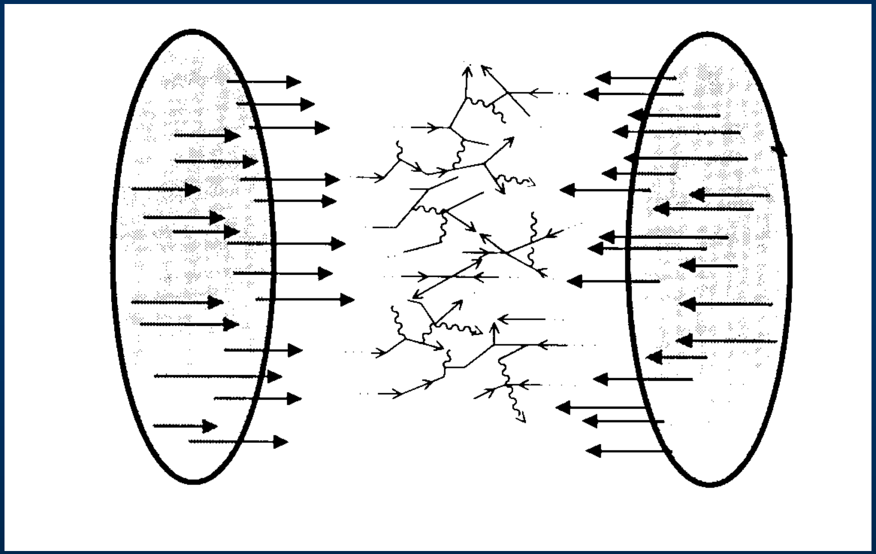
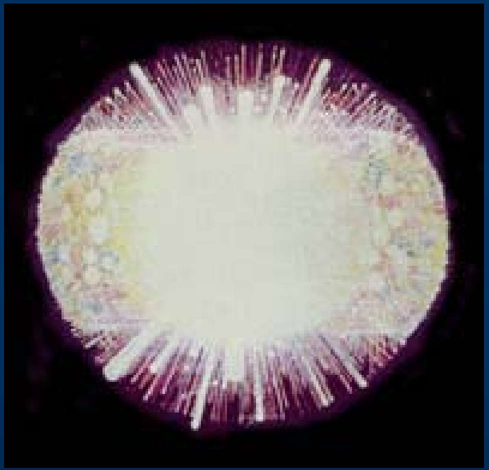
Relativistic Heavy Ion Physics

Where Are We and Where Are We Going?





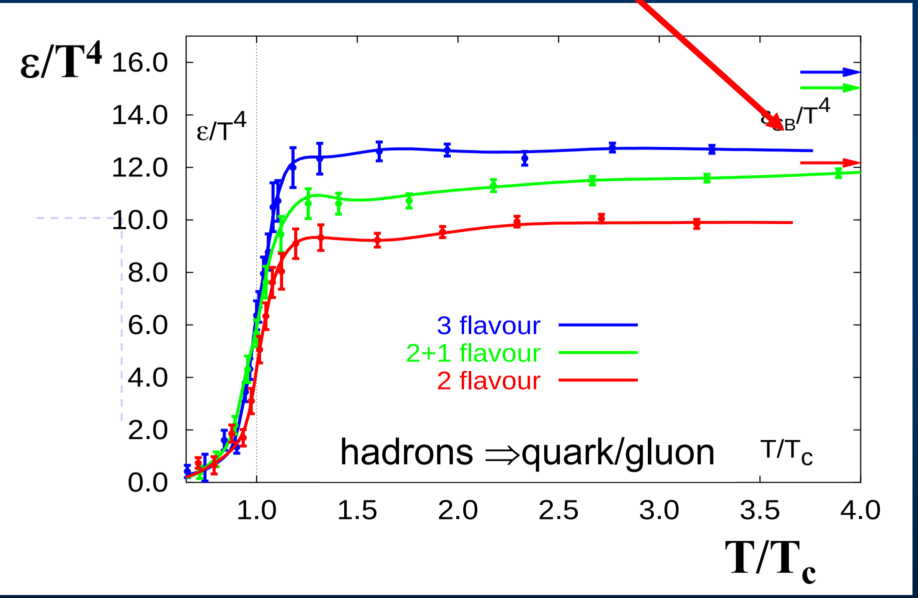
Jamie Nagle
University of Colorado at Boulder
Aspen 2004 Winter Conference

Quark Gluon Plasma

Lattice QCD predicts a phase 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



Phase Transition:

T = 170 MeV ~ 10^{12} ^{0}F

ε = 0.8 GeV/fm^3

Assumes thermal system.

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

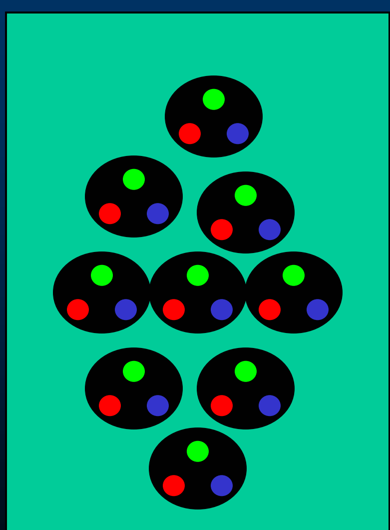
Deconfinement Transition

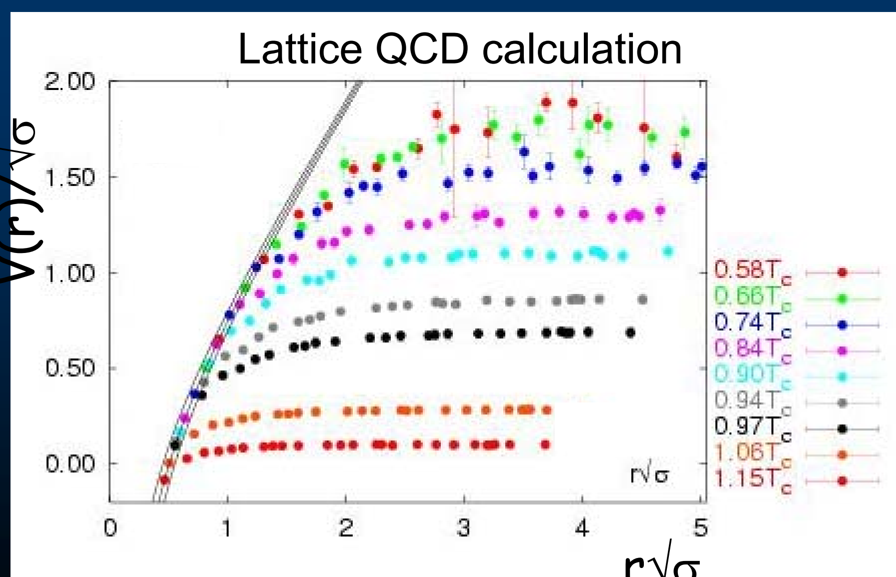
QCD in Vacuum

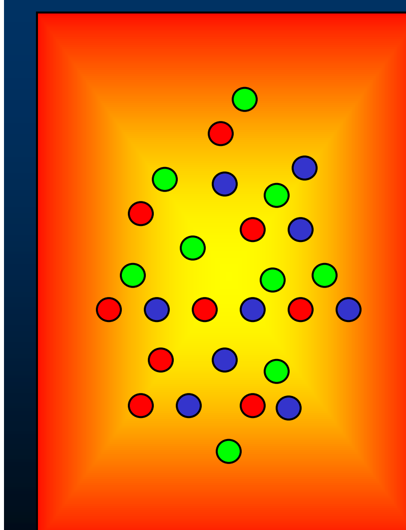
- linear increase in potential with distance from color charge
- strong attractive force
- spontaneous breaking of chiral symmetry
- confinement of quarks to hadrons baryons (qqq) and mesons ($q\bar{q}$)

QCD in dense and hot matter

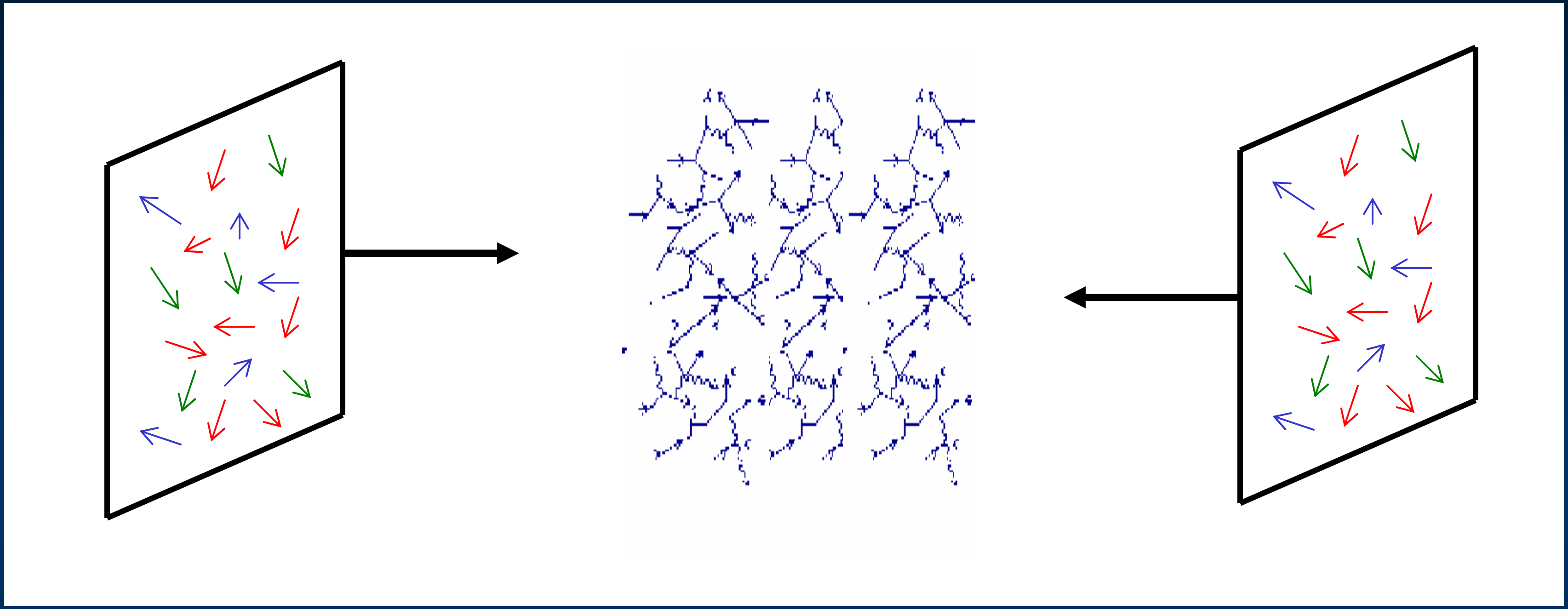
- screening of color charges
- potential vanishes for large distance scales
- restoration of approximate chiral symmetry as quarks act as nearly massless particles
- deconfinement of quarks !





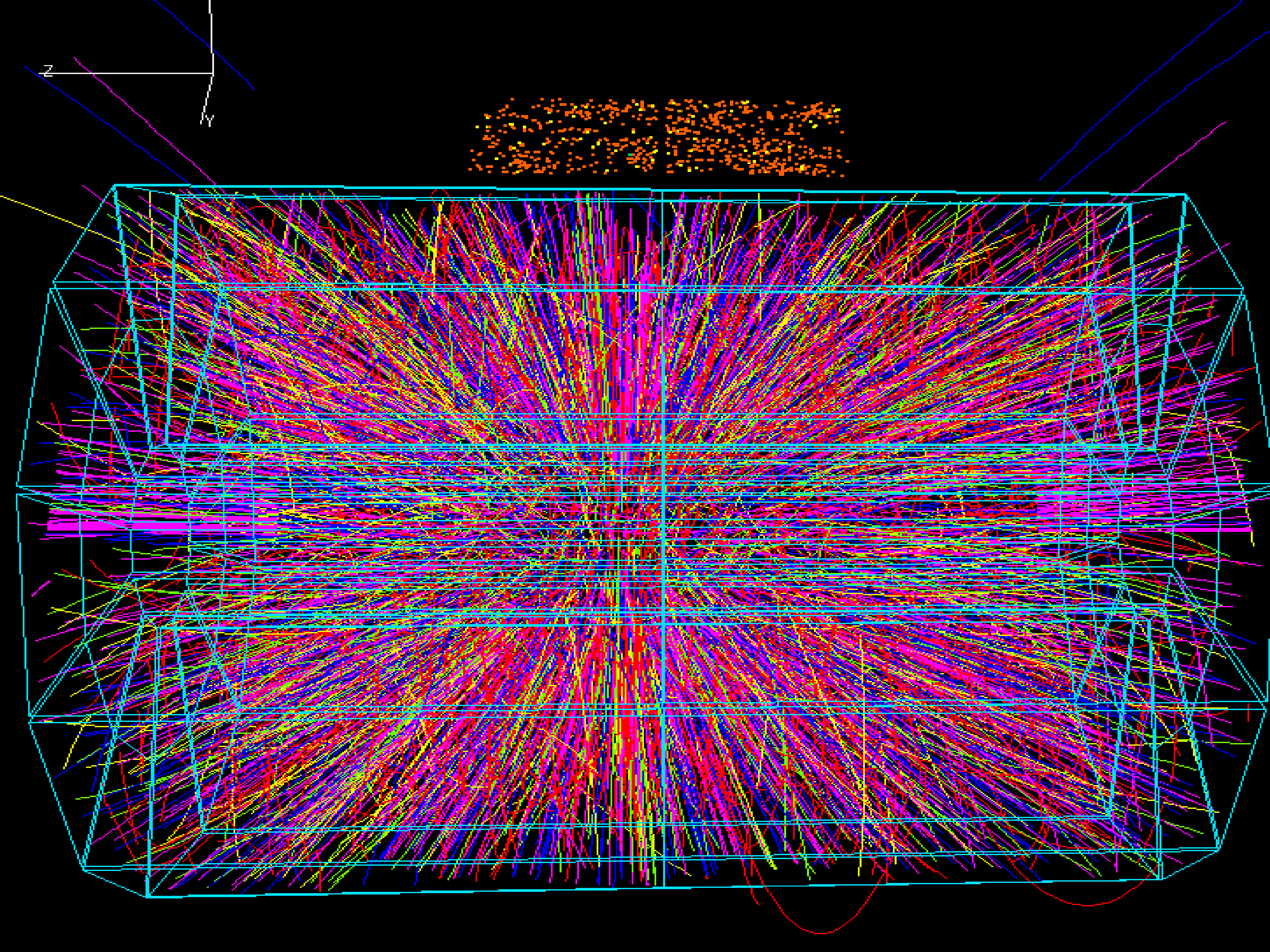


Heavy Ion Collisions



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?

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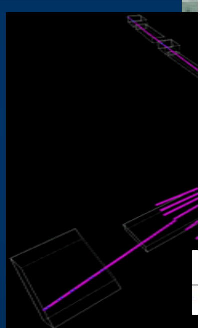
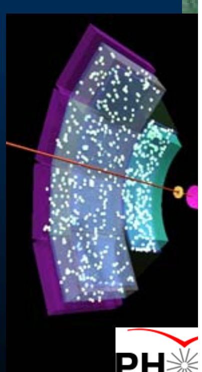
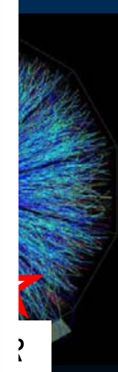
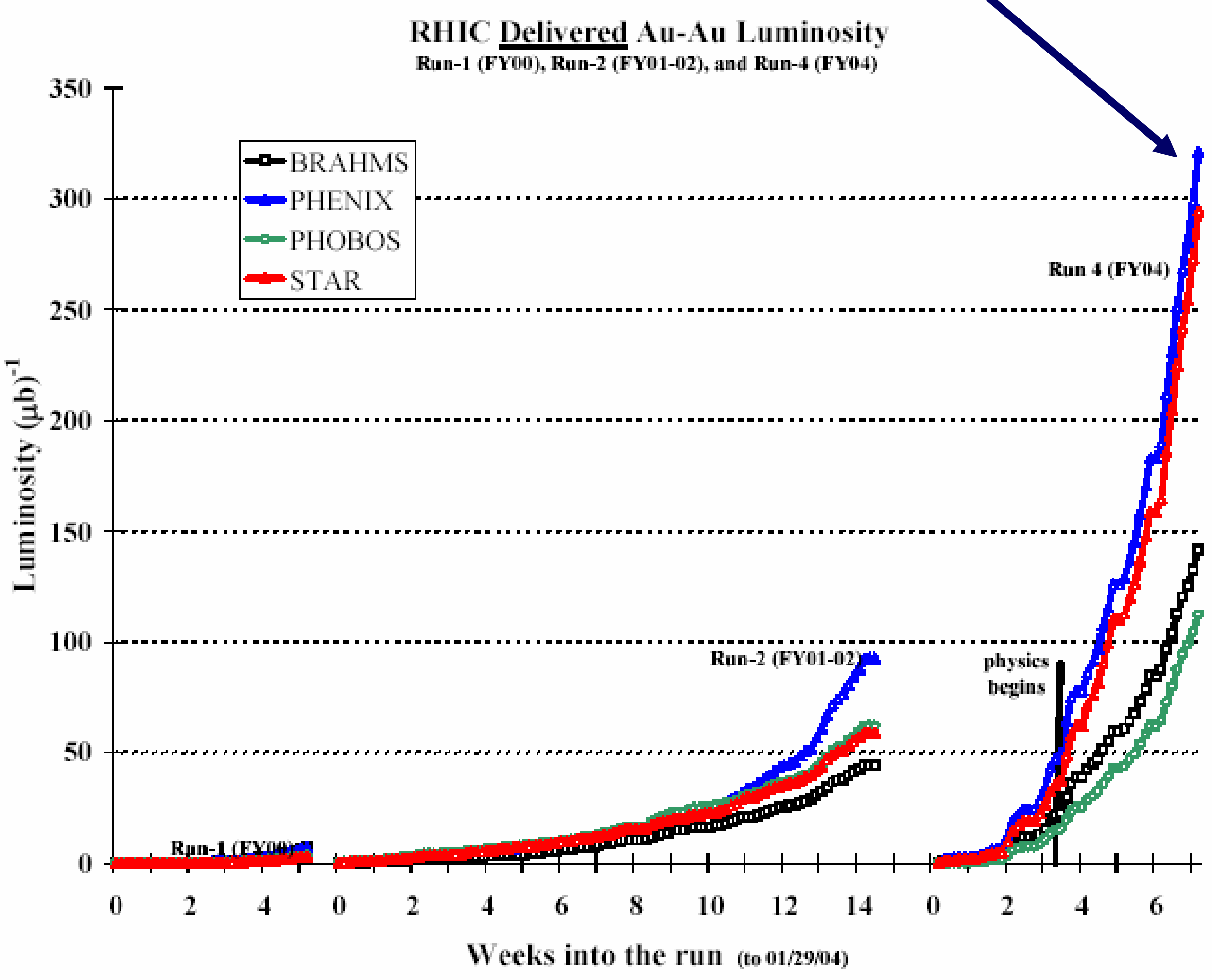





RHIC is kicking butt !

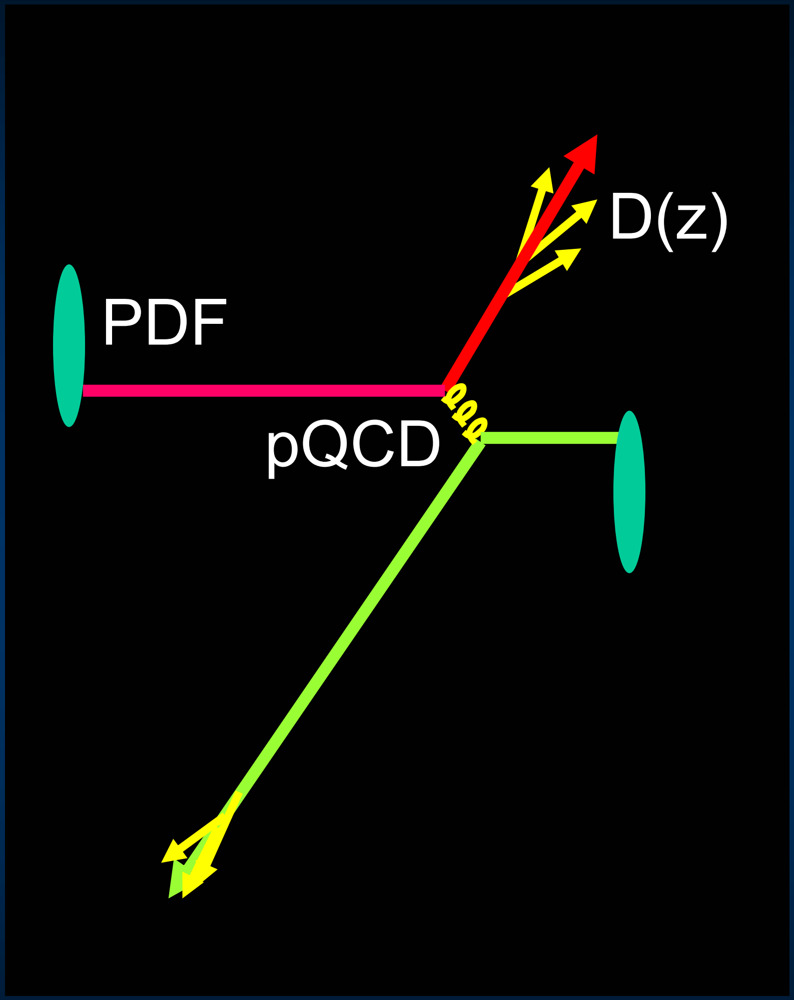


Experimental Observations

As an experimentalist, let the data speak for itself.

At least as much as possible.

Perturbative QCD and Factorization

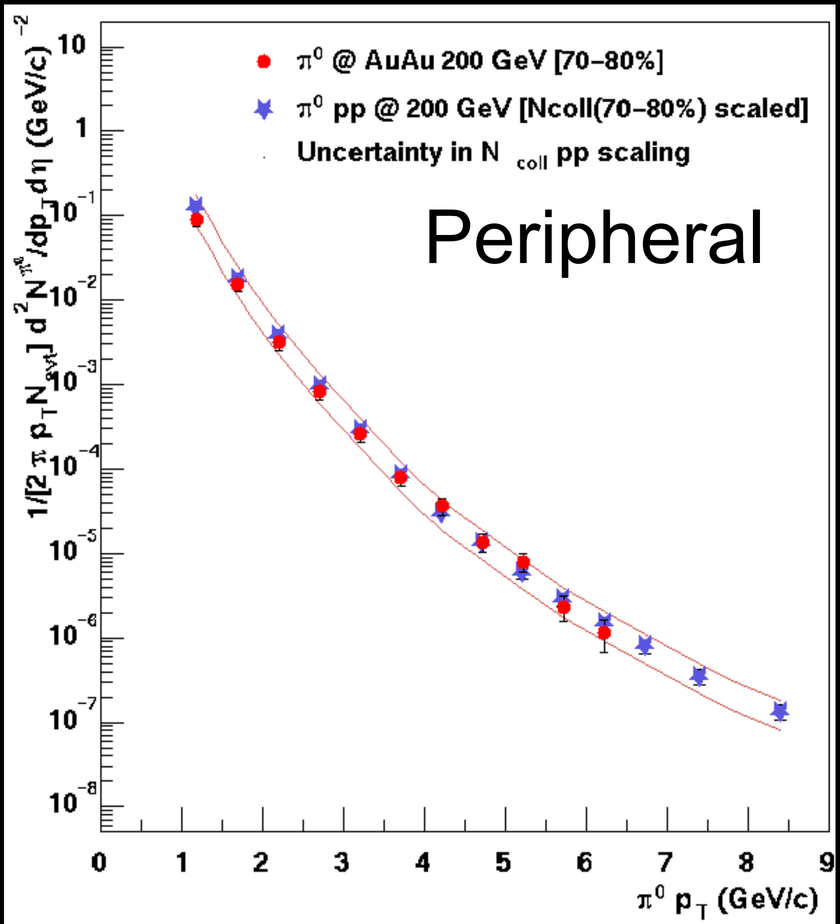


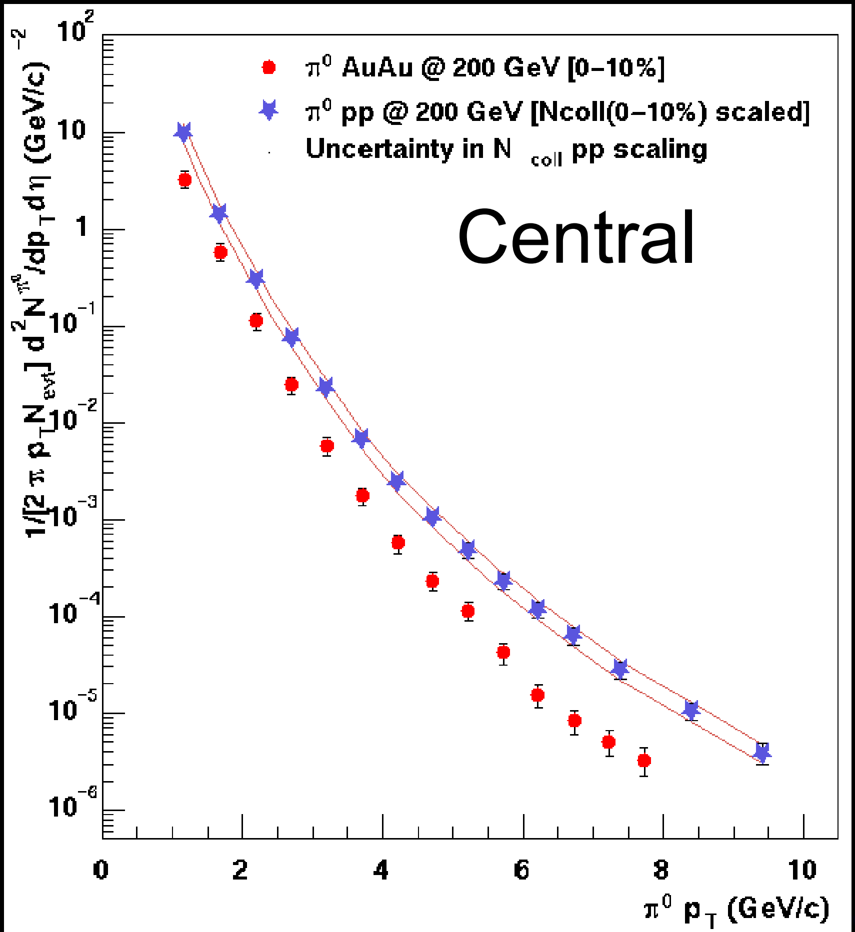
- Proton+Proton→ π^0 + X
- NLO pQCD calculation agrees with data from 2-13 GeV
- Extend to nuclei by expected scaling with nuclear thickness calculated as a function of impact parameter

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

What About Heavy Ion Reactions?

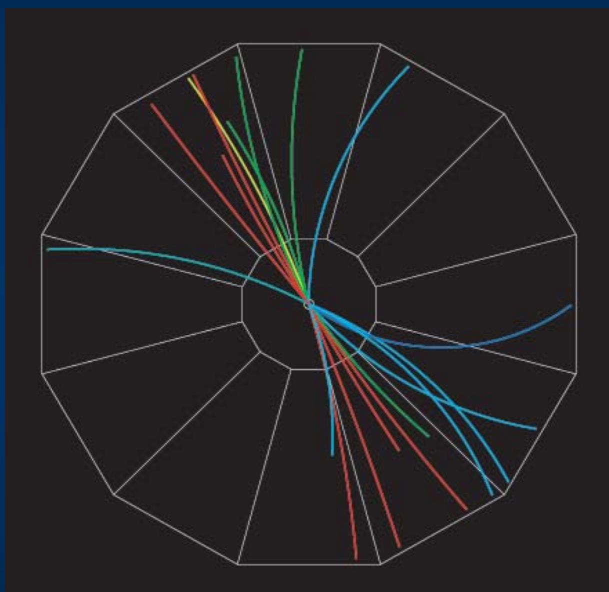
- Peripheral Au+Au = superposition of p+p reactions.
- Central Au+Au reveals a significant suppression !

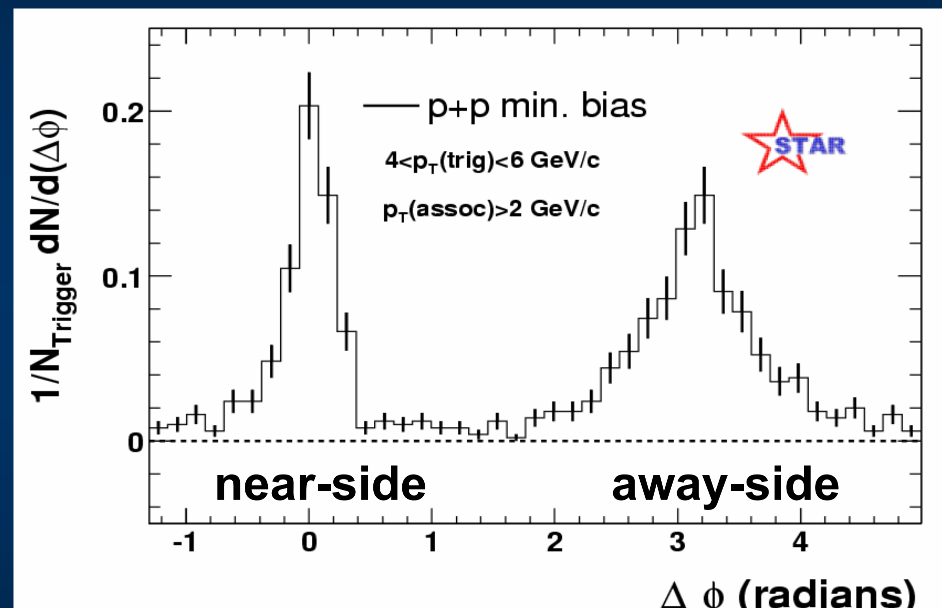


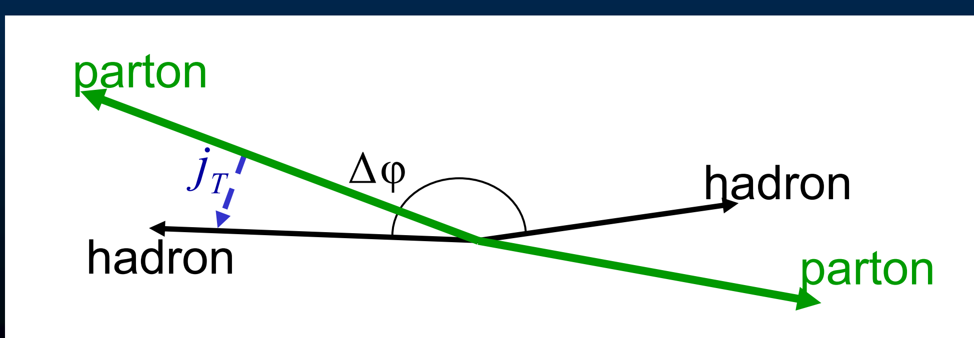


Jet Correlations

- Complete jet reconstruction is not available
- 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

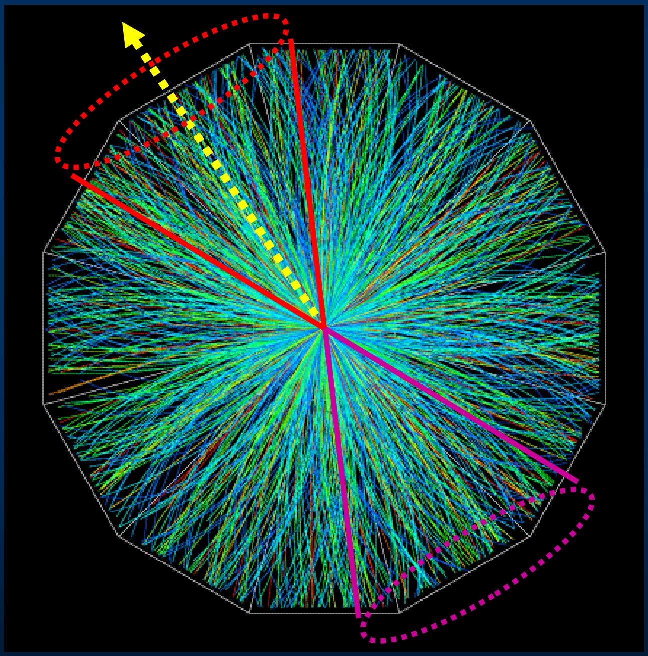
STAR

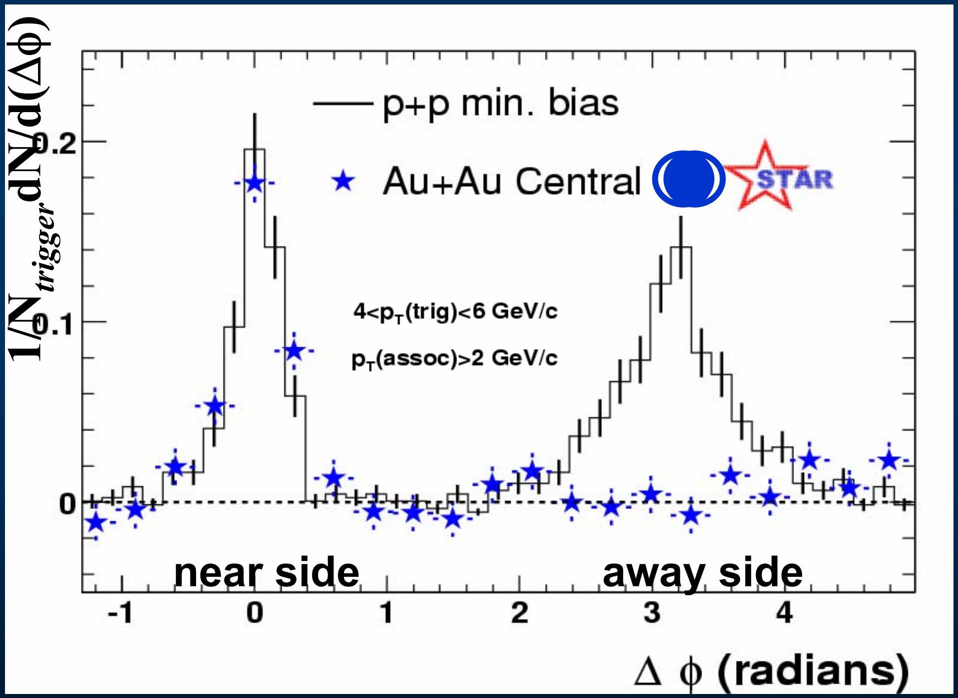
- $J_t = 636 \pm 20$ MeV/c
- $k_t = 1.7 \pm 0.1$ GeV/c

PHENIX

"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

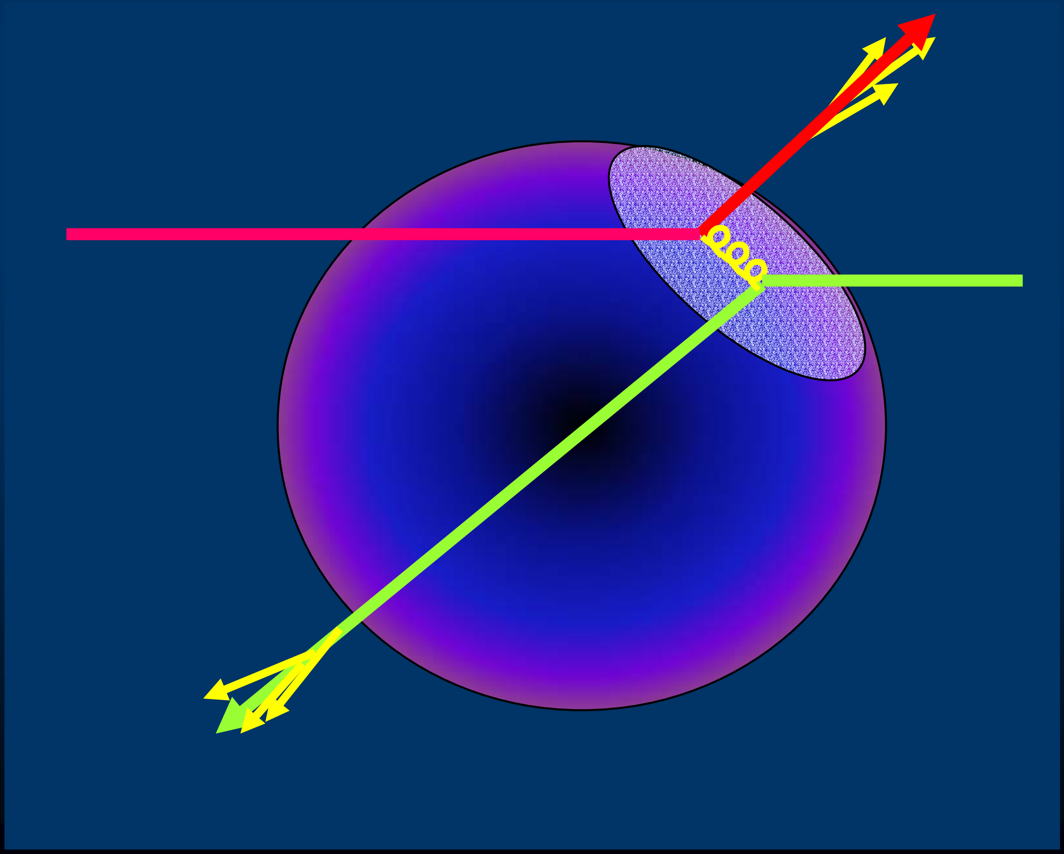




- Conservation of energy and momentum says that away side jet cannot really disappear

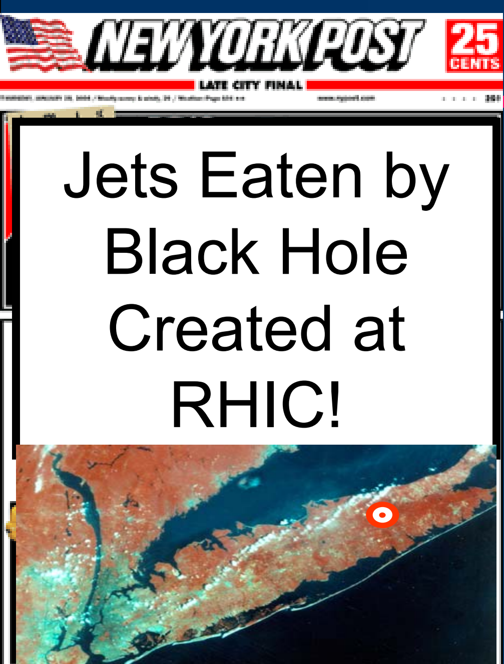
Where is the Energy?

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



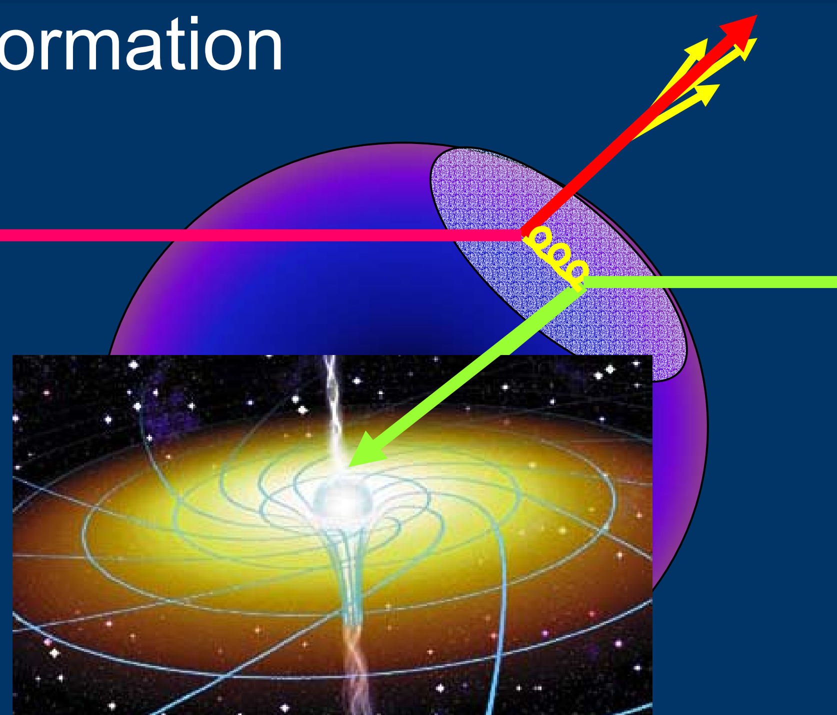
Opaque Medium

- 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


NEW YORK POST 25 CENTS

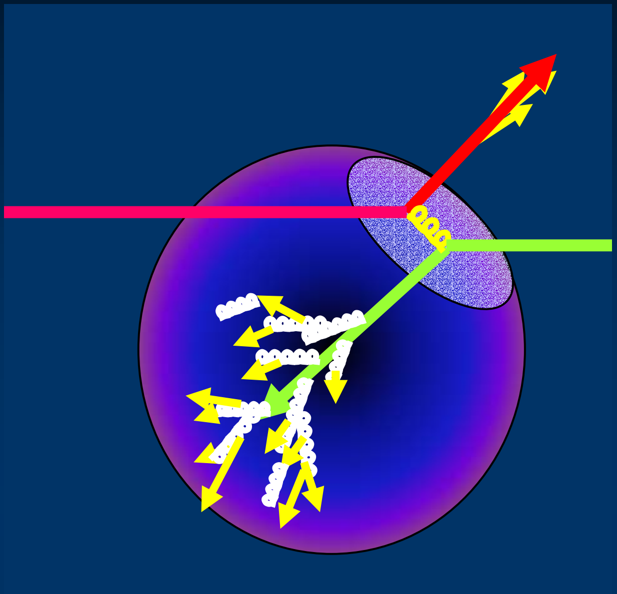
LATE CITY FINAL

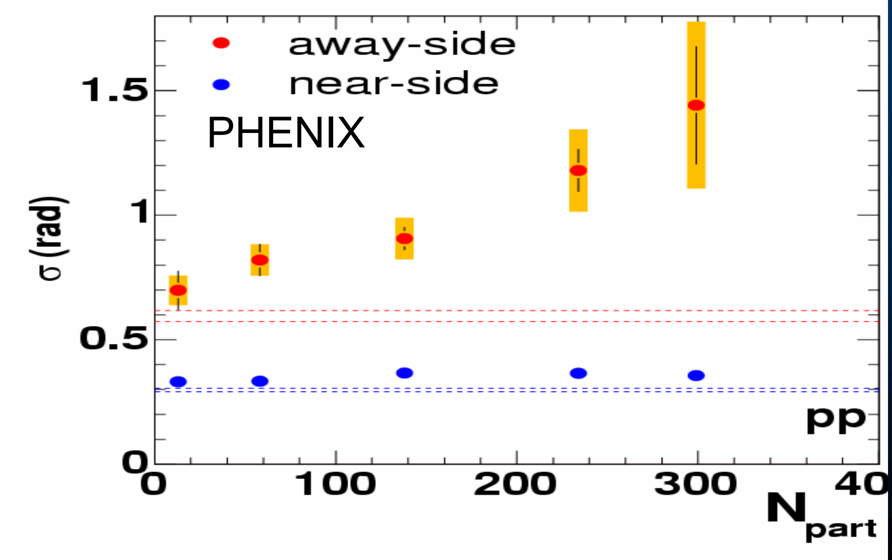
Jets Eaten by Black Hole Created at RHIC!

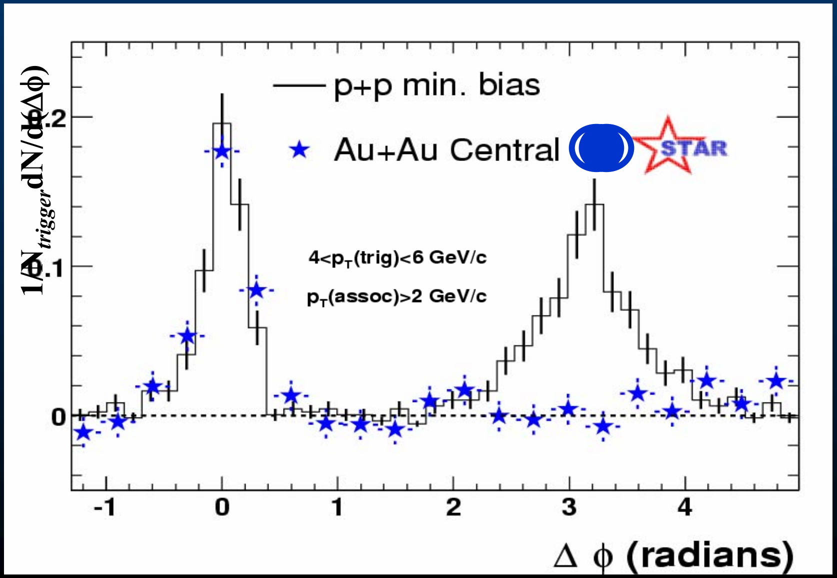


Thermalization of Energy !

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

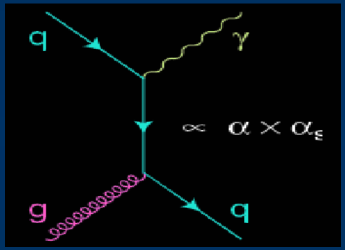


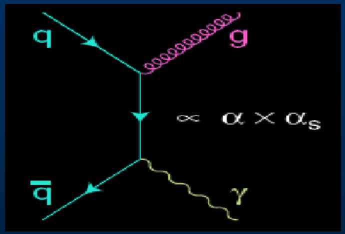


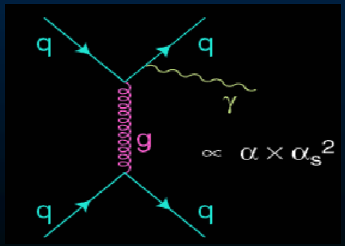


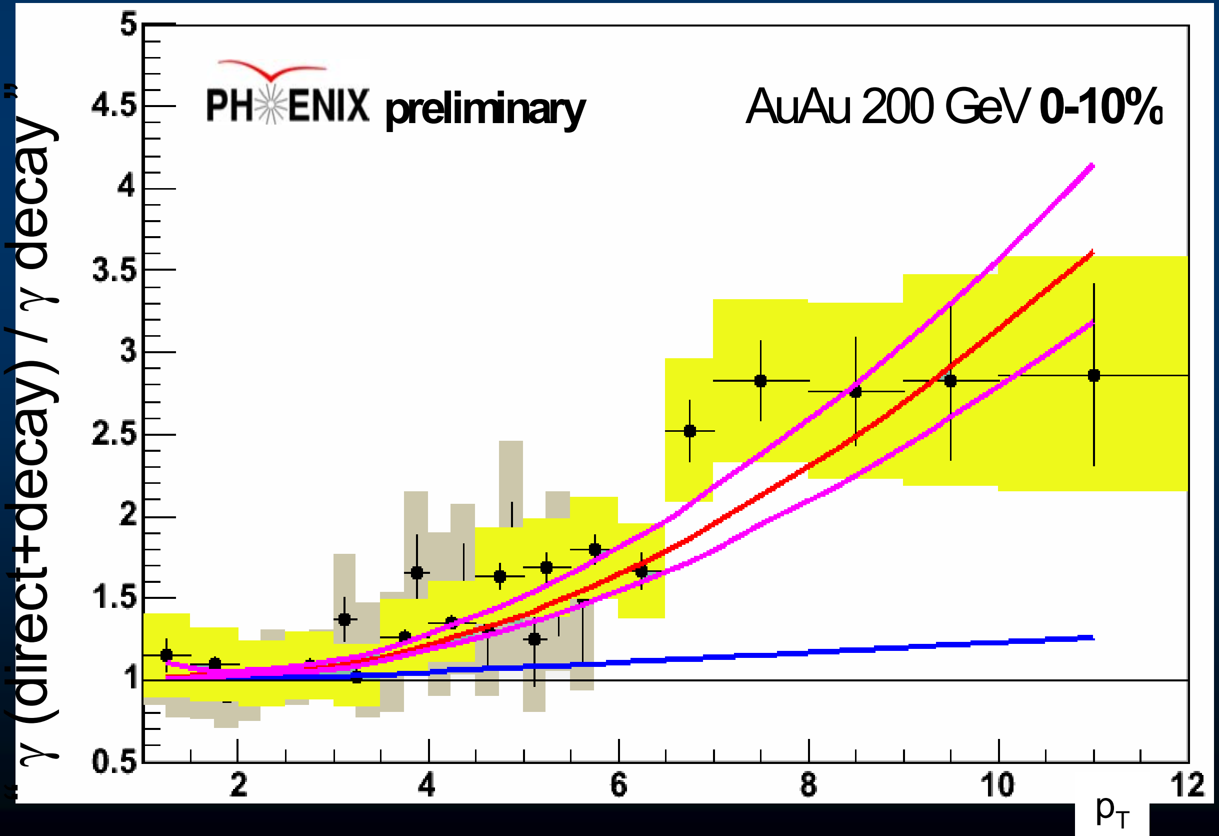
Direct Photons Shine!

- 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





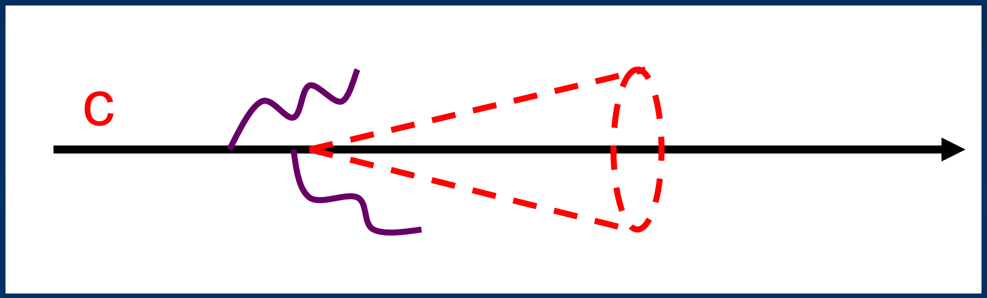


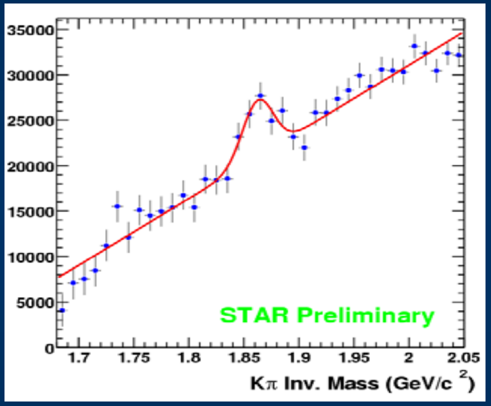


Charm and Beauty

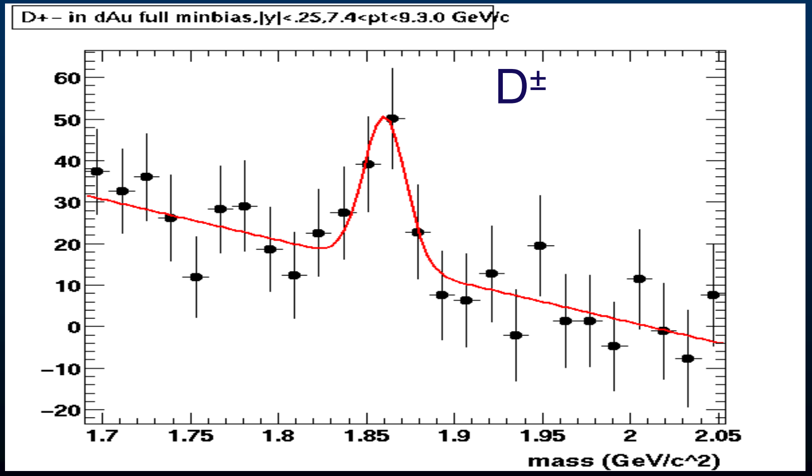
QCD is flavor independent, but heavy quarks at same p_T are moving much slower than light quarks.

Expected “dead-cone” with no induced gluon radiation.



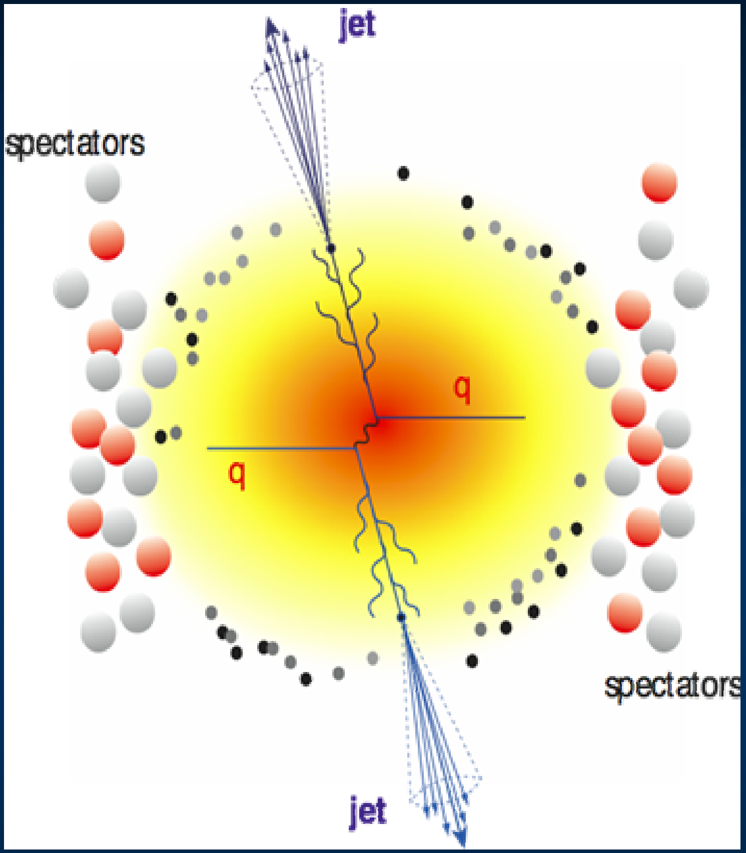


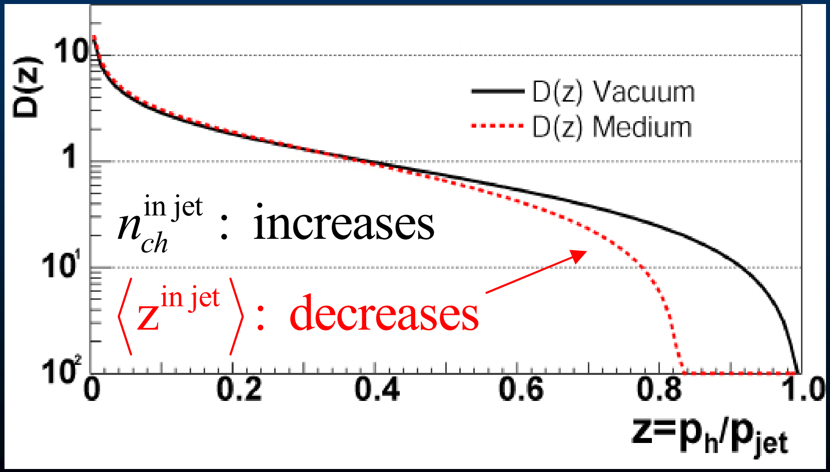
Recent single lepton and direct D reconstruction allow us to address this physics.



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

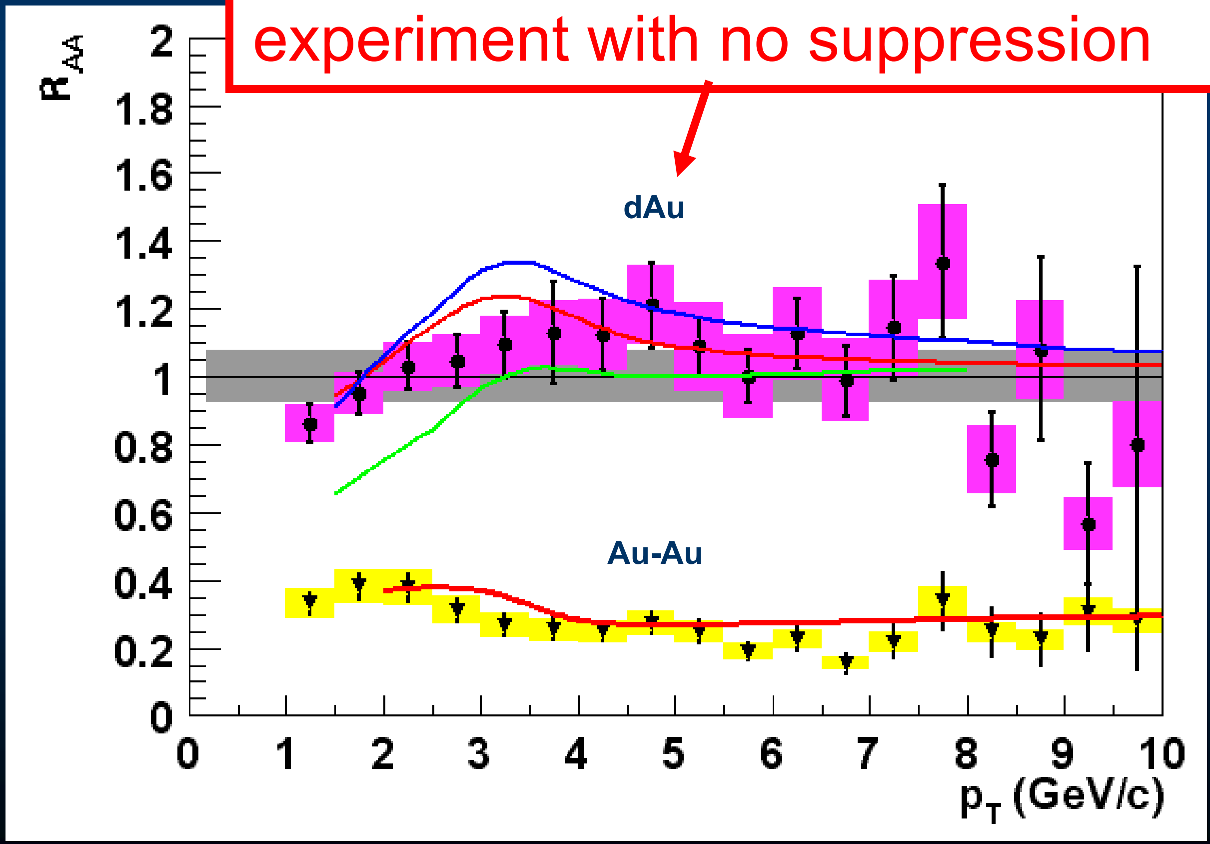
Induced gluon brehmstrahlung pQCD calculation
Agrees with data with initial gluon density:

$dN_g/dy \sim 1100$

$\varepsilon > 100\ \varepsilon_0$

Lowest energy radiation sensitive to infrared cutoff.

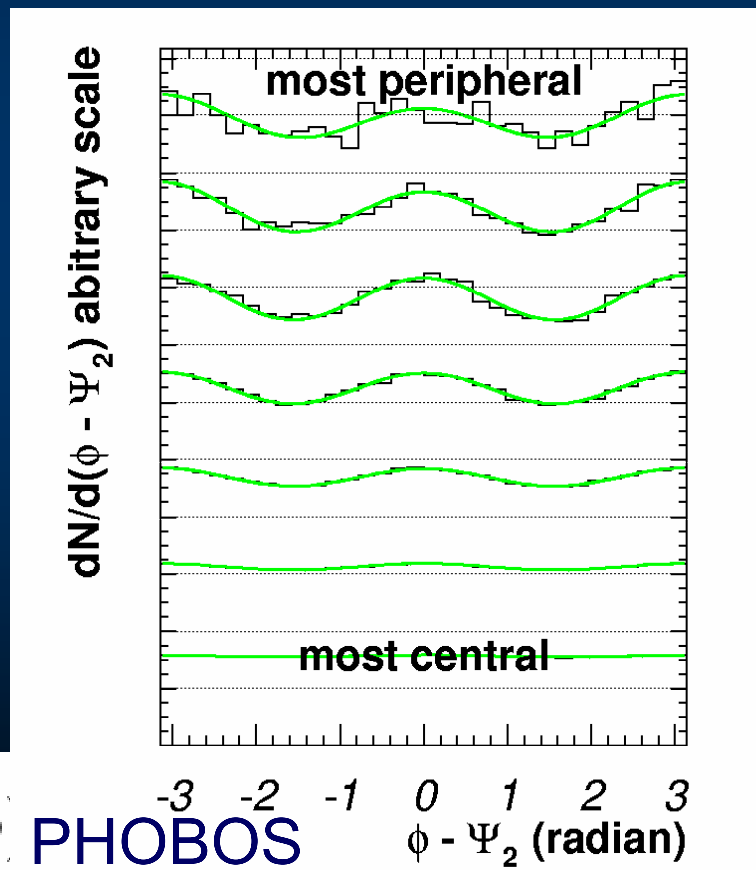
* Note deuteron-gold control experiment with no suppression



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

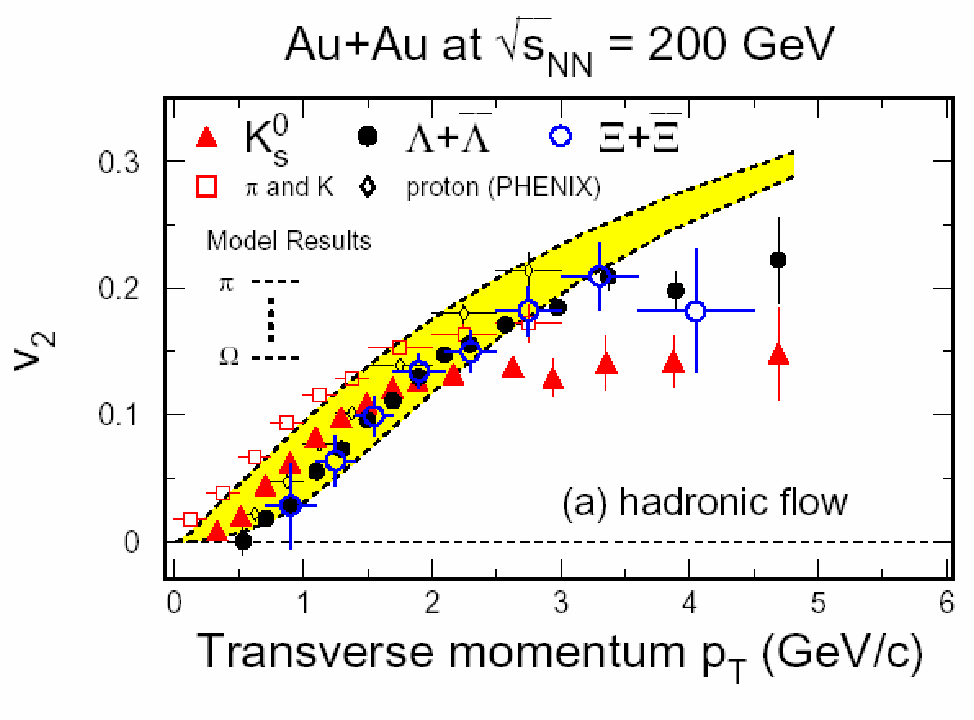


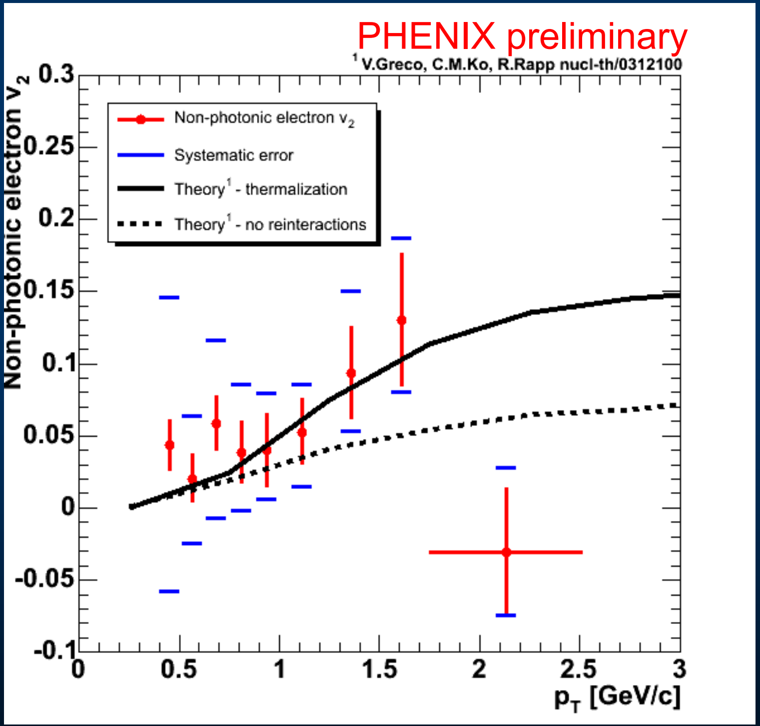
$$\frac{dN}{p_T\,dp_T\,dy\,d\varphi}(p_T,\varphi;b$$

$$_T;b)\cos(2\varphi)+\ldots)$$

Large Pressure Felt By All Hadrons

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



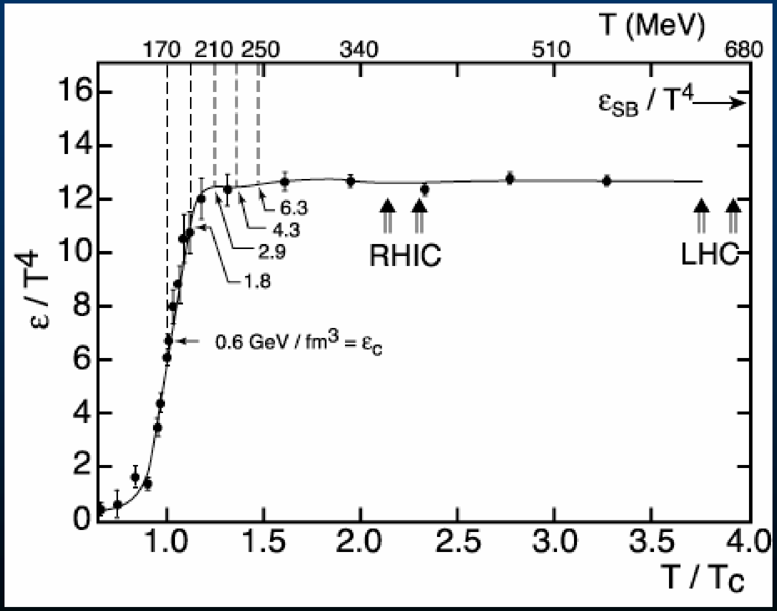


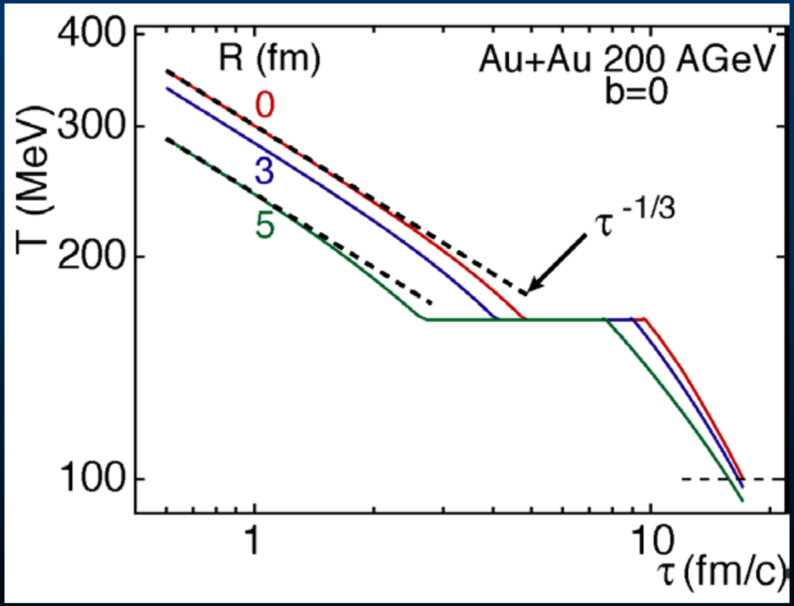
Hydrodynamics

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

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

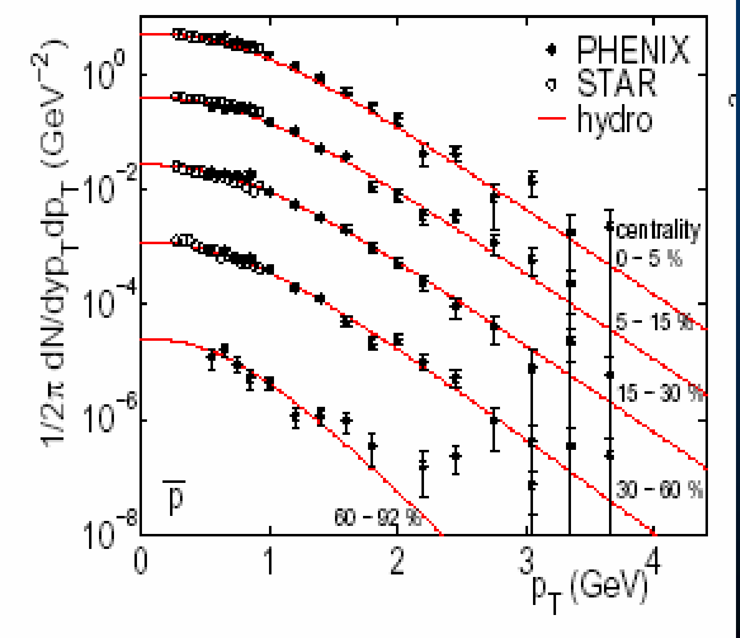
- Equation of State from lattice QCD

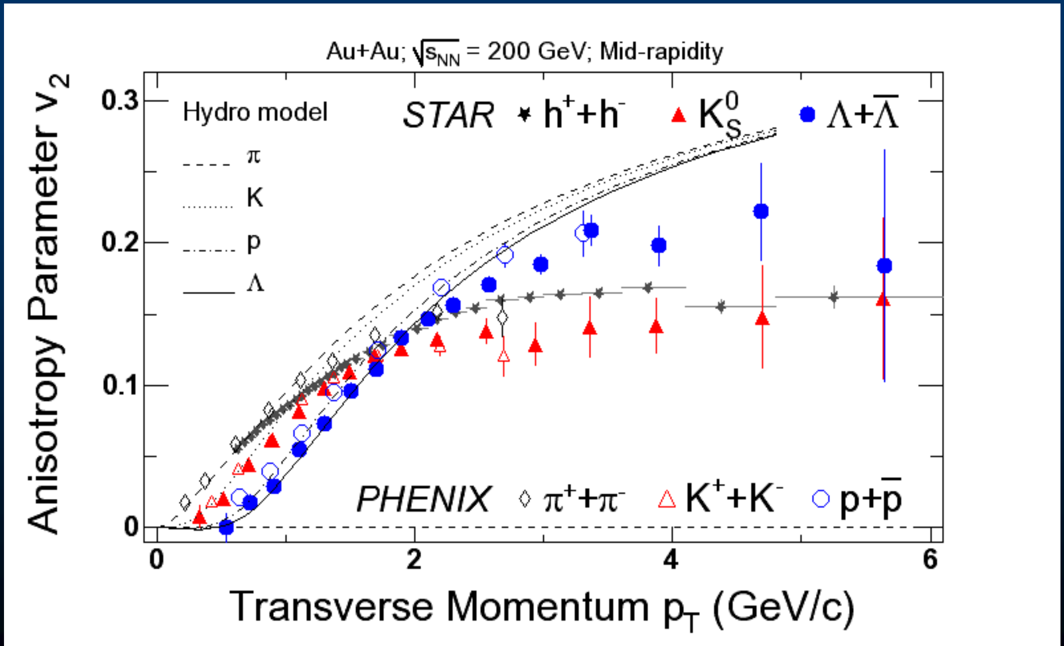




Data and Theory Collide (II)

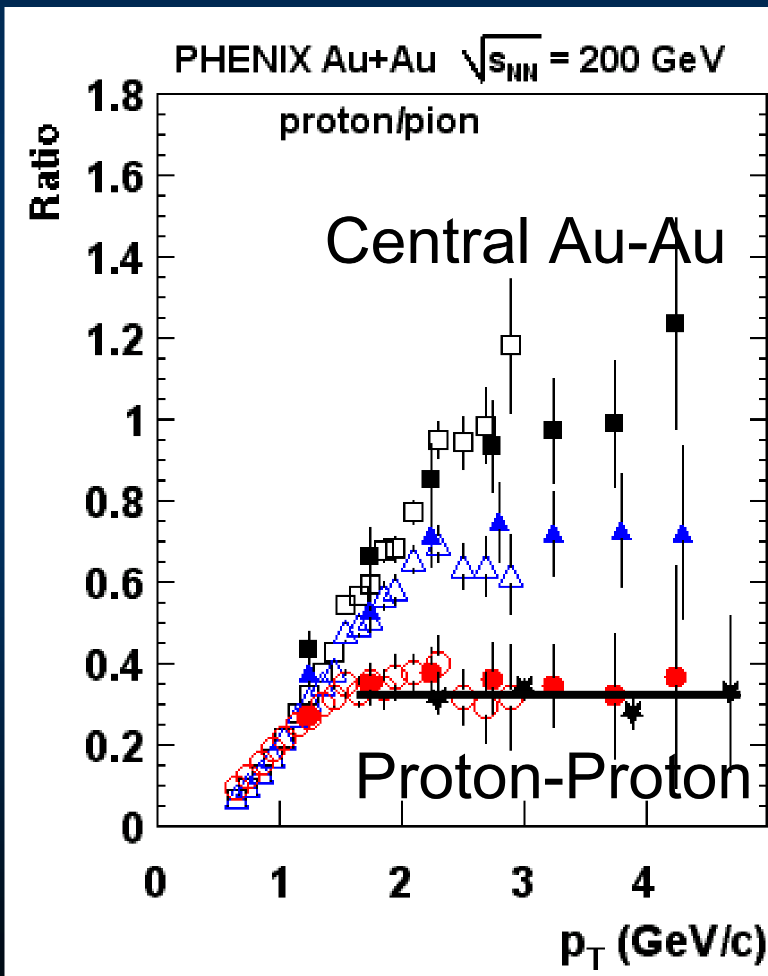
- Agreement between hydrodynamics at mid-rapidity for hadron spectra and elliptic flow (v_2) up to $p_T \sim 2$ GeV
- First time hydrodynamics without any viscosity describes heavy ion reactions



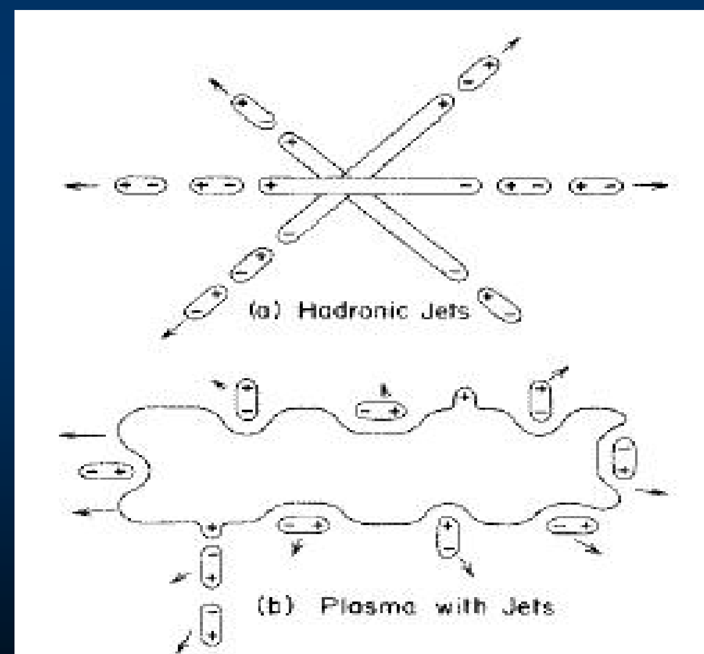


Some Puzzles?

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



Factorization assumption of jet fragmentation completely breaks down.



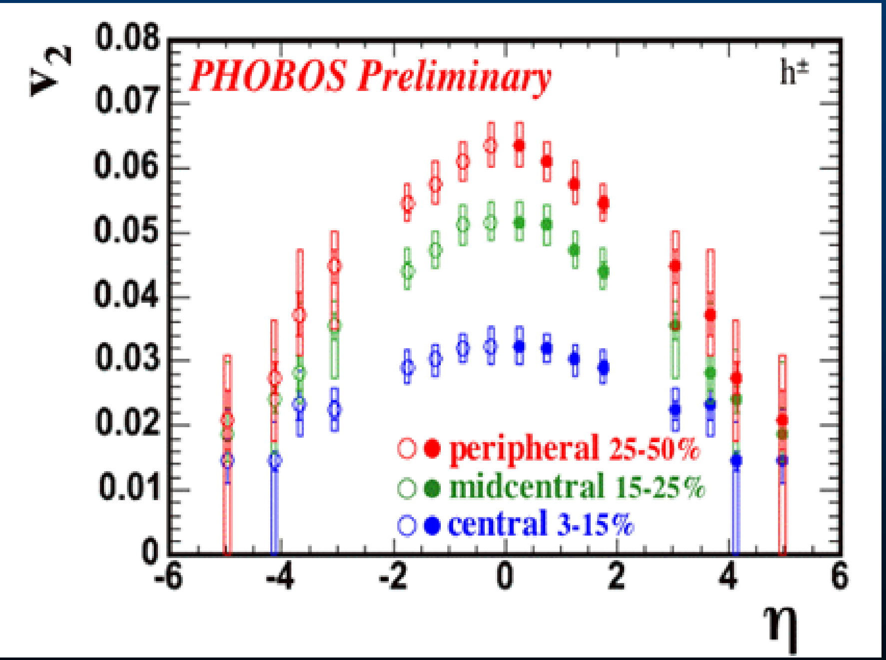
Color recombination ?

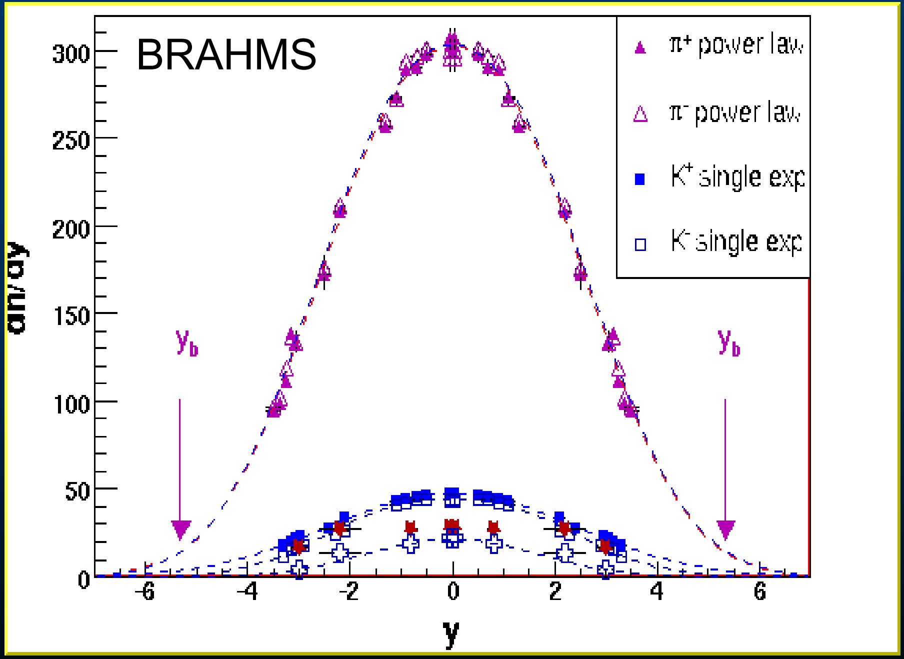
Some Puzzles?

Hydrodynamic models have trouble describing longitudinal motion

Many assume boost-invariance (plateau in rapidity)

Particle correlations indicate shorter lifetime





Quark-Gluon Plasma?

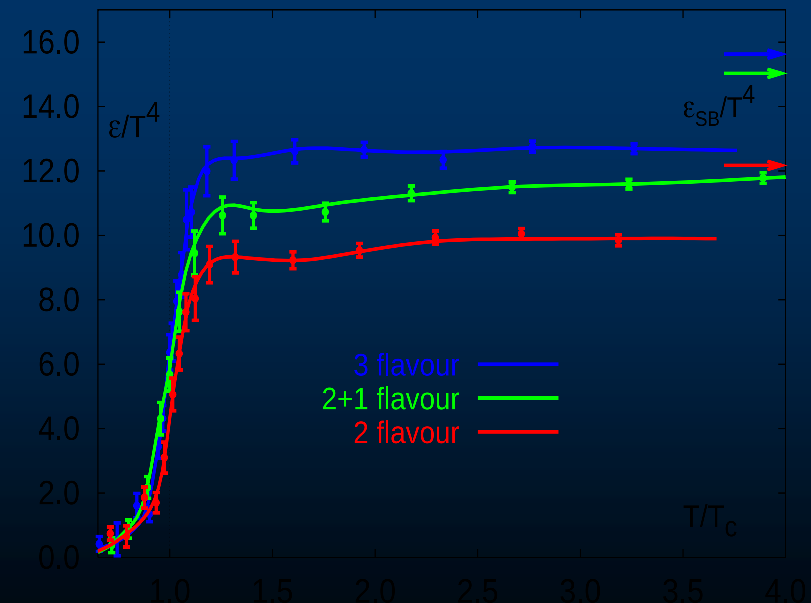
Many indications of energy density well above phase transition value.

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

More like a liquid with zero viscosity.

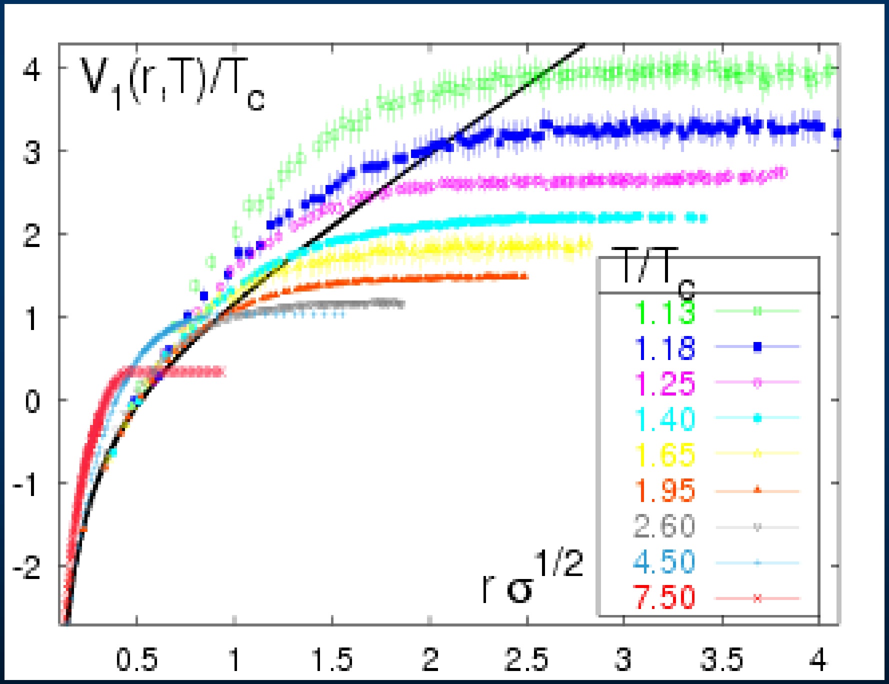
New quasi-particles or couplings?

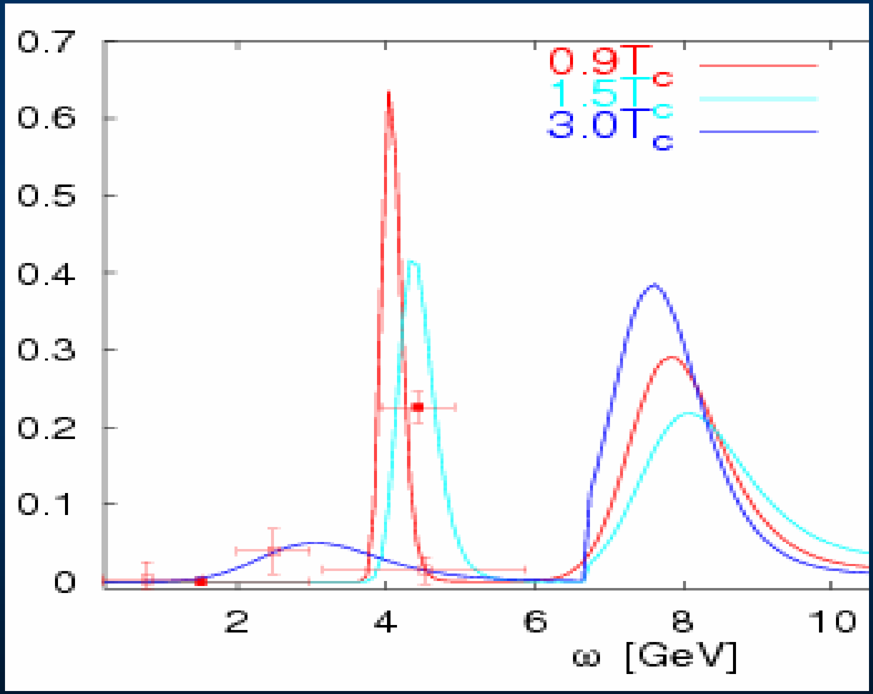
Help needed from lattice, effective theory, string theory



Interactions Above T_c

Recent lattice QCD calculations indicate
- Bound states at $T \sim 1.5\ T_c$
- Quark-Antiquark interactions persist above T_c





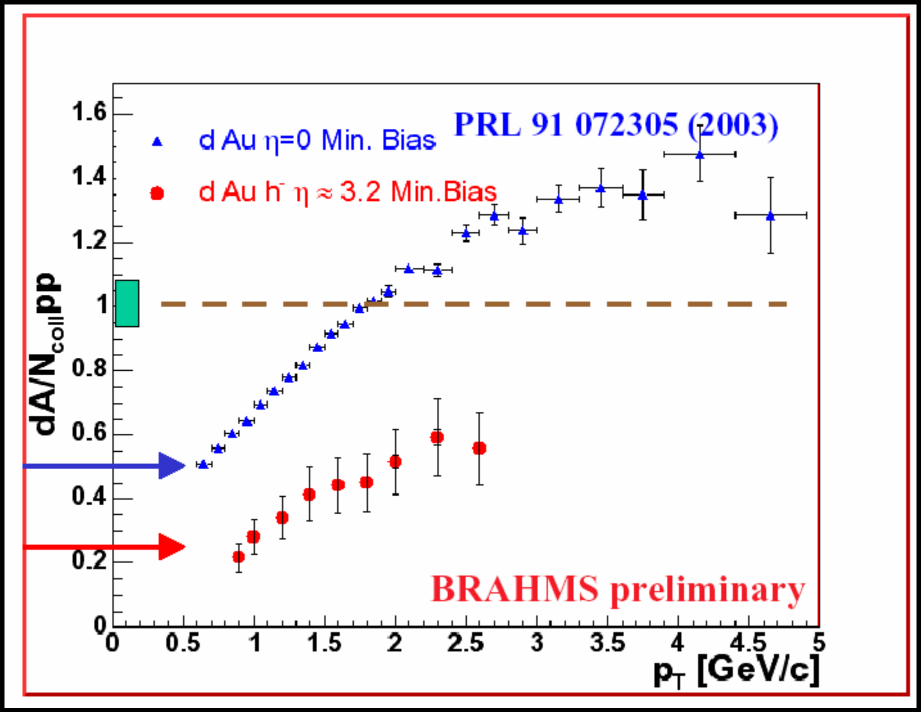
Key measurements of quarkonia and low mass vector meson spectral functions are the next step

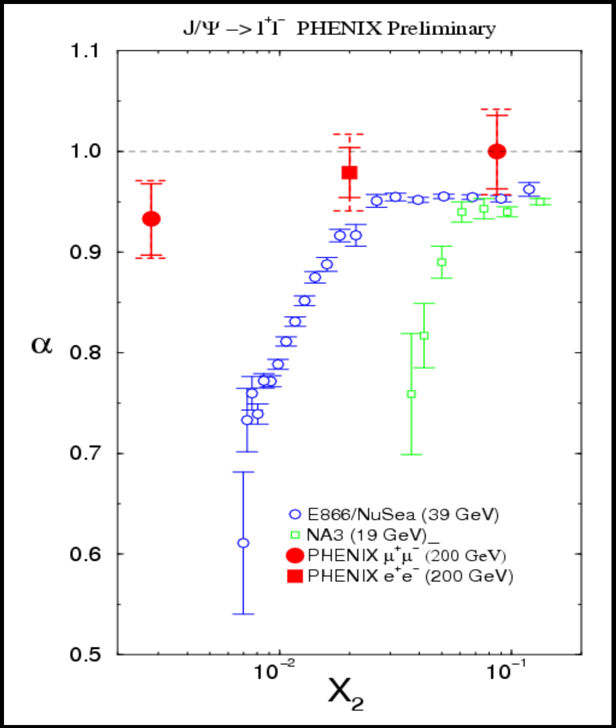
Nuclear Structure Function Physics

Proton-Nucleus and Deuteron-Nucleus reactions at RHIC are extending studies from FNAL fixed target program.

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

J/ψ probing nuclei x ~ 10^{-3}





Where Are We Going?

RHIC has passed the first key test.
Nuclear Physics community is capable of constructing and running world class "high-energy" type experiments and re-constructing the physics from the 10,000 particle debris.

The second phase has arrived.
First observations of very dense gluonic medium with strong pressure built up.
Gluon density well above predicted phase transition level and behaving as zero viscosity opaque liquid.

The third phase is next.
Quarkonia measurements to test deconfinment.
Low mass vector mesons for parton correlations in plasma.
Large Hadron Collider heavy ion program will add many complementary studies.

Where are We Going?

For Relativistic Heavy Ions,
The Future is Now.