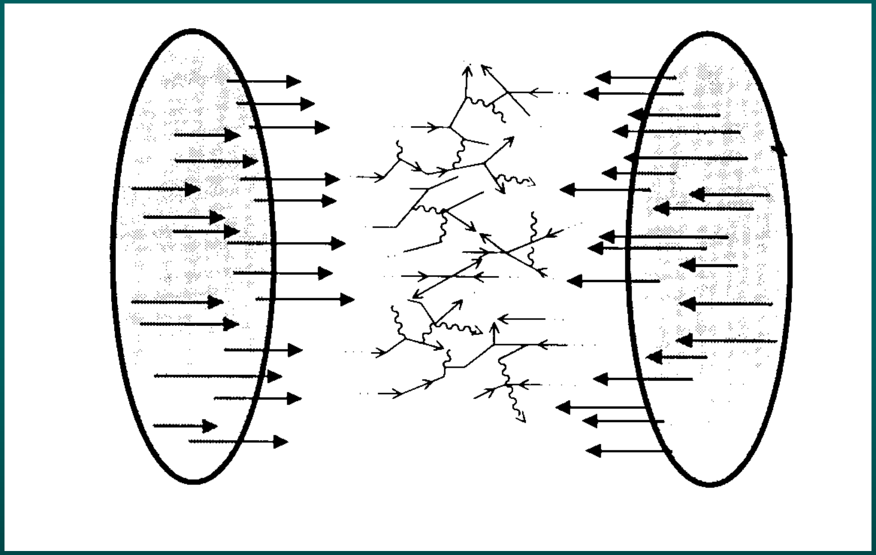
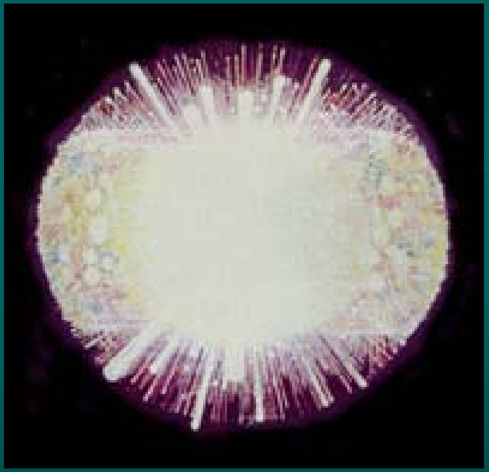
Heavy Ion Physics and Quark-Gluon Plasma





Jamie Nagle
University of Colorado at Boulder
Division of Particles and Fields Meeting

Start with the Bottom Line

The Relativistic Heavy Ion Collider has been operational since 2000 to study matter at extreme temperatures.

Have the accelerator and experiments been successfully commissioned and operated?

Yes

Have we created a system that is not hadronic?

Yes

Have we created a weakly interacting gas of quarks and gluons (the Quark-Gluon Plasma)?

No

Have we created a strongly interacting partonic system (a different type of Quark-Gluon Plasma)?

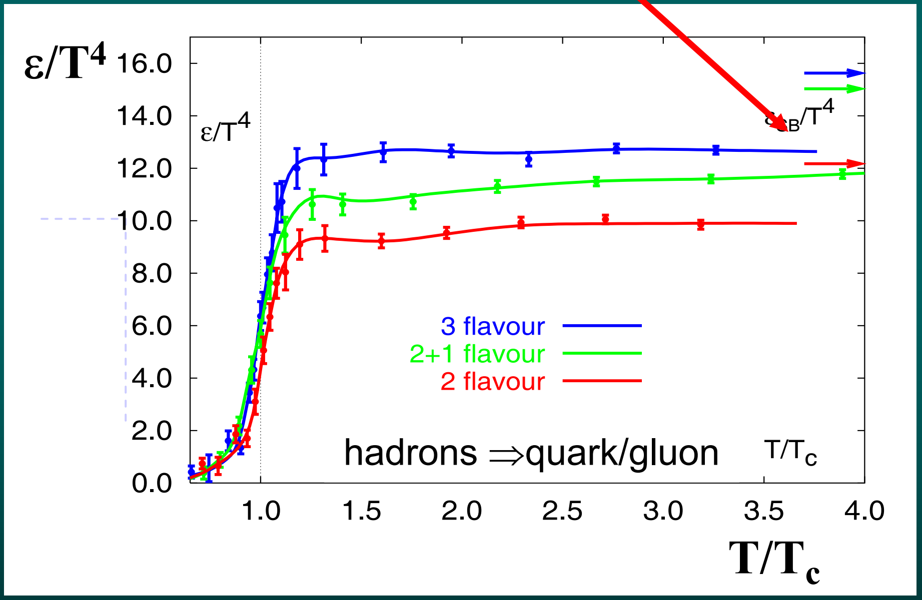
Yes

The Quark Gluon Plasma

Lattice QCD predicts a transition to a Quark Gluon Plasma at high temperature where the number of degrees of freedom is significantly increased.

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

Non-Interacting Gas Limit



Transition values:

T = 170 MeV

ε = 0.8 GeV/fm^3

Assumes thermal system.

"Weakly" interacting gas of quarks and gluons where the long range confining potential is screened.

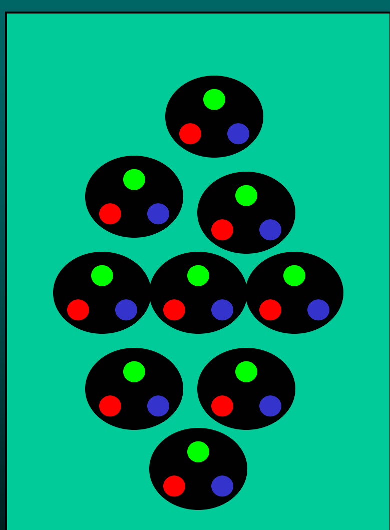
Deconfinement Transition

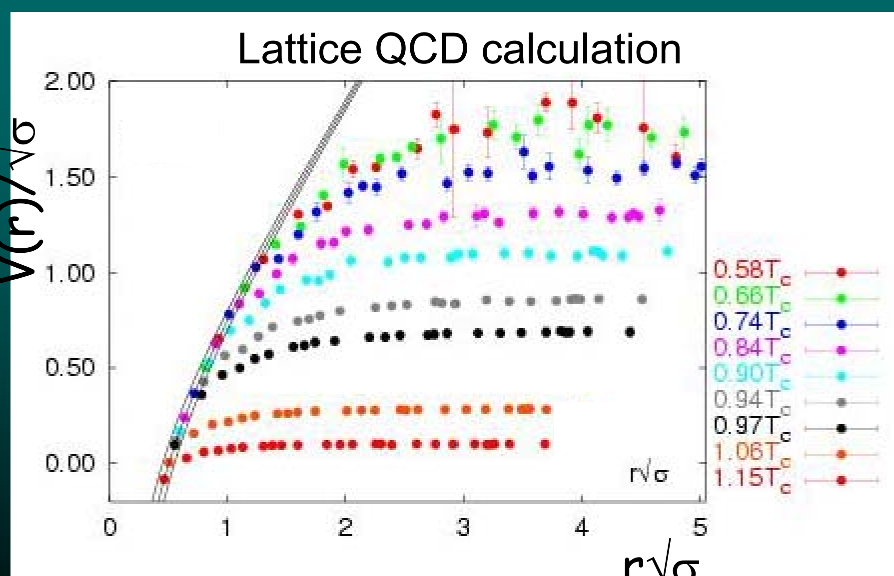
QCD in Vacuum

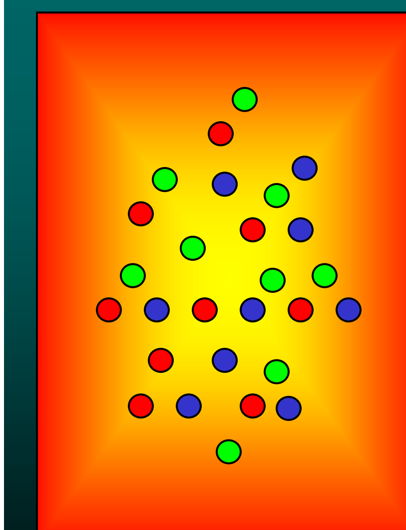
- linear increase in potential with distance from color charge
- strong attractive force
- spontaneous breaking of chiral symmetry
- confinement of quarks to hadrons baryons (qqq) and mesons (qq)

QCD in dense and hot matter

- screening of color charges
- potential vanishes for large distance scales
- restoration of approximate chiral symmetry as quarks act as nearly massless particles
- deconfinement of quarks !





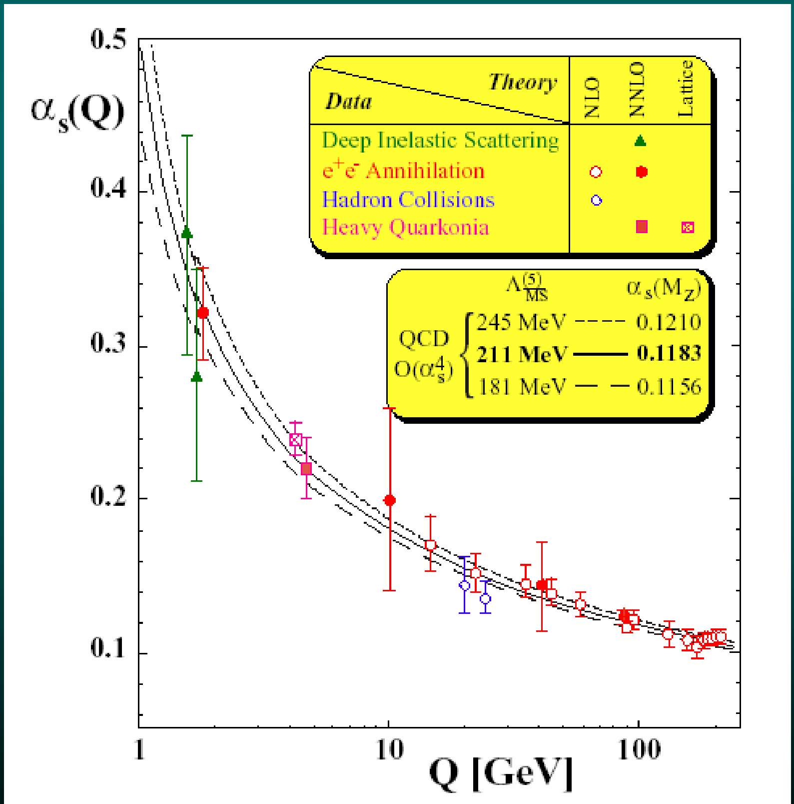


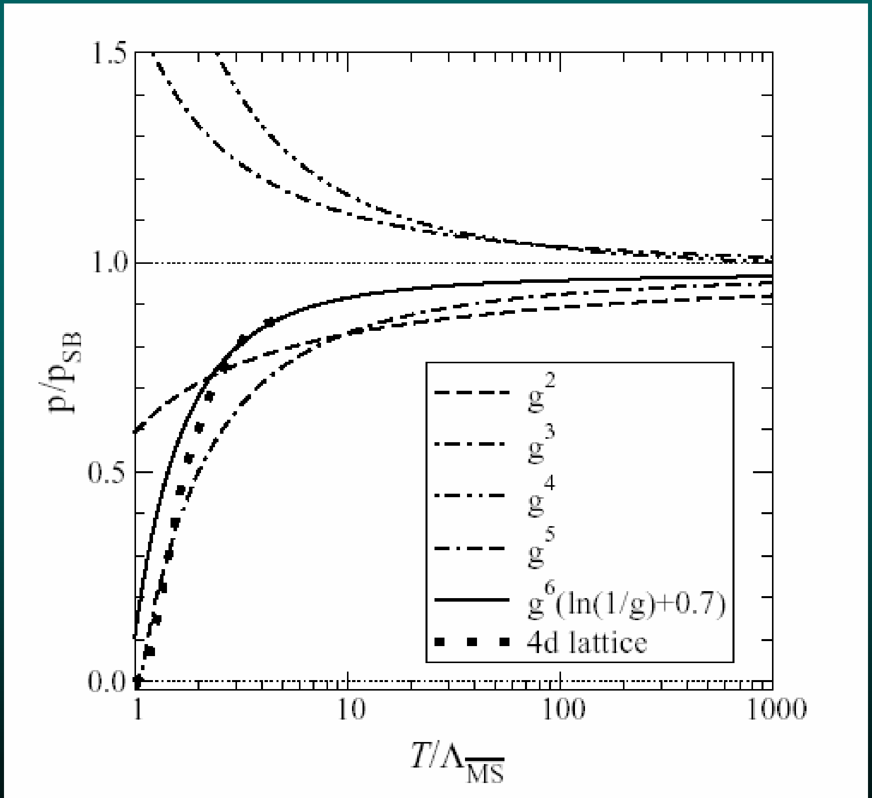
Weak versus Strong

Many calculations done in weak-coupled limit for simplicity.

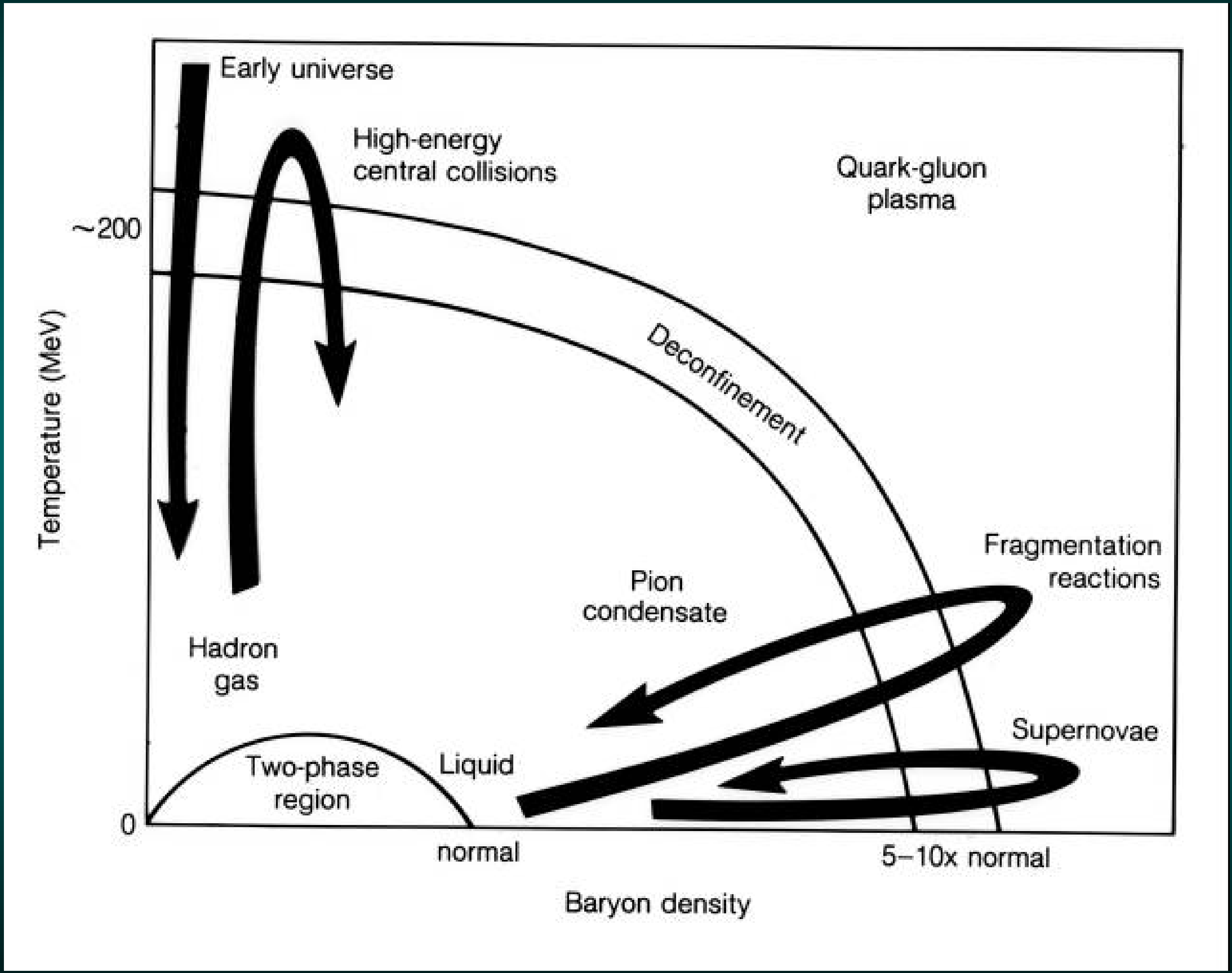
Only at very, very high temperatures does one achieve asymptotic freedom.

Really we expect a <u>strongly-coupled quark-gluon plasma</u>!



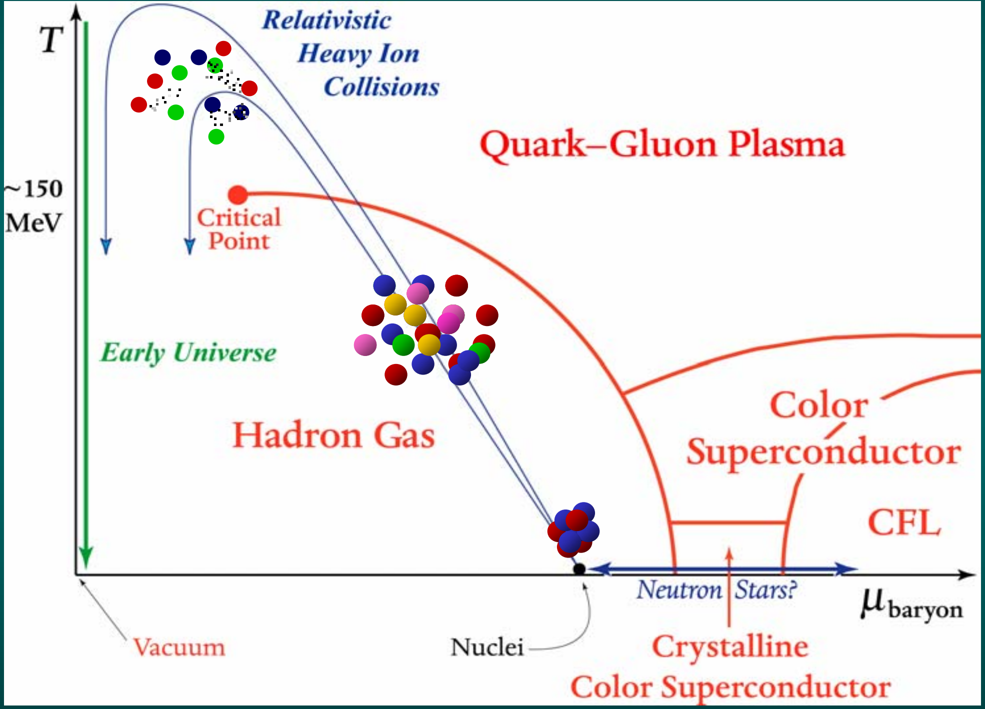


Phase Diagram



Phase Diagram Update

Major theoretical advances for high density matter (Wilczek, Rajogopal).
Quark-Quark interactions allow for Cooper pairs to form (not color neutral).
Renaming of QGP to Color Superconductor in high density region!

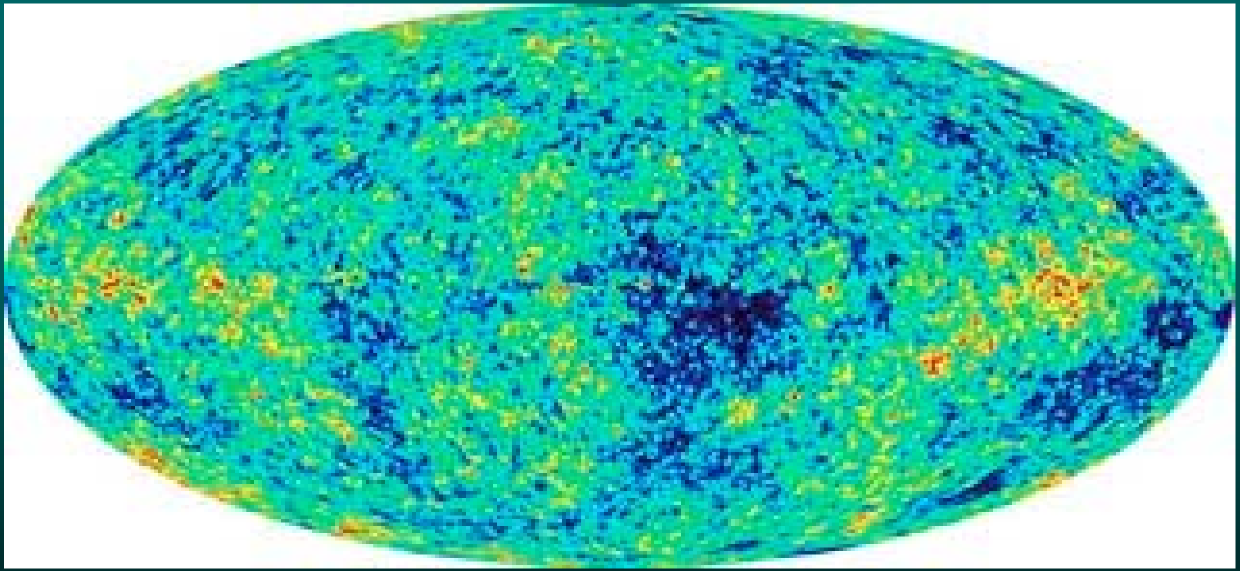


In the high temperature region we will here use the QGP definition as simply <u>a new state of matter where the fundamental degrees of freedom are not color neutral hadrons</u>.
Perhaps later we will come up with a more exciting name !

Early Universe

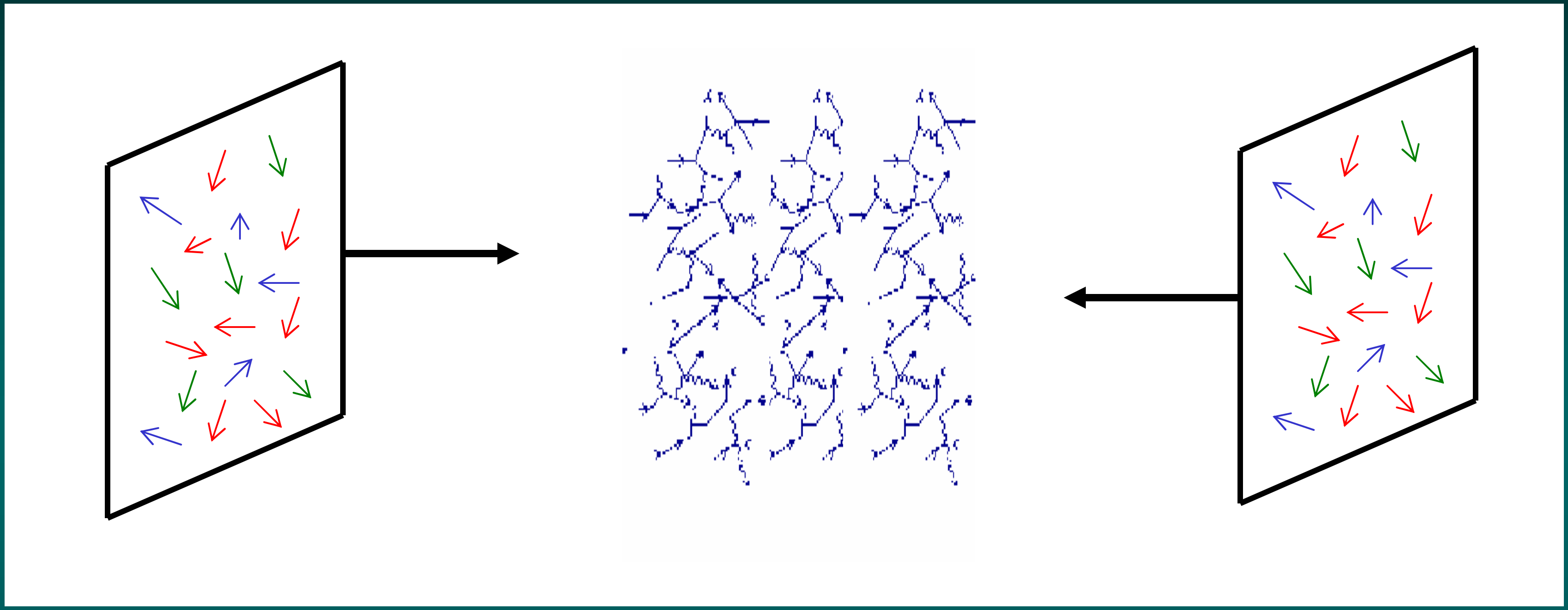
"A first-order QCD phase transition that occured in the early universe would lead to a surprisingly rich cosmological scenario." Ed Witten

Perhaps a very inhomogeneous universe even at the time of Big Bang Nucleosynthesis.



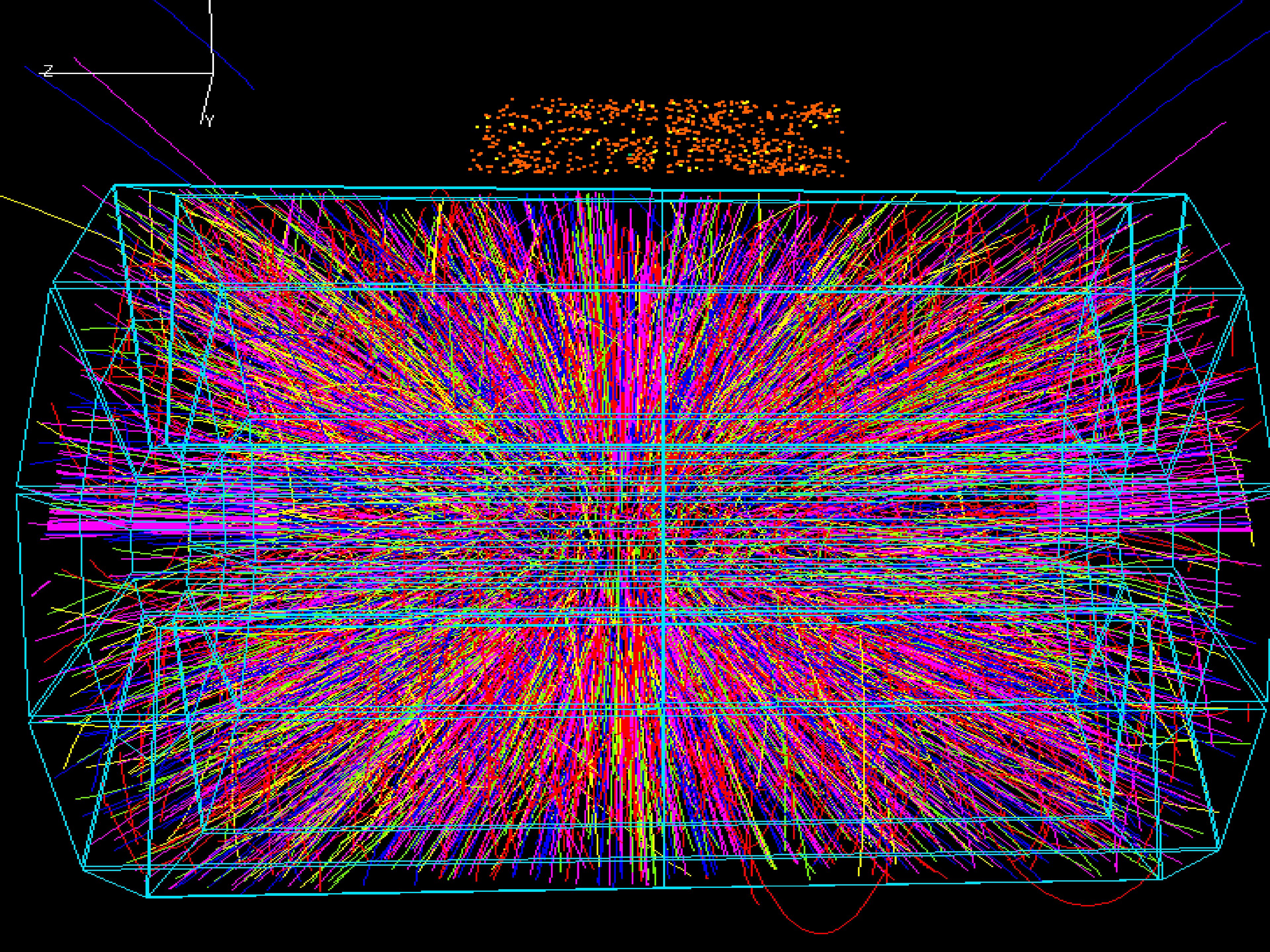
WMAP shows that it did not. Thus, we must study this aspect of QCD with accelerators.

Heavy Ion Collisions



10,000 gluons, quarks, and antiquarks
from the nuclear wavefunctions
are made physical in the laboratory !

What is the nature of this ensemble of partons?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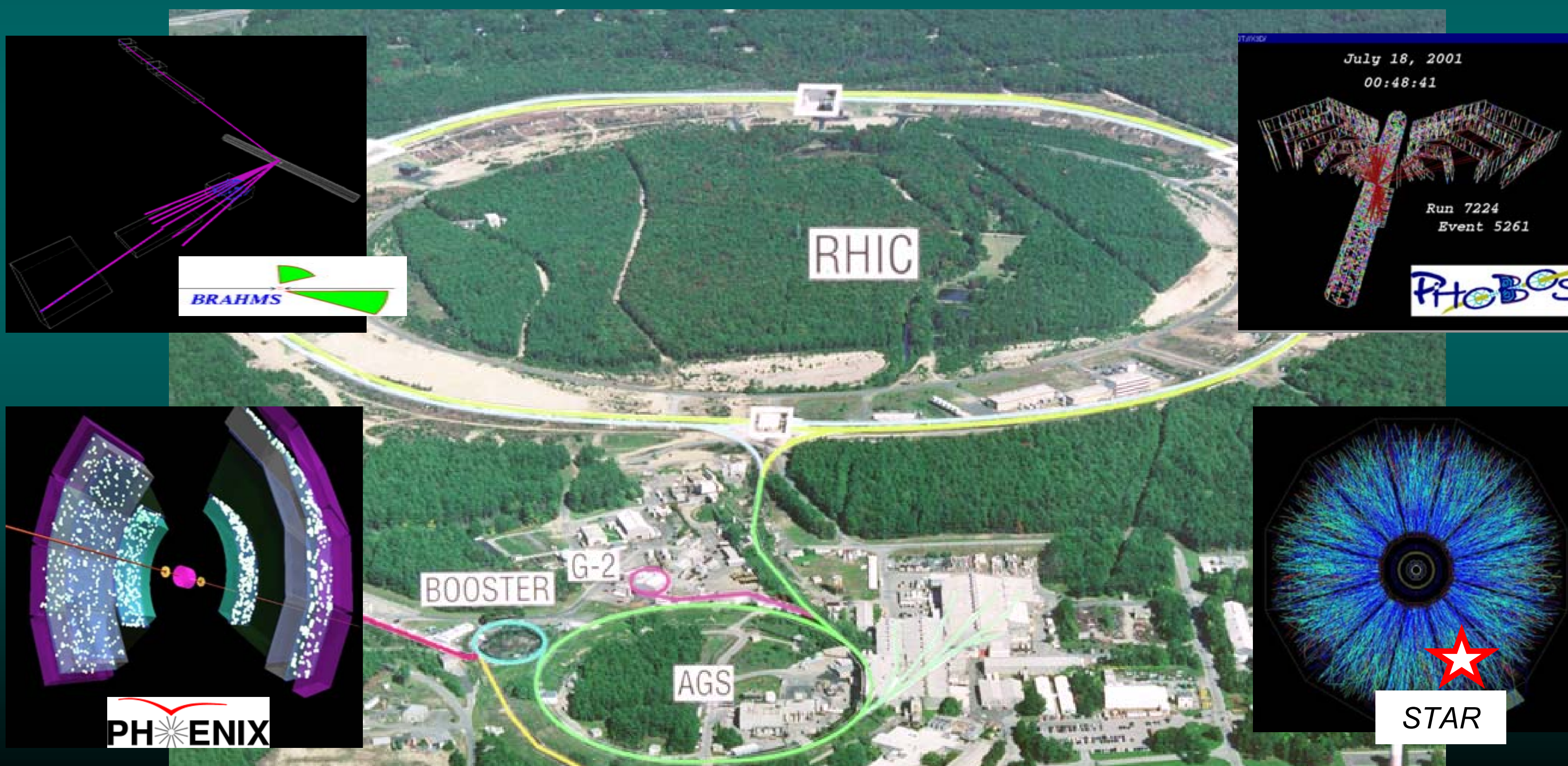
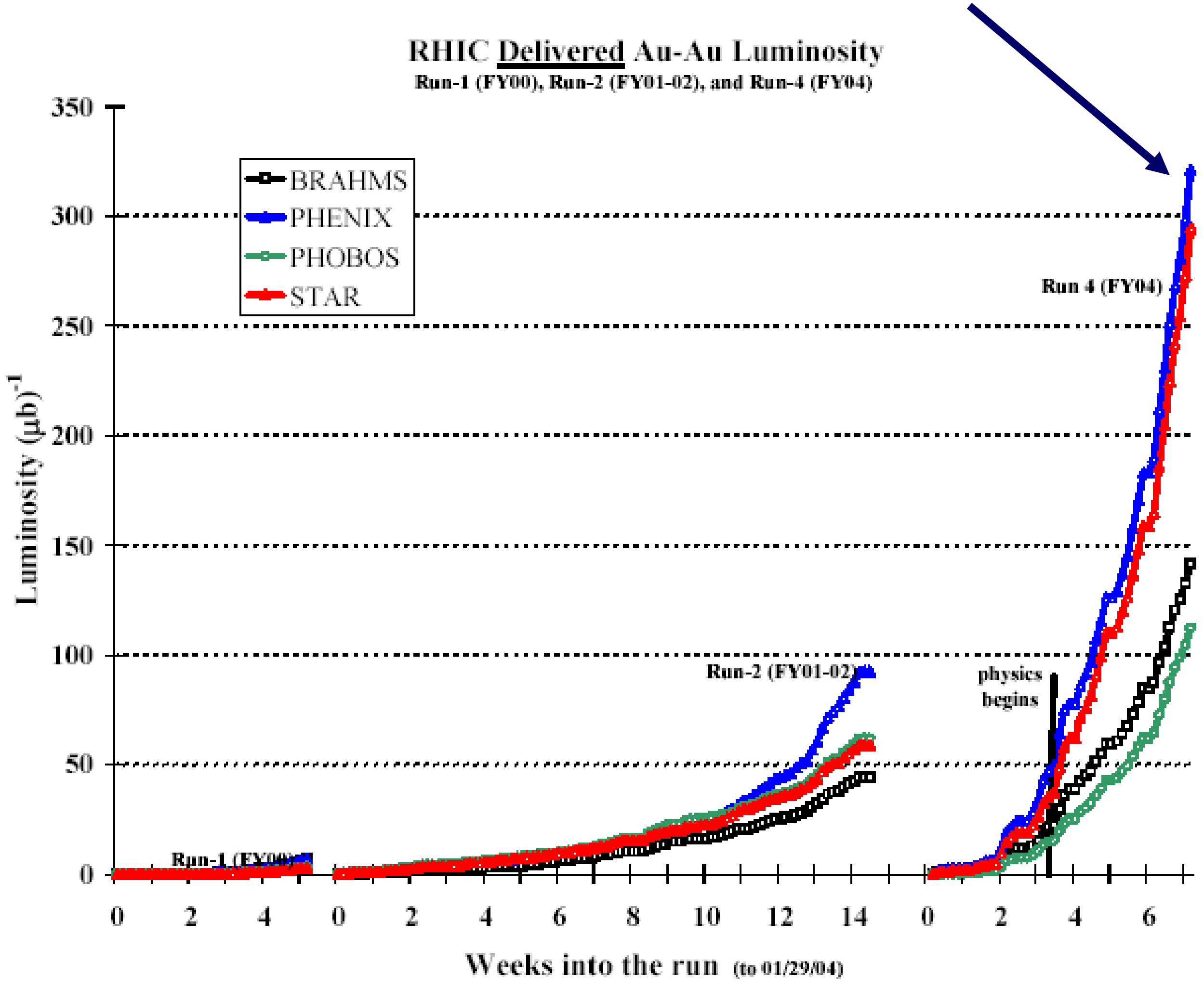
Where Are We?

- Relativistic Heavy Ion Collider online since 2000.
- Design Au+Au energy and luminosity achieved.
- All experiments successfully taking data
- Polarized proton-proton (spin) program also underway



RHIC is doing great !



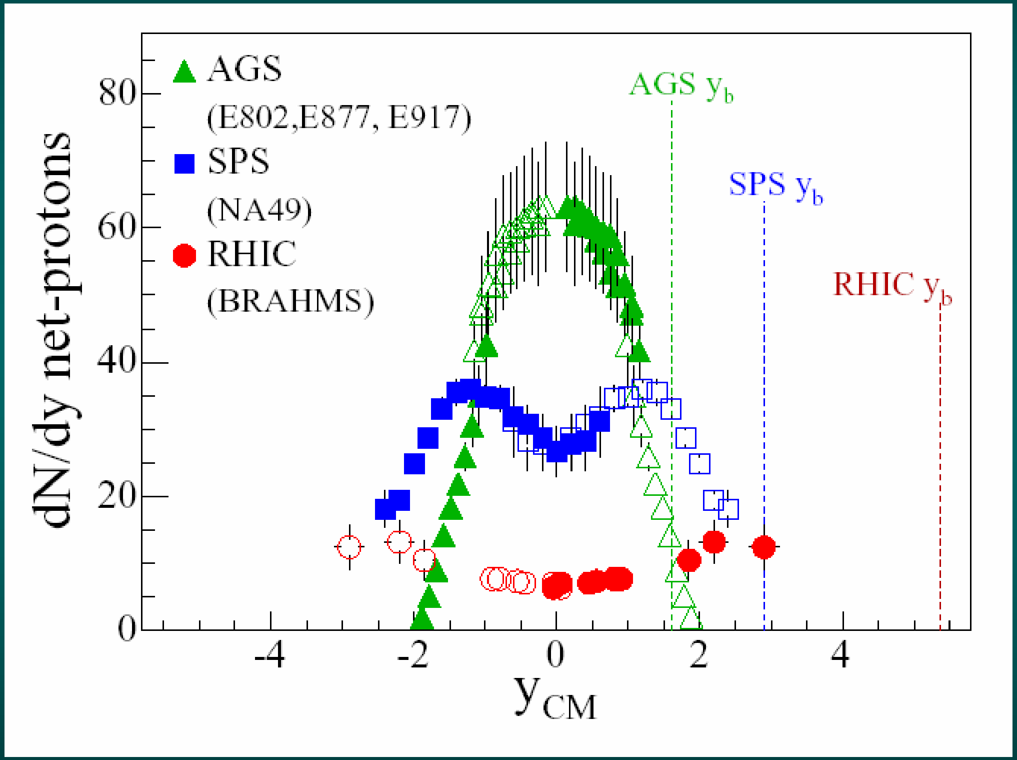
Experimental Observations

As an experimentalist, let the data speak for itself.

At least as much as possible.

26 TeV of Available Energy !

BRAHMS has measured the net-proton distribution.

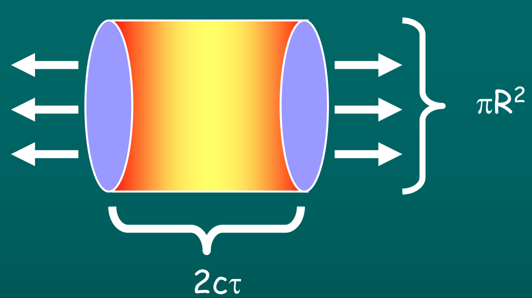


Out of a maximum energy of 39.4 TeV in central Au-Au reactions, 26 TeV is made available for heating the vacuum and eventually producing particles.

Energy Density

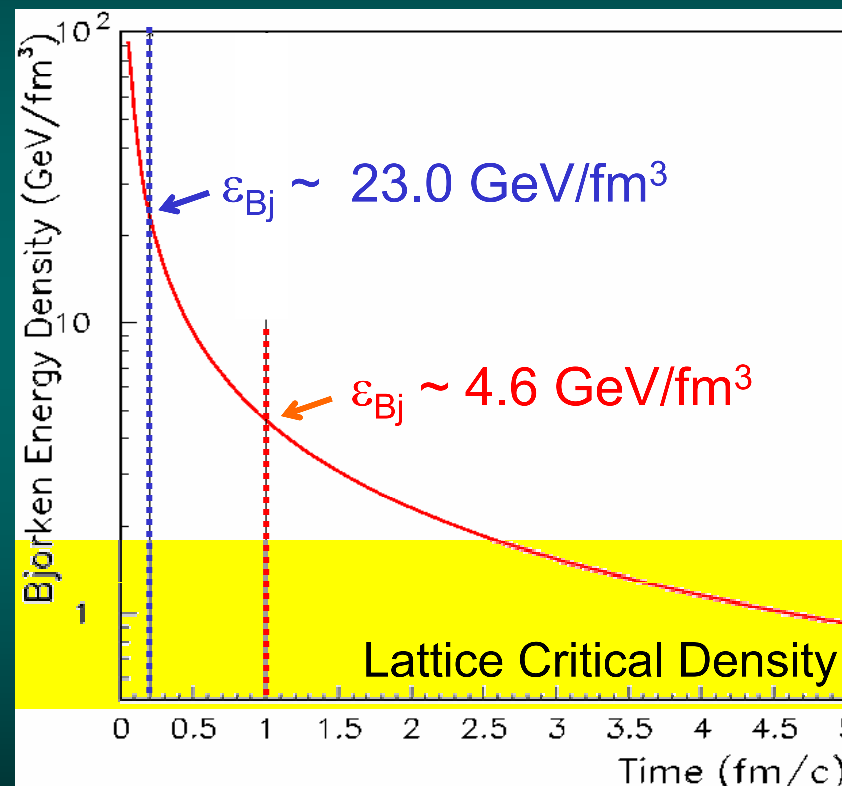
Energy density far above transition value predicted by lattice.

$$\varepsilon_{Bj} = \frac{1}{\pi R^2}\frac{1}{2c\tau}\left(2\frac{dE_T}{dy}\right)$$

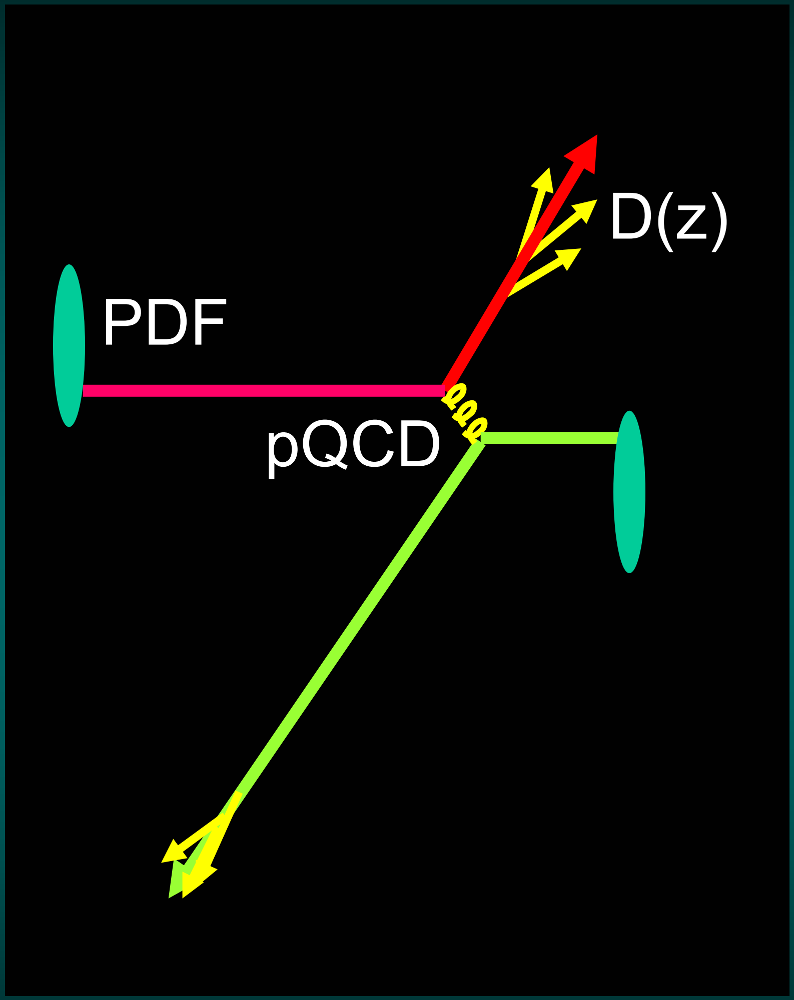


PHENIX: Central Au-Au yields

$$\left\langle \frac{dE_T}{d\eta} \right\rangle_{\eta=0} = 503 \pm 2\,GeV$$



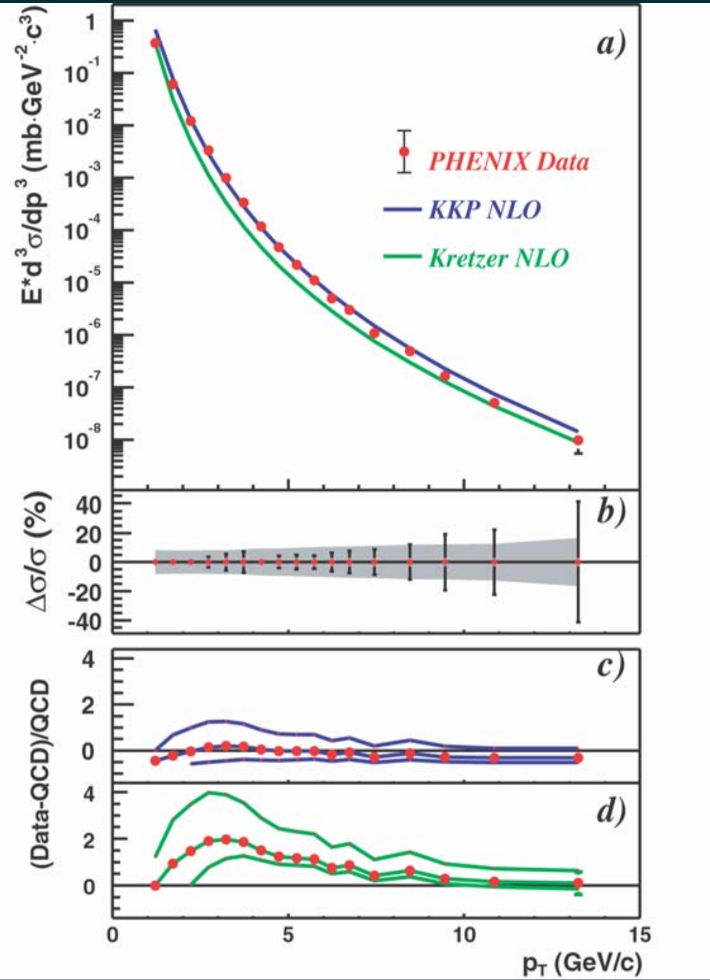
Perturbative QCD and Factorization



- Proton+Proton→ π^0 + X
- NLO pQCD calculation agrees with data from 2-13 GeV
- Extend to nuclei by expected scaling with nuclear thickness calculated as a function of impact parameter

$$\frac{d\sigma_{pp}^{h}}{dyd^{2}p_{T}} = K \sum_{abcd} \int dx_a dx_b f_a(x_a, Q^2) f_b(x_b, Q^2) \frac{d\sigma}{d\hat{t}}(ab \rightarrow cd) \frac{D_{h/c}^{0}}{\pi z_c}$$

Perturbative QCD and Factorization



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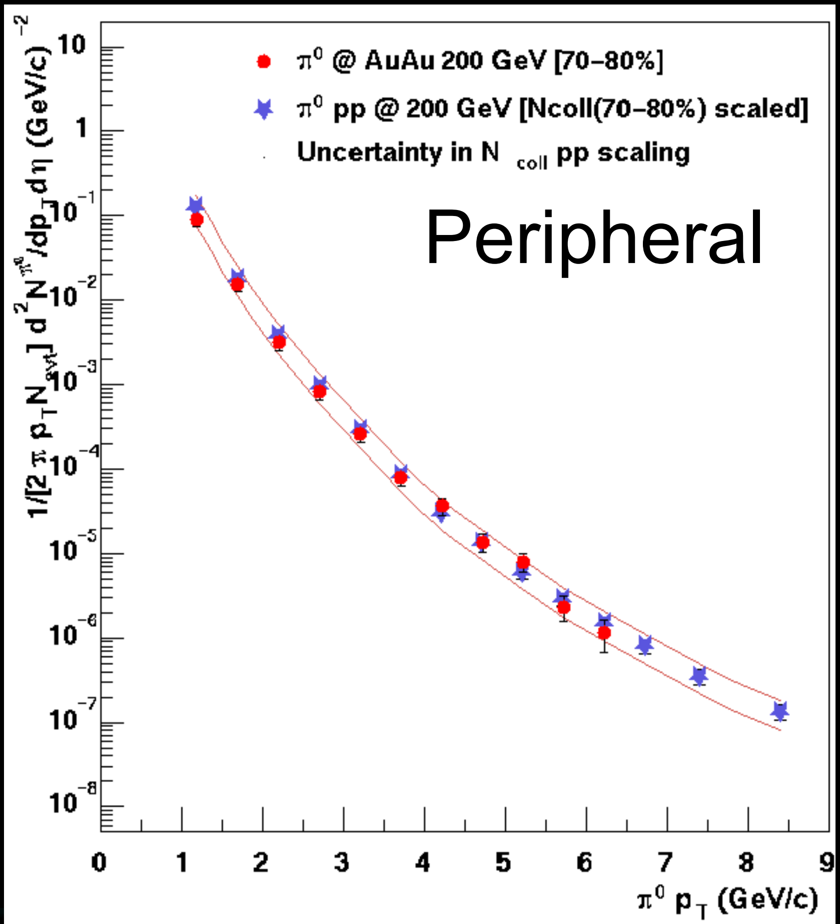
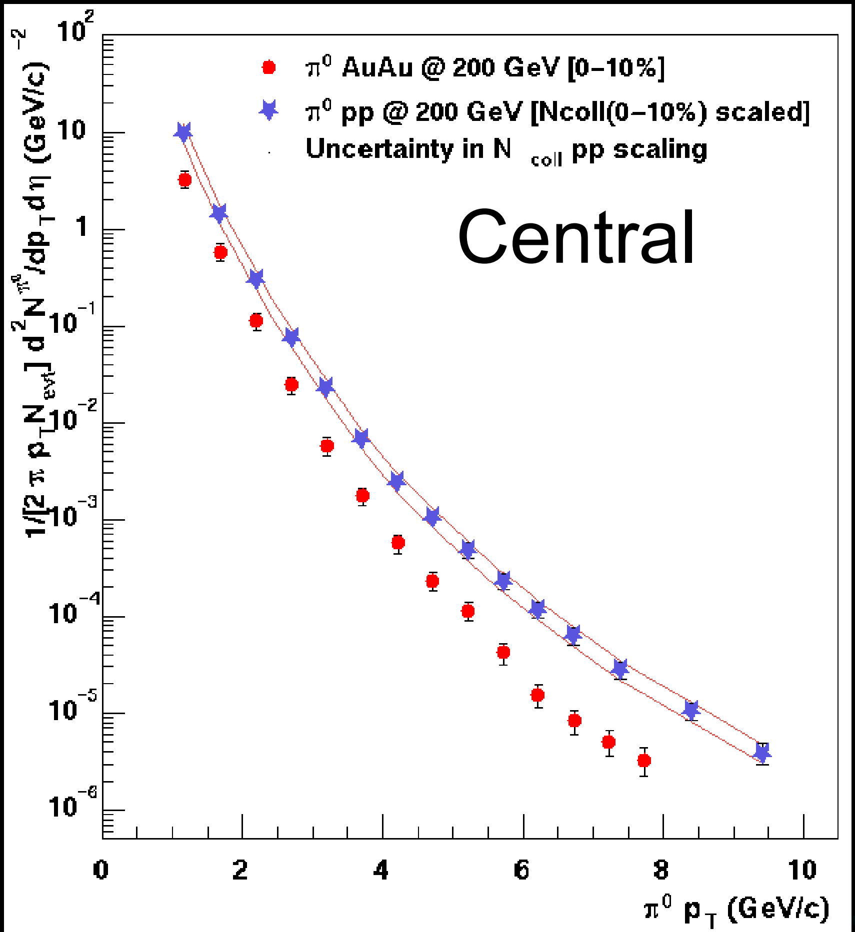
What About Heavy Ion Reactions?

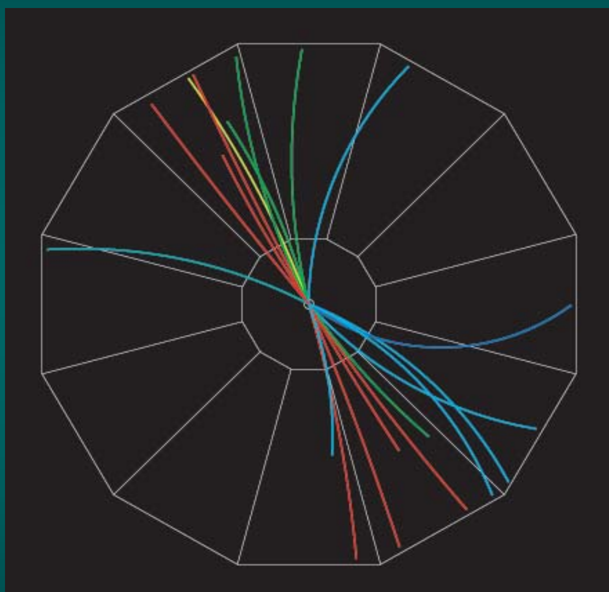
- Peripheral Au+Au = superposition of p+p reactions.
- Central Au+Au reveals a significant suppression !

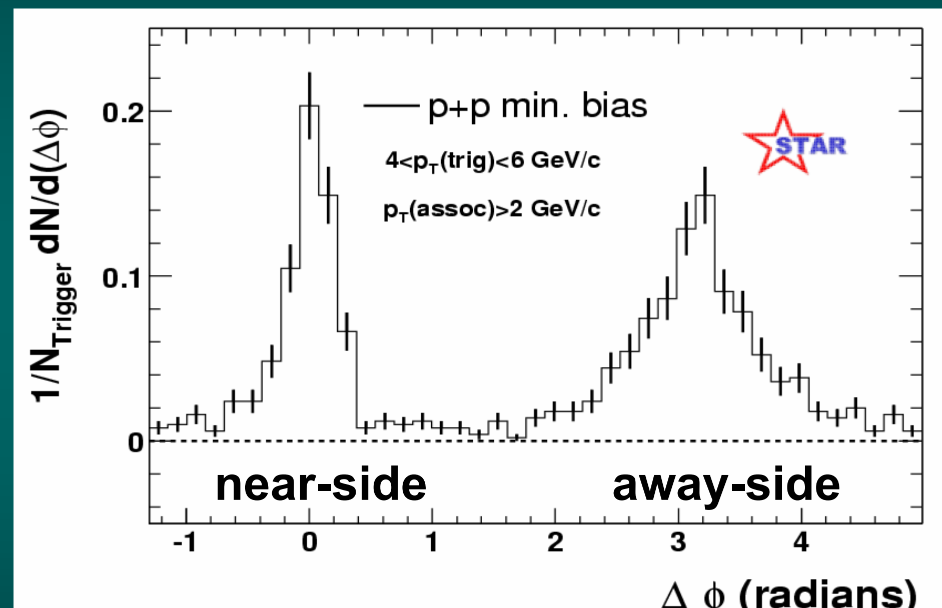


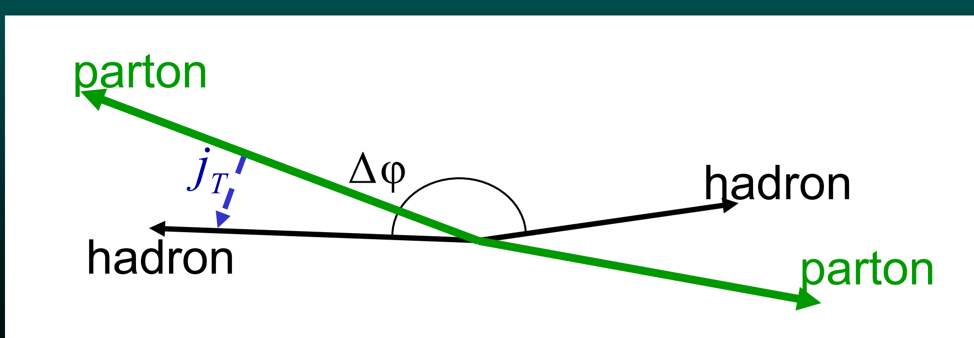


Jet Correlations

- Complete jet reconstruction is not available yet
- We study back to back jets via angular correlations







- $J_t = 615 \pm 60_{sys}$ MeV/c
- $k_t = 2.3 \pm 0.4 \pm^{0.67}_{1.11}$ GeV/c

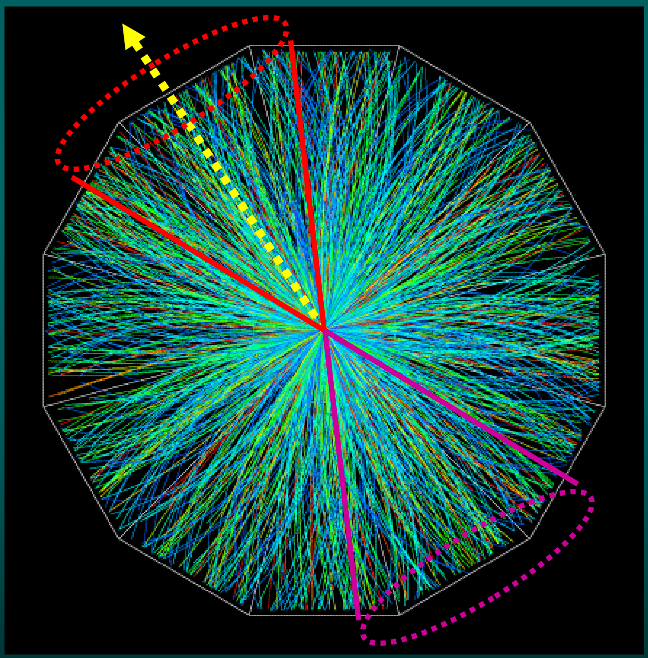
STAR

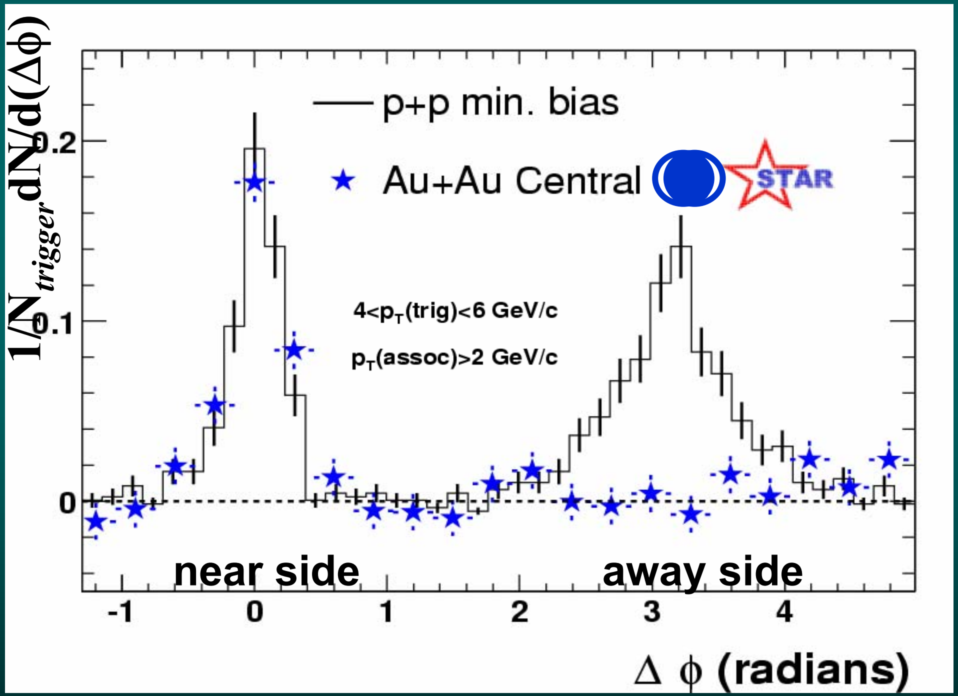
- $J_t = 636 \pm 20$ MeV/c
- $k_t = 1.7 \pm 0.1$ GeV/c

PHENIX Preliminary

"Disappearance" of Away-Side Jet

- In central Au+Au reactions, the away-side jet disappears (blue points)
- No correlation for particles with p_T > 2 GeV

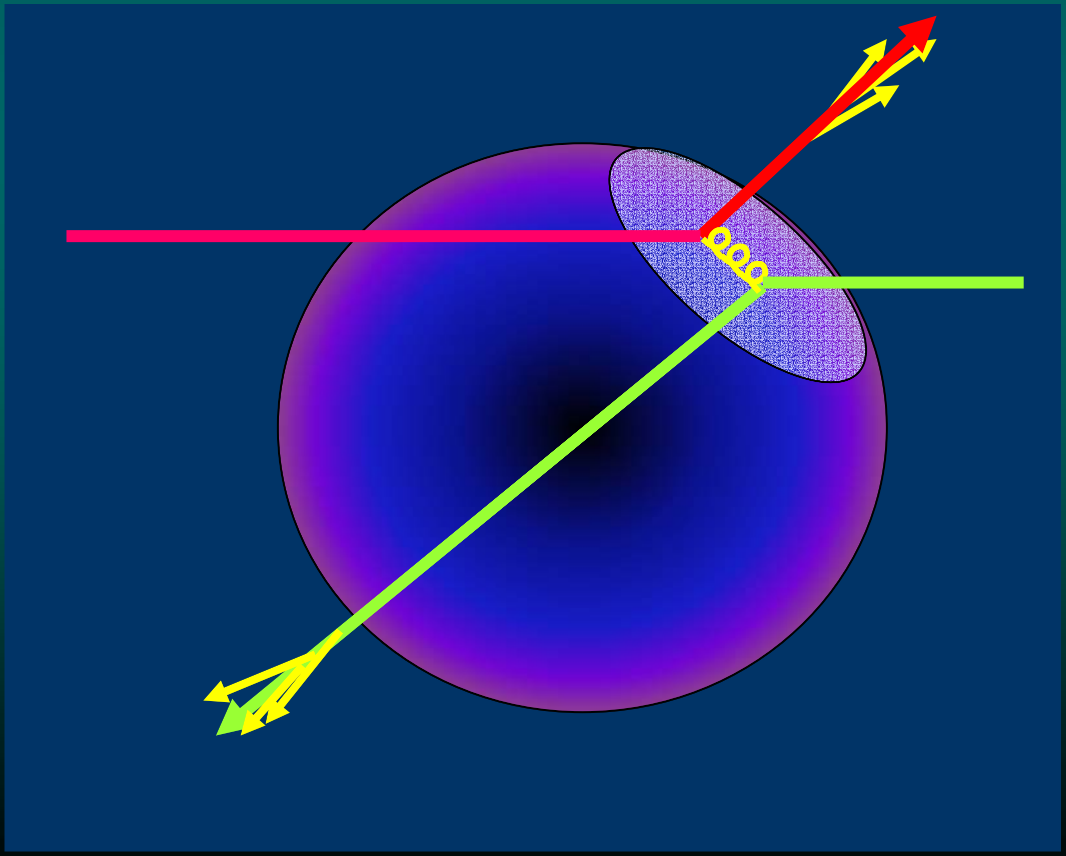




- Conservation of energy and momentum says that away side jet cannot really disappear

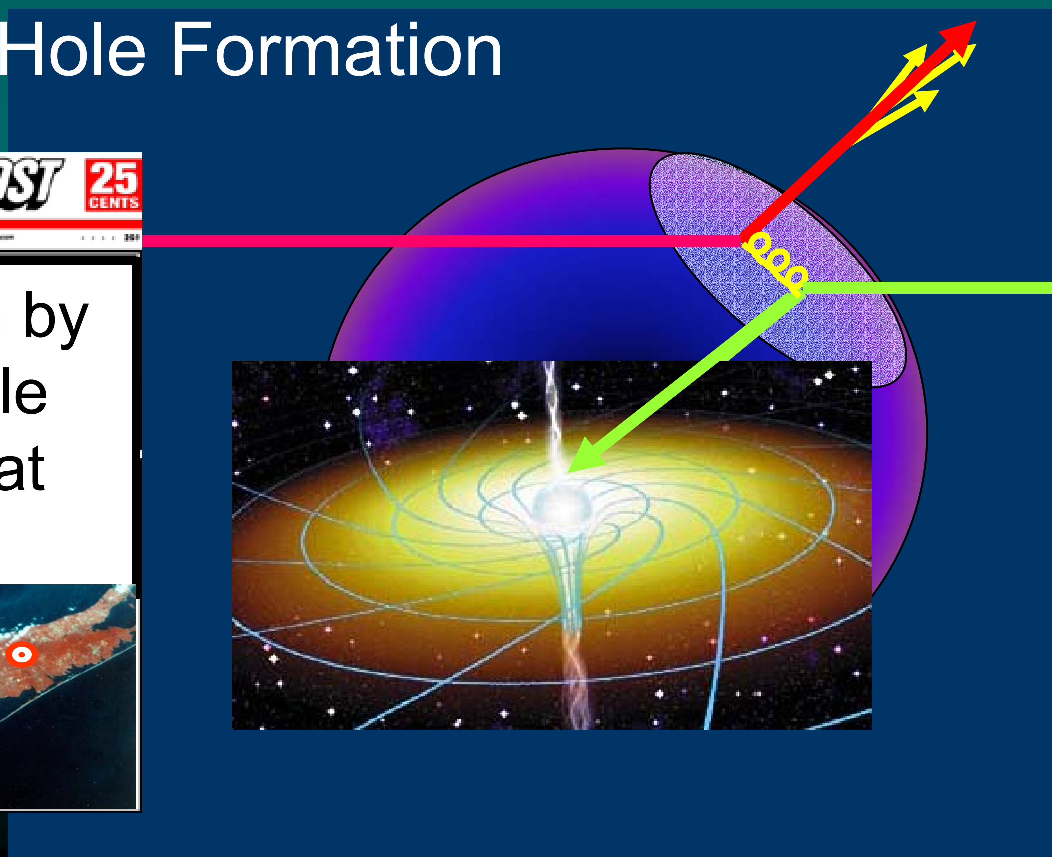
Where is the Energy?

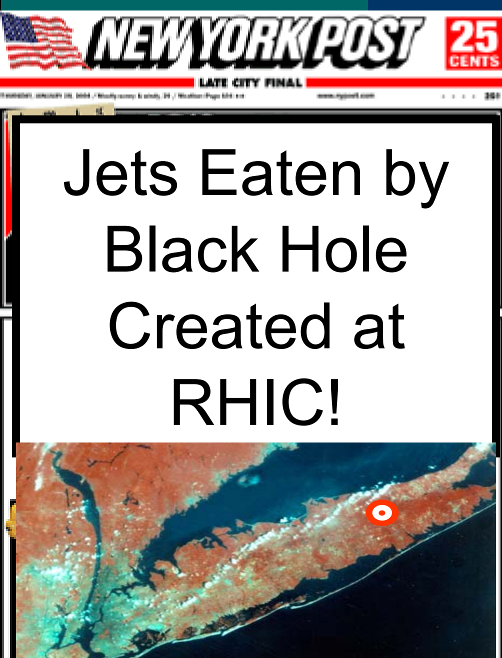
- High p_T trigger hadron selects surface emission.
- Thus, away-side partner has maximum path through the medium.



Opaque Medium

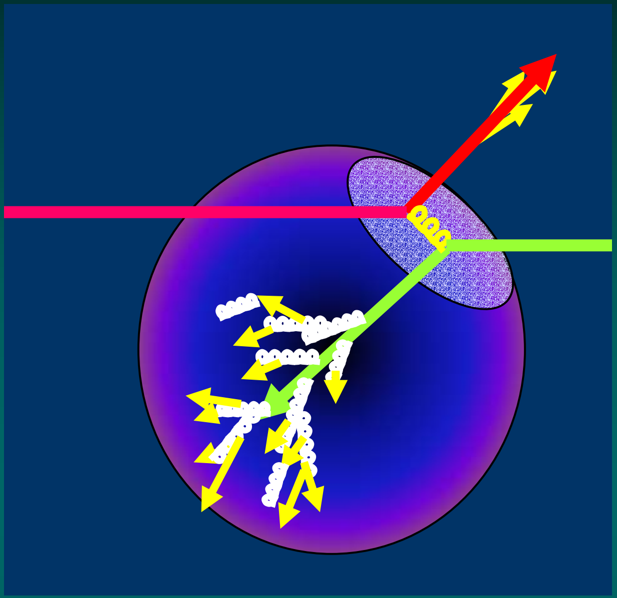
- Perhaps partons lose energy in medium, and thus fragmentation products are below $p_T > 2$ GeV.
- Perhaps scattering causes broadening of angular distribution.
- Black Hole Formation

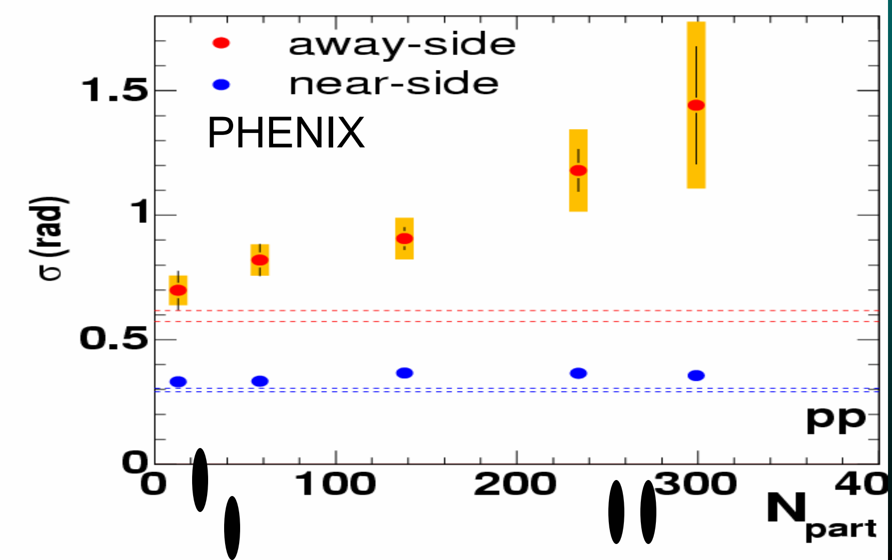


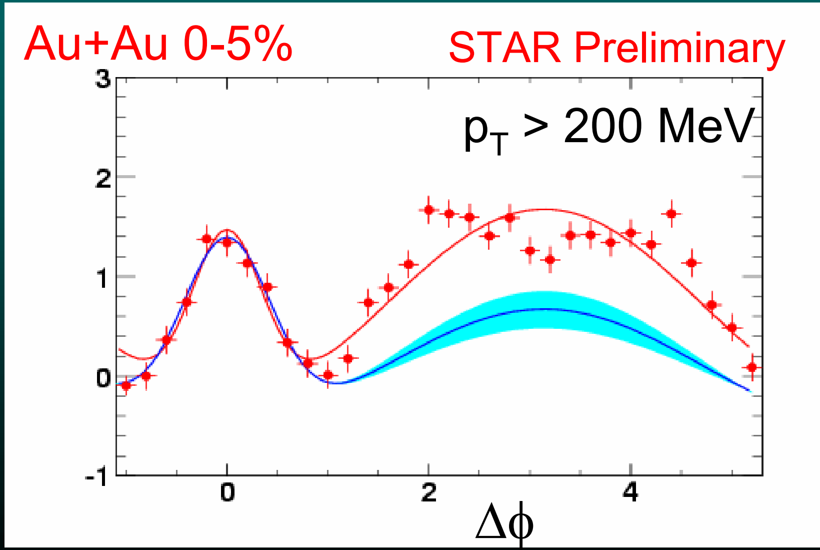


Thermalization of Energy !

- Away side jet is significantly broadened
- One recovers energy in hadrons ~ 500 MeV.
- Not so different from <p_T> of the bulk medium.

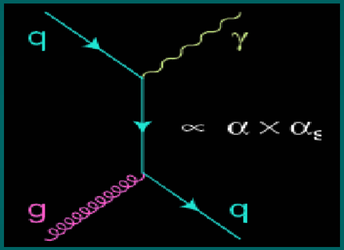


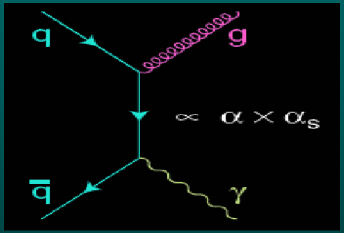


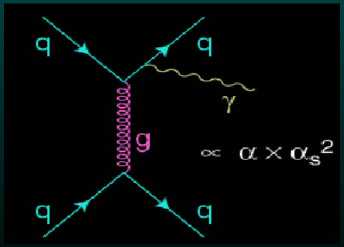


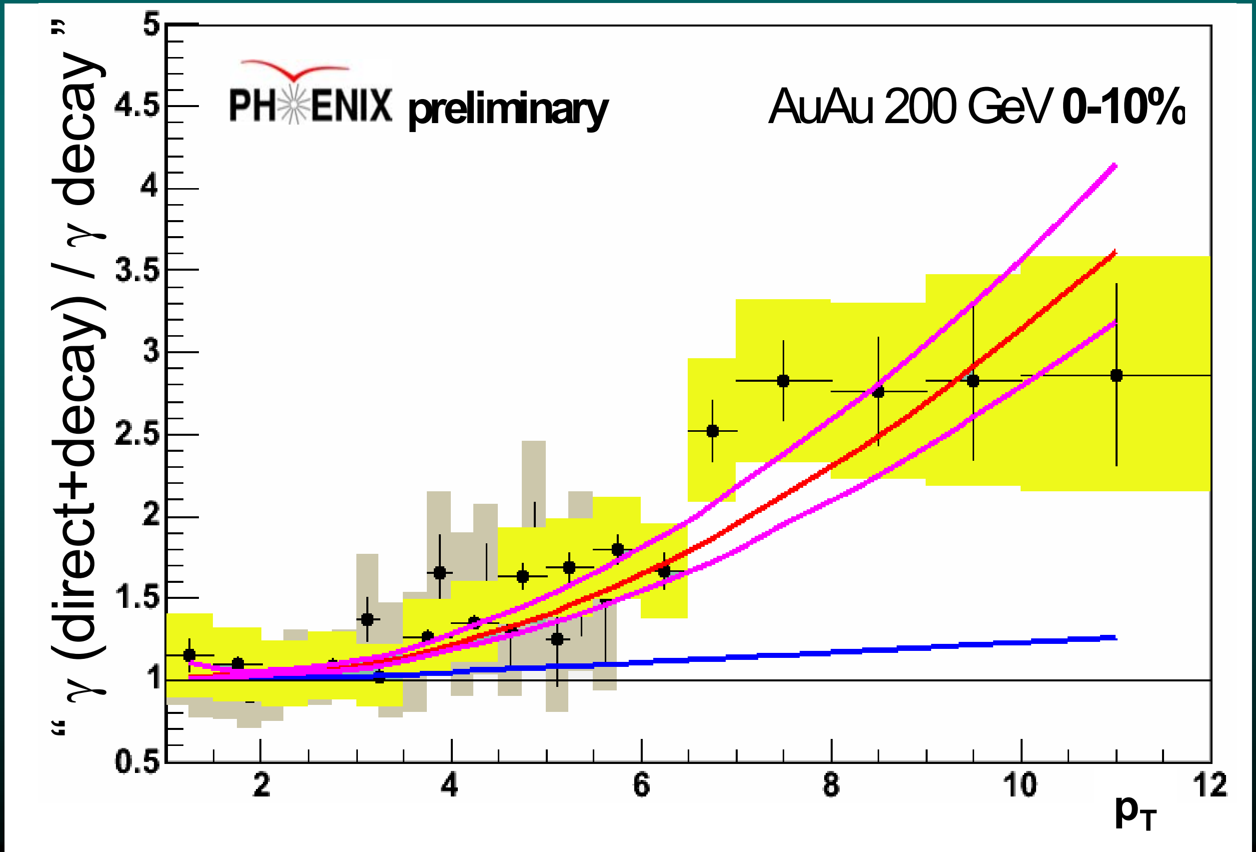
Direct Photons Shine!

- Use measured $\pi^0 \rightarrow \gamma\gamma$, and look for photon excess
- Excess agrees with NLO pQCD direct photons scaled by nuclear thickness
- Direct photons unaffected by medium as expected



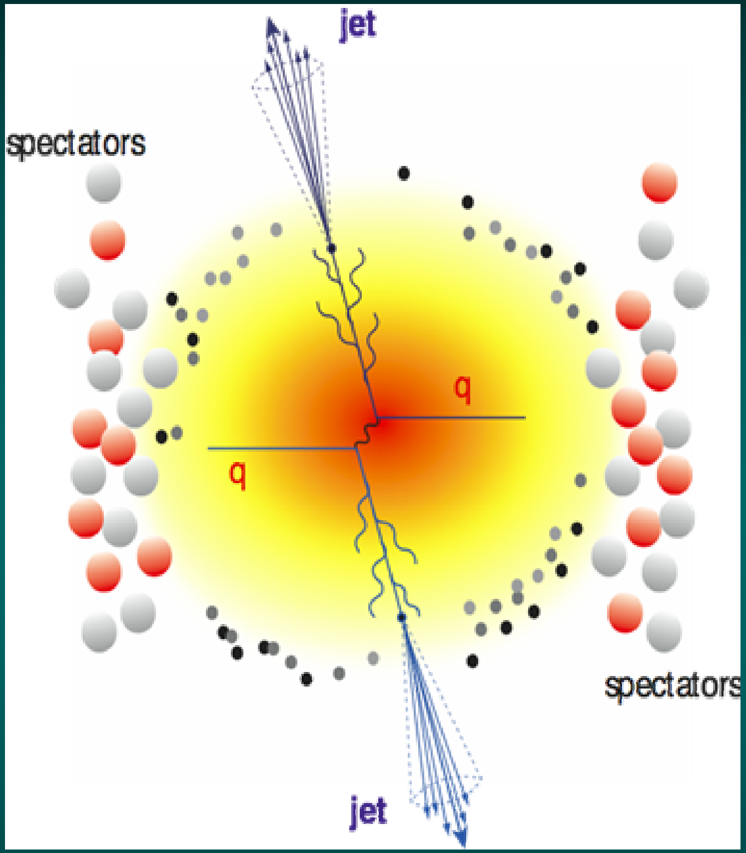


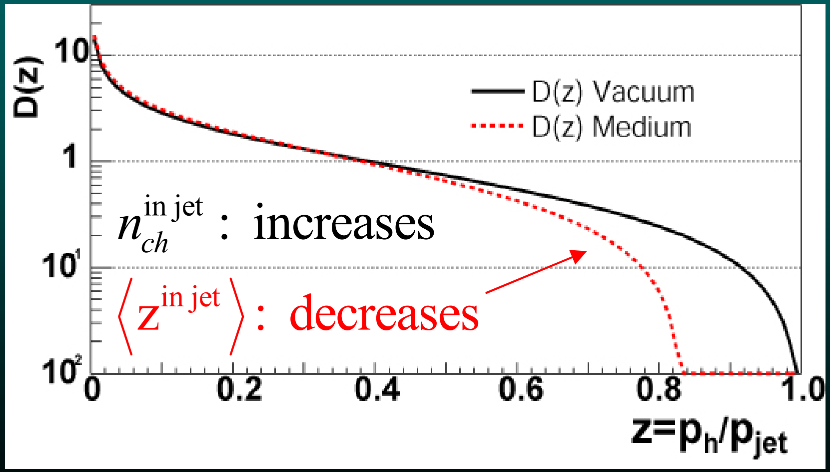




Jet Quenching

- Partons are expected to lose energy via induced gluon radiation in traversing a dense colored medium.
- Coherence among these radiated gluons leads to $\Delta E \propto L^2$
- Effective softening of fragmentation function.





Baier, Dokshitzer, Mueller, Schiff, hep-ph/9907267
Gyulassy, Levai, Vitev, hep-pl/9907461
Wang, nucl-th/9812021
and many more…..

Data and Theory Collide

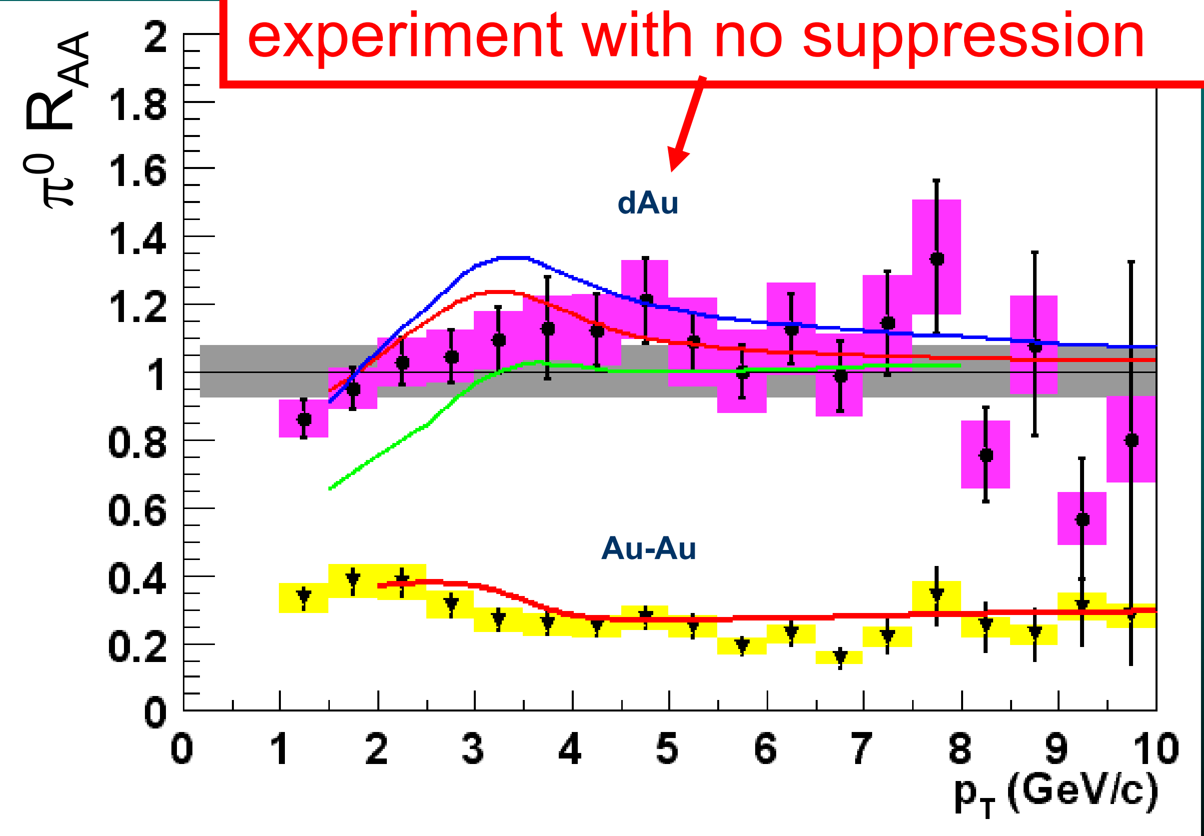
Induced gluon brehmstrahlung pQCD calculation
Agrees with data with initial gluon density:

$dN_g/dy \sim 1100$

$\underline{\varepsilon \sim 15 \text{ GeV/fm}^3}$

Lowest energy radiation sensitive to infrared cutoff.

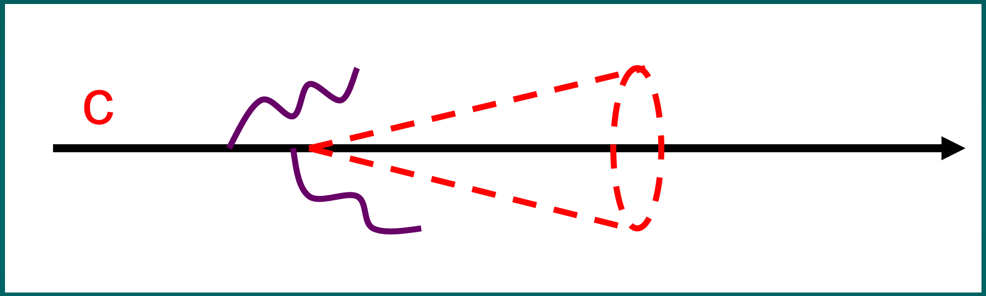
* Note deuteron-gold control experiment with no suppression

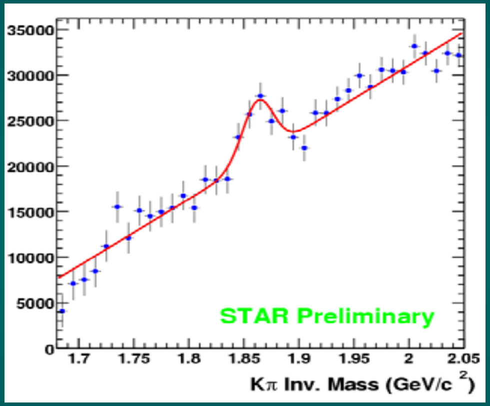


Charm and Beauty

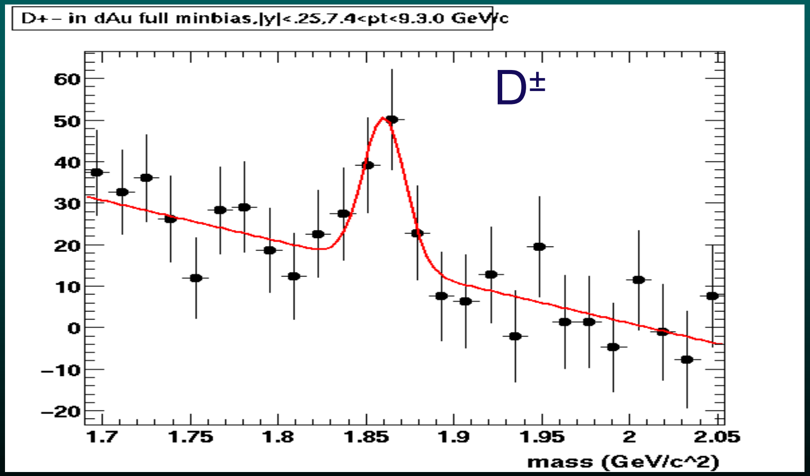
QCD is flavor independent, but heavy quarks at same p_T are moving much slower than light quarks.

Expected "dead-cone" with no induced gluon radiation.



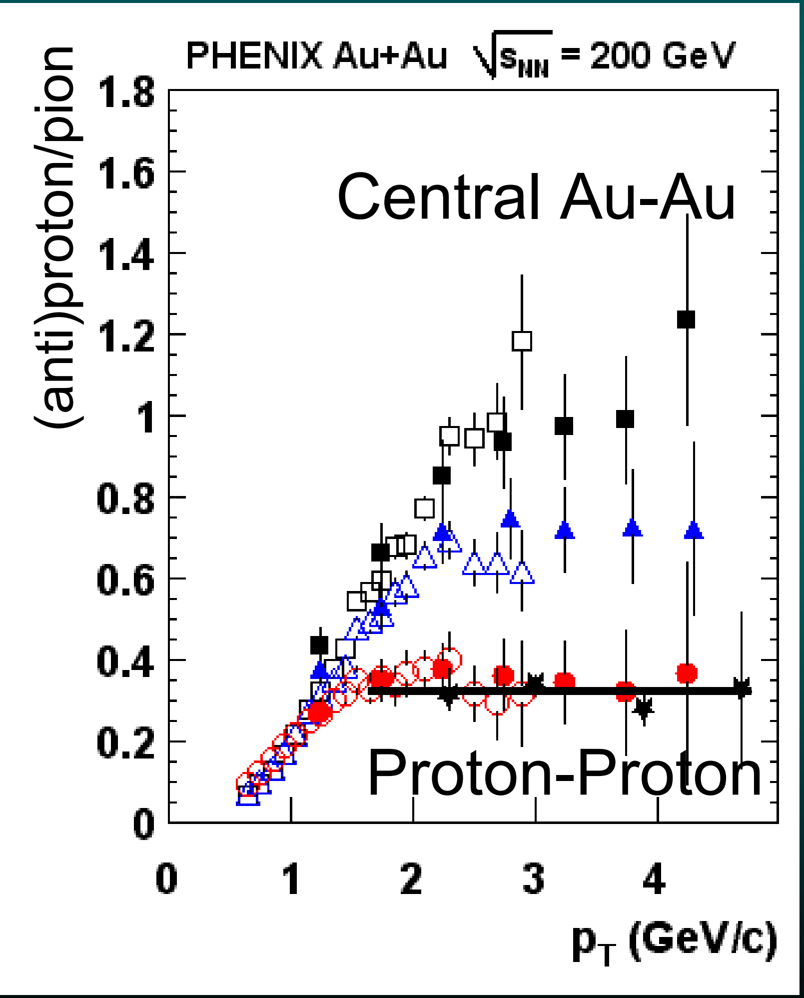


Recent single lepton and direct D reconstruction allow us to address this physics.

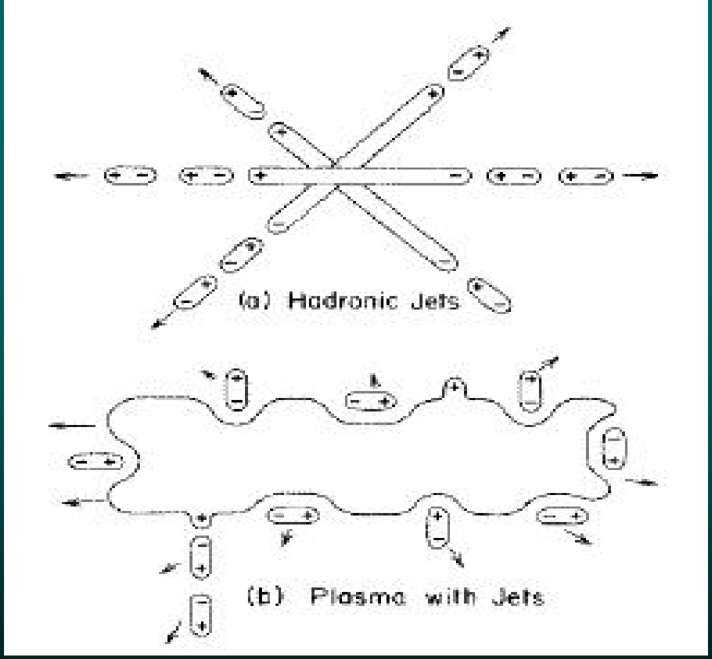


Some Puzzles?

More (anti) baryons than pions at moderate p_T.
Does not look like vacuum jet fragmentation.



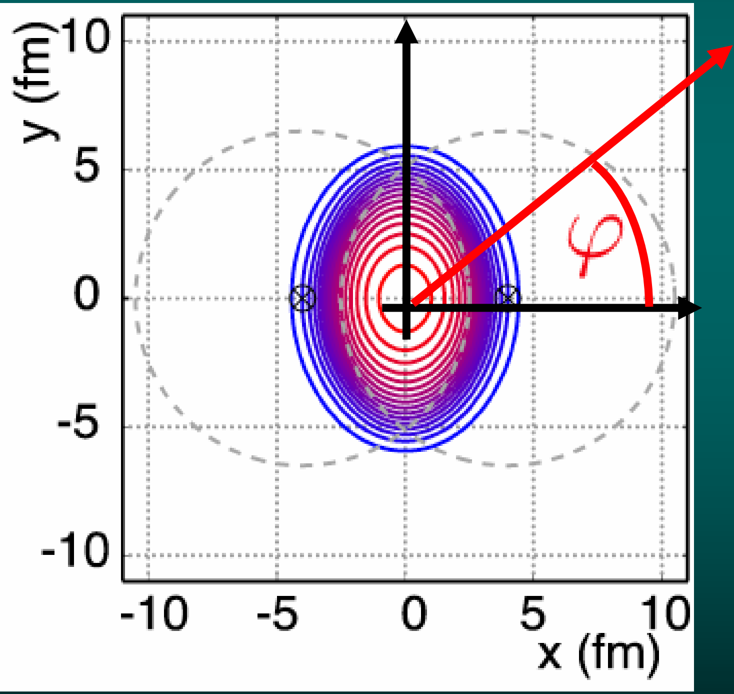
Factorization assumption of jet fragmentation completely breaks down.

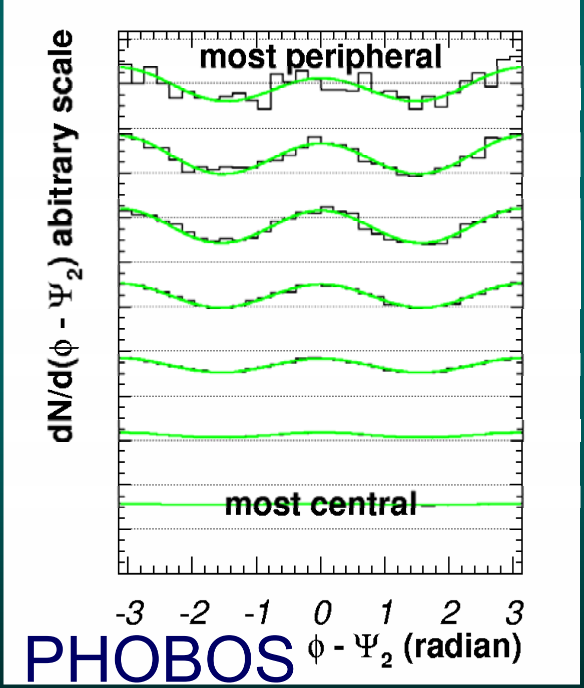


Color recombination ?

Collective Motion

- In non central collisions, large initial spatial anisotropy
- The degree to which this translated into momentum space is an excellent measure of the pressure

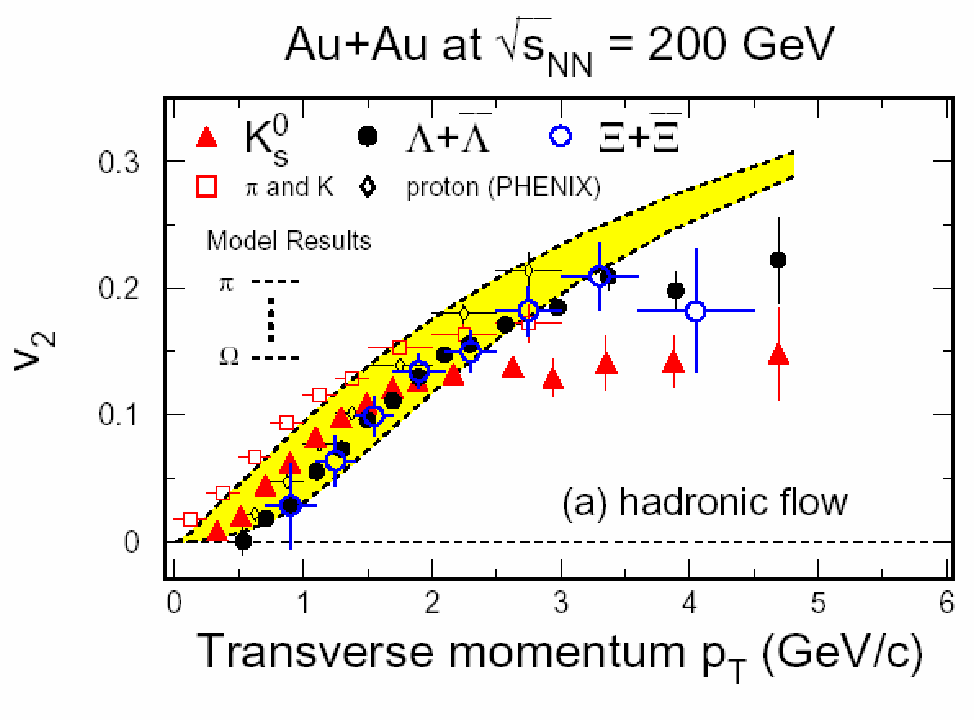


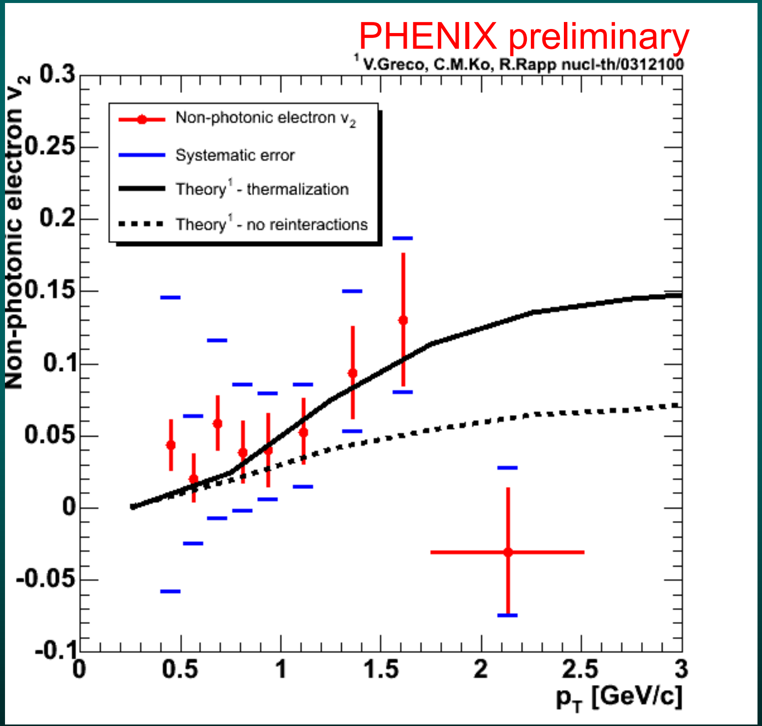


$$\frac{dN}{p_T dp_T dy d\varphi}(p_T, \varphi; b) = \frac{dN}{2\pi p_T dp_T dy}\left(1 + 2\underline{v_2}(p_T; b)\cos(2\varphi) + \ldots\right)$$

Large Pressure Felt By All Hadrons

- Very large rescattering, more than most predicted
- Multi-strange baryons flow, and maybe charm too !



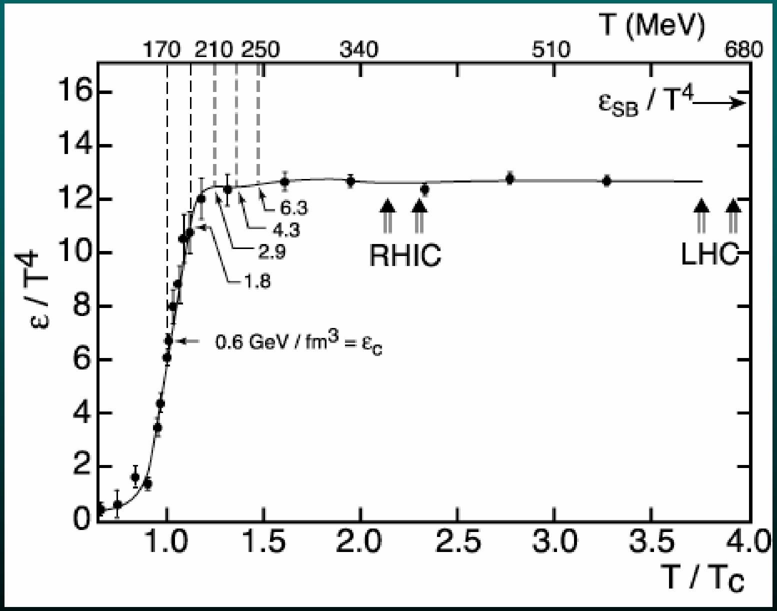


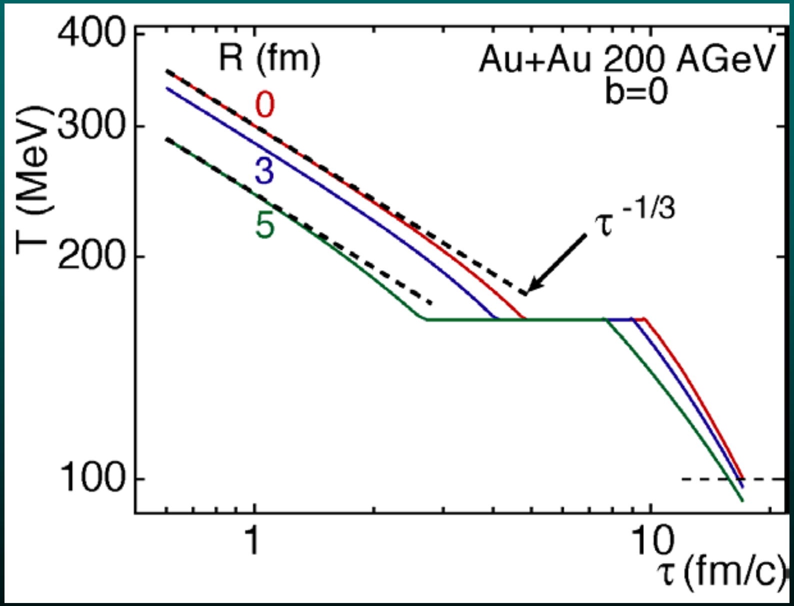
Hydrodynamics

- Assume early equilibration, and initial energy density from gluon radiation calculations
- Equations of Motion

$$\partial_\mu \left[(e+p)\, u^\mu u^\nu - p\, g^{\mu\nu} \right] = 0$$
$$\partial_\mu \left[s\, u^\mu \right] = 0$$

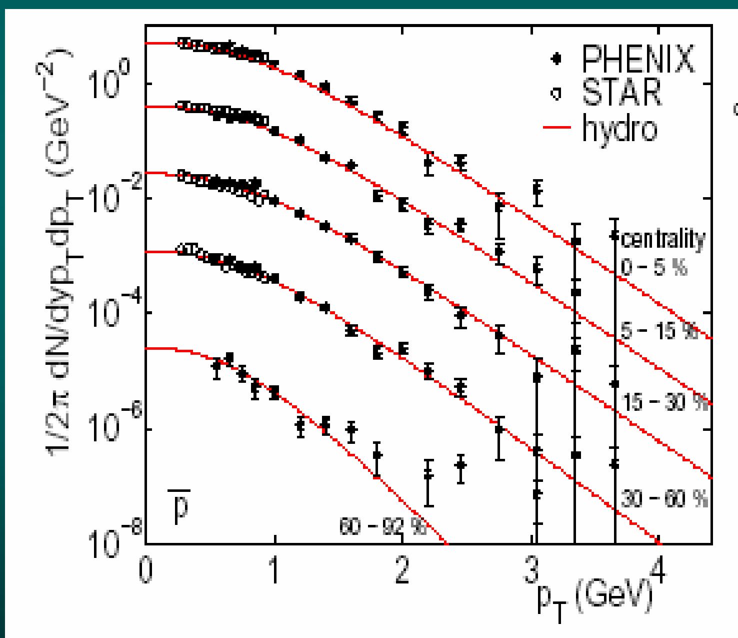
- Equation of State from lattice QCD

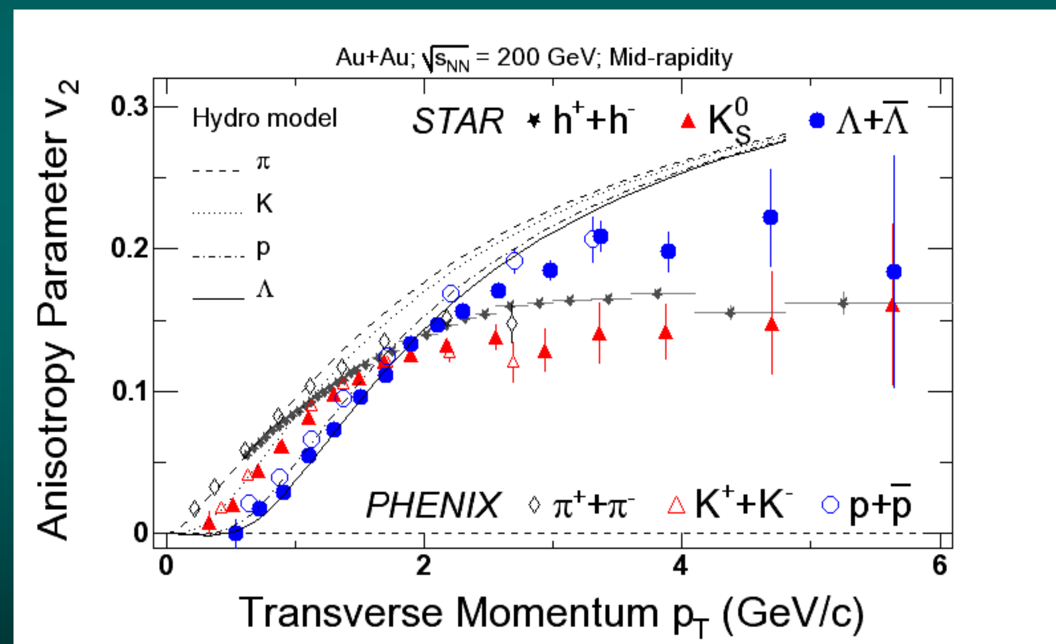




Data and Theory Collide (II)

- Agreement between hydrodynamics at mid-rapidity for hadron spectra and elliptic flow (v_2) up to p_T~2 GeV
- First time hydrodynamics without any viscosity* describes heavy ion reactions

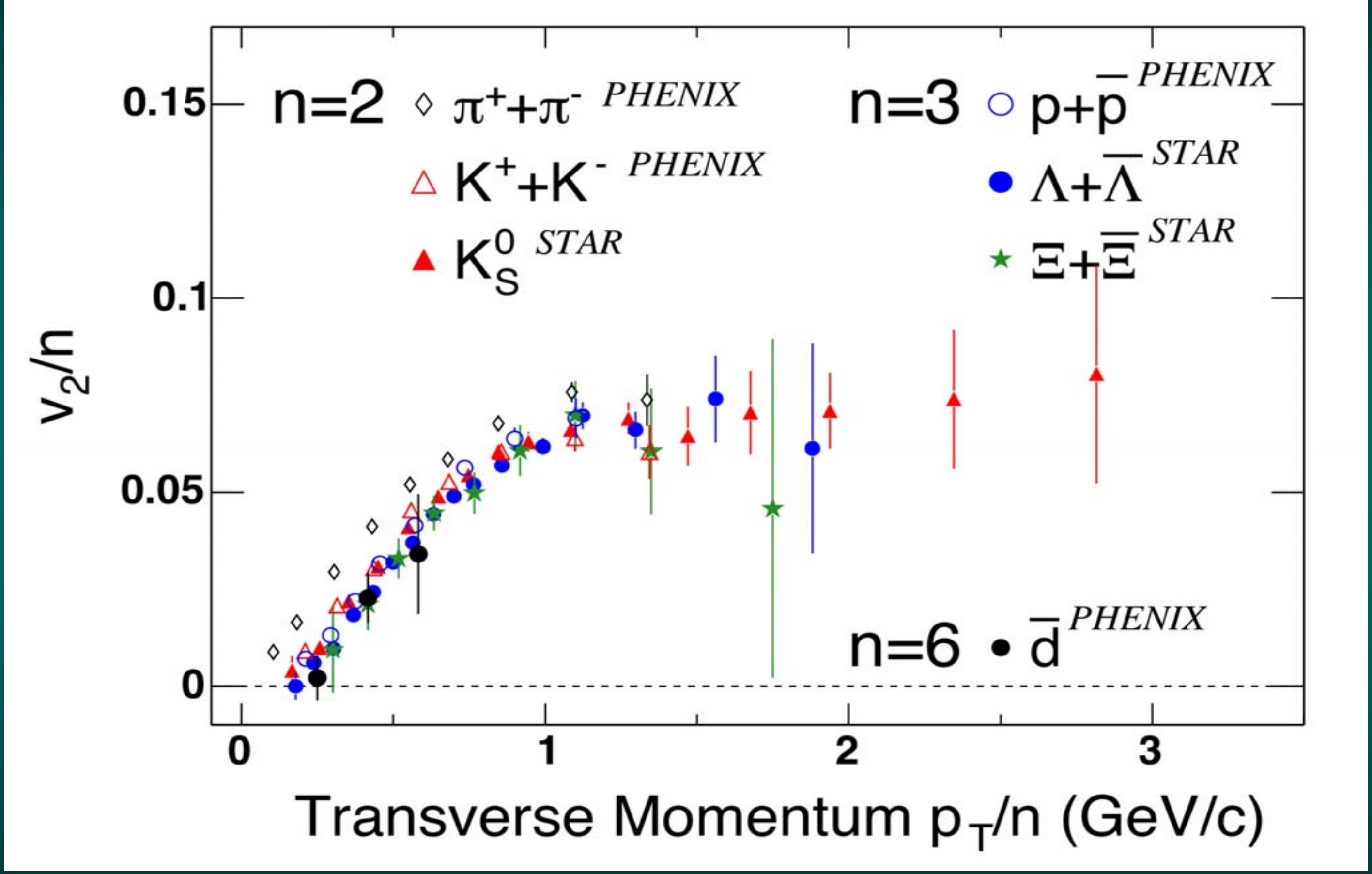




- Requires thermalization time t=0.2 fm/c and 20 GeV/fm^3

*viscosity = resistance of liquid to shear forces (and hence to flow)

New Scaling Law?



Hadrons appear to follow a pattern in terms of valence quarks.

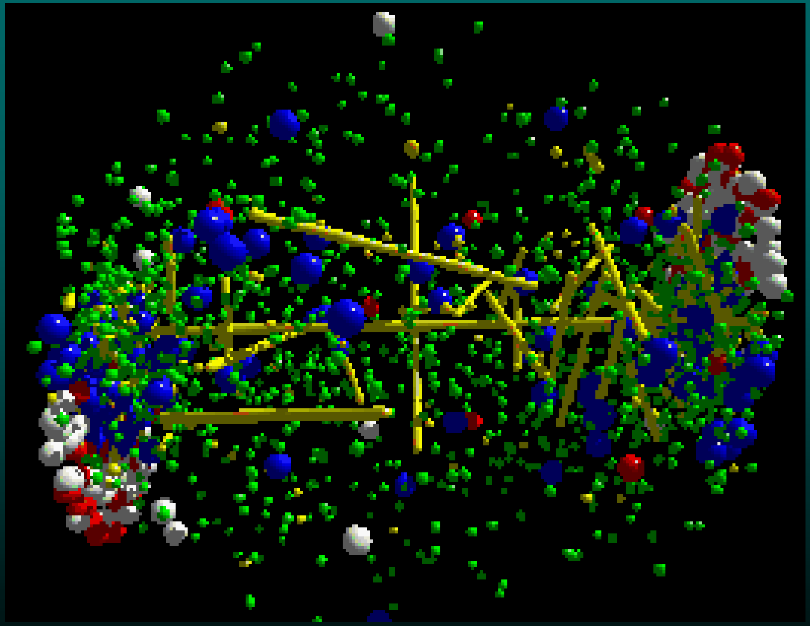
Partonic or Hadronic?

High energy proton-proton reactions cannot be described in terms of purely hadronic degrees of freedom.

Phenomenological descriptions include color string models.

This is not a quark-gluon plasma because strings fragment into hadrons without time for thermalization (re-interactions).

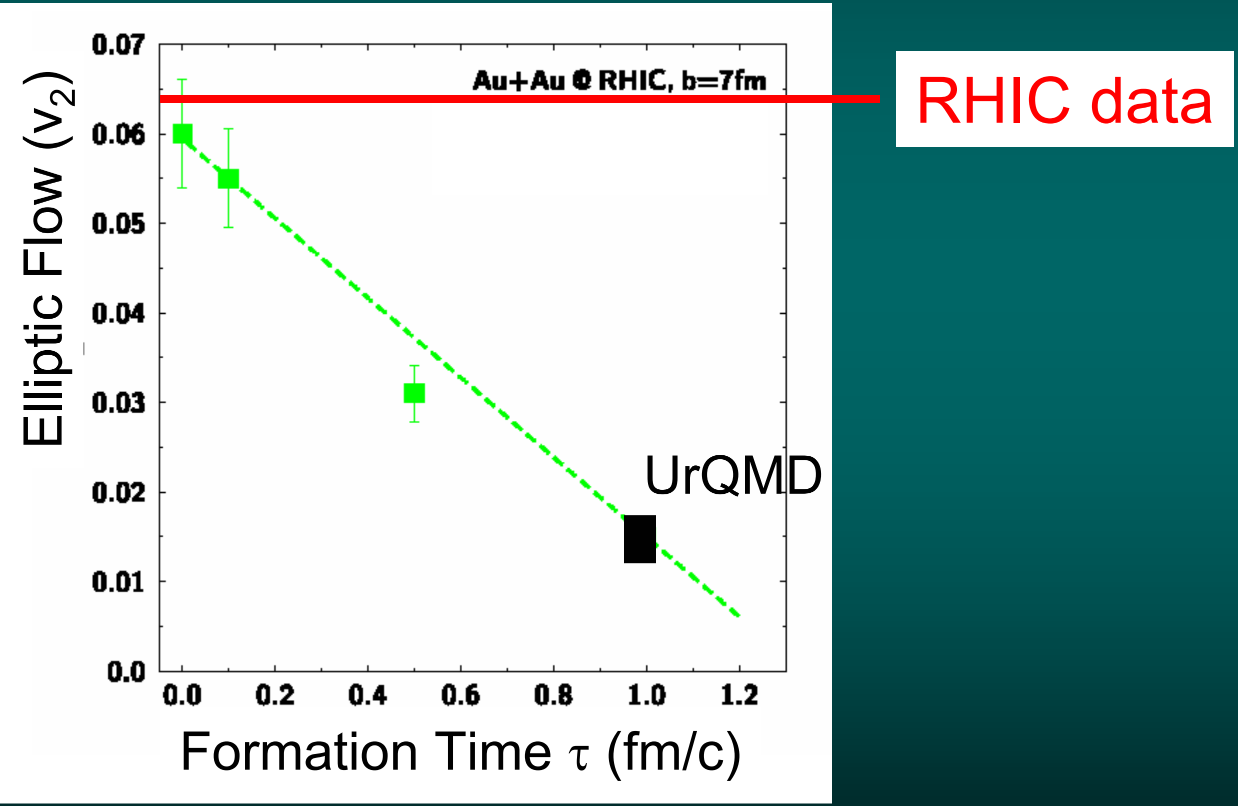
Transport models have been developed for nuclear collisions that include strings + resonances + hadronic interactions.



UrQMD, HSD, RQMD, ...

Partonic

These string + hadronic transport models under-predict the collective motion by a factor of 4-10.



Only if we violate quantum mechanics and allow hadronic wavefunctions to fully form in τ→0 can we reproduce the data.

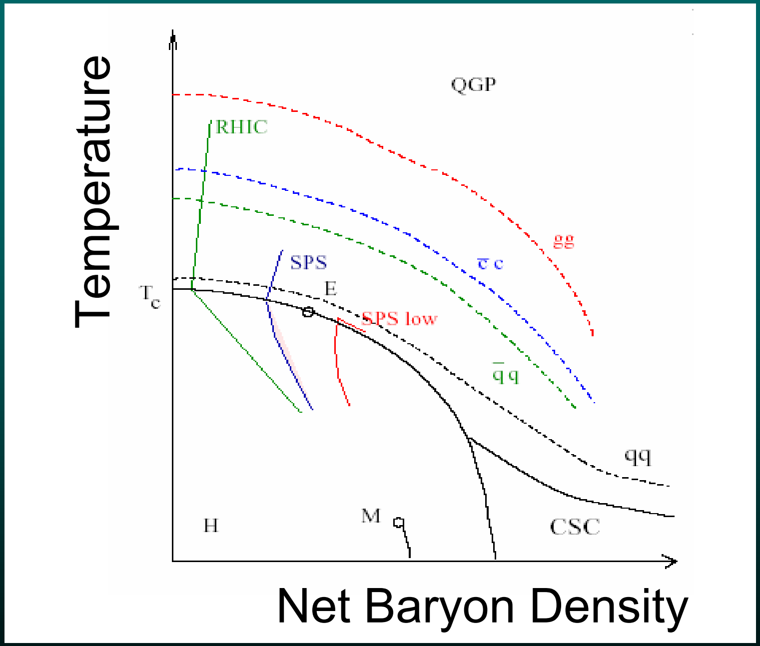
Quark-Gluon Plasma?

Many indications of energy density well above phase transition value.

However, it does not look anything like a “weakly” interacting gas of quarks and gluons.

More like a liquid (zero mean free path) with zero viscosity (zero resistance to flow).

New quasi-particles or parton couplings?

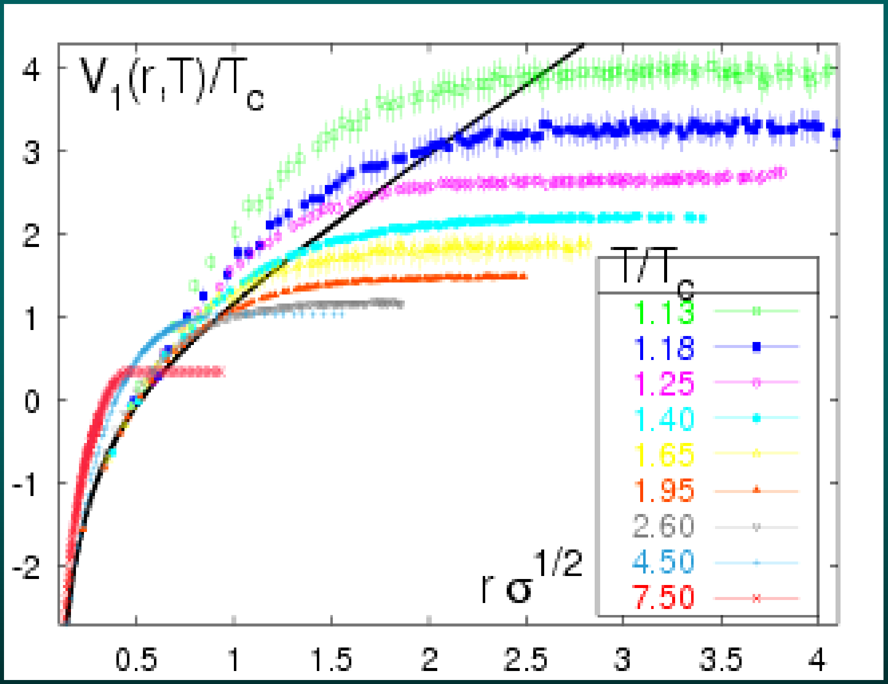


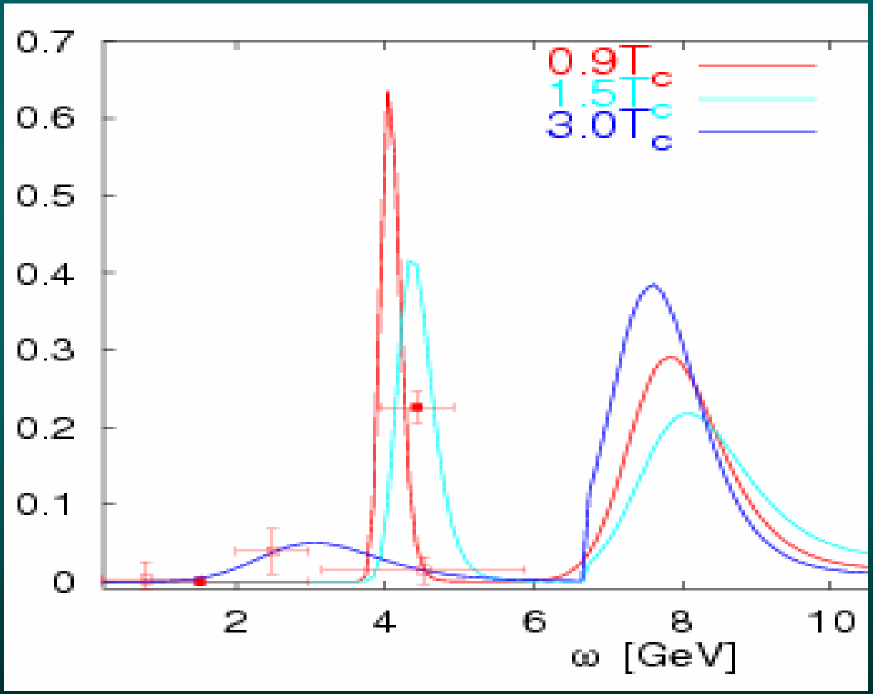
E. Shuryak, hep-ph/0312227

Interactions Above T_c

Recent lattice QCD calculations indicate

- Bound states at T ~ 1.5 T_c
- Quark-Antiquark interactions persist above T_c

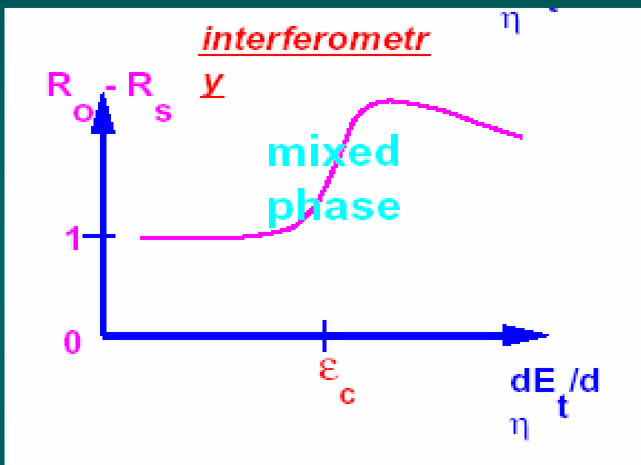


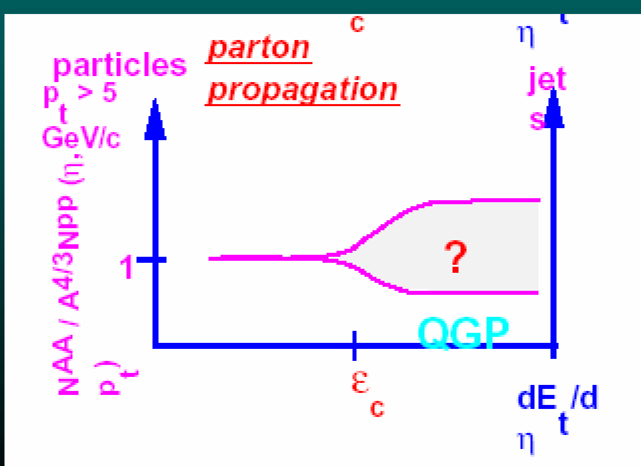


Key measurements of quarkonia and low mass vector meson spectral functions are the next step

Phase Transitions and Discontinuities?

Many early calculations predicted discontinuities in observables based on the sharp transition seen in lattice QCD.
These are the advertised “smoking gun” signatures.





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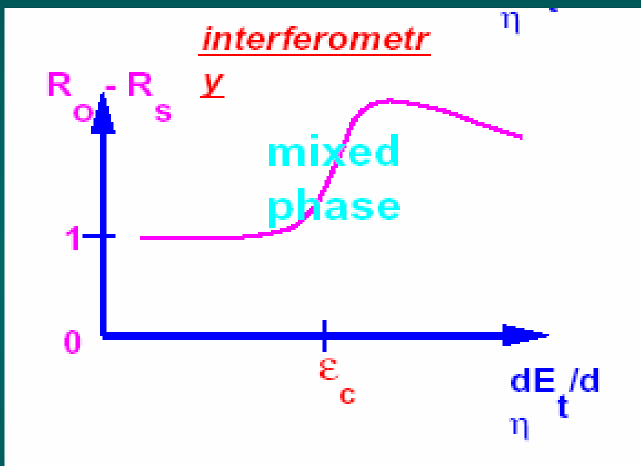

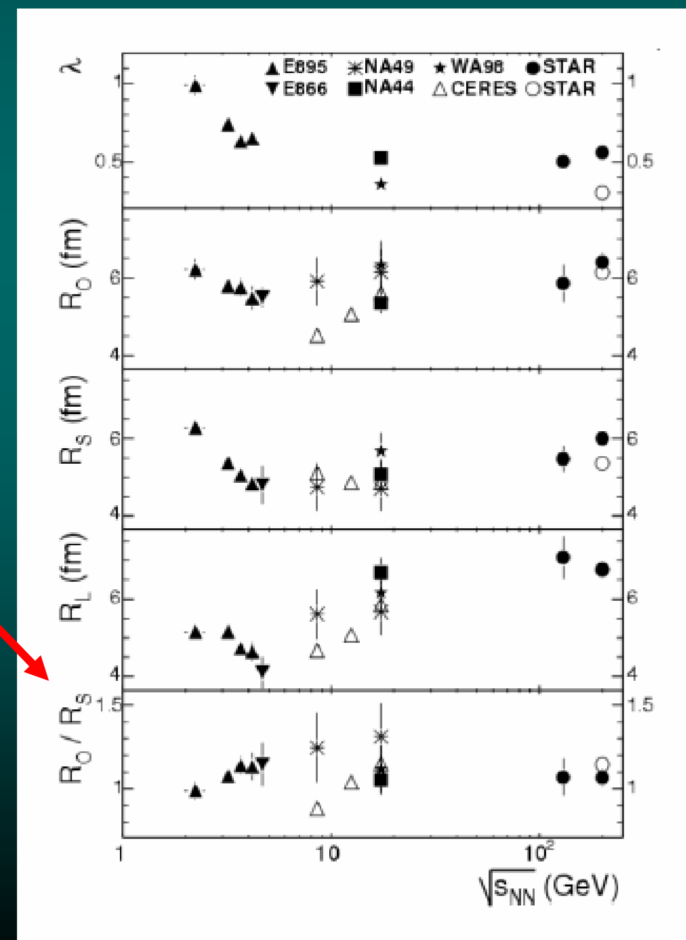

Two Particle Correlations (HBT) measures the size of the system at decoupling. No unambiguous discontinuity in the data.

Phase Transitions and Discontinuities?

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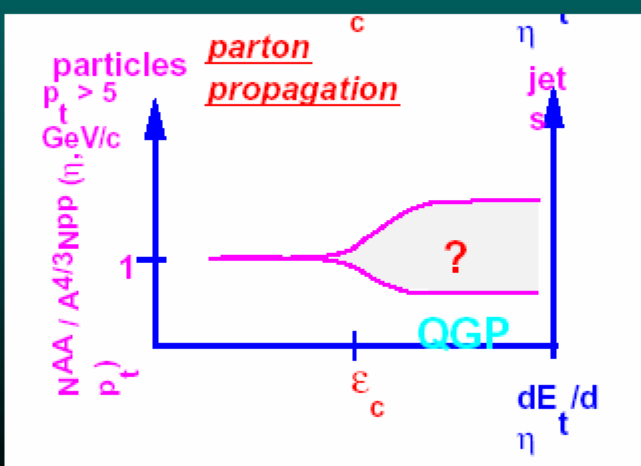
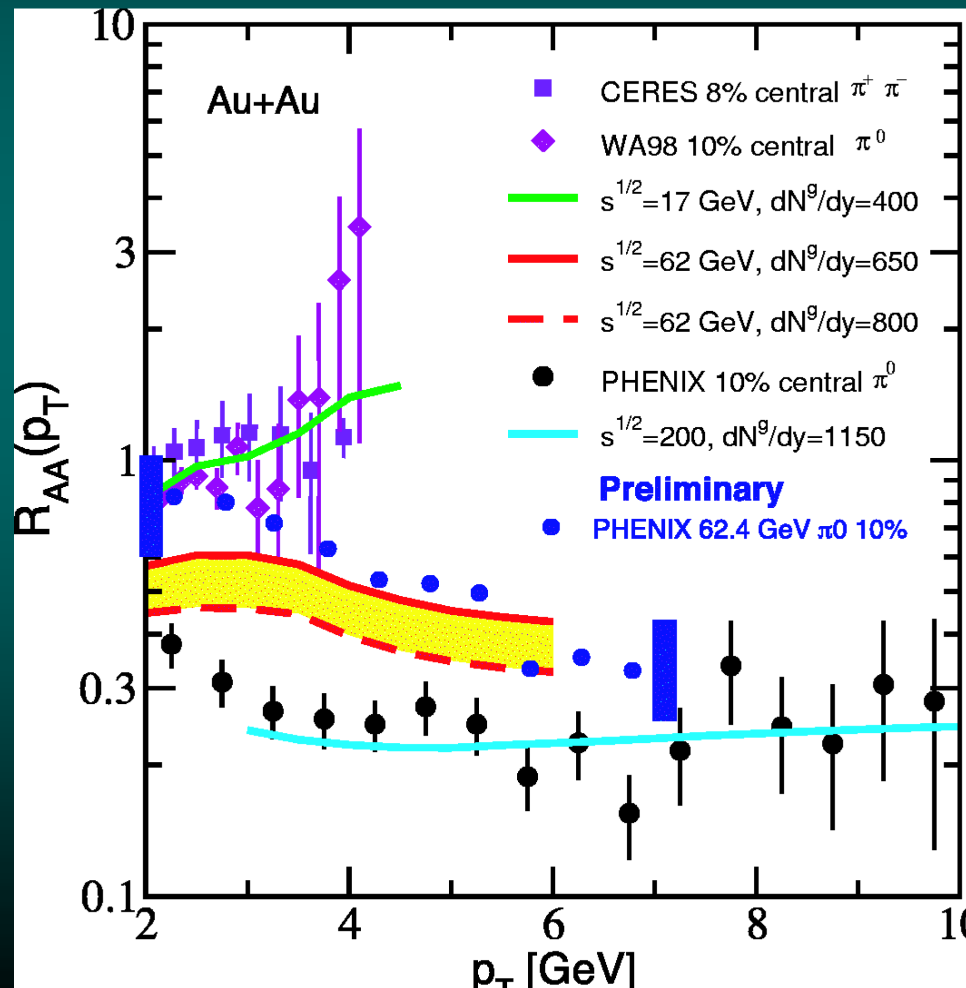
These are the advertised “smoking gun” signatures.

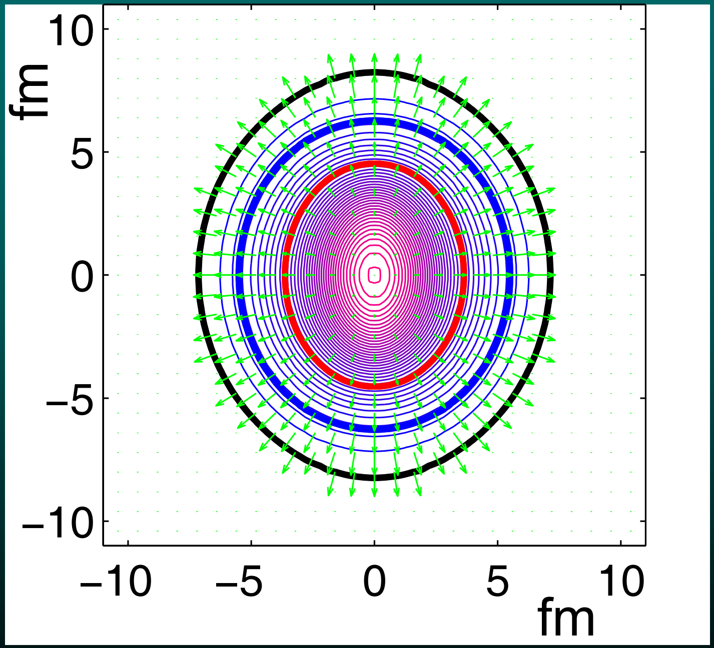
Parton Energy Loss in medium increases with energy. Measures growth in color charge density but not change in degrees of freedom.





Reality

• A single heavy ion collision does not measure at one energy density, but rather an energy density profile.
• The system expands too quickly for nucleation from the center region.
• Thus it is unlikely to to see a true discontinuity in the data.



What does this mean?

We have had a much more challenging task to demonstrate the properties of the created system, instead of measuring one “smoking gun” observable.

I believe we have met this challenge.

Conclusions

RHIC program is operating very successfully.

Gluon density well above lattice QCD predicted transition level and behaving as zero viscosity “perfect” liquid.

This is not the traditionally thought of weakly-interacting gas of quarks and gluons (“the QGP”).

However, this is the creation of a strongly-interacting Quark-Gluon Plasma (or Quark-Gluon Liquid).

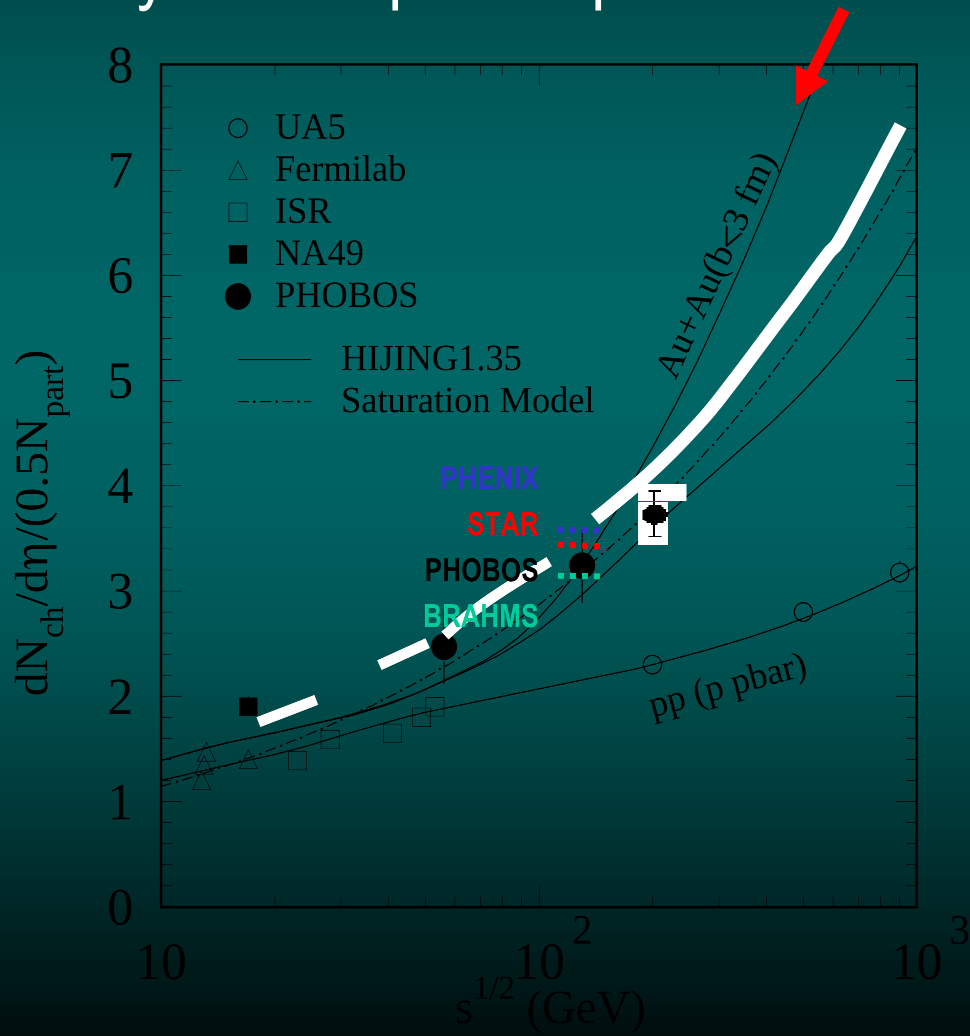
Direct experimental identification of new quasi-particles and medium properties remains a challenge for the future.

The next couple of years should be very exciting.

Extra Slides

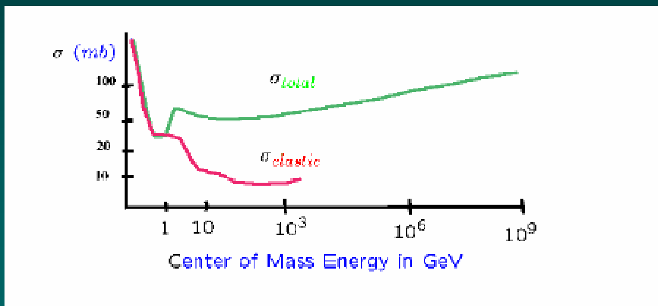
Charged Particle Multiplicity

We observe fewer charged particles relative to the sum of incoherent binary scaled proton-proton reactions.

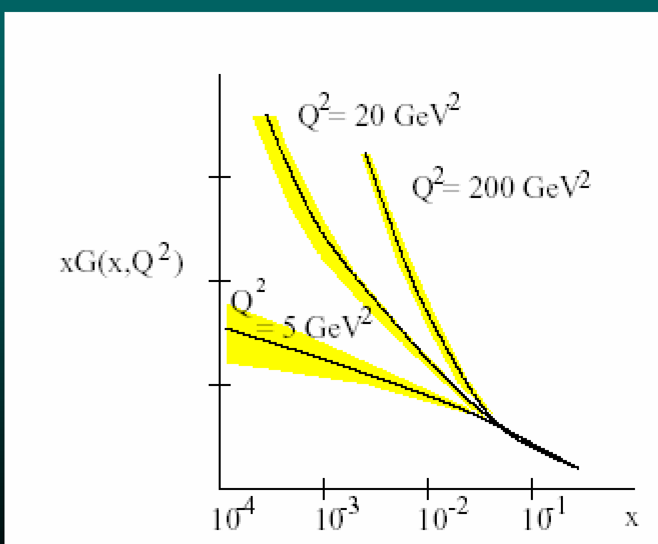


What do they have

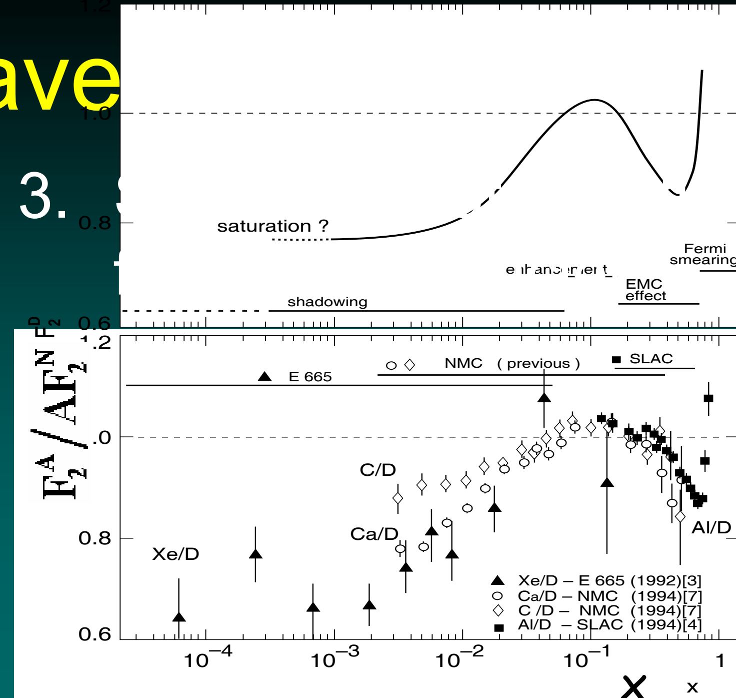
1. Scaling of the total p-p cross section



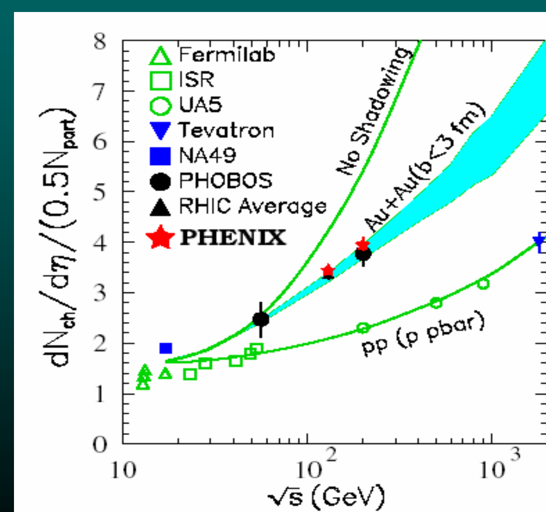
2. Growth of low x gluons in the proton



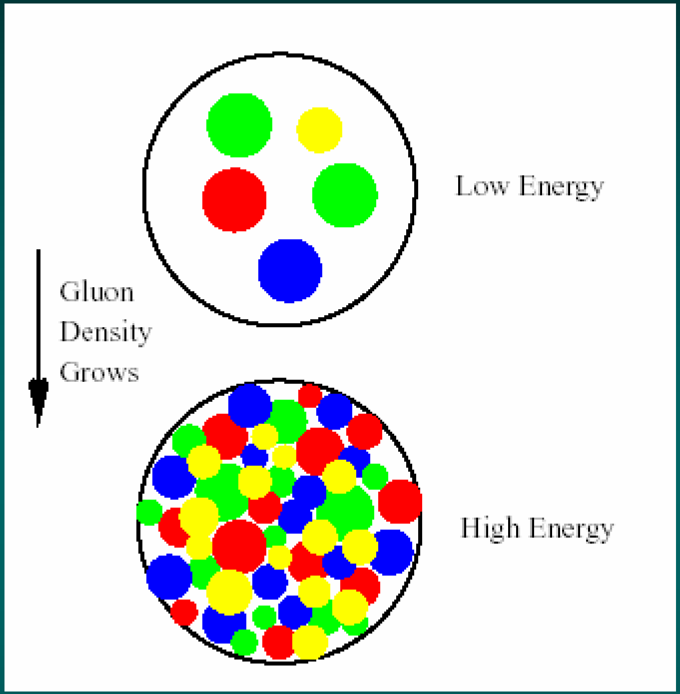
3.



4. Particle production in nucleus-nucleus reactions



Color Glass Condensate



When protons or nuclei are viewed at short wavelength, there is a large increase in low x gluons.

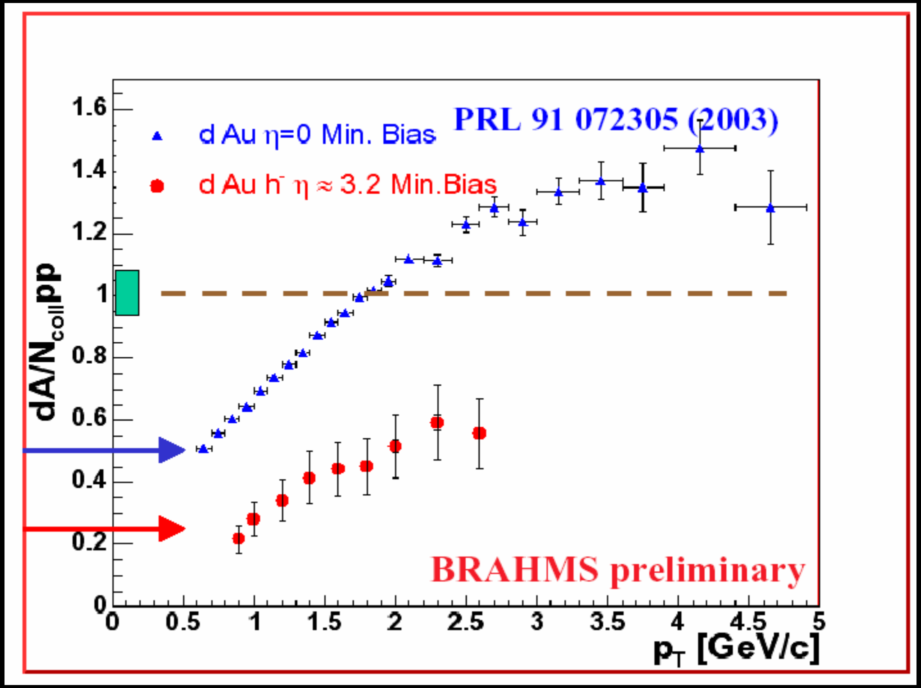
These low x gluons can saturate the available phase space and fuse forming a “color glass condensate.”

Gluon fields can be calculated classically as solutions of Yang-Mills.

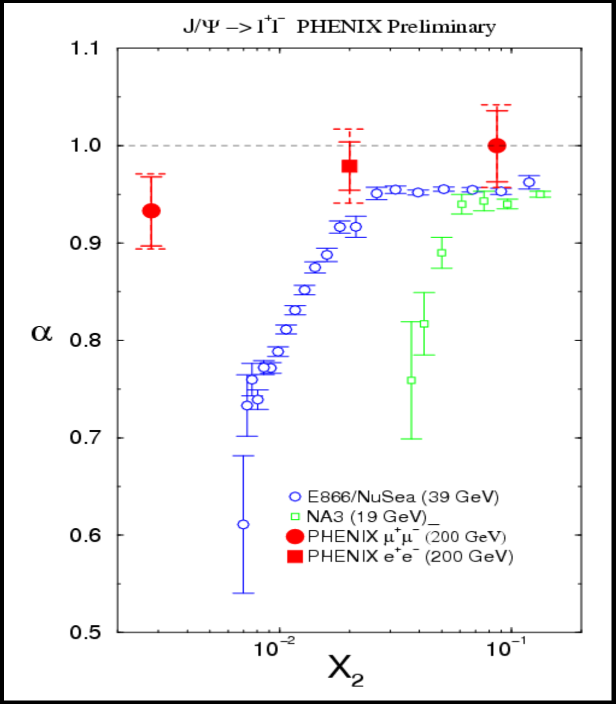
These universal solutions may explain all of this physics.

Highest Energy p(d) – Nucleus Reactions

Hadrons probing x ~ 10^{-3} - 10^{-4}



J/ψ probing x ~ 10^{-3}



Thus, RHIC may provide critical checks on these universal Color Glass Condensate calculations.

Frank Wilczek:

“In the quest for evidence of the quark-gluon plasma, there are two levels to which one might aspire. At the first level, one might hope to observe phenomena that are very difficult to explain from a hadronic perspective but have a simple qualitative explanation based on quarks and gluons.

But there is a second, more rigorous level ~~that remains a challenge for the future~~. is being addressed presently. Using fundamental aspects of QCD theory, one can make quantitative predictions for the emission of various kinds of “hard” radiation from the quark-gluon plasma. We will not have done justice to the concept of ~~weakly~~ strongly interacting plasma of quarks and gluons until some of the predictions are confirmed by experiment.”

The future is now.

The New York Times ON THE WEB

NATIONAL DESK | January 13, 2004, Tuesday

Newly Found State of Matter Could Yield Insights Into Basic Laws of Nature

By JAMES GLANZ (NYT) 866 words
Late Edition - Final , Section A , Page 19 , Column 2

ABSTRACT - Scientists from Brookhaven National Laboratory say fleeting, ultradense state of matter, comparable in some respects to bizarre kind of subatomic pudding, has been discovered deep within core of ordinary gold atoms; some scientists describe finding as breakthrough in understading powerful, immensely complex forces that hold together building blocks of atomic nuclei: protons and neutrons (M)

NATIONAL DESK | January 14, 2004, Wednesday

Tests Suggest Scientists Have Found Big Bang Goo

By JAMES GLANZ (NYT) 832 words
Late Edition - Final , Section A , Page 12 , Column 3

DISPLAYING FIRST 50 OF 832 WORDS - At least three advanced diagnostic tests suggest that an experiment at the Brookhaven National Laboratory has cracked open protons and neutrons like subatomic eggs to create a primordial form of matter that last existed when the universe was roughly one-millionth of a second old, scientists said here on Tuesday. ......

SCIENCE DESK | January 20, 2004, Tuesday

Like Particles, 2 Houses of Physics Collide

By JAMES GLANZ (NYT) 1356 words
Late Edition - Final , Section F , Page 1 , Column 1

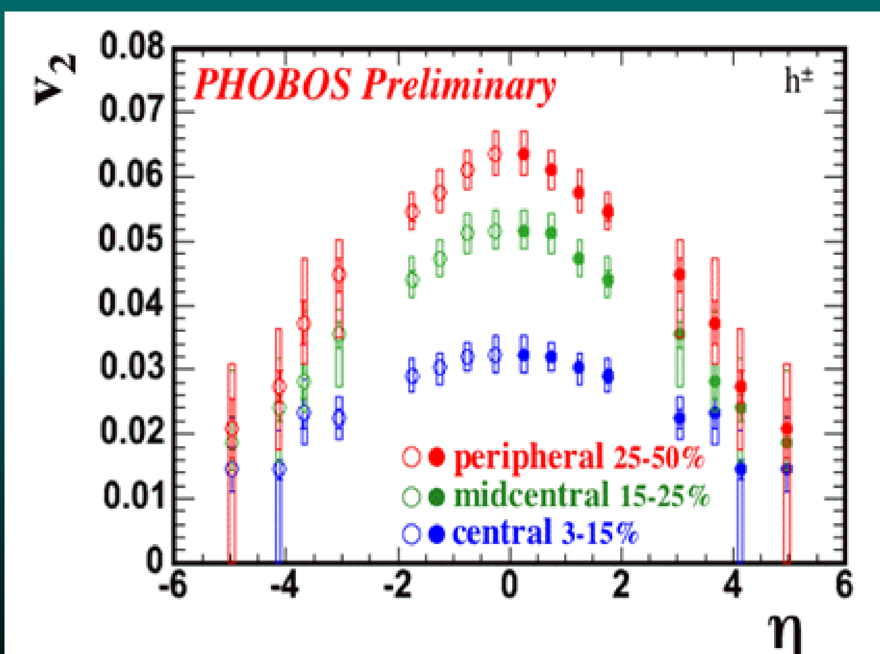
DISPLAYING FIRST 50 OF 1356 WORDS - ... What, has this thing appear'd again ... I have seen ... -- "Hamlet," Act I, Scene ... A bland and bulky conference center in this city's fogbound downtown was transformed in recent days into the Elsinore of particle physics. The ghost that continually appeared, disappeared and appeared again during...

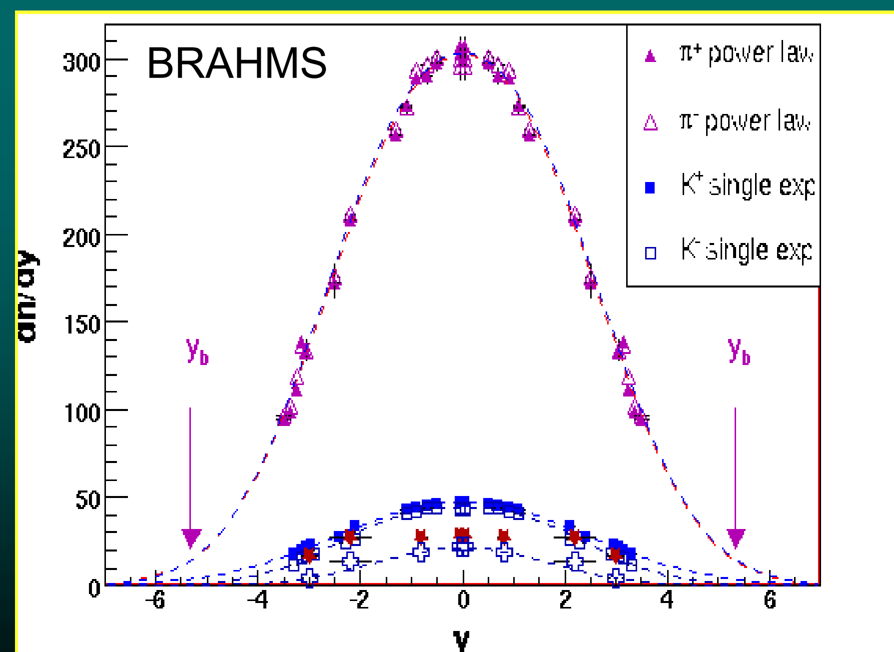
Some Puzzles?

Hydrodynamic models have trouble describing longitudinal motion

Many assume boost-invariance (plateau in rapidity)

Particle correlations indicate shorter lifetime



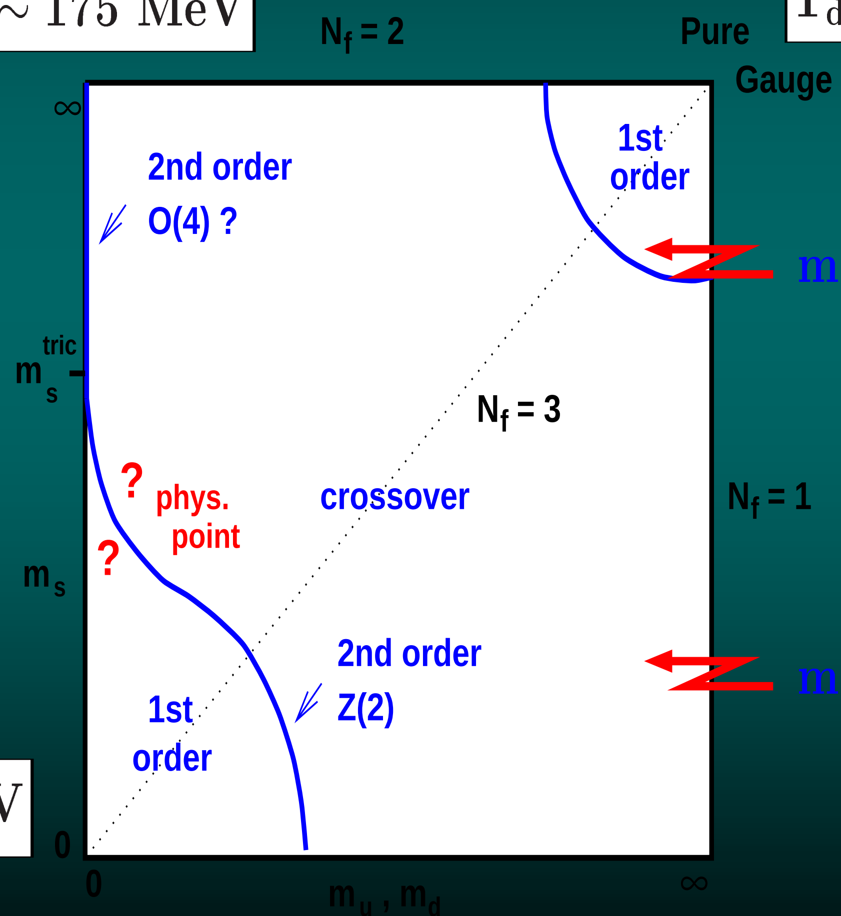


Transition Order

3-flavour phase diagram

$T_\chi^{n_f=2} \sim 175$ MeV

$T_d \sim 270$ MeV



$m_{PS}^{crit} \simeq 2.5$ GeV

$m_{PS}^{crit} \simeq 300$ MeV

$T_\chi^{n_f=3} \sim 155$ MeV