The Perfect Fluid of Quarks

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based on W. A Zajc, arXiv:0802.3552 [nucl-ex]
and M. Riordan and W. A. Zajc, Sci.Am.294N5:24-31,2006

Working Title: The *Fluid* Nature of QGP

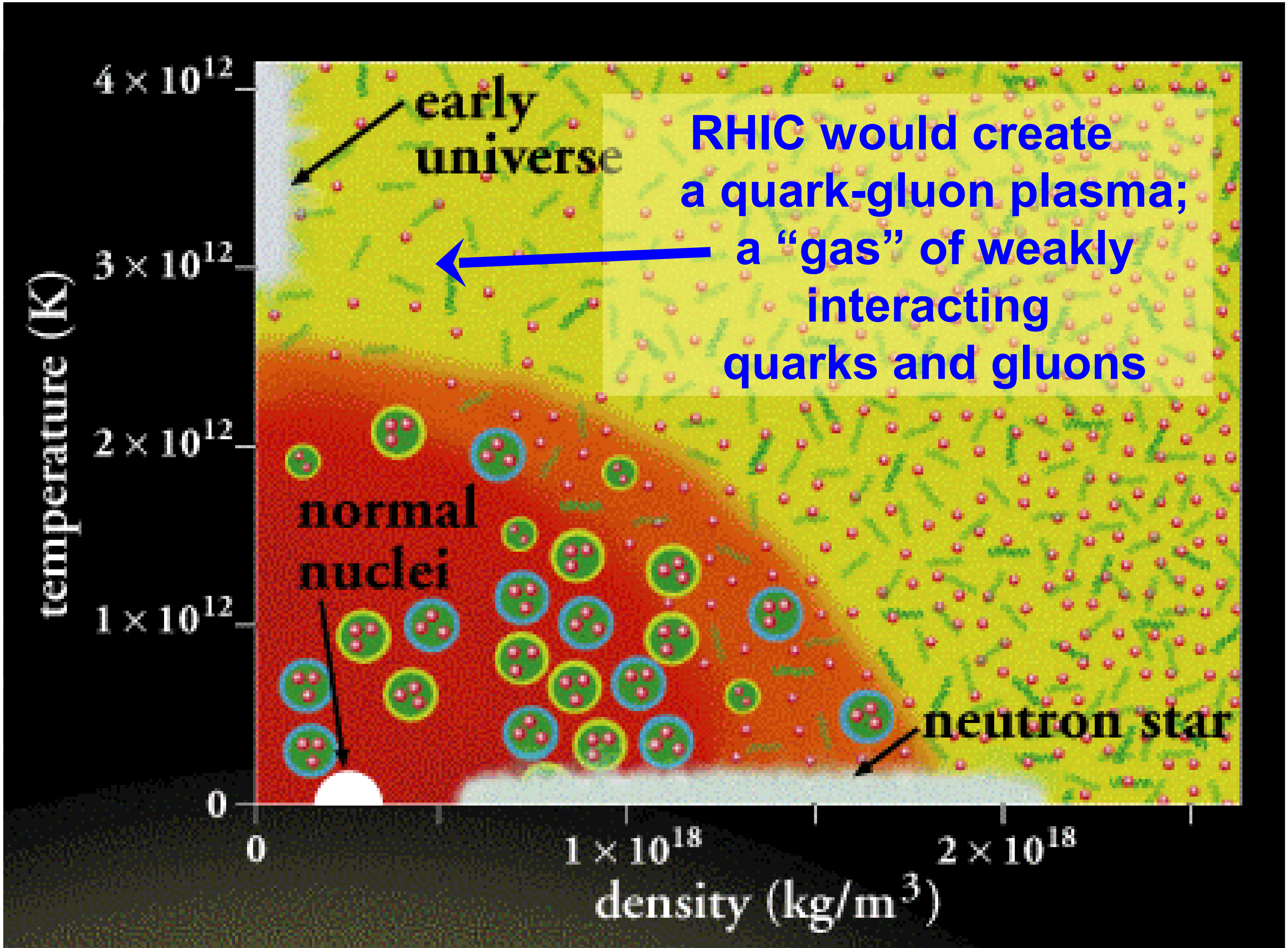
- From the Oxford English Dictionary:

  1) Primary definition: (adj.) *fluid* :
  "*Having the property of flowing; consisting of particles that move freely among themselves, so as to give way before the slightest pressure. (A general term including both gaseous and liquid substances.)*"

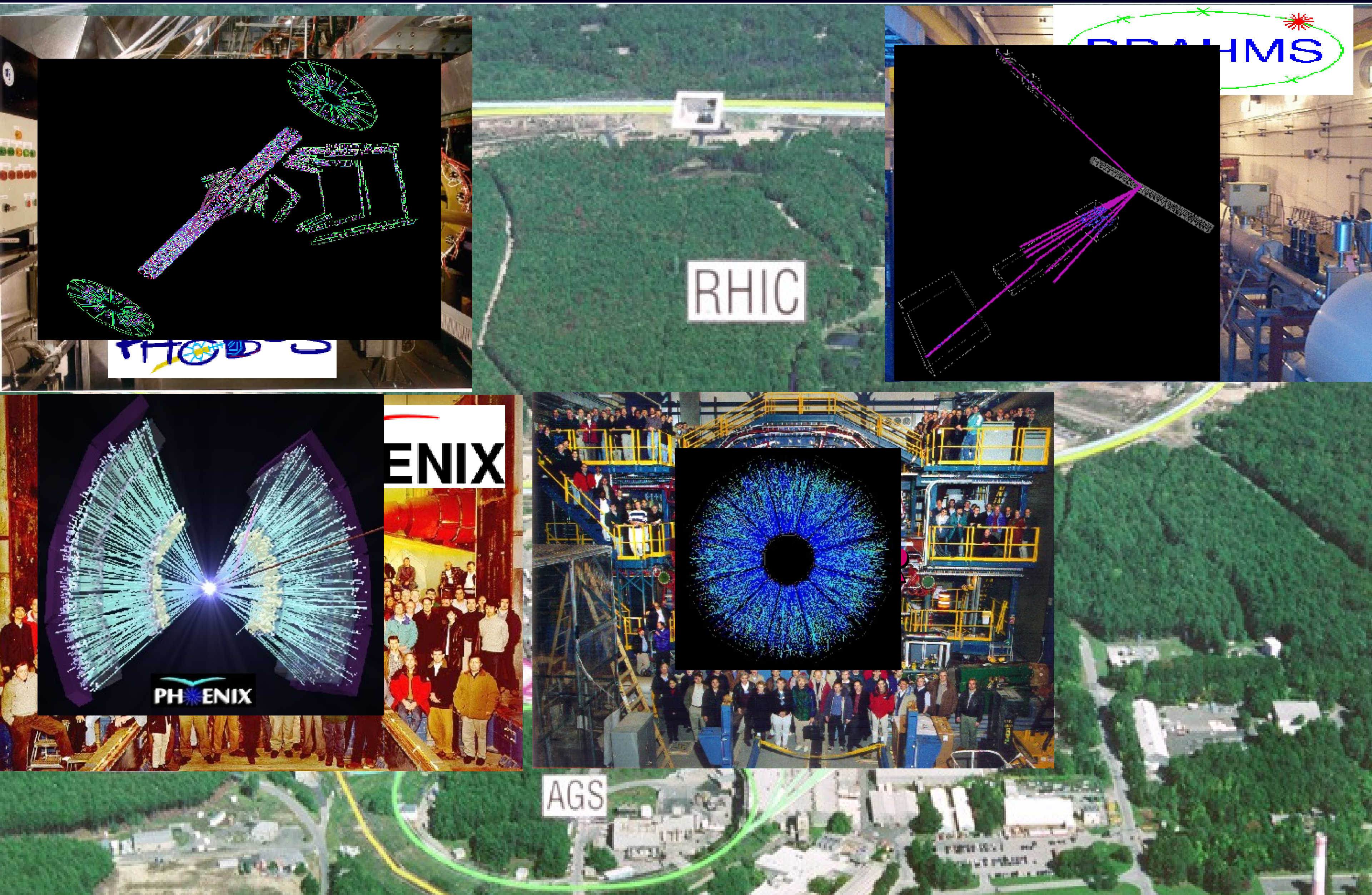
  2) Secondary definition: (adj.)
  "*Flowing or moving readily; not solid or rigid; not fixed, firm, or stable.*"

- SUMMARY: Following
  a) *a discovery period*, during which time our understanding of "quark-gluon plasma" was fluid(2),
  and
  b) *a paradigm shift,*
  we are now developing a *solid* understanding
  of the extraordinary fluid(1) produced at RHIC.

Expectations circa 2000



RHIC and Its Experiments



The Plan circa 2000

Use RHIC’s unprecedented capabilities

- Large √s
  - Access to reliable pQCD probes
  - Clear separation of valence baryon number and glue
  - To provide definitive experimental evidence for/against Quark Gluon Plasma (QGP)
- Polarized p+p collisions

Two small detectors, two large detectors

- Complementary but overlapping capabilities
- Small detectors envisioned to have 3-5 years lifetime
- Large detectors ~ facilities
  - Major capital investments
  - Longer lifetimes
  - Potential for upgrades in response to discoveries

Since Then…

Accelerator complex

- Routine operation at 2-4 x design luminosity (Au+Au)
- Extraordinary variety of operational modes
  - Species: Au+Au, d+Au, Cu+Cu, p↑ +p↑
  - Energies: 22 GeV (Au+Au, Cu+Cu, p↑), 56 GeV (Au+Au), 62 GeV (Au+Au,Cu+Cu, p↑ +p↑), 130 GeV (Au+Au), 200 GeV (Au+Au, Cu+Cu, d+Au, p↑ +p↑), 410 GeV (p↑), 500 GeV (p↑)

Experiments:

- Worked !

Science

- >300 refereed publications, among them 112+ PRL's
  - *Major* discoveries

Future

- Demonstrated ability to upgrade
- Key science questions identified
- Accelerator and experimental upgrade program underway to perform that science

Language

We all have in common basic nuclear properties

A, Z …

But specific to heavy ion physics

v_2 Fourier coefficient of azimuthal anisotropy, "elliptic flow"

R_{AA} 1 if yield = perturbative value from initial parton-parton flux

T Temperature (MeV)

μ_B Baryon chemical potential (MeV) ~ *net* baryon density

η Viscosity (MeV^3)

s Entropy density (MeV^3) ~ "particle" density

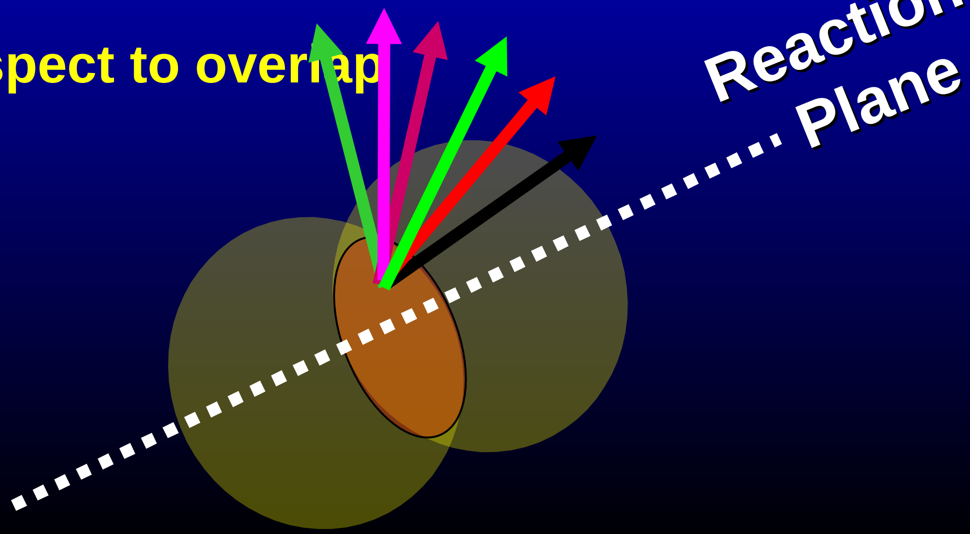
Assertion

In these complicated events, we have (*a posteriori*) control over the event geometry:

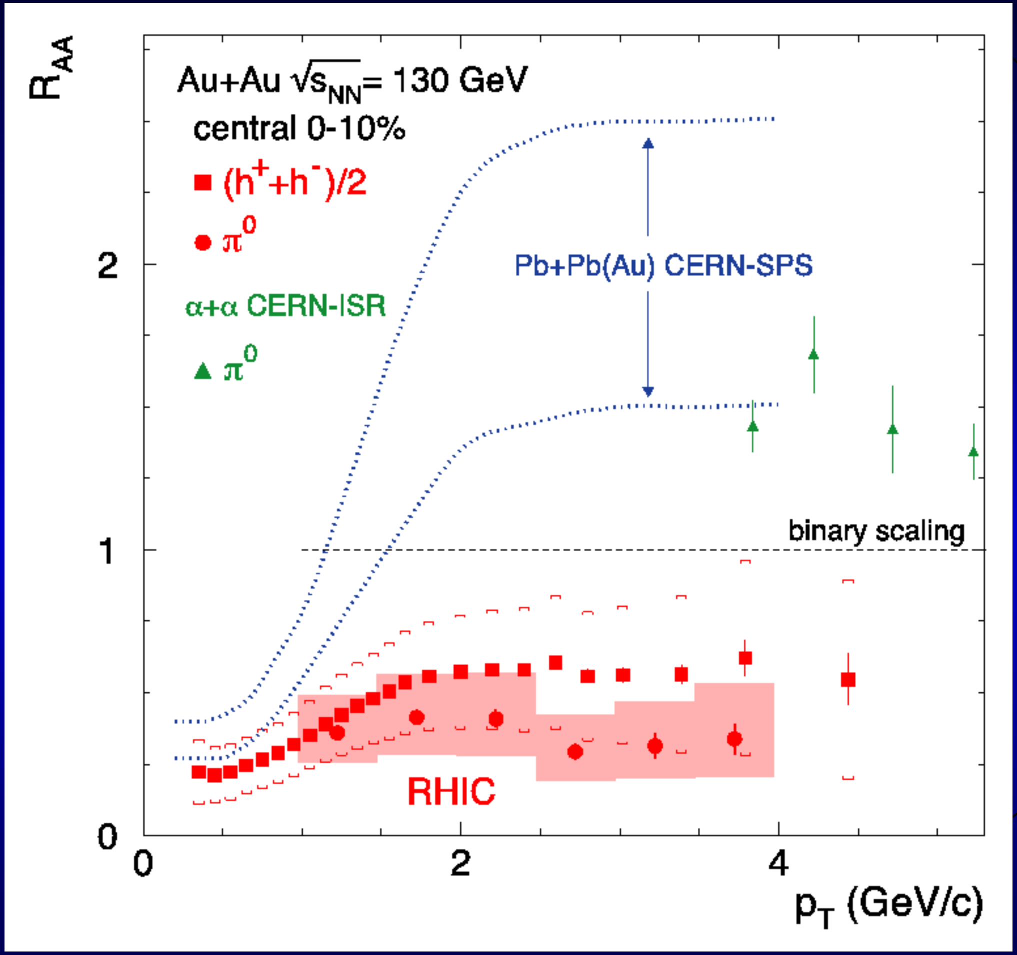
Degree of overlap

"Central" **"Peripheral"**

Orientation with respect to overlap

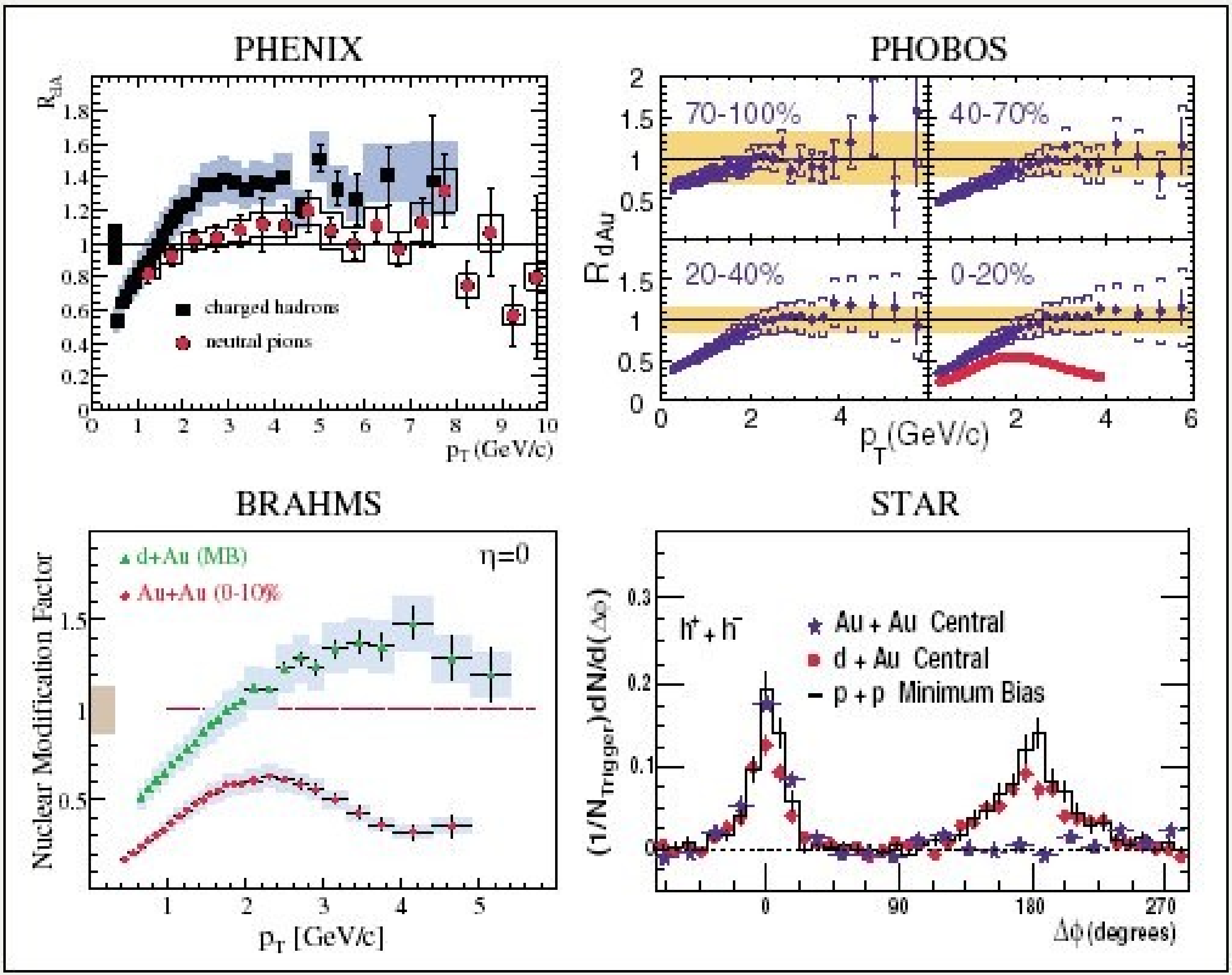


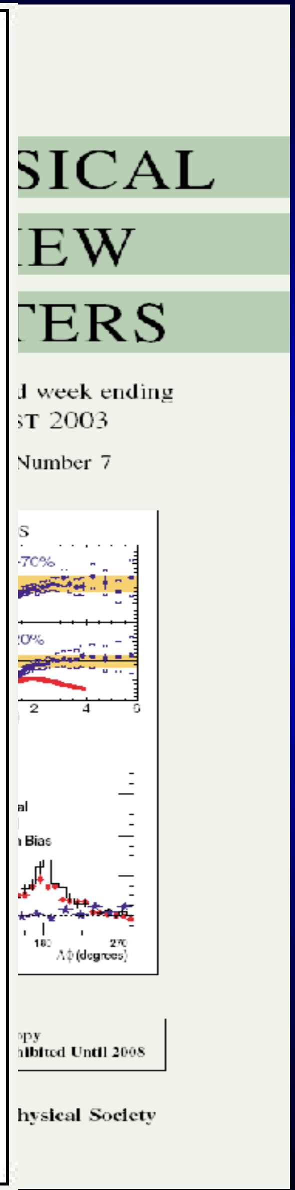
1st milestone: new phenomena



Suppression of high p_t particle production in Au+Au collisions at RHIC

2^{nd} milestone: new form of matter



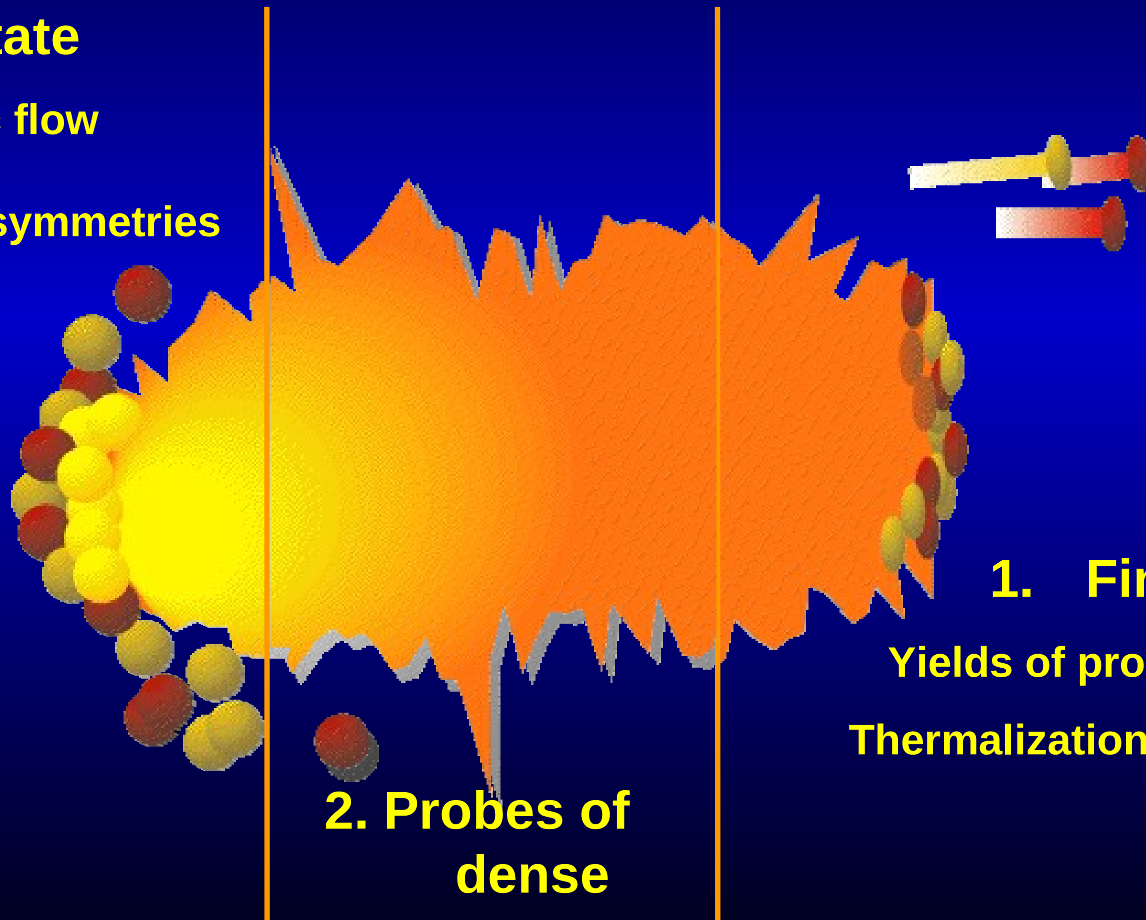


Approach

Will present *sample* of results from various points of the collision process:

3. Initial State

Hydrodynamic flow
from
initial spatial asymmetries



1. Final State

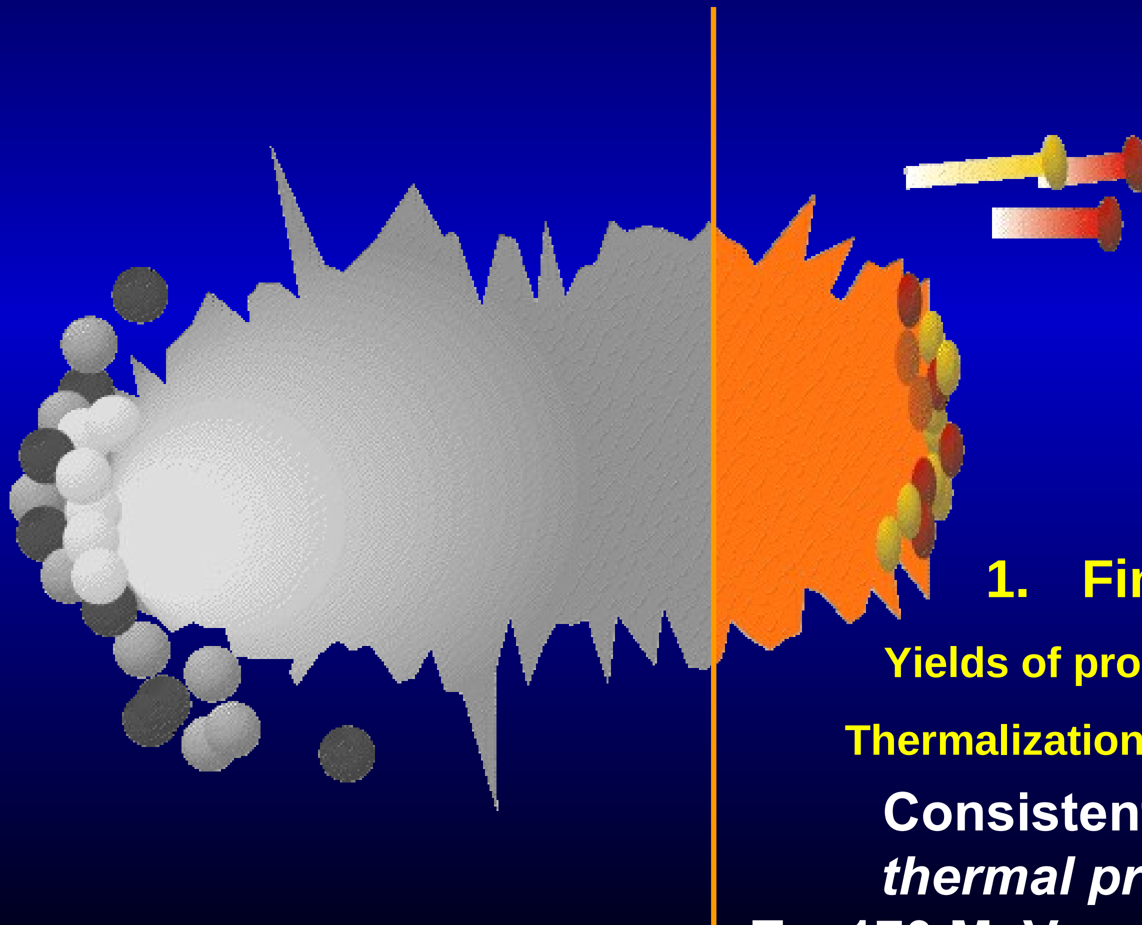
Yields of produced particles

Thermalization, Hadrochemistry

2. Probes of dense matter

1: Final State

Does the huge abundance of final state particles reflect a *thermal* distribution?:



1. Final State

Yields of produced particles

Thermalization, Hadrochemistry

Consistent with *thermal production*

$T \sim 170$ MeV , $\mu_B \sim 30$ MeV

RHIC

Origin of the (Hadronic) Species

- **Apparently:**
  - Assume all distributions described by one temperature T and

$$dn \sim e^{-(E-\mu)/T} d^3 p$$

  one (baryon) chemical potential μ :

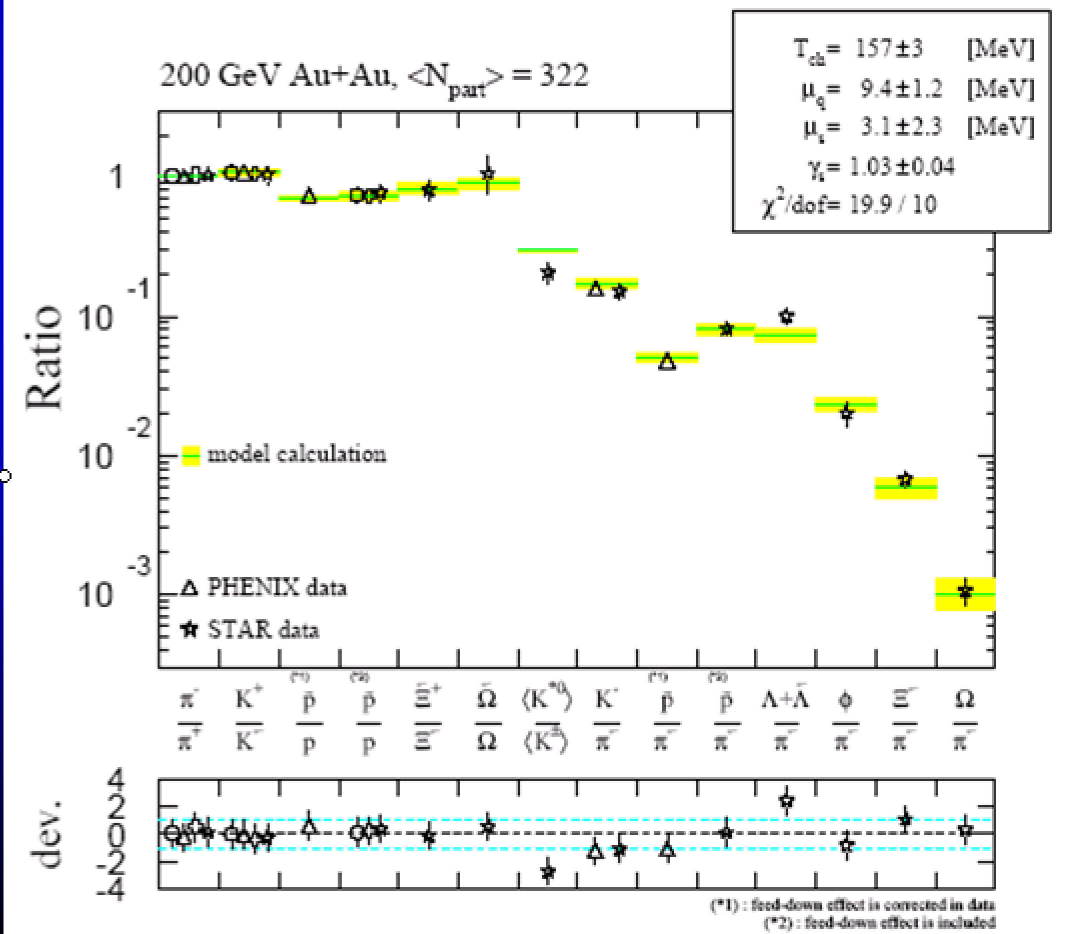
$$\frac{\bar{p}}{p} = \frac{e^{-(E+\mu)/T}}{e^{-(E-\mu)/T}} = e^{-2\mu/T}$$

  - One ratio (e.g., $\bar{p}$ / p) determines μ / T :
  - A second ratio (e.g., K / π) provides T → μ
- **Then predict all other hadronic yields and ratios:**
- **NOTE: Truly thermal implies *No memory (!)***

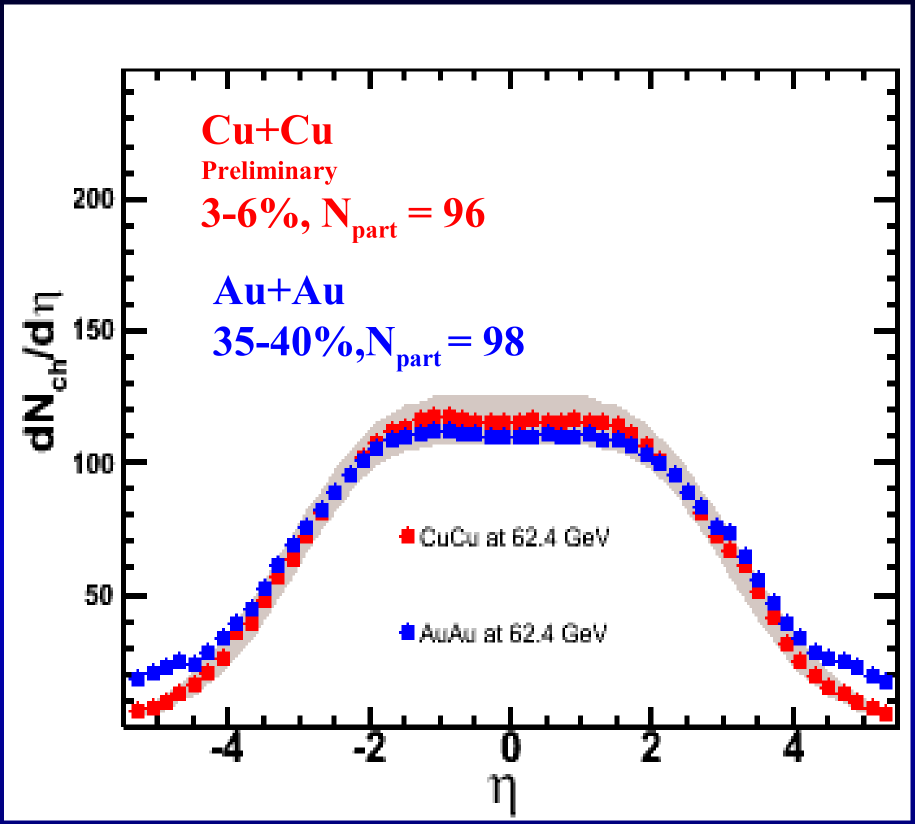
$\pi^{\pm}$, π^0, $K^{\pm}$, $K^{*0}(892)$, K_s^0, η, p, d, ρ^0, φ, Δ,

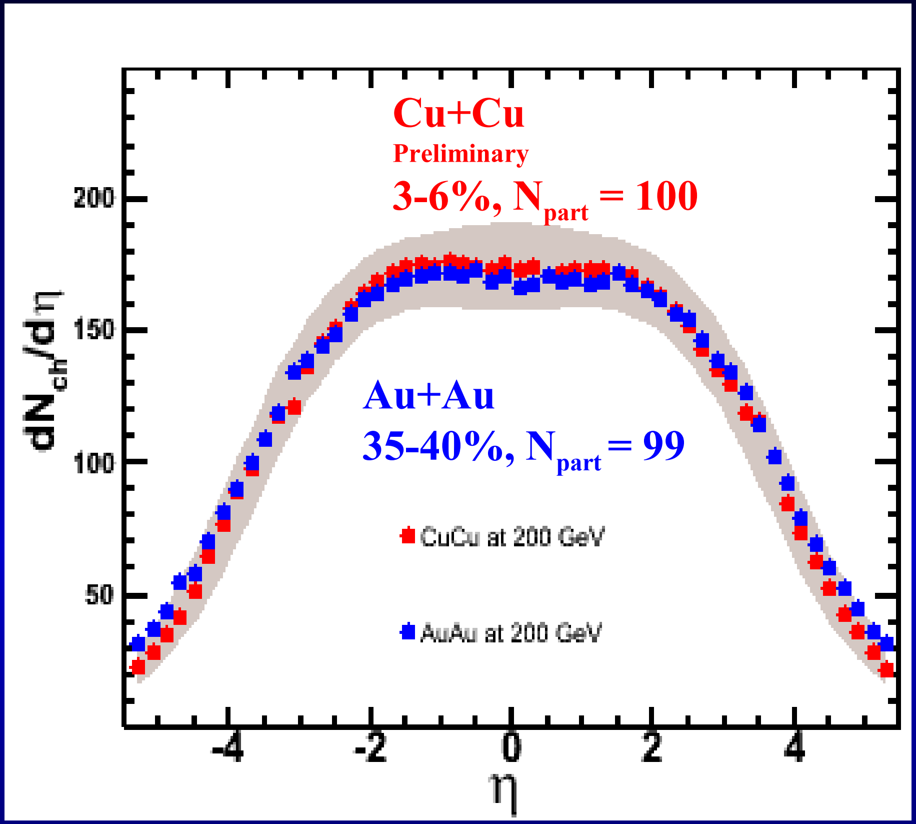
Λ, Σ*(1385), Λ*(1520), $\Xi^{\pm}$, Ω, D^0, $D^{\pm}$, J/Ψ's,

(+ anti-particles) … ➡T ~ 170 MeV ~ 2 x 10^{12} K



PHOBOS: thermal state has no memory

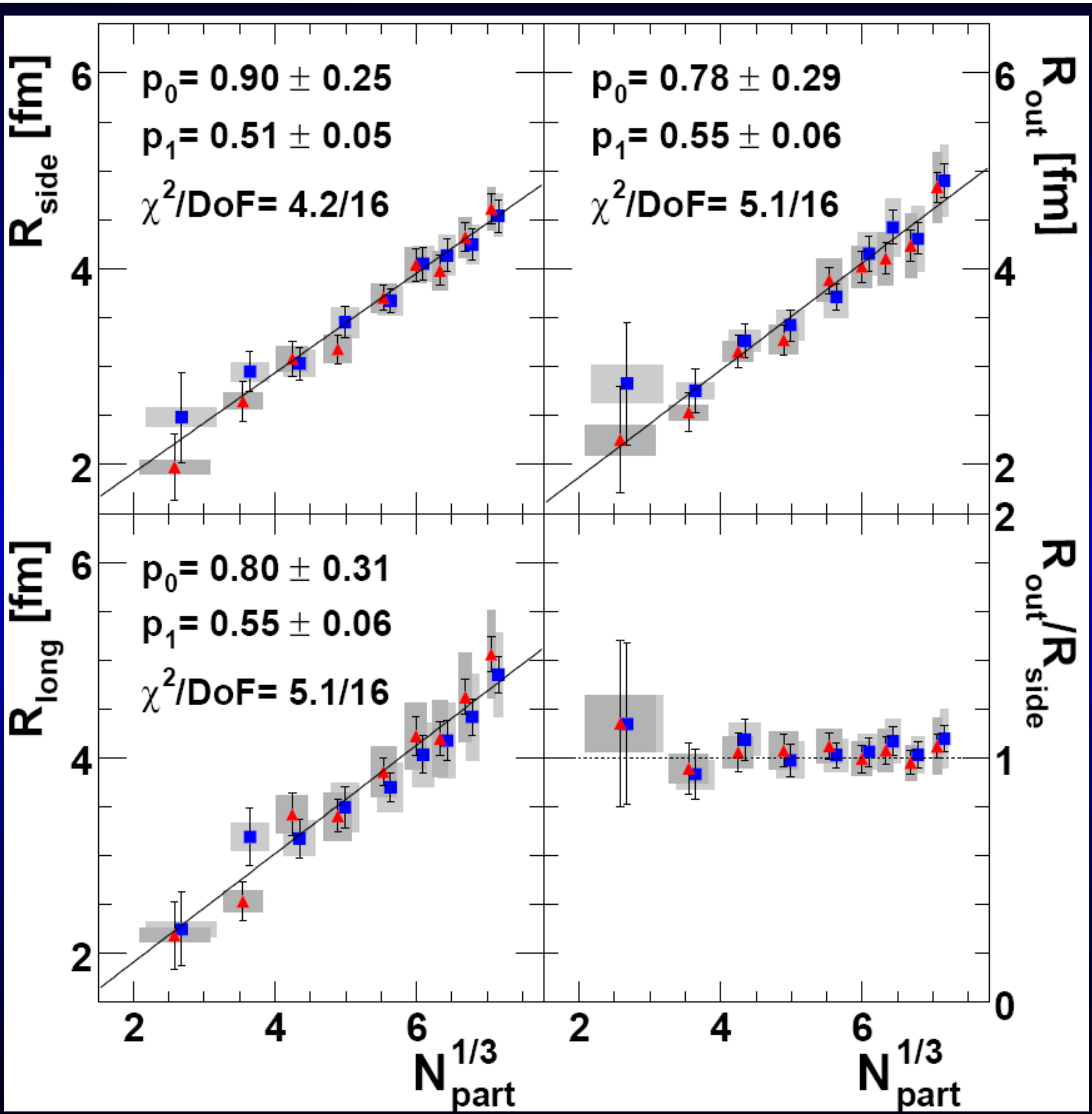




dN/dη very similar for Au+Au and Cu+Cu at same N_{part}

Multiplicity distribution follows the independence hypothesis !

PHENIX HBT: thermal, no memory



HBT radii symmetric depend on N_{part}

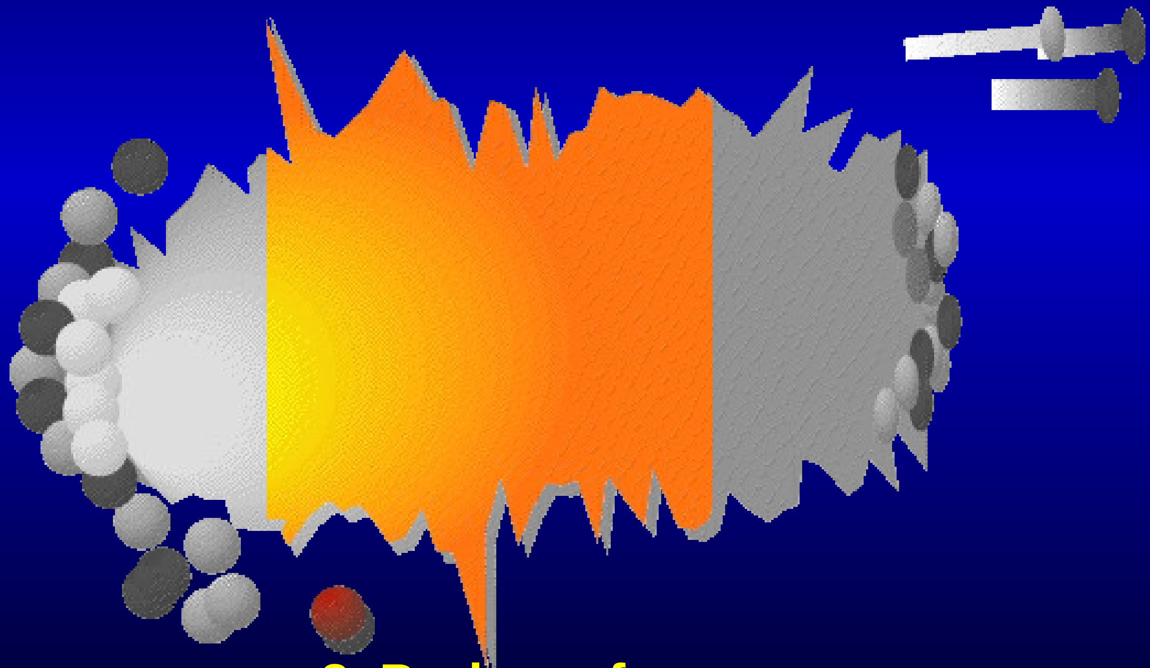
Implies 3d spherical Hubble flow

possible asymmetry in density

2: Probes of Dense Matter

Q. How dense is the matter?

A. Do pQCD Rutherford scattering on deep interior using "auto-generated" probes:



2. Probes of dense matter

Baseline p+p Measurements with pQCD

Consider measurement of π^0's in p+p collisions at RHIC.

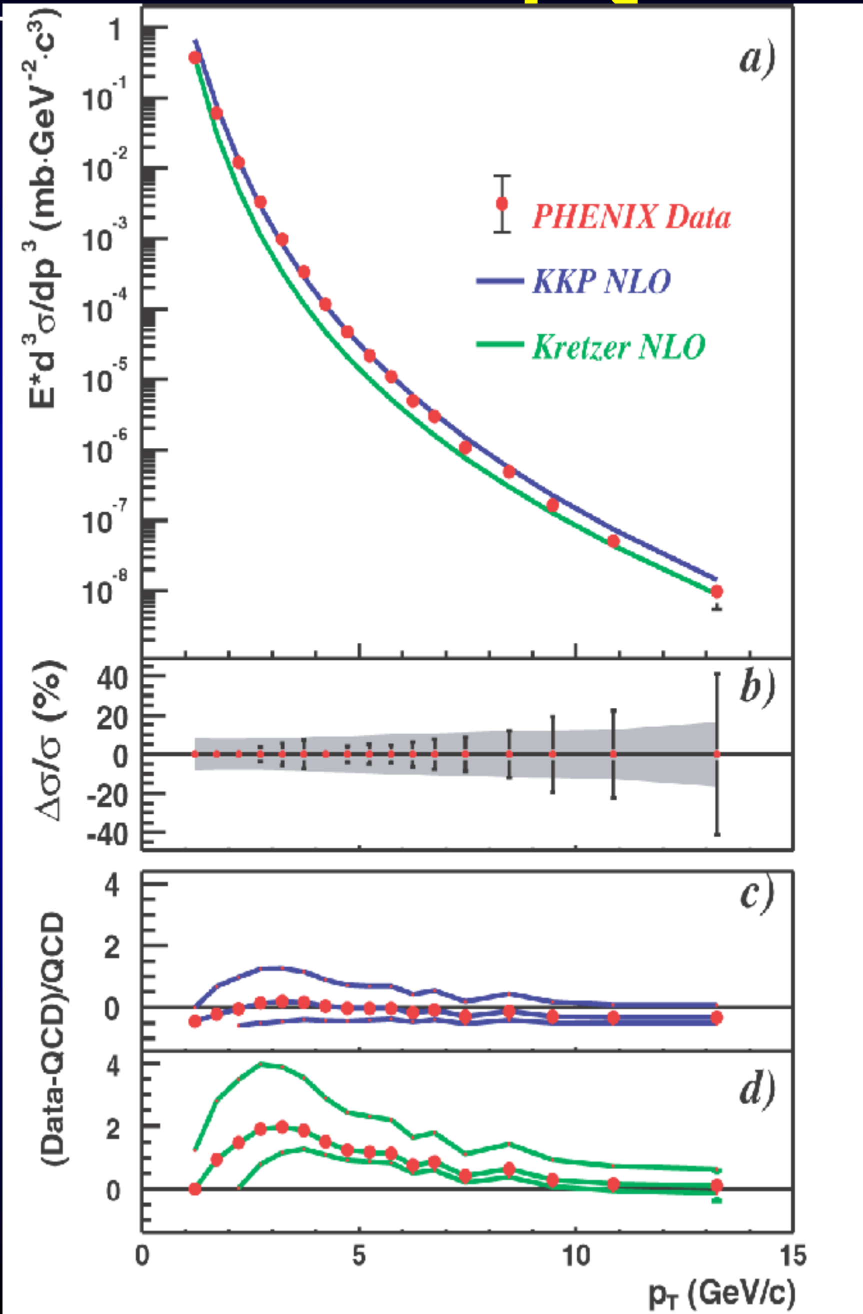
Compare to pQCD calculation

- parton distribution functions, for partons a and b
- measured in DIS, universality

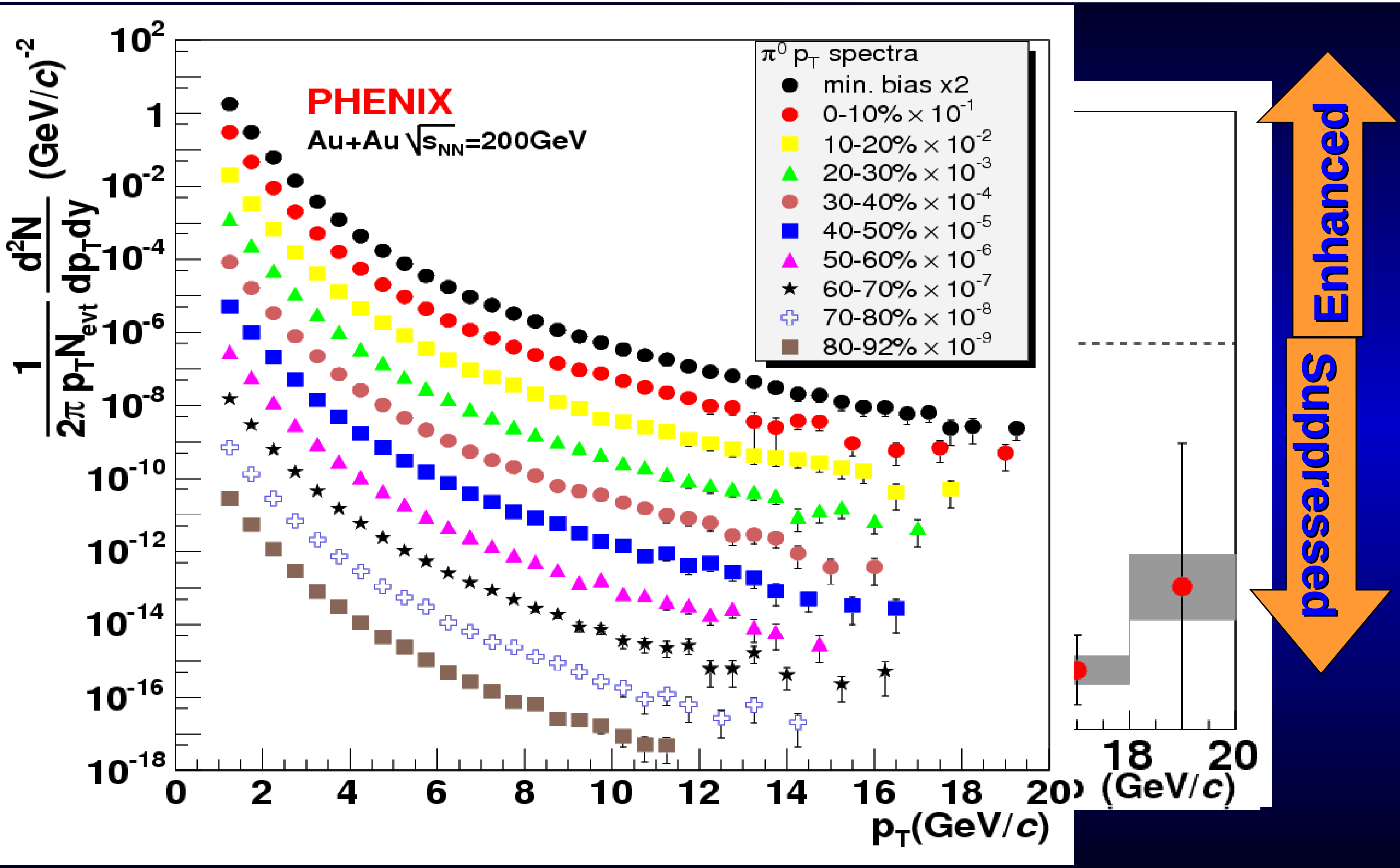
- perturbative cross-section (NLO)
- requires hard scale
- factorization between pdf and cross section

- fragmentation function
- measured in e+e-

Phys. Rev. Lett. 91, 241803 (2003)

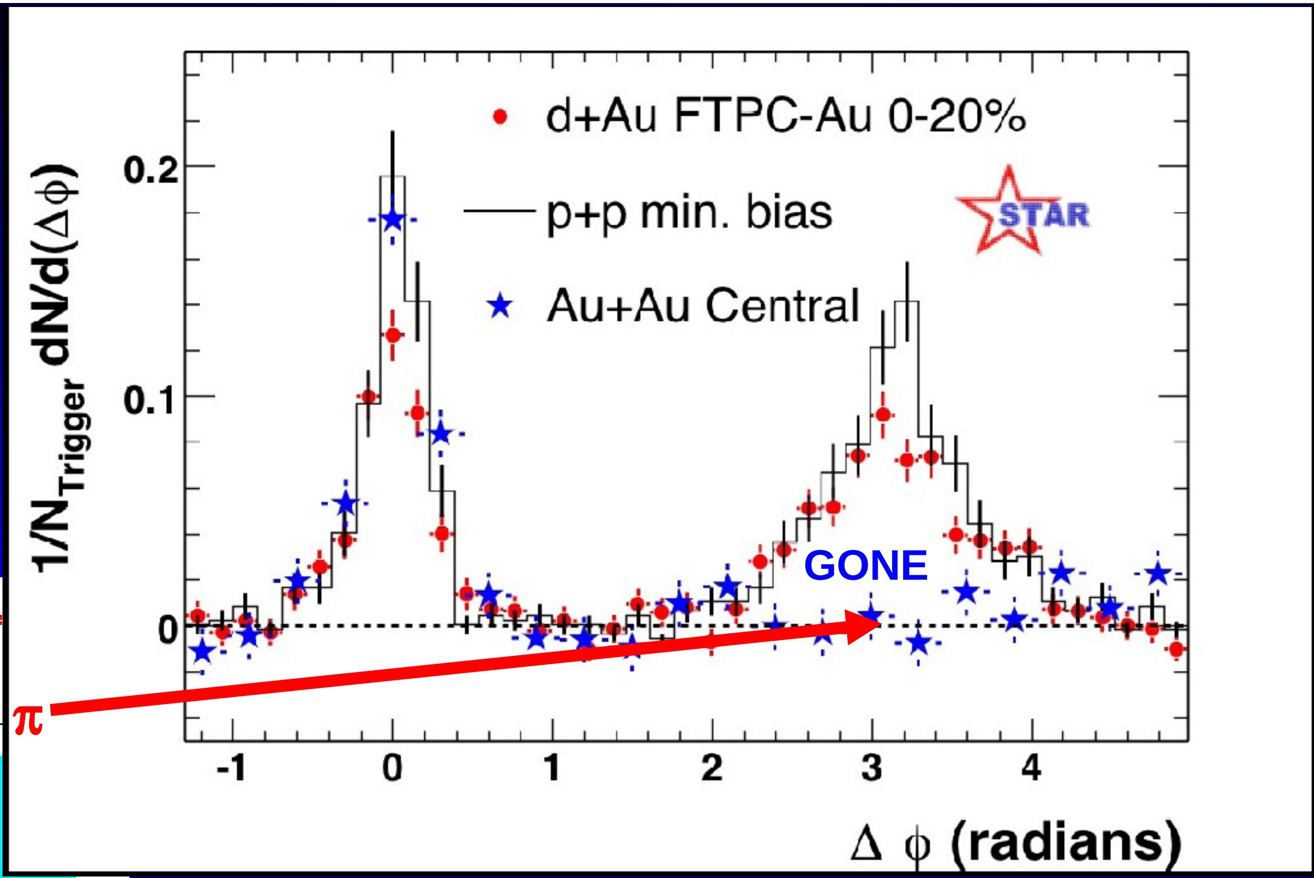


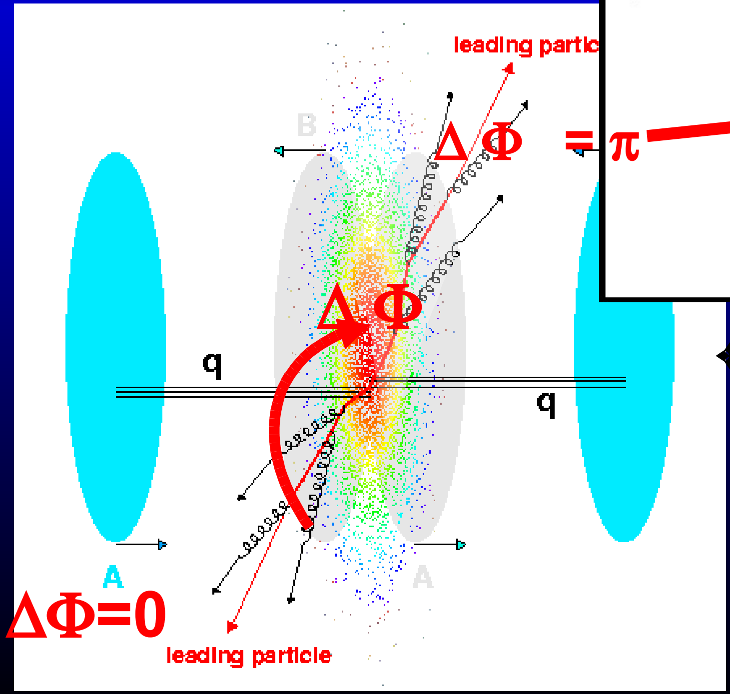
Au+Au: Systematic Suppression Pattern



The Matter is Opaque

- STAR azimuthal correlation function shows ~ complete absence of “away-side” jet

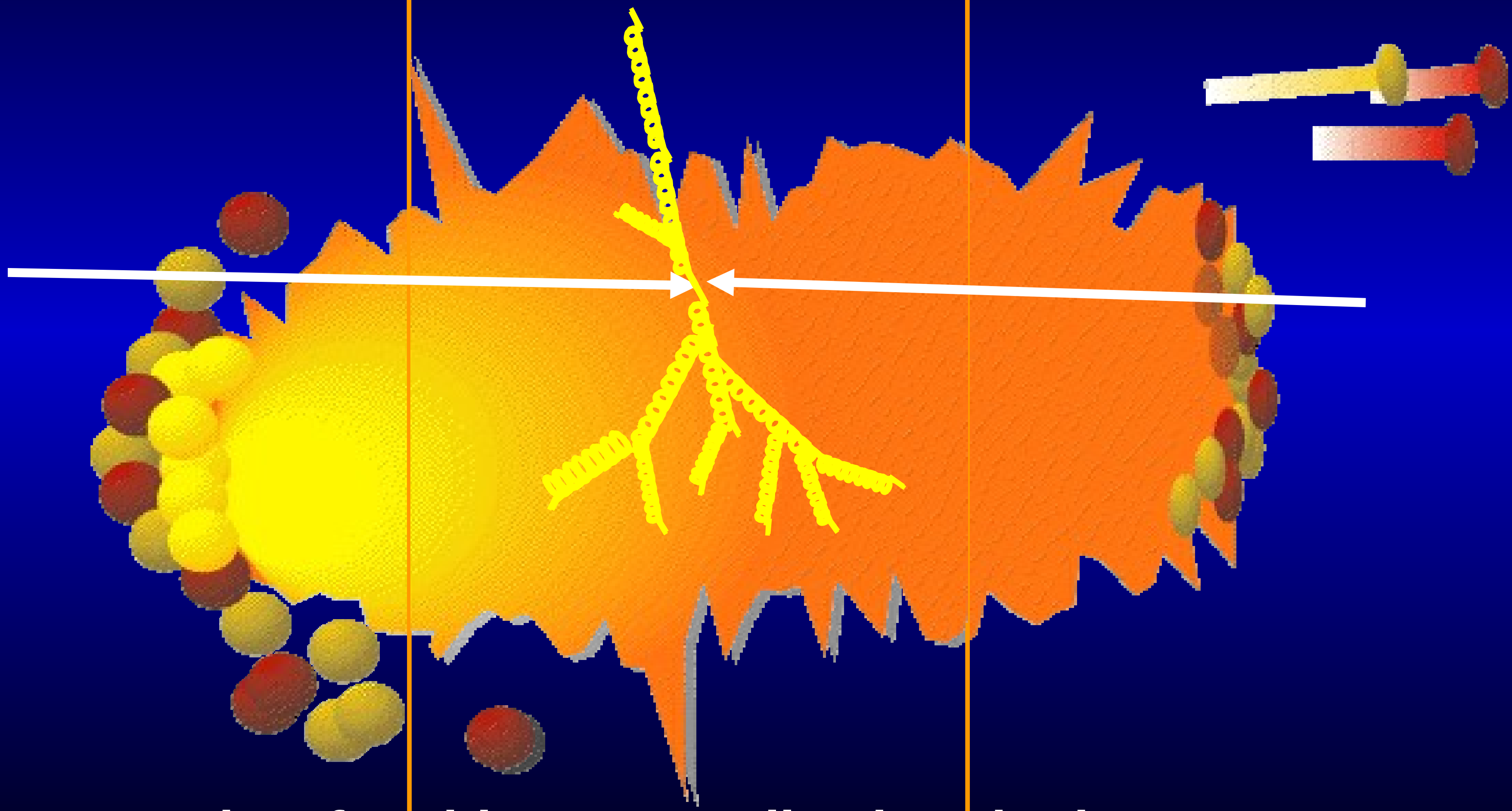




- Partner in hard scatter is *completely absorbed* in the dense medium

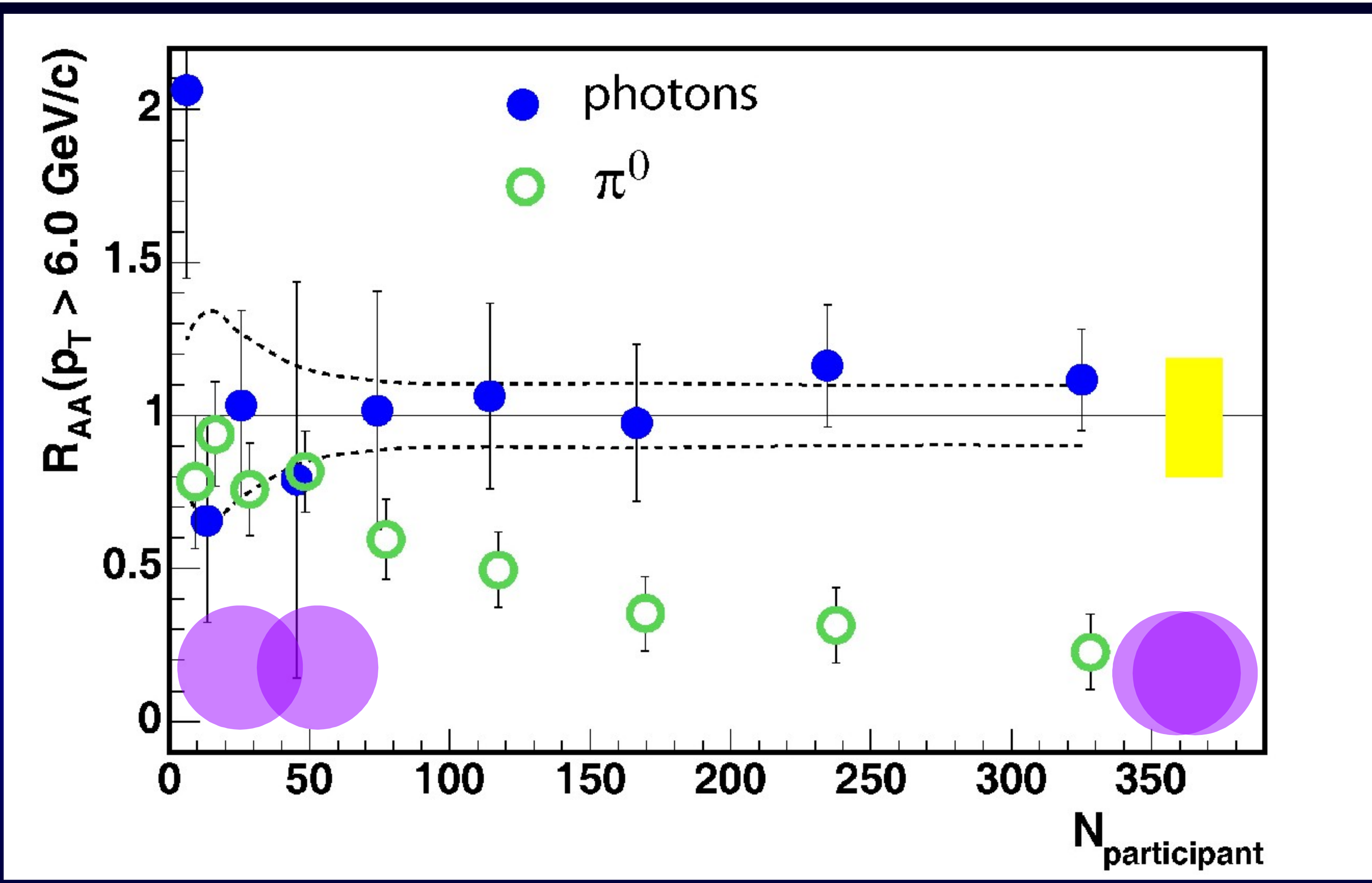
Schematically (Partons)

Scattered partons on the “near side” *lose energy*, but emerge;



those on the “far side” are totally absorbed

Control: Photons shine, Pions don’t

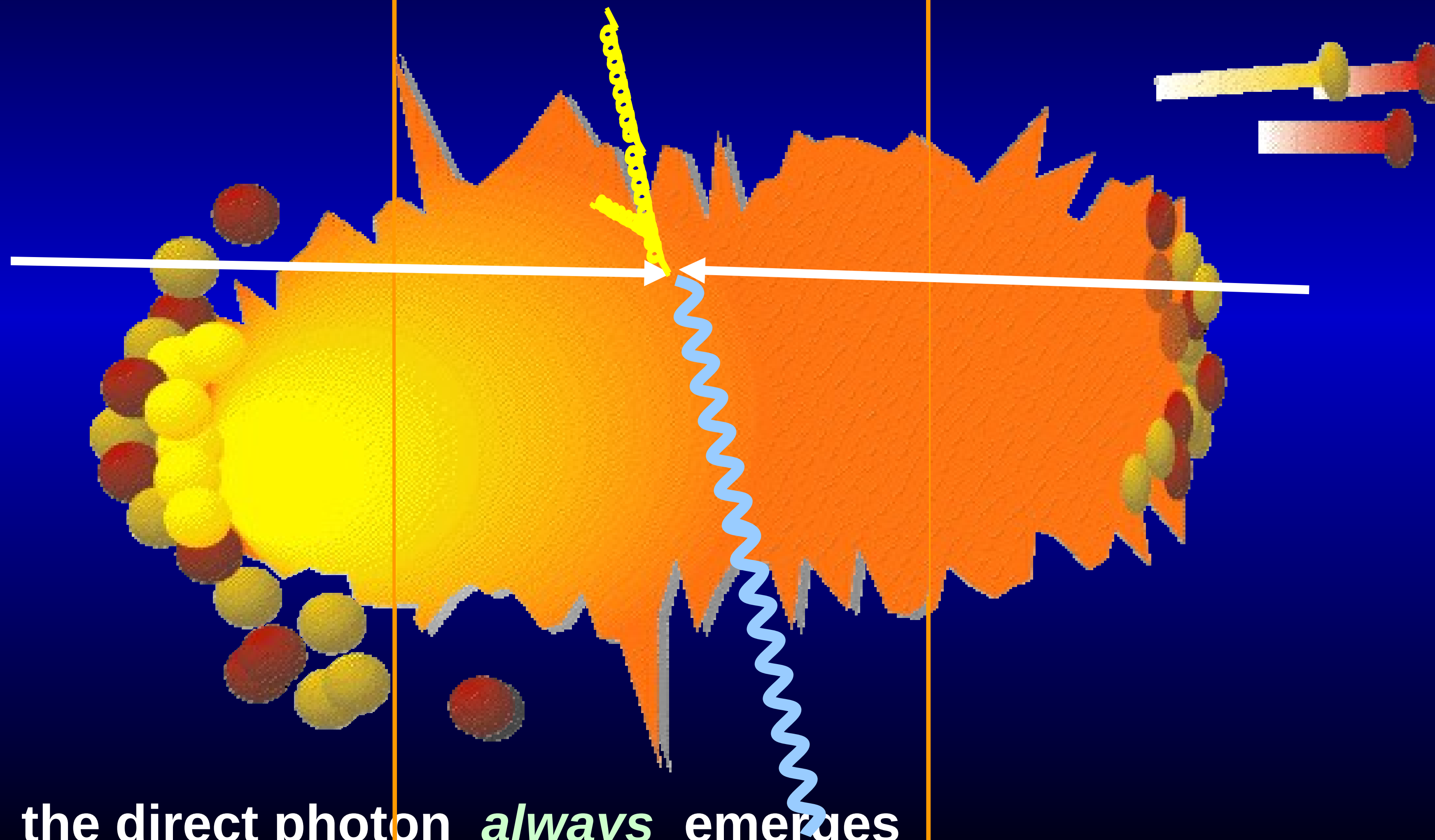


Direct photons are *not* inhibited by hot/dense medium

Rather: *shine* through consistent with pQCD

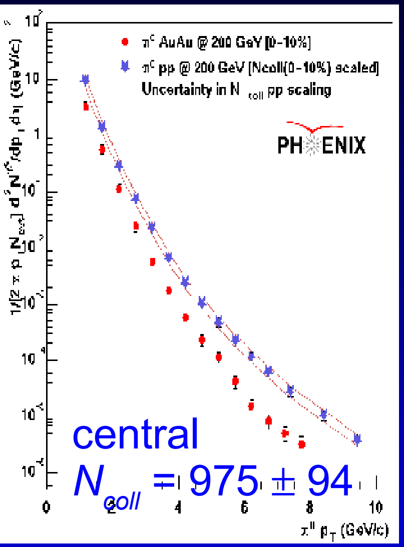
Schematically (Photons)

Scattered partons on the "near side" ***lose energy***, **but emerge;**

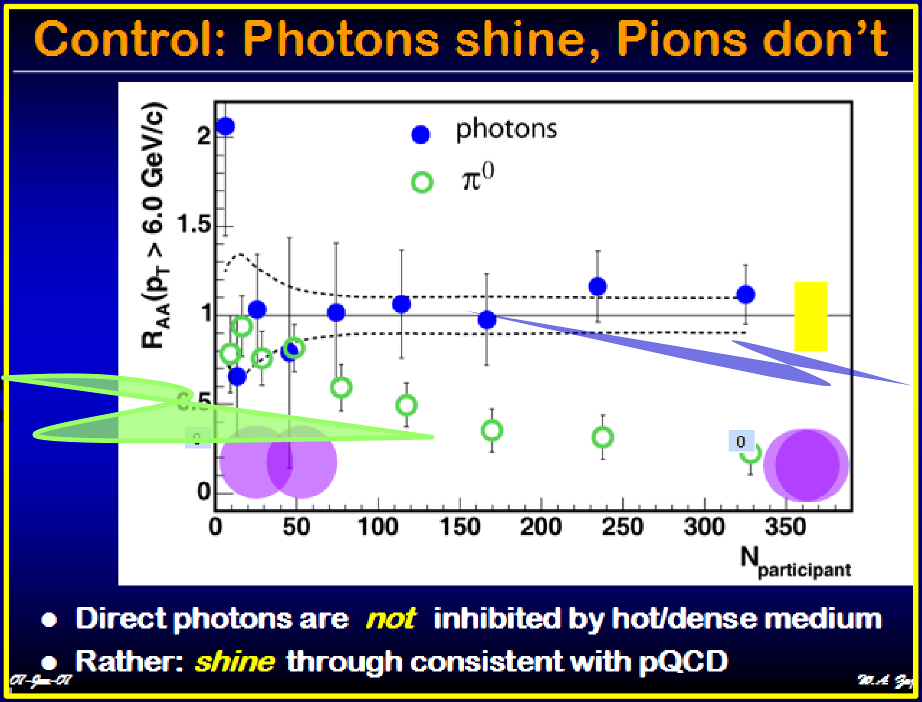


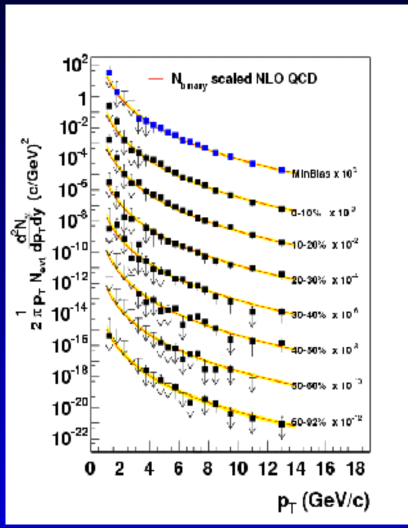
the direct photon *always* emerges

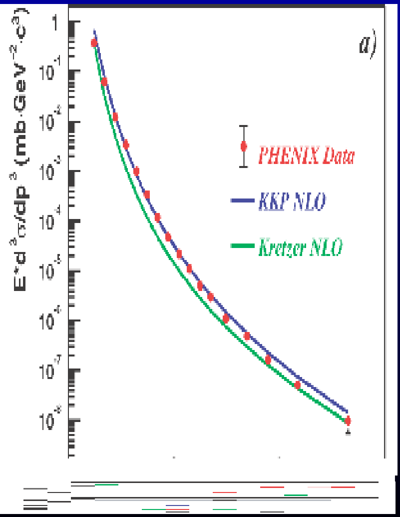
Precision Probes

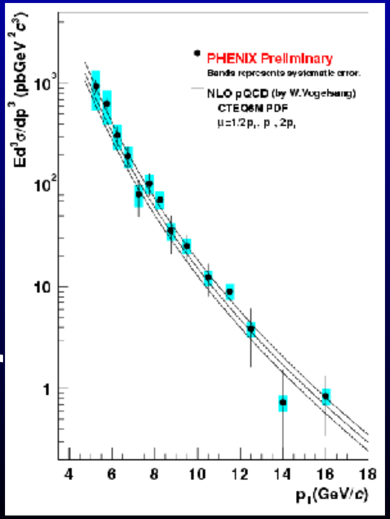


This one figure encodes
rigorous control of systematics









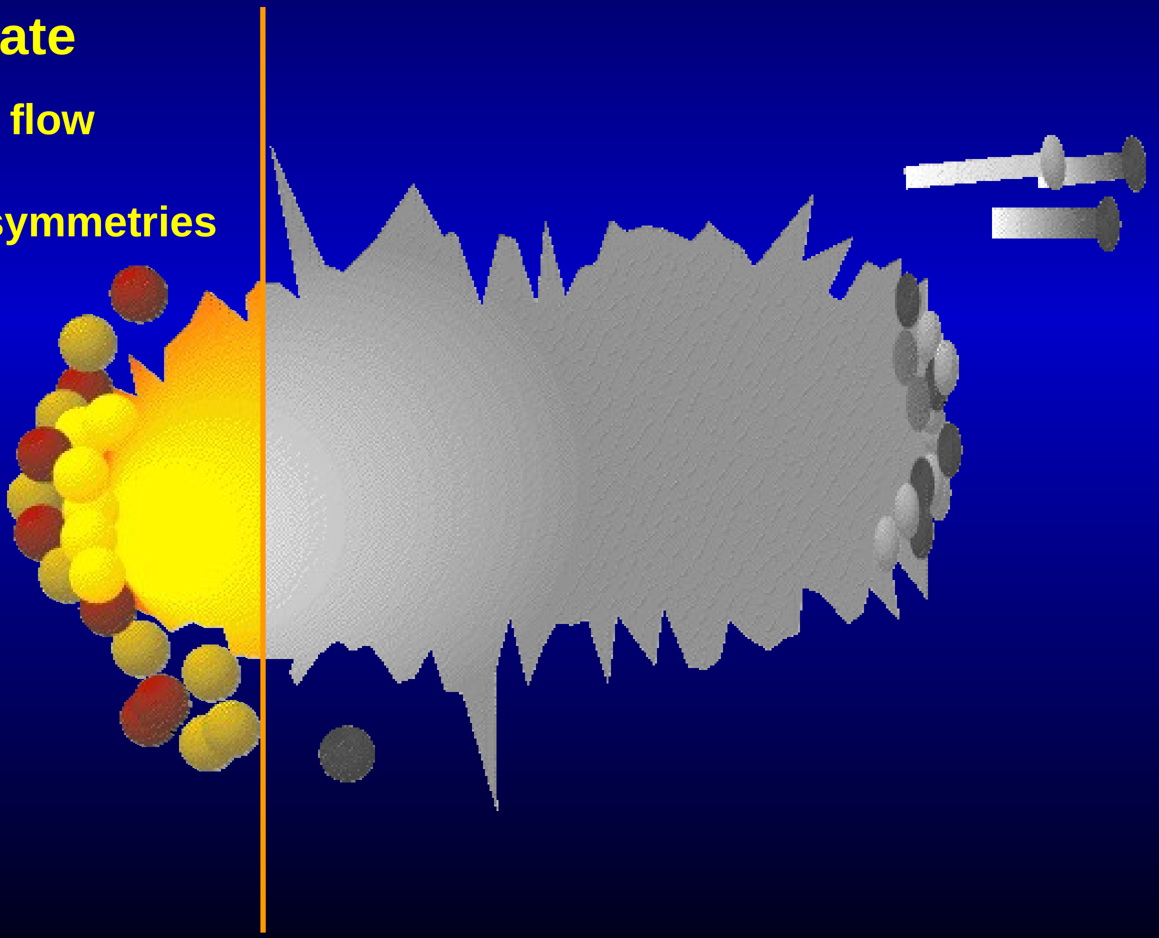
in four different measurements over
many orders of magnitude

3: Initial State

How are the initial state densities and asymmetries imprinted on the detected distributions?

3. Initial State

Hydrodynamic flow from initial spatial asymmetries



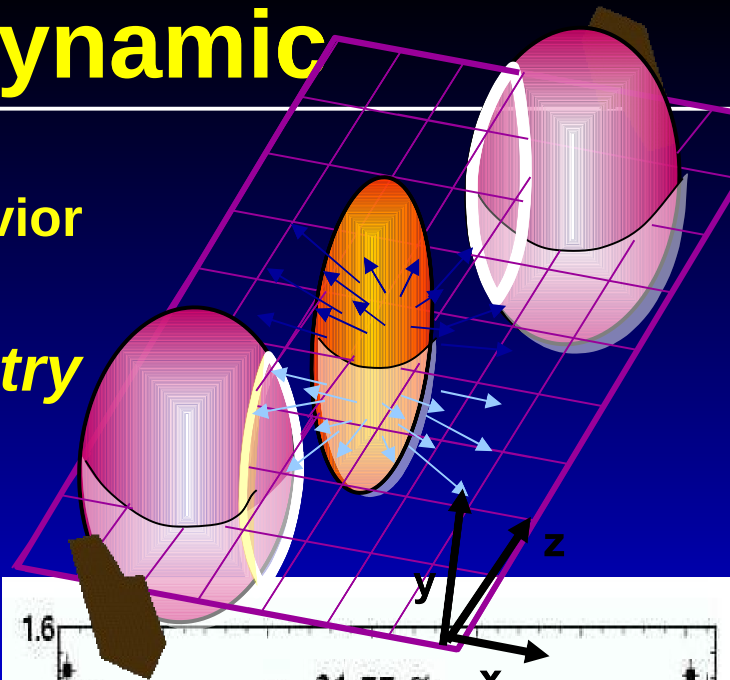
Motion Is Hydrodynamic

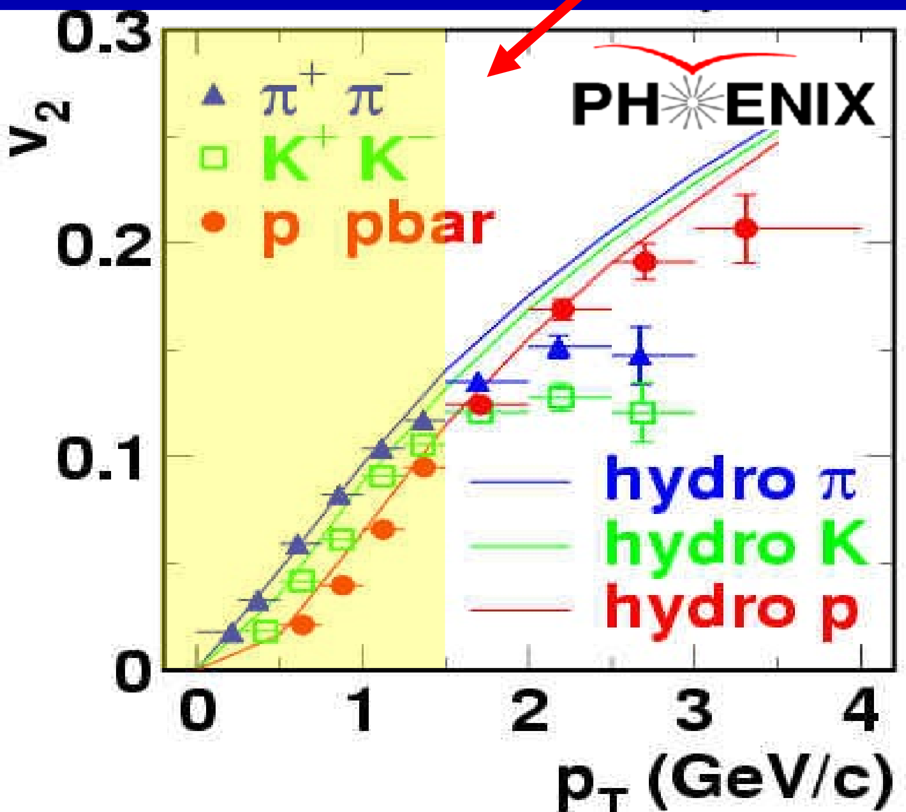
When does thermalization occur?

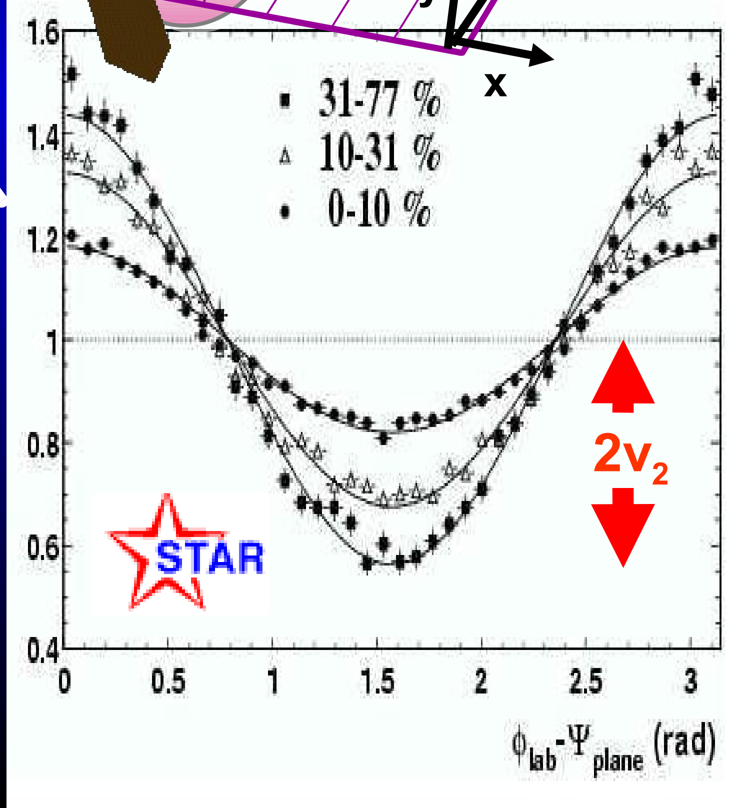
Strong evidence that final state bulk behavior reflects the initial state geometry

Because the initial *azimuthal asymmetry* persists in the final state

$dn/d\phi \sim 1 + 2\, v_2(p_T) \cos(2\phi) + \ldots$



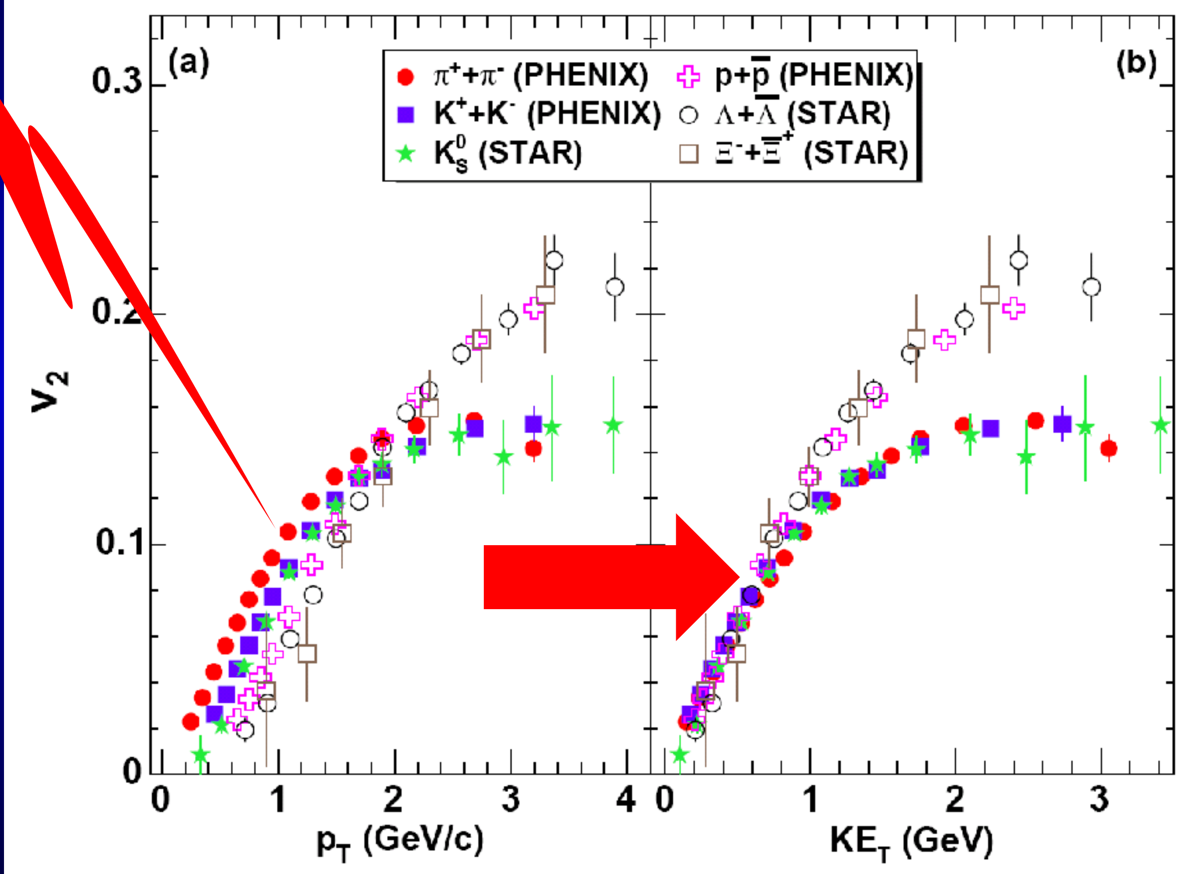




The "Flow" Is ~*Perfect*

The "fine structure" $v_2(p_T)$ for different mass particles shows good agreement with perfect fluid hydrodynamics

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



Roughly: $\partial_\nu T^{\mu\nu} = 0 \rightarrow$ Work-energy theorem

$$\rightarrow \int \nabla P \, d(vol) = \Delta E_K \cong m_T - m_0 \equiv \Delta KE_T$$

3rd milestone: Top Physics Story 2005

Cím http://www.aip.org/pnu/2005/split/757-1.html

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Number 757 #1, December 7, 2005 by Phil Schewe and Ben Stein

The Top Physics Stories for 2005

At the Relativistic Heavy Ion Collider (RHIC) on Long Island, the four large detector groups agreed, for the first time, on a consensus interpretation of several year's worth of high-energy ion collisions: the fireball made in these collisions -- a sort of stand-in for the primordial universe only a few microseconds after the big bang -- was not a gas of weakly interacting quarks and gluons as earlier expected, but something more like a liquid of strongly interacting quarks and gluons (PNU 728).

Other top physics stories for 2005 include, in general chronological order of their appearance throughout the year, the following:

the arrival of the Cassini spacecraft at Saturn and the successful landing of the Huygens probe on the moon Titan (PNU 716);

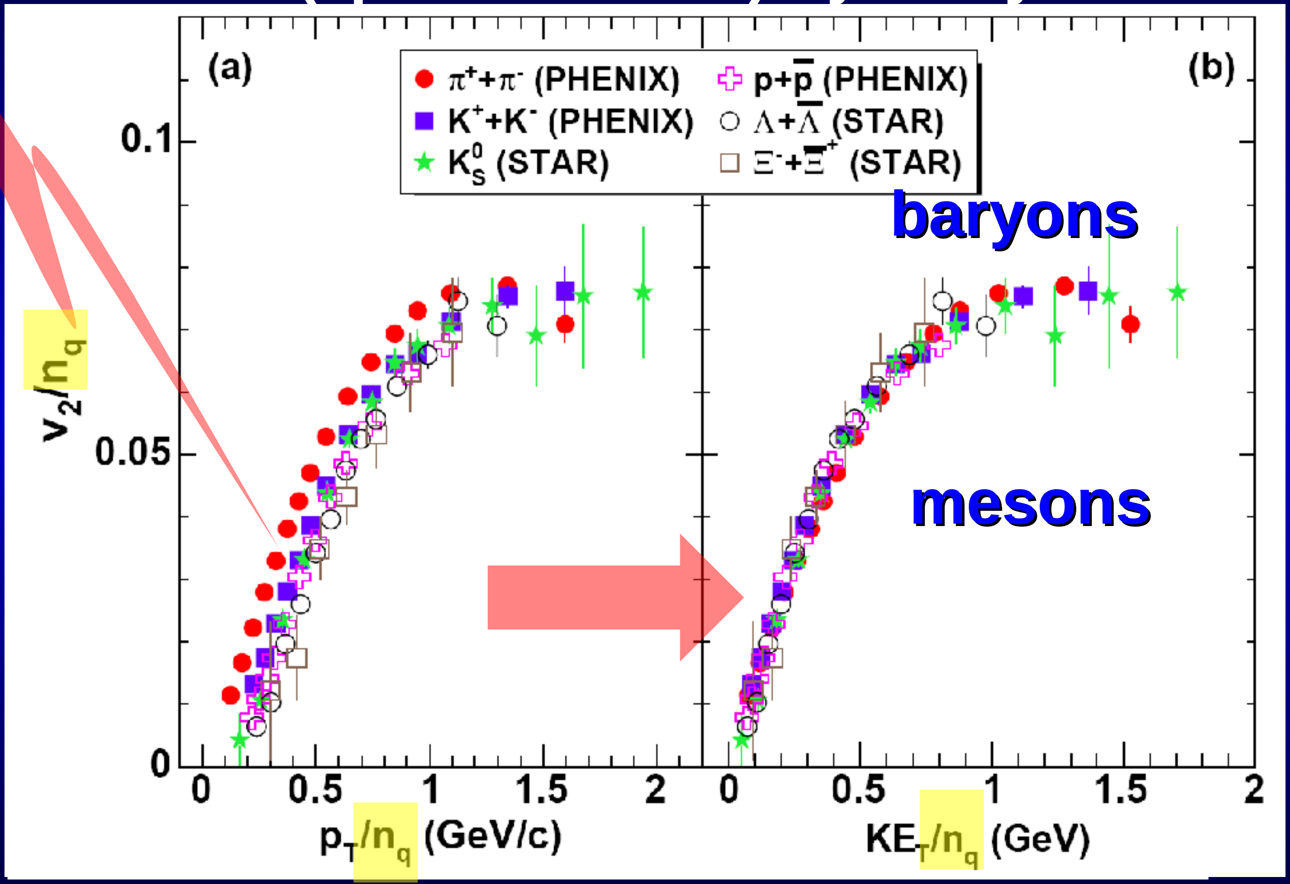
the development of lasing in silicon (Nature 17 February);

http://arxiv.org/abs/nucl-ex/0410003

PHENIX White Paper: 750+ citations

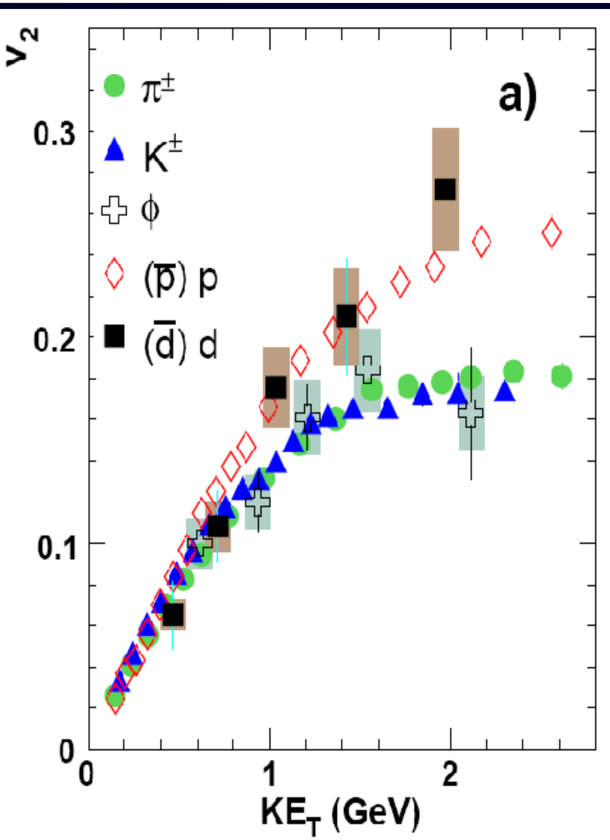
The “Flow” Knows Quarks

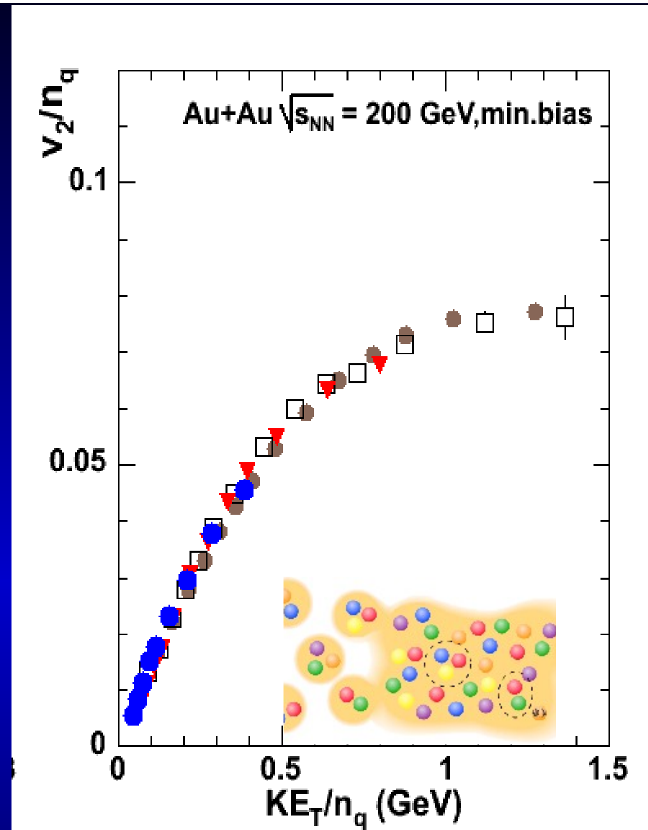
The “fine structure” $v_2(p_T)$ for different mass particles shows good agreement with ideal (“perfect fluid”) hydrodynamics

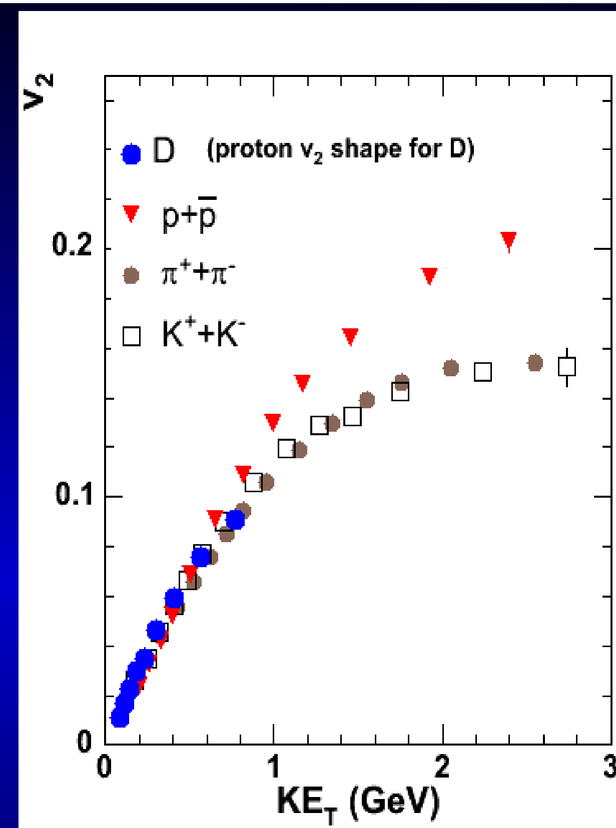


Scaling flow parameters by quark content n_q resolves meson-baryon separation of final state hadrons

4th Milestone: A fluid of quarks







v_2 for the φ follows that of other mesons

$$v_2^{hadron}(KE_T^{hadron}) \approx n v_2^{quark}(KE_T^{quark})$$
$$KE_T^{hadron} \approx n KE_T^{quark}$$

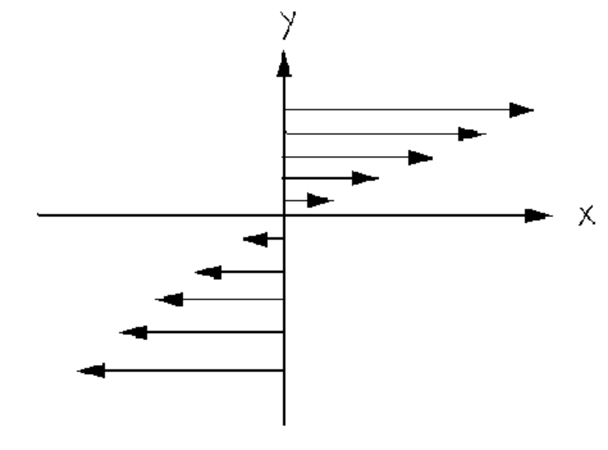
v_2 for the D follows that of other mesons

Strange and even charm quarks participate in the flow

Viscosity Primer

- **Remove your organic prejudices**
  - ***Don't* equate viscous with "sticky" !**
- **Think instead of a not-quite-ideal fluid:**
  - **"not-quite-ideal" ≡ "supports a shear stress"**
  - **Viscosity η then defined as**

$$\frac{F_x}{A} = -\eta \frac{\partial v_x}{\partial y}$$



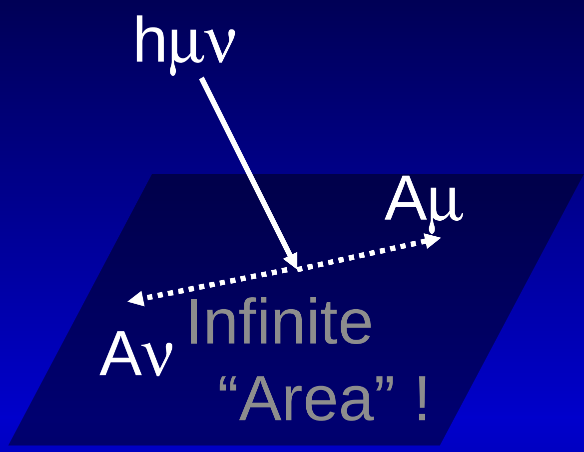
  - **Dimensional estimate:**

$$\eta \approx (momentum\ density) \times (mean\ free\ path)$$
$$\approx n\,\bar{p}\,mfp = n\,\bar{p}\,\frac{1}{n\sigma} = \frac{\bar{p}}{\sigma}$$

- ***small* viscosity ➡ *Large* cross sections**
- ***Large* cross sections ➡ *strong* couplings**
- ***Strong* couplings ➡ perturbation theory *difficult* !**

The (Assumed) Connection

- ***Exploit*** **Maldacena's "D-dimensional strongly coupled gauge theory ⇔ (D+1)-dimensional stringy gravity"**
- ***Thermalize*** **with massive black brane**



- ***Calculate*** **viscosity η = "Area"/16πG**
- ***Normalize*** **by entropy (density) s = "Area" / 4G**
- ***Dividing out*** **the infinite "areas" :**

$$\frac{\eta}{s} = \left(\frac{\hbar}{k}\right)\frac{1}{4\pi}$$

- ***Conjectured*** **to be a lower bound "*for all relativistic quantum field theories at finite temperature and zero chemical potential*".**
- ***See*** **"*Viscosity in strongly interacting quantum field theories from black hole physics*", P. Kovtun, D.T. Son, A.O. Starinets, Phys.Rev.Lett.94:111601, 2005, hep-th/0405231**

How Perfect is "Perfect" ? Measure η/s !

Damping (flow, fluctuations, heavy quark motion) ~ η/s

FLOW: *Has the QCD Critical Point Been Signaled by Observations at RHIC?*, R. Lacey *et al*., Phys.Rev.Lett.98:092301,2007 (nucl-ex/0609025)

$$\frac{\eta}{s} = (1.1 \pm 0.2 \pm 1.2)\frac{1}{4\pi}$$

The Centrality dependence of Elliptic flow, the Hydrodynamic Limit, and the Viscosity of Hot QCD, H.-J. Drescher *et al*., (arXiv:0704.3553)

$$\frac{\eta}{s} = (1.9 - 2.5)\frac{1}{4\pi}$$

FLUCTUATIONS: *Measuring Shear Viscosity Using Transverse Momentum Correlations in Relativistic Nuclear Collisions*, S. Gavin and M. Abdel-Aziz, Phys.Rev.Lett.97:162302,2006 (nucl-th/0606061)

$$\frac{\eta}{s} = (1.0 - 3.8)\frac{1}{4\pi}$$

C H A R M !

DRAG, FLOW: *Energy Loss and Flow of Heavy Quarks in Au+Au Collisions at $\sqrt{s_{NN}}$ = 200 GeV* (PHENIX Collaboration), A. Adare *et al*., Phys.Rev.Lett.98:172301,2007 (nucl-ex/0611018)

$$\frac{\eta}{s} = (1.3 - 2.0)\frac{1}{4\pi}$$

Milestone # 5: Perfection at limit!

All "realistic" hydrodynamic calculations for RHIC fluids to date have assumed zero viscosity

$\eta = 0$ → "perfect fluid"

But there is a (conjectured) quantum limit:

$$\eta \geq \frac{\hbar}{4\pi}(Entropy\ Density) \equiv \frac{\hbar}{4\pi} s$$

"*A Viscosity Bound Conjecture*", P. Kovtun, D.T. Son, A.O. Starinets, hep-th/0405231

Where do "ordinary" fluids sit wrt this limit?

$(4\pi)\ \eta/s > 10$!

RHIC's perfect fluid

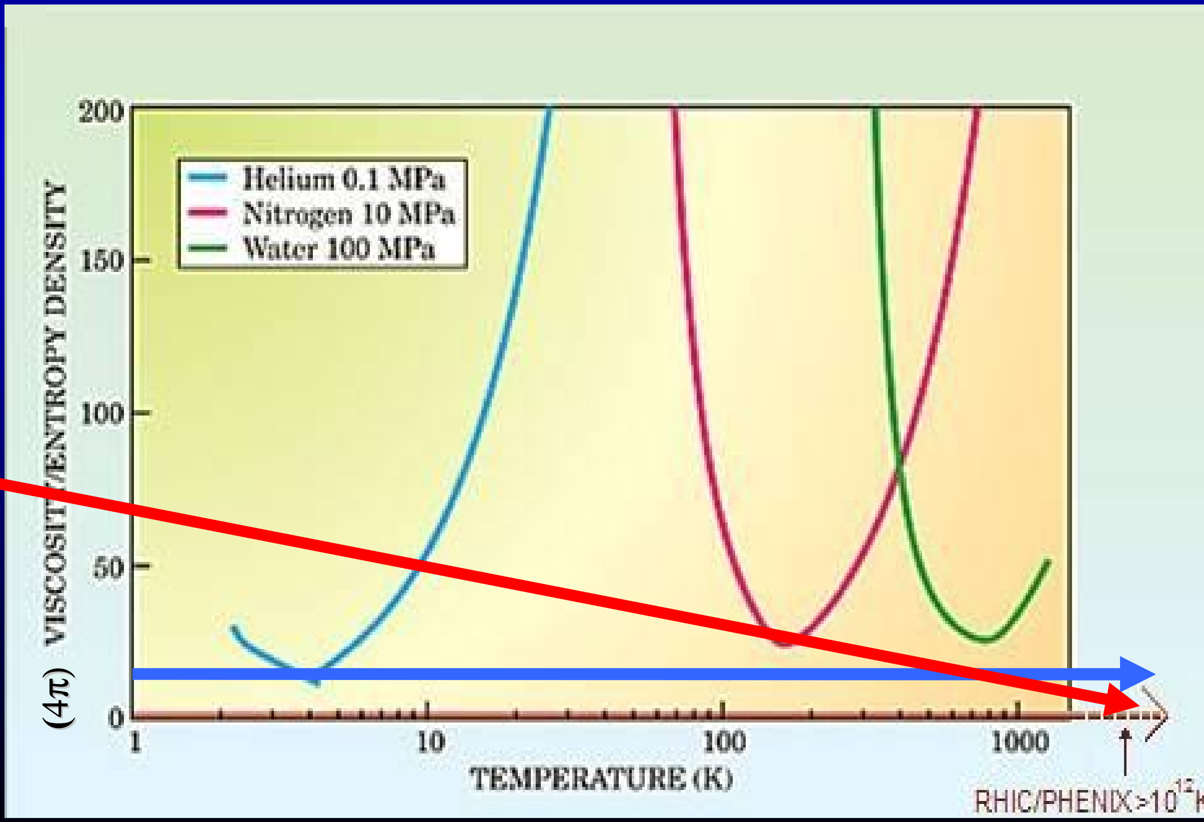
$(4\pi)\ \eta/s \sim 1$

on this scale:

The hottest

($T > 2$ Terakelvin)

and the most perfect fluid ever made…



The Primacy of QCD

- **While the (conjectured) bound**

  is a purely quantum mechanical result . . .

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

- ***It was derived in and motivated by the Anti-de Sitter space / Conformal Field Theory correspondence***

- **Weak form:**
  - **"Four-dimensional *N* =4 supersymmetric SU(N_c) gauge theory is equivalent to IIB string theory with AdS_5 x S^5 boundary conditions."**

    (*The Large N limit of superconformal field theories and supergravity*, J. Maldacena, Adv. Theor. Math. Phys. 2, 231, 1998 hep-th/9711200)

- **Strong form:**
  - **"Hidden within *every* non-Abelian gauge theory, even within the weak and strong nuclear interactions, is a theory of quantum gravity."**

    (*Gauge/gravity duality*, G.T. Horowitz and J. Polchinski, gr-qc/0602037)

- **Strongest form: *Only with QCD can we explore experimentally these fascinating connections over the full range of the coupling constant to study QGP***

≡ Quantum Gauge Phluid

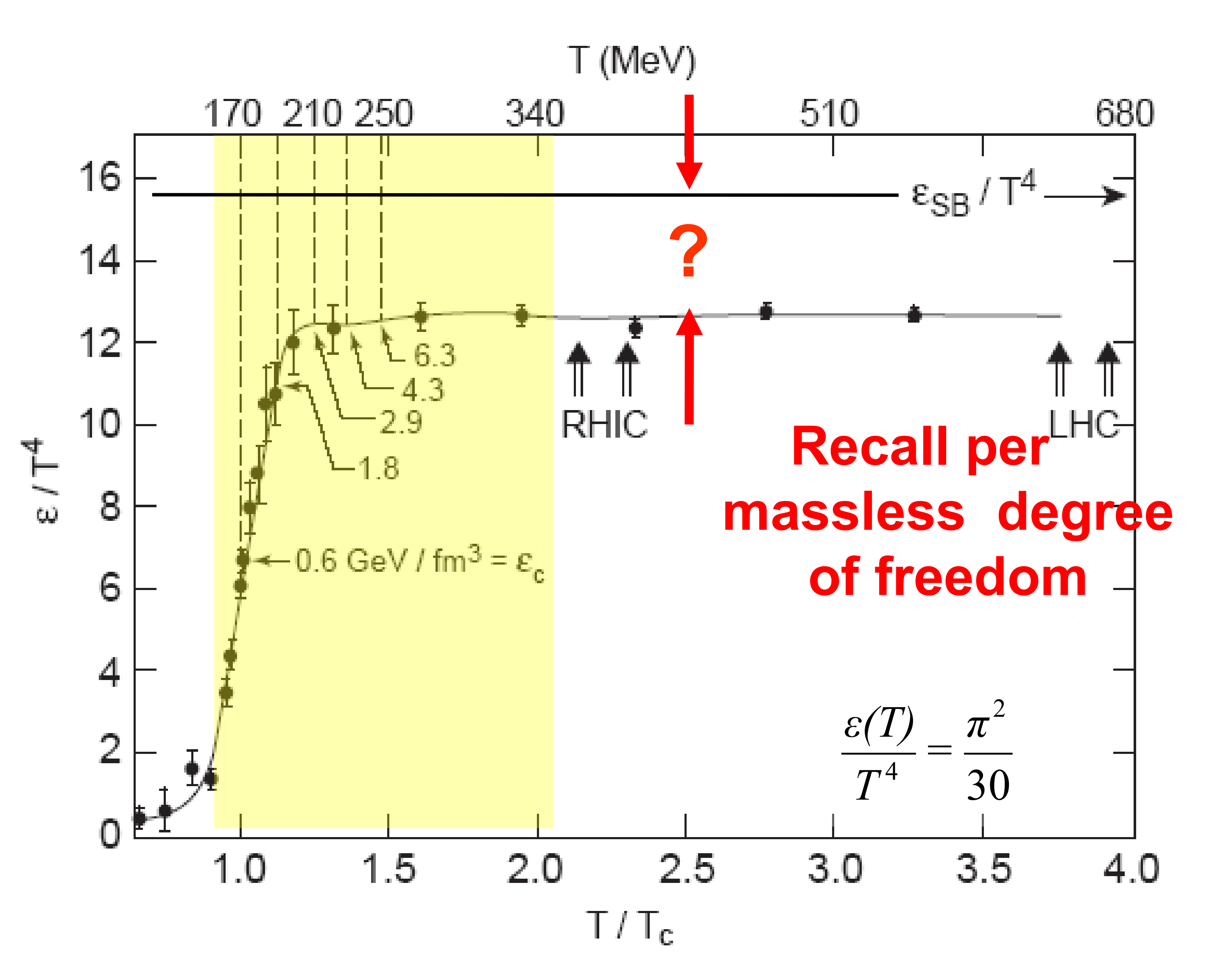
RHIC and the Phase "Transition"

The lattice tells us that collisions at RHIC map out the *interesting* region from

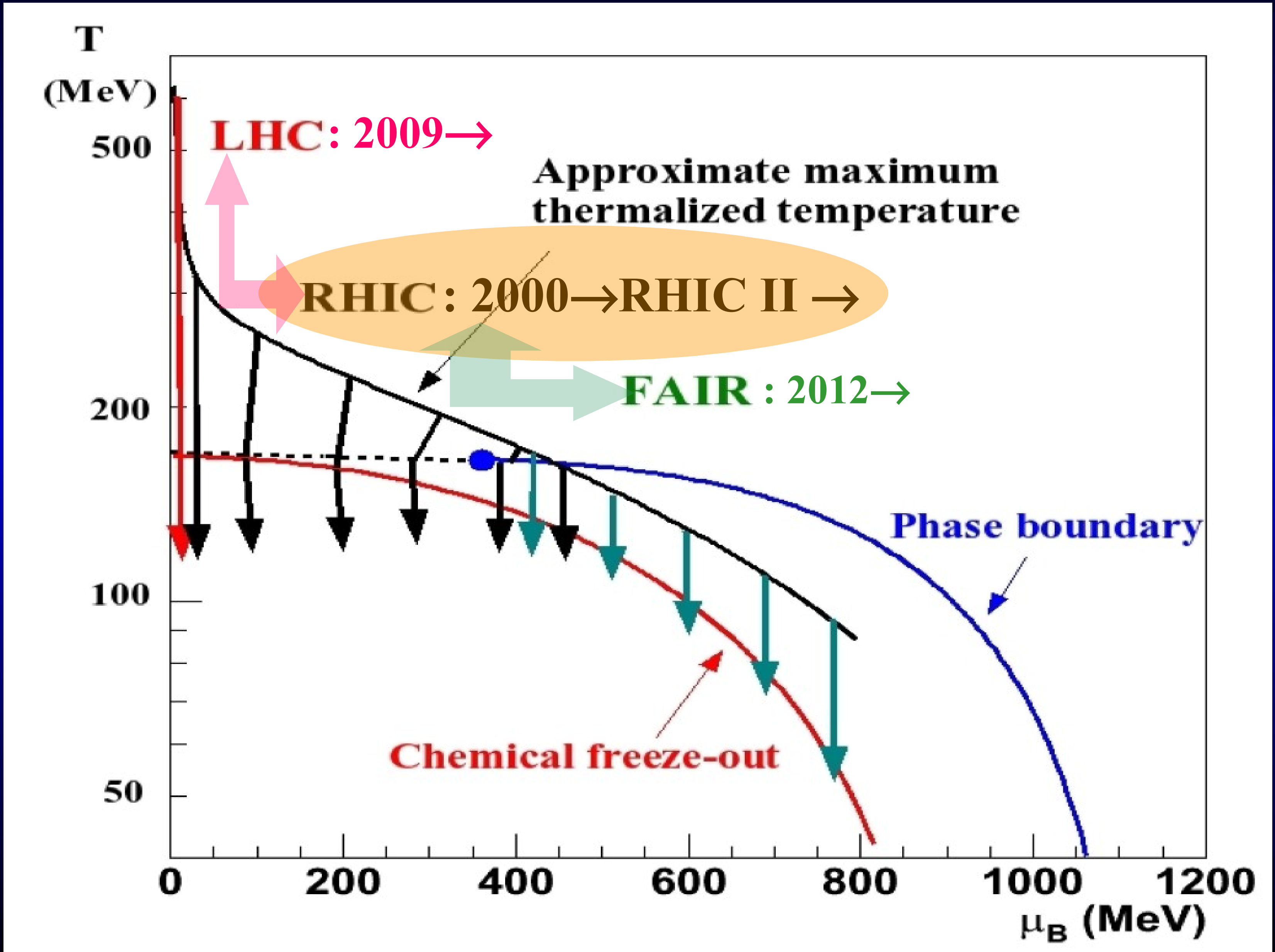
High T_{init} ~ 300 MeV

to

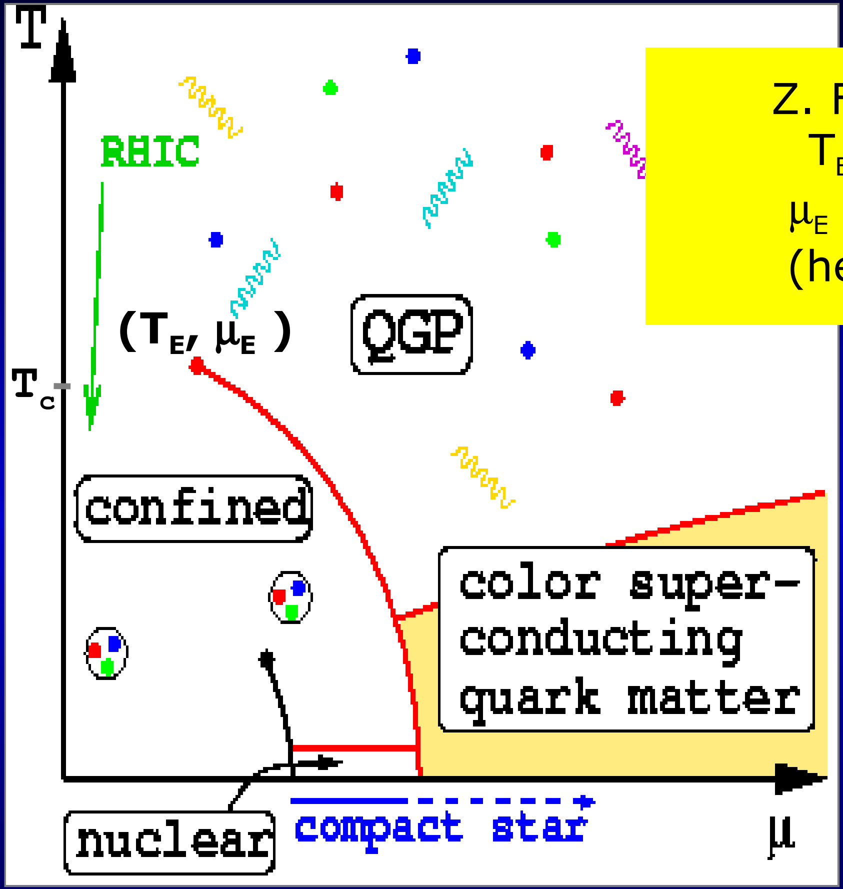
Low T_{final} ~ 100 MeV



World Context: Search for the CEP



Lattice QCD: EoS of QCD Matter



Z. Fodor, S.D. Katz:
T_E=162±2 MeV,
μ_E = 360±40 MeV
(hep-lat/0402006)

At the Critical End Point, the phase transition is of 2nd order.

Stepanov, Rajagopal,Shuryak:

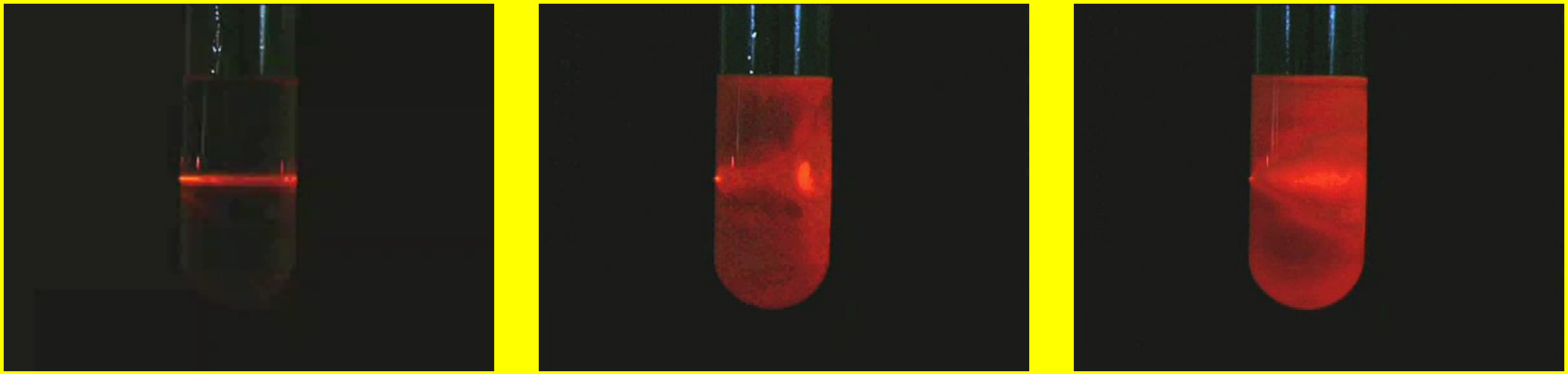
Universality class of QCD -> 3d Ising model PRL 81 (1998) 4816

Critical Opalescence

Critical Opalescence: a laboratory method to observe a 2nd order PT

correlation length diverges, clusters on all scales appear incl. the wavelength of the penetrating (laser) probe

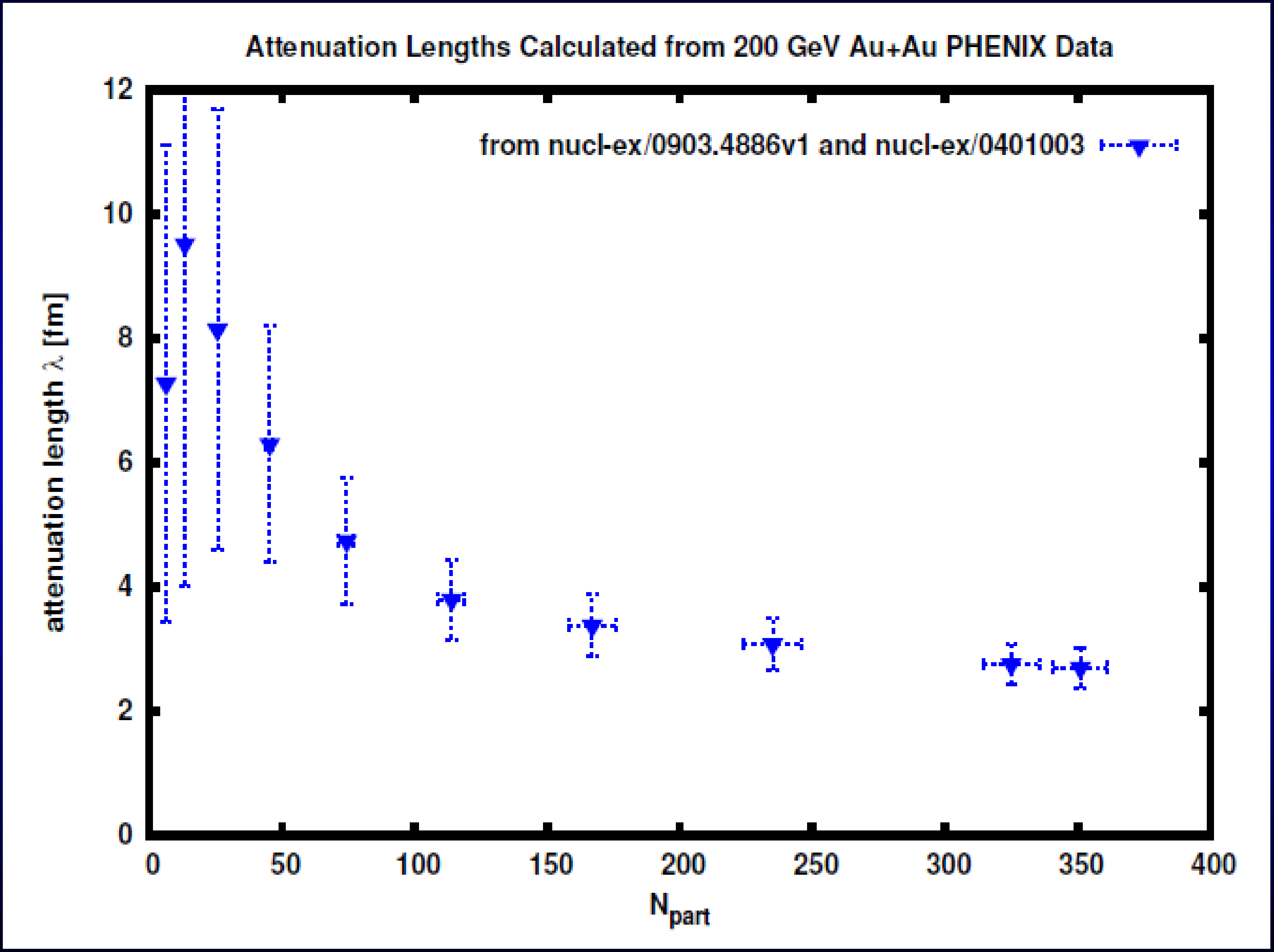
side view: http://www.msm.cam.ac.uk/doitpoms/tlplib/solidsolutions/videos/laser1.mov



front view: **matter becomes opaque at the critical point (CP)**

$T >> T_c$ **$T >\sim T_c$** **$T = T_c$**

Quantitative Opalescence 1



T. Cs, arXiv:0903.0669 [nucl-th] and in prep.

Quantitative Opalescence 2

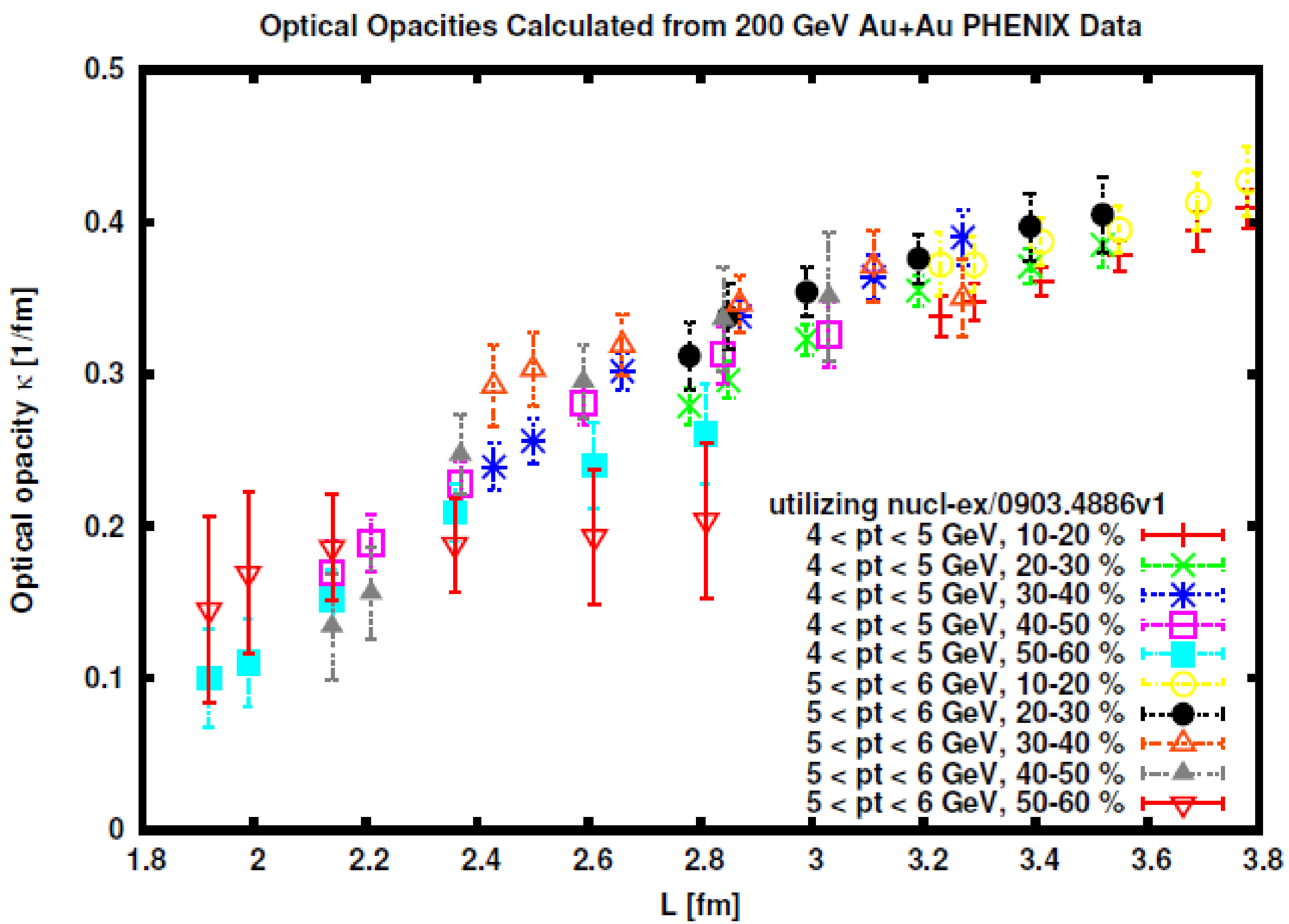


Figure 4: Optical opacity, evaluated from PHENIX reaction plane angle dependent nuclear suppression factor measurements and Glauber calculations of the relevant length scale L.

T. Cs, arXiv:0903.0669 [nucl-th] and in prep.

Quantitative Opalescence 3

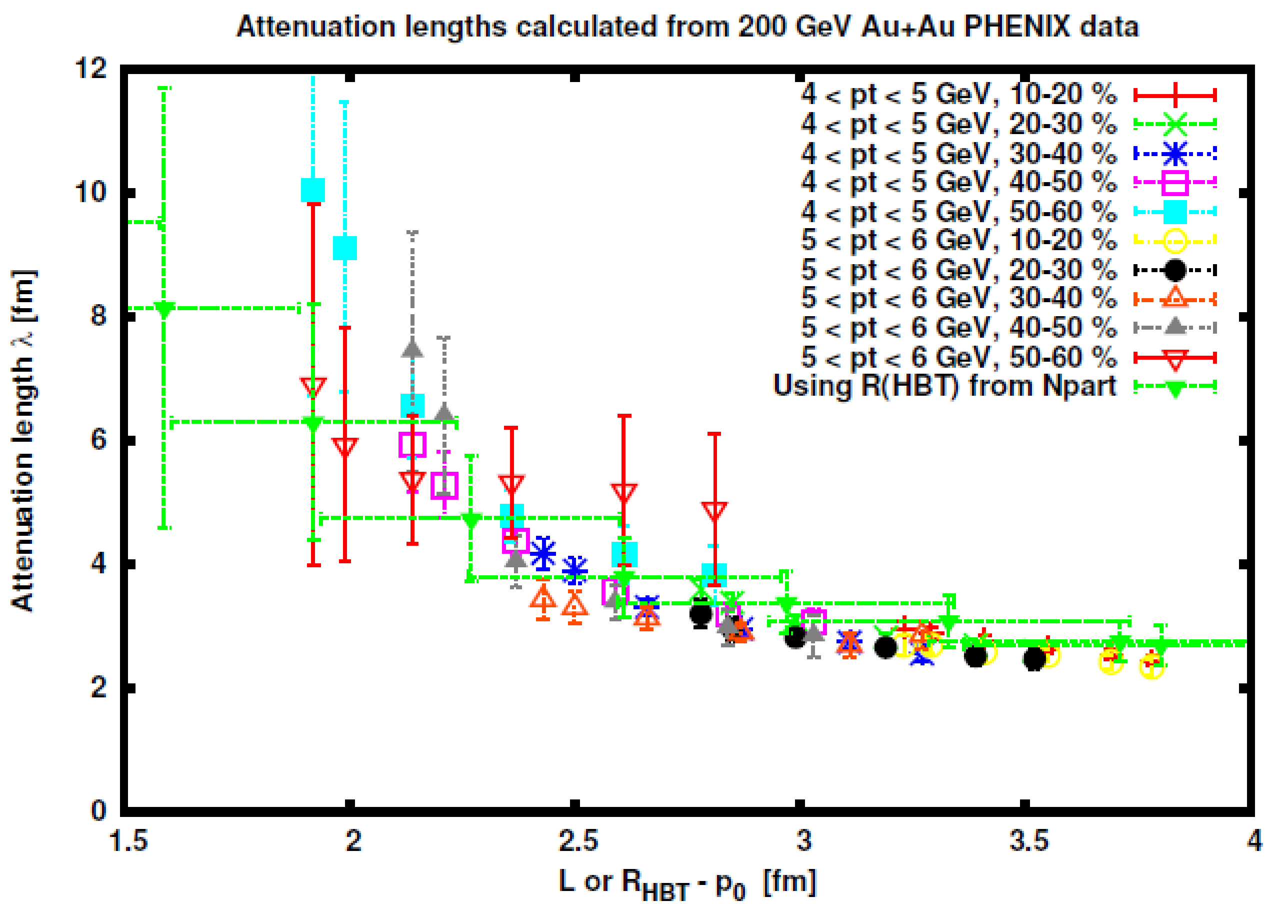


Figure 5: Attenuation length, evaluated from PHENIX reaction plane angle dependent nuclear suppression factor measurements and Glauber calculations and compared with attenuation lenght evaluated from PHENIX pt integrated R_{AA} measurement combined with lenght-scale estimates from the centrality dependence of PHENIX HBT data, $R_{HBT} = p_0 + p_1 N_{part}^{(1/3)}$. Note that the two scaling laws coincide if the latter is plotted as a function of $R_{HBT} - p_0$.

T. Cs, arXiv:0903.0669 [nucl-th] and in prep.

Summary I

Heavy Ion Program at RHIC, discoveries::

paradigm shift: from wQGP to a strongly coupled limit
evidence for a ~ perfect fluid of quarks
transition: cross-over or non-equilibrium

The hottest, most perfect and most opaque fluid - ever made

AdS/CFT correspondence in various forms:

(1) Malcadena:
Four-dimensional *N*=4 supersymmetric SU(N_c) gauge theory is
eq. to IIB string theory with AdS_5 x S^5 boundary conditions.

(2) Horowitz, Polchinski:
Hidden within *every* non-Abelian gauge theory, even within the
weak and strong nuclear interactions, is a theory of quantum gravity.

(3) Zajc: Only with heavy ion collisions can we study experimentally
the strongly coupled limits of a quantum gauge theory, QCD.

Backup slides

Correlations for VARIOUS Quark Matters

Transition to hadron gas may be:

- (strong) 1st order
- second order (Critical Point, CP)
- cross-over
- from a supercooled state (scQGP)

<u>Type of phase transition:</u>	<u>its correlation signature:</u>
Strong 1st order QCD phase transition: (Pratt, Bertsch, Rischke, Gyulassy)	$R_{out} >> R_{side}$
Second order QCD phase transition: (T. Cs, S. Hegyi, T. Novák, W.A. Zajc)	non-Gaussian shape α(Lévy) decreases to 0.5
Cross-over quark matter-hadron gas transition: (lattice QCD, Buda-Lund hydro fits)	hadrons appear from a region with $T > T_c$
Supercooled QGP (scQGP) -> hadrons: (T. Cs, L.P. Csernai)	pion flash ($R_{out} \sim R_{side}$) same freeze-out for all strangeness enhancement no mass-shift of ϕ