RHIC RESULTS:
The Search for High Density Matter

What are we trying to understand?

What have we already learned?

What do we expect to learn?

What do we hope to learn?

What Are We Trying to Understand?

What is the behavior of matter at asymptotic energy density?

Quark Gluon Plasma

$E/V > 1$ Gev/Fm ^{3}

Early universe, neutron stars

What is the matter important for high energy hadrons?

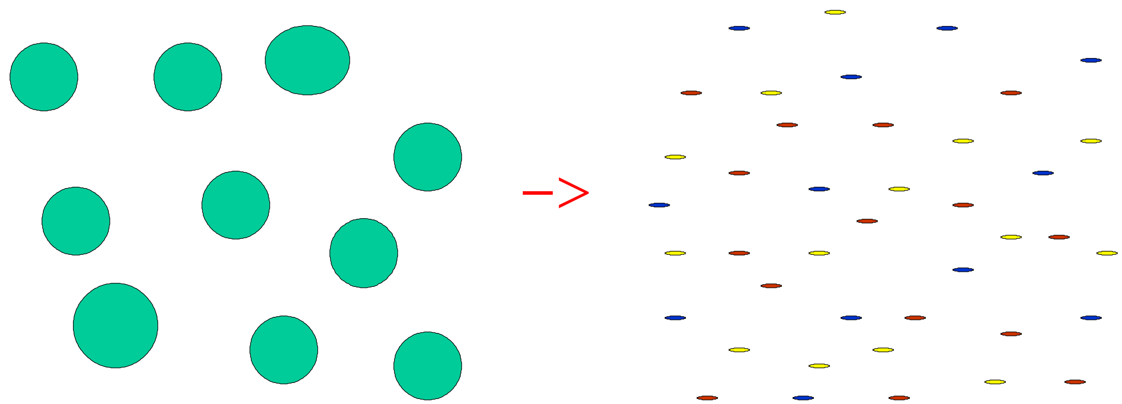
Color Glass Condensate

$E/A > 1$ Gev/Fm ^{2}

Universal high energy limit of strong interactions

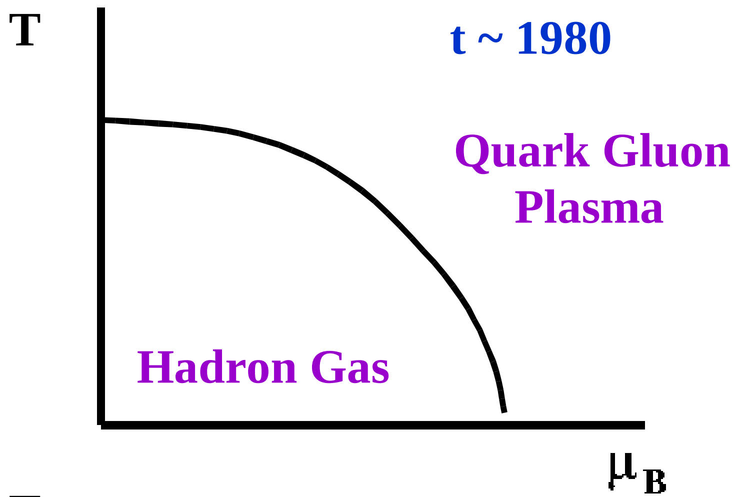
The Quark Gluon Plasma

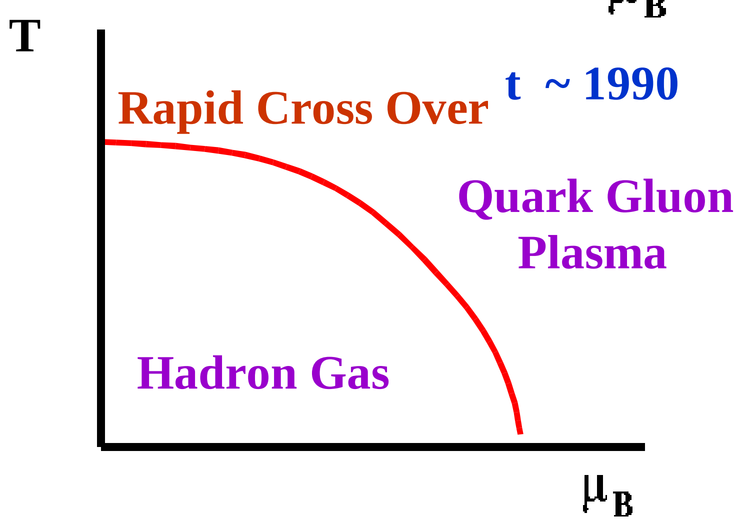
Nucleons, mesons –> quarks, gluons



Low Energy Density –> High Energy Density

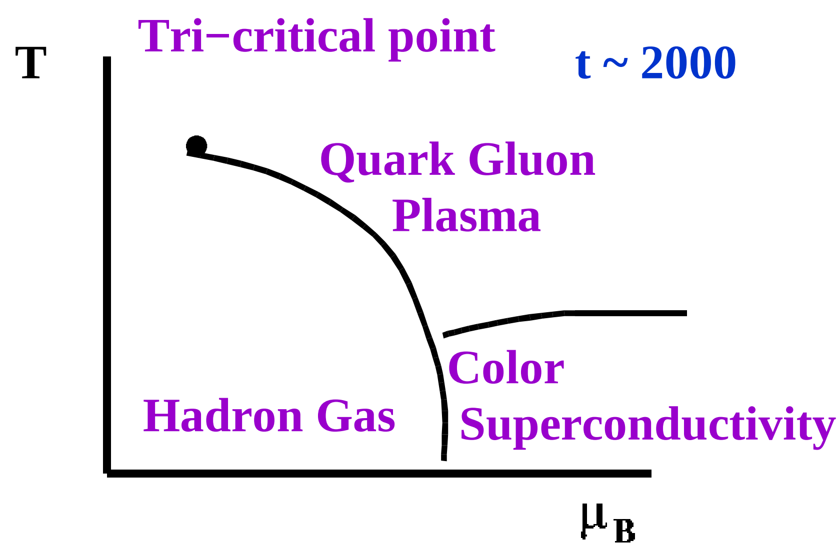
The Evolving Phase Diagram





Critical Temperature
150 − 200 MeV

Critical Density
½ − 2 Baryons/Fm^3

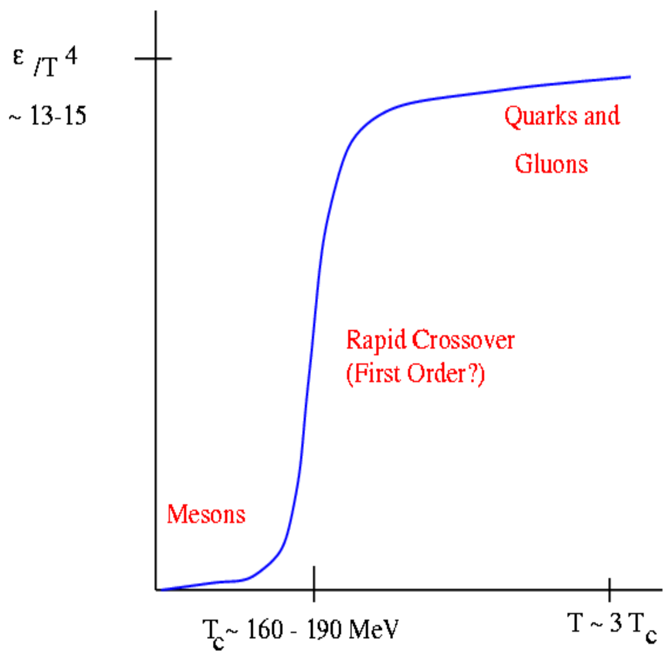


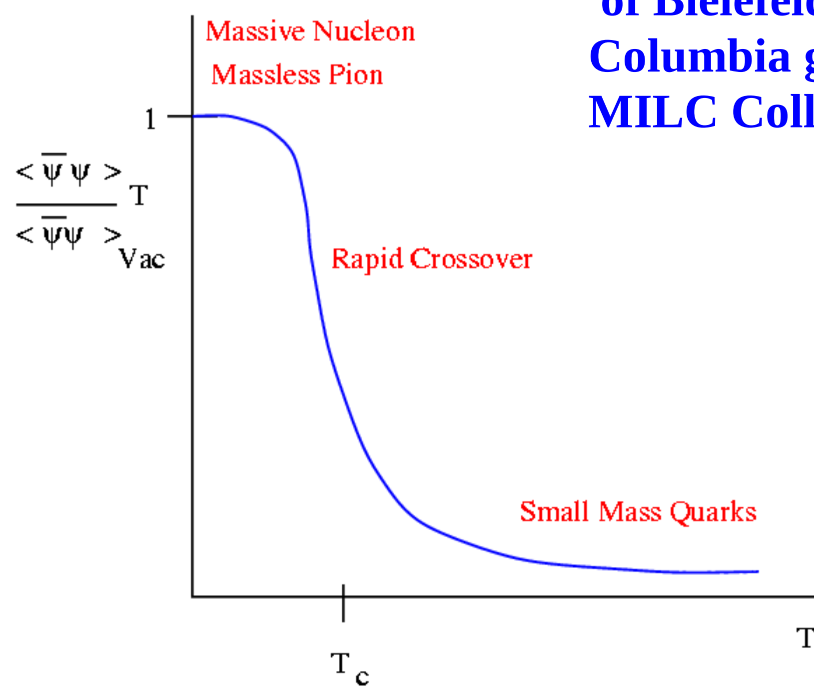
Recent work stimulated by Wilczek and Rajagopal; Schaeffer and Shuryak on Color Superconductivity; also Stephanov, Son, Pisarski, Rischke.

What have lattice simulations shown?

Chiral symmetry : $m_{up}, m_{down} \sim 0$, $M_{nucleon} \sim 1$ GeV

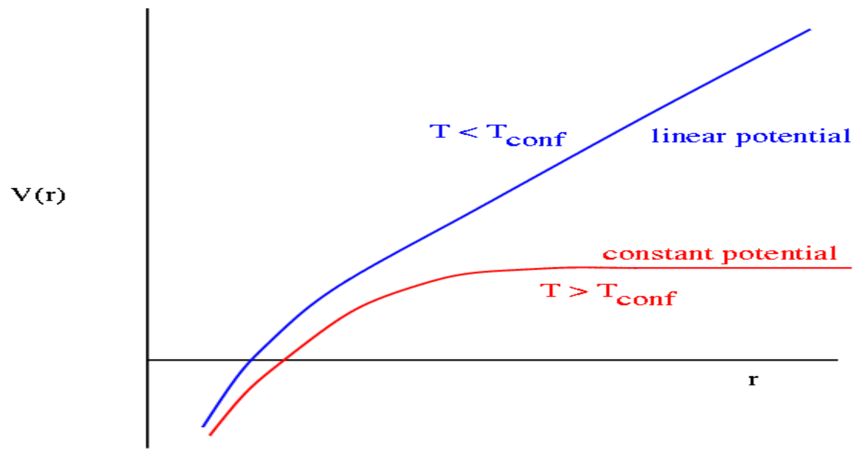
How do particles get their mass?
Why is the pion mass so small?
Is this related to confinement?



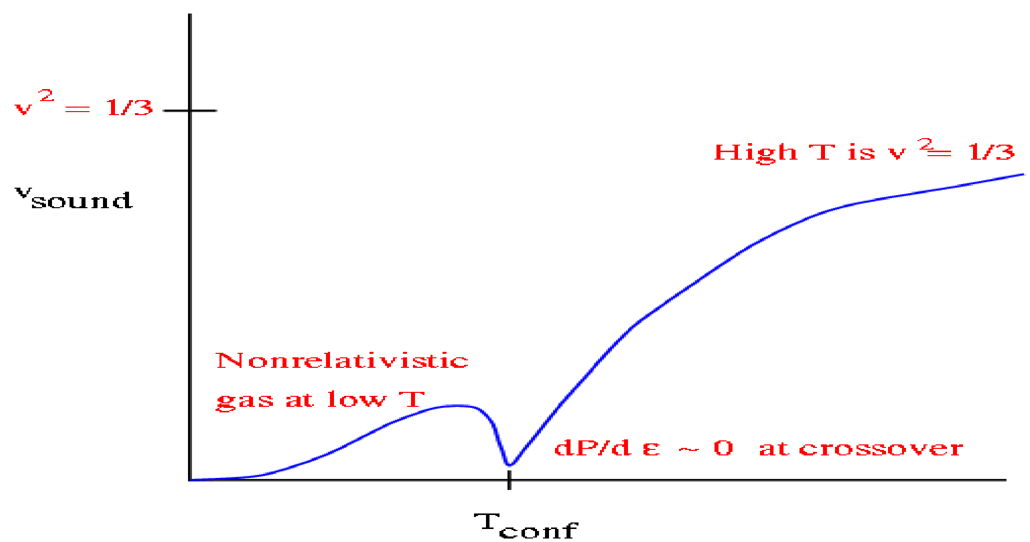


Lattice simulations of Bielefeld group, Columbia group, MILC Collaboration

Is the confining force still linear at $T > T_{dec}$?



What is the equation of state? Sound velocity?

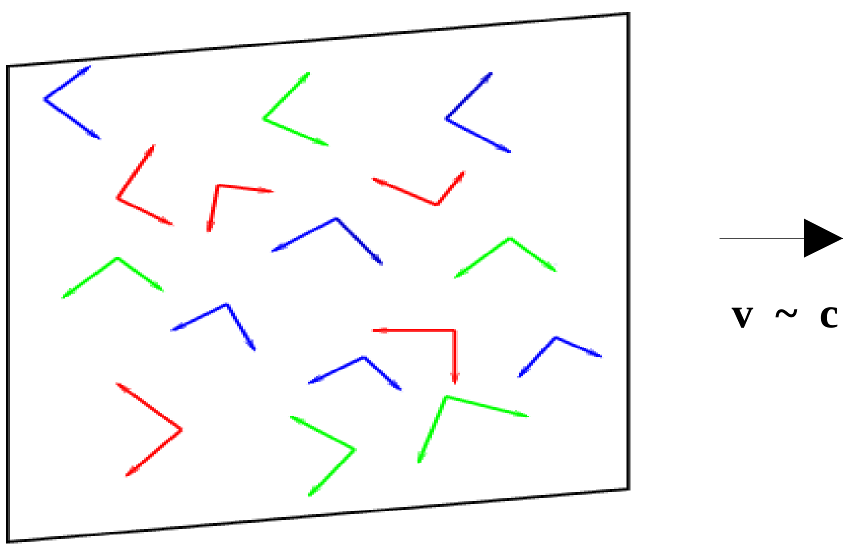


The Color Glass Condensate

Hadron in frame where it has high momenta:

High momenta constituents generate low momentum wee partons.
Density of gluons per unit area becomes large.
Fields are random on thin sheet traveling near speed of light.

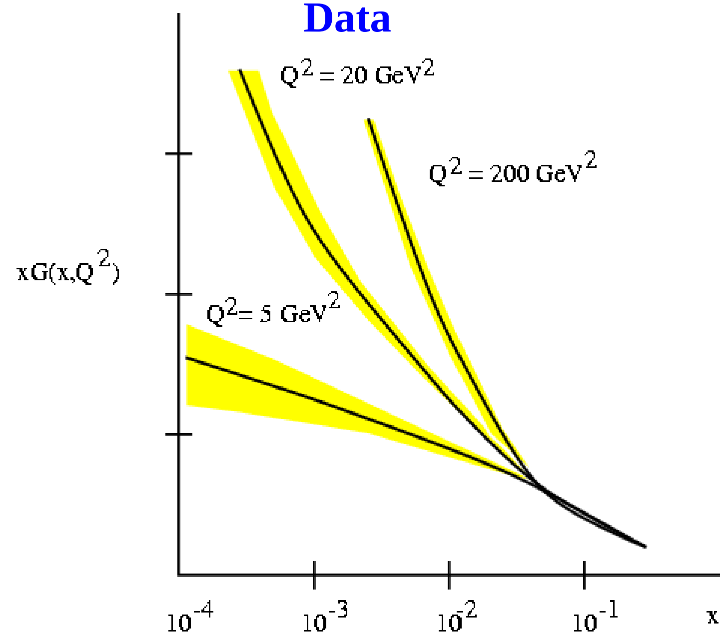
Universal high energy behavior for all hadrons.

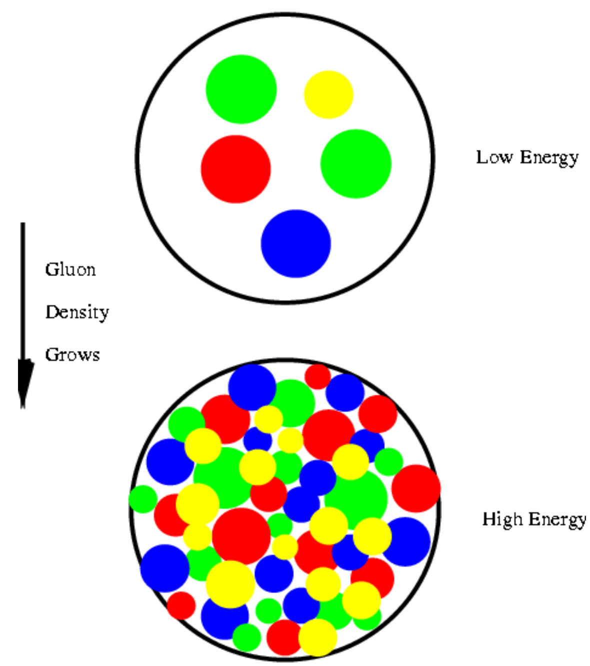


Random Non−Abelian Wiezsacker−Williams Fields

Color Glass Condensate and Saturation

Hera Data





Gribov, Levin, Ryskin;
Mueller; McLerran,Venugopalan

Gluon phase space density per unit area,

$$\rho = \frac{1}{\pi R^2} \frac{dN}{dp_T^2}$$

grows until

$$\rho \sim Q_{sat}^2 / \alpha_{strong}$$

$$Q_{sat} >> \Lambda_{QCD} \Rightarrow \alpha_{strong} << 1$$

Color Glass Condensate

Minnesota Mob and
East Coast and
European Affiliates

Color: Made of colored gluons

Glass: Wee fields (low momentum) are produced by higher momentum constituents. Time scales are Lorentz contracted compared to natural time scales

Condensate: Gluon density as large as it can

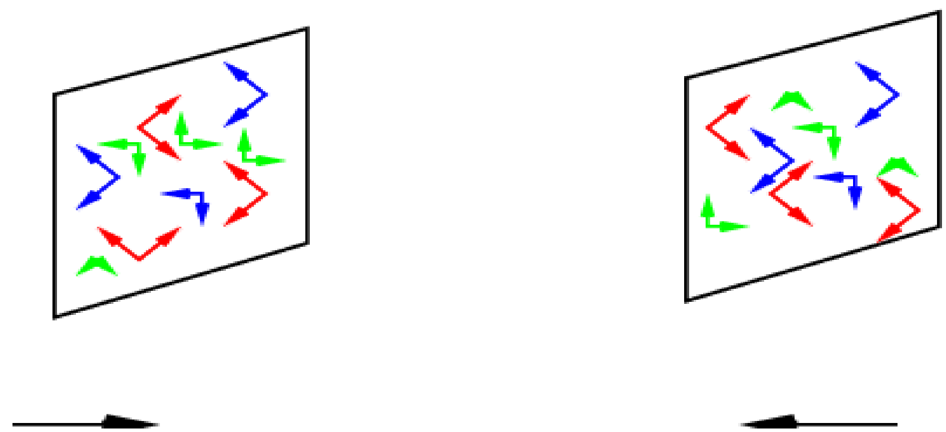
$$\rho \sim Q_{sat}^{2} / \alpha_s$$

$1/\alpha_s$ is typical of Boson Condensation

If there are repulsive interactions, negative energy terms of order ρ become of order interaction terms, $\alpha \rho^2$

so $\rho \sim 1/\alpha_s$

Space Time Evolution of Ultrarelativistic Nuclear Collisions



Mclerran, Kovner, Weigert; Krasnitz, Nara, Venugopalan

$t < 0$

Color Glass Condensate in Each Nucleus

$0 < t < t_{form}$

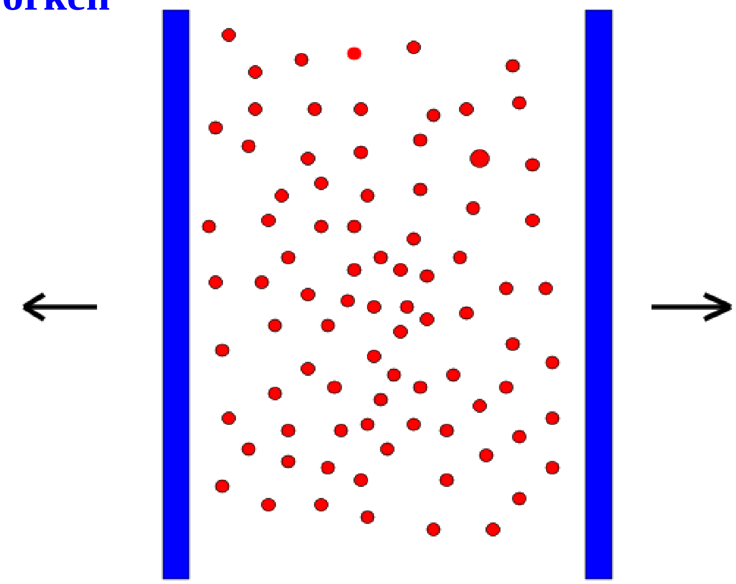
Color Glass Condensate Melts Into Quark-Gluon Plasma

$t_{form} \sim 1/Q_{sat} \sim .3$ Fm/c at RHIC

$\varepsilon_{form} \sim Q^4_{sat}/\alpha_s \sim 50 - 100$ Gev/Fm^3 at RHIC

Space Time Evolution of Ultrarelativistic Nuclear Collisions

Bjorken



Matter is formed with correlation between momentum and position due to Lorentz time dilation of the formation time

Similar to Hubble expansion in Cosmology:
$N/V \sim 1/t$

If not equilibrated, $E/N \sim$ constant

If equilibrated, $E/N \sim T$, $T^3 \sim N/V \sim 1/t$
or $T \sim t^{-1/3}$

$t_{form} \lesssim t \lesssim t_{therm}$

Matter thermalizes and Hubble Expands

$t_{therm} \sim .5 - 1$ Fm/c

$t_{form} \lesssim t \lesssim t_{decoupling}$

Matter expands as thermal system

$t_{decoupling} \sim R/v_s \sim 10$ Fm/c

Space Time Evolution inUltrarelativistic Nuclear Collisions

A variety of intermediate time scales between thermalization and decoupling:

Quark Gluon Plasma until it begins hadronizing into a mixed phase of quarks gluons and hadrons

Mixed phase expands until it is entirely a hadron gas

Decoupling occurs at roughly the time the matter is entirely hadron gas, at RHIC energies, t ~ 10 Fm/c

Can show the temperature always slower than

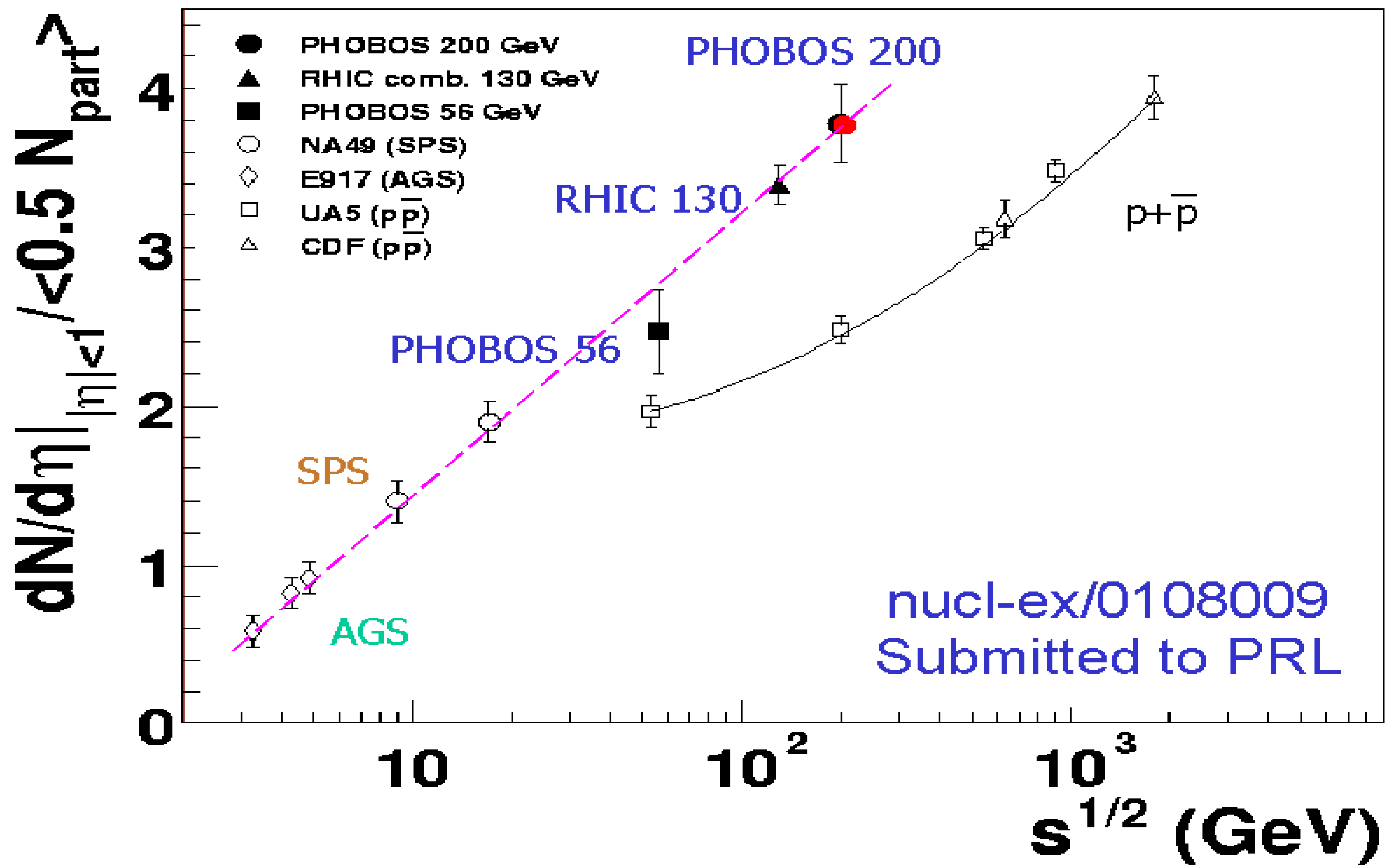
$$T \sim t^{-v_s^2} \lesssim t^{-1/3}$$

(so long as t is smaller than time at which expansion becomes 3 dimensional. System begins to decouple then)

What Have We Learned?

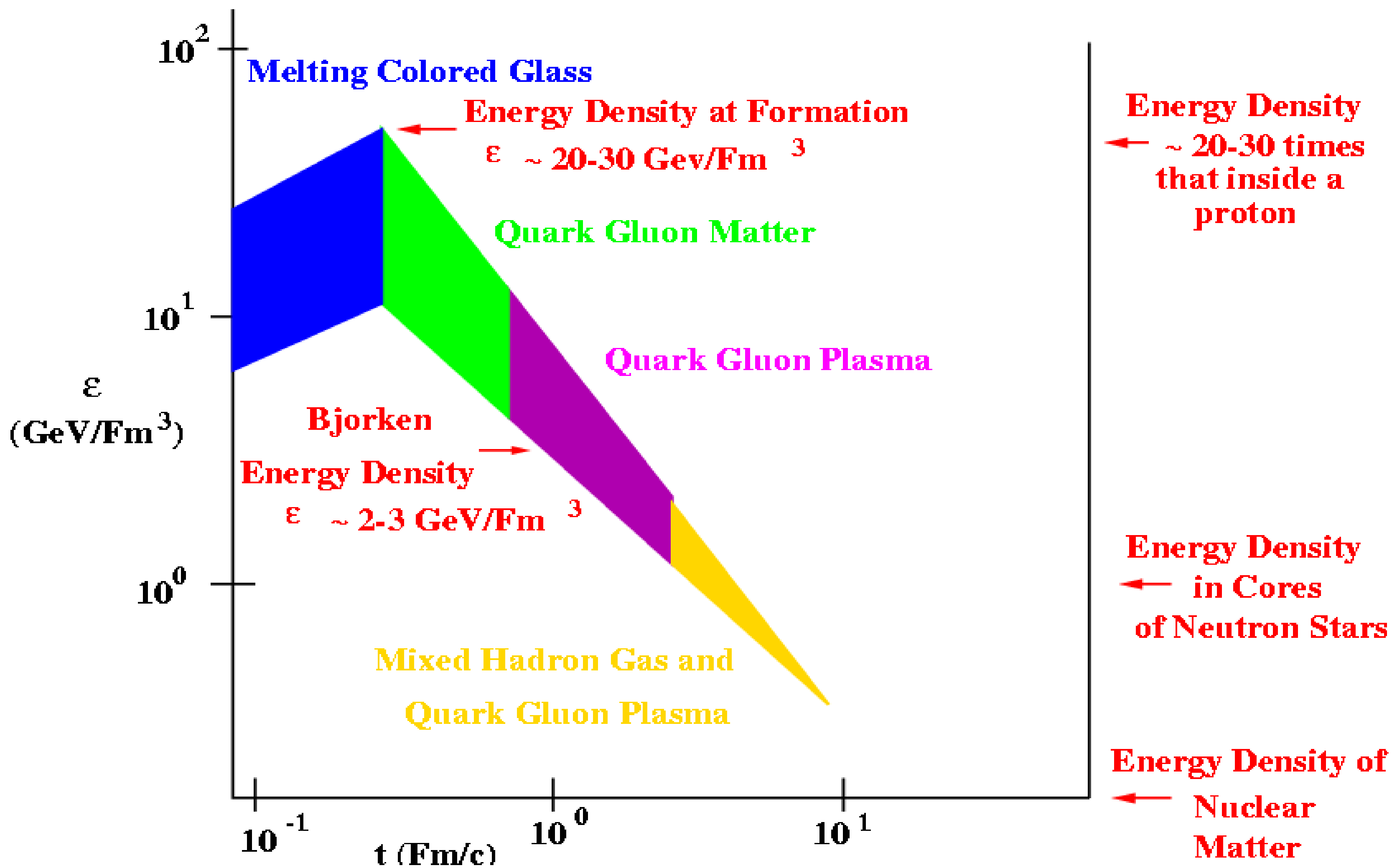
The Mulitplicity as a Function of Energy

$dN_{ch}/d\eta|_{|\eta|<1}$ vs Energy



What Have We Learned?

Bounds on energy density

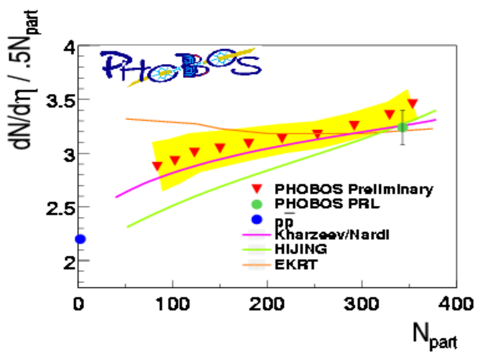


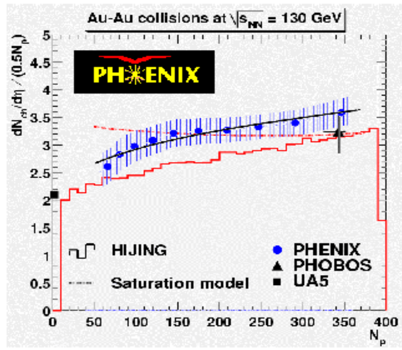
Energy Density is Too Big for a Hadron Gas !

What Have We Learned?

Gross Properties of Multiplicities Consistent with Color Glass !

dN/dη vs Centrality at η=0





Kharzeev and Nardi: $dN/dy \sim 1/\alpha_s$

$\alpha\,(Q_{sat})$ depends on multiplicity per unit area

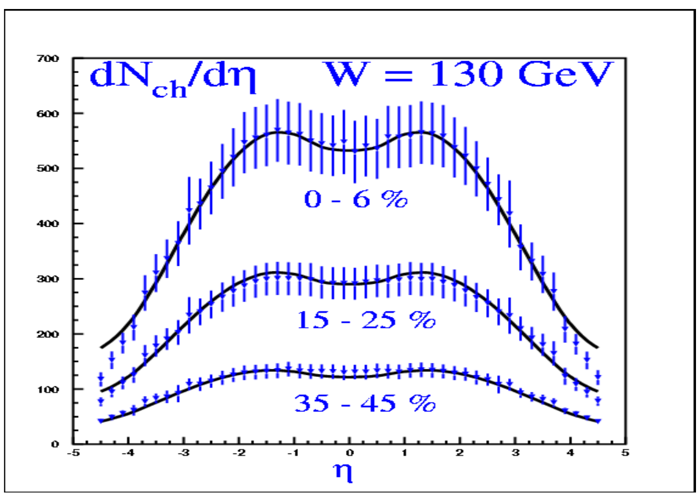
Kharzeev and Levin: Rapidity density as function of y can be computed in terms of Q_{sat}

Q_{sat} is the only scale !

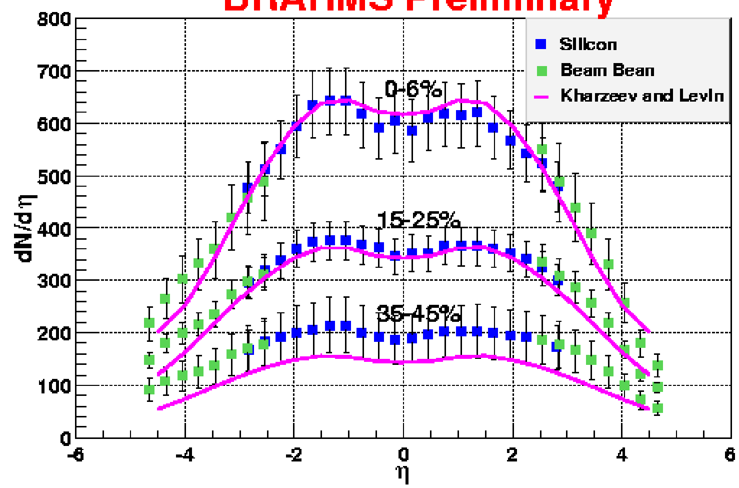
Peter Steinberg

BROOKHAVEN NATIONAL LABORATORY

PHOBOS



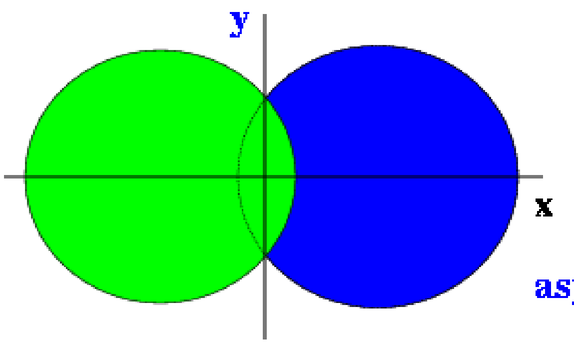
BRAHMS Preliminary



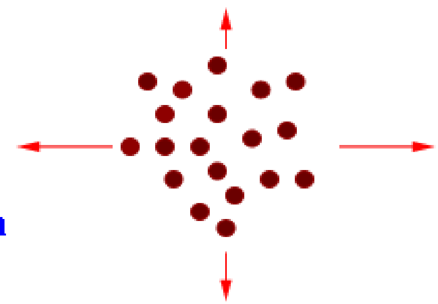
What Have We Learned?

It is Matter and It Interacts Strongly!

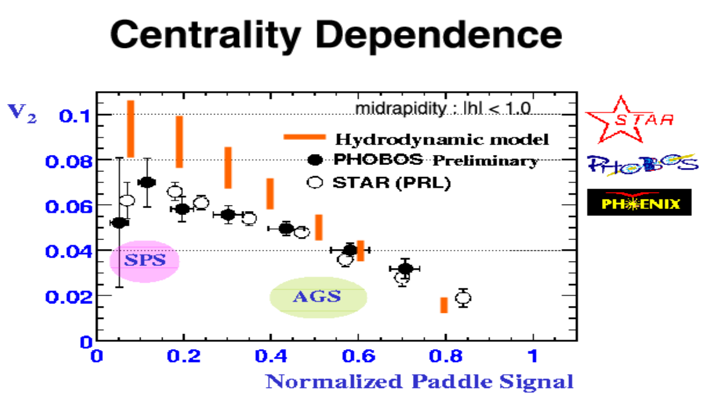
Collective Flow and v2

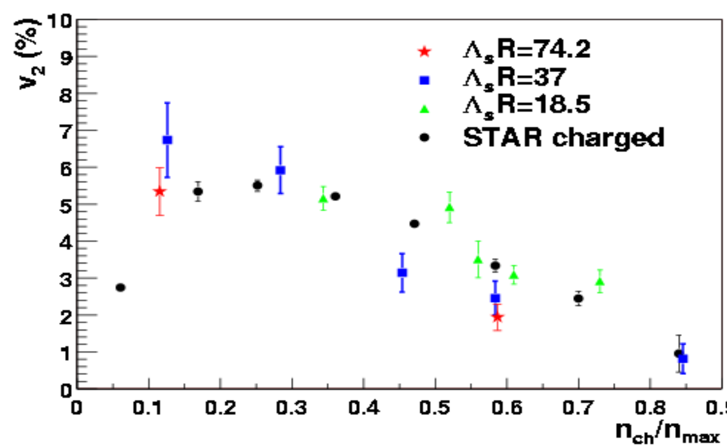


In region of overlap
asymmetry of spatial
distribution ->
asymmetry of momentum
distribution



$v_2 = <\cos(2\phi)>$ $\tan(\phi) = p_y/p_x$





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BROOKHAVEN NATIONAL LABORATORY

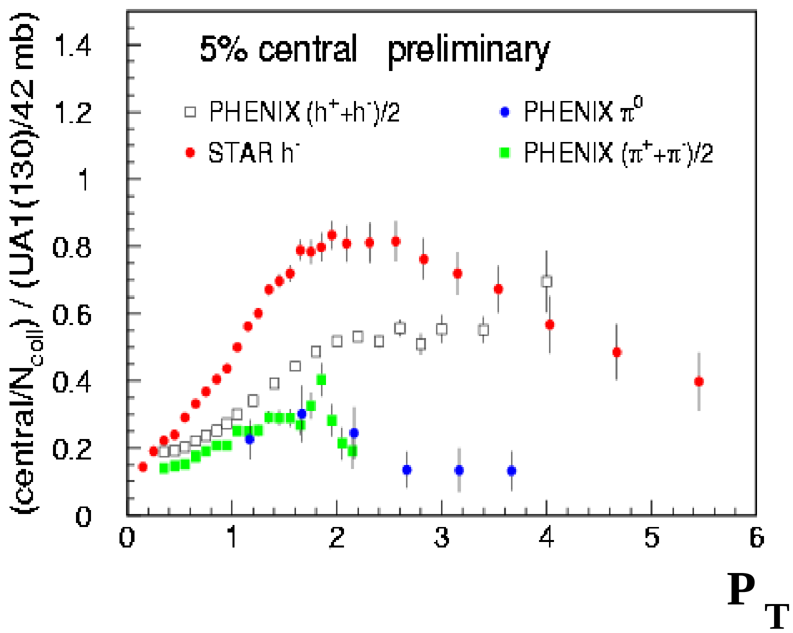
Heinz et al;
Teaney, Shuryak

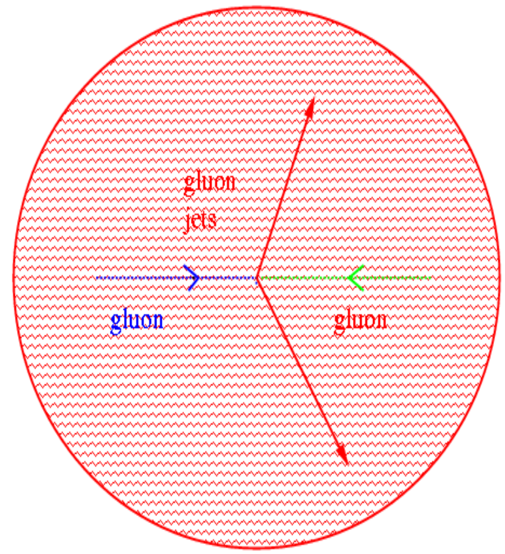
Nara, Krasnitz,
Venugopalan

Quark Gluon Plasma or Colored Glass?
(or both?)

What Would Do We Expect to Learn?

Does the matter equilibrate?





Gluon jets produced in a medium will scatter on the media;

The high momentum component of the jet spectrum will be depleted.

Problems with interpretation:

1) Large uncertainty in pp data
2) Systematic uncertainty in AA data
3) Nuclear modification of gluon distribution
4) Transverse momentum limited by statistics

Gyulassy, Wang; Dokshitzer, Mueller, Baier, Schiff; Levai; Wiedemann

Sytematics reduced by comparing data at same energy in same detector

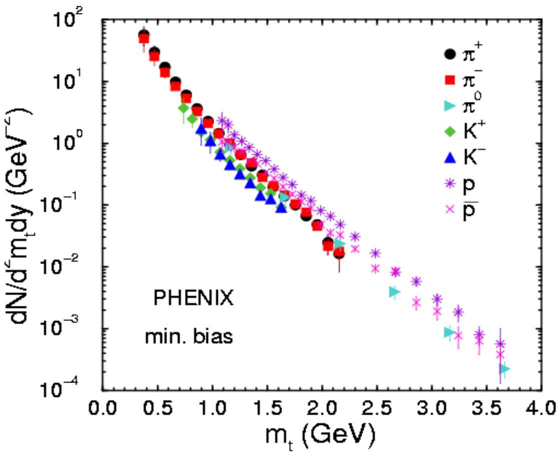
Nuclear modification of distribution functions determined by pA (or eA)

Higher transverse momentum with higher accelerator luminosity

What Do We Expect to Learn?

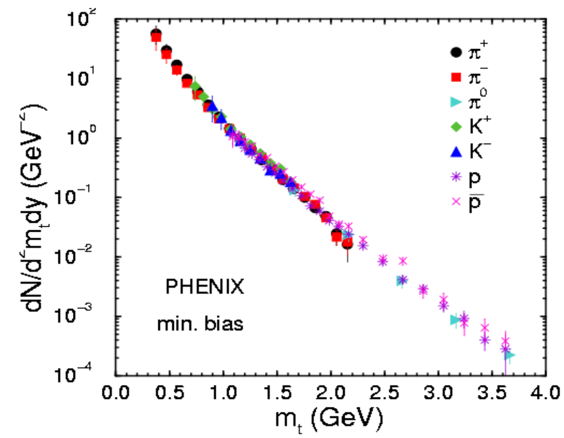
Schaffner−Bielich et al

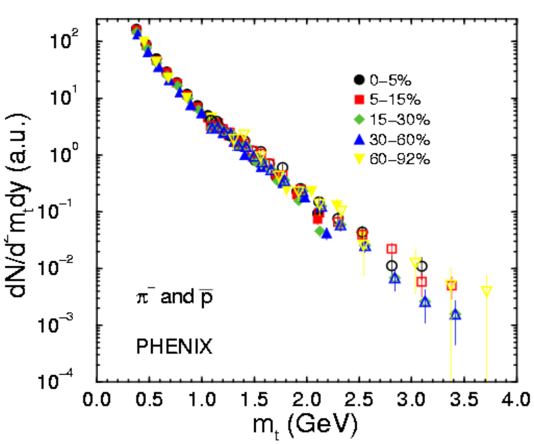
Is the pT Spectrum Modified Because of Color Glass or Quark Gluon Plasma?



M_T scaling: At fixed impact parameter, distributions are functions only of M_T up to an overall multiplicative constant dependent on particle species

$$M_T^2 = p_T^2 + M^2$$

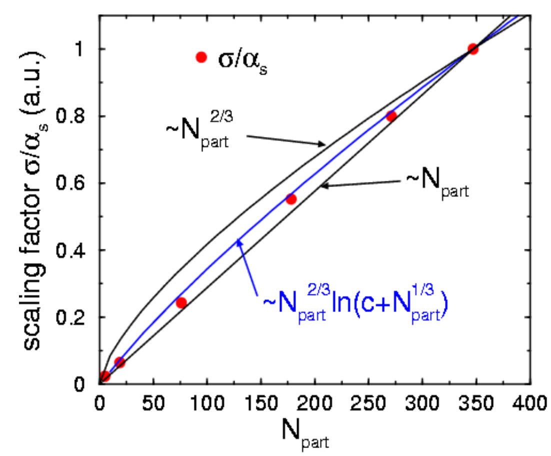




Color Glass Scaling:

$$\frac{dN}{d^2p_T} = \frac{\pi R^2}{\alpha_s} F(M_T/Q_{sat})$$

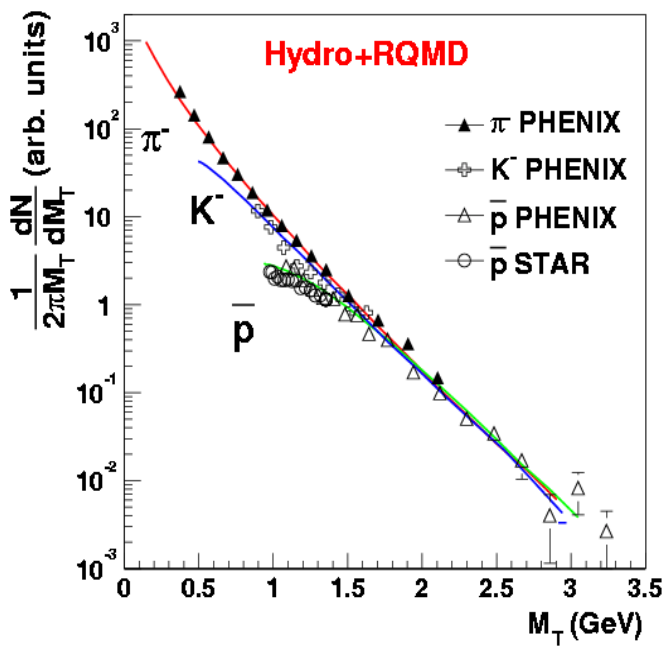
where $\alpha = \alpha(Q_{sat})$



Results are consistent with Color Glass picture!

What Do We Expect to Learn?

Also Consistent with Hydrodynamics of Quark Gluon Plasma !



Heinz, Huovinen, Kolb;
Shuryak, Teaney; Hirono

For Hydrodynamics:

Shape of curve predicted in hydrodynamics.
Deviations from Mt scaling at Mt ~ M.
Deviation larger for more massive particles

For Color Glass:

Non−trivial relations for different centrality
Correctly generates dependence of strong coupling

Probably both contribute?

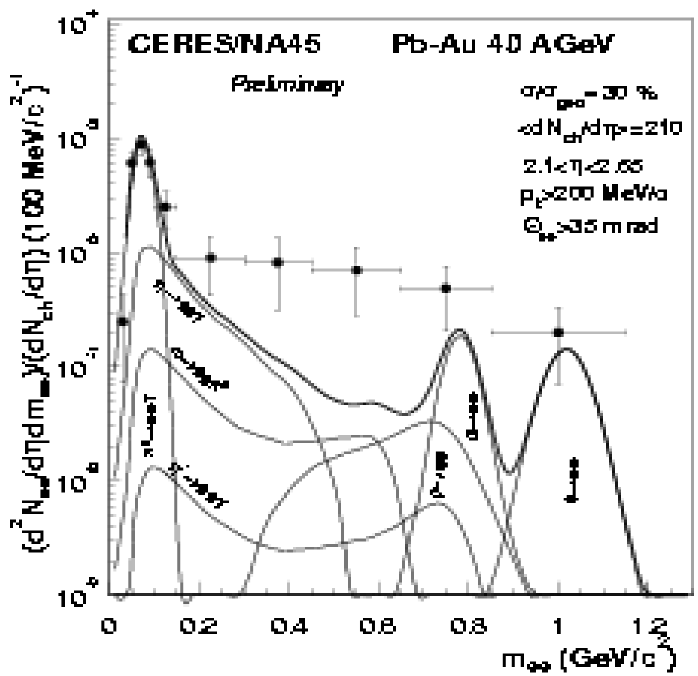
Srivastava

If hydrodynamics is valid, can determine equation of state!

What Do We Hope to Learn?

Does deconfinement occur in high density matter?

Does chiral symmetry restoration change particle masses?



Spectrum of low mass dileptons:
Measured at CERN

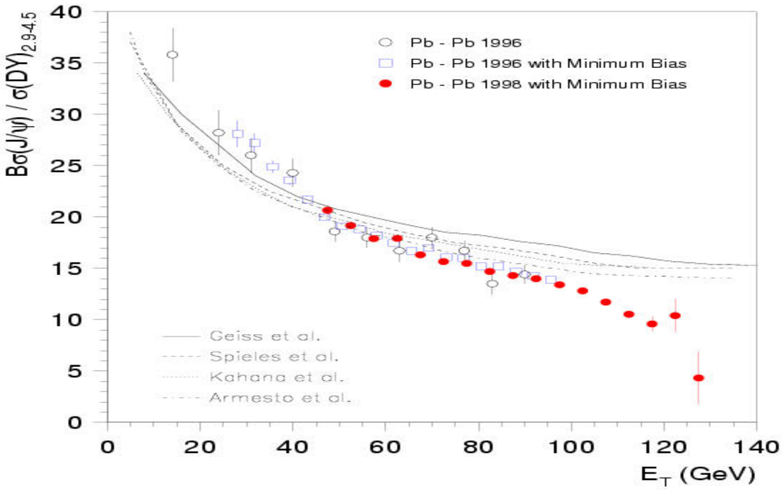
Probably resonance broadening
Rapp, Weise, Wambach

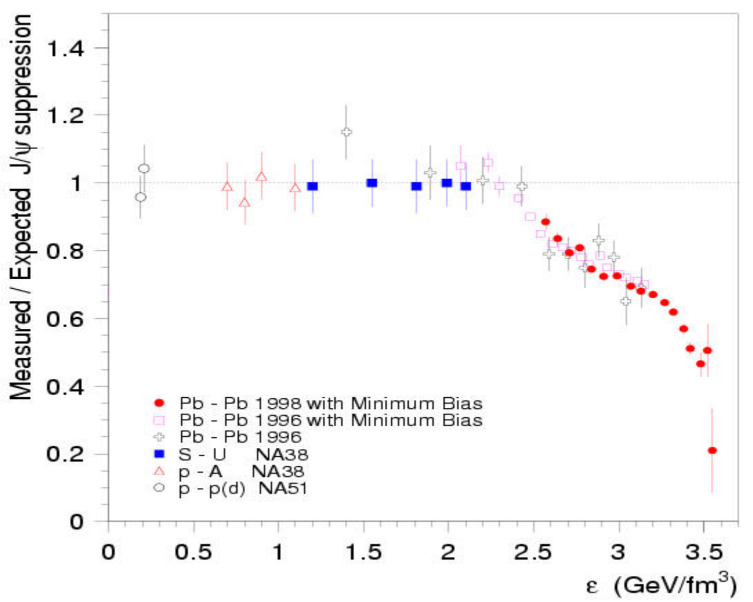
Difficult to measure low mass pairs
at RHIC due to backgrounds.

Very difficult, but very powerful technique.

What Do We Hope to Learn?

Melting of the J/Psi





Is J/ ψ suppression due to hadronic scattering? Changes in gluon distribution function? Higher twist effects? Deconfinement?

At RHIC energies, does increased open charm production result in increased probability of final state recombination into charm.

Is the J/ ψ enhanced at RHIC energies?

Need independent measurement of open charm

Must understand energy dependence.

Measurements in pA and pp essential!

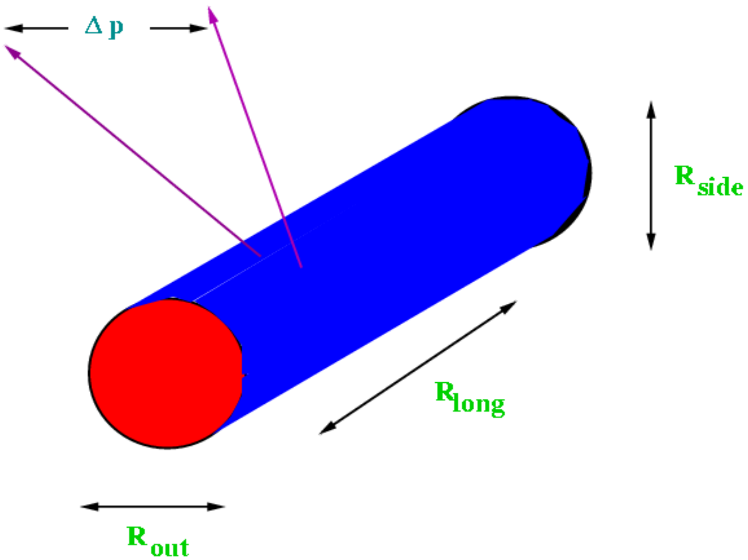
Suppressors: Matsui, Satz Kharzeev Blaizot, Ollitrault

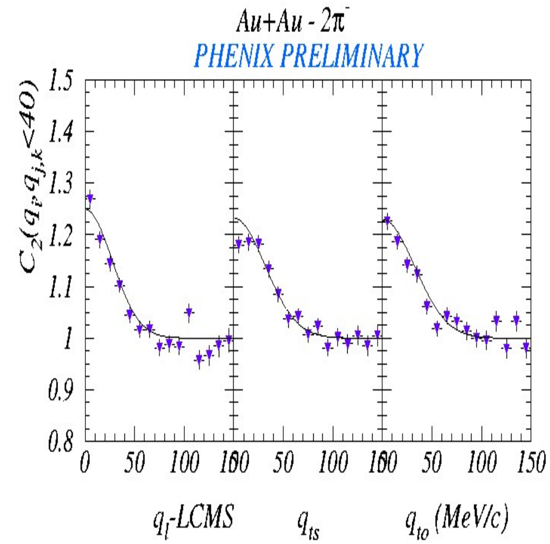
Twister: Qiu

Enhancers: Rafelski, Thews, Stachel, Braun−Munzinger, Redlich, Gorenstein

Rescatter: Capella

What Do We Hope to Learn?
Lifetime and spatial extent of matter produced

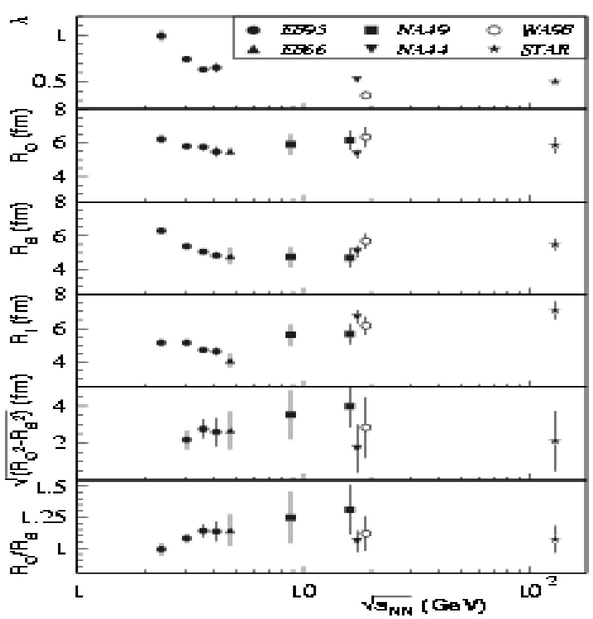




Rside = 4.42 (0.22) Fm

Rout = 4.45 (0.22) Fm

Rlong = 5.28 (0.32) Fm



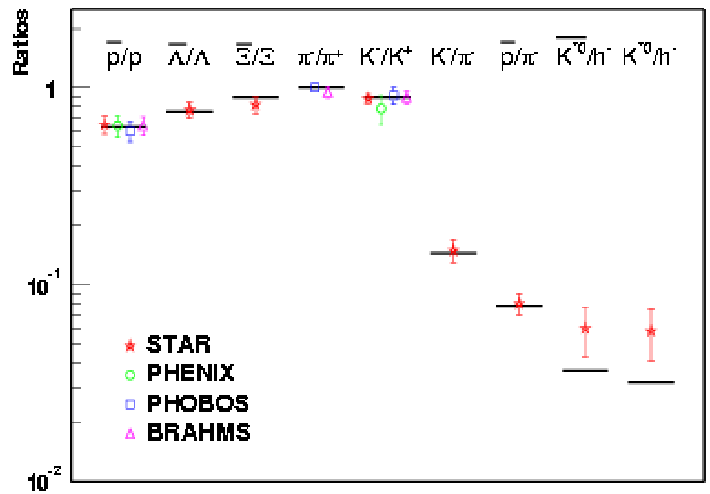
Difficult to interpret the ratio of Ro/Rs:
Might be due to Color Glass initial conditions?
Might be new phenomena associated with phase transition?

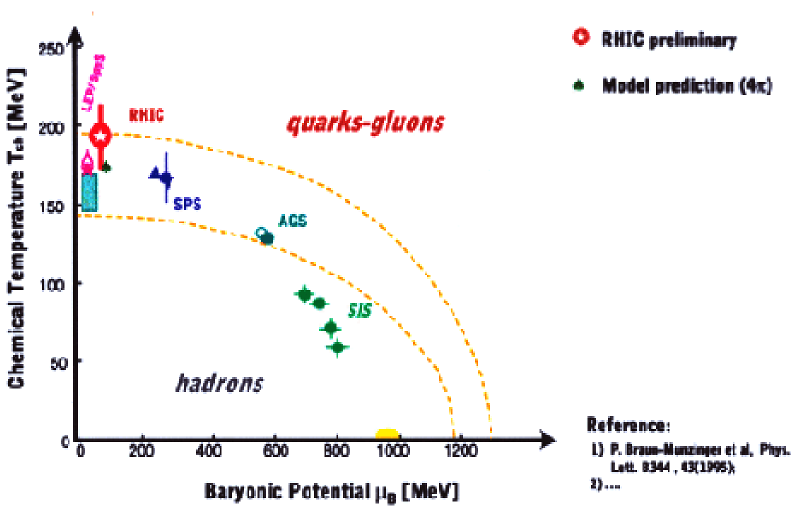
Do we really understand the space-time evolution ?

Soff, Bass, Dumitru; Kolb, Heinz; Teaney

What Do We Hope to Learn?

Flavor Composition of Quark−Gluon Plasma





Can fit particle abundances with temperature and chemical potential for baryon number and strangeness.

It works too well! Works for electron−positron collisions!

Are we not understanding something fundamental and universal about hadron collisions?

Is strangeness abundance a signal for quark−gluon plasma?

Mueller, Rafelski; Cleymans, Redlich; Braun−Munzinger, Stachel; Gorenstein Gazdzicki

Summary:

What are we trying to undertsand:

New forms of matter:

Color Glass Condensate and Quark Gluon Plasma
(Color Glass at early times, Plasma later)

What have we already learned:

Matter has been produced at energy densities so high it can only be made from quarks and gluons

The matter is strongly interacting

Multiplicity distributions consistent with Colored Glass

Flow and pT distributions consistent with both Colored Glass and Quark−Gluon Plasma

What do we expect to learn:

**By measuring low pT heavy hadrons,
resolve differences between various theory descriptions.**

**By measuring high pT hadrons in AA and pA collisions
determine whether jet quenching occurs, and to what degree thermalization occurs.**

If thermalization is established, then can measure properties of

Equation of State

What do we hope to learn:

Through lepton pair measurements,
whether or not resonances shifted in mass, boadened or melted.

What the HBT determined sizes tell us about the space−time pictures.

What flavor abundances tell us about properties of high density matter

We must turn to the problem of determining the properties of the high density matter made in heavy ion collisions

We are learning what are the useful theoretical and experimental tools

Will need experiments on AA and pA to resolve:
Initial state effects: Color Glass Condensate
Evolution of the matter: Quark Gluon Plasma
(eA for precise determination of Color Glass)