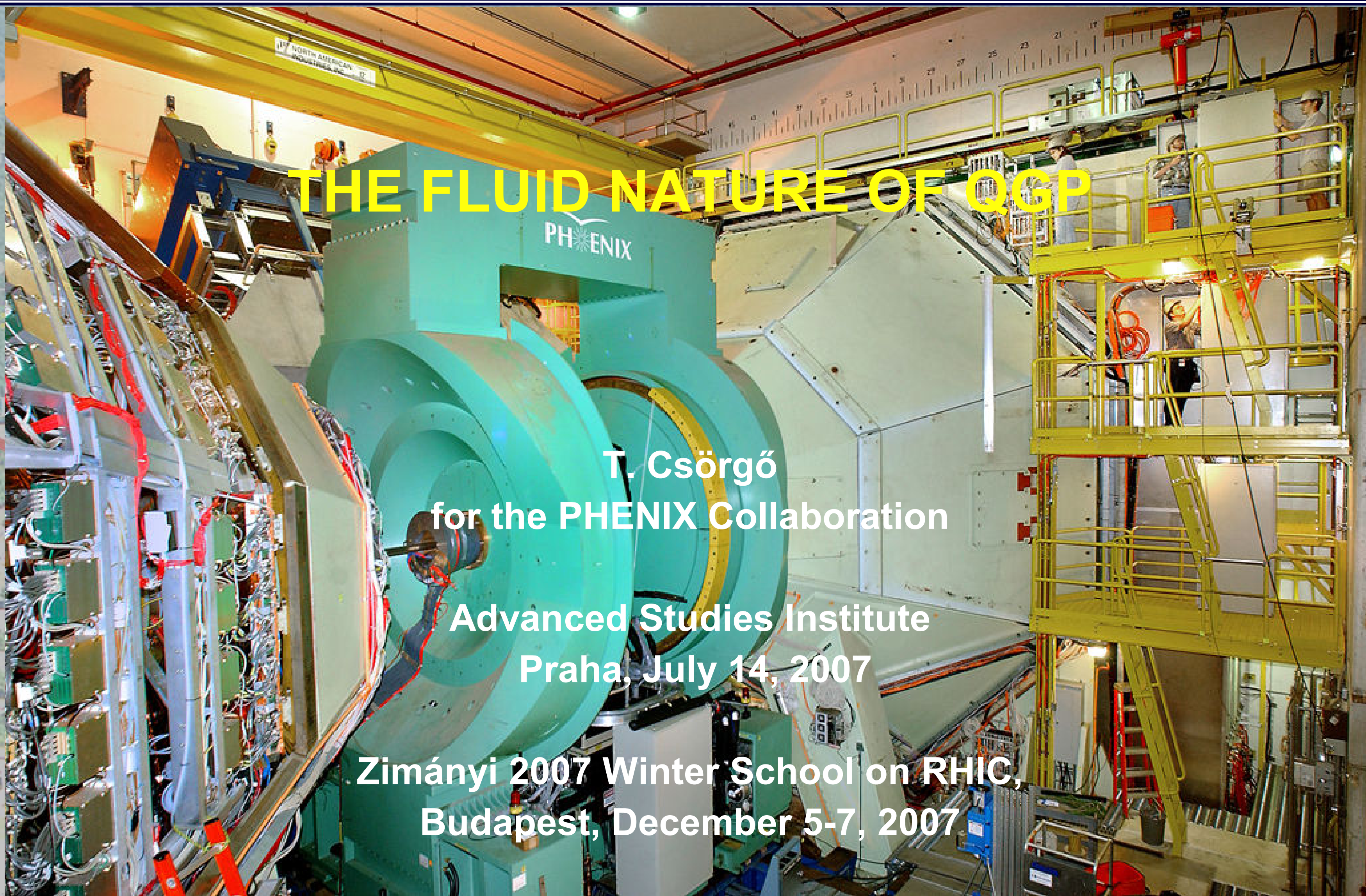


THE FLUID NATURE OF QGP

T. Csörgő
for the PHENIX Collaboration

Advanced Studies Institute
Praha, July 14, 2007

Zimányi 2007 Winter School on RHIC,
Budapest, December 5-7, 2007

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.

The Plan circa 2000

- **Use RHIC's unprecedented capabilities**
  - Large $\sqrt{s}$ ⇨
    - 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 year lifetime
  - Large detectors ~ facilities
    - Major capital investments
    - Longer lifetimes
    - Potential for upgrades in response to discoveries

RHIC and Its Experiments

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

- >160 refereed publications, among them > 90 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 …

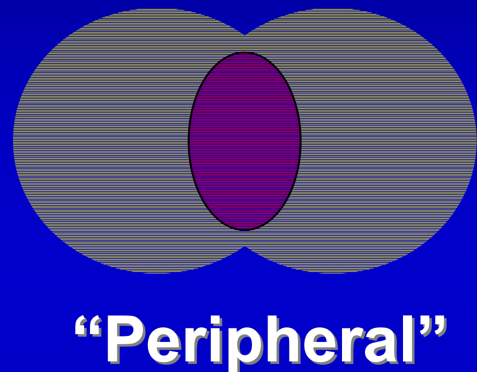
But specific to heavy ion physics

v_2	Fourier coefficient of azimuthal anisotropies ⇨ "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

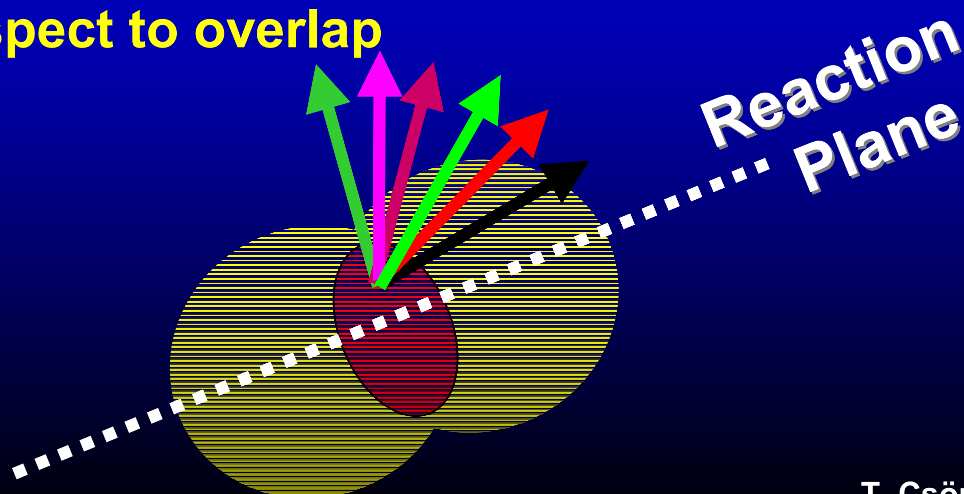
Assertion

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

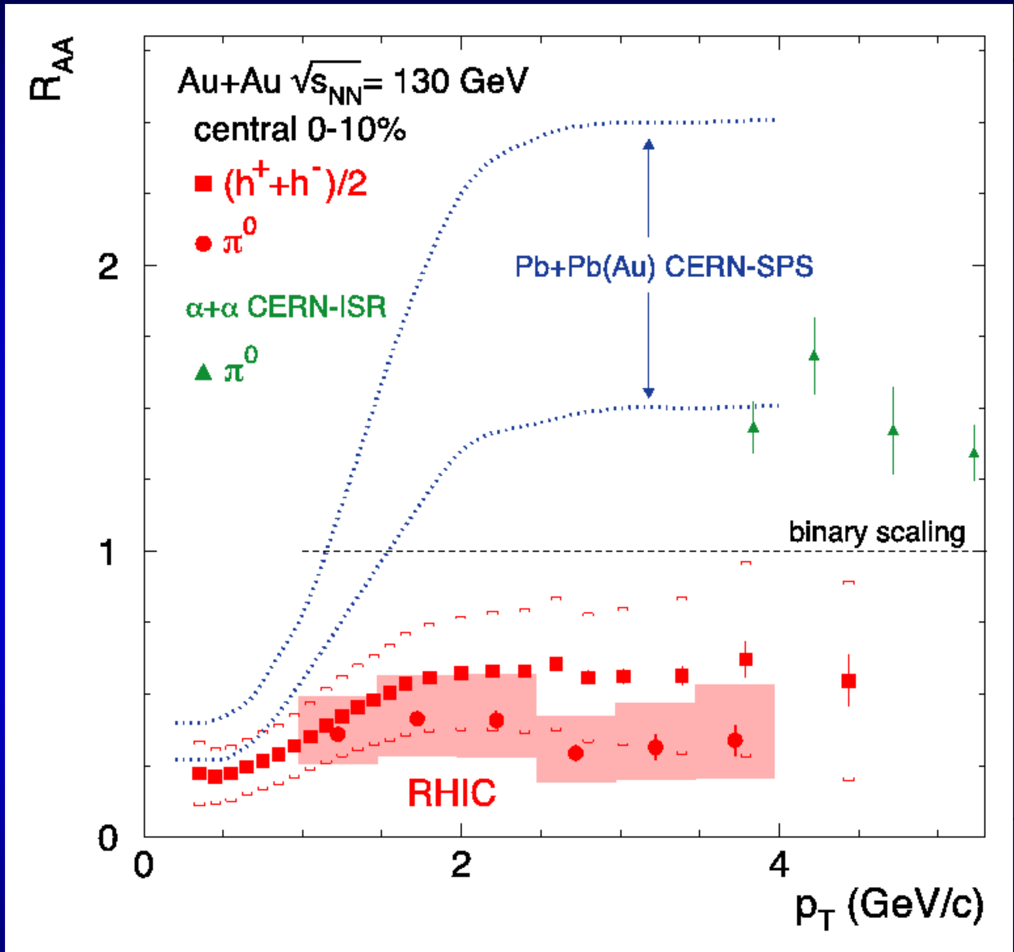
Degree of overlap

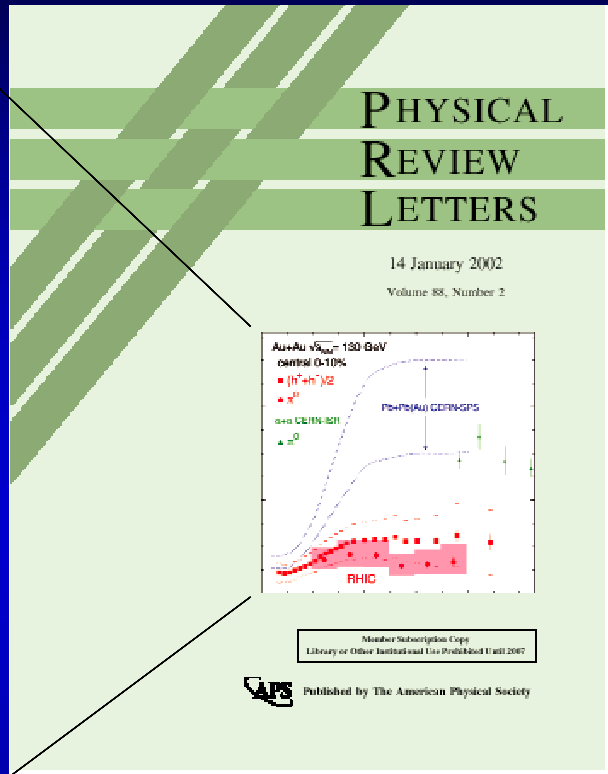


Orientation with respect to overlap



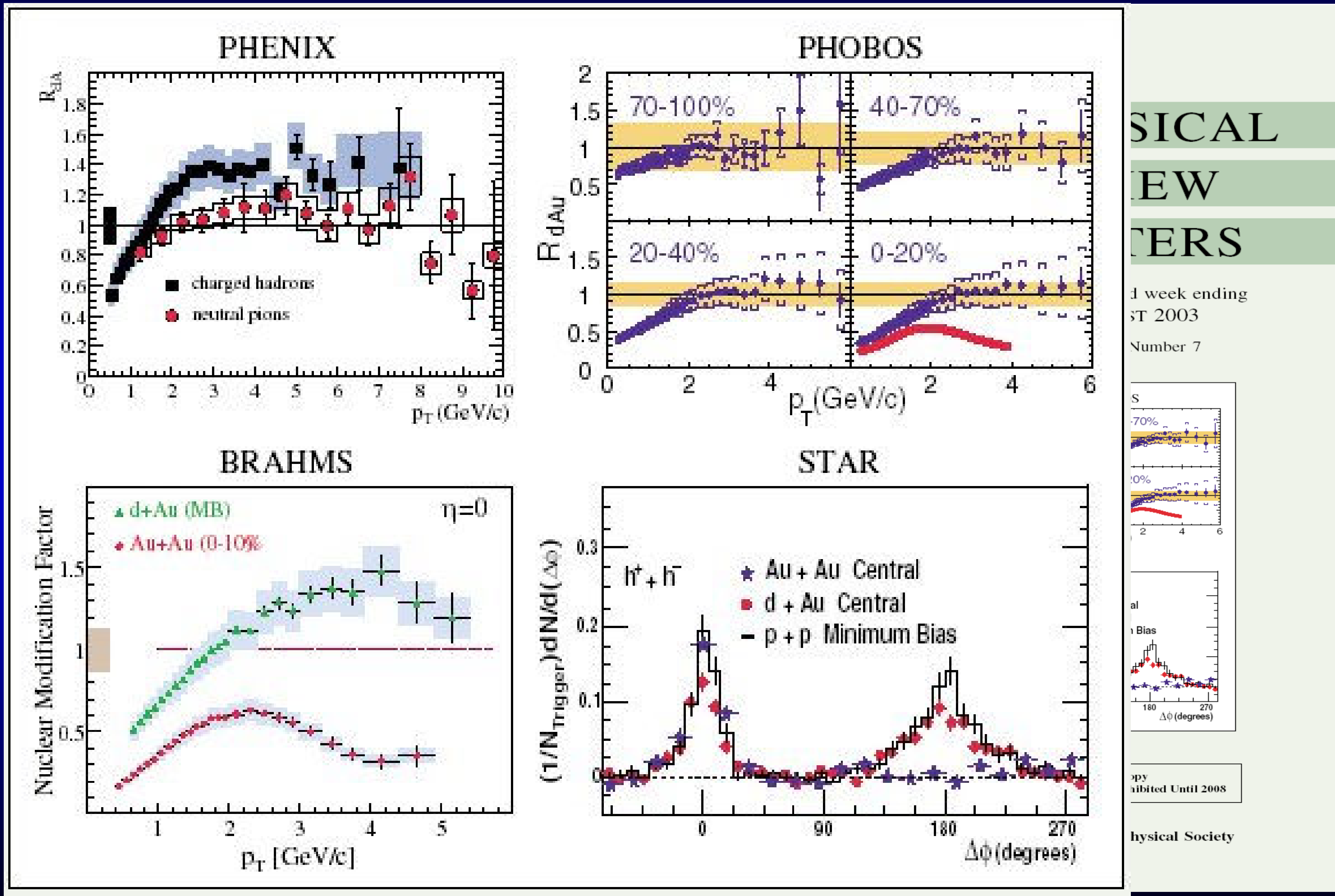
1st milestone: new phenomena





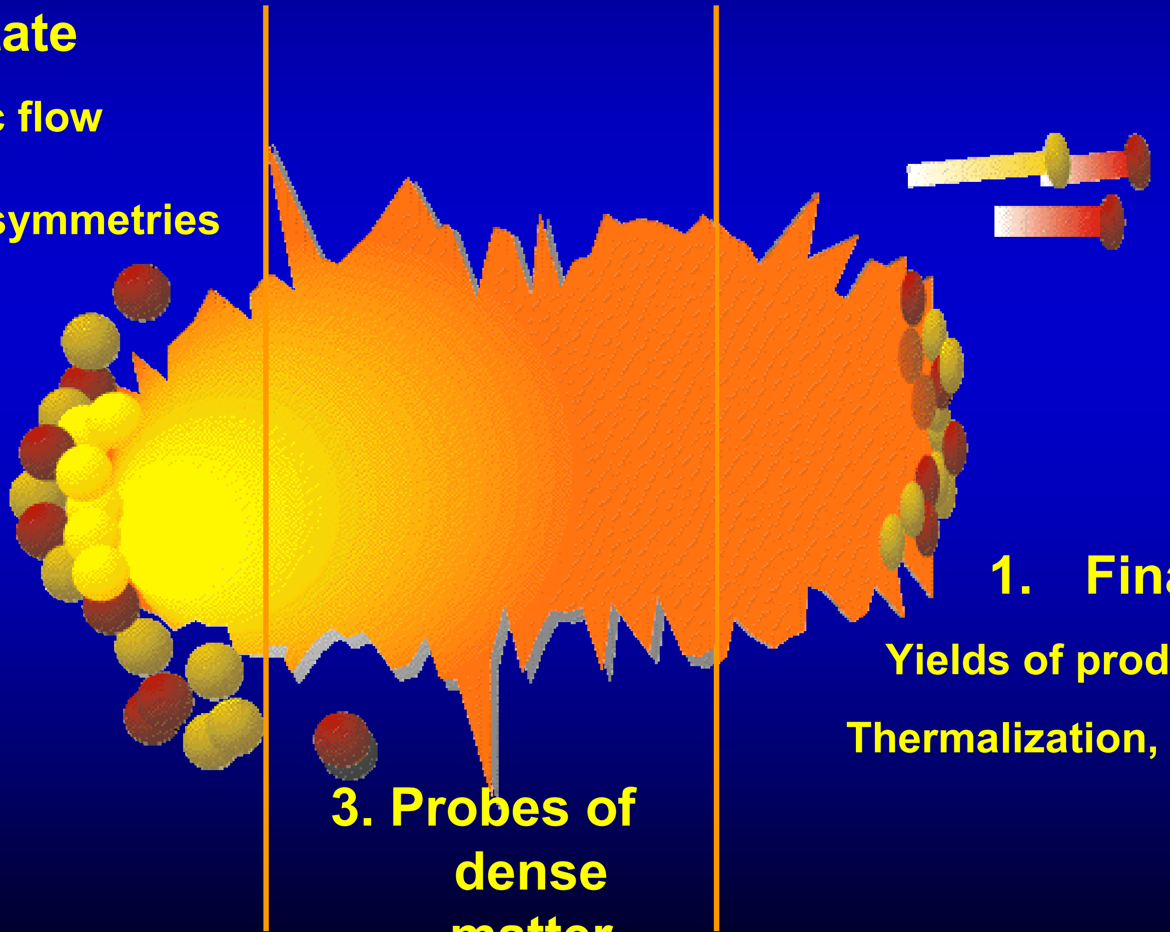
Suppression of high p_t particle production in Au+Au collisions at RHIC

2nd milestone: new form of matter



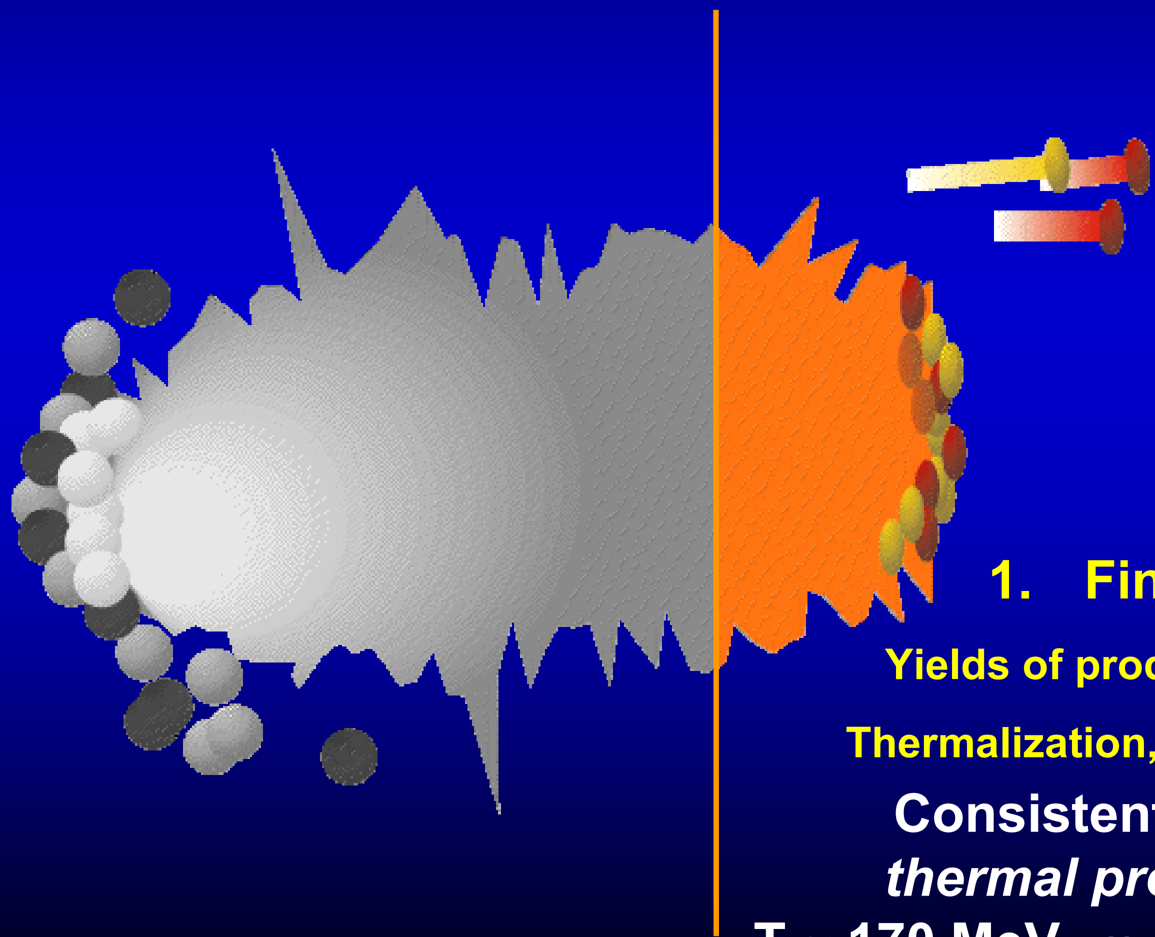
Approach

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



Final State

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



1. **Final State**

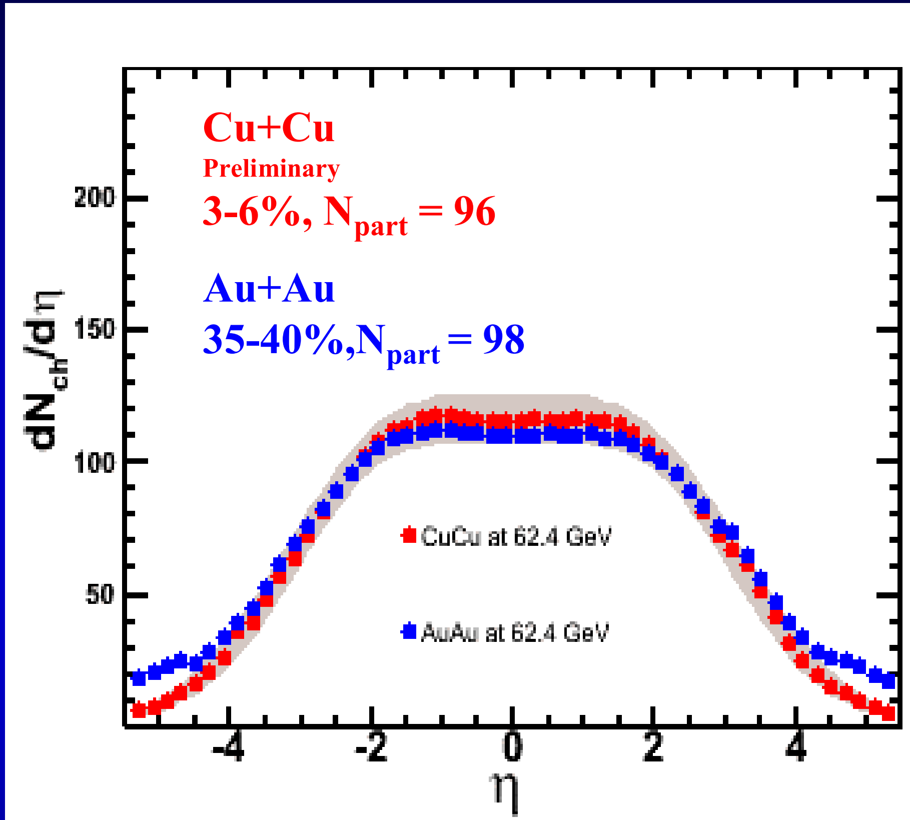
   Yields of produced particles

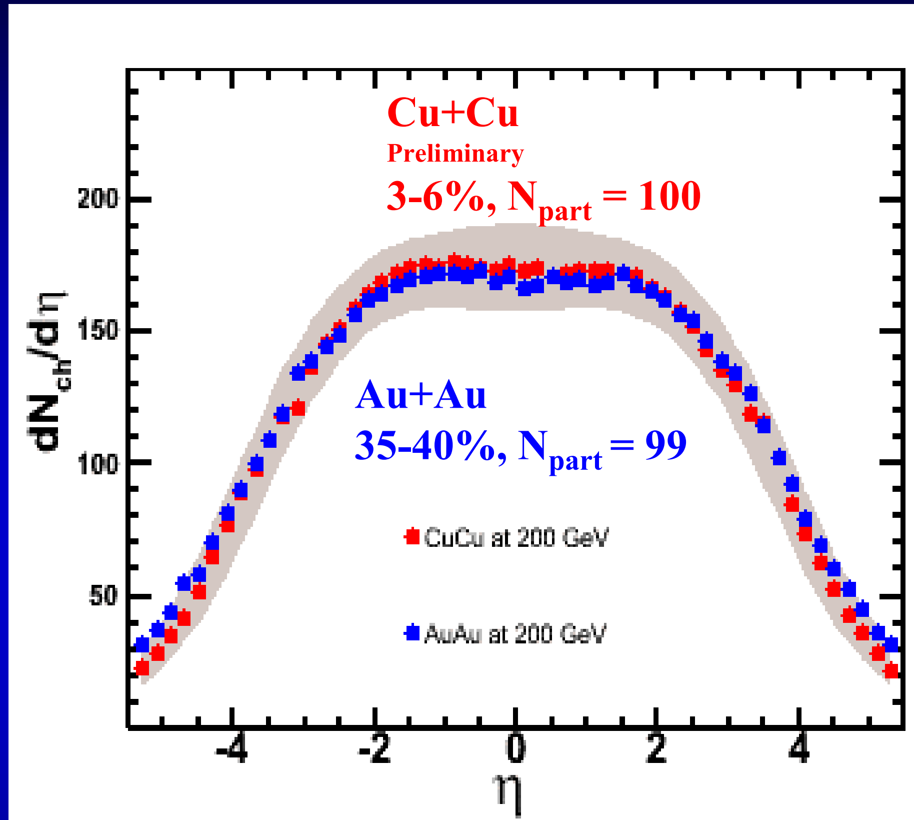
   Thermalization, Hadrochemistry

Consistent with *thermal production*

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

PHOBOS: thermal state has no memory

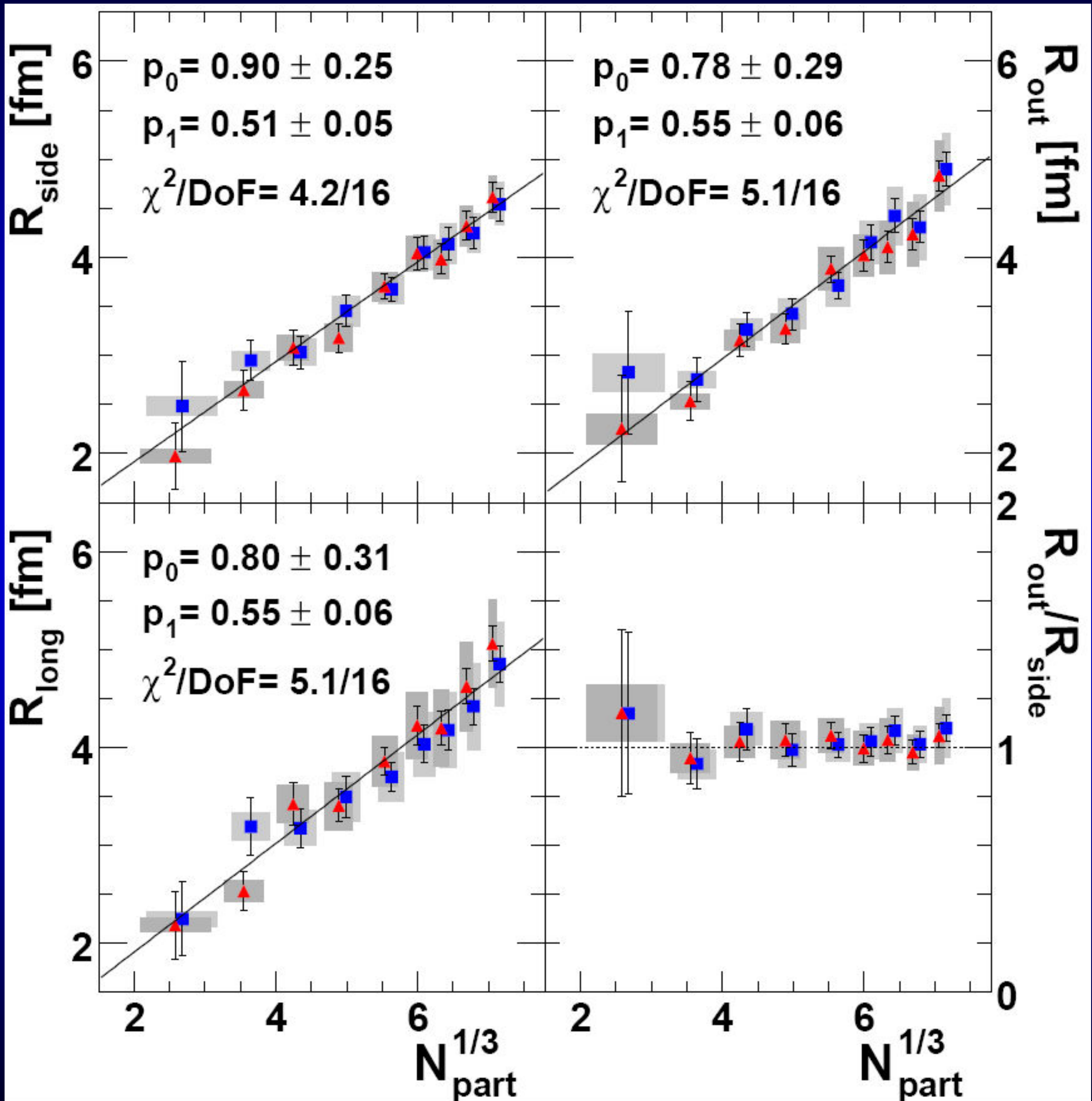




$dN/d\eta$ very similar for Au+Au and Cu+Cu at same N_{part}

Multiplicity distribution follows the independence hypothesis !

PHENIX HBT: thermal, no memory

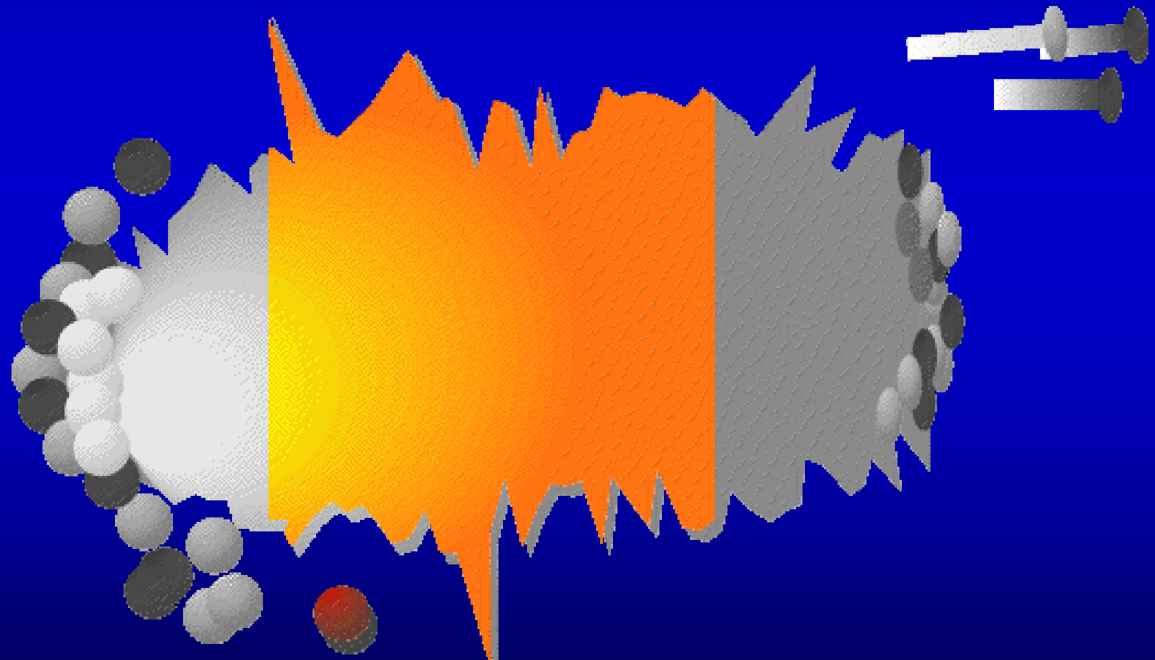


HBT radii symmetric depend on N_{part}

Probes of Dense Matter

Q. How dense is the matter?

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



Baseline p+p Measurements with pQCD

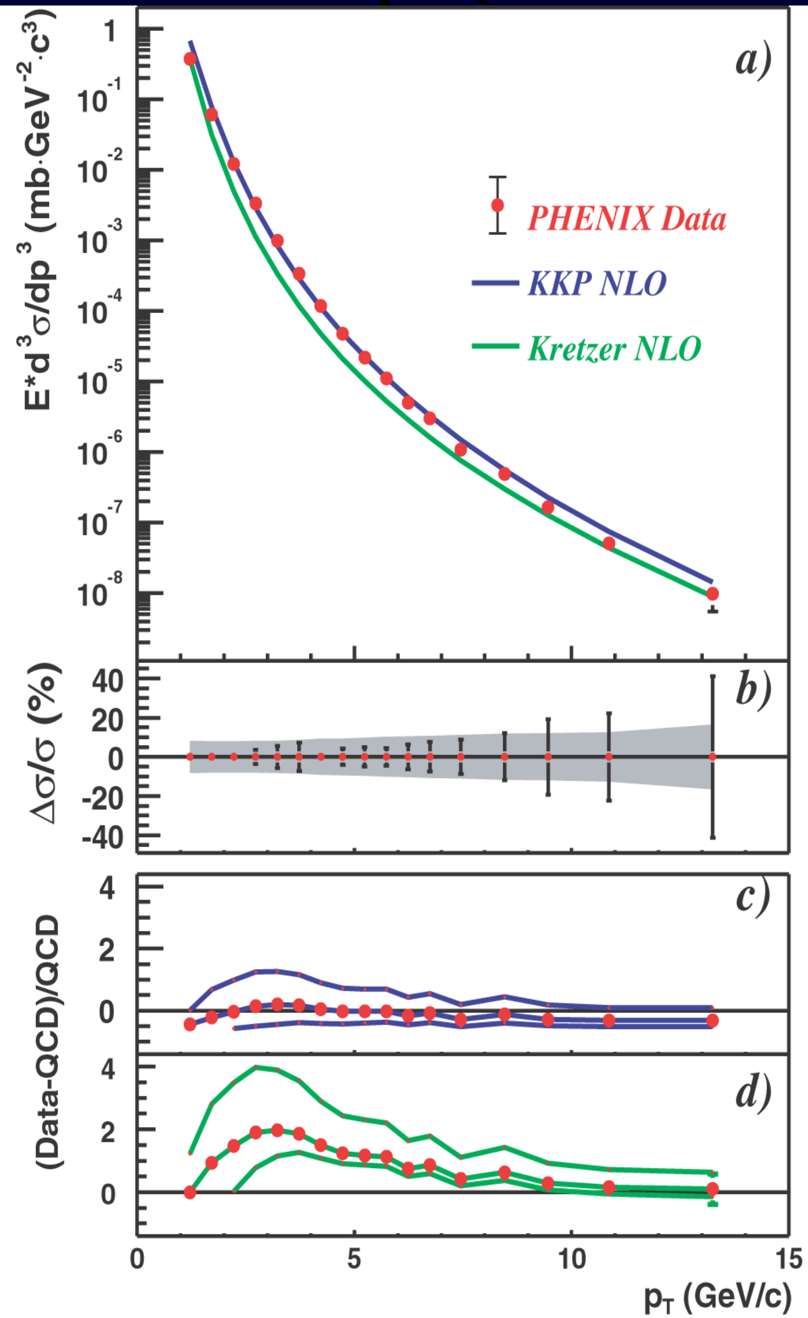
Consider measurement of π^0's in p+p collisions at RHIC.
Compare to pQCD calculation

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

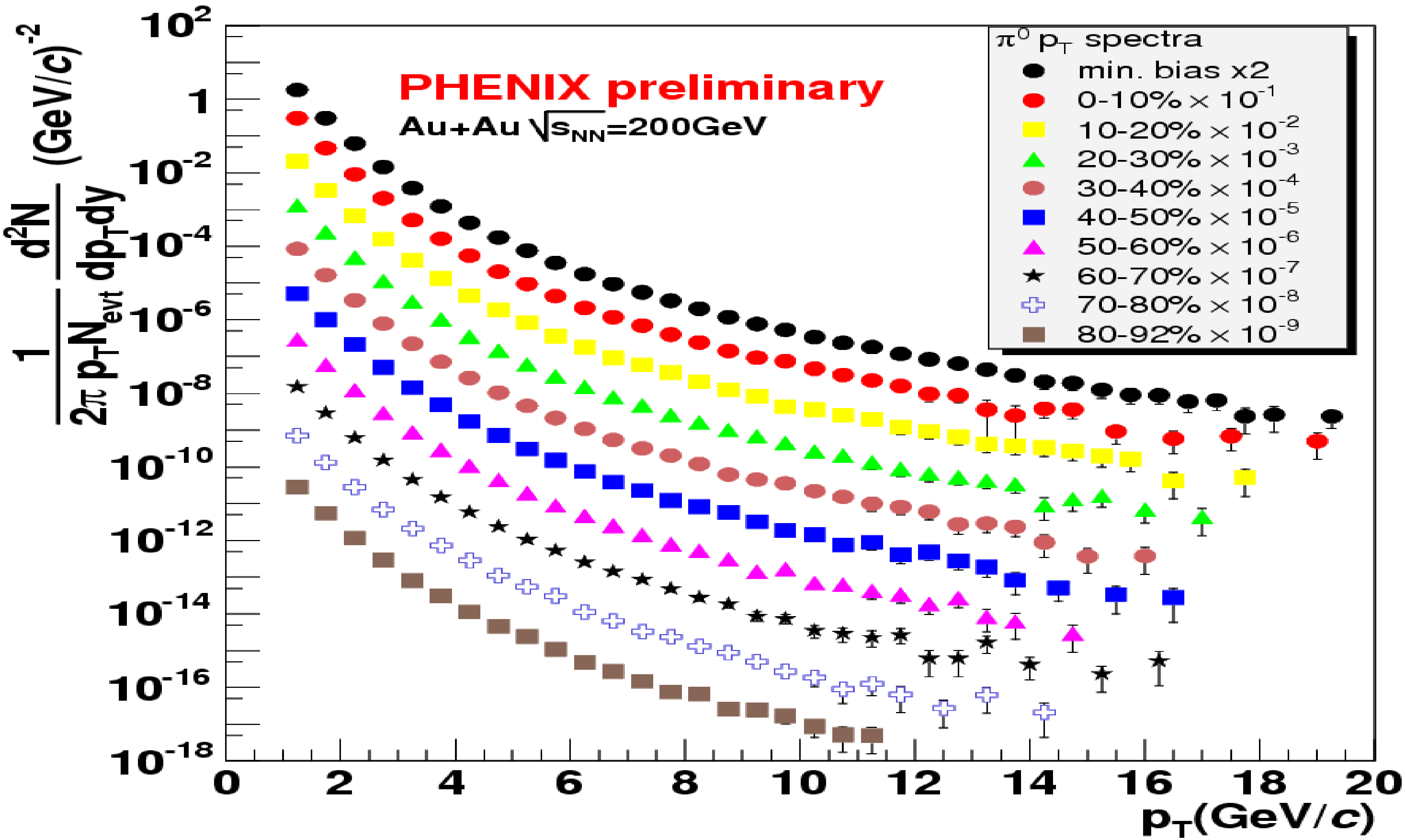
- perturbative cross-section (NLO)
- requires hard scale
- factorization between pdf and cross section

- fragmentation function
- measured in e+e-

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

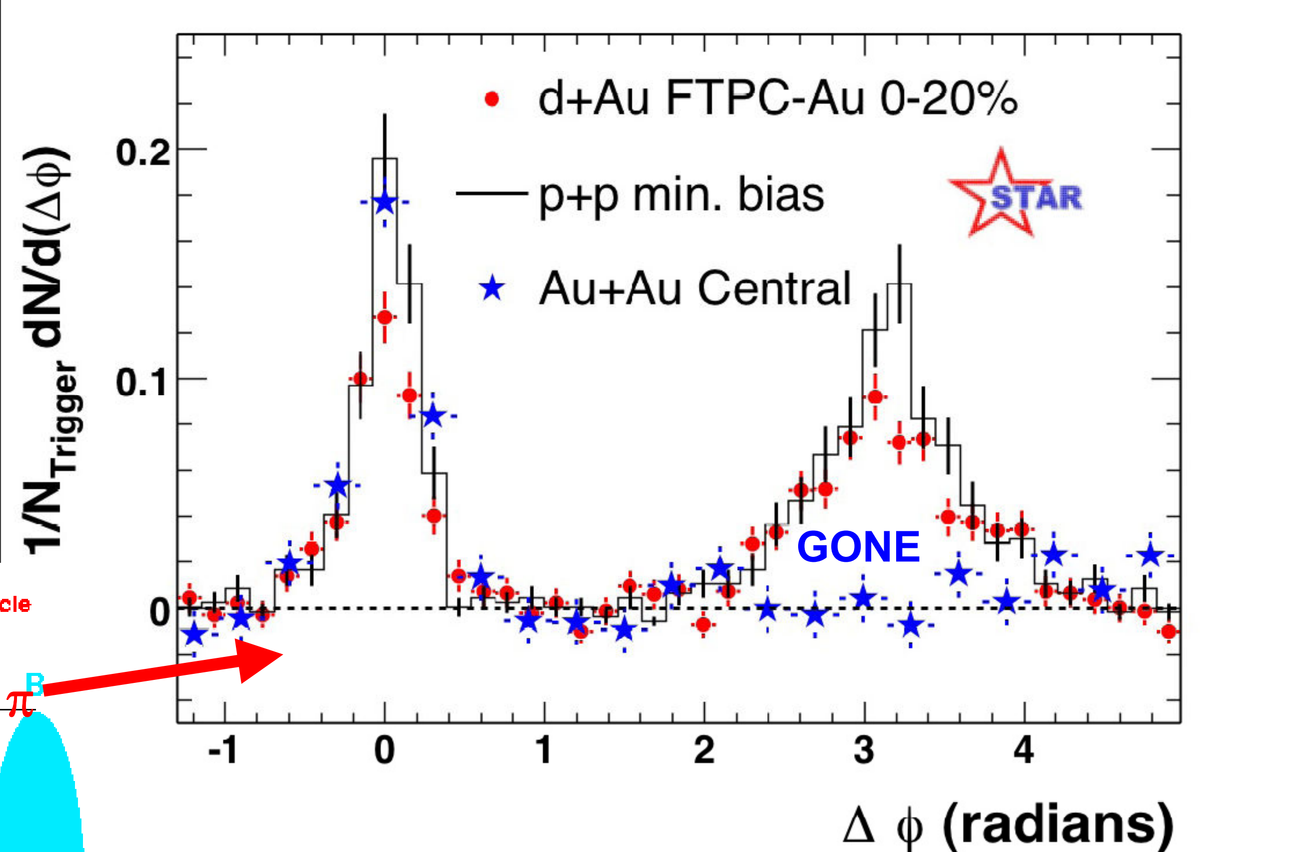


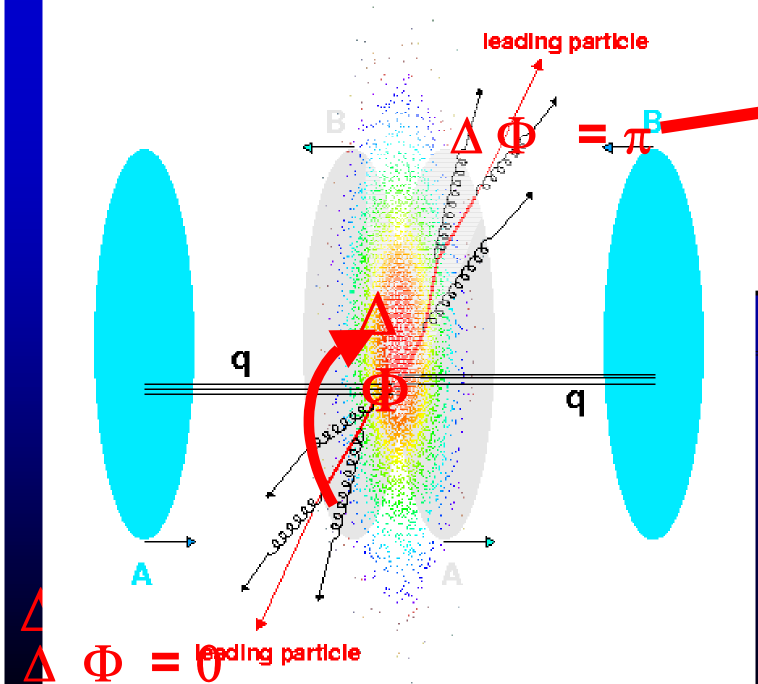
Au+Au: Systematic Suppression Pattern



The Matter is Opaque

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

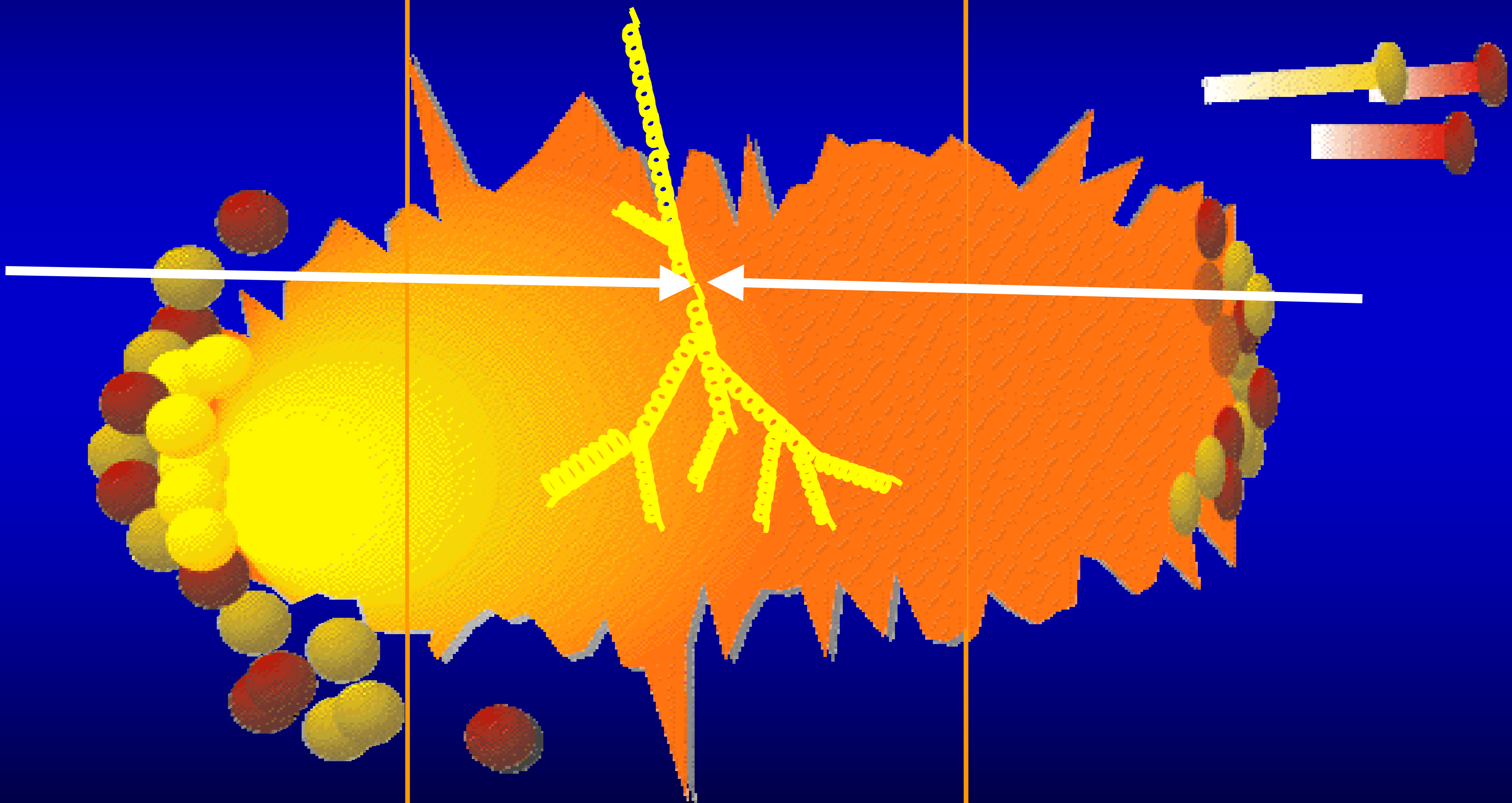




Partner in hard scatter is ***completely absorbed*** in the dense medium

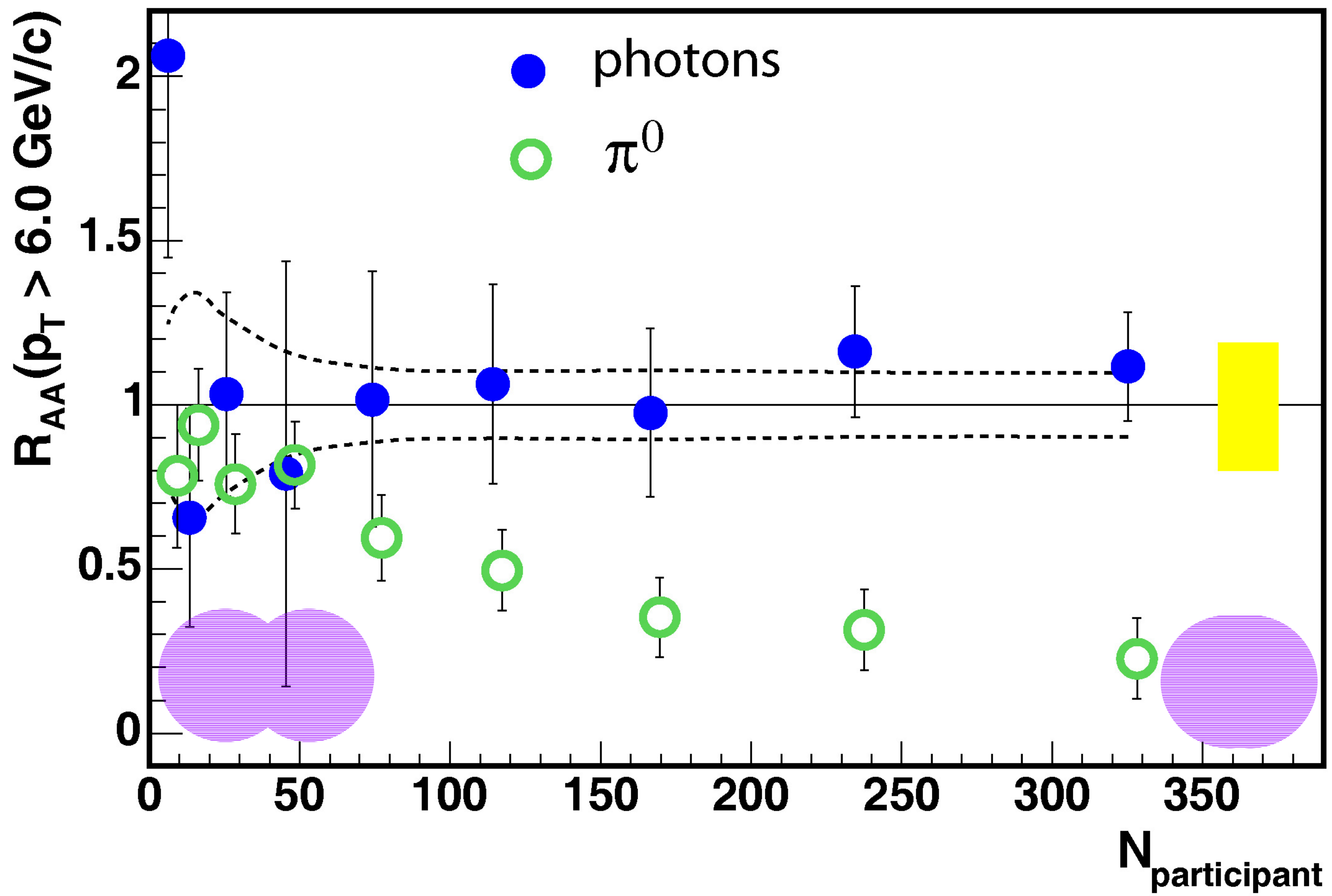
Schematically (Partons)

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



those on the "far side" are totally absorbed

Control: Photons shine, Pions don't

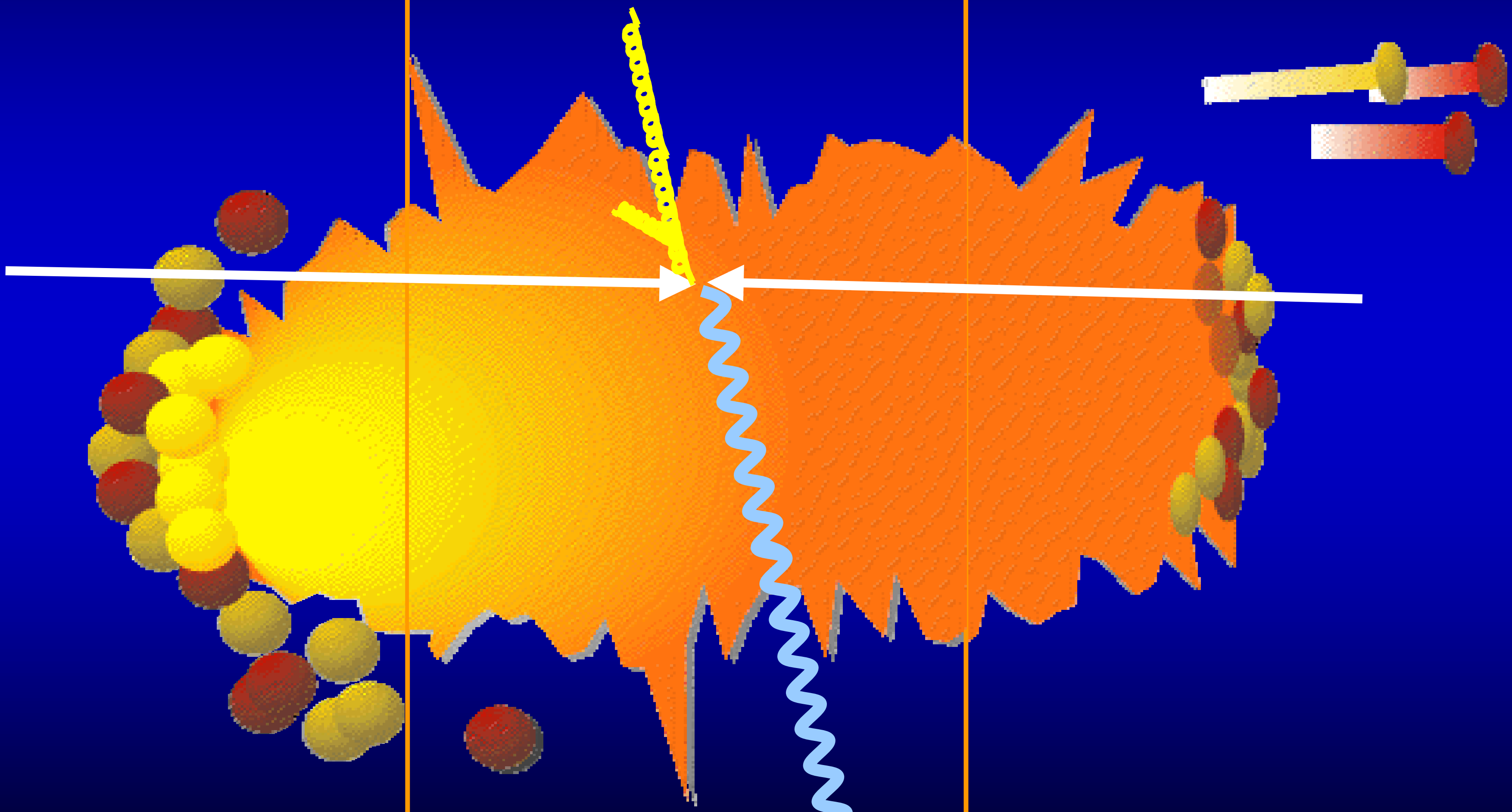


Direct photons are *not* inhibited by hot/dense medium

Rather: *shine* through consistent with pQCD

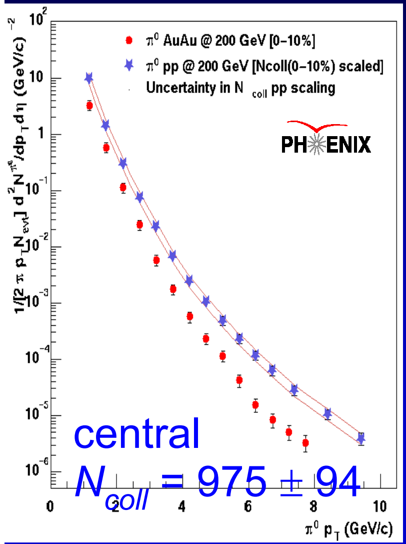
Schematically (Photons)

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

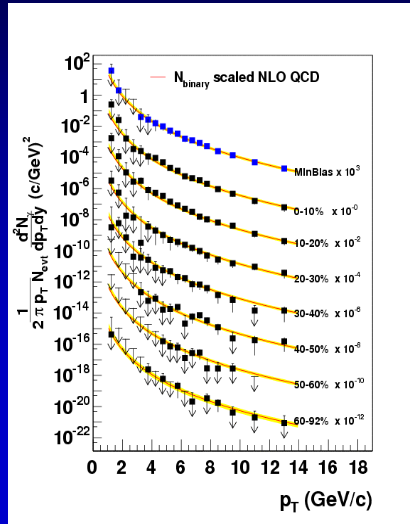


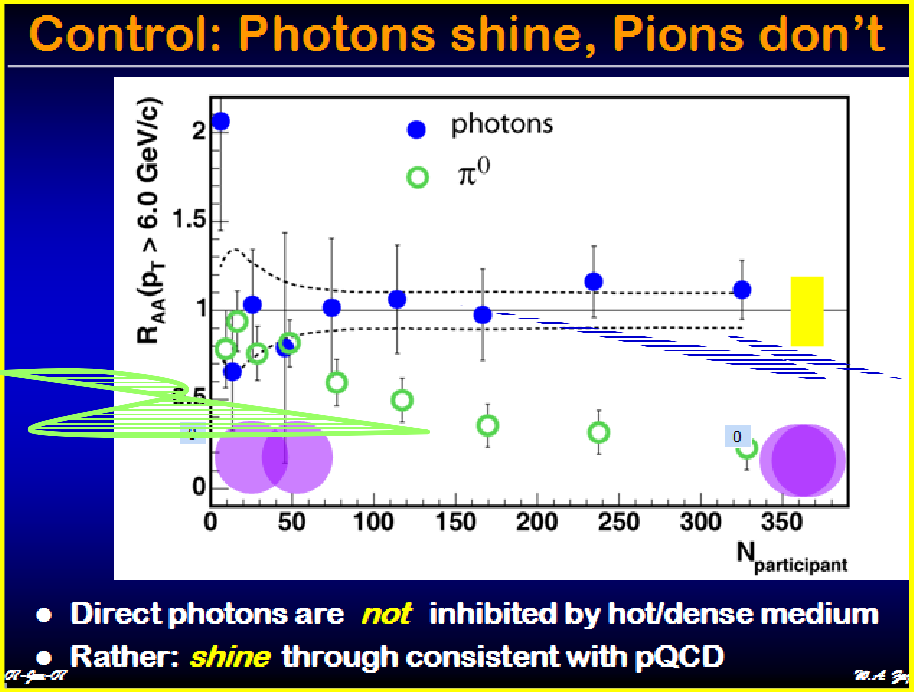
the direct photon ***always*** **emerges**

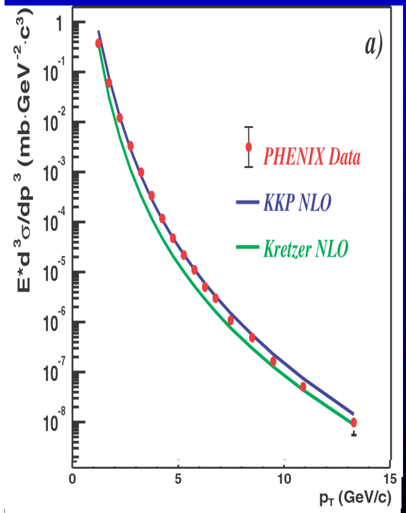
Precision Probes

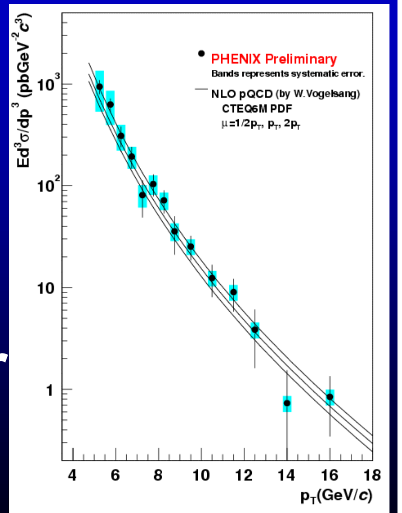


This one figure encodes rigorous control of systematics









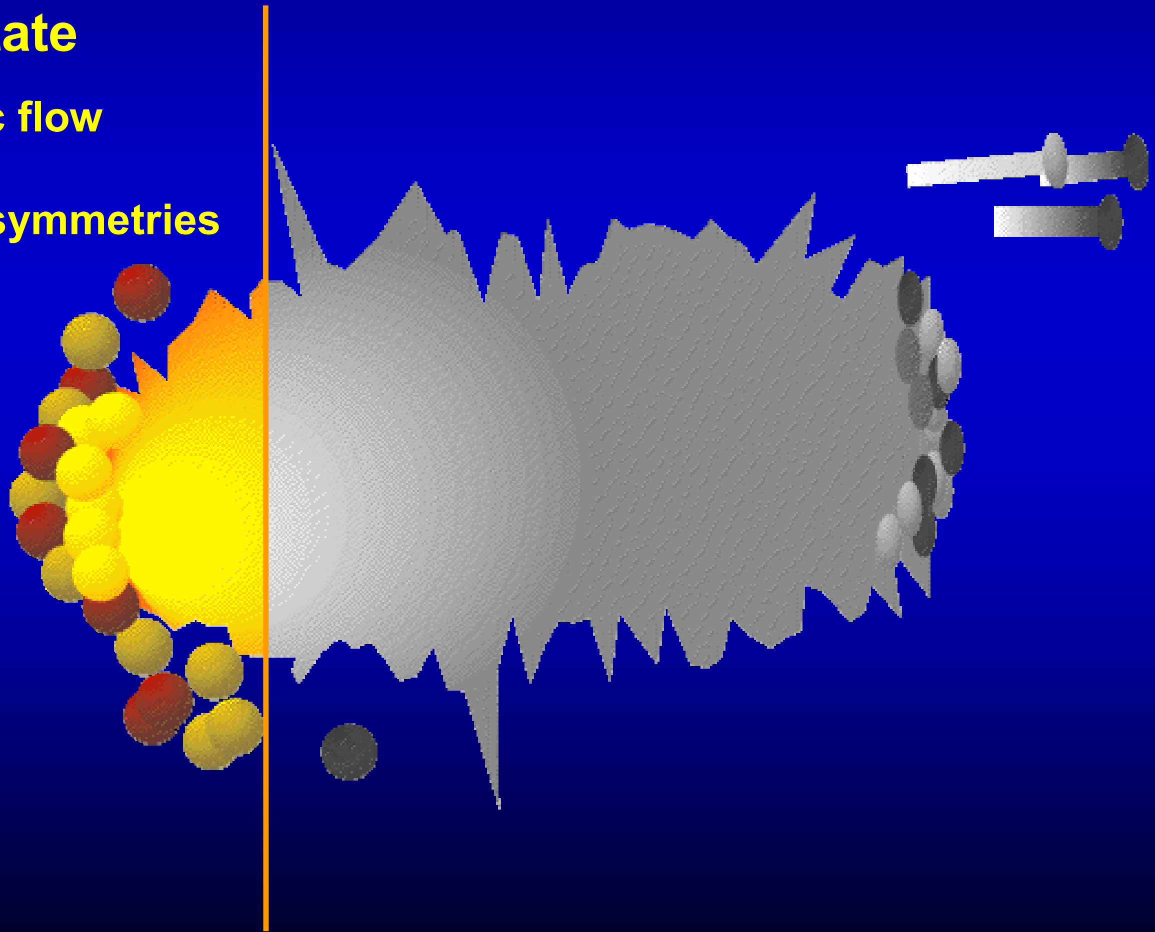
in four different measurements over many orders of magnitude

Initial State

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

2. Initial State

**Hydrodynamic flow
from
initial spatial asymmetries**



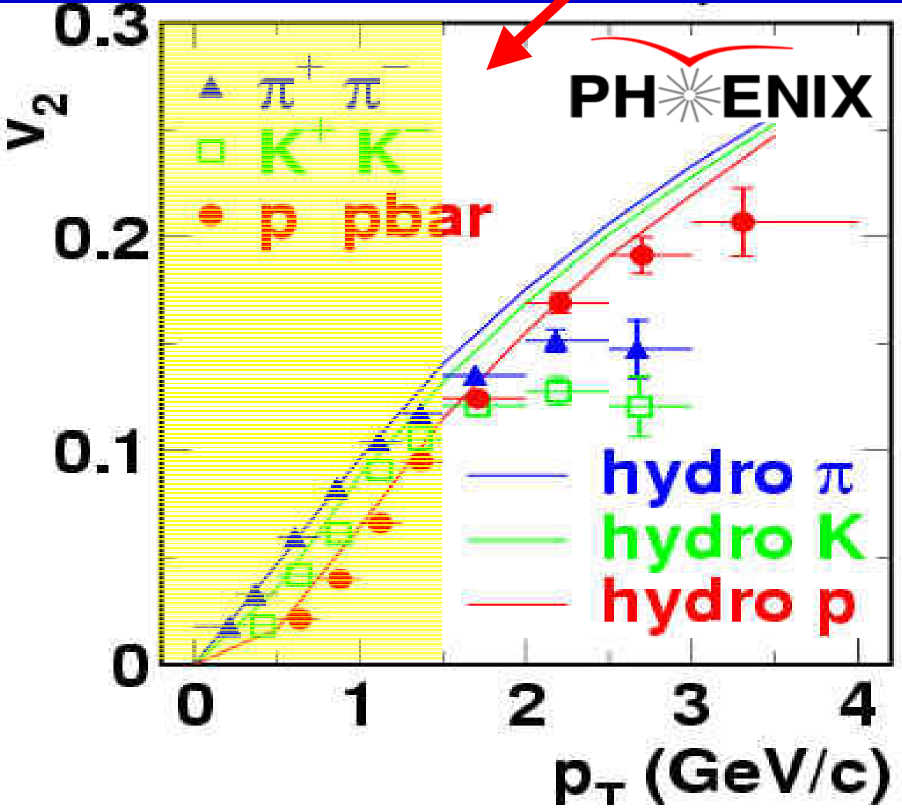
Motion Is Hydrodynamic

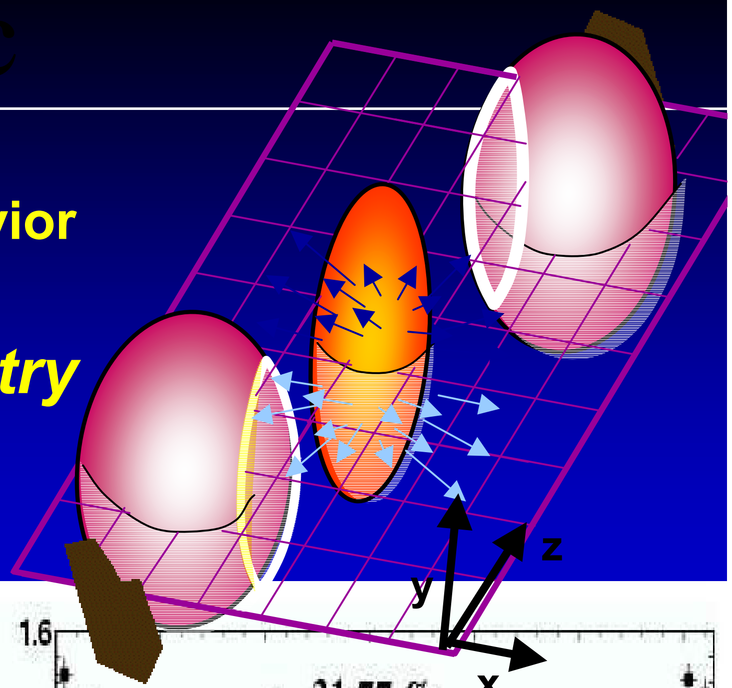
When does thermalization occur?

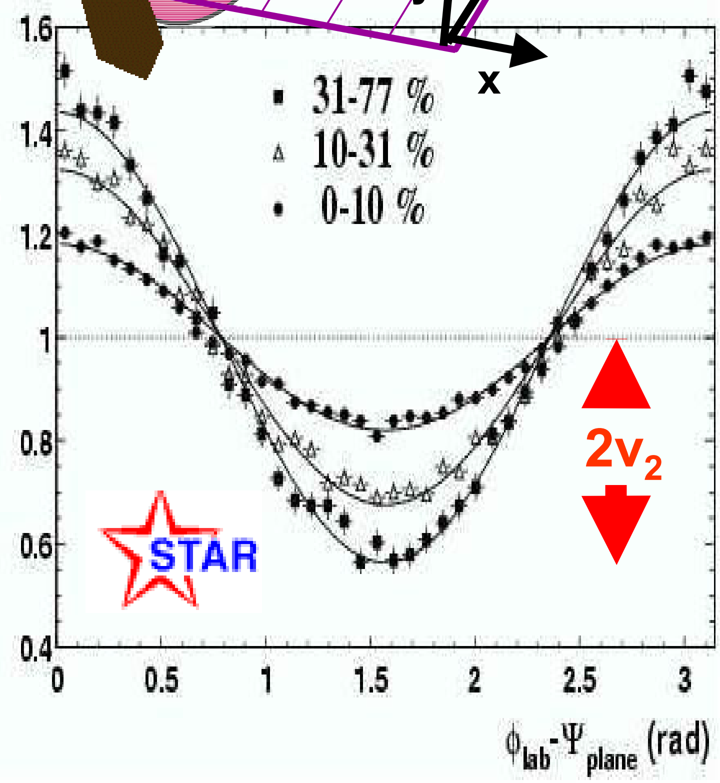
Strong evidence that final state bulk behavior reflects the initial state geometry

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

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



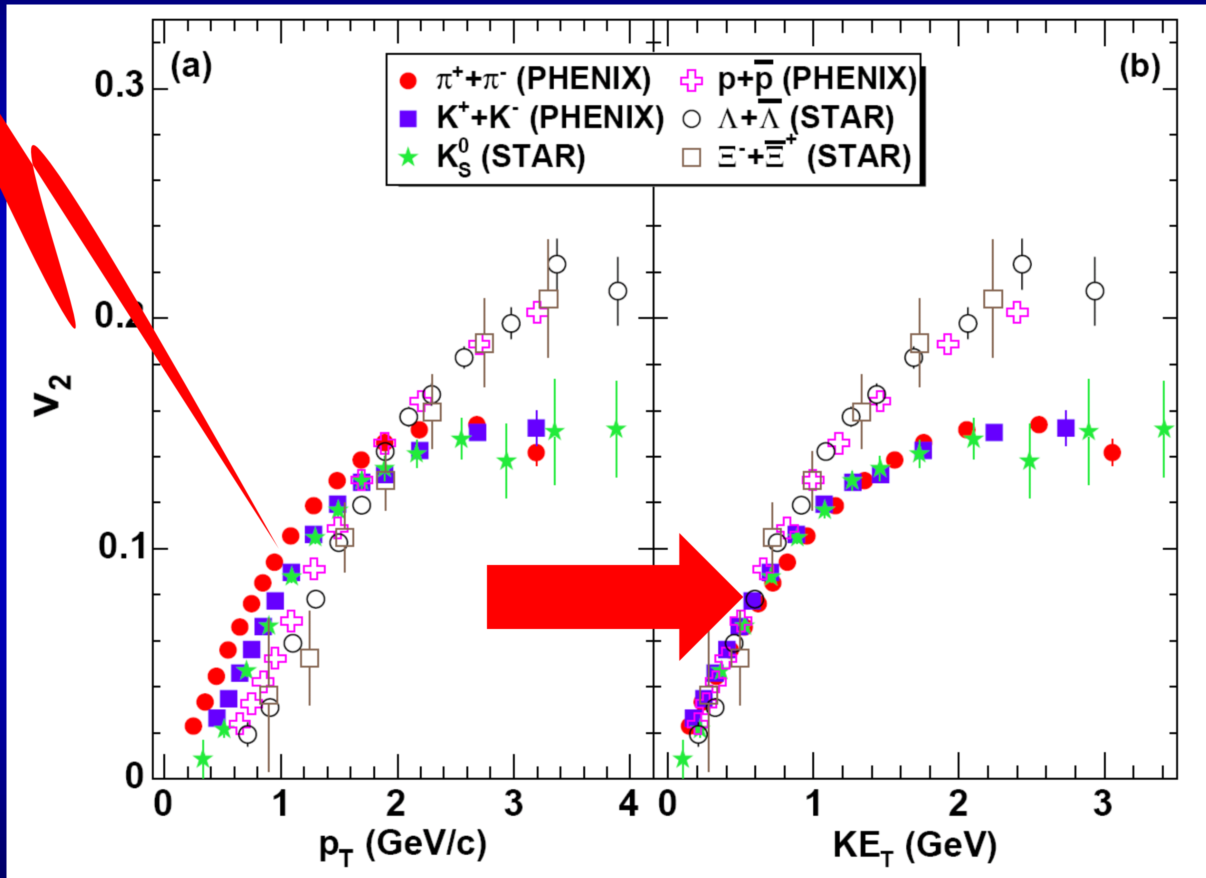




The "Flow" Is *Perfect*

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

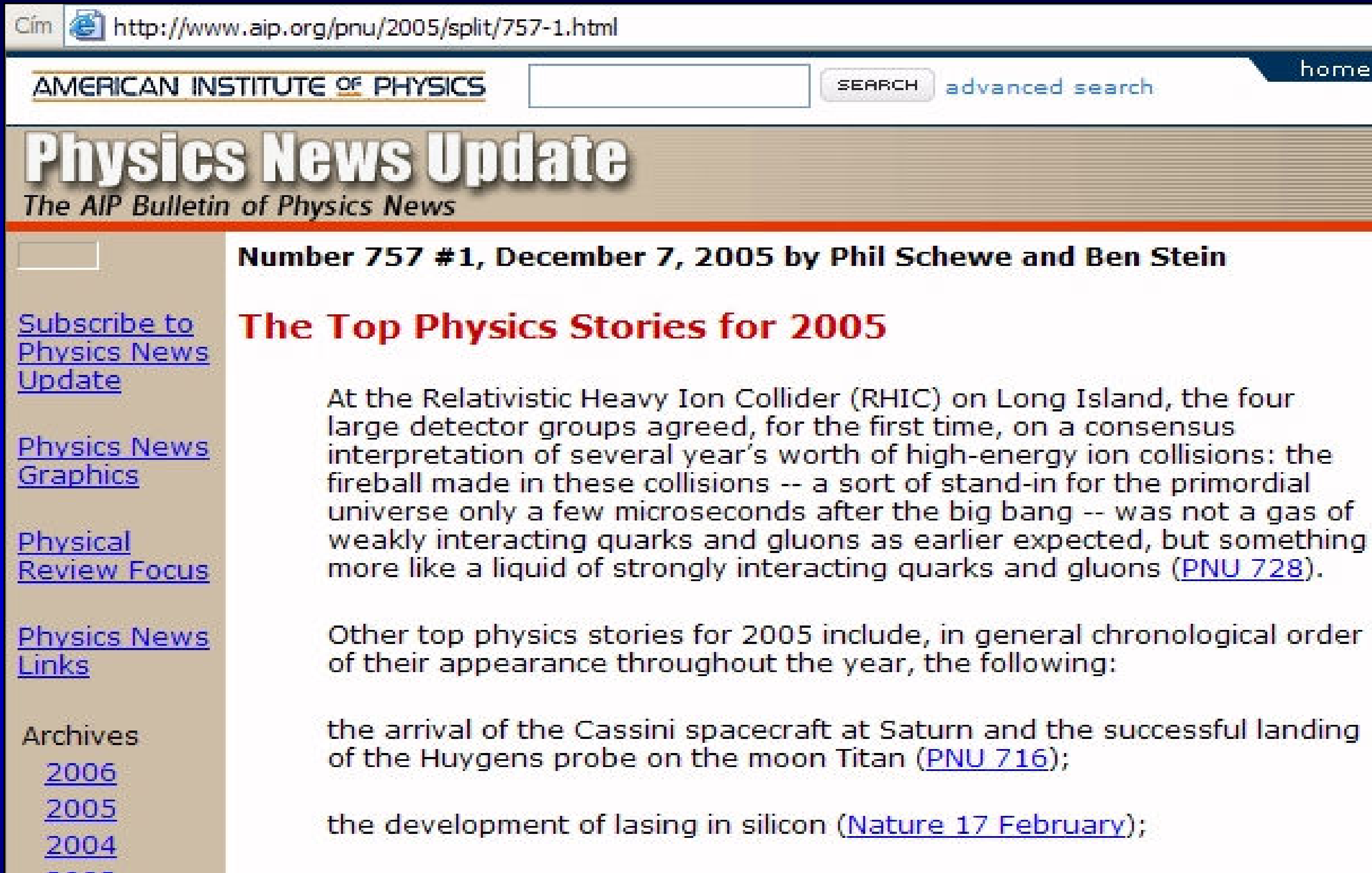
$$KE_T = \sqrt{m^2 + p_T^2}$$



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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2006
2005
2004

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);

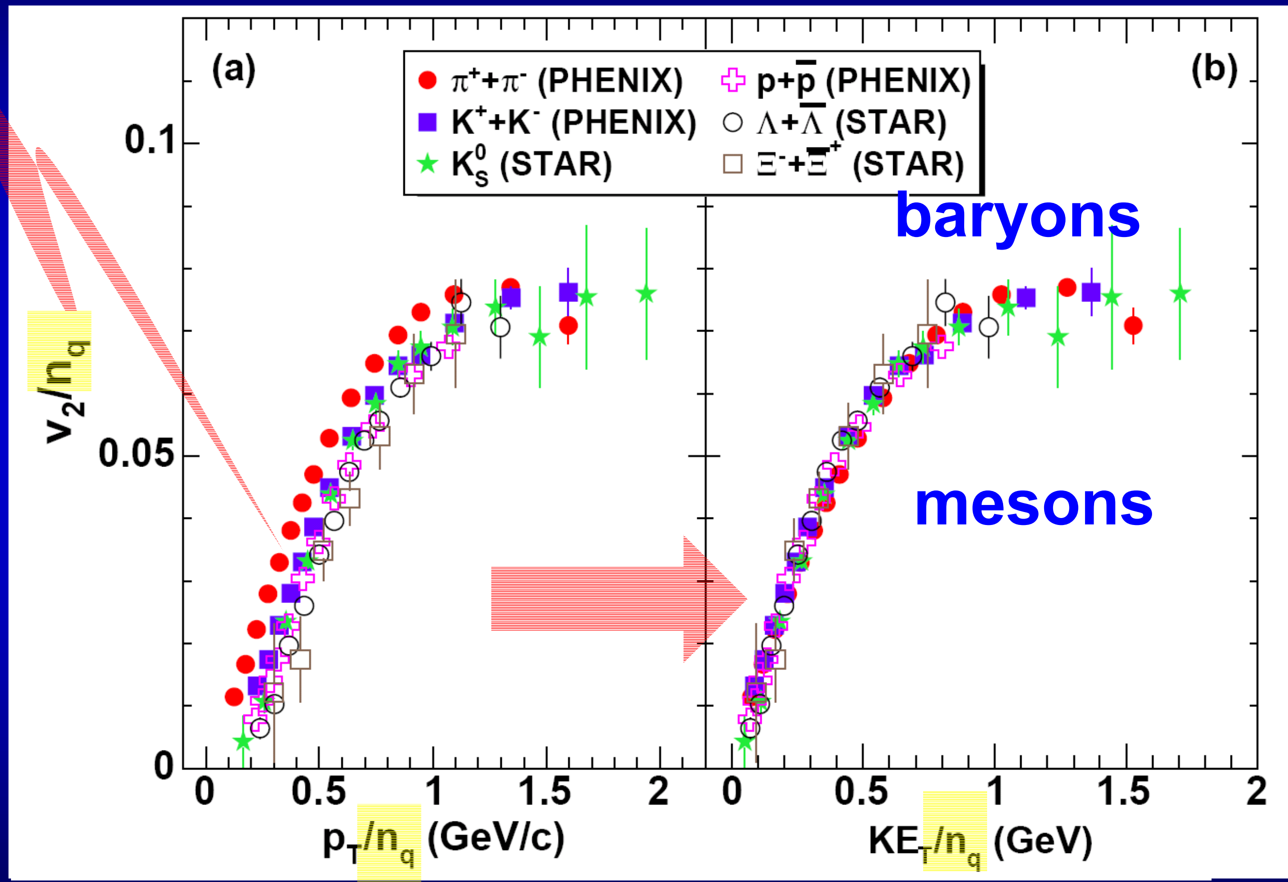
the development of lasing in silicon (Nature 17 February);

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

PHENIX White Paper: second most cited in nucl-ex during 2006

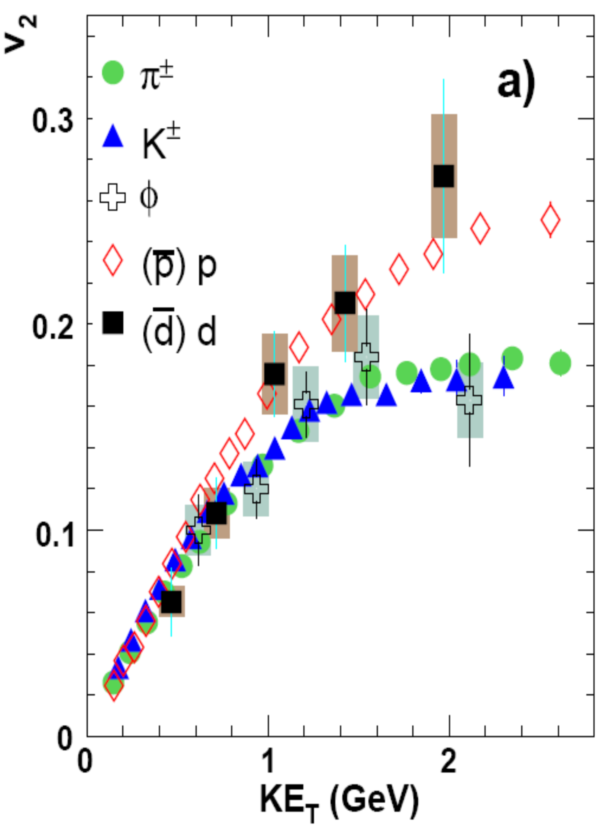
The "Flow" Knows Quarks

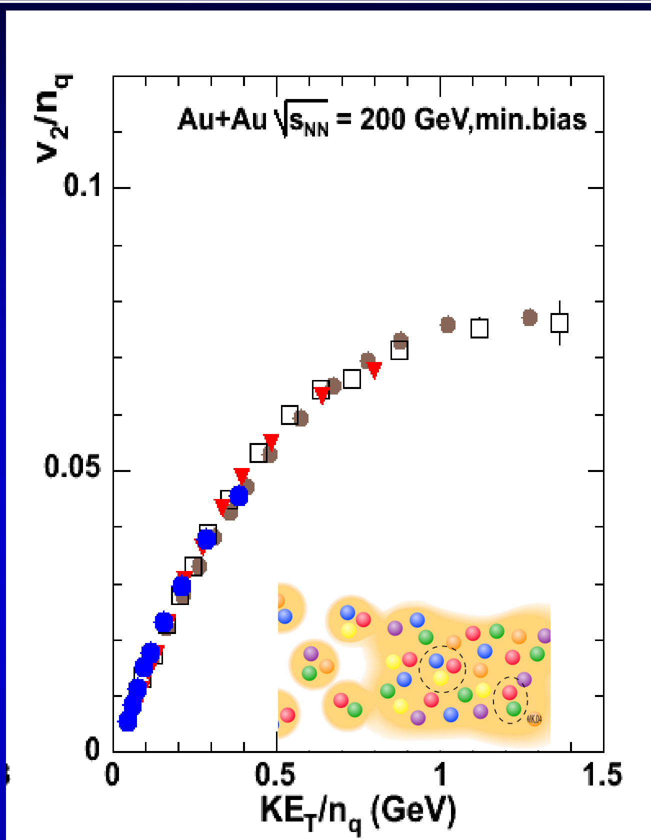
The "fine structure" $v_2(p_T)$ for different mass particles shows good agreement with ideal ("perfect fluid") hydrodynamics

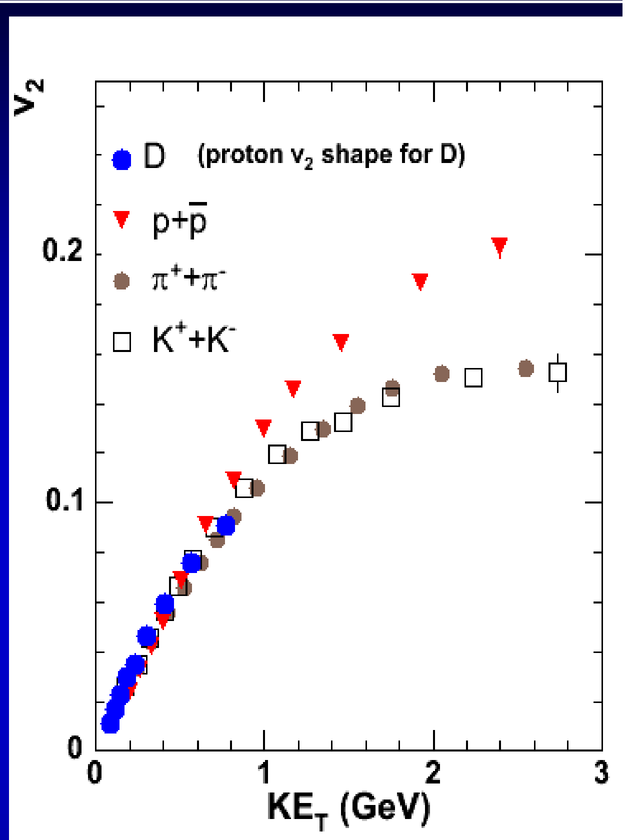


Scaling flow parameters by quark content n_q resolves meson-baryon separation of final state hadrons

4^{th} Milestone: A fluid of quarks







v_2 for the φ follows that of other mesons

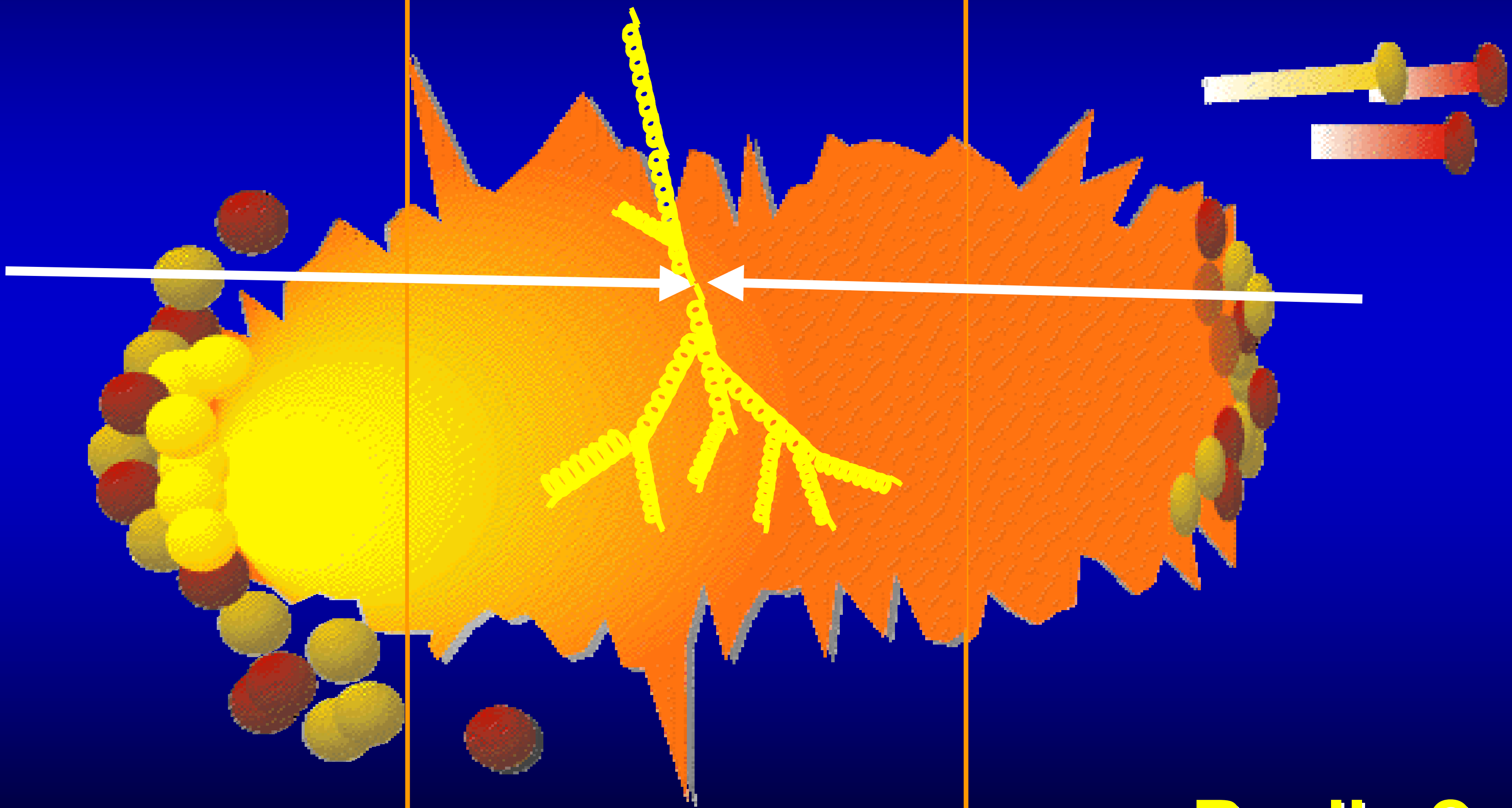
$$v_2^{hadron}\left(KE_T^{hadron}\right) \approx n v_2^{quark}\left(KE_T^{quark}\right)$$
$$KE_T^{hadron} \approx n KE_T^{quark}$$

v_2 for the D follows that of other mesons

Strange and even charm quarks participate in the flow

Connecting Soft and Hard Regimes

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



those on the "far side" are totally absorbed → Really ?

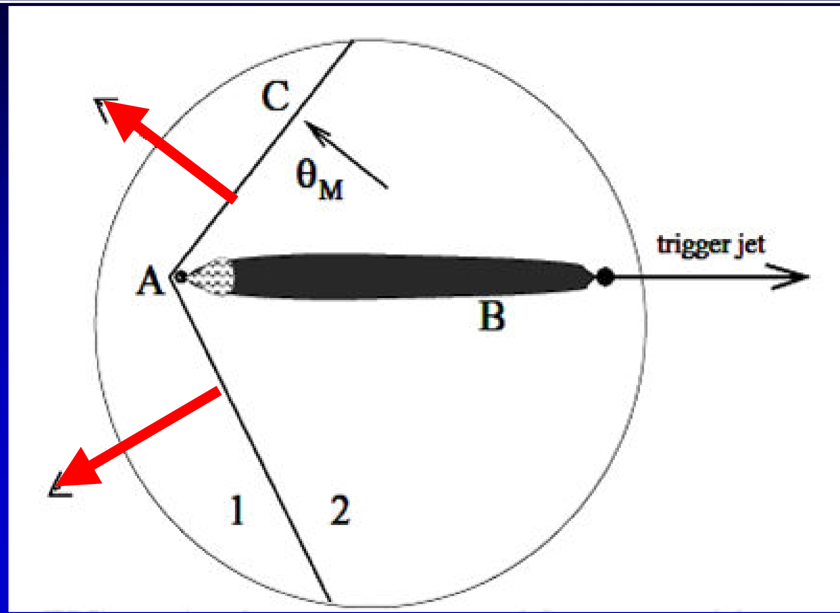
Fluid Effects on Jets ?

Mach cone?

- **Jets travel faster than the speed of sound in the medium.**
- **While depositing energy via gluon radiation.**

QCD "sonic boom" (?)

To be *expected* in a *dense fluid* which is *strongly-coupled*



High p_T Parton → Low p_T "Mach Cone"?

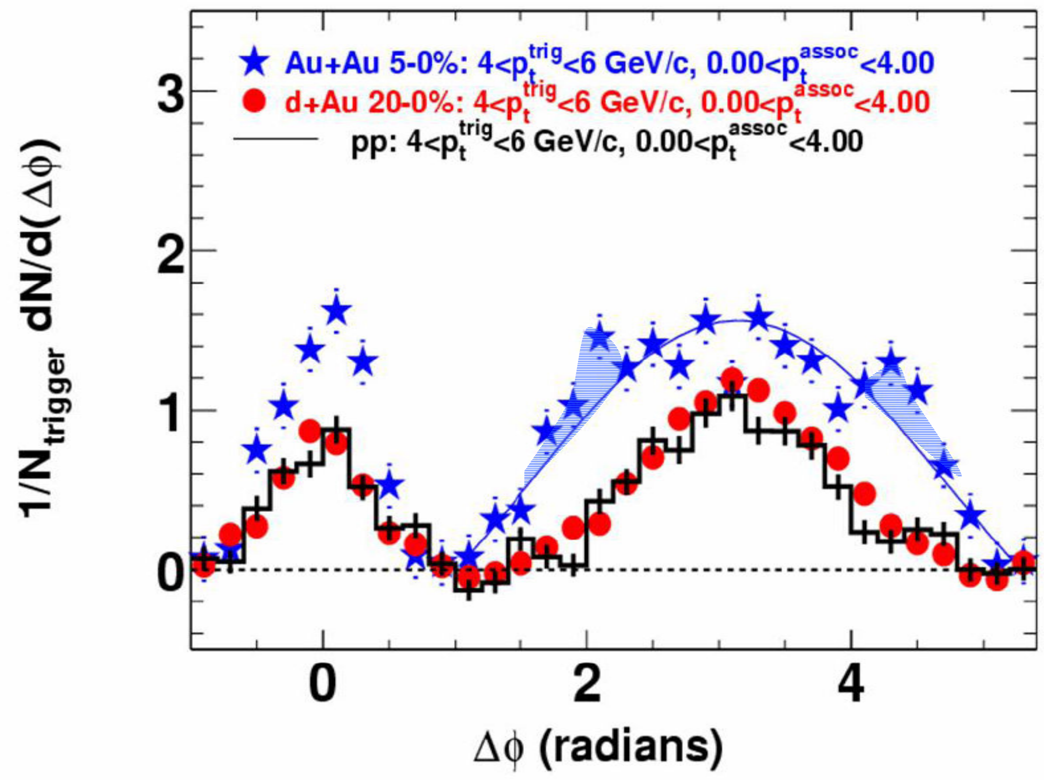
The "*disappearance*" is
that of the
high p_T partner

But at low p_T,
see *re-appearance*

and

"Side-lobes"
(Mach cones?)

… Matter is Opaque



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

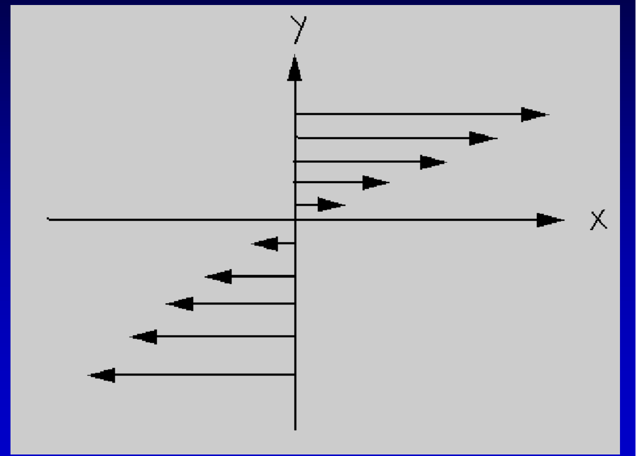
Viscosity Primer

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 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 $AdS_5 \times S^5$ 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

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)

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

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)

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

C
H
A
R
M
!

Milestone # 5: Perfection at limit!

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

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

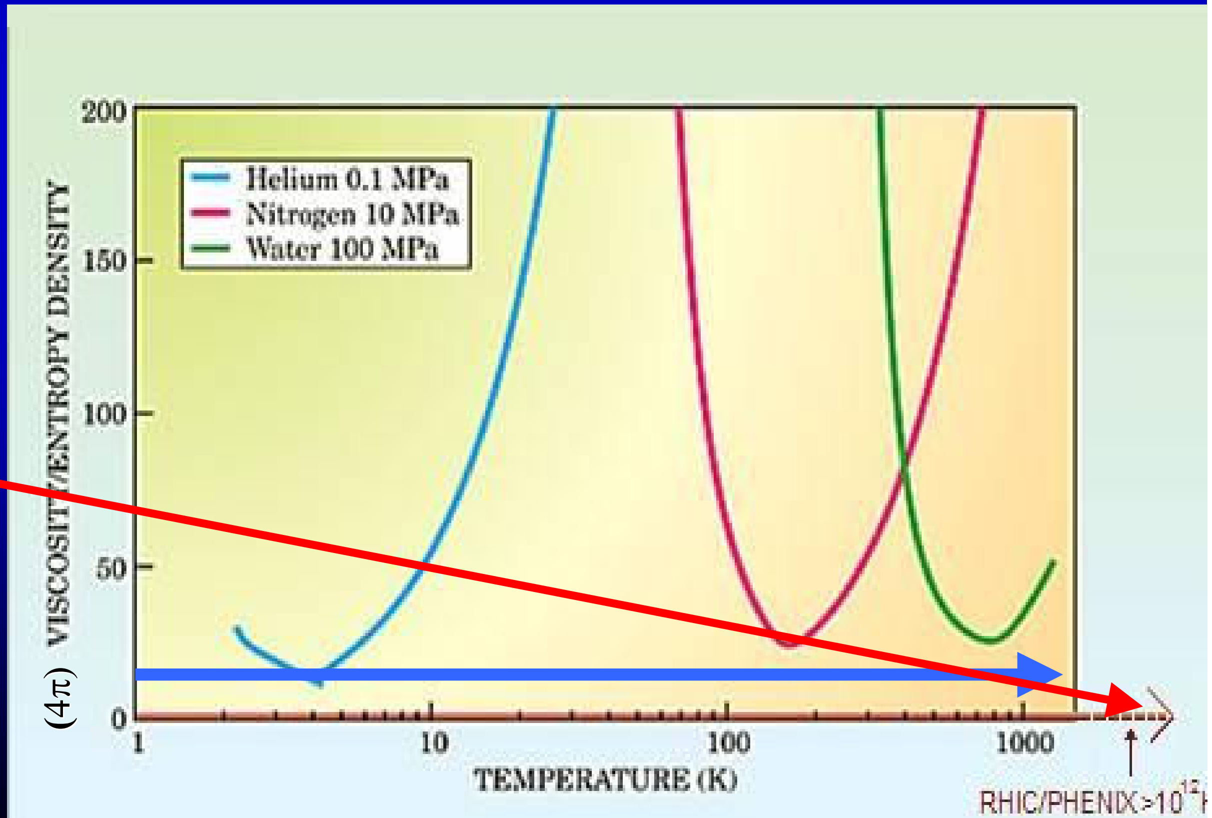
$\eta = 0 \rightarrow$ "perfect fluid"

But there is a (conjectured) quantum limit:

"*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…

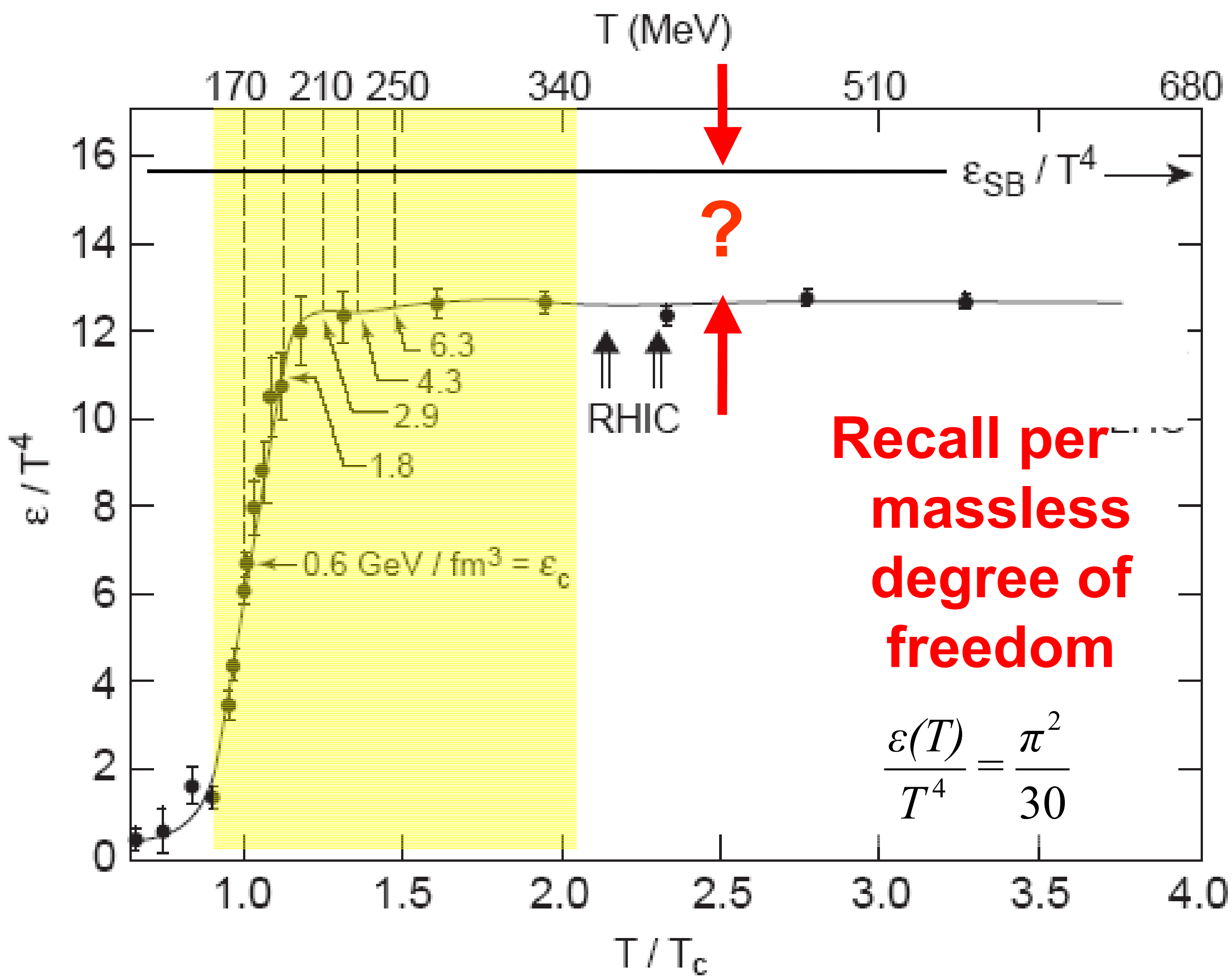
RHIC and the Phase "Transition"

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

High T_{init} ~ 300 MeV

to

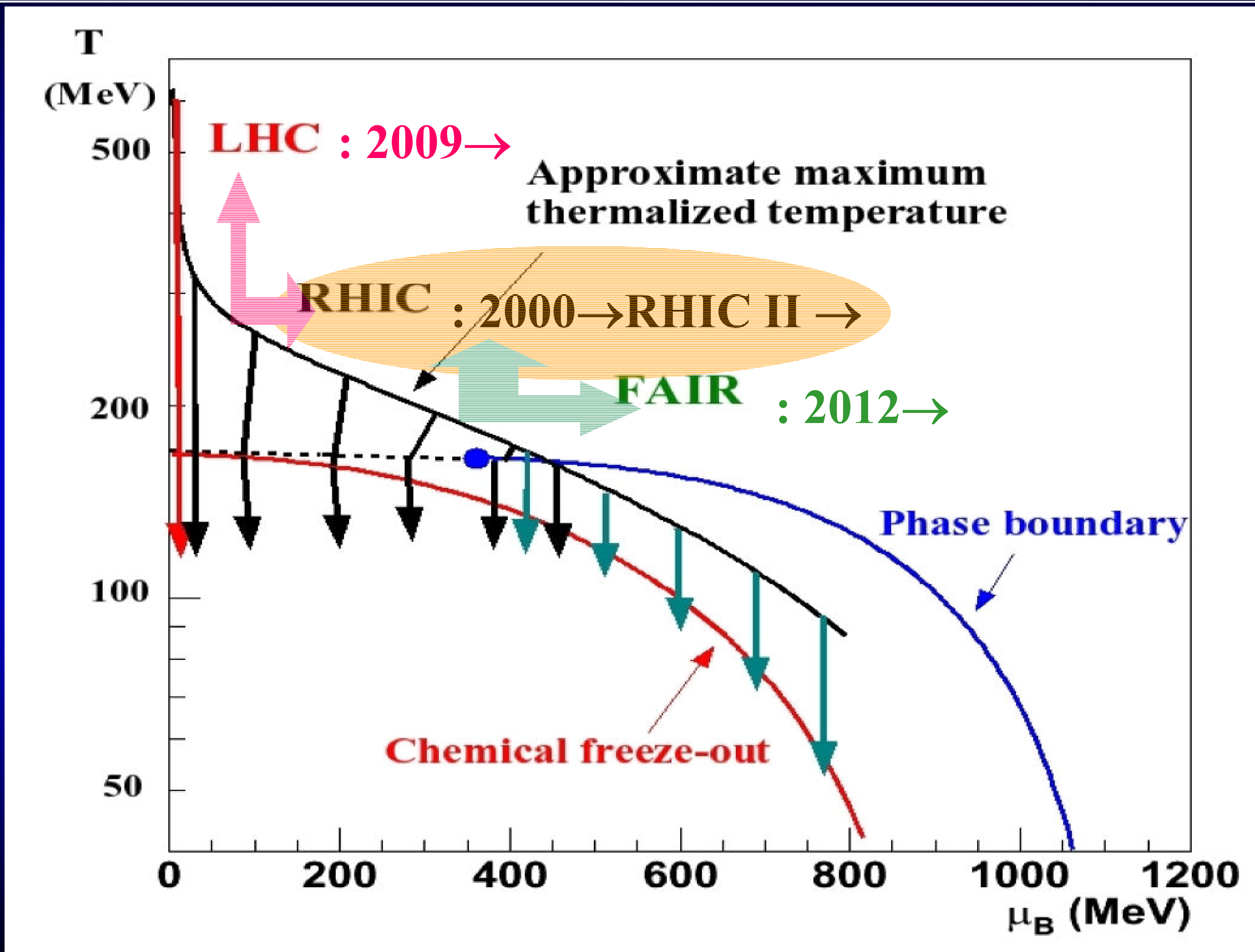
Low T_{final} ~ 100 MeV



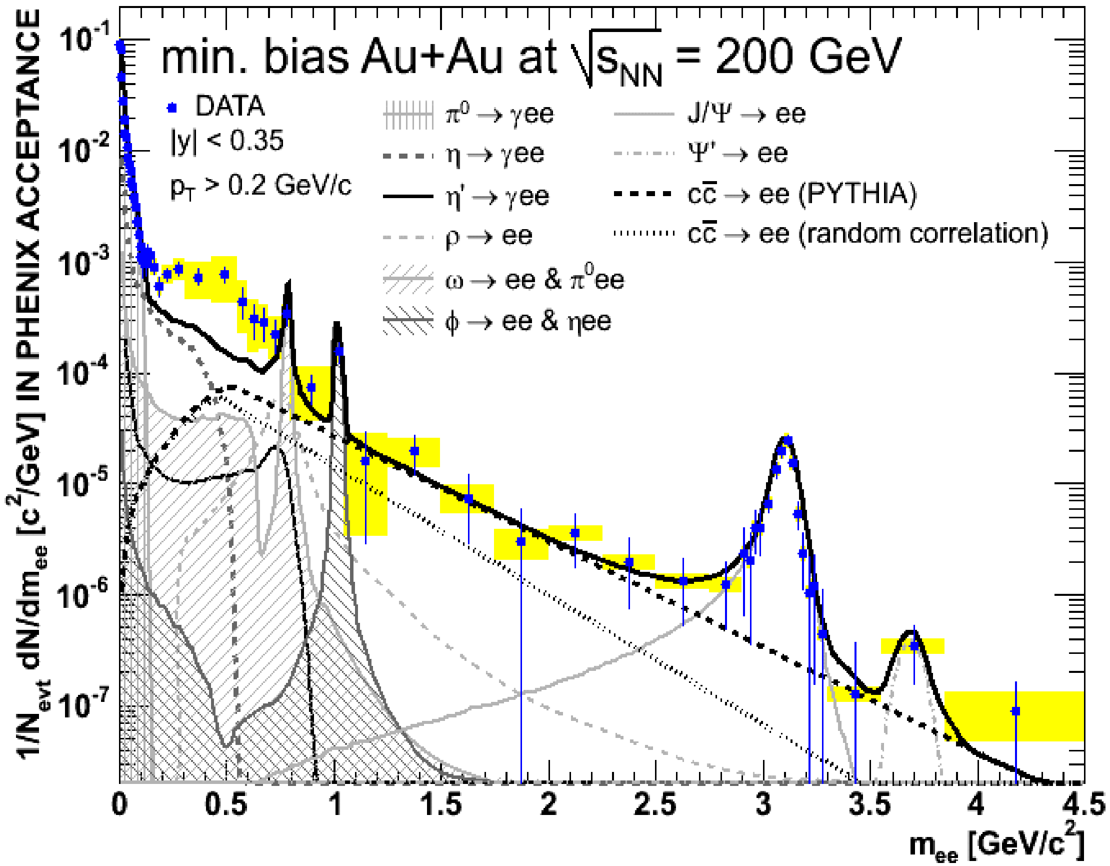
Recall per massless degree of freedom

$$\frac{\varepsilon(T)}{T^4} = \frac{\pi^2}{30}$$

World Context



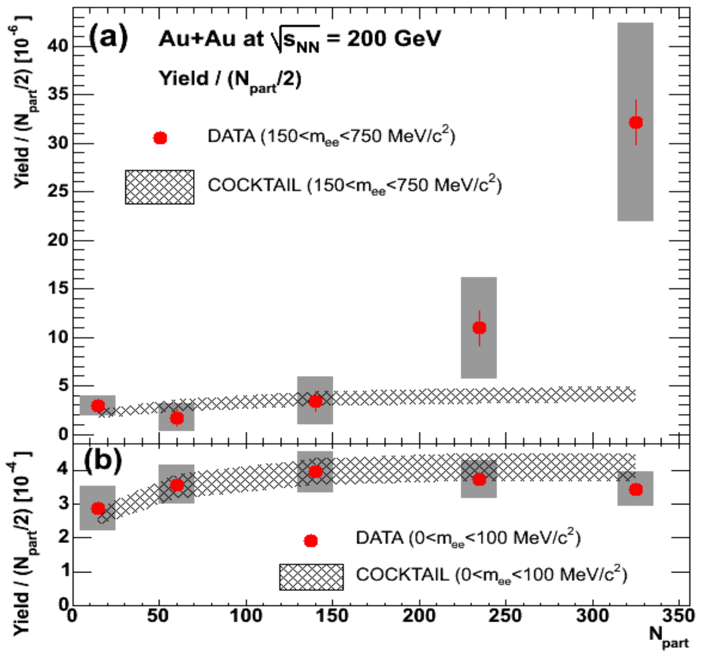
PHENIX dileptons: signal of chiral dynamics ?



low mass dilepton excess at RHIC!

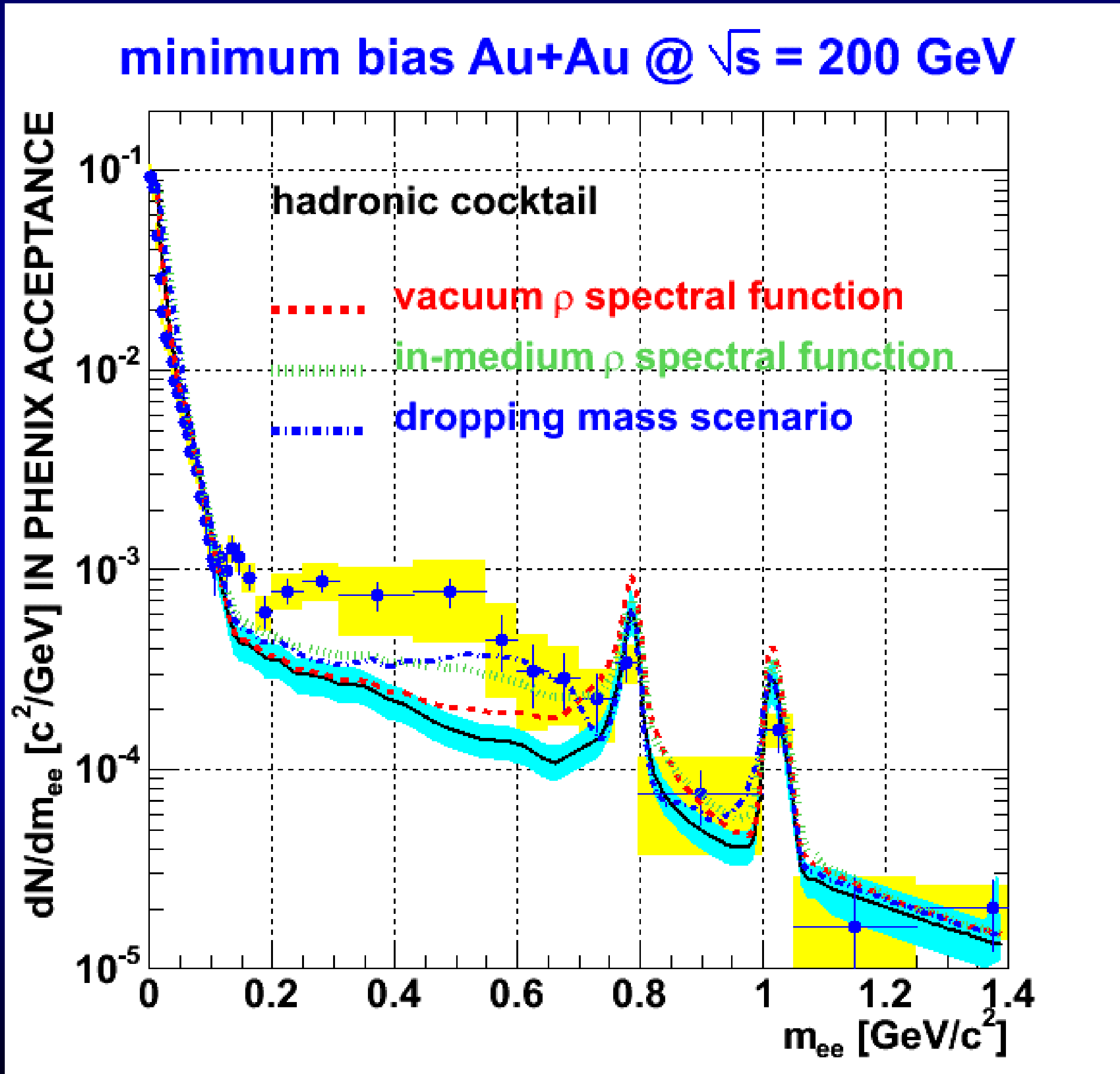
yield grows faster than N_{part}

excess > ρ modification



PHENIX
submitted to Phys. Rev. Lett
arXiv:0706.3034

Comparison: ρ mass modification



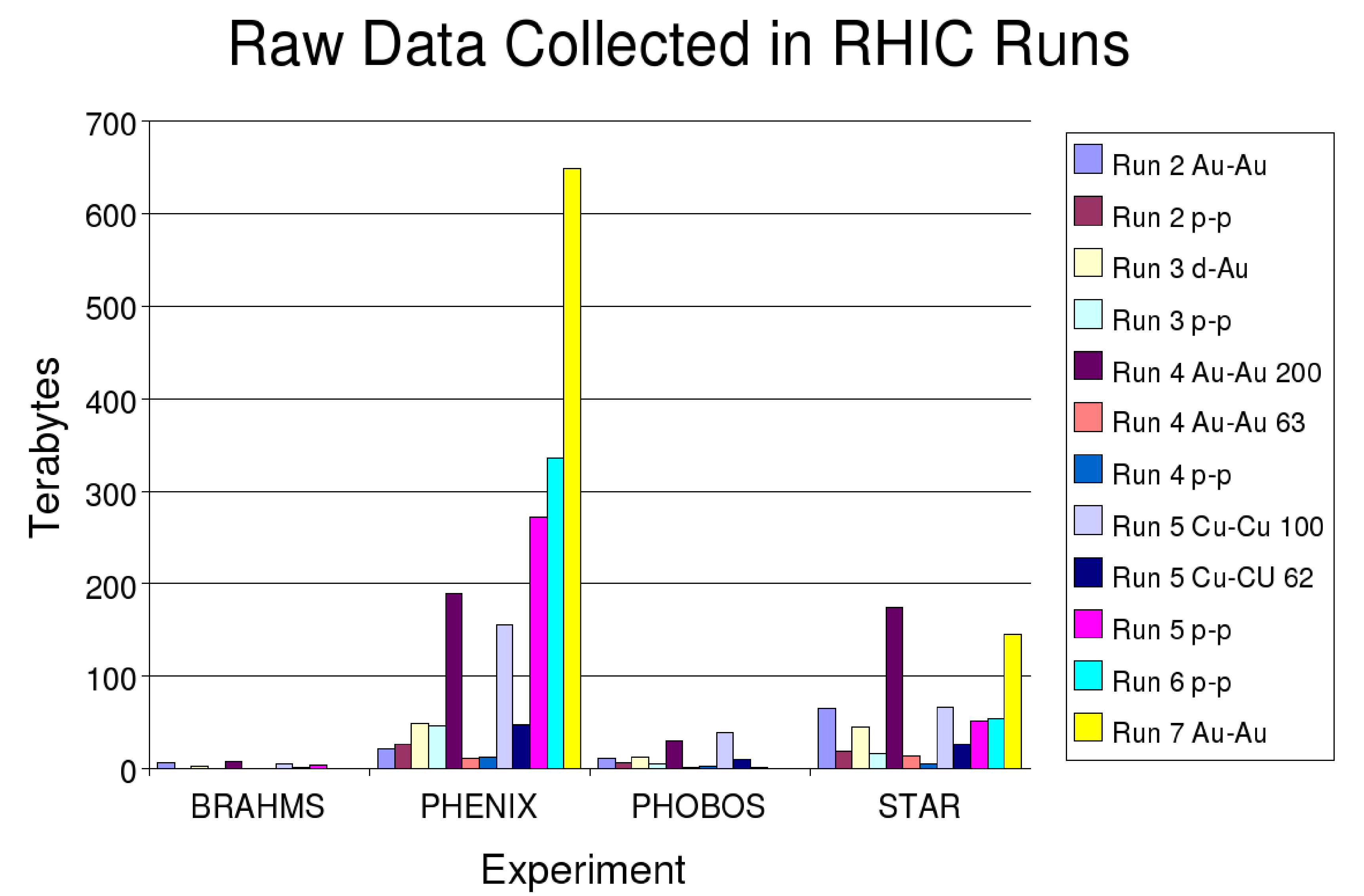
calculations
for min bias QGP
thermal radiation included

Broad range enhancement
$150 < m_{ee} < 750$ MeV
3.4±0.2(stat.)
±1.3(syst.)±0.7(model)

PHENIX
submitted to Phys. Rev. Lett
arXiv:0706.3034

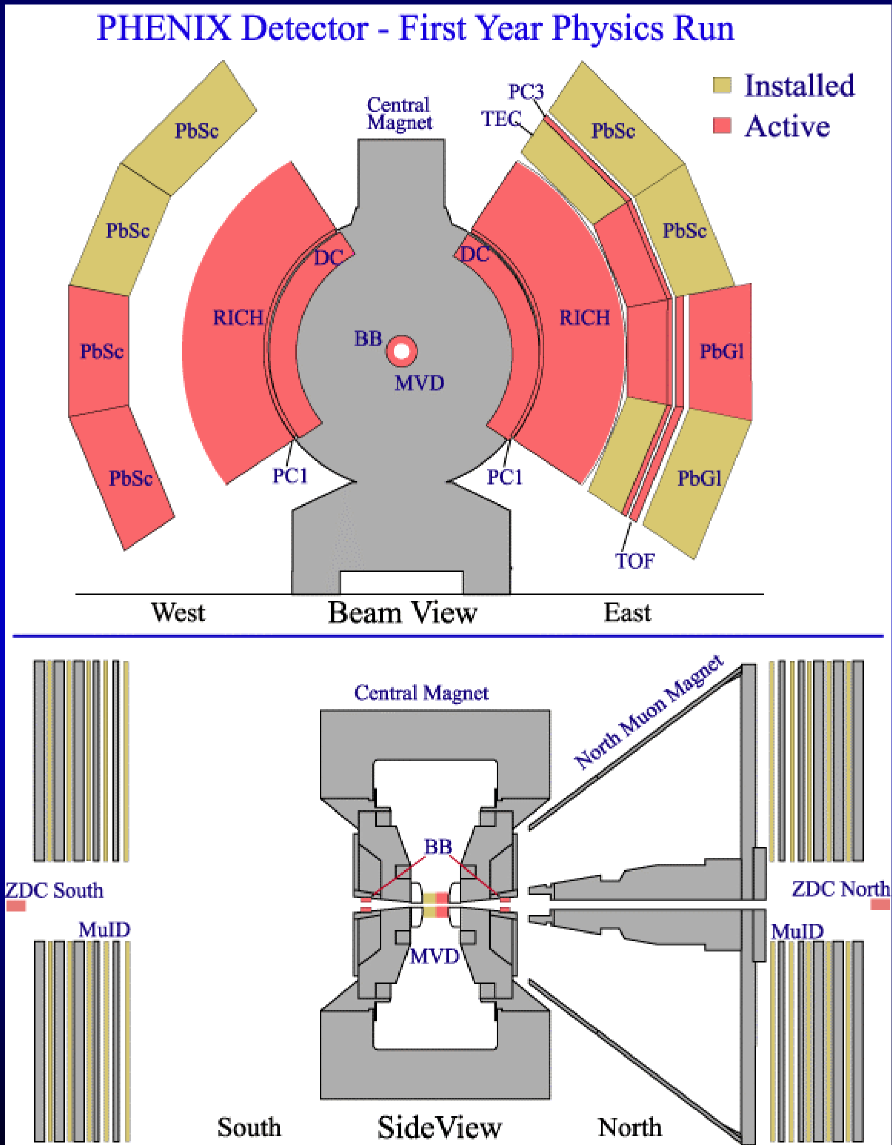
R.Rapp, Phys.Lett. B 473 (2000)
R.Rapp, Phys.Rev.C 63 (2001)
R.Rapp, nucl/th/0204003

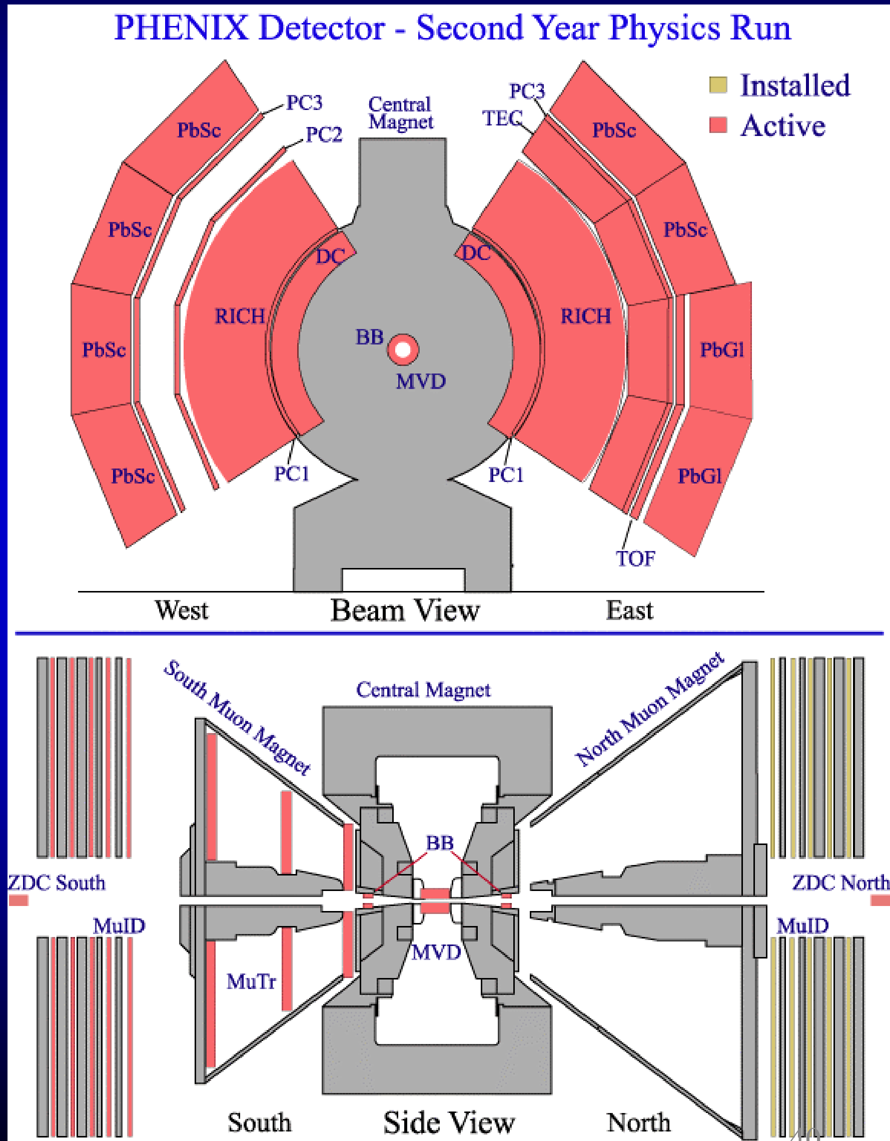
Run-7 a major success!



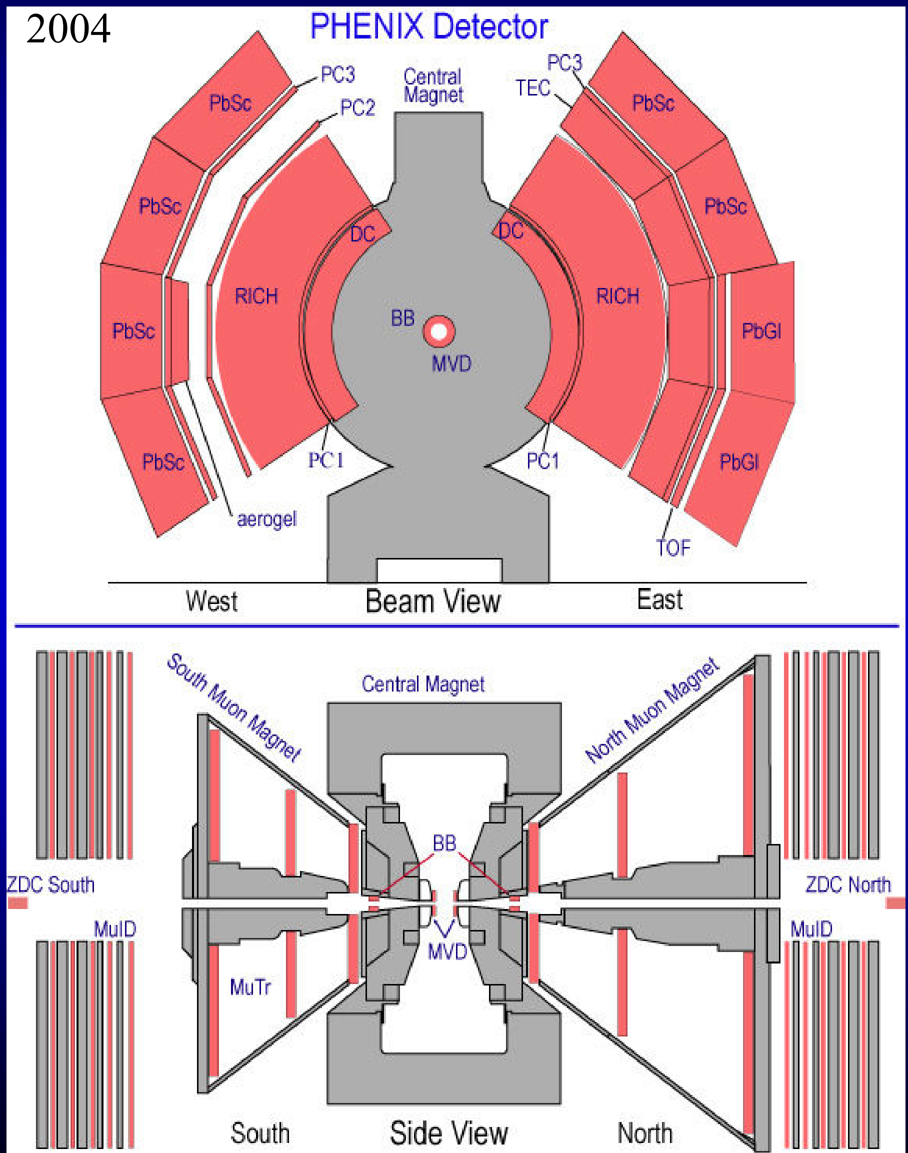
+ RXNP, TOF-W, MPC, HBD

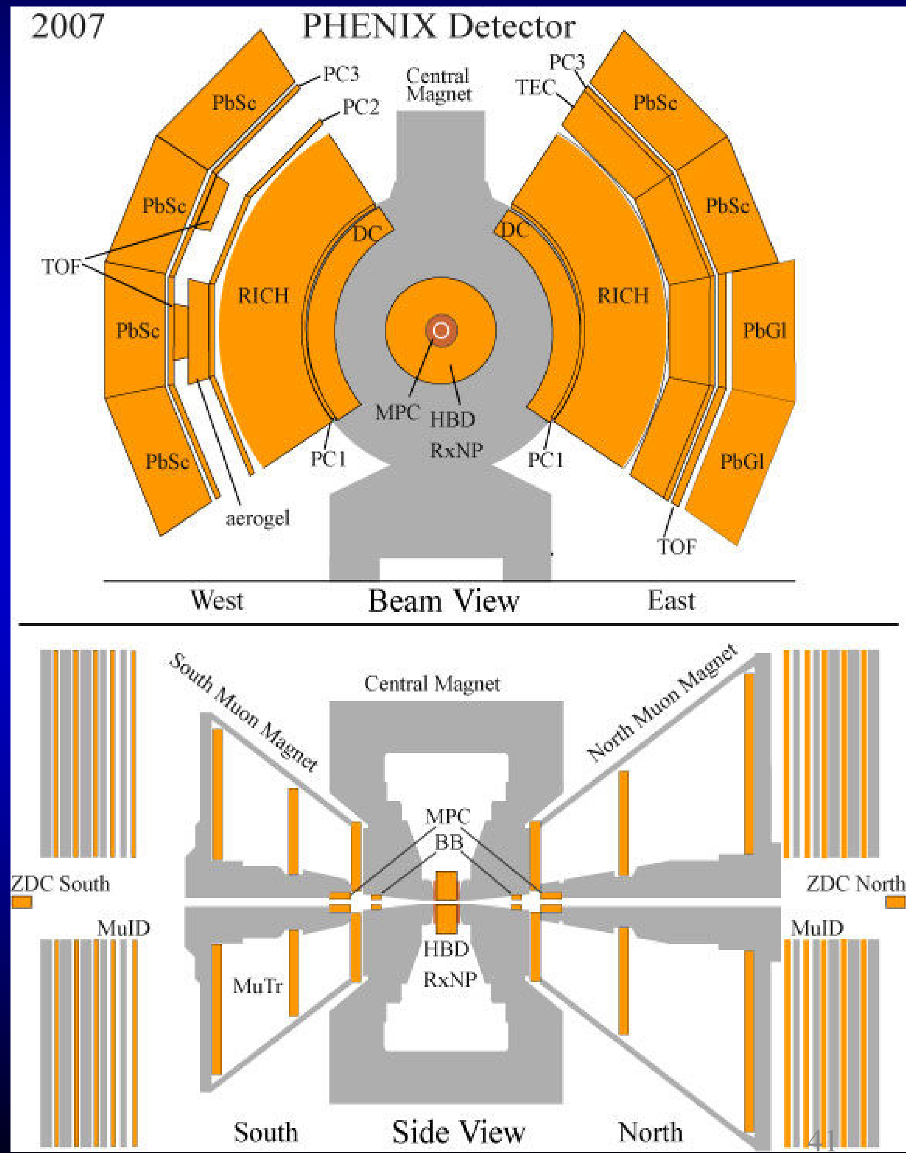
Earlier detector configurations





Recent detector configurations





PHENIX Upgrades

Run-7 had 4 new detector systems!

RXNP, TOF-W, MPC, HBD

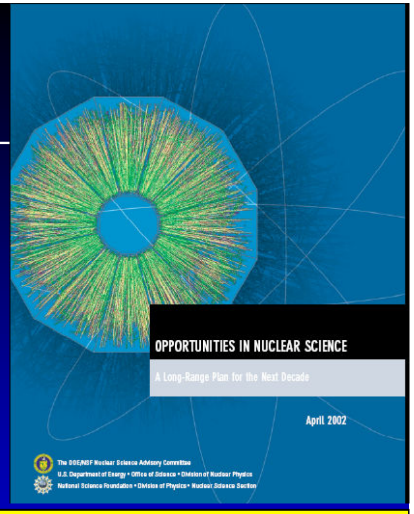
- integration was smooth thanks to PHENIX team!
- will use in data analysis; HBD repairs underway

Muon trigger, VTX, DAQup in construction

FVTX and NCC are jumping the approval hoops

- add MAJOR physics capabilities: χ_c, forward c/b separation, gamma-jet acceptance, low x π^0, γ

US-Nucl.Phys. Long Range Plan



exercise every ~ 5 years

met in Galveston in May, report in fall

RHIC II luminosity upgrade discussed

recommendation:

The experiments at the Relativistic Heavy Ion Collider have discovered a new state of matter at extreme temperature and density—a quark-gluon plasma that exhibits unexpected, almost perfect liquid dynamical behavior. **We recommend implementation of the RHIC II luminosity upgrade, together with detector improvements, to determine the properties of this new state of matter.**

good news:

RHIC II construction recommended in next 5 years

bad news: NP budget constrained, MAY grow

→ need to make RHICII as cheap as possible

→ we will be asked to trade off running time to offset part of the cost

Summary: PHENIX Collaboration, 2007

One of today's major accelerator based hep-ex and nucl-ex projects,

thanks to

14 countries
68 institutions
~550 participants

including:
- **Debrecen University, Debrecen, Hungary**
- **ELTE University, Dept. Atomic Physics, Budapest, Hungary**
- **MTA KFKI RMKI, Hungarian Academy of Sciences**

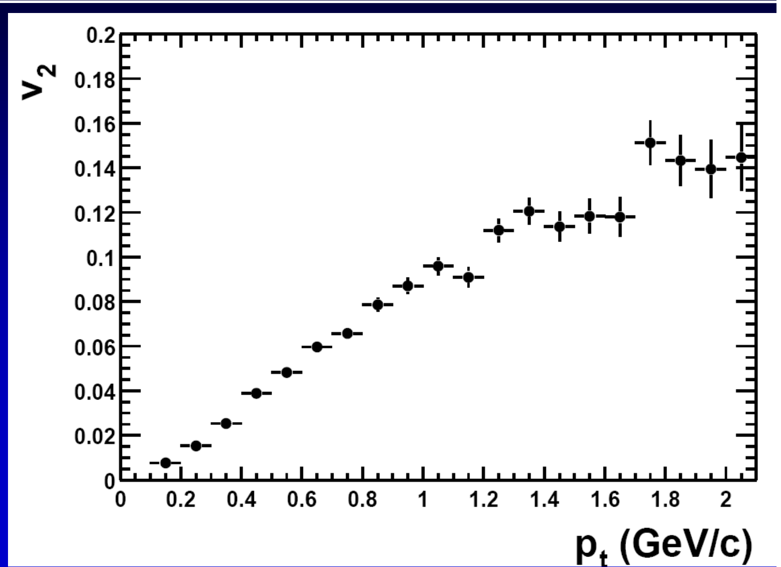
Back-up Slides

RHIC's Two Major Discoveries

Discovery of strong "elliptic" flow:

Elliptic flow in Au + Au collisions at $\sqrt{s_{NN}}$= 130 GeV, STAR Collaboration, (K.H. Ackermann *et al.*). Phys.Rev.Lett.86:402-407,2001

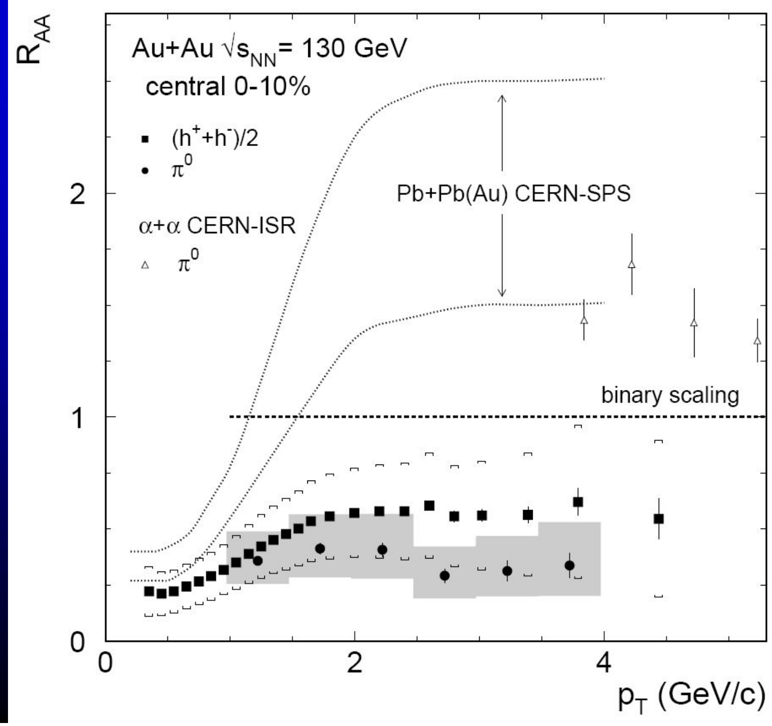
318 citations



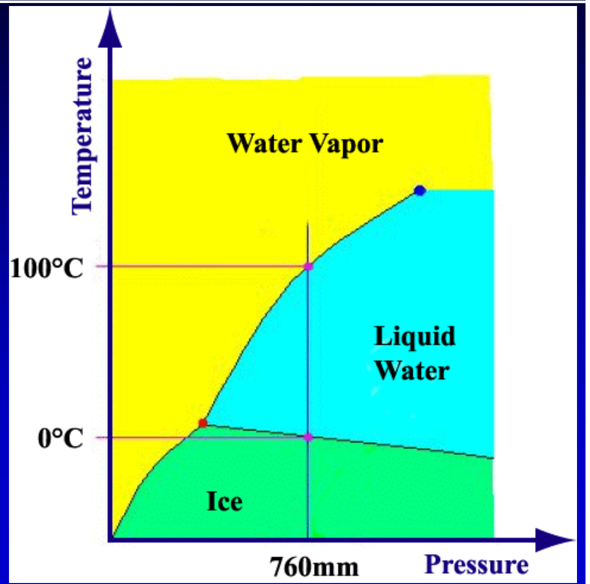
Discovery of "jet quenching"

Suppression of hadrons with large transverse momentum in central Au+Au collisions at $\sqrt{s_{NN}}$ = 130 GeV, PHENIX Collaboration (K. Adcox *et al.*), Phys.Rev.Lett.88:022301,2002

384 citations



Is There a QCD Critical Point?



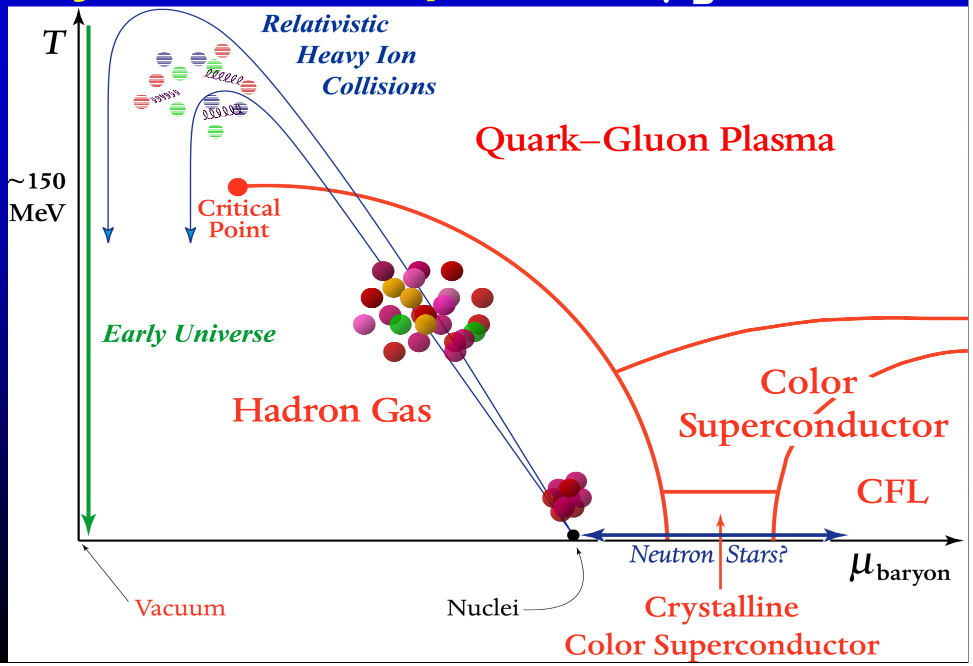
Here the analogy with phase transitions in ordinary matter breaks down:

Recall " Properties of the medium are (at zero baryon number) uniquely determined by T "

Pressure = P(T) can't vary independently (unlike water)

But if baryon number is non-zero

⇨ (intensive order parameter) baryon chemical potential μ_B :



To increase μ_B :

Lower collision energy

Raise atomic mass

Both part of RHIC II and GSI-FAIR

The New QGP

"Formerly known as quark-gluon plasma?"

You can still use that label if you like, but- ***PARADIGM SHIFT***

- RIHC does not produce asymptotically "free" quarks and gluons
- Contrary to expectations (and announcements !), we did not find evidence for "*quarks (that) are liberated to roam freely*"

The analogy to atomic plasmas is also strained:

- Atomic plasmas:
  - Can vary density and temperature independently
  - Photon momentum-energy density (usually) irrelevant
  - Can be strongly-coupled or weakly coupled
- "QGP"
  - One number (the temperature T) determines all properties
  - Intrinsically strongly-coupled fluid for any(?) accessible T

Only with QCD can we experimentally explore fundamental matter in this unique state $\equiv$ ***Quantum Gauge Perfect fluid***

Heavy Flavor

All(?) length scales in the QCD plasma are "degenerate":

- i.e. they all are proportional to 1/T
  - (times various powers of g)

Fix this by introducing heavy flavor:

- $M_c \sim 1.3$ GeV
- $M_b \sim 5.0$ GeV

to introduce new scales

- $1 / M_c \sim 0.15$ fm
- $1 / M_b \sim 0.04$ fm
- Flavor tagged jets

Bohr radii (onium):

- $J/\Psi \sim 0.29$ fm
- $\Upsilon \sim 0.13$ fm
- "Onium" spectroscopy

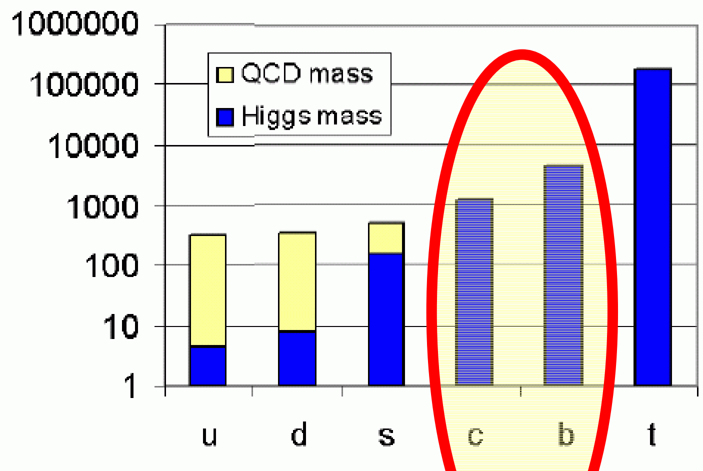
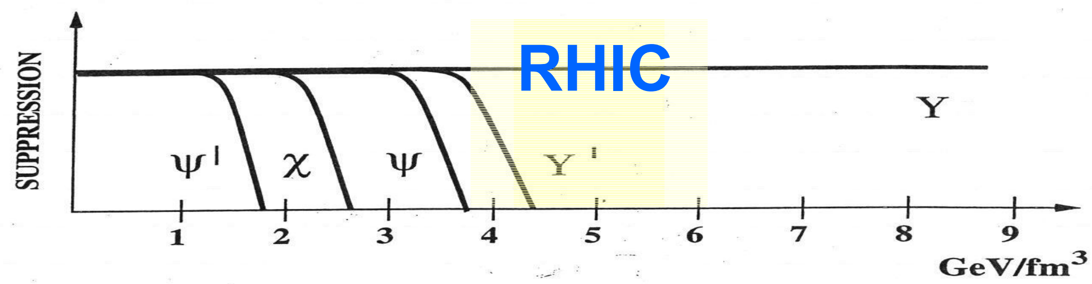


FIG. 1: Masses of the six quark flavors. The masses generated by electroweak symmetry breaking (current quark masses) are shown in dark blue; the additional masses of the light quark flavors generated by spontaneous chiral symmetry breaking in QCD (constituent quark masses) are shown in light yellow. Note the logarithmic mass scale.



Performing these measurements is a goal of the ongoing upgrades program at RHIC

Ideal Hydrodynamics

Why the interest in viscosity?

A.) Its vanishing is associated with the applicability of ideal hydrodynamics (Landau, 1955):

$$\text{Ideal Hydro} \equiv \text{Reynolds number} \quad \Re \approx \frac{\text{Inertial Forces}}{\text{Drag Forces}} \equiv \frac{\rho V_{BULK} L}{\eta} >> 1$$

$$\eta \approx \rho \, v_{thermal} \, (mfp) \quad \text{so} \quad \Re \approx \frac{\rho V_{BULK}}{\rho v_{thermal}} \frac{L}{mfp} >> 1 \quad \Rightarrow \frac{L}{mfp} >> 1$$

B.) Successes of ideal hydrodynamics applied to RHIC data suggest that the fluid is "as perfect as it can be", that is, it approaches the (conjectured) quantum mechanical limit

$$\eta \geq \frac{\hbar}{4\pi} (\text{entropy density}) = \frac{\hbar}{4\pi} s$$

See "*A Viscosity Bound Conjecture*",

P. Kovtun, D.T. Son, A.O. Starinets, hep-th/0405231

Static Slide Images

Origin of the (Hadronic) Species

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

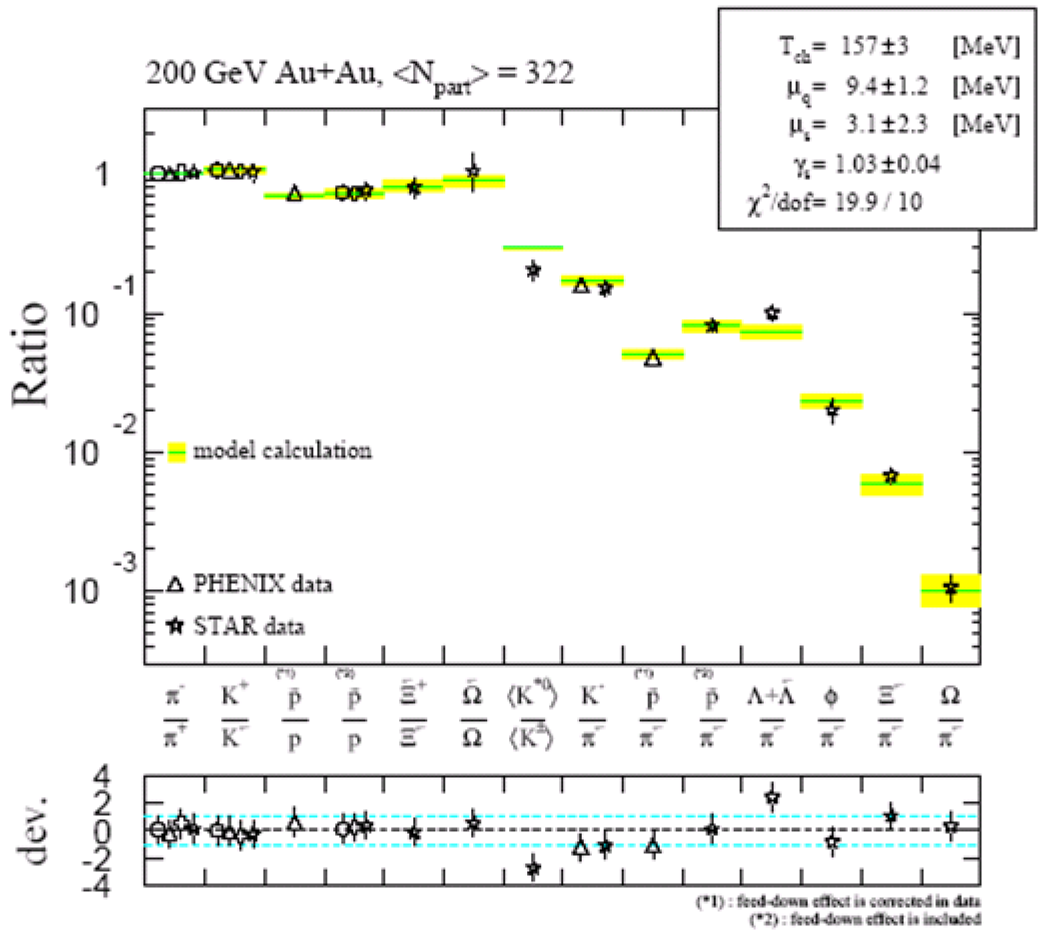
    $$dn \sim e^{-(E-\mu)/T} d^3 p$$

    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



22-Sep-06

Thermal QCD

- In relativistic nuclear collisions
  - Wave-functions? No
  - Partition functions? Yes!
- Start over-
  - Inputs: Same QCD Lagrangian with
    - *Massless* quanta
    - Temperature T
    - Running coupling g(T)
- Reference points:
  - Thermal energy density ε for massless degree of freedom:

$$\varepsilon(T) = \frac{\pi^2}{30} T^4$$

  - Count the quanta:

$$= \left\{ 2 \cdot 8_g + \frac{7}{8} \cdot 2_s \cdot 2_a \cdot 2_f \cdot 3_c \right\} \frac{\pi^2}{30} T^4$$

$$= 37 \cdot \frac{\pi^2}{30} T^4$$

8 gluons, 2 spins;
← 2 quark flavors, anti-quarks, 2 spins, 3 colors

37 (!)