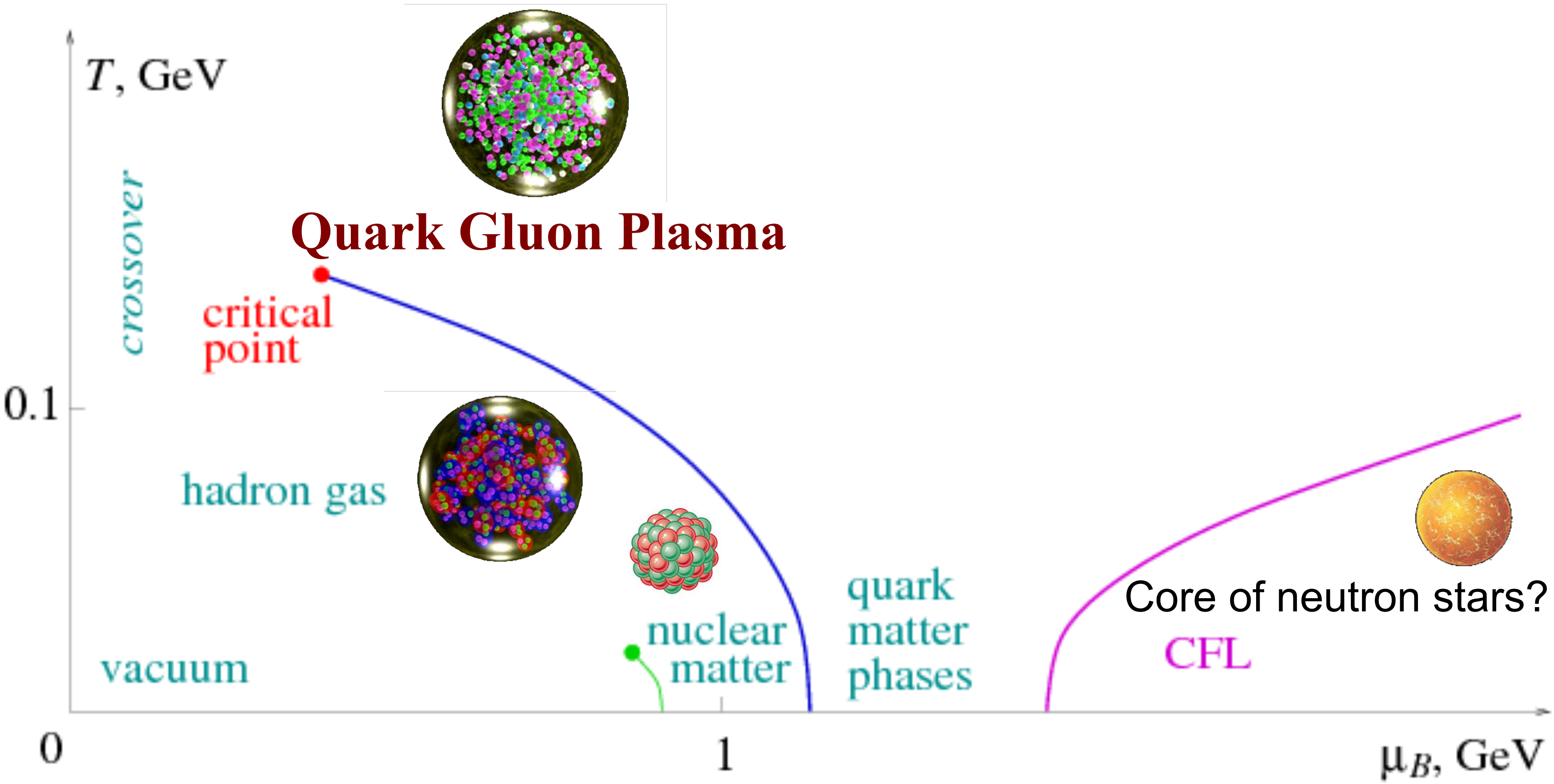
The Big Bang & Quark-Gluon Plasma

Time



Time

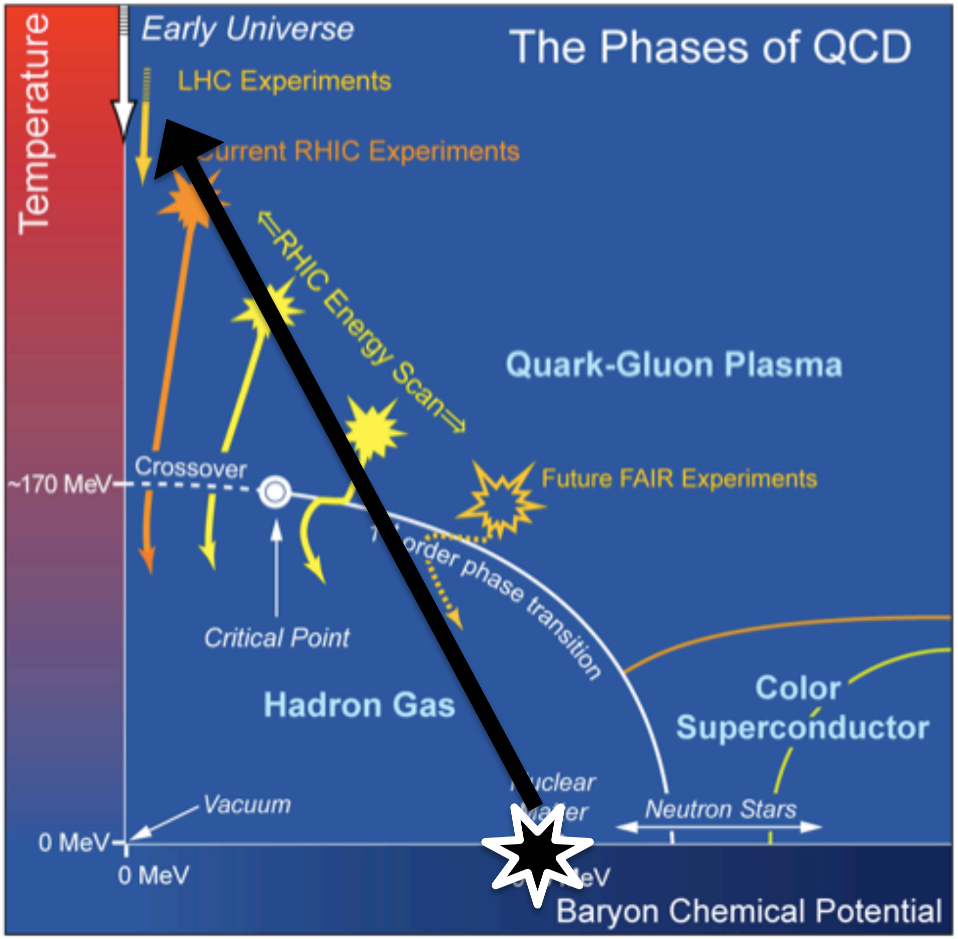
Phase diagram of nuclear matter

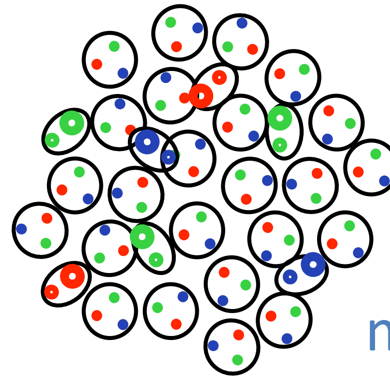


Quark Gluon Plasma – a *liquid* of quarks and gluons created at temperatures above ~170 MeV ($2 \cdot 10^{12}$ K) – over a million times hotter than the core of the sun or ~15 billion times hotter than a cup of coffee!

How do we get there?

Compress and heat normal nuclear matter

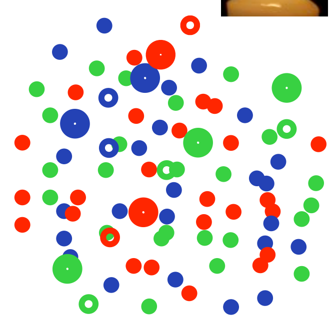




Normal nuclear matter (confined)

+ Heat

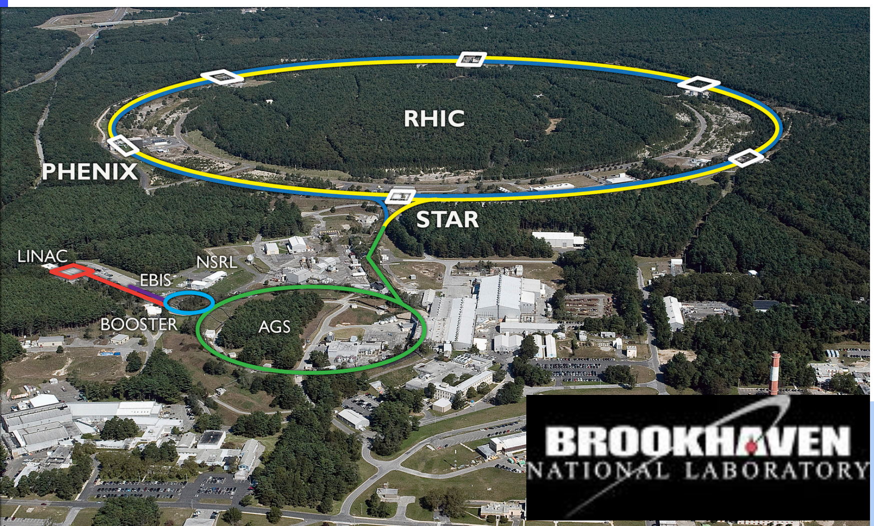
+ Pressure



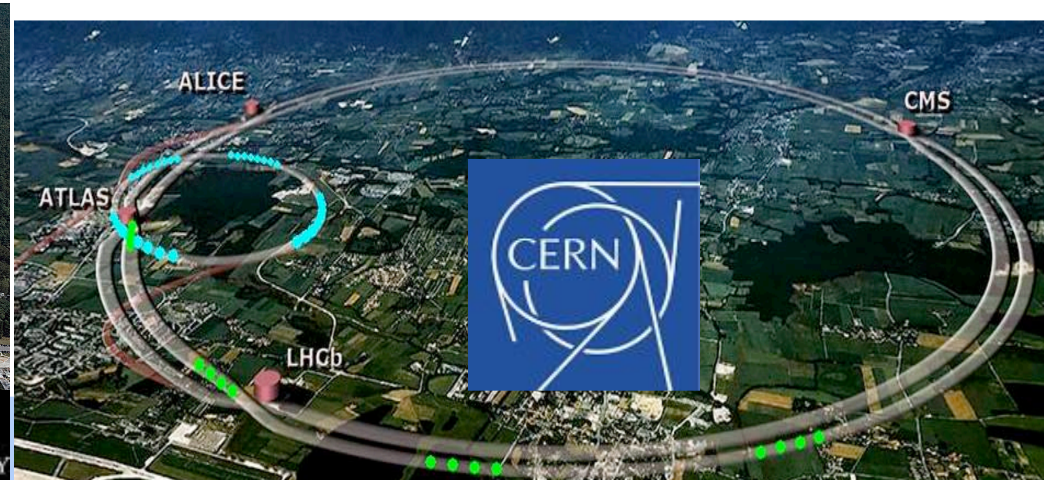
QGP (deconfined)

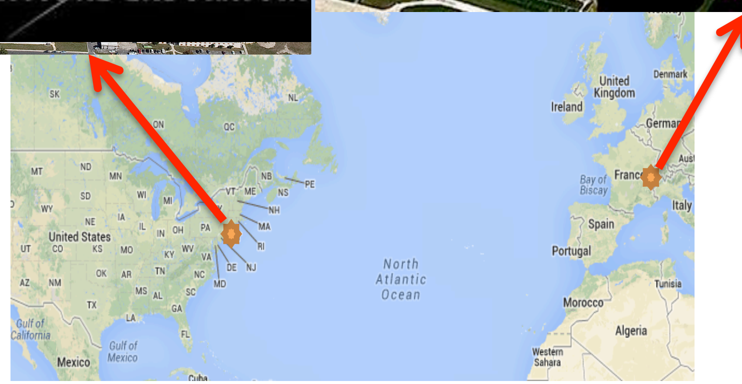
QGP Making Machines

RHIC



LHC





Long Island, NY
1.2 km diameter
Versatile machine colliding a variety of species over 7-500 GeV
pp, dAu, AuAu at $\sqrt{s_{NN}}$ = 200 GeV

Geneva, Switzerland
8.6km diameter
Highest energies = higher temperature and access to rare probes
pp, PbPb at $\sqrt{s_{NN}}$ = 2.76
pPb at $\sqrt{s_{NN}}$ = 5.02 TeV

Comparison of colliders

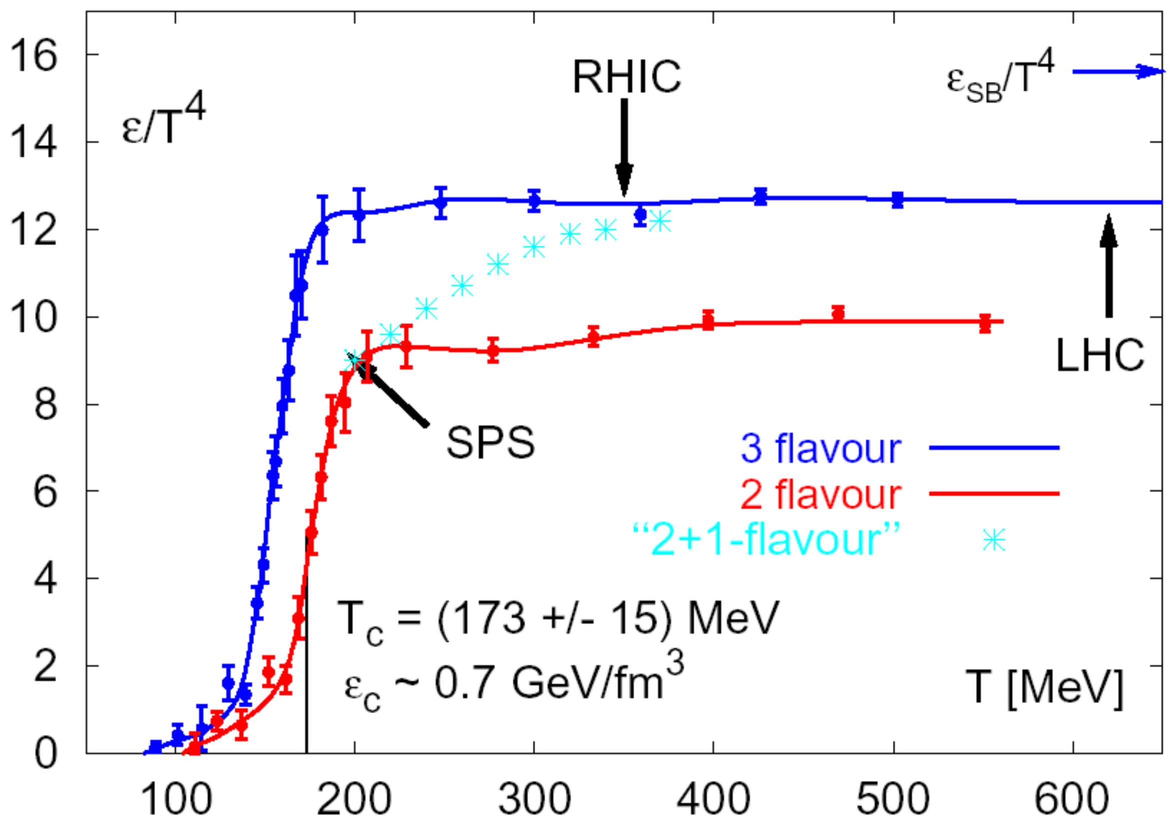
	RHIC	**LHC**	
$\sqrt{s_{NN}}$ (GeV)	7-200	2760, 5500	*center of mass energy*
$dN_{ch}/d\eta$	~1200	~1600	*number of particles*
T/T_c	1.9	3.0-4.2	*temperature*
ε (GeV/fm^3)	5	12, 16	*energy density*
τ_{QGP} (fm/c)	2-4	>10	*lifetime of QGP*

QCD at high Temperatures

What to expect when we get there?

F. Karsch, et al
Nucl. Phys. B605 (2001) 579

T_c = Critical temperature



Lattice QCD indicates that at a temperature > T_c we have **partonic degrees of freedom** (Deconfinement)

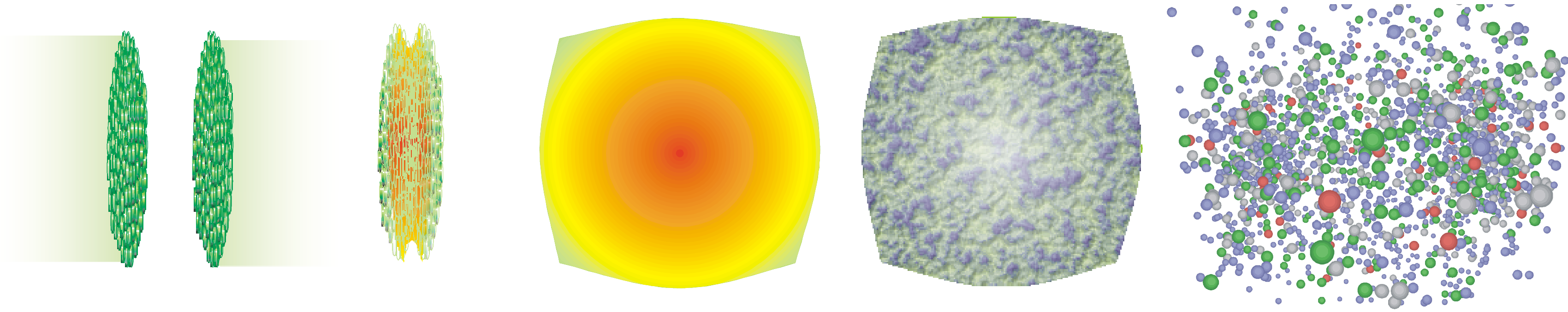
rather than hadronic

Hot Dense Quark Gluon Plasma

170 MeV ➔ $2 \cdot 10^{12}$K 100,000 times hotter than the sun's core!

Evolution of the Collision

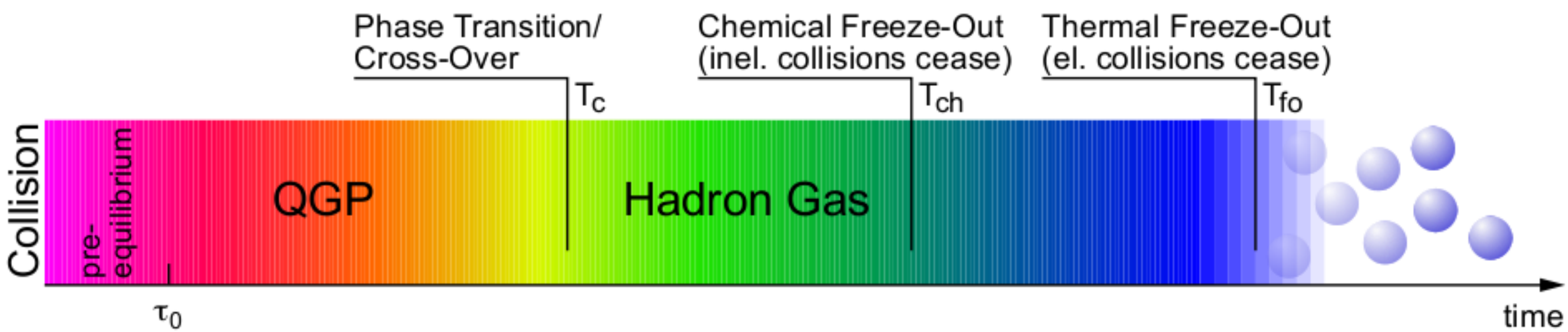
Initial State Hadronization

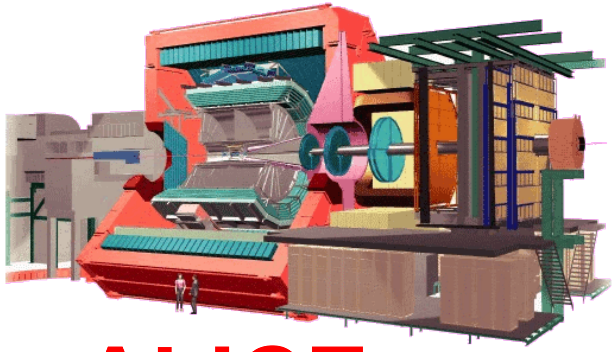


Incoming Nuclei

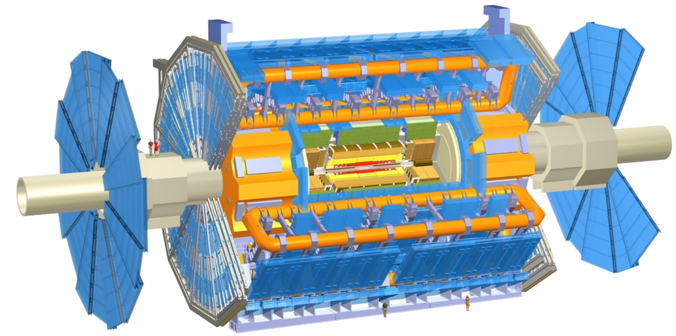
QGP
Hydrodynamic expansion

Freeze-out

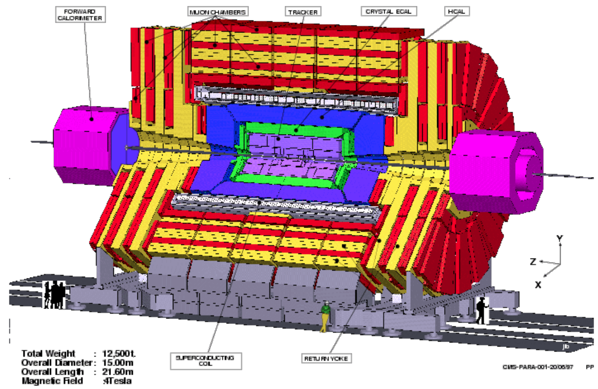




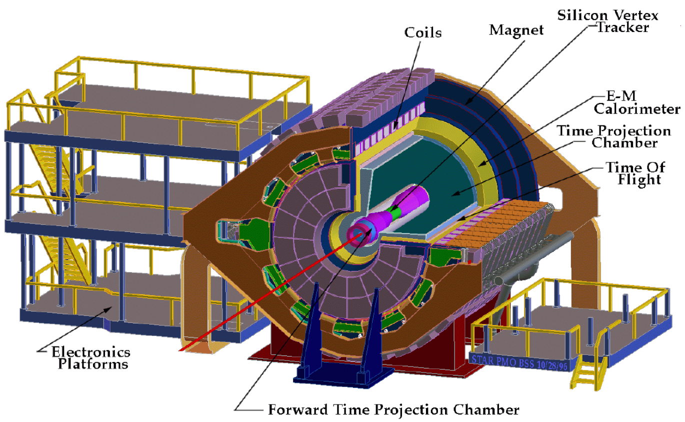
ALICE



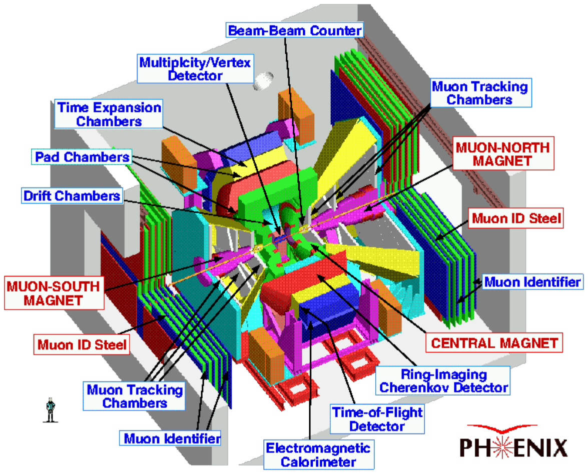
ATLAS



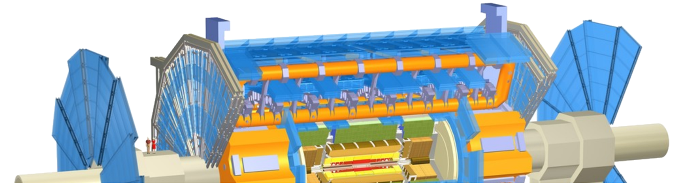
CMS



STAR



PHENIX

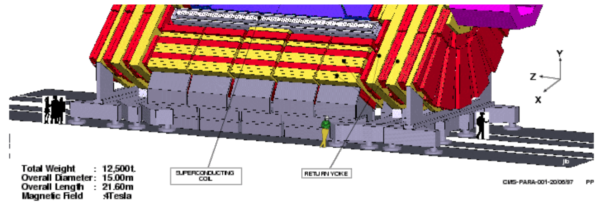


Trigger detectors: When do we have a collision?

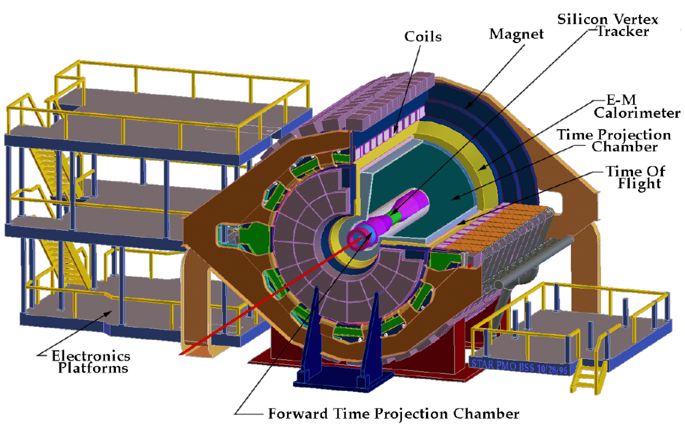
Tracking detectors: Where and how fast did the particle go?

Identification detectors: What kind of particle is it?

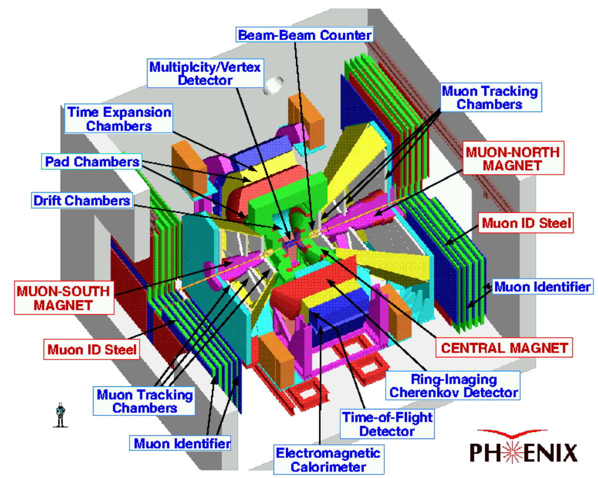
Calorimeters: How much energy does the particle have?



CMS



STAR

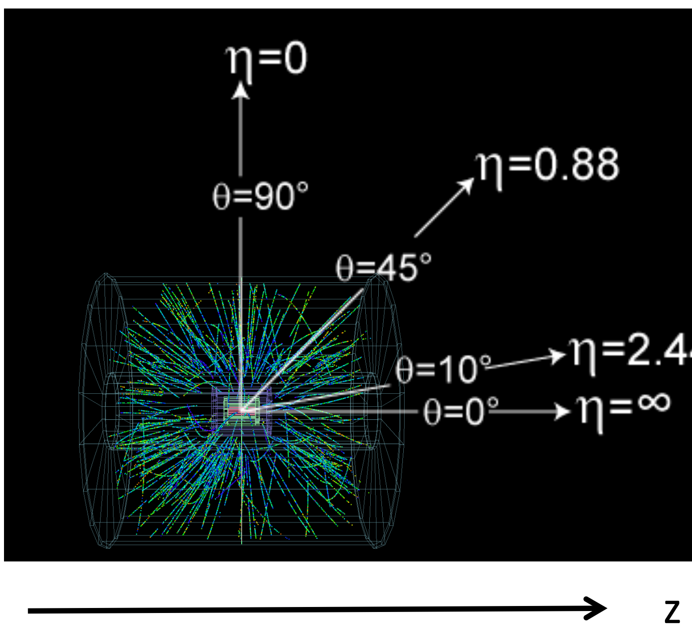


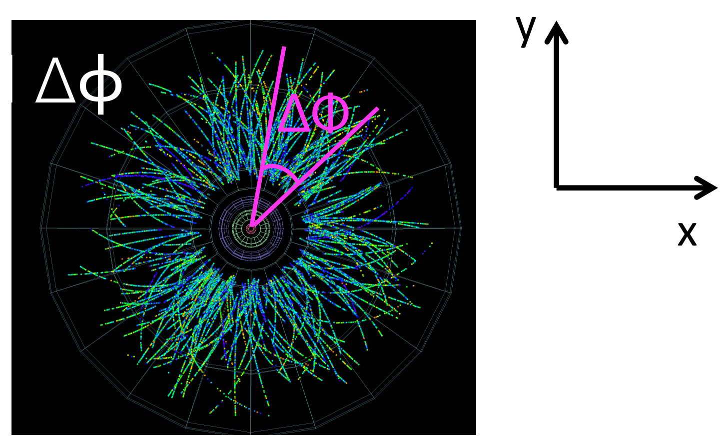
PHENIX

Recall our favorite variables

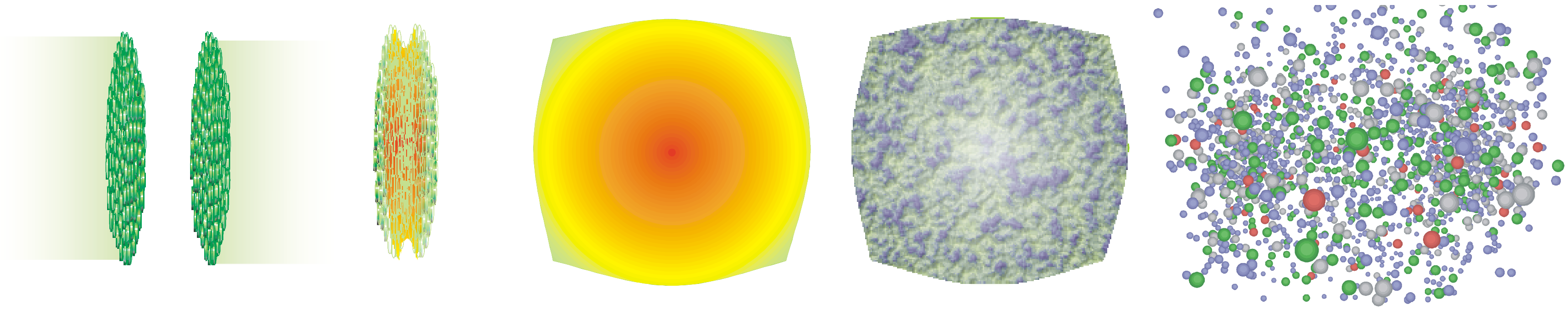
$$\eta = -\ln[\tan(\theta/2)]$$

$$p_T = \sqrt{p_x * p_x + p_y * p_y}$$





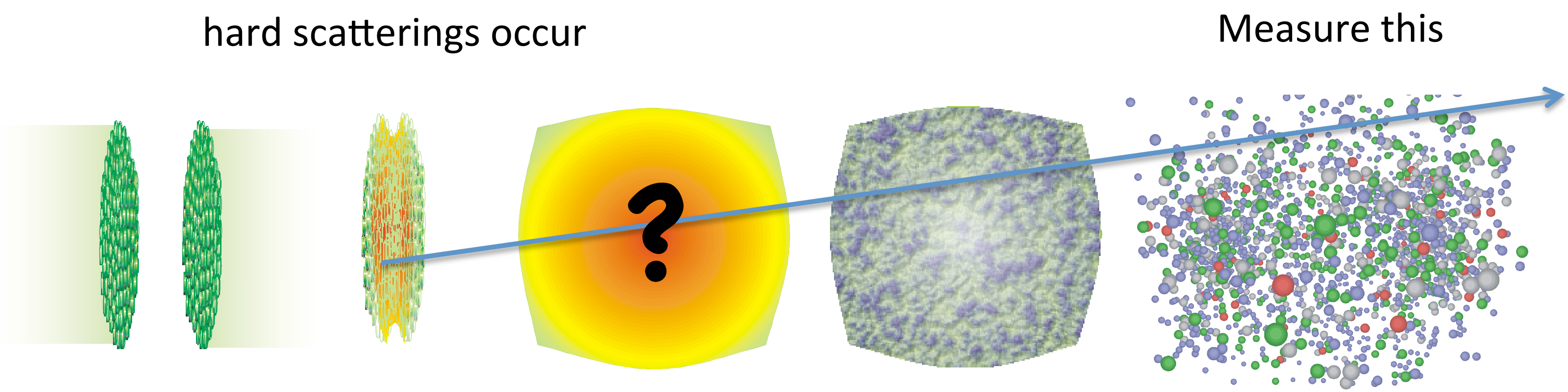
Evolution of the Collision



- 2 classes of observables
  - Hard probes (jets, high p_T hadrons, heavy flavor)
  - Bulk measurements (elliptic flow)

Hard = high momentum

How do you know you created a QGP?

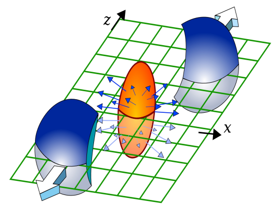


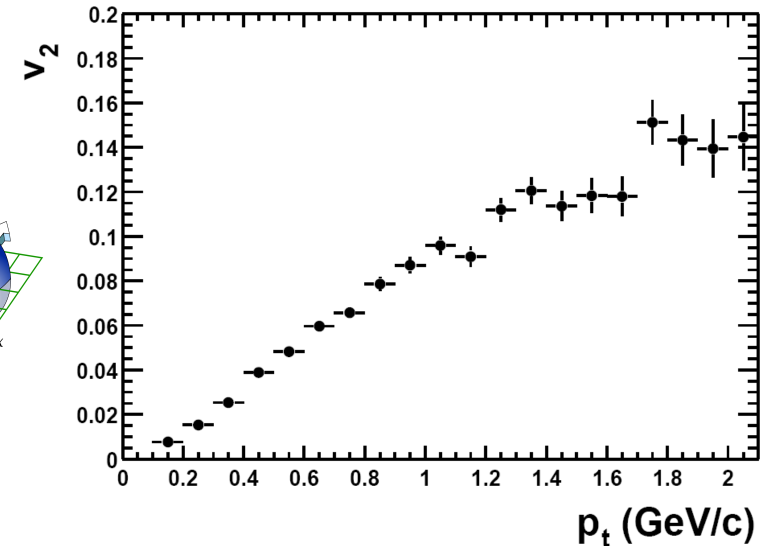
- Bulk medium properties
- Interaction of hard probes with the medium
  - Yield should scale according to number of these binary collisions: N_{coll}

$$R_{AA} \equiv \frac{\text{Yield in Au + Au Events}}{(\text{Ncoll})(\text{Yield in p + p Events})}$$

RHIC's First Two Major Discoveries

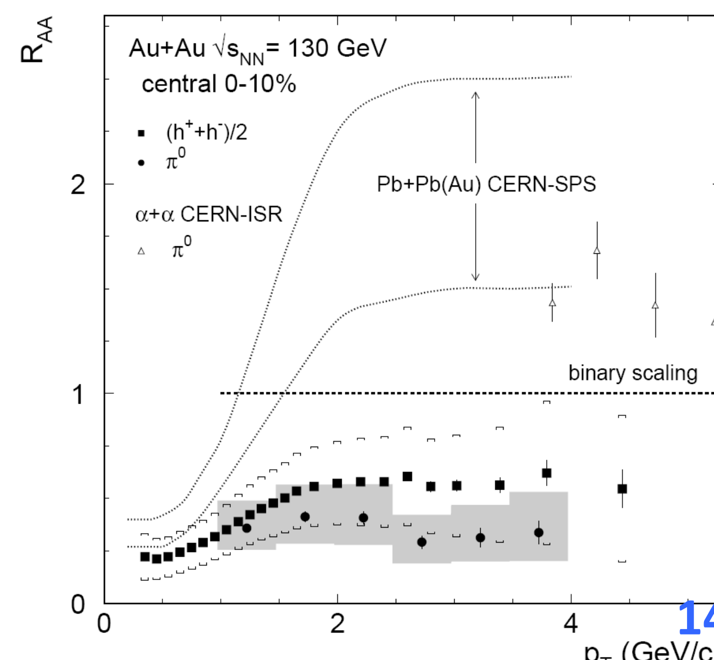
- Discovery of "elliptic flow":
  - Elliptic flow in Au+Au collisions at $\sqrt{s_{NN}}$= 130 GeV, STAR Collaboration, Phys.Rev.Lett.86:402-407,2001





$$\frac{1}{N_{\rm trig}}\frac{dN^{\rm pair}}{d\Delta\phi} \sim 1 + 2\sum_{n=1}^{n=\infty} V_{n\Delta}(p_T^{\rm trig}, p_T^{\rm assoc})\cos(n\Delta\phi)$$

- Discovery of "jet quenching"
  - Suppression of hadrons with large transverse momentum in central Au+Au collisions at $\sqrt{s_{NN}}$ = 130 GeV, PHENIX Collaboration, Phys.Rev.Lett.88:022301,2002



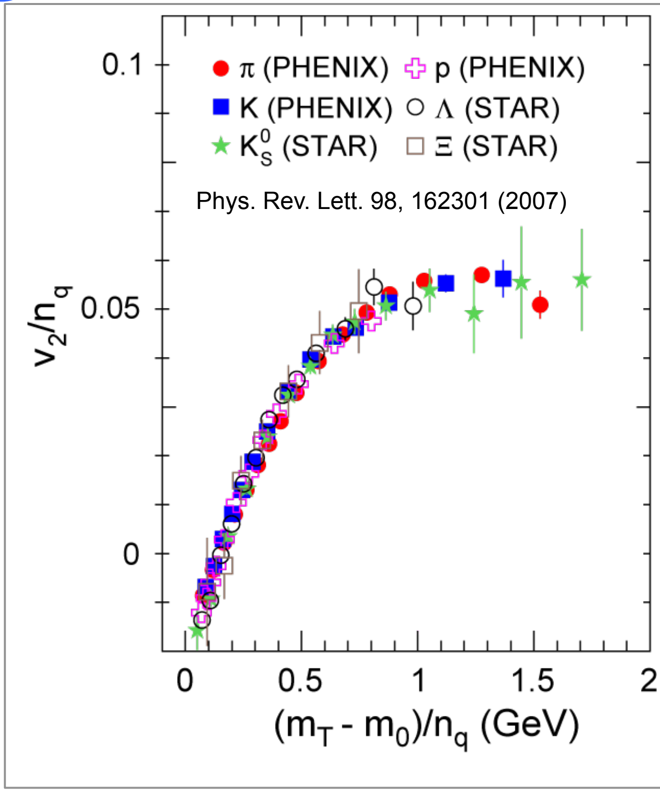
How do you know you created a QGP?

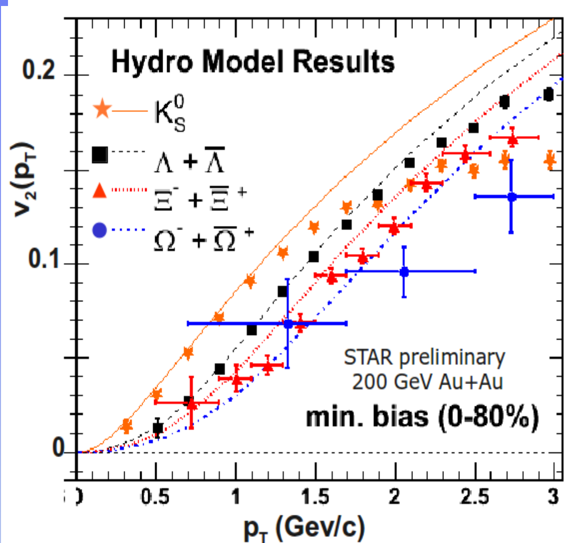
- What is flowing?
- Is p+p the right baseline? How does a nucleus influence change the initial state?
- Is N_{coll} correct description correct in R_{AA} calculation?

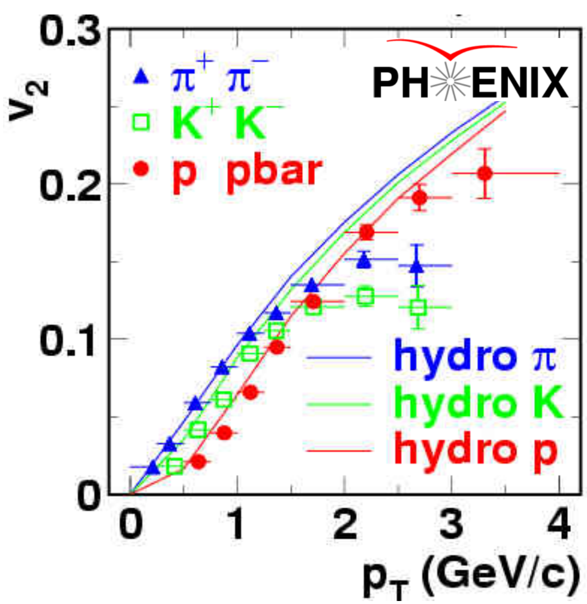
What is flowing?

- "Fine structure" in elliptic flow:
  - Elliptic flow of identified hadrons in Au+Au collisions at $\sqrt{s_{NN}}$= 200 GeV, PHENIX Collaboration, [Phys.Rev.Lett.91:182301,2003]

Hydro from P. Huovinen et al., Phys. Lett. **B503**, 58 (2001)



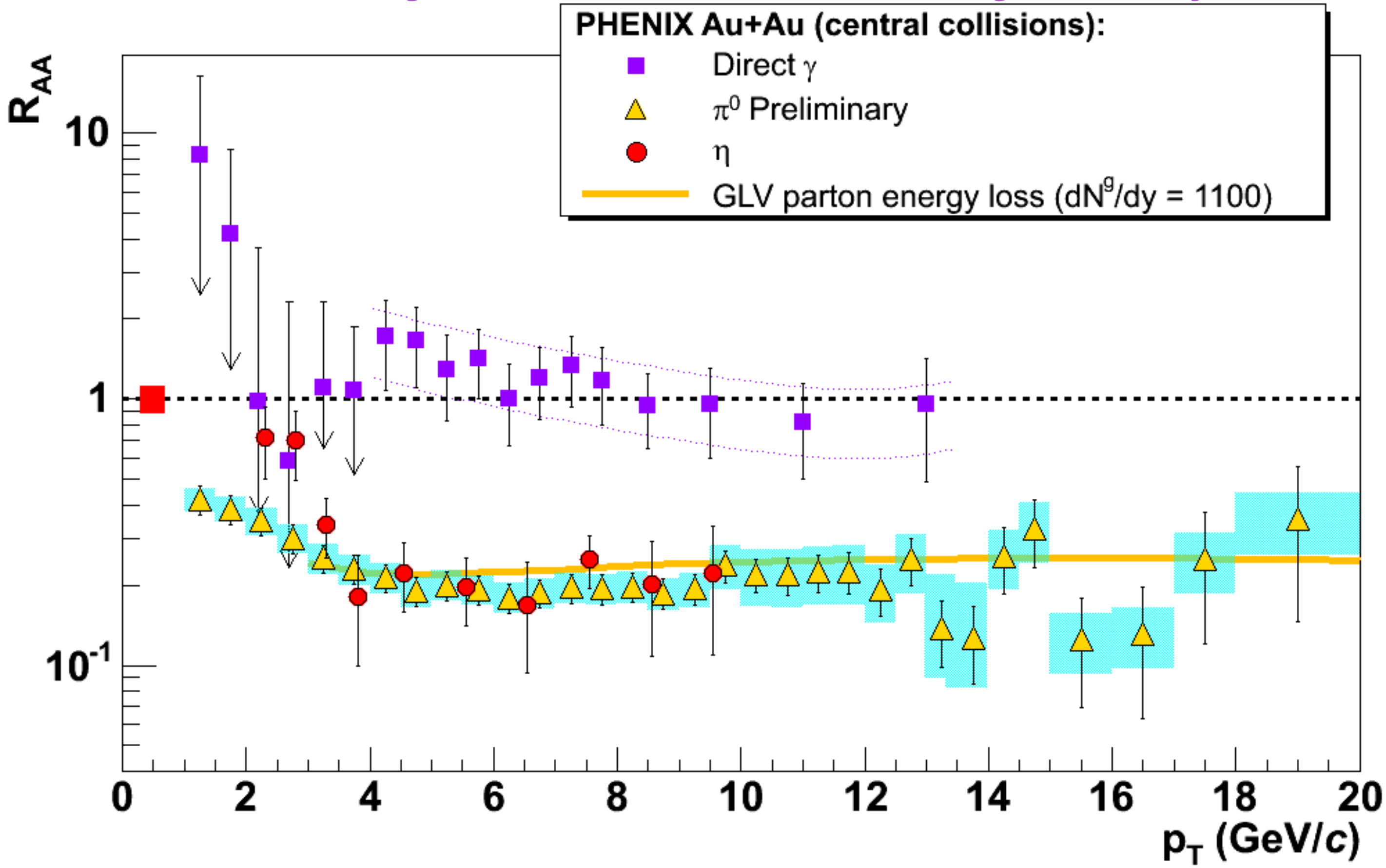




We have a liquid of quarks and gluons!

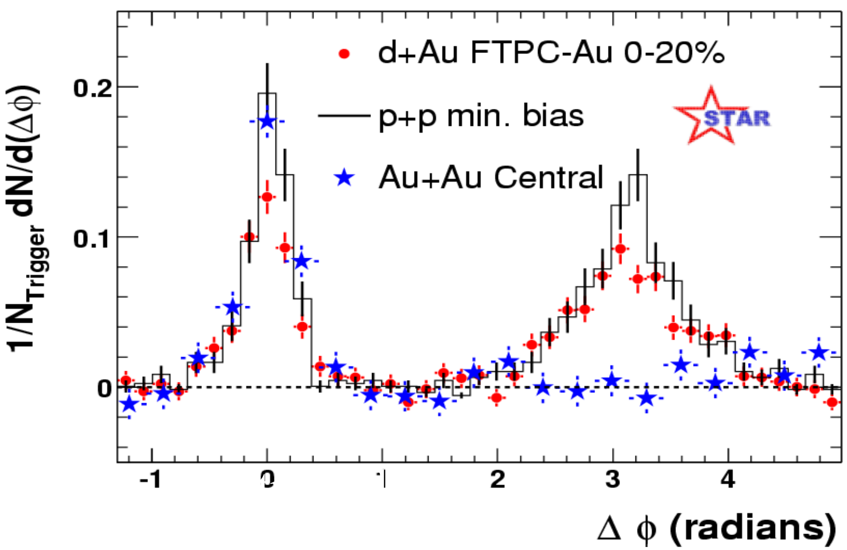
Direct Photons as a Cross Check

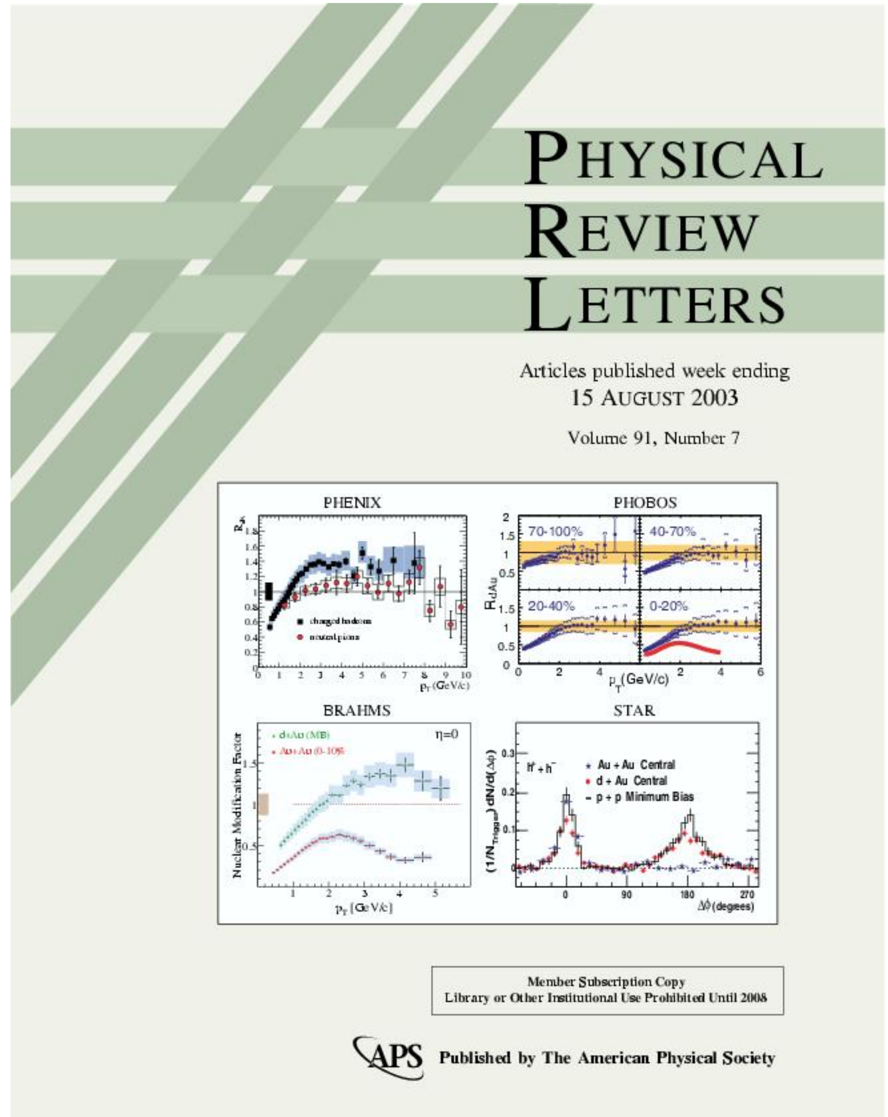
Direct photons do not interact via the strong force and therefore are not modified by the QGP



Quantifying Cold Nuclear Matter Effects

- Suppression in Au+Au not observed in d+Au
- Au+Au "Disappearance of the awayside jet" not in d+Au





How do you know you created a QGP?

- But what is flowing?
  - Quarks!
- Is p+p the right baseline? How does a nucleus influence change the initial state?
  - d+Au consistent with p+p measurements
- Is N_{coll} correct description correct in R_{AA} calculation?
  - Direct photon R_{AA} is 1 as expected for non-interacting probe

How do you know you created a QGP?

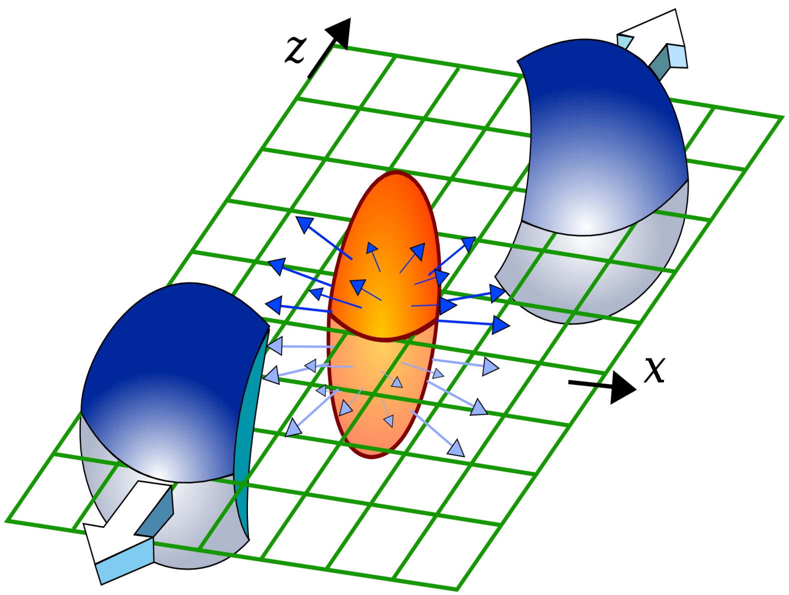
- The RHIC White Papers summarizing first 3 years of data:
  - *Quark gluon plasma and color glass condensate at RHIC? The Perspective from the BRAHMS experiment,*
    Nucl.Phys. **A757** (2005) 1-27, nucl-ex/0410020
  - *Formation of dense partonic matter in relativistic nucleus-nucleus collisions at RHIC: Experimental evaluation by the PHENIX collaboration,*
    Nucl.Phys. **A757** (2005) 184-283, nucl-ex/0410003
  - *The PHOBOS perspective on discoveries at RHIC,*
    Nucl.Phys. **A757** (2005) 28-101, nucl-ex/0410022
  - *Experimental and theoretical challenges in the search for the quark gluon plasma: The STAR Collaboration's critical assessment of the evidence from RHIC collisions,*
    Nucl.Phys. **A757** (2005) 102-183, nucl-ex/0501009

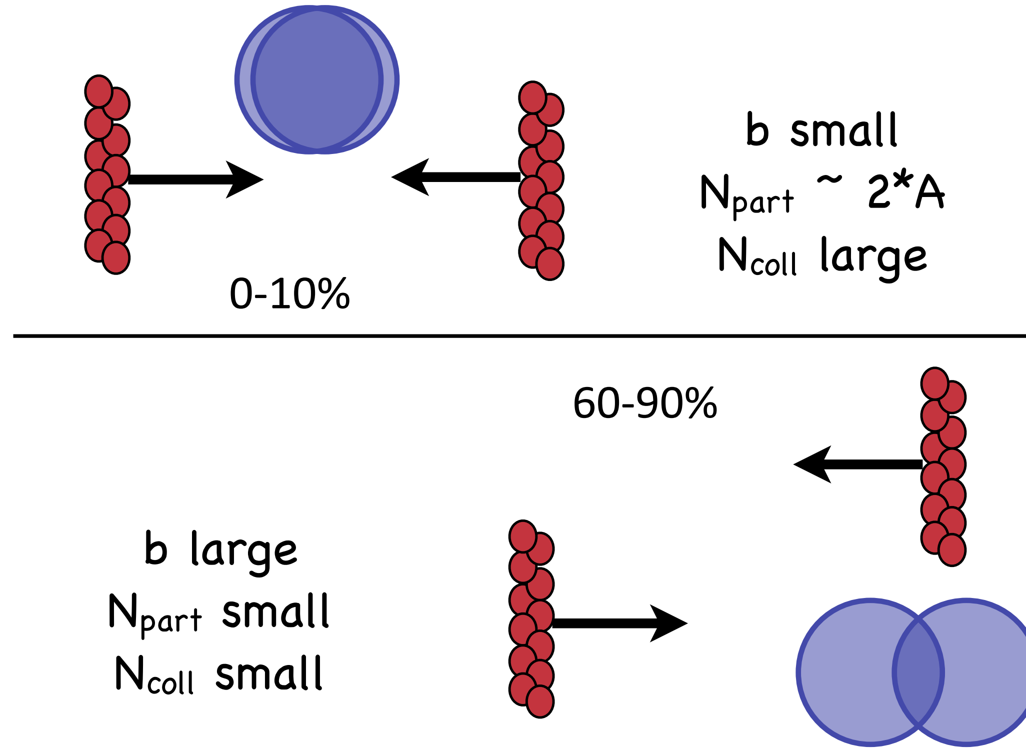
- The conclusion was **YES!** collectively these results indicate a new state matter of known as the **QGP**

Bulk properties

- Temperature
- Energy density
- Flow
- Viscosity
- Source size

Event Categorization Review

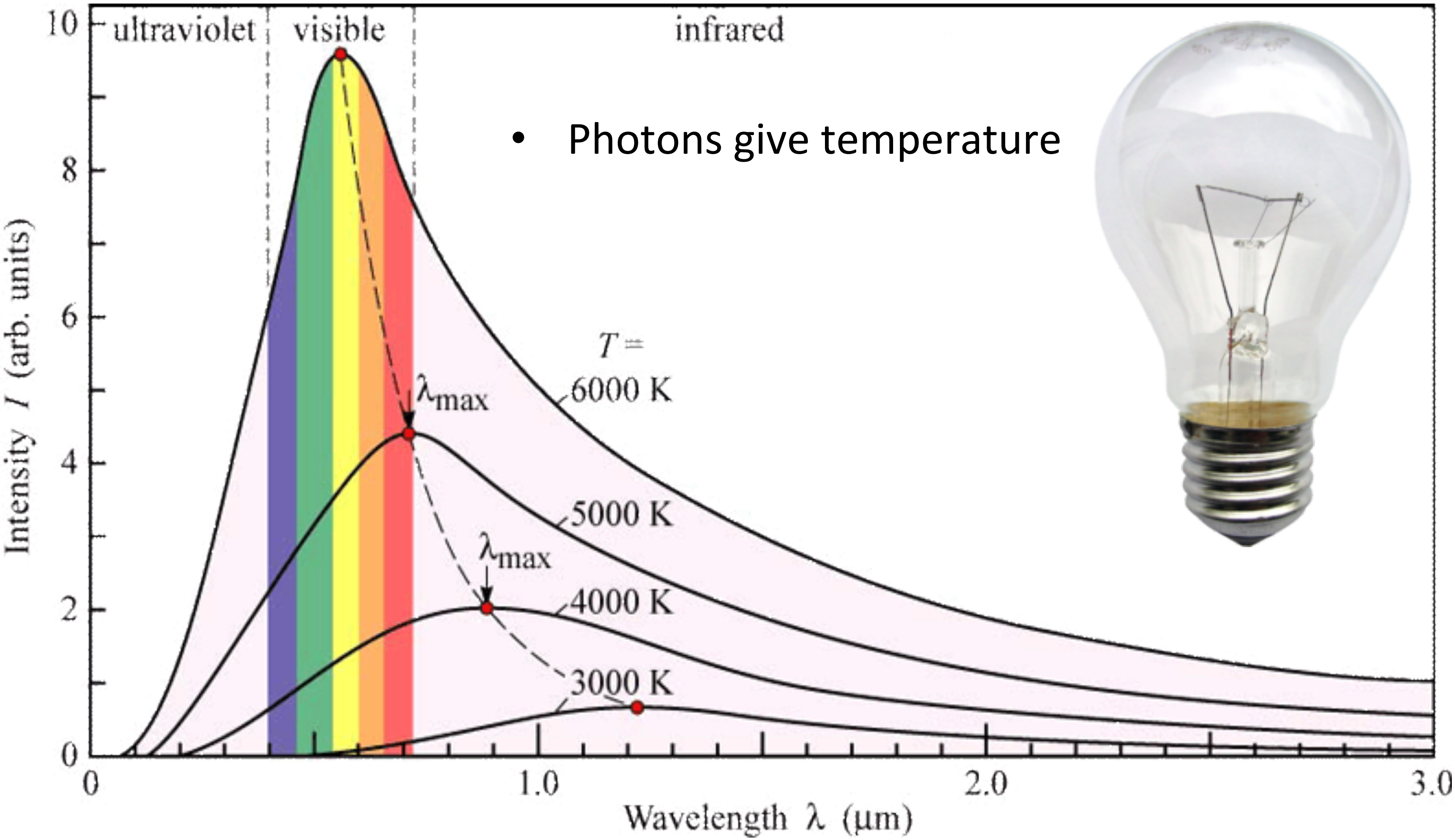




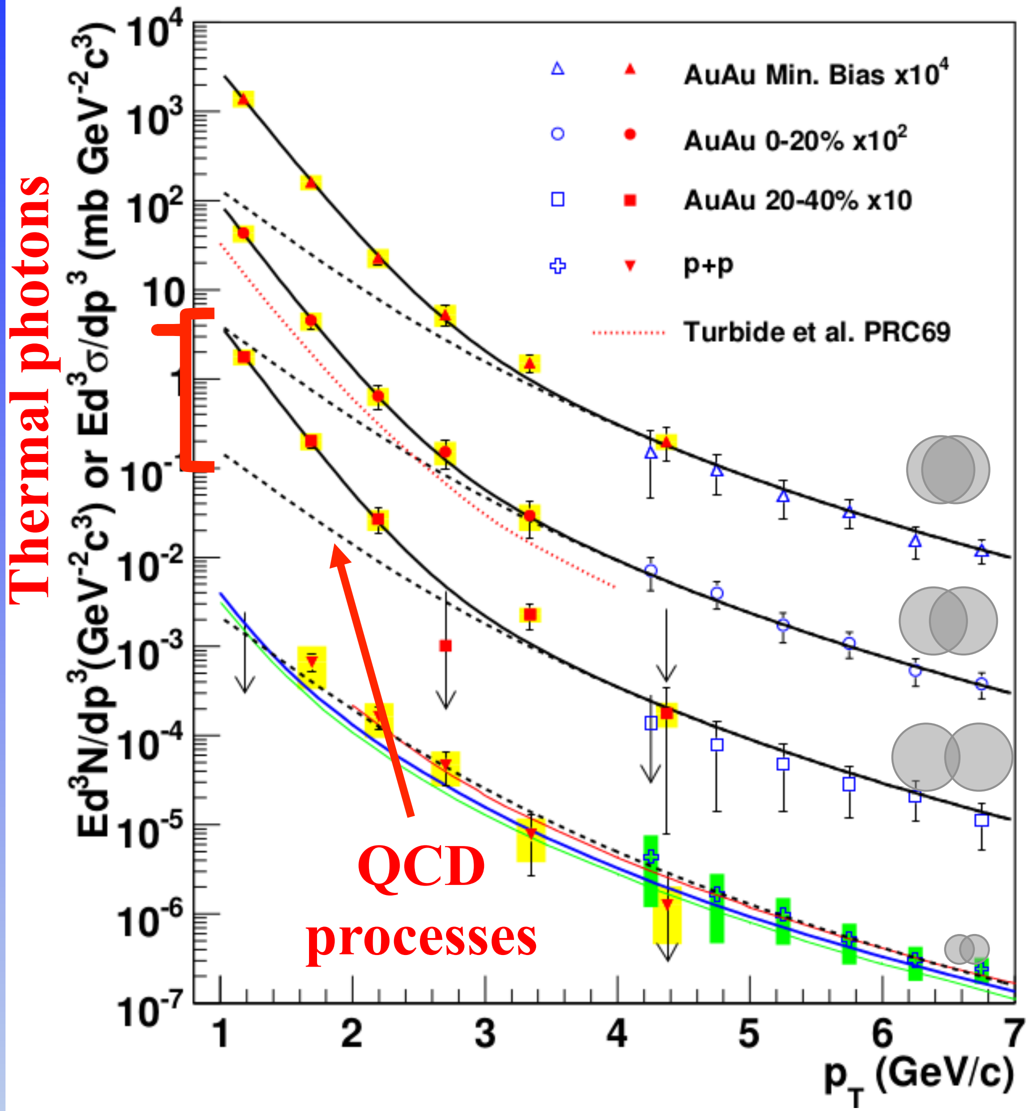
- Centrality relates to impact parameter (b) or amount of overlap
- % refers to total section
- Pop Quiz:
  - Draw 0-10% and 60-90%

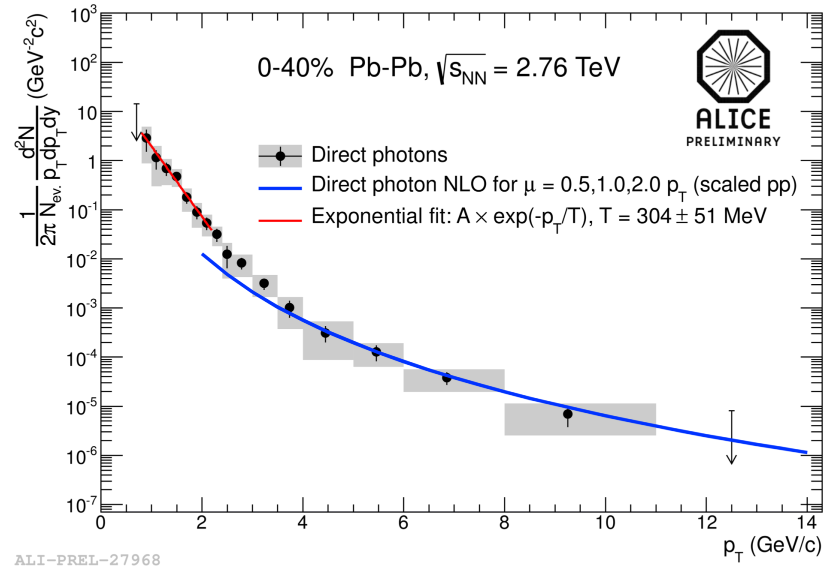
Bulk Properties: Temperature

- Photons give temperature



Thermal Photons

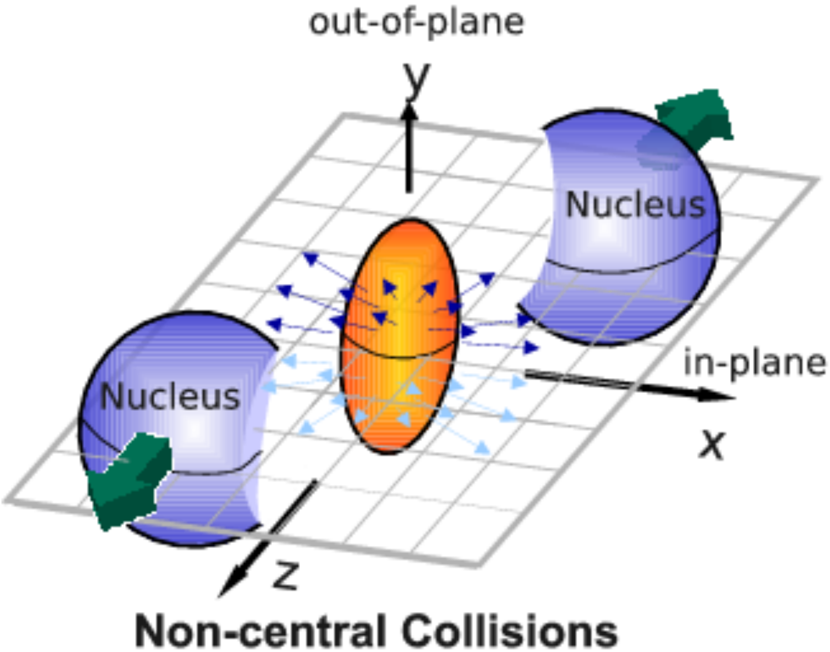


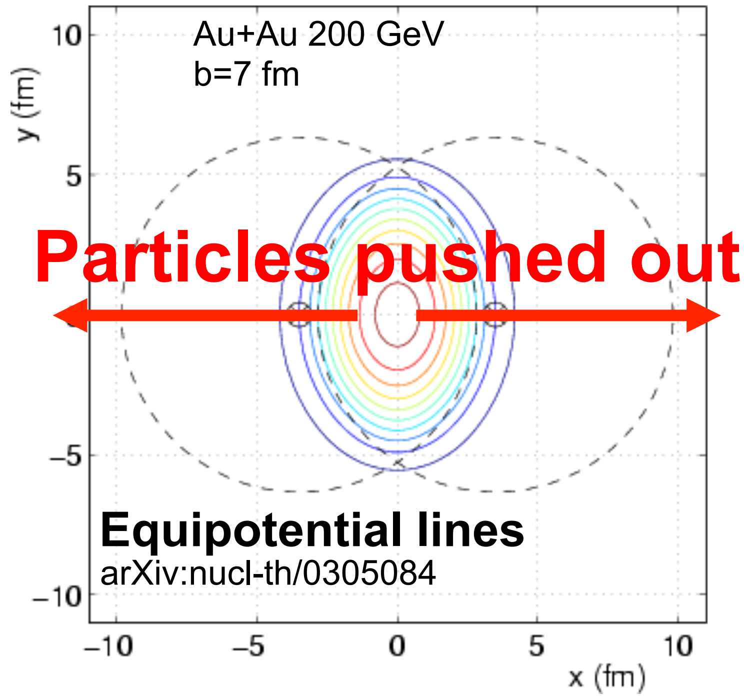


Measure direct photons
Observe excess above QCD processes
Excess = themal photon contribution
Extract temperature from fits

Phys.Rev.Lett.104:132301,2010

Flow revisited

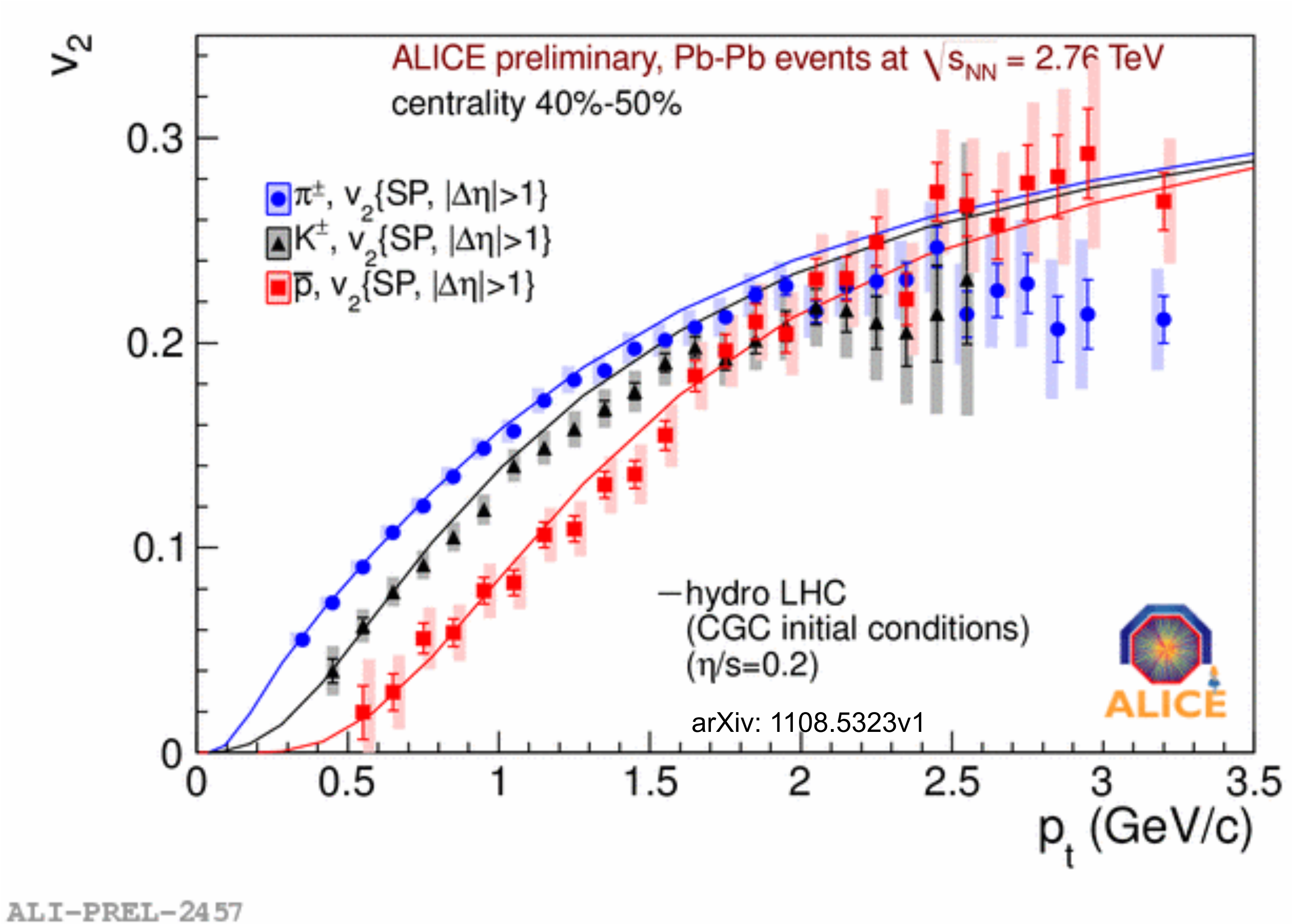




Initial overlap asymmetric → pressure gradients
Momentum anisotropy → Fourier decomposition:

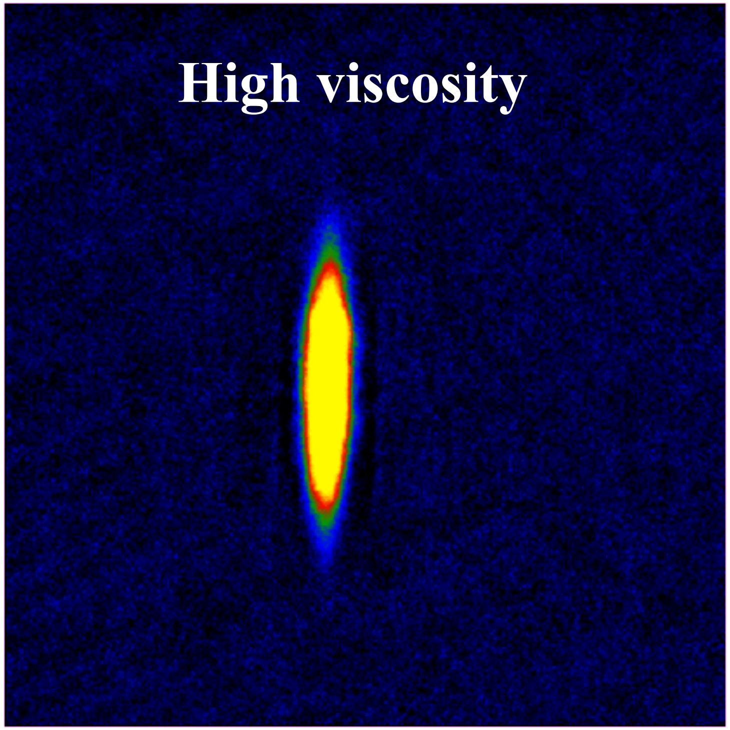
$$\frac{d^2N}{dp_T\,d\varphi} \approx 1 + 2v_1\cos(d\varphi) + 2v_2\cos(2d\varphi) + 2v_3\cos(3d\varphi) + 2v_4\cos(4d\varphi) + 2v_5\cos(5d\varphi) + \ldots$$

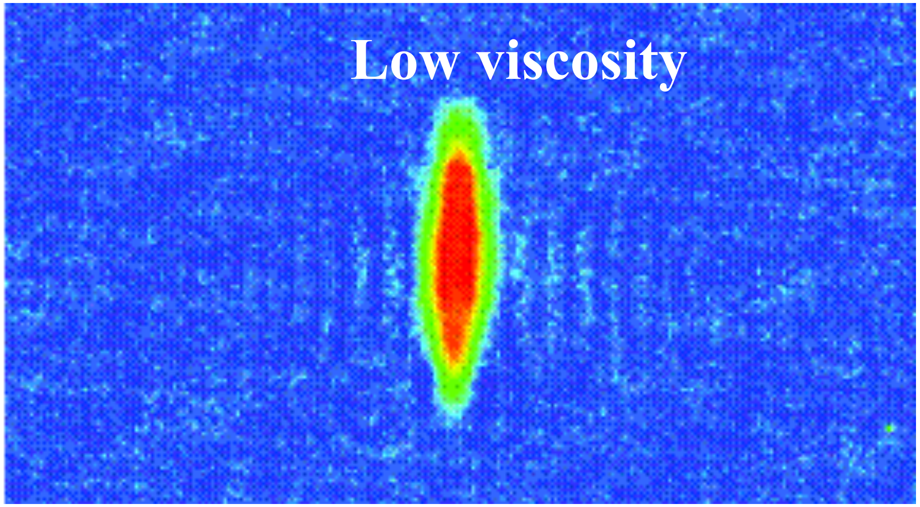
Also observed by the LHC



What does this say about viscosity?

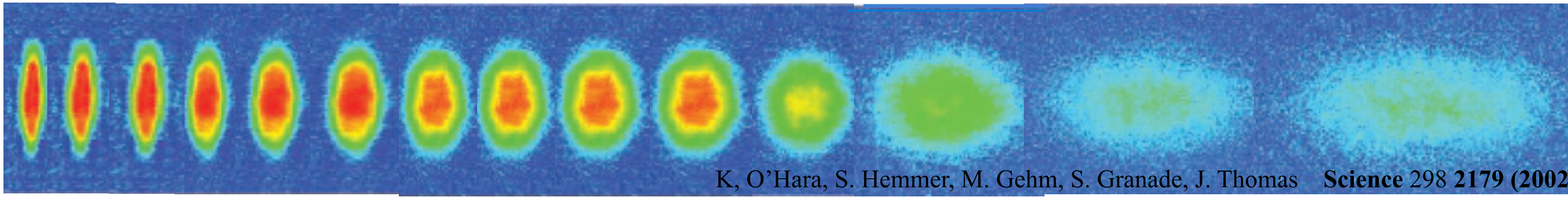
- Same phenomena observed in gases of strongly interacting atoms
  - K, O'Hara, S. Hemmer, M. Gehm, S. Granade, J. Thomas **Science** 298 **2179 (2002)**





Low Viscosity

Same phenomena observed in gases of strongly interacting atoms



K, O'Hara, S. Hemmer, M. Gehm, S. Granade, J. Thomas **Science** 298 **2179 (2002)**

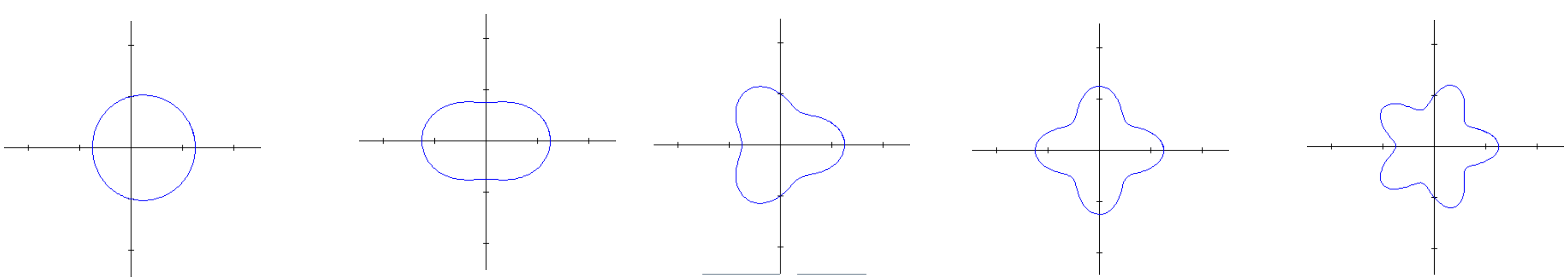
Time →

Initial state anisotropies converted to final state anisotropies

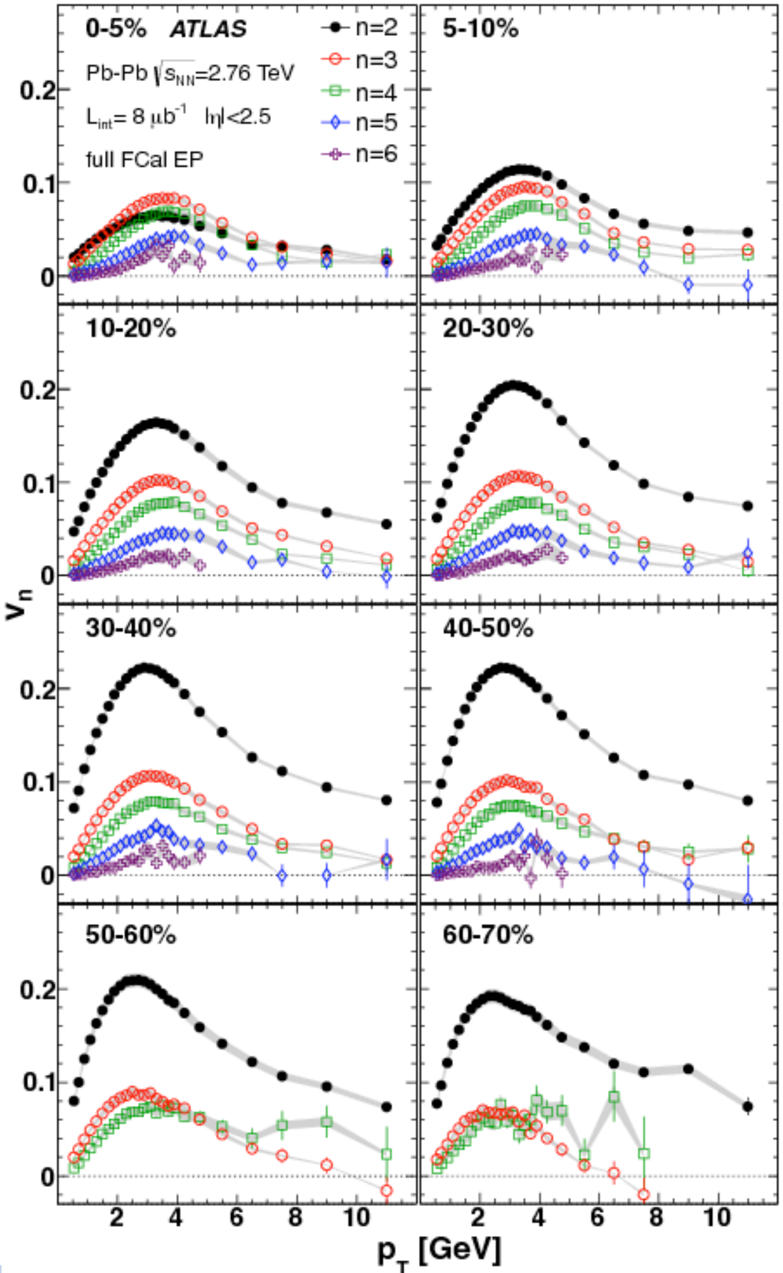
Fluctuations in the geometry of initial state give rise to odd harmonics

Fourier decomposition:

$$\frac{d^2N}{dp_T\,d\varphi} \approx 1 + 2v_1\cos(d\varphi) + 2v_2\cos(2d\varphi) + 2v_3\cos(3d\varphi) + 2v_4\cos(4d\varphi) + 2v_5\cos(5d\varphi) + \ldots$$

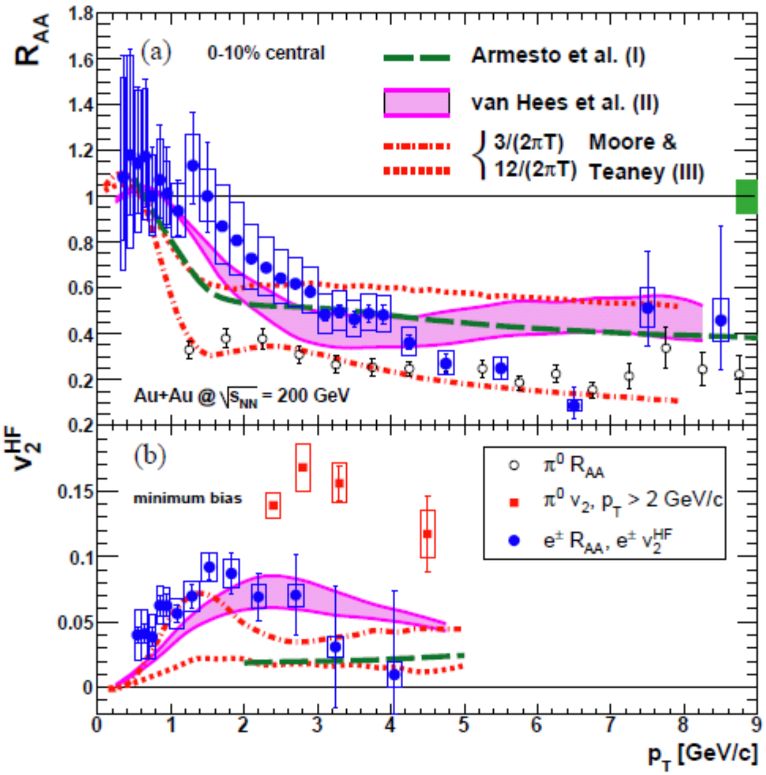


Higher Order Harmonics



The Quark Gluon Plasma has a very low viscosity

Implications for viscosity



Phys.Rev.Lett. 98 (2007) 172301
e-Print: nucl-ex/0611018

Charm quarks

- Energy loss

and

- Flow

v_2 is similar to that from [31], again implying that small τ and/or $D_{HQ} \times (2\pi T)$ are required to reproduce the data. Note that D_{HQ} provides an upper bound for the bulk matter's diffusion coefficient D. Using the observation [32] that $D \approx 6 \times \eta/(\epsilon + p)$ with $\epsilon + p = Ts$ at $\mu_B = 0$ provides an estimate for the viscosity to entropy ratio $\eta/s \approx (\frac{4}{3} - 2)/4\pi$, intriguingly close to the conjectured quantum lower bound $1/4\pi$ [33]. This result is consistent with estimates obtained in the light quark sector from elliptic flow [34] and fluctuation analyses [35].

What do we learn about the QGP?

Hydrodynamics works →
- (local) thermalization
- image of the initial state

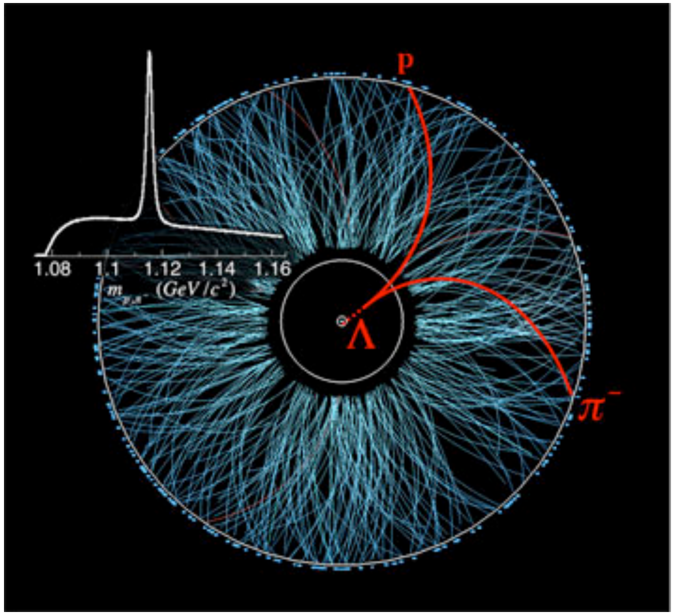
Really low viscosity
- Near AdS/CFT bound
- $\eta/S \sim 1/4\pi$

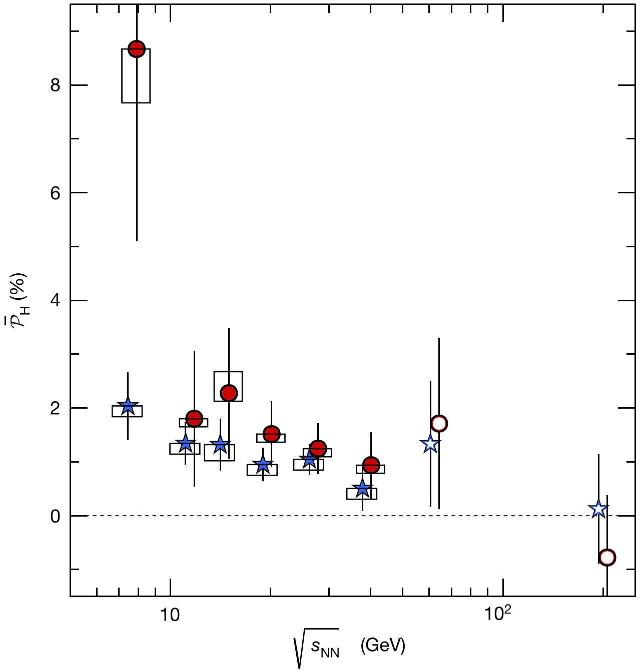
The QGP is the perfect liquid!

(not the gas of "free" quarks and gluons we expected)

Vorticity

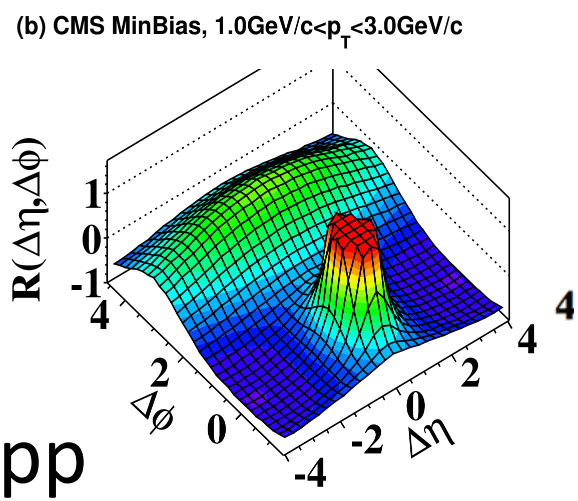
- New discoveries: **'Perfect Liquid' Quark-Gluon Plasma is the Most Vortical Fluid**





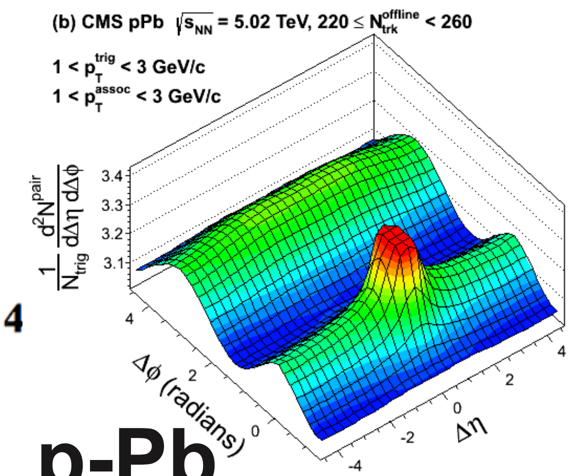
Surprises in p+Pb

[1009.4122]

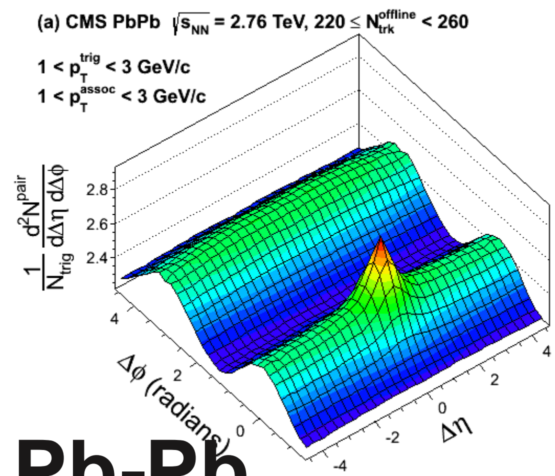


pp

[1210.5482]



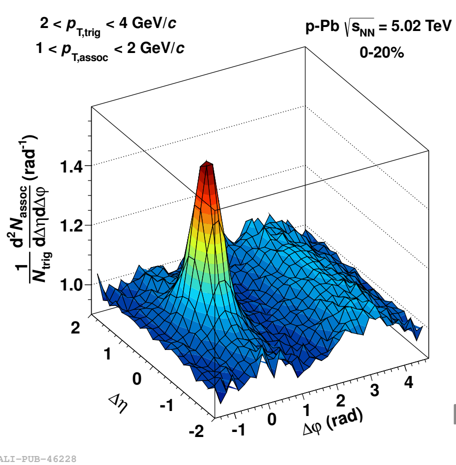
p-Pb



Pb-Pb

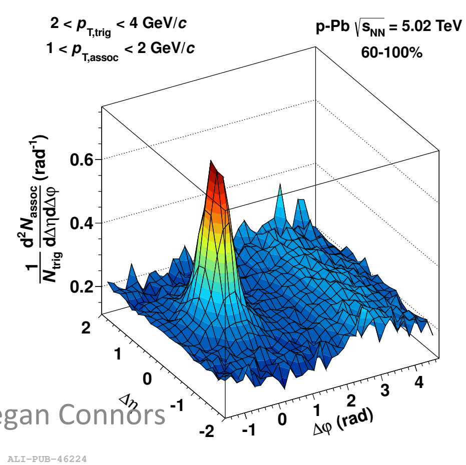
- Double Ridge

0-20%



-

60-100%



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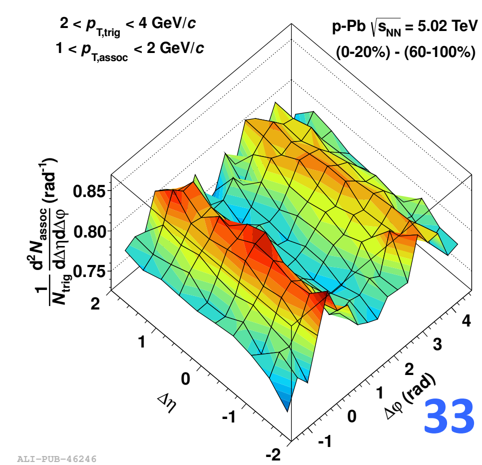
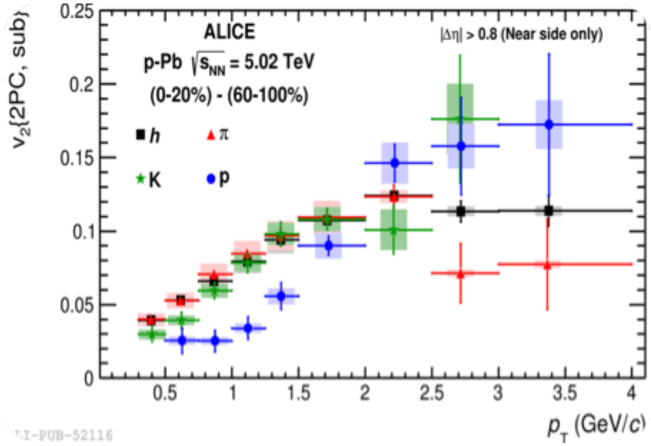
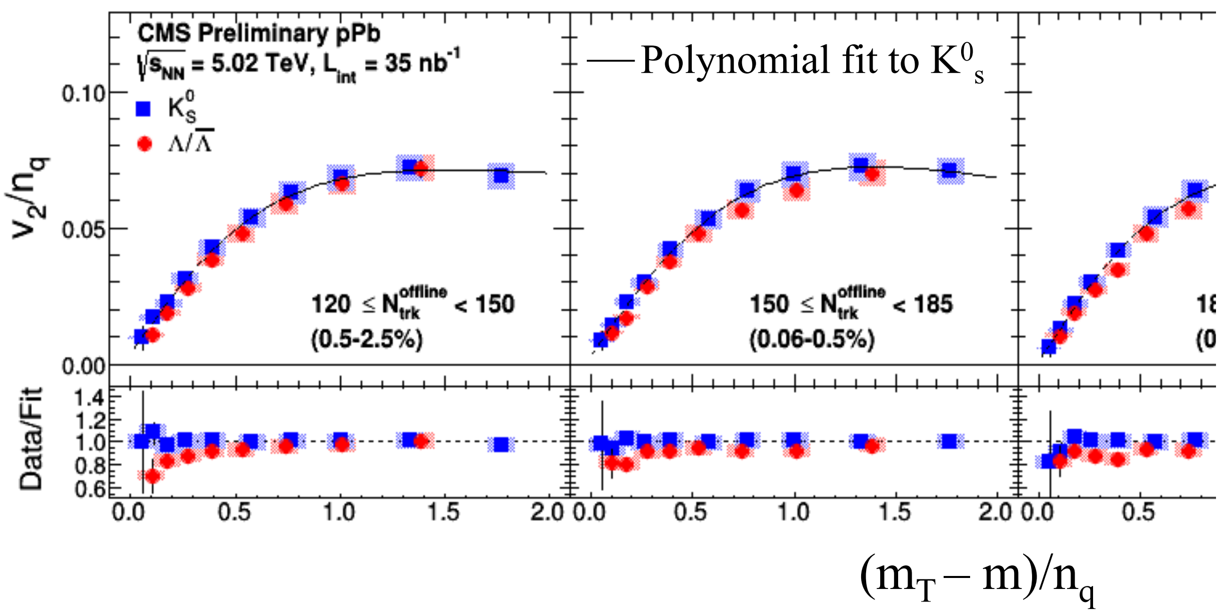


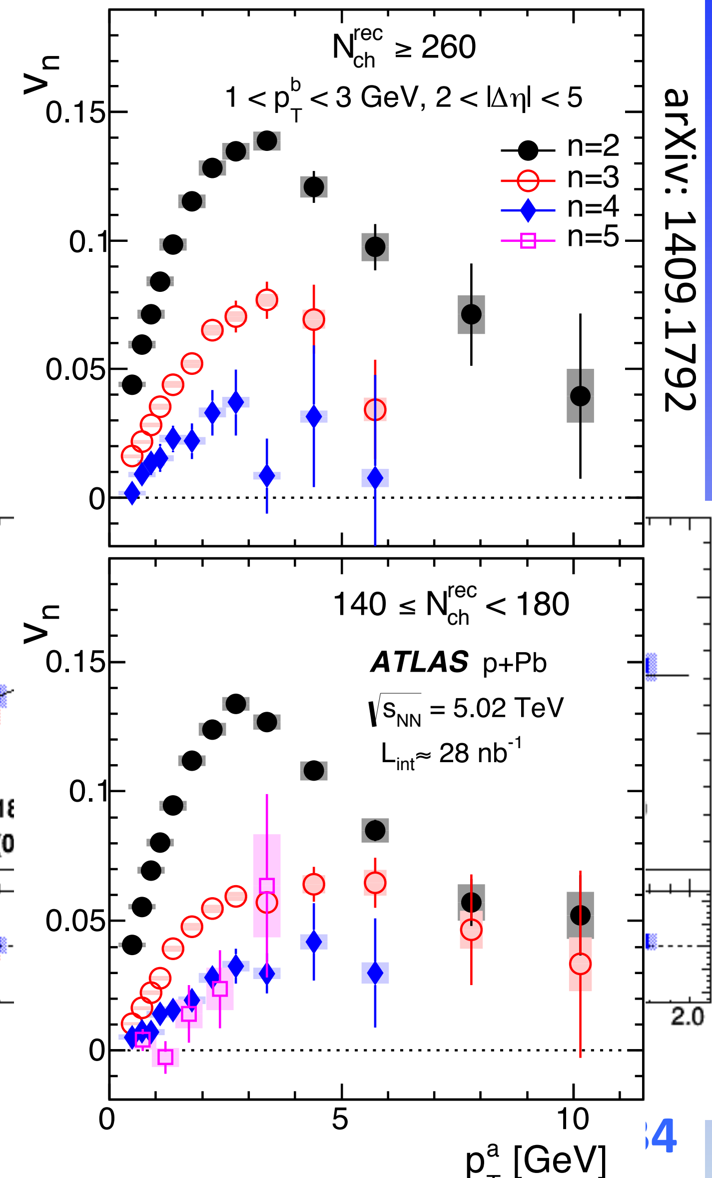
What does that imply?



Flow?

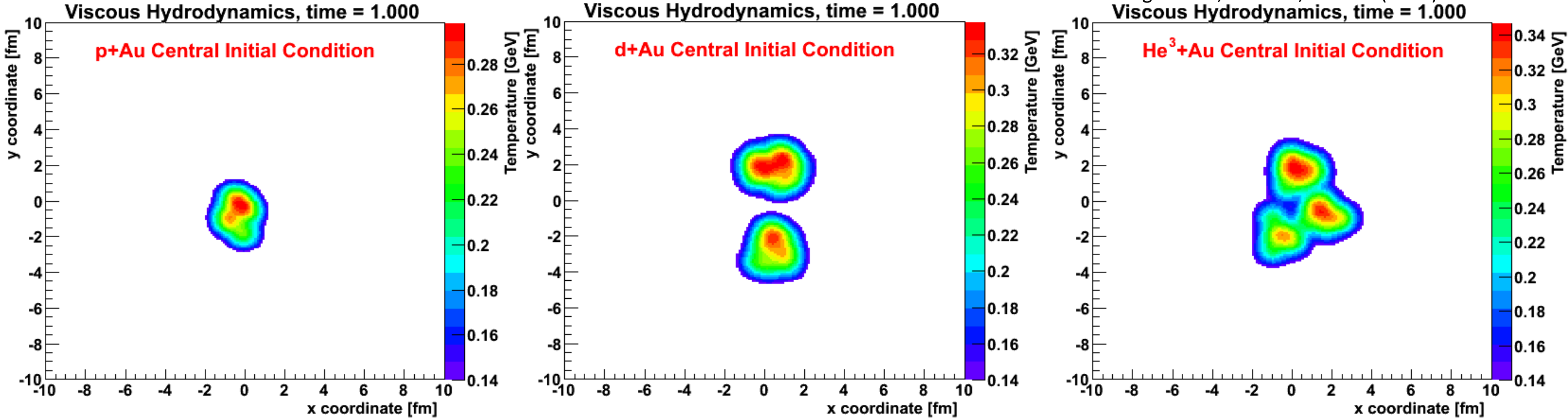
QGP Droplet?

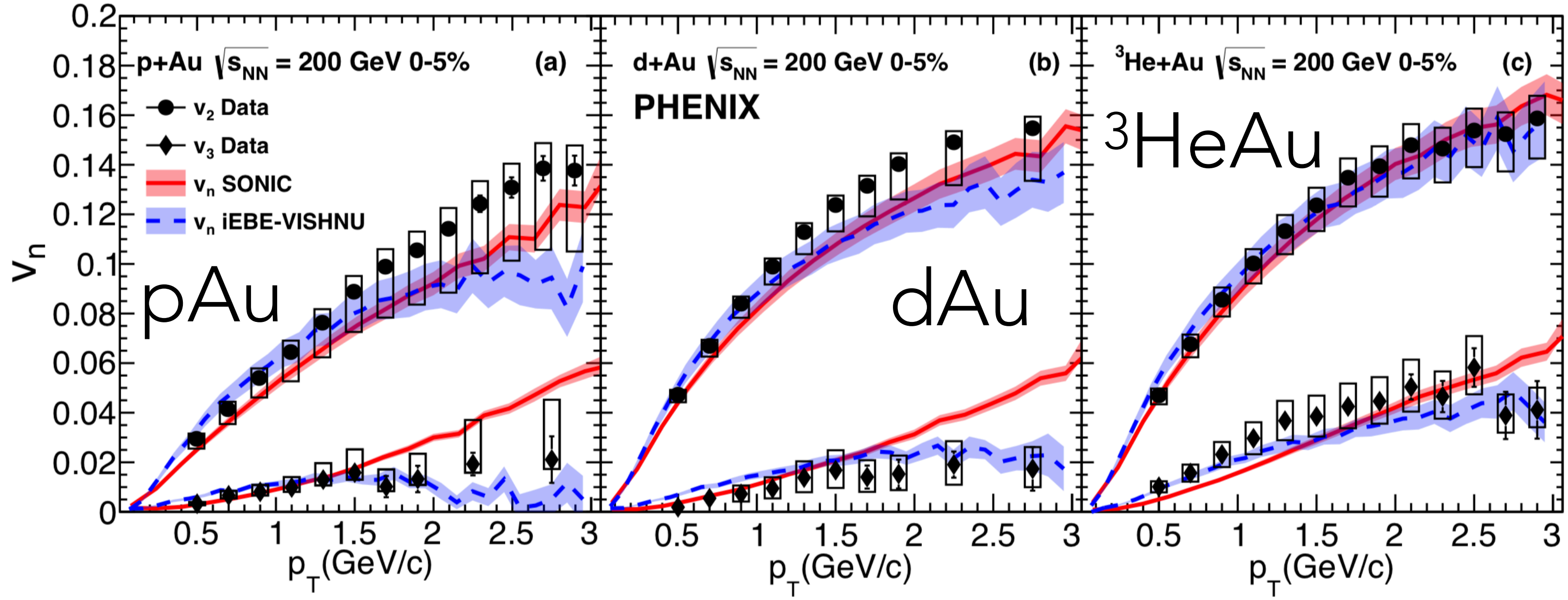




Geometry Scan at RHIC

J. Nagle et al., PRL **113**, 112301 (2014)





PHENIX, arXiv:1805.02973

Take home messages

- Heavy Ion colliders allow us to study QCD under extreme conditions
- The QGP flows like a nearly perfect liquid of quarks and gluons
  - Described with Hydrodynamics
  - Low viscosity
  - Vortical
- Geometric fluctuations in the initial state are observed as higher order harmonics
- Evidence for QGP flow behavior observed in small systems
- Beam Energy Scan II at STAR will give insight to the critical point and QCD phase diagram