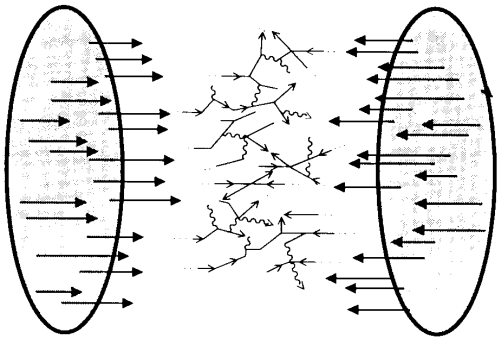
Relativistic Heavy Ion Physics:
A New QCD Frontier



CTEQ Summer School
Lecture #1 - June 7, 2002

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COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

University of Colorado, Boulder

Outline

Lecture #1:

Physics Motivations for Heavy Ion Physics

- New Regime of Hadronic Physics.
- Particle Production and Gluon Saturation.
- Quark-Gluon Plasma Studies.

Lecture #2:

Focus on Hard Scattering and Heavy Quarks

Many open questions for young people to help resolve.

Brief History of Heavy Ion Physics

Bevalac-LBL and SIS-GSI fixed target
max. **2.2 GeV**

1992 Au-Au

AGS-BNL fixed target
max. **4.8 GeV**

E864/941, E802/859/866/917, E814/877, E858/878, E810/891, E896, E910 ...

1994 Pb-Pb

SPS-CERN fixed target
max. **17.3 GeV**

NA35/49, NA44, NA38/50/51, NA45, NA52, NA57, WA80/98, WA97, ...

TEVATRON-FNAL (fixed target p-A)
max. **38.7 GeV**

2000 Au-Au

RHIC-BNL collider
max. **200.0 GeV**

BRAHMS, PHENIX, PHOBOS, STAR

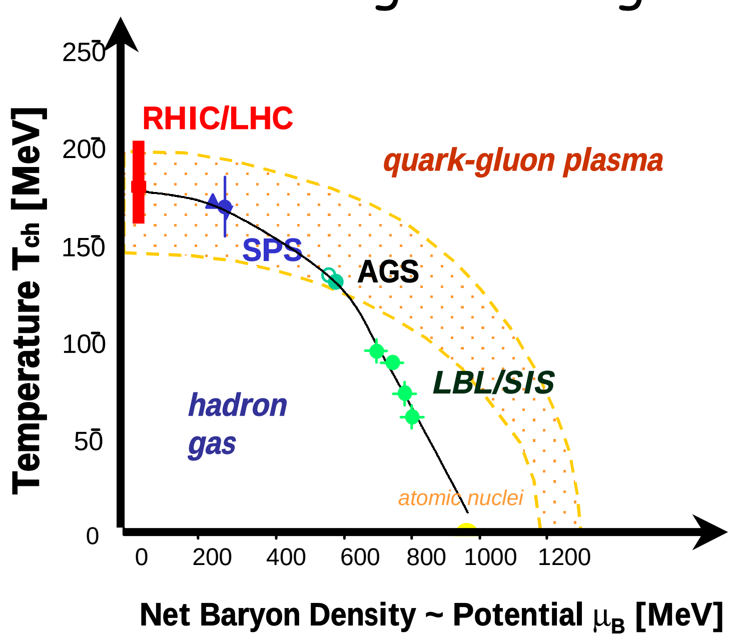
2007? Pb-Pb

LHC-CERN collider
max. **2760.0 GeV**

ALICE, ATLAS, CMS

Relevant Physics

Many basic goals of the field have remained the same over the last 20 years.
However, the character of the system created is a strong function of energy.
Many new probes and theoretical handles are available at higher energies.



Bevalac-LBL
2.2 GeV

Nuclear Fragmentation
Resonance Production
Strangeness Near Threshold

AGS-BNL
4.8 GeV

Resonances Dominate
Large Net Baryon Density
Strangeness Important

SPS-CERN
17.3 GeV

Charm Production Starts

TEVATRON-FNAL
38.7 GeV

RHIC-BNL
200.0 GeV

Low Net Baryon Density
Hard Parton Scattering

LHC-CERN
2760.0 GeV

Beauty Production

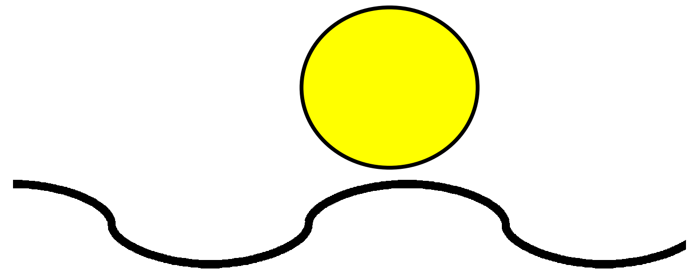
Structure of the Proton

See the whole proton

Momentum transfer

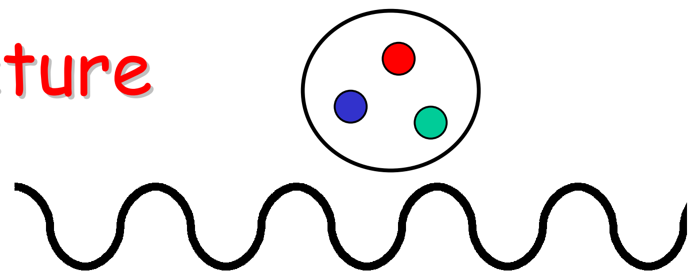
$Q^2 = 0.1$ GeV^2

Wavelength $\lambda = \hbar/p$



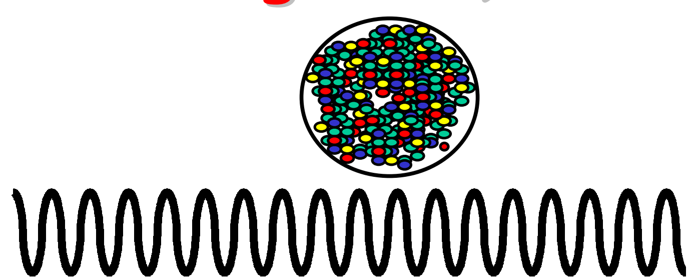
See the quark substructure

$Q^2 = 1.0$ GeV^2



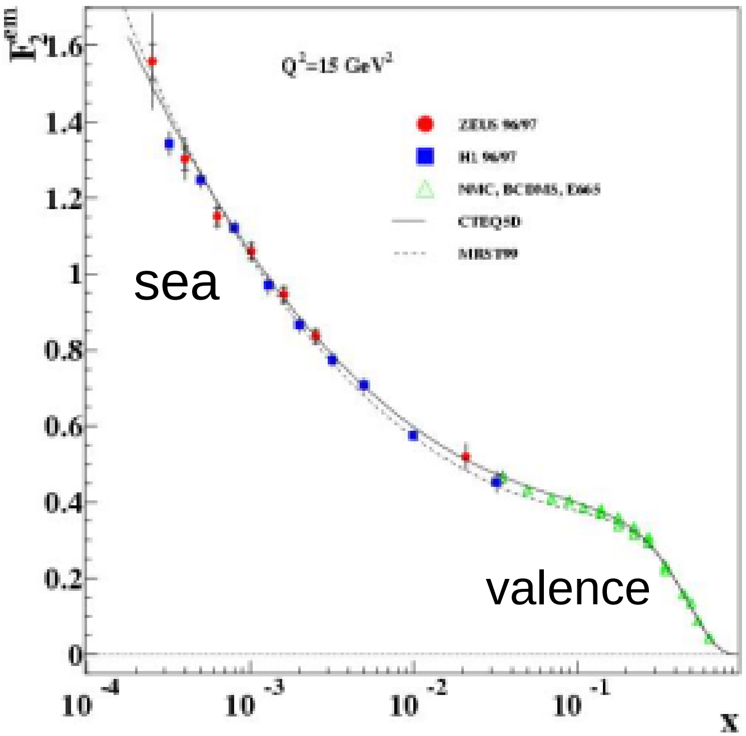
See many partons (quarks and gluons)

$Q^2 = 20.0$ GeV^2

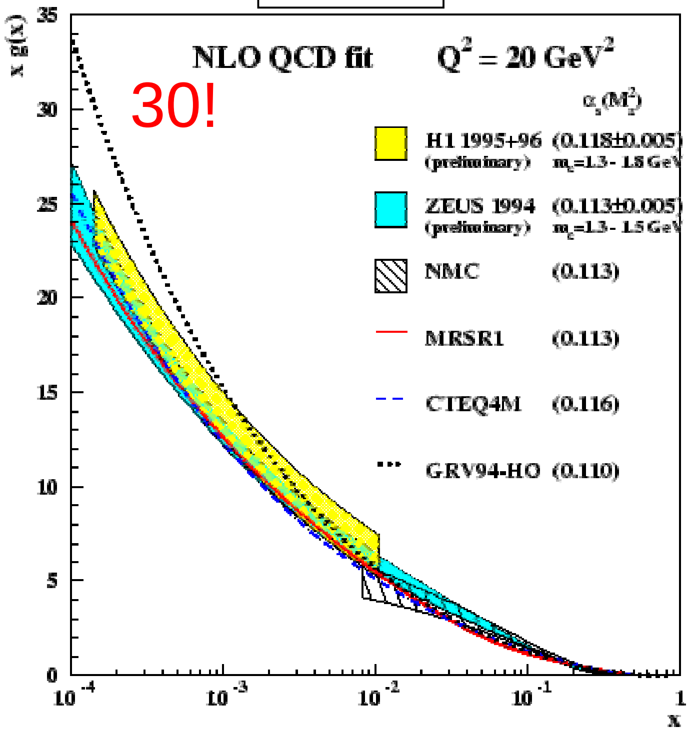


Parton Distribution Functions

Quarks

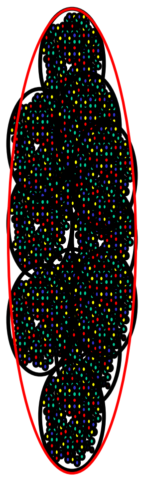


Gluons



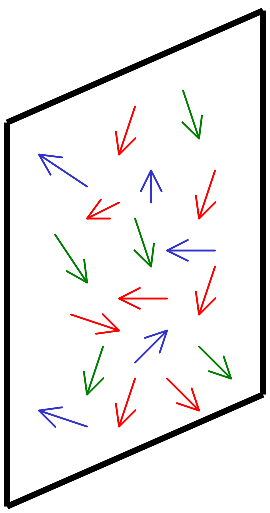
- Structure functions rise rapidly at low-x
- More rapid for gluons than quarks

Color Glass Condensate



Put many nucleons into a nucleus and
Lorentz boost to the infinite momentum frame

Creates a 2-dimensional sheet of very high
density color charges.

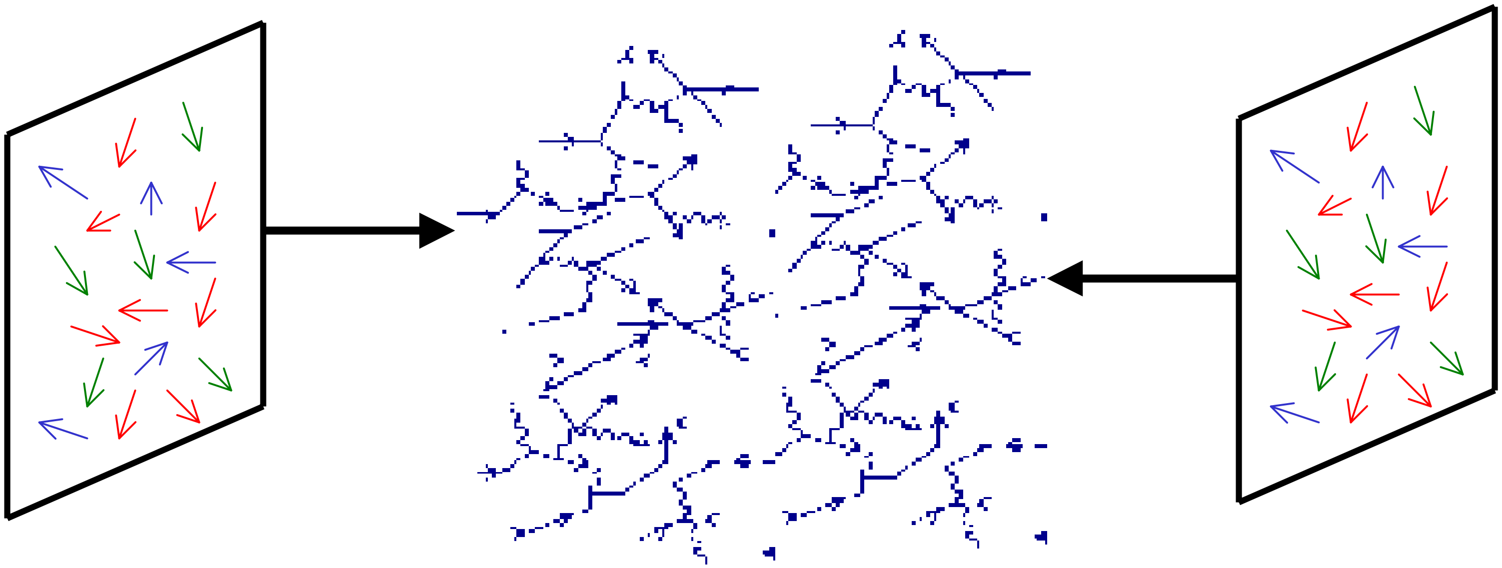


High density of gluons (saturation) allows for
the simplification of Quantum Chromodynamics

Color fields can be described as classical wave
solutions to the Yang-Mills equation

Color Glass Condensate is a description of the
nuclear wavefunction in a particular gauge

RHIC = Gluon Collider



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

What is the nature of this ensemble of partons?

Lattice QCD

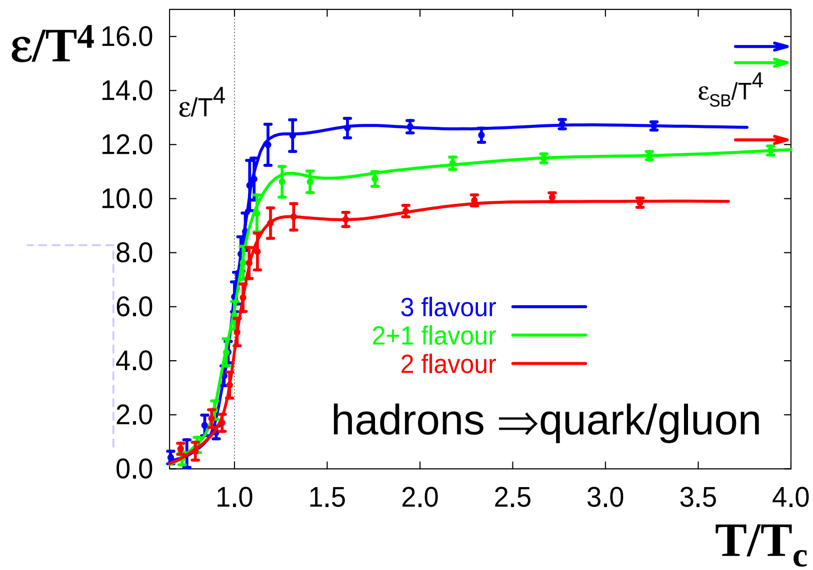
The nature of this bath of quarks and gluons cannot be calculated directly with Quantum Chromodynamics (QCD).

Lattice QCD predicts a phase transition to a Quark-Gluon Plasma where the number of degrees of freedom is increased.

Phase Transition:

T = 150-200 MeV ~ 10^{12} ^{0}F
ε ~ 0.6-1.8 GeV/fm^3

Assumes thermal system.



(F. Karsch, hep-lat/0106019)

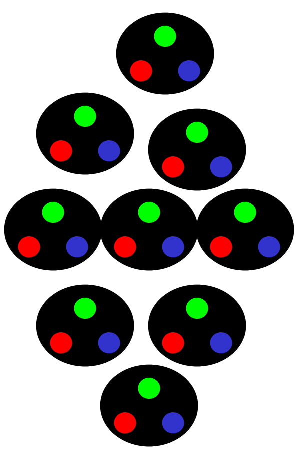
Deconfinement

QCD in Vacuum

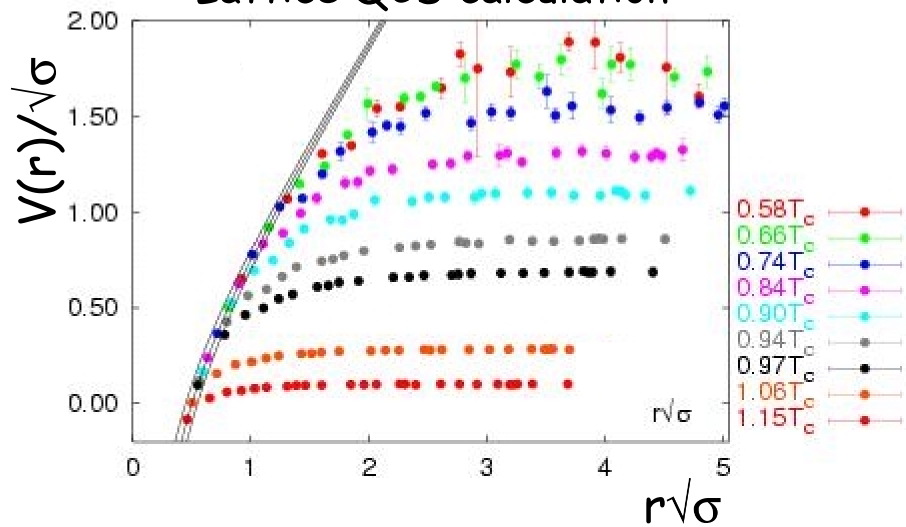
- linear increase with distance from color charge
- strong attractive force
- **confinement of quarks** to hadrons baryons (qqq) and mesons ($q\bar{q}$)

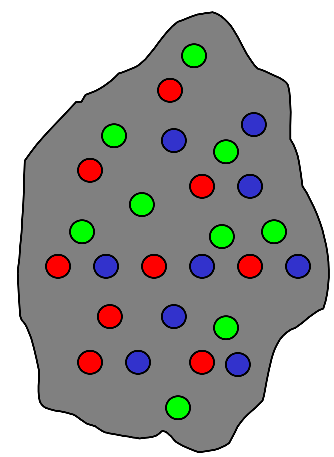
QCD in dense and hot matter

- 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 !**

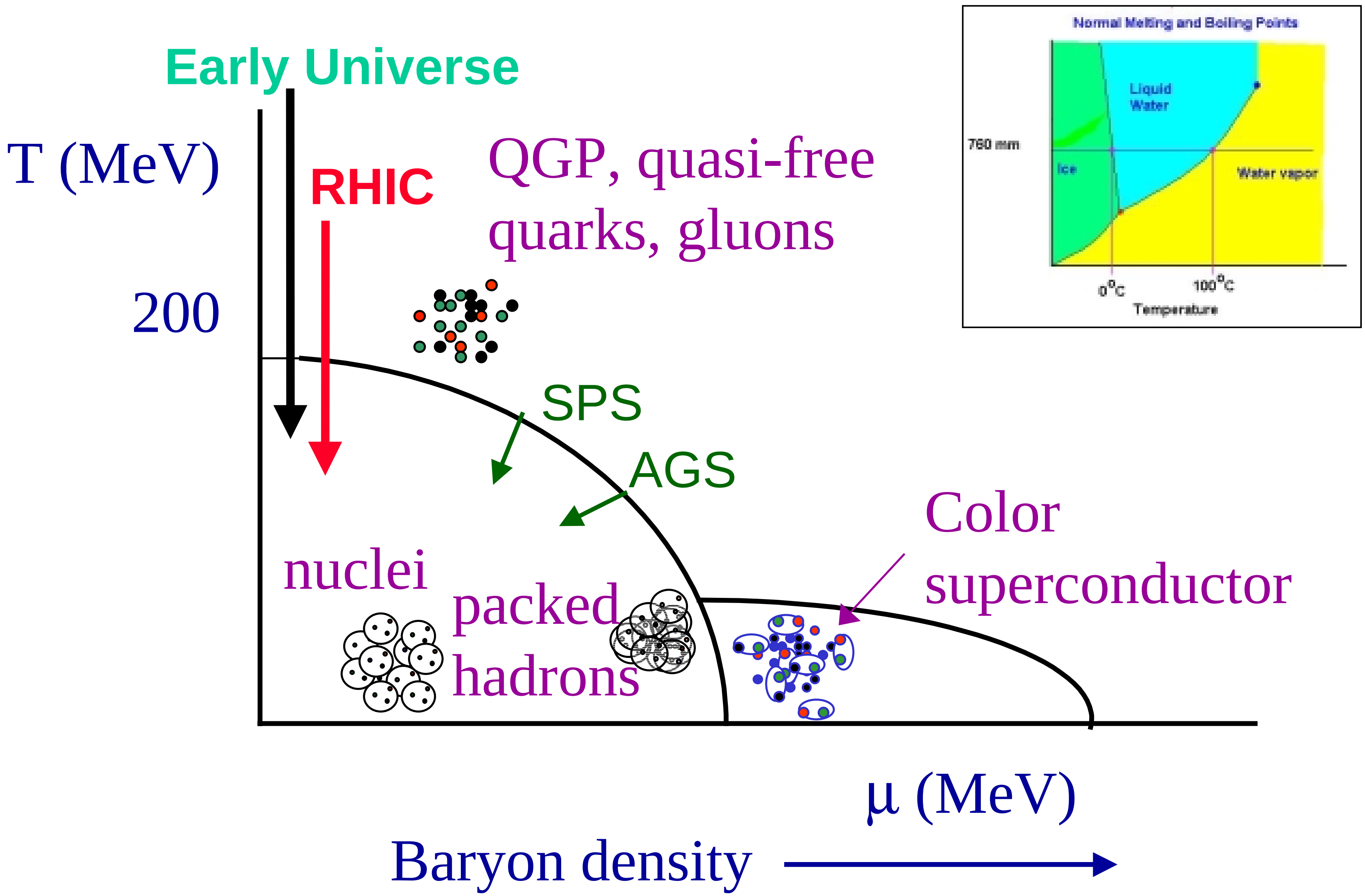


Lattice QCD calculation

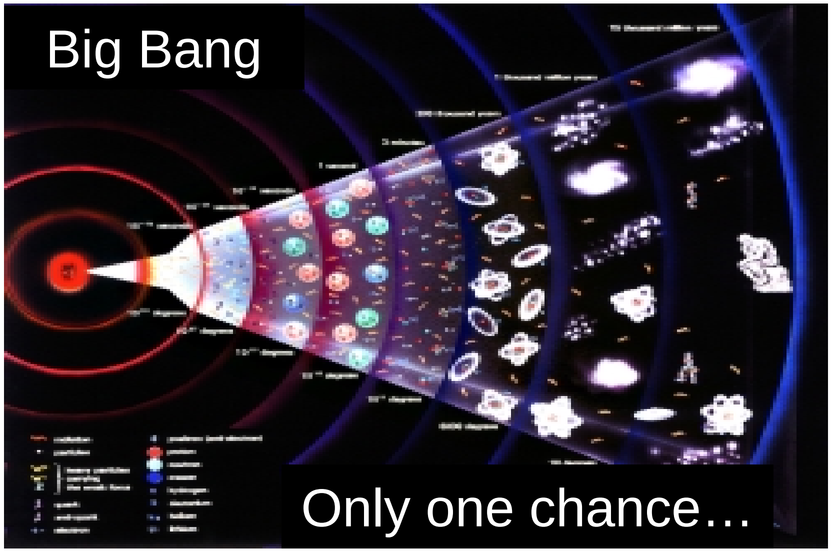


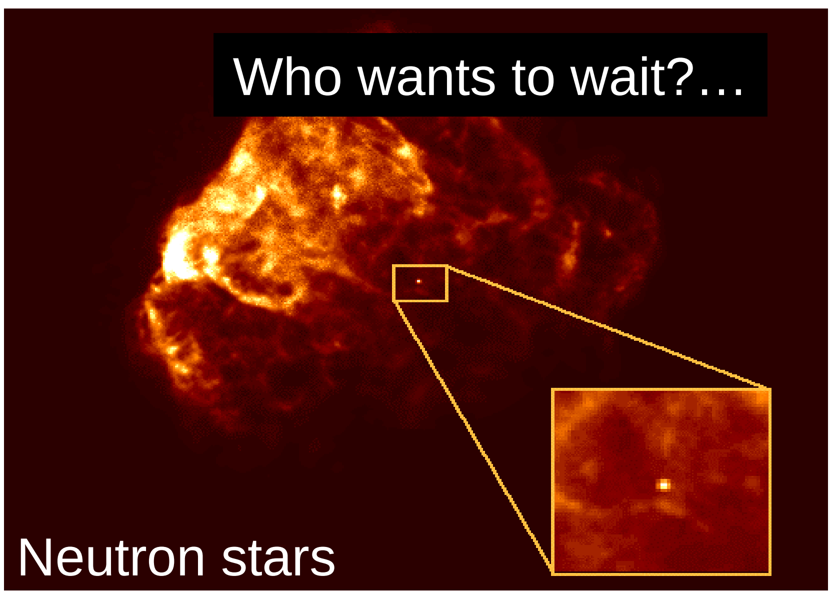


Phase Diagram



Where to Study Extreme QCD?



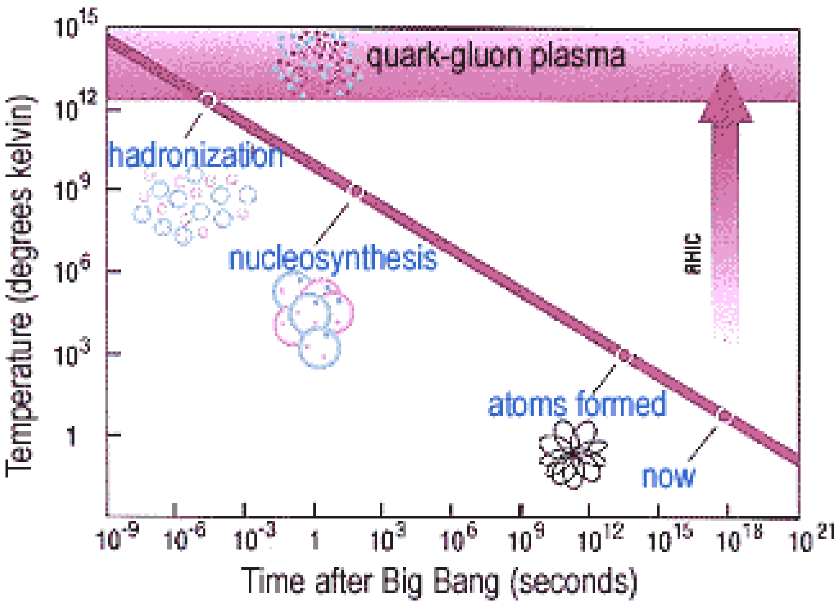


Slide from Jeff Mitchell

Early Universe

Physics Today, July 2001: Cosmic Microwave Background Observations

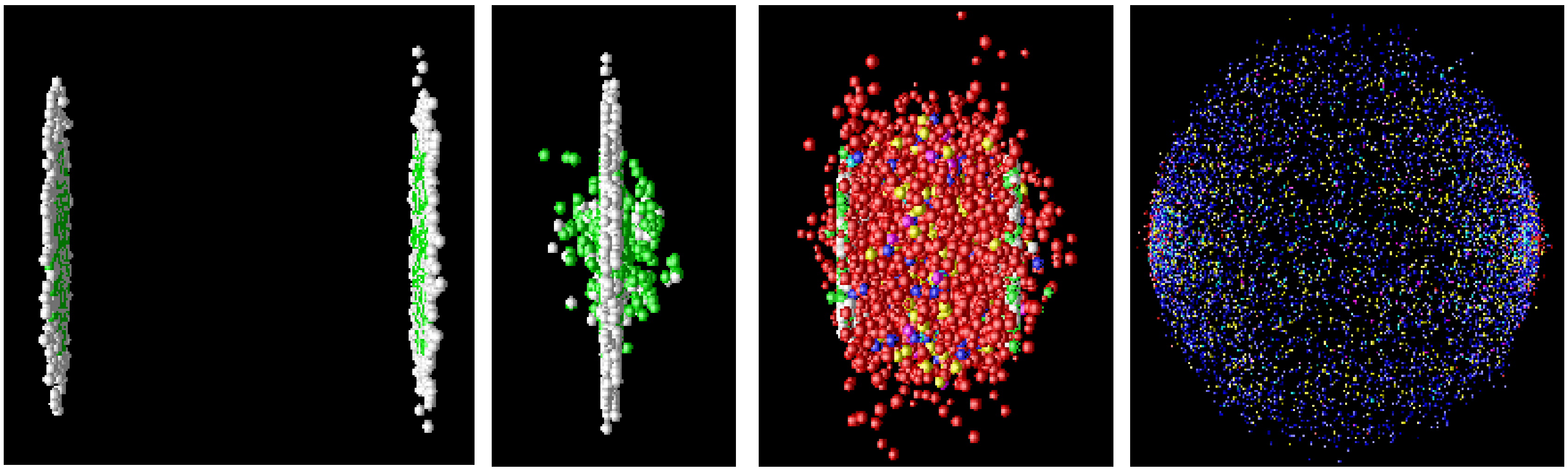
"The value deduced from the second harmonic in the acoustic oscillations for Ω_B=0.042 ± 0.008 (cosmic baryon mass density) is in very good agreement with the value one gets by applying the theoretical details of primordial big bang nucleosynthesis to the observations of cosmic abundances of deuterium."



If the plasma to hadrons transition were strongly first order, bubble formation could lead to an inhomogeneous baryon density, thus impacting big bang nucleosynthesis.

Are the bubbles too small and close together such that diffusion before nucleosynthesis erases the inhomogeneities?

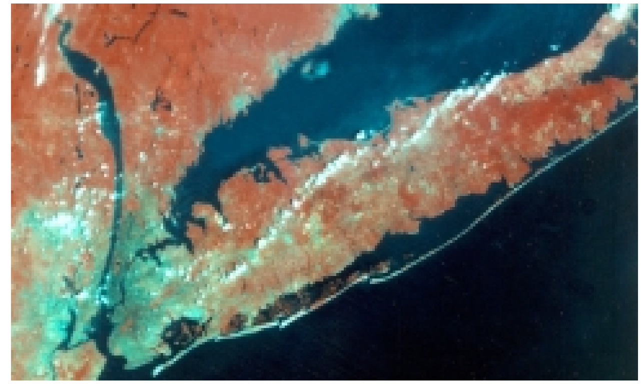
Heavy Ion Collisions

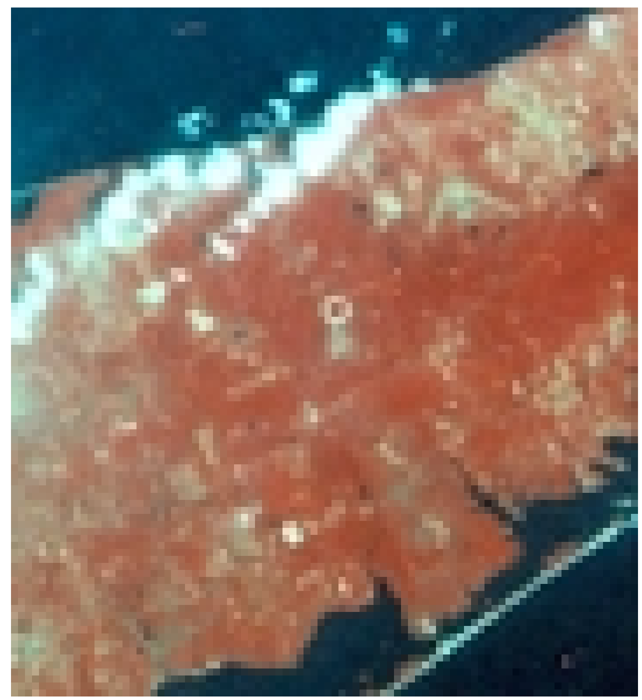


1. Initial Nuclei Collide
2. Partons are Freed from Nuclear Wavefunction
3. Partons interact and potentially form a Quark-Gluon Plasma
4. System expands and cools off
5. System Hadronizes and further Re-Scatters
6. Hadrons and Leptons stream towards our detectors

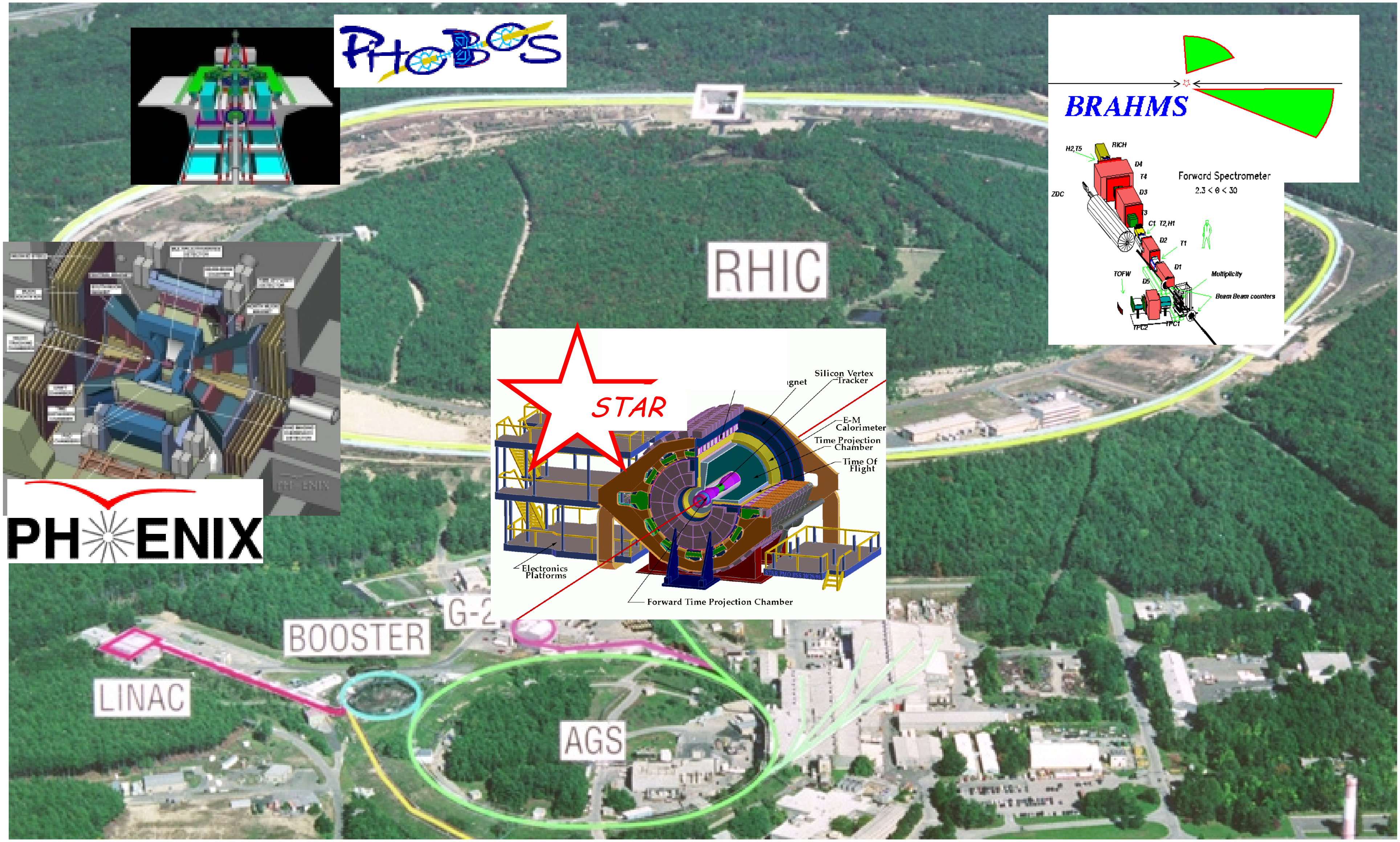
Relativistic Heavy Ion Collider

- Au + Au collisions at **200** GeV/u
- p + p collisions at 500 GeV
- spin polarized protons
- lots of combinations in between





Four Experiments

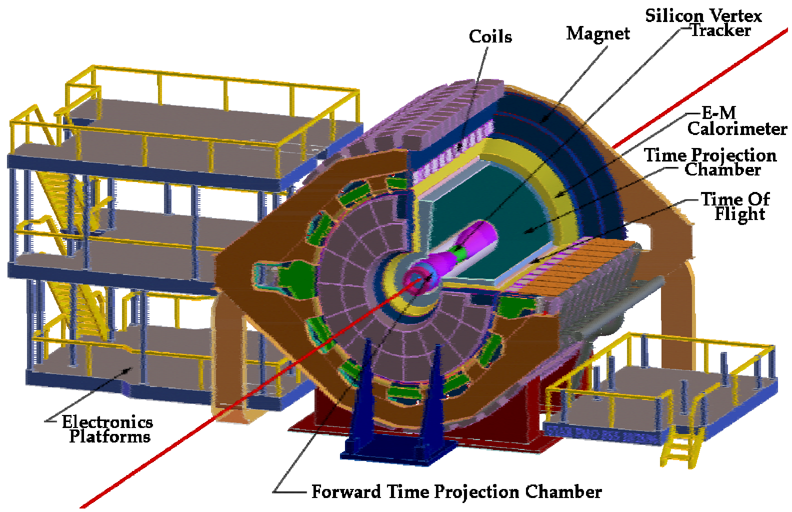


Two Large Experiments

STAR

Hadronic Observables over a Large Acceptance
Event-by-Event Capabilities

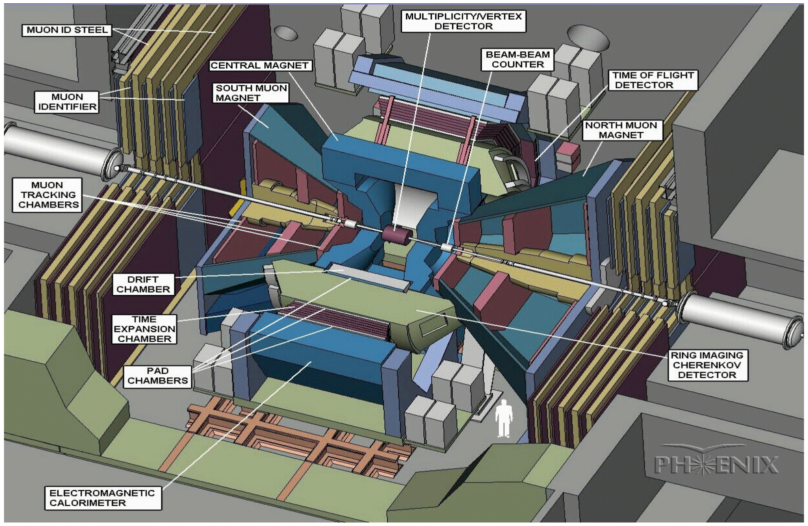
Solenoidal magnetic field
Large coverage Time-Projection Chamber
Silicon Tracking, RICH, EMC, TOF



PHENIX

Electrons, Muons, Photons and Hadrons Measurement Capabilities
Focus on Rare Probes: J/ψ, high-p_T

Two central spectrometers with tracking and electron/photon PID
Two forward muon spectrometers

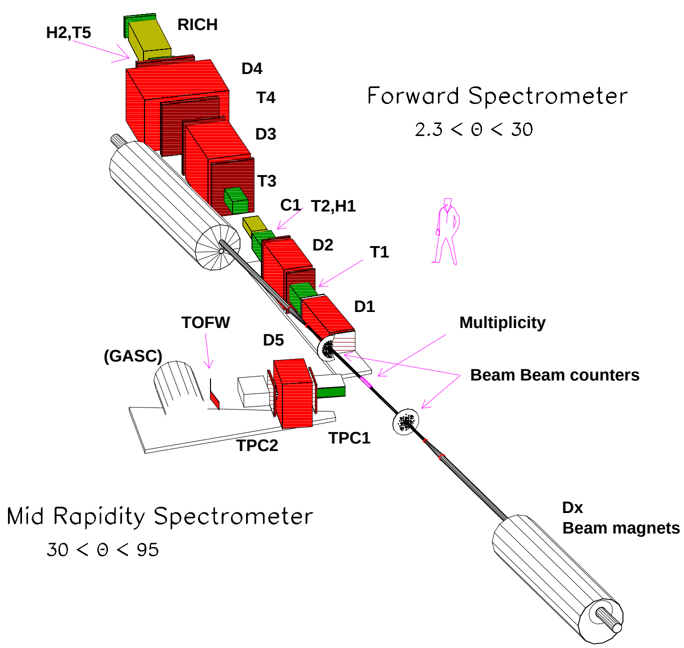


Two Small Experiments

BRAHMS

Hadron PID over broad rapidity acceptance

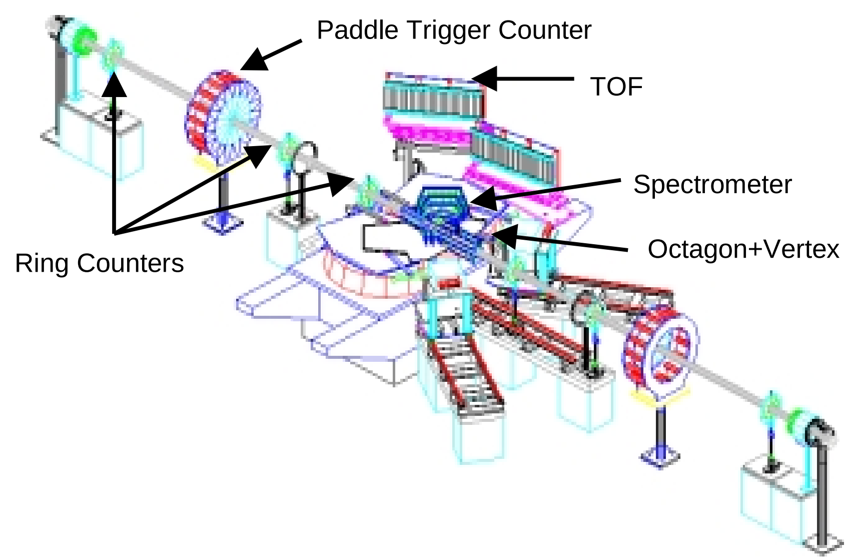
Two conventional beam line spectrometers
Magnets, Tracking Chambers, TOF, RICH



PHOBOS

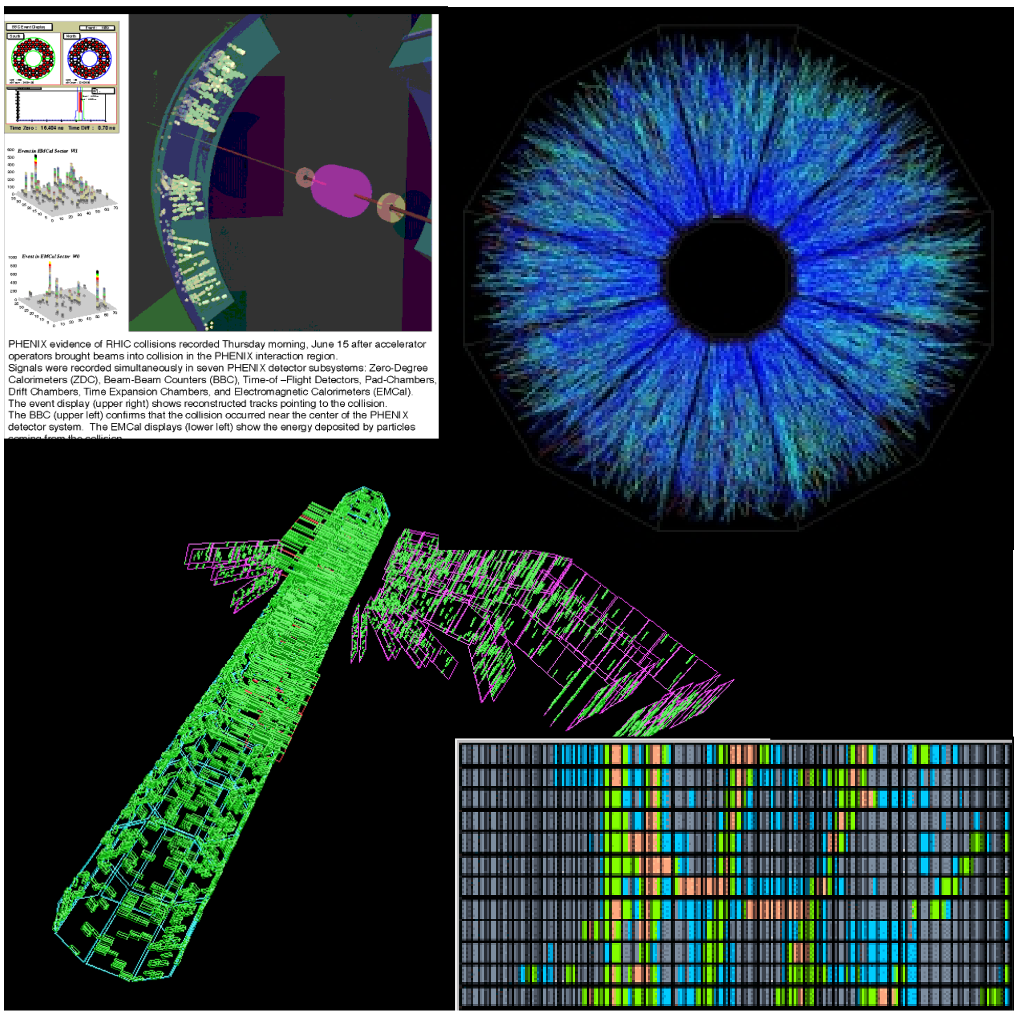
Charged Hadrons in Central Spectrometer
Nearly 4π coverage multiplicity counters

Silicon Multiplicity Rings
Magnetic field, Silicon Strips, TOF



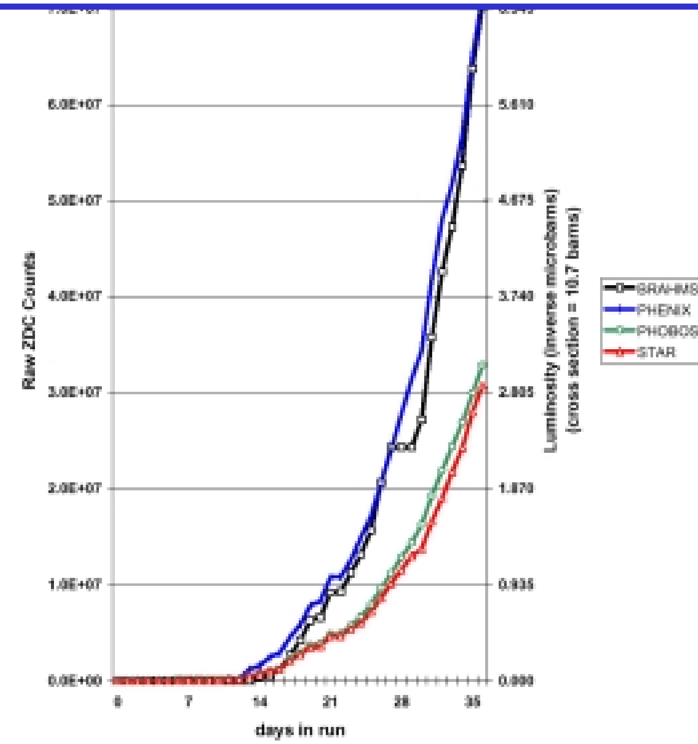
Run I at RHIC

June 2000



Running in August

Performance	Au + Au	RHIC Design
$\sqrt{s_{nn}}$	130 GeV	200 GeV
L [cm^{-2} s^{-1}]	~ 2 x 10^{25}	2 x 10^{26}
Interaction rates	~ 100 Hz	1400 Hz



Creating Black Holes ? !

Can be dismissed with some basic General Relativity

$$R_S = \frac{2GM}{c^2} = 10^{-49}\, meters$$

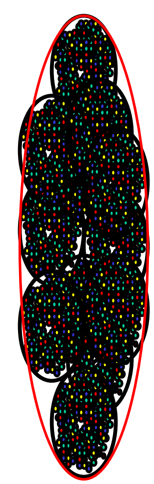
much less than Planck length !

$$R = 10^{-15}\, meters$$

Even if it could form, it would evaporate by Hawking Radiation in 10^{-83} seconds !

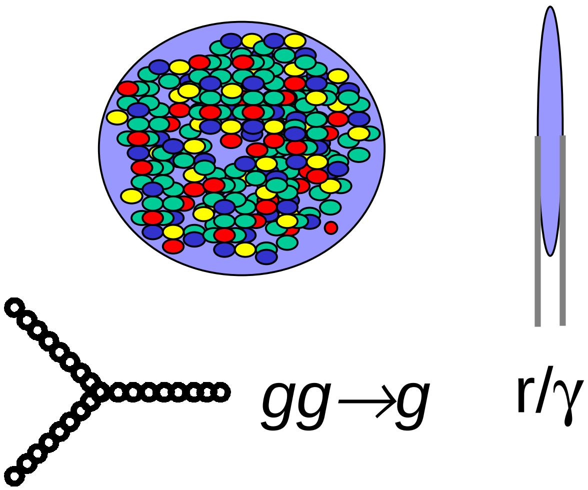
(1) Initial Conditions

- What is the density of created quarks and gluons?
- Does the saturation description at high gluon occupation number apply at RHIC or LHC?
- How does this relate to HERA observations?
- Does it reflect the Color Glass Condensate description of the initial nuclei?

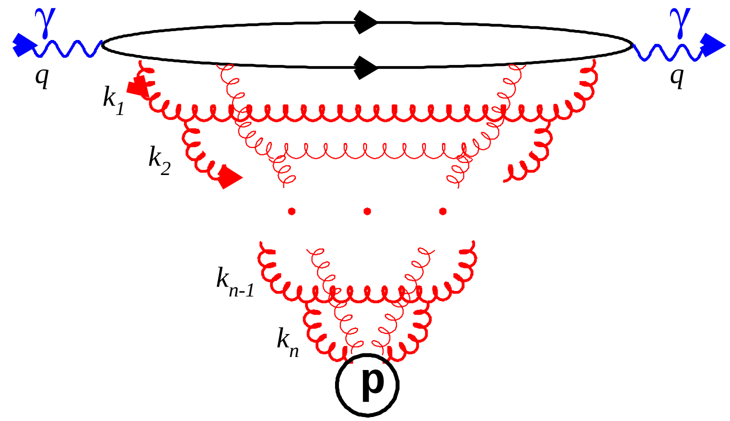


Gluon Saturation

probe rest frame



target rest frame



Transverse size of the quark-antiquark cloud is determined by $r \sim 1/Q \sim 2\ 10^{-14}$cm/ Q (GeV)

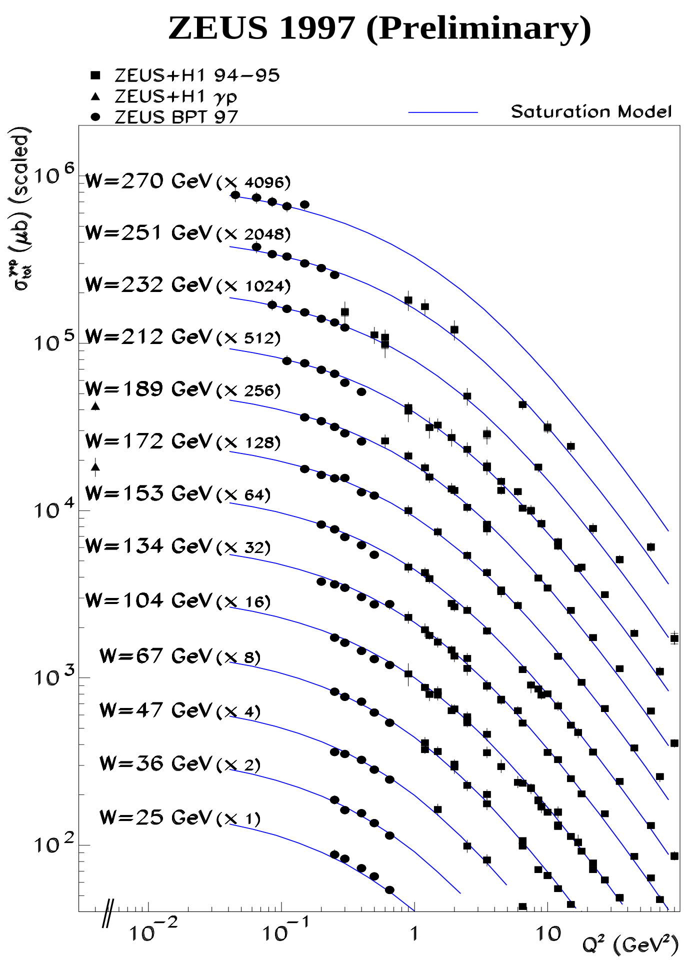
Wavefunction of low x gluons overlap and the self-coupling gluons fuse, thus saturating the density of gluons in the initial state

Fluctuations from dipole increase and the unitary limit of the photon cross section in deep inelastic scattering is the equivalent to saturation.

[1] J.P Blaizot, A.H. Mueller, Nucl. Phys. B289, 847 (1987).

Saturation in the Proton

HERA deep inelastic scattering data has been interpreted in the context of gluon saturation models.



Lowest x data is at modest Q^2 (should QCD+DGLAP work?)

Current HERA running may not resolve these issues since machine changes limit the coverage at low-x.

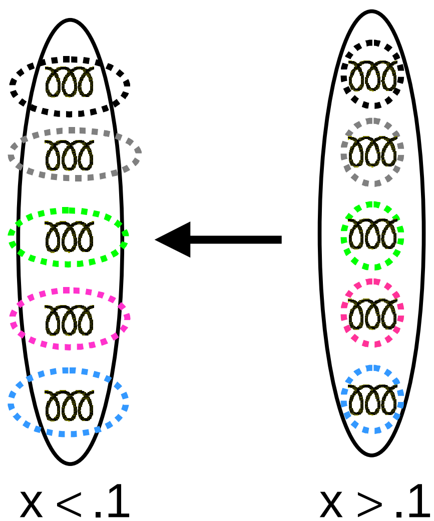
Future Electron-Ion Collider at RHIC or HERA upgrade may be necessary.

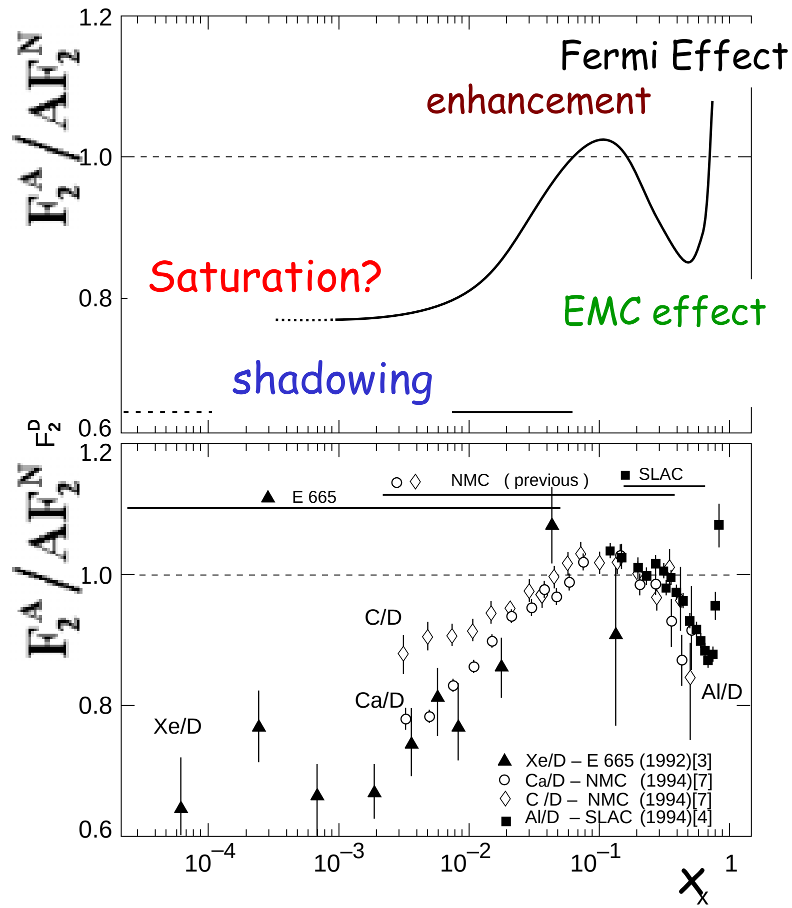
K. Golec-Biernat, Wuesthoff, others

What about Nuclei?

Nucleon structure functions are known to be modified in nuclei.

Can be modeled as recombination effect due to high gluon density at low x (in the frame where the nucleus is moving fast).





RHIC probes $\mathbf{x} \approx \frac{\mathbf{2p_T}}{\sqrt{\mathbf{s}}} > 10^{-2}$

Gluon Number Density

Gluon number density:

$$\rho_g = A\, xG_N(x,Q^2)/\pi R^2$$

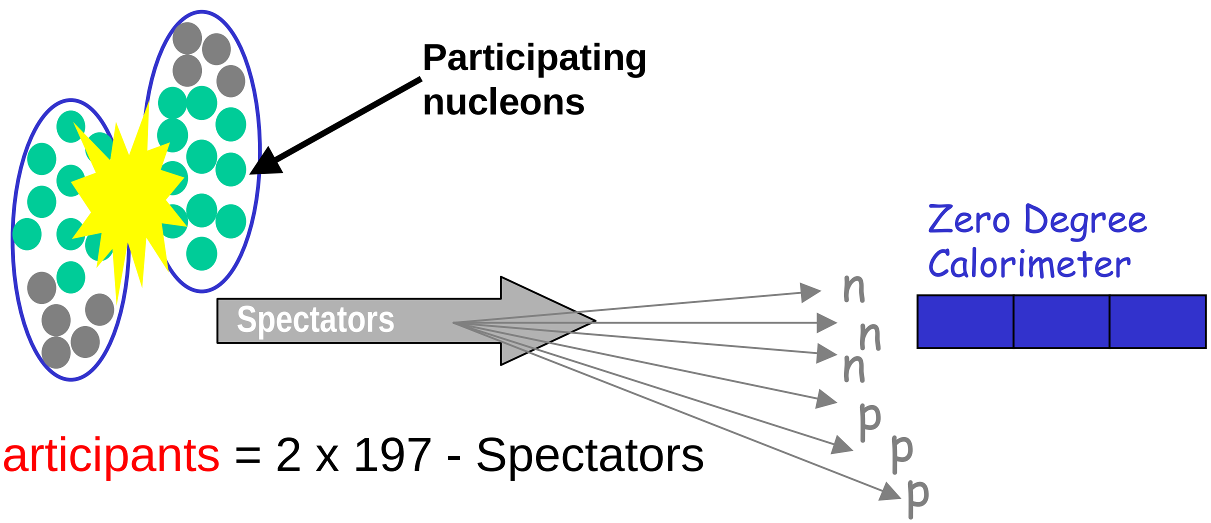
Gluon density depends on the nuclear overlap area ($\pi R^2 \propto A^{2/3}$) and the momentum scale (Q^2) since DGLAP evolution requires:

$$G(x, Q^2) \sim \ln (Q^2 / \Lambda_{QCD}{}^2)$$

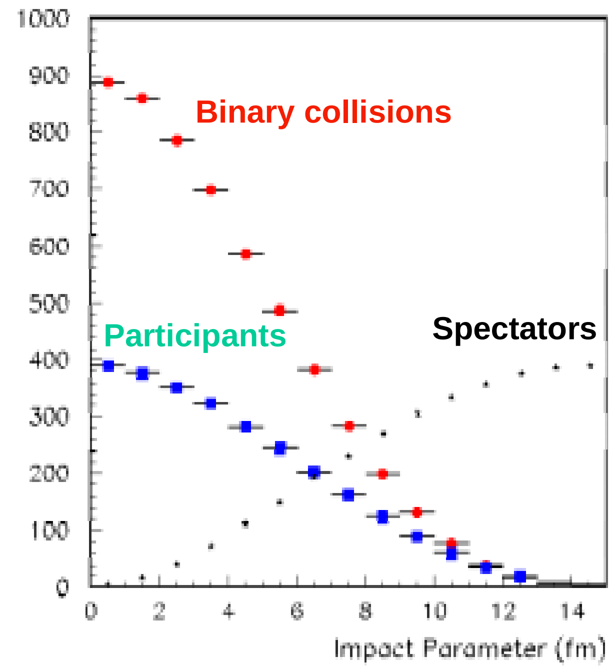
HERA tests gluon density in the proton at very low x. RHIC can test similar gluon density at significantly higher x values. LHC heavy ion collisions probe even higher gluon densities.

Collision Characterization

The impact parameter determines the number of nucleons that participate in the collision.



Participants = 2 x 197 - Spectators



Many models of particle production identify two components.

(A) Soft interactions where production scales with $N_{participants}$

(B) Hard interactions where production scales with N_{binary}

$$\mathbf{dN_{ch}/d\eta\big|_{\eta=0} = A \times N_{part} + B \times N_{bin}}$$

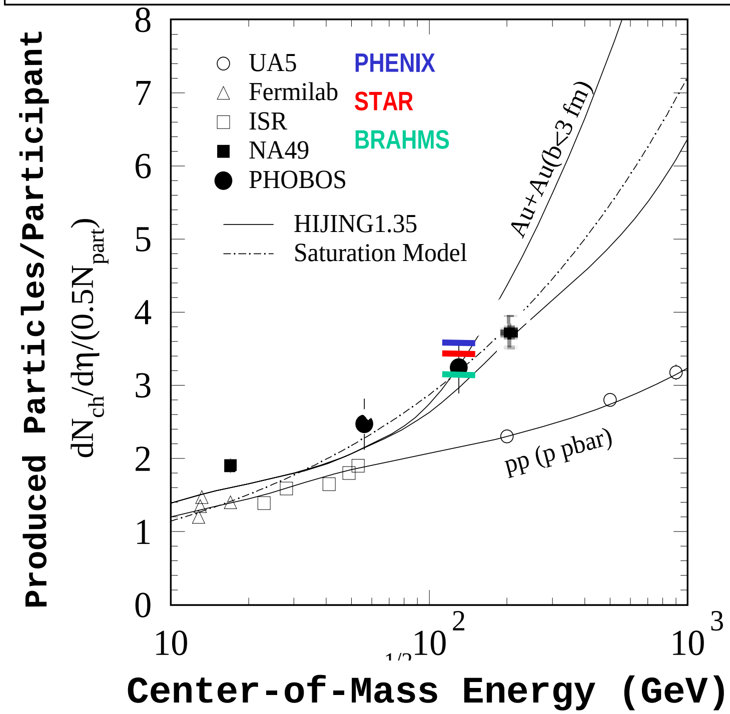
Wang, Gyulassy: nucl-th/0008014
Kharzeev, Nandi: nucl-th/0012025

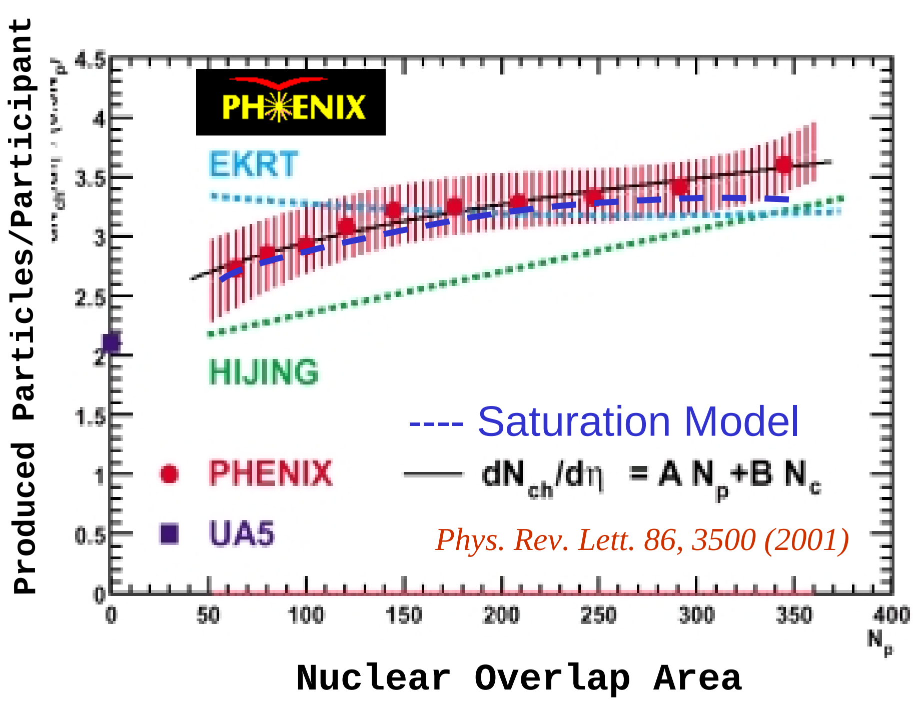
Testing the Models

Over 7500 new particles are produced in Au-Au collisions !

Saturation model calculations agree with energy and overlap area dependence.

However, they are not very sensitive and thus other pictures of particle production cannot be ruled out.

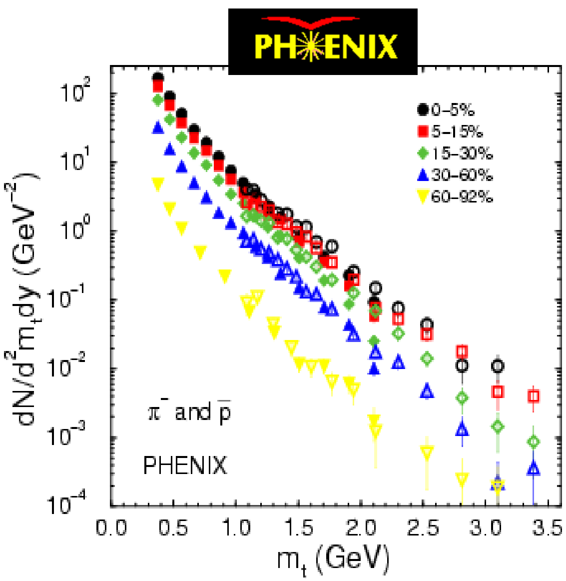


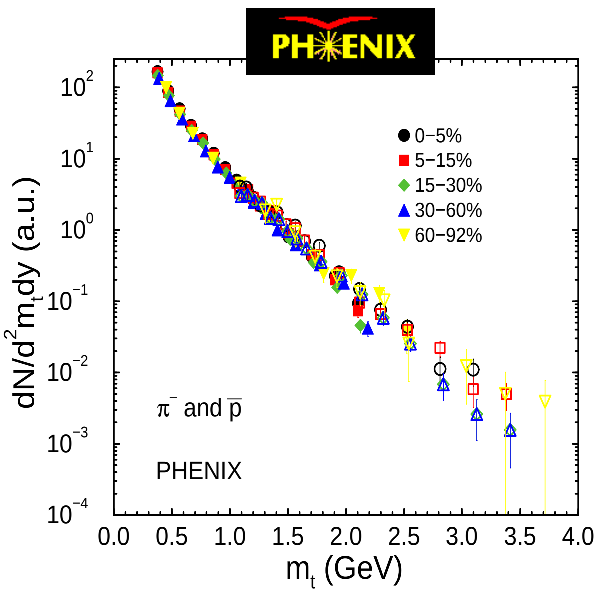


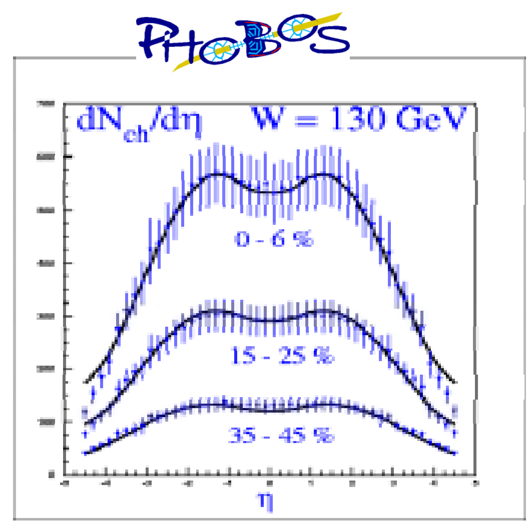
More Stringent Tests

Saturation models predict the angular distribution and transverse momentum distribution of initial gluons.

$$\frac{dN}{d\eta}=\frac{\cosh y}{\sqrt{m_T^2/p_T^2+\sinh^2 y}}\times cN_{part}\left(\frac{s}{s_o}\right)^{\frac{\lambda}{2}}\times e^{-\lambda|y|}\ln\left(\frac{Q_s^2 e^{-\lambda|y|}}{\Lambda_{QCD}^2}\right)\times\left[1+\lambda|y|\left(1-\frac{Q_s}{\sqrt{s}}e^{\lambda|y|/2}\right)^4\right]$$







-log(tan(θ/2))

Kharzeev & Levin, nucl-th/0108006
Schaffner-Bielich et al, nucl-th/0108048

Jury is Still Out on Saturation

Do the final state hadron distributions simply reflect the initial gluon distribution in the nuclei?

Latest Yang-Mills results require final state gluon multiplication x2-3 as well as hydrodynamic work to reduce the transverse energy at midrapidity by x2-3.

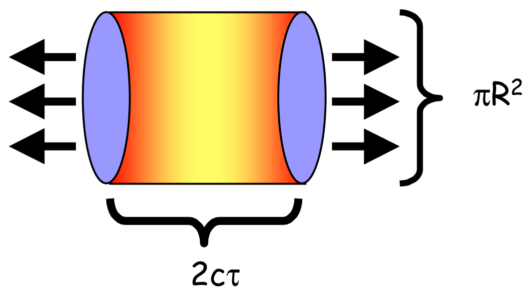
If that is true, then parton rescattering and perhaps later hadron rescattering breaks the direct connection between initial partons in nuclear wavefunction and final state hadrons.

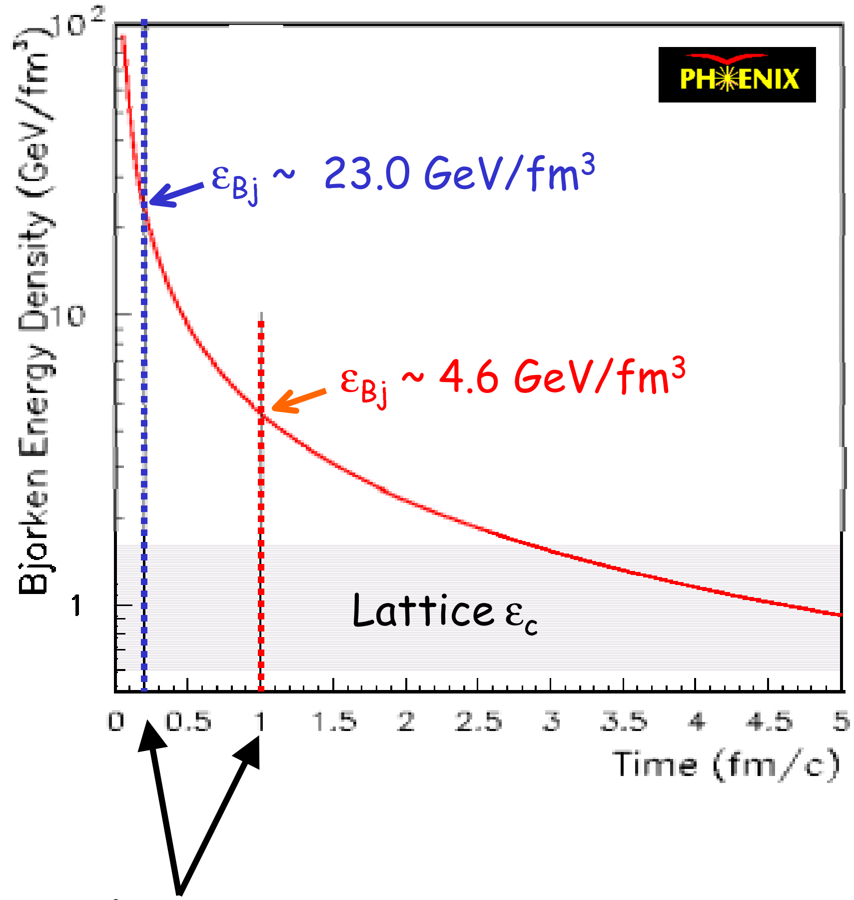
Al Mueller: "Deep inelastic scattering provides a precision tool for studying saturation effects. However at RHIC one makes all of the gluons physical in the laboratory and can observe their interactions."

(2) Quark-Gluon Plasma

Bjorken formula for energy density in terms of measured transverse energy E_T

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





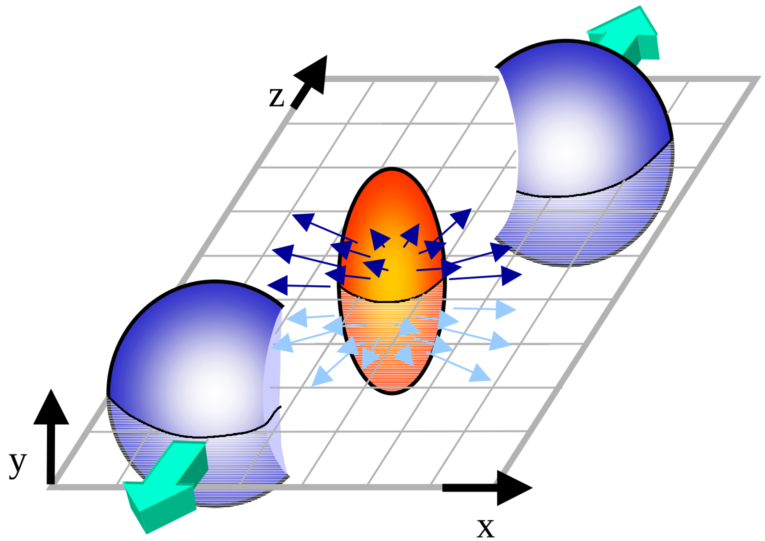
PHENIX: Central Au-Au yields

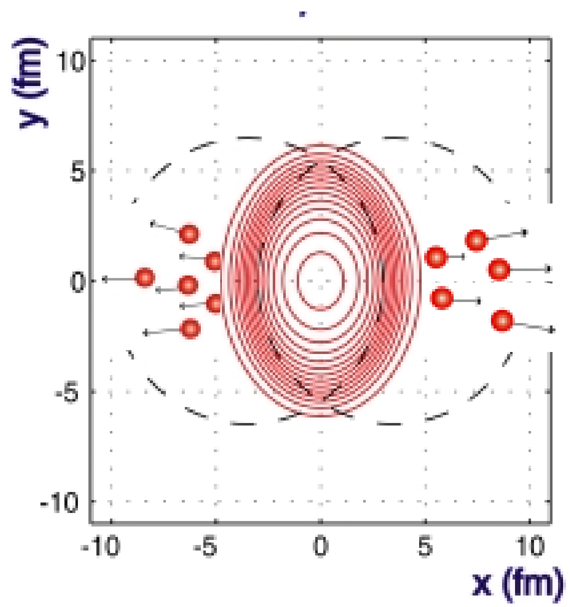
$$\left\langle \frac{dE_T}{d\eta} \right\rangle_{\eta=0} = 503 \pm 2\,GeV$$

Thermalization time?

Hydrodynamic Flow

Spatial anisotropy leads to momentum anisotropy in the presence of large re-scattering.





$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

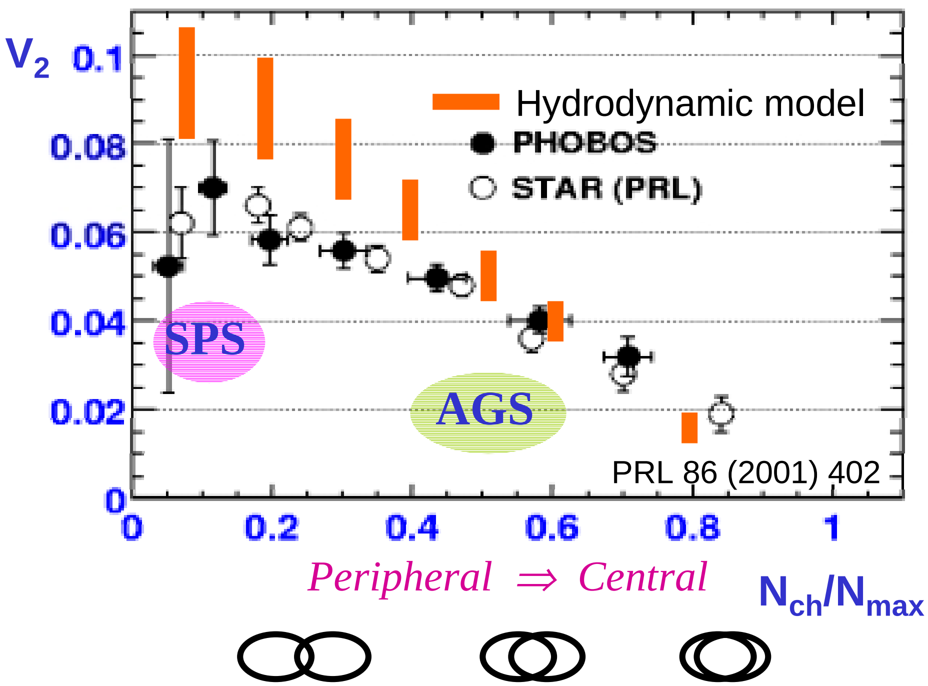
$$v_2 = \langle \cos 2\phi \rangle$$

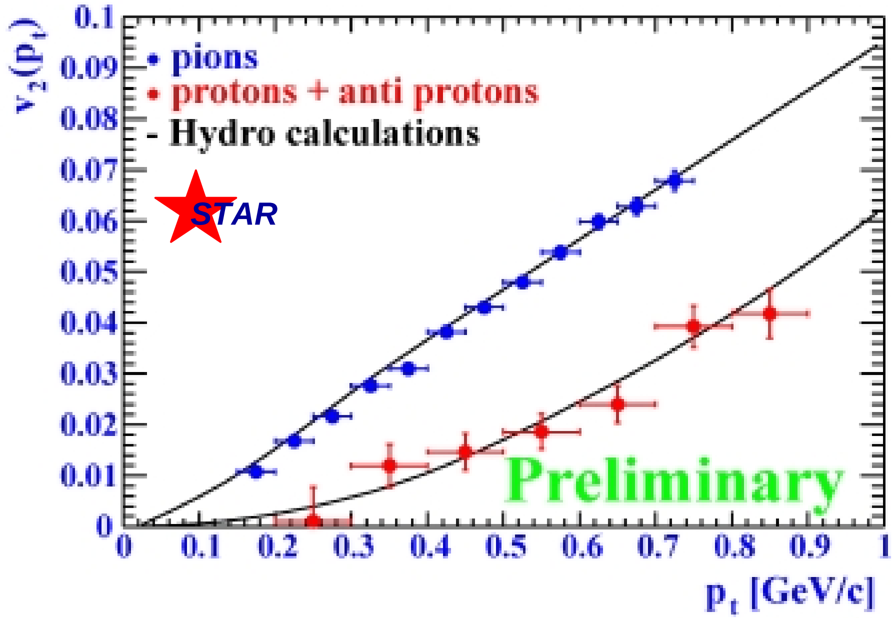
$$\phi = \mathrm{atan}\frac{p_y}{p_x}$$

v_2: 2nd harmonic Fourier coefficient

Large Parton Re-Scattering

Strong elliptic flow near the hydrodynamic limit





Hadronic re-scattering is insufficient to describe the data.

Implies strong partonic re-scattering and high initial density

ε = 20 GeV/fm^3 and τ = 0.6 fm/c

Hydro calculations: P. Huovinen, P. Kolb and U. Heinz

Temperature? Phase?

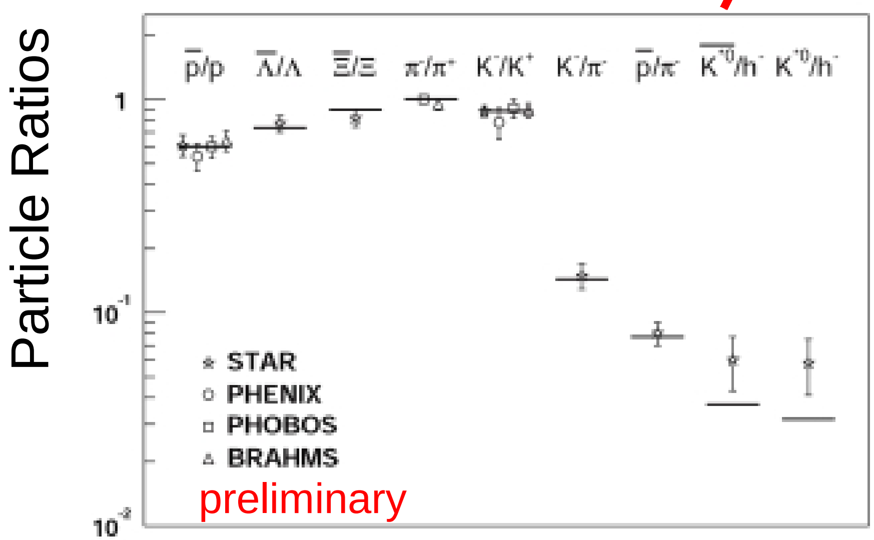
Simple Grand Canonical Ensemble analysis fitting particle ratios to determine μ_B, T

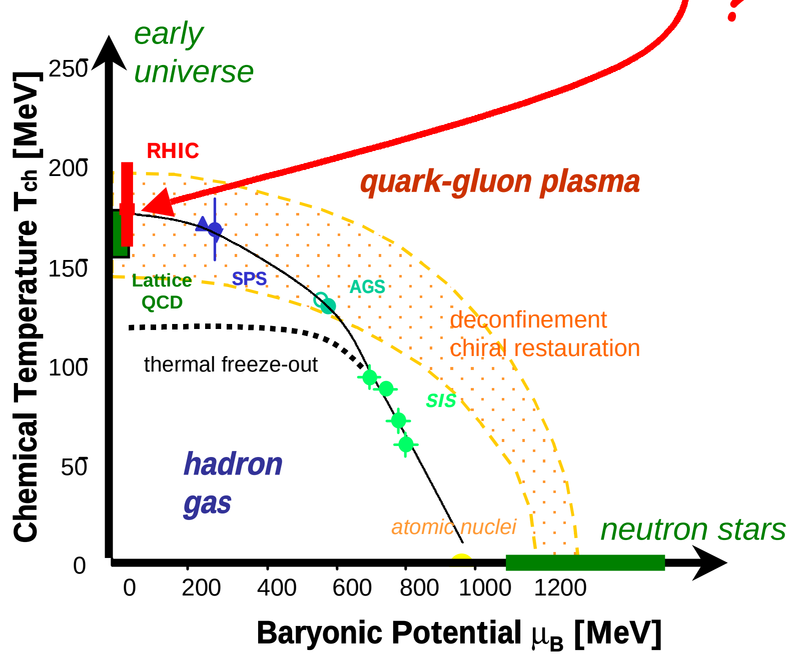
$$\frac{n_\pi}{n_p} = \frac{\frac{g_\pi}{2\pi^2}\int \frac{1}{e^{E/T}-1}p^2dp}{\frac{g_p}{2\pi^2}\int \frac{1}{e^{(E-\mu_B)/T}+1}p^2dp}$$

$$T = 175 \pm 7\ \text{MeV}$$

$$\mu_B = 51 \pm 6\ \text{MeV}$$

?



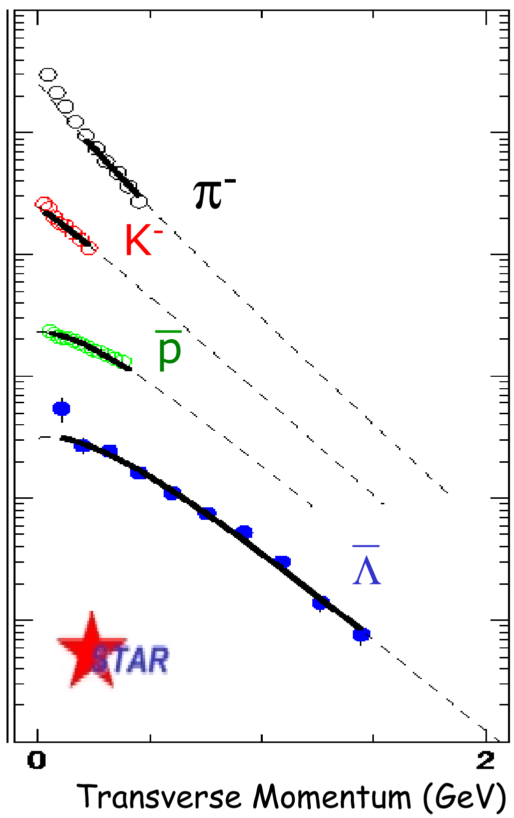


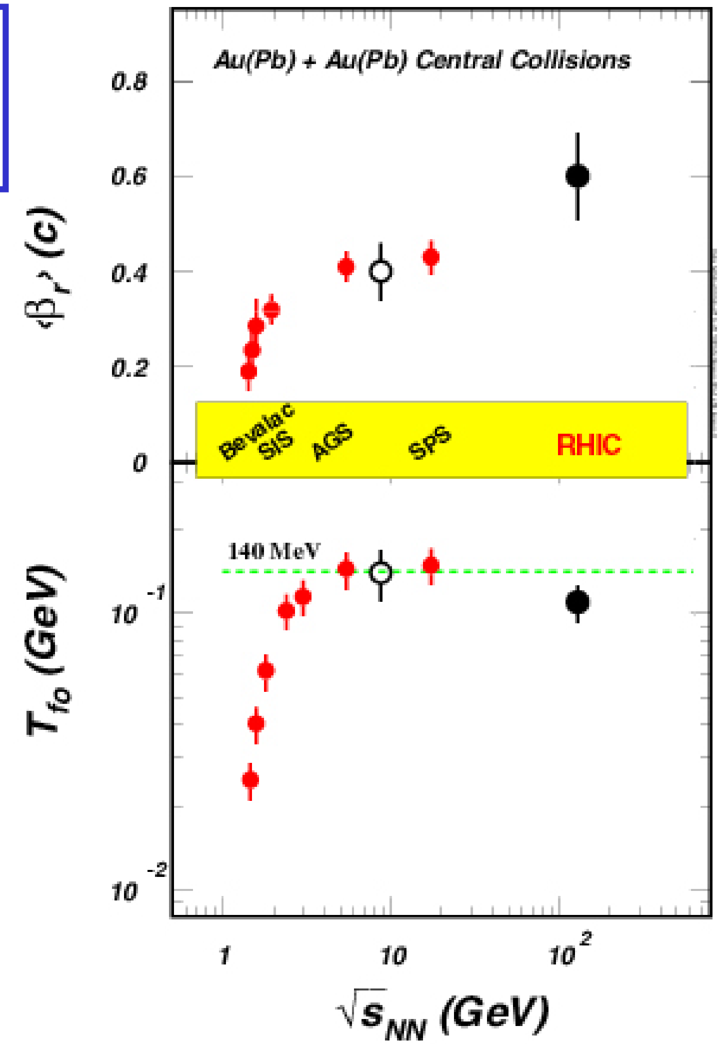
Exploding System

Hadron spectra indicate massive transverse expansion of the system.
Very large initial pressure may lead to a short plasma lifetime.

Simple: $T = T_{freeze\text{-}out} + m \langle \beta_r \rangle^2$

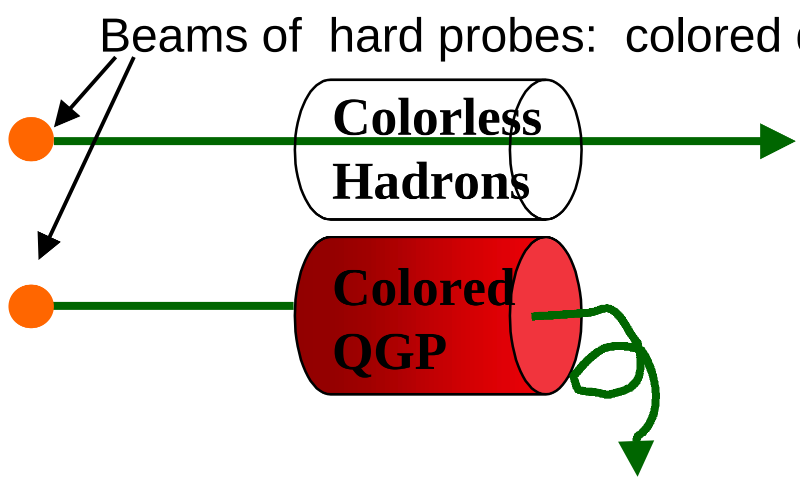
where $\langle \beta_r \rangle$ = averaged flow velocity



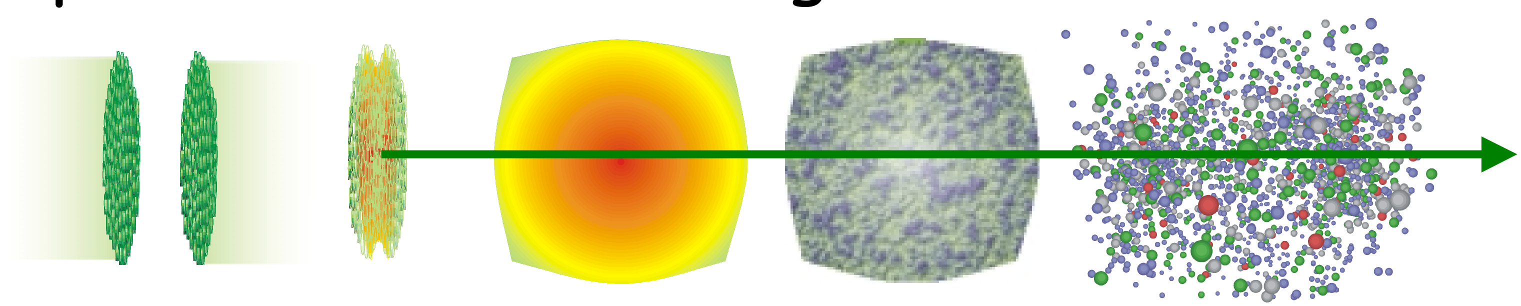


(3) Probes of the System

Quarks are excellent probes of the volume.



All probes must be auto-generated.

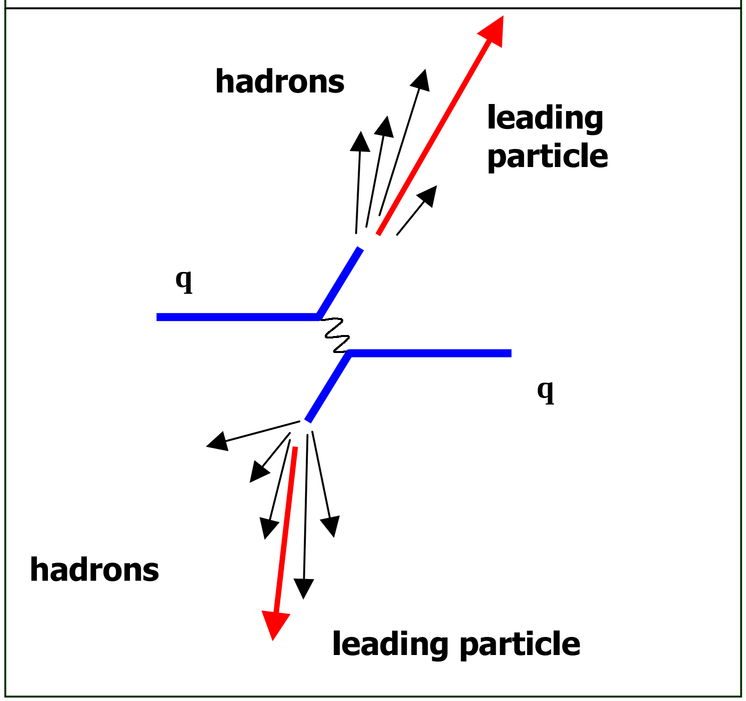


Hard Scattering

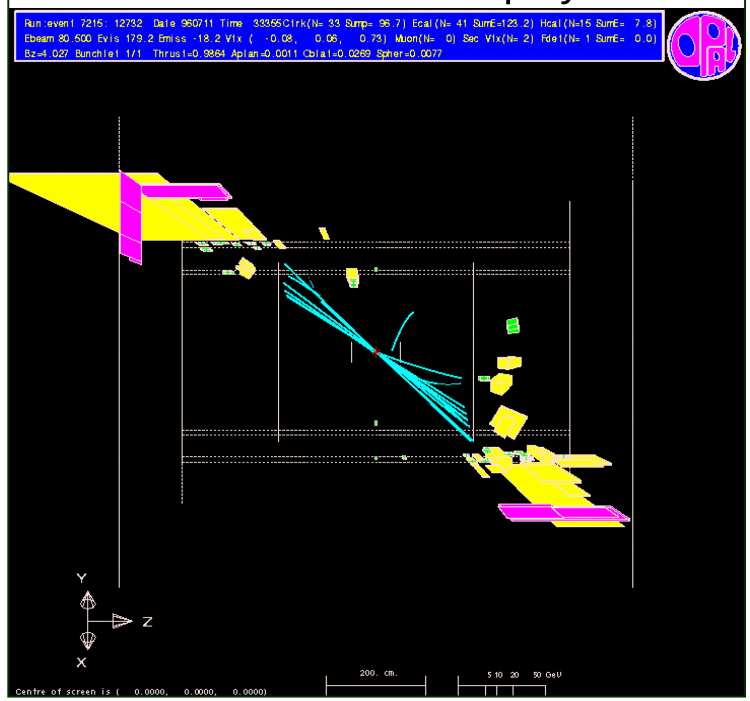
Hard scattering of partons (large Q^2) have calculable rates in perturbative QCD.

The partons manifest themselves as jets, fragmented hadrons in a collimated angular cone.

Schematic View of Jet Production



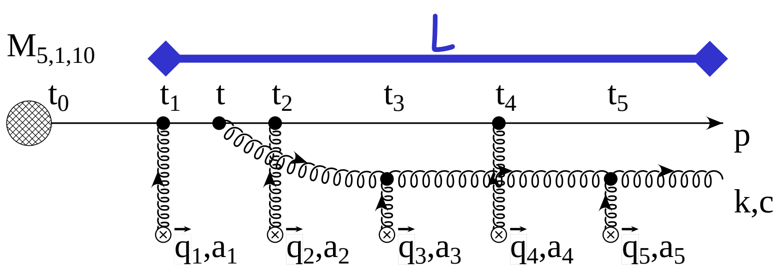
OPAL Event Display



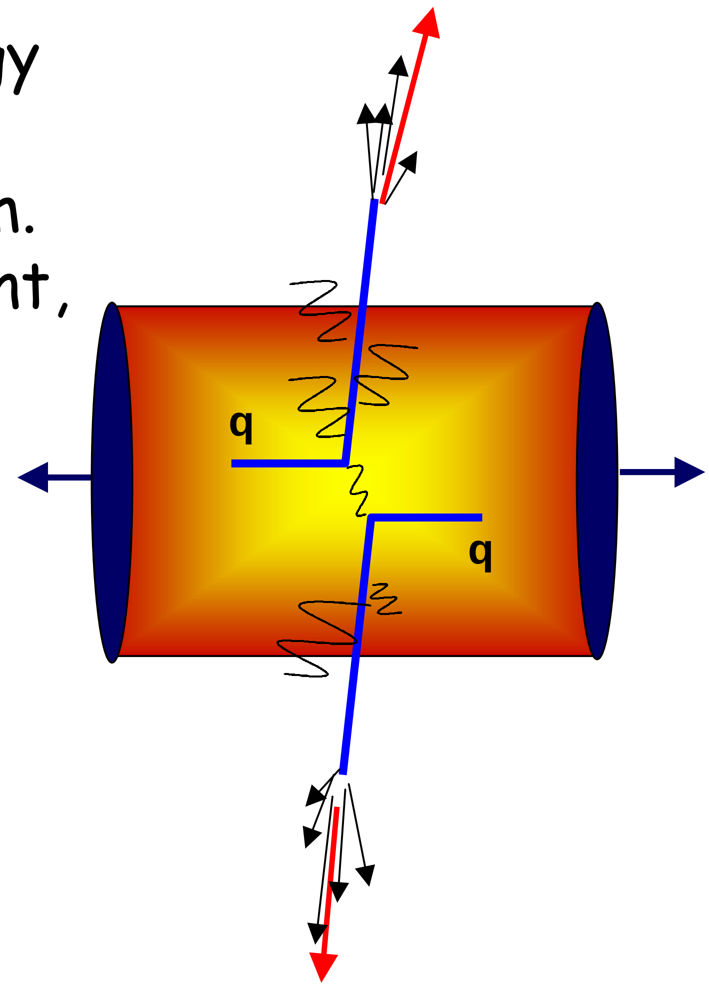
Gluon Radiation

Partons are expected to lose energy via induced gluon radiation in traversing a dense partonic medium. Not very sensitive to deconfinement, but only gluon density.

Coherence among these radiated gluons leads to $\Delta E \propto L^2$



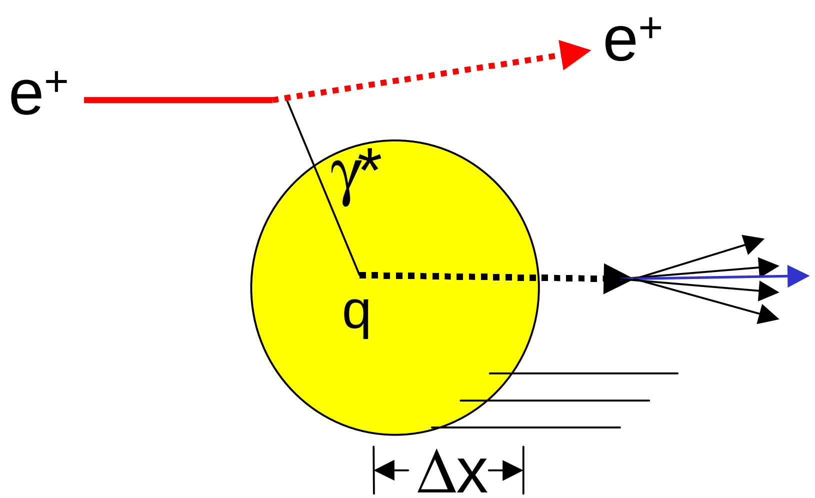
Look for an effective modification in the jet fragmentation properties.

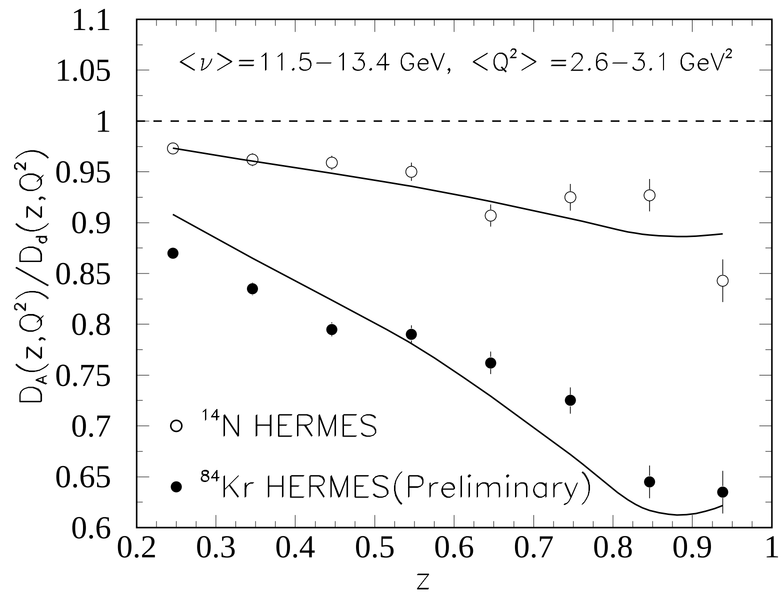


Baier, Dokshitzer, Mueller, Schiff, hep-ph/9907267
Gyulassy, Levai, Vitev, hep-pl/9907461
Wang, nucl-th/9812021
and many more…..

Cold Nuclear Matter

HERMES Experiment





Measure quark energy from electron scattering off nuclei.
Measure hadron fragmentation function D(z).
Larger nuclei show fewer high z hadrons in fragmentation.

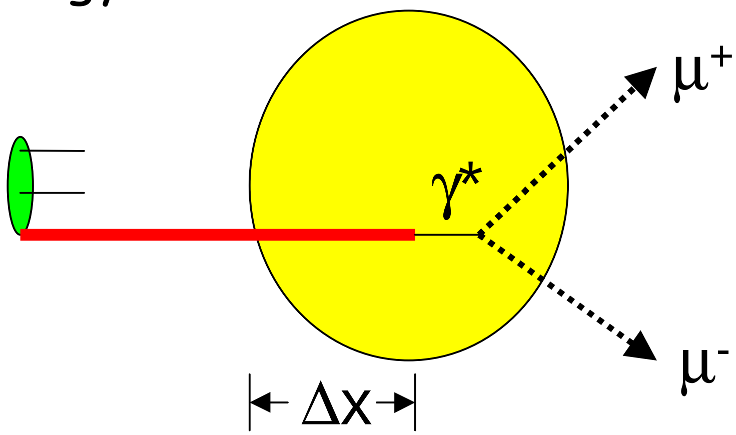
Calculations of Wang *et al.* indicate radiative energy loss α L^2 and for Kr target <dE/dx> ~ 0.3 GeV/fm

HERMES - Eur. Phys. J. C20, 479 (2001).
Wang et al., hep-ph/0202105

Initial State Energy Loss

E866 at Fermilab

Drell-Yan production in proton-A collisions is sensitive to parton energy loss.



Need to separate shadowing from energy loss, and then

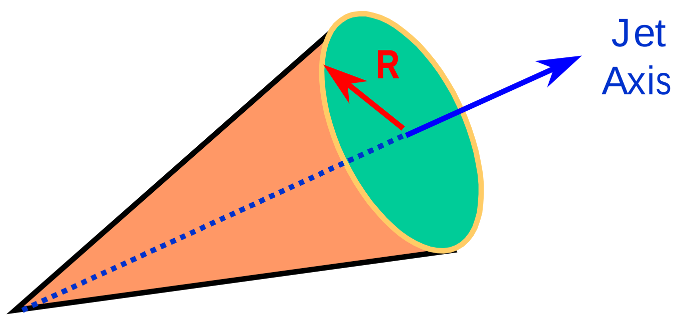
$-dE/dx = 2.32 \pm 0.52 \pm 0.5$ GeV/fm

hep-ex/0109014

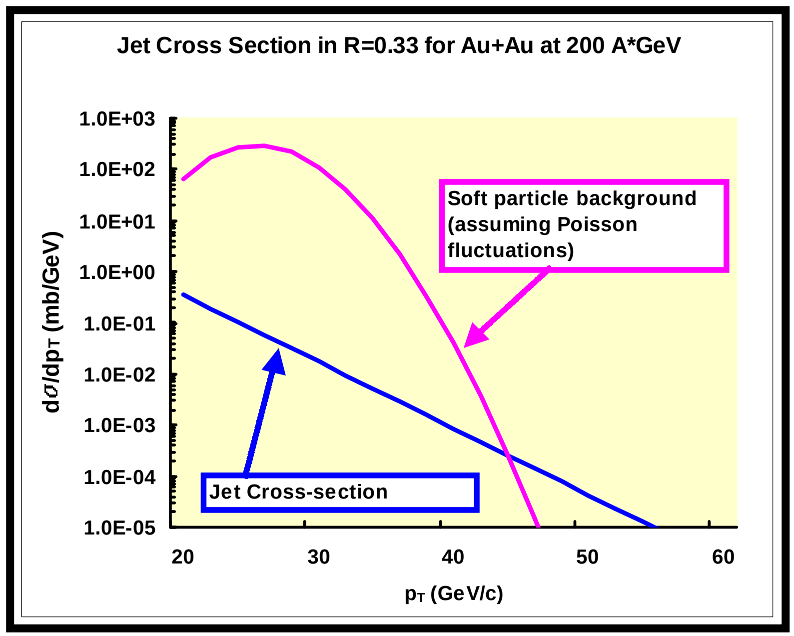
Energy and Fragmentation

"Traditional" jet methodology fails at RHIC because jets are dominated by the soft background.

For a typical jet cone R = 0.33

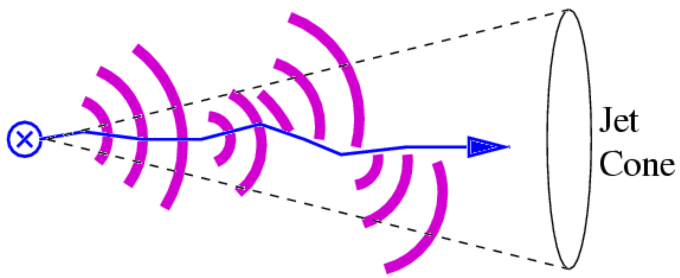


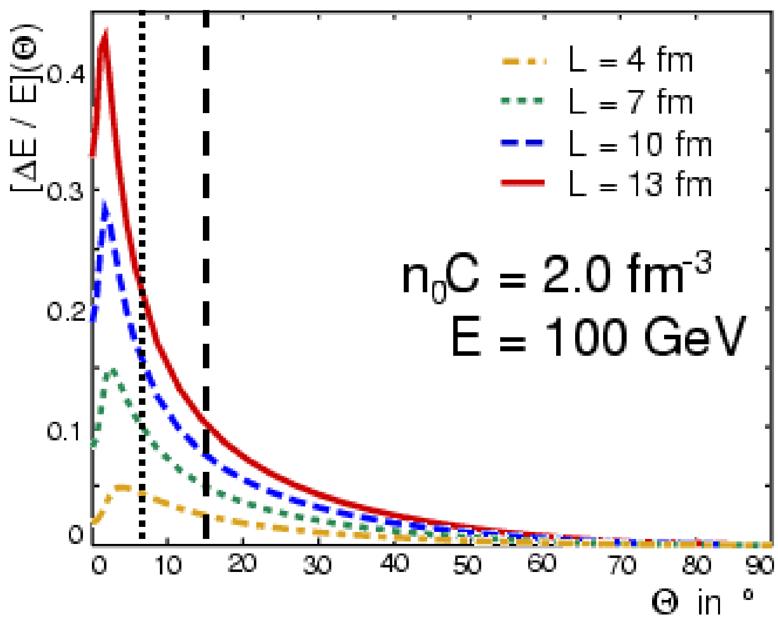
Fluctuations in this soft background swamp any jet signal for pt < ~ 40 GeV



Wider Angular Distribution

The induced gluon radiation may be measurable due to the broader angular energy distribution than from the jet.





$\theta < 20^0$ - 80% of jet energy contained
5% loss of energy outside

$\theta < 12^0$ - 70% of jet energy contained
8% loss of energy outside

Possible observation of reduced "jet" cross section from this effect. This is not going to be easy at RHIC.

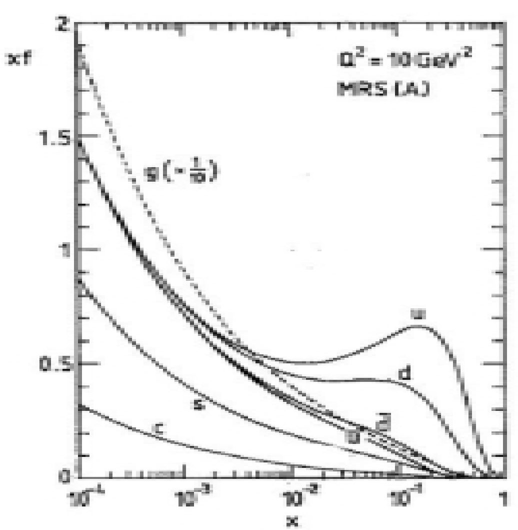
U.A. Wiedemann, hep-ph/0008241.
BDMS, hep-ph/0105062.

Ingredients

In heavy ion collisions we can calculate the yield of high p_T hadrons

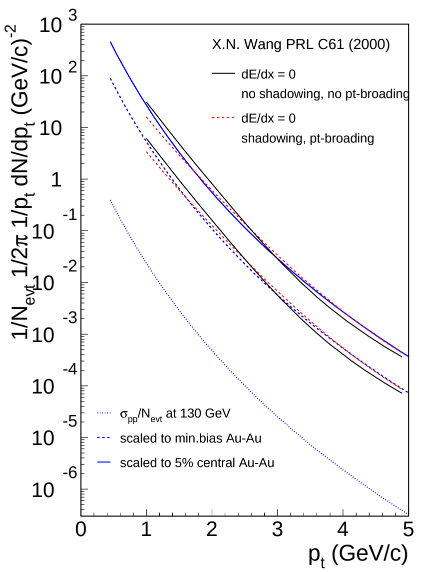
$$E_h \frac{d\sigma_h^{pp}}{d^3p} = K \sum_{abcd} \int dz_c dx_a dx_b \int d^2\mathbf{k}_{Ta} d^2\mathbf{k}_{Tb} f(\mathbf{k}_{Ta}) f(\mathbf{k}_{Tb}) f_{a/p}(x_a, Q_a^2) f_{b/p}(x_b, Q_b^2)\, D_{h/c}(z_c, Q_c^2) \frac{\hat{s}}{\pi z_c^2} \frac{d\sigma^{(ab\to cd)}}{d\hat{t}} \delta(\hat{s}+\hat{u}+\hat{t})$$

Flux of incoming partons (structure functions) from Deep Inelastic Scattering

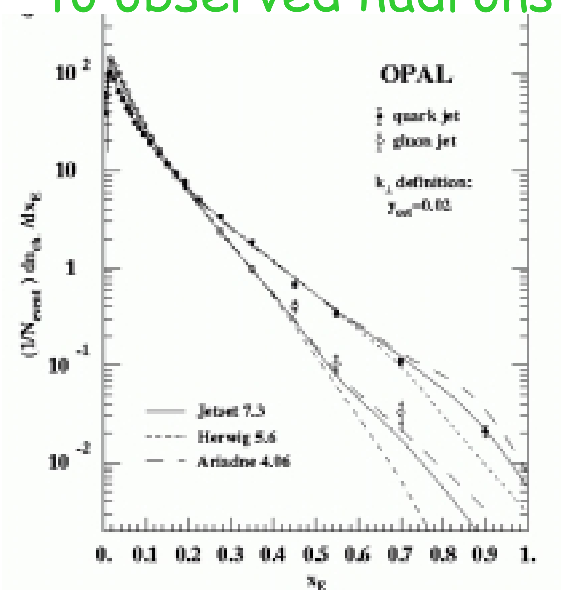


Perturbative QCD

$$\sigma_{AA}(b_c) = \sigma_{pp} \int_0^{b_c} db^2 T_{AA}$$

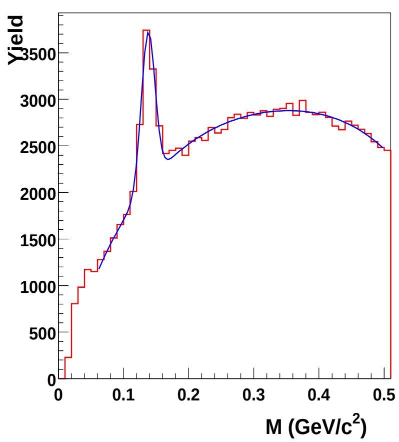


Fragmentation functions D(z) in order to relate jets to observed hadrons



Neutral Pions

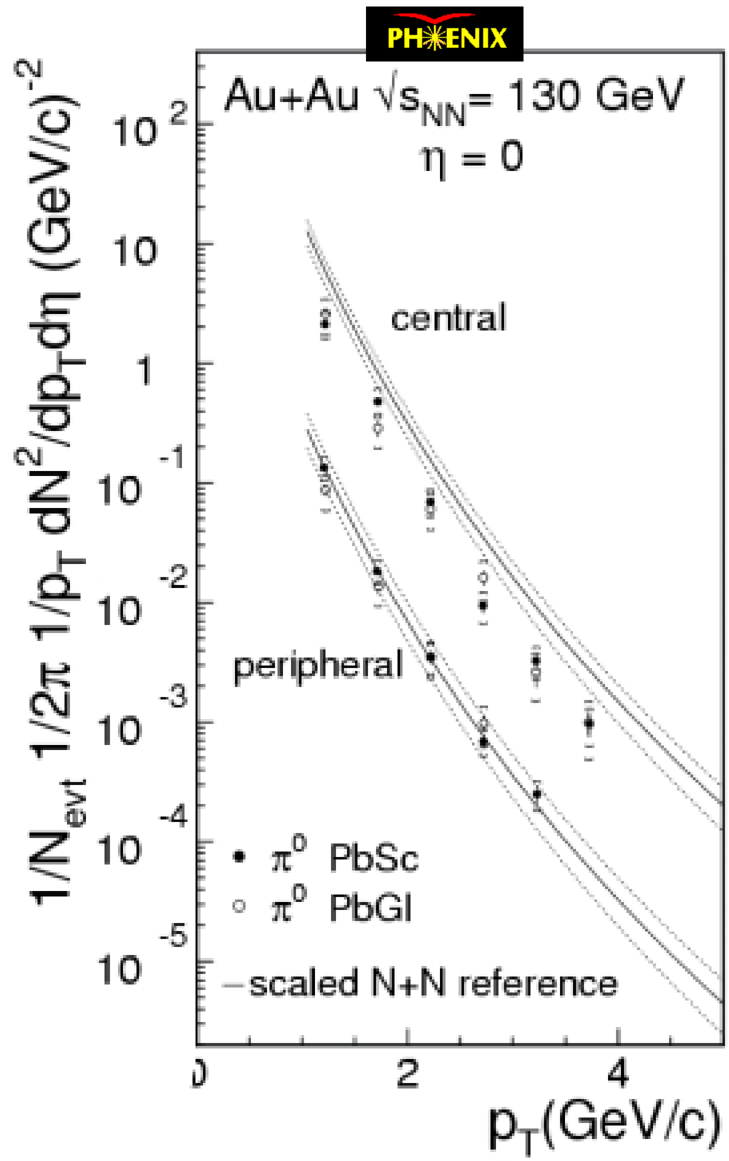
PHENIX measures π^0 with two types of calorimeters



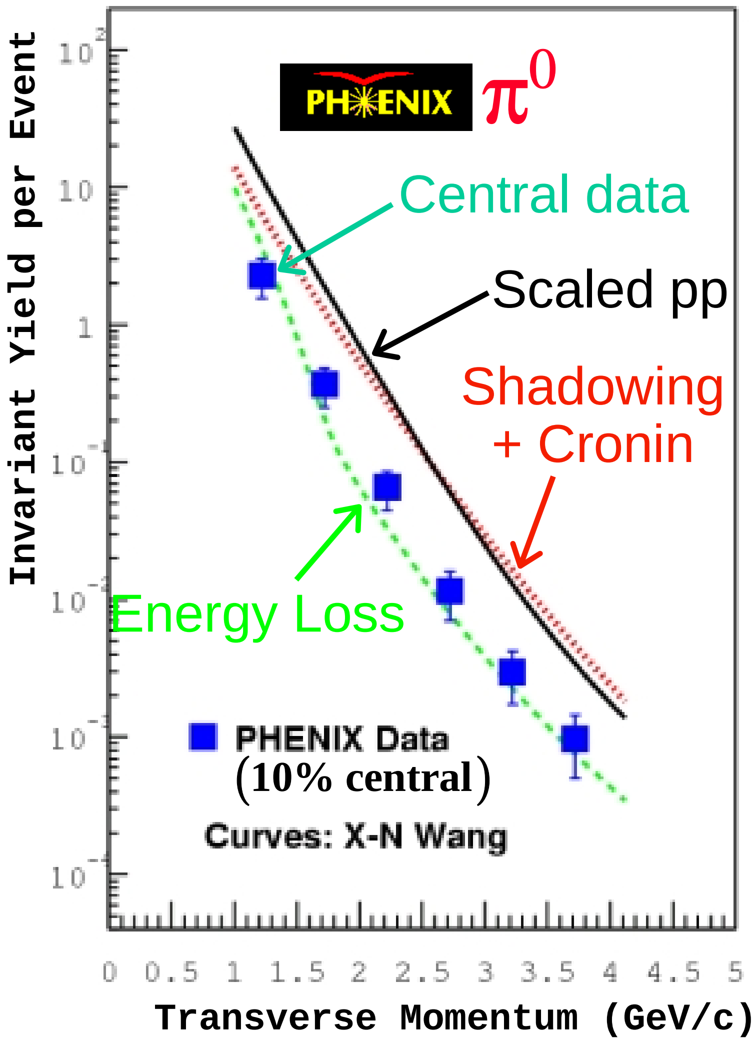
Significant suppression relative to proton-proton scaling in central collisions

$$N_{collisions}^{60-80\%} = 20 \pm 6 \quad \text{(peripheral)}$$

$$N_{collisions}^{0-10\%} = 905 \pm 96 \quad \text{(central)}$$



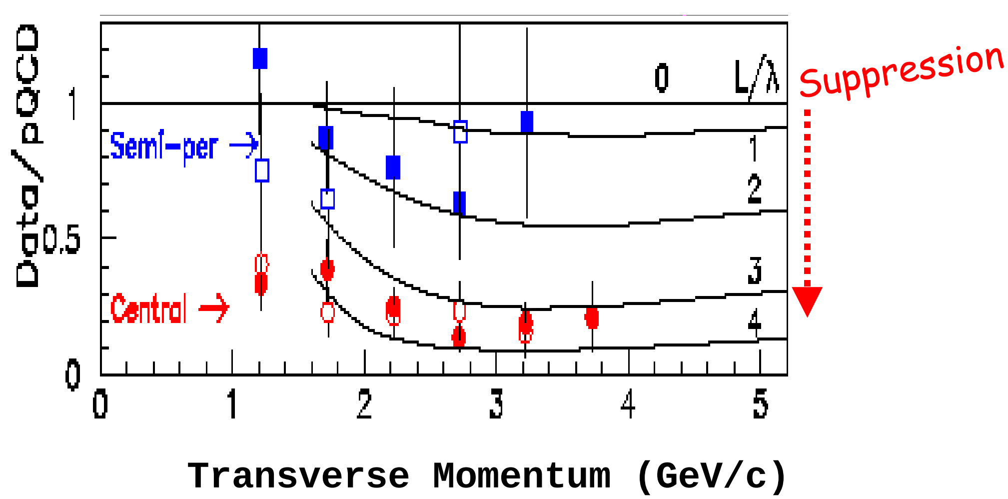
Energy Loss from π^0



Theoretical calculations agree that there is a suppression of high momentum pions.

Plot the ratio of yield/expectation.

$$R_{AA} = \frac{\text{Yield}_{central} / \langle N_{binary} \rangle_{central}}{\text{Yield}_{pp}}$$

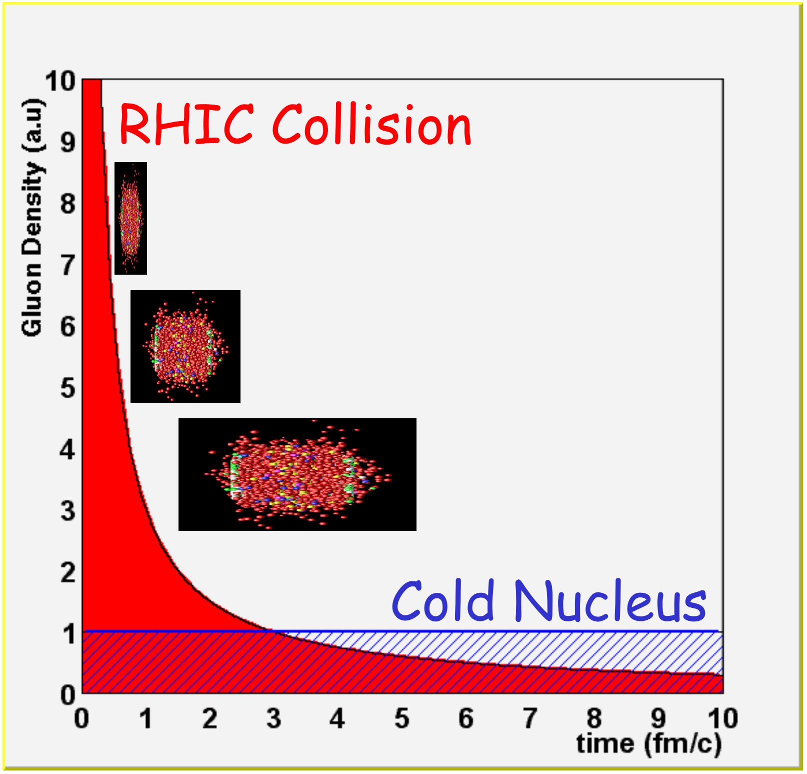


X.N. Wang, Phys. Rev. C 61, 064910 (2000).

Larger Energy Loss !

Wang *et al.* have compared the implied energy loss in RHIC collisions from our π^0 data and the HERMES results.

Longitudinal expansion in RHIC collisions leads to a dissipating gluon dense medium.



If the density were maintained at the initial level, calculations indicate equivalent energy loss

$$\langle dE/dx \rangle \sim 7 \text{ GeV/fm}$$

Over an order of magnitude higher than in cold nuclear matter !

Theoretical systematics need to be worked out.

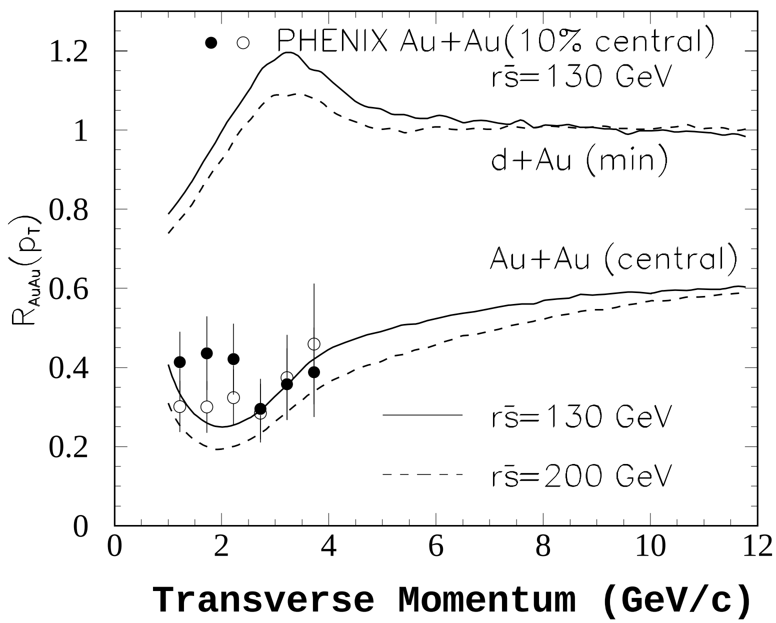
Be Careful

This is a very exciting result because it is a suppression relative to point-like scaling and is qualitatively in agreement with large energy loss expectations.

Larger energy jets must be studied and checks in proton-nucleus collisions need to be done.

We must check issues related to shadowing, Cronin enhancement, fragmentation pictures, etc.

What other experimental handles do we have?



Time Scales

What if the quark or gluon jet begins to fragment inside the medium?

Then the fragmented hadrons can interact with the hadron gas medium, rescatter, and thus suppression high momentum hadrons.

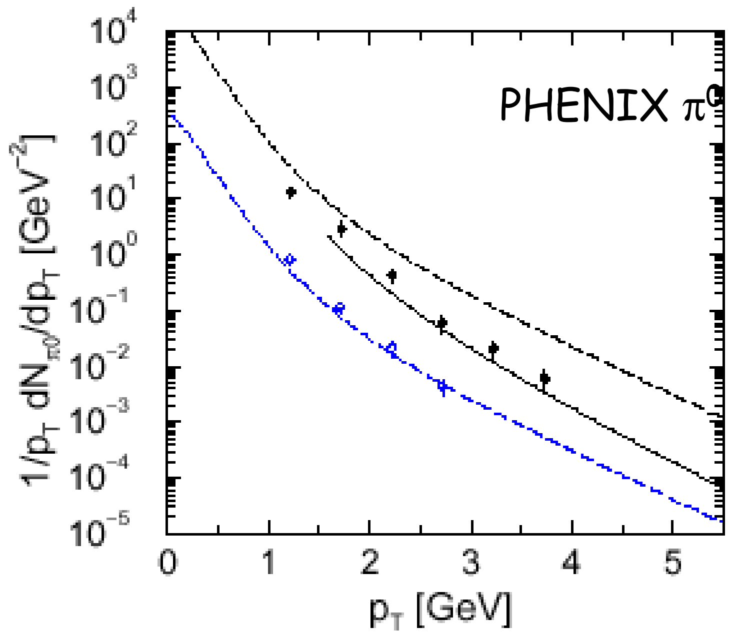


Fig. 3: Like Fig. 2, but now a comparison of the present calculations with the PHENIX data [3] on π_0.

Hadronization time =
time to build up the hadronic wavefunction

τ (light) ~ 1.2 (E/GeV) * fm/c

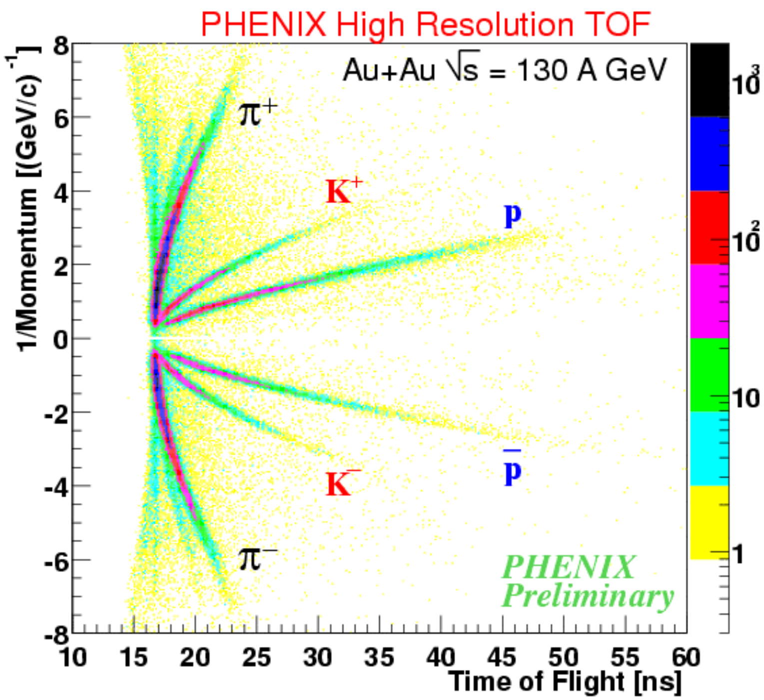
Nuclear systems are excellent laboratories for testing formation time issues. However, calculations seem to have factors of 2 floating around.

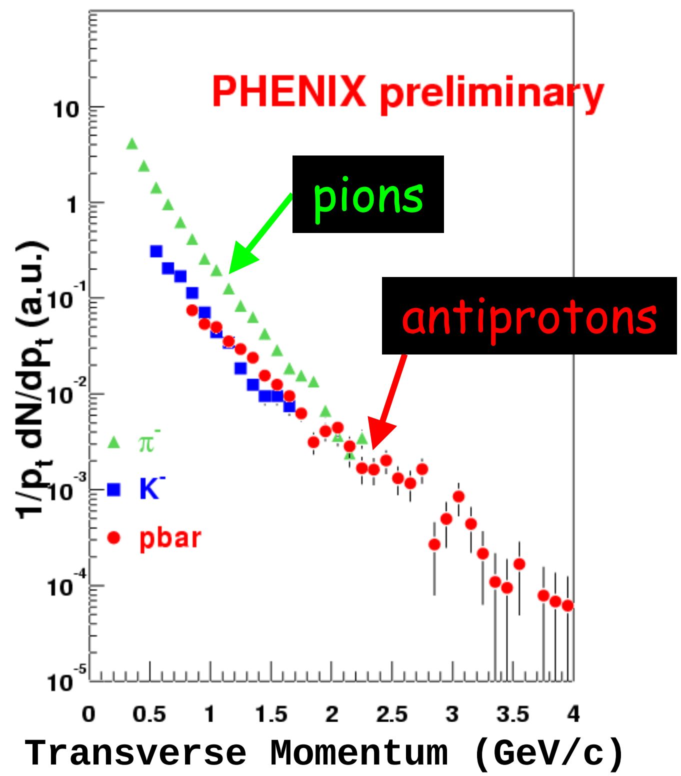
Gallmeister et al., nucl-th/0202051

Jet Fragmentation?

We identify other hadrons via their time-of-flight.

Pions are suppressed as seen before, but protons and antiprotons are not.



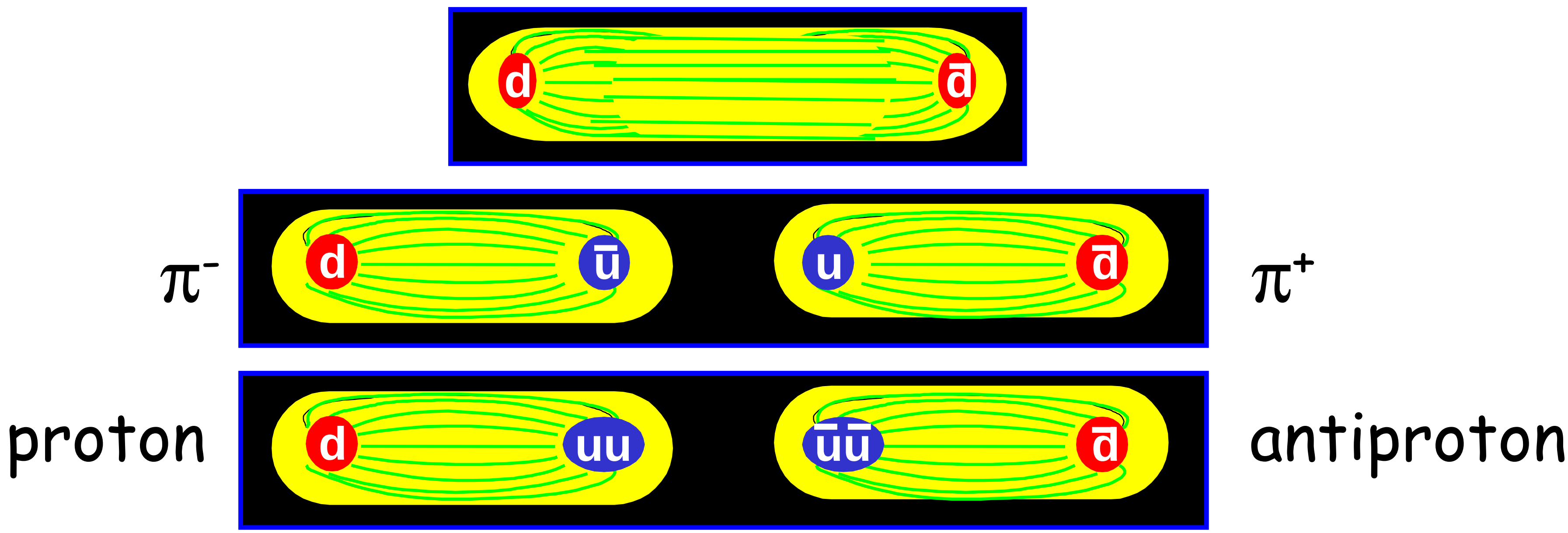


This is not the expected jet fragmentation function D(z).

Quantum Tunneling

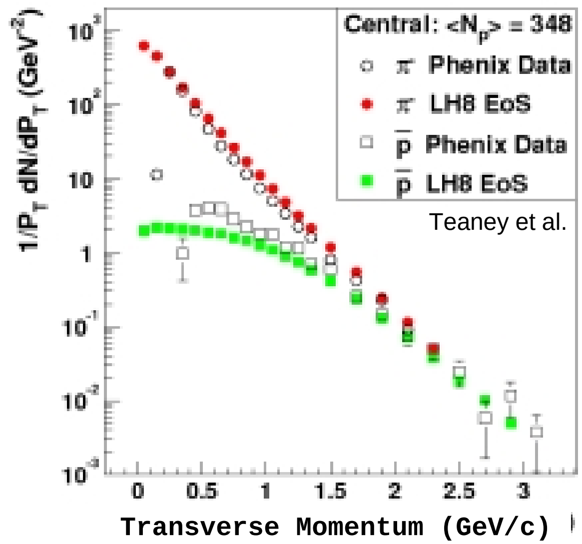
Jet fragmentation occurs when particle pairs tunnel out of the vacuum from the flux tube potential energy. Analogous to Schwinger mechanism in QED.

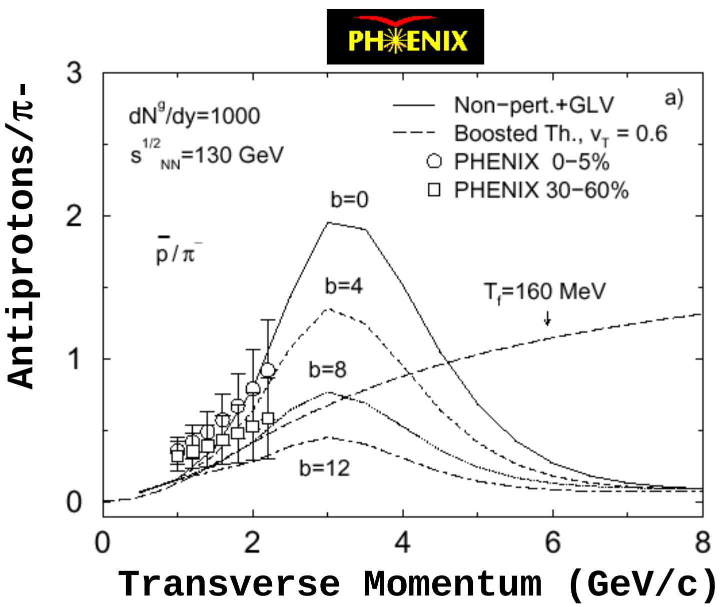
Production of $q\bar{q}$ leading to pions is much more likely than $qq\ \overline{qq}$ (diquark-antidiquark) leading to protons and antiprotons.



Hydrodynamics + Jets

Hydrodynamic expansion may boost "soft" physics into what was previously thought to be only "hard" physics p_T region.



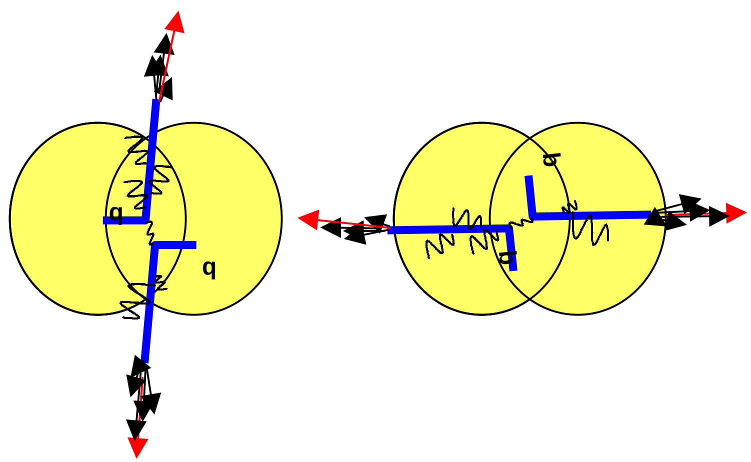


Vitev *et al.* predict that "hard" jet fragmentation eventually dominates over hydrodynamics for antiprotons above p_T~6 GeV

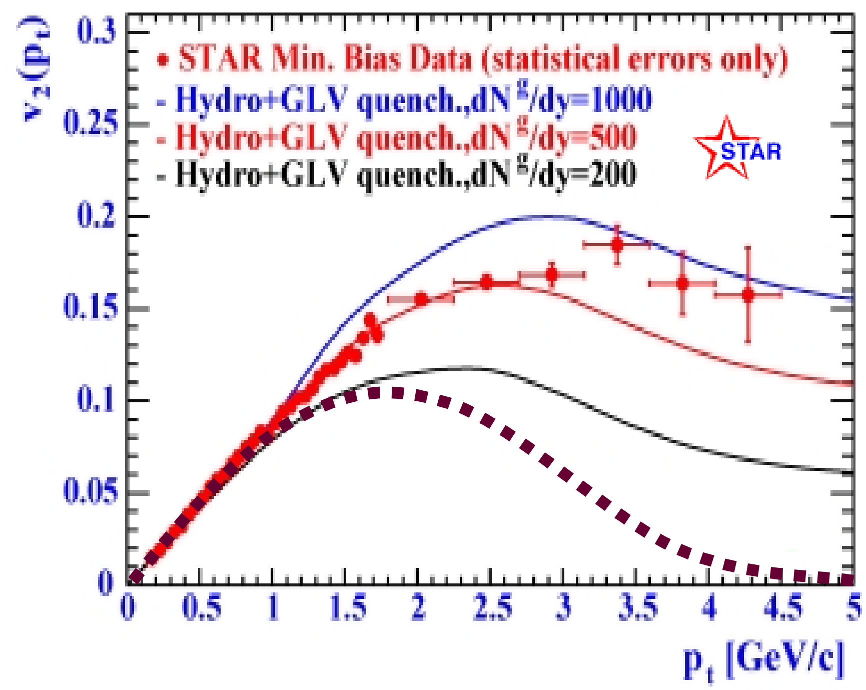
Back-to-Back Correlations

At p_T<1.5 GeV, hydrodynamic description is good. Above this, hard scattering may dominate which is uncorrelated with impact parameter plane, unless….

Parton energy loss could be correlated to reaction plane due to different average path lengths

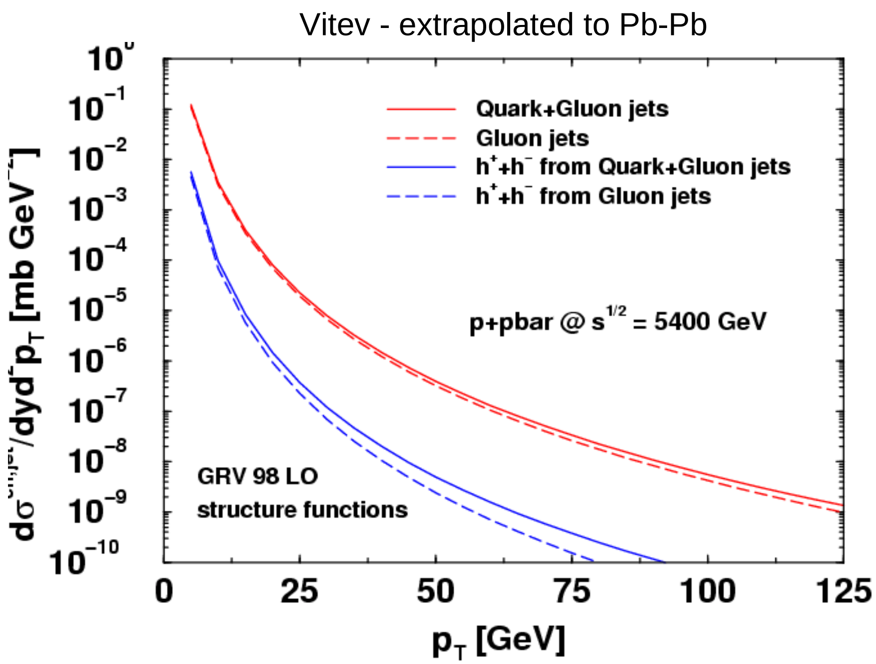


$$dN/dydp_T^2d\phi \propto 1 + 2v_2(p_T)\cos(2\phi)$$



LHC Jet Rates

At the LHC, jet rates are so high, and ATLAS and CMS have such broad coverage, new studies of jet modification in heavy ion collisions will be available. Also photon-jet and jet-jet studies are more accessible.



200 GeV jet overlay on
central Pb-Pb event
with ATLAS segmentation