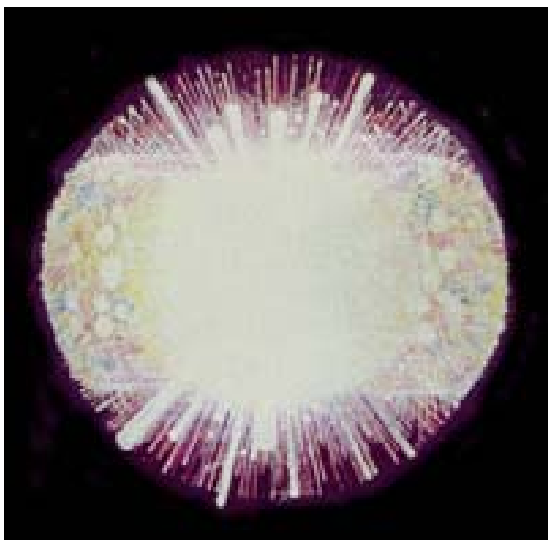
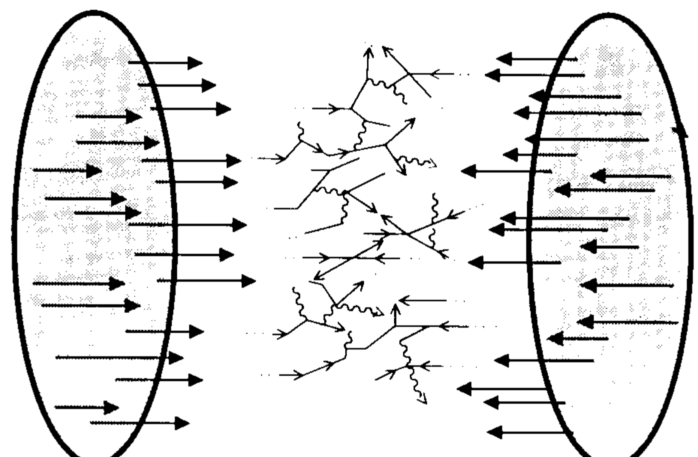
Quark-Gluon Plasma: Six Microseconds After the Big Bang and Today





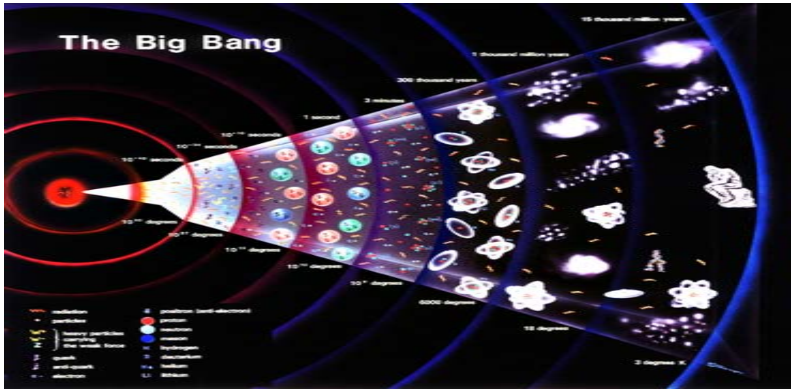
Jamie Nagle
University of Colorado at Boulder

University of New Mexico
Colloquium, September 26, 2003

Outline

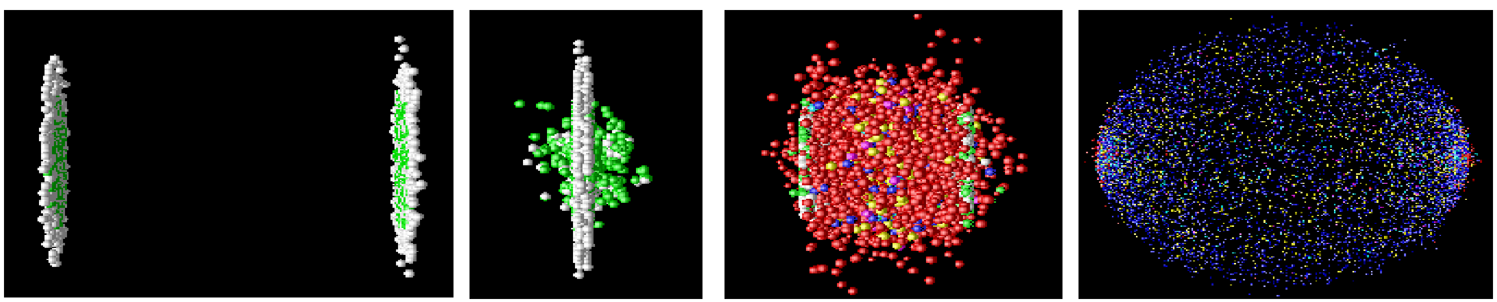
History of the Universe

Early Phase Transitions



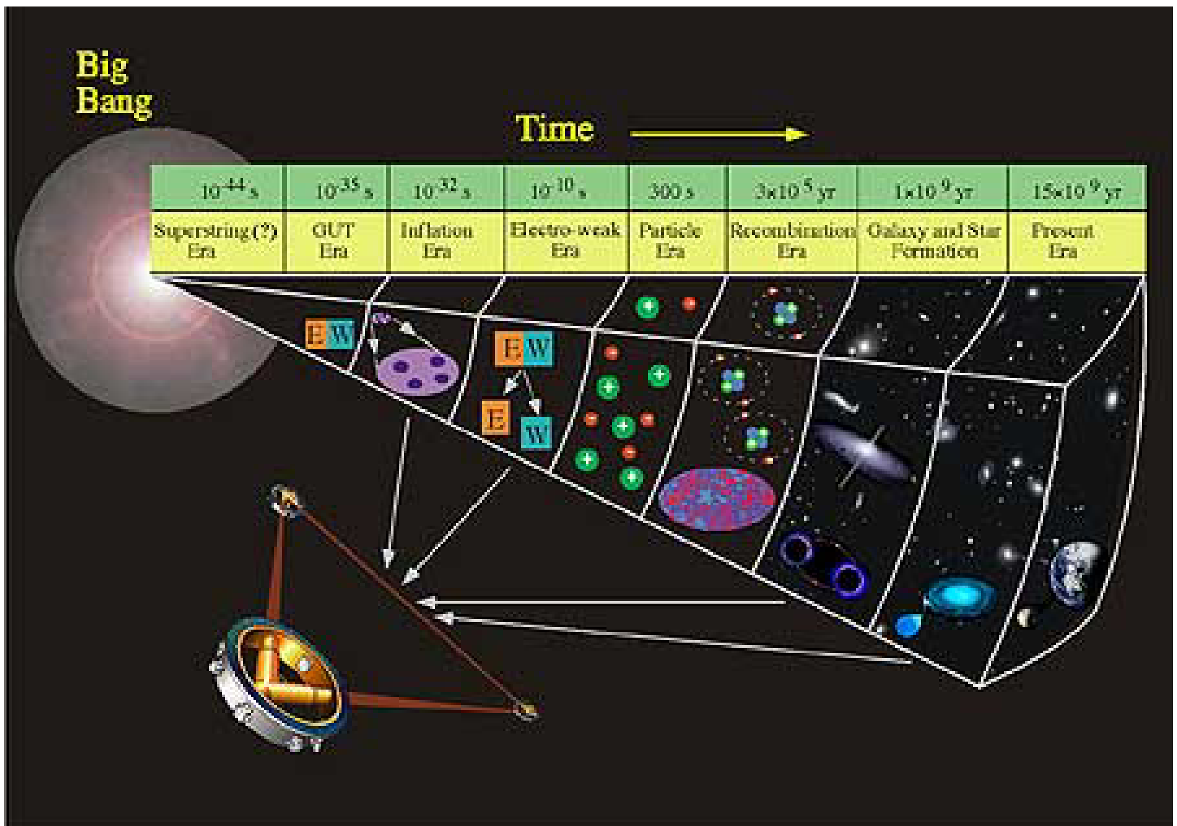
Quark Gluon Plasma

Relativistic Heavy Ion Collisions



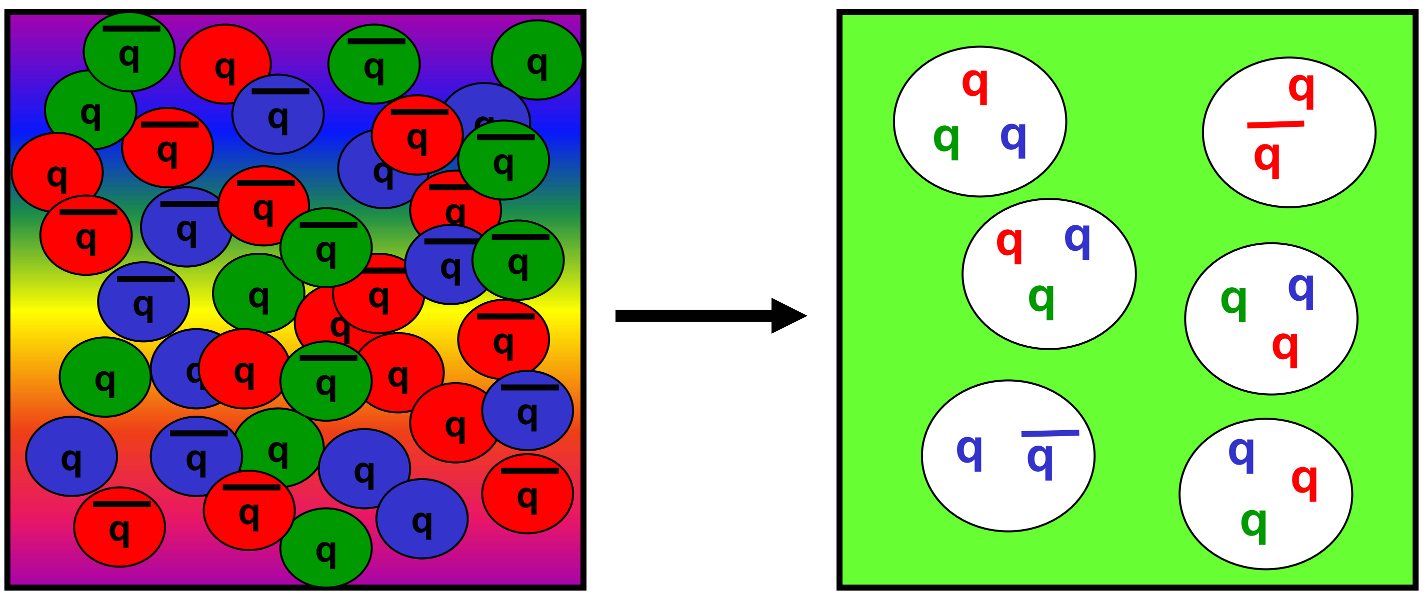
Transitions of the Early Universe

- Post Inflation, radiation yields quark-gluon plasma.
- Six microseconds after the Big Bang, all quarks and gluons are confined into hadrons.
- One second later, light nuclei are formed.
- 300,000 years later, atoms are formed.



Quark Gluon Plasma

Nuclear physicists are particularly interested in the transition from a bath of free quark and gluons (Quark-Gluon Plasma) to bound systems of hadrons (for example protons and neutrons).



“Rich Cosmological Scenario”

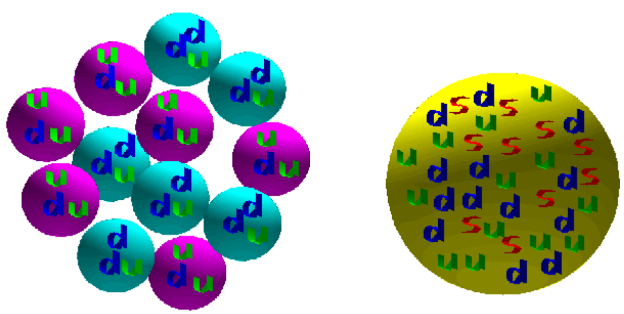
“A first-order QCD phase transition that occured in the early universe would lead to a surprisingly rich cosmological scenario.”

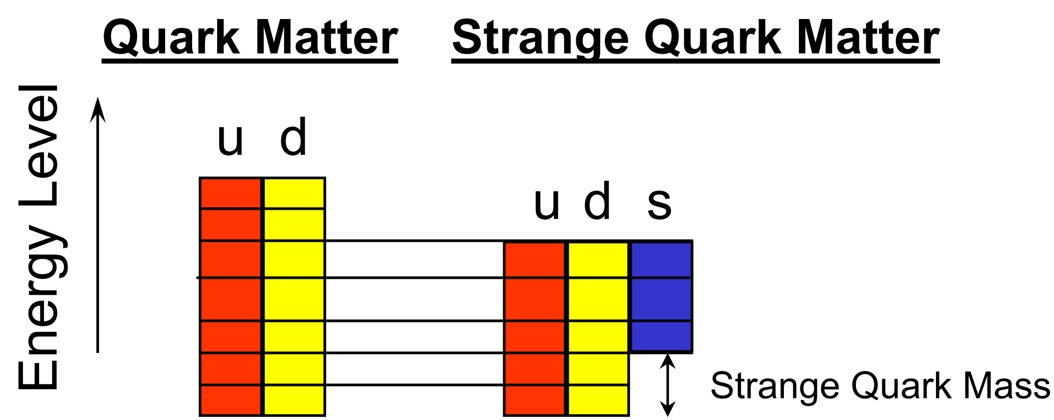
“Although observable consequences would not necessarily survive, it is at least conceivable that the phase transition would concentrate most of the quark excess in dense, invisible quark nuggets.”

Ed Witten
Phys. Rev. D (1984)
Over 1000 citations

Strange Quark Matter

- Bubbles of supercooled quark-gluon plasma could have formed strange quark matter. A >> 1000.
- Strange Quark Matter could be more stable that Fe^{55} and thus be the ground state of nulcear matter.
- If stable, it could be a source of baryonic dark matter.

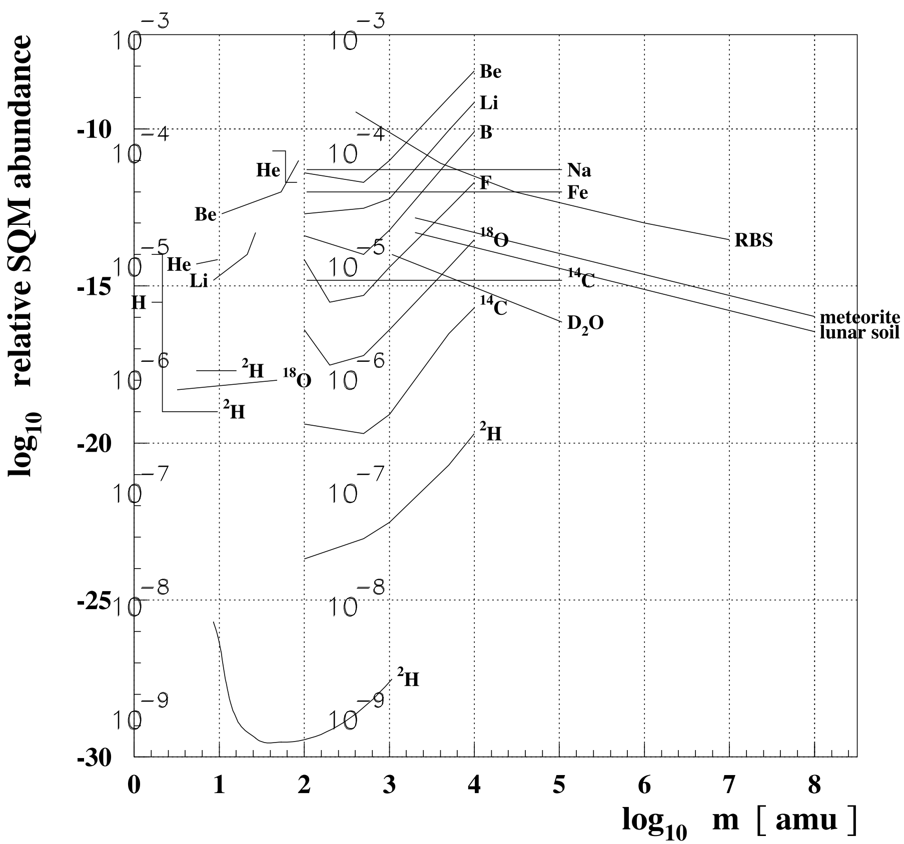


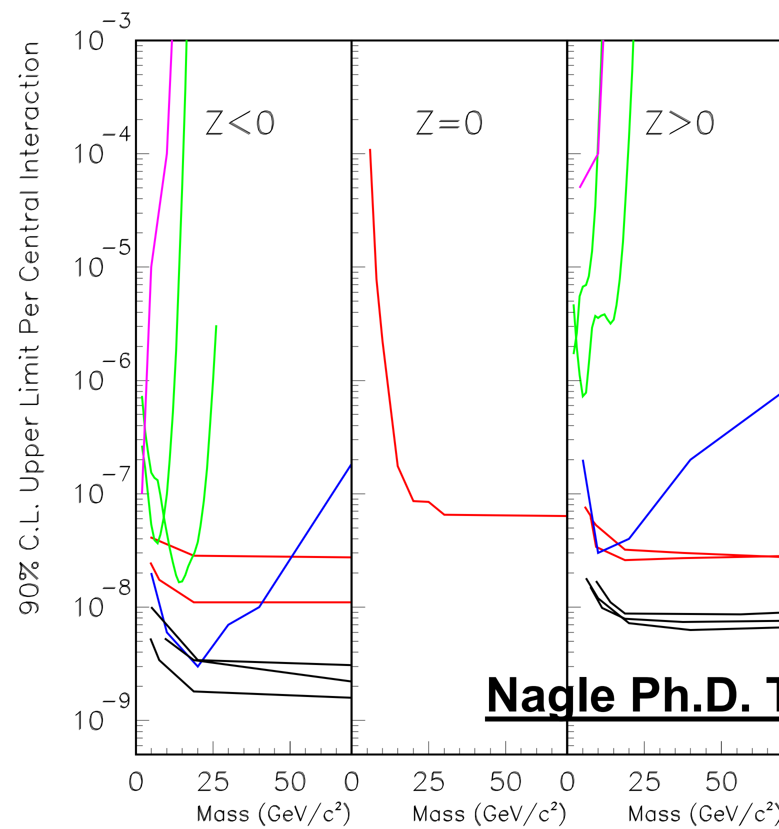


SQM Not Yet Observed

Twenty years later, SQM still theoretically allowed.

Experiments searches in terrestrial matter and nuclear reactions for small A< 100 SQM have yielded null results.





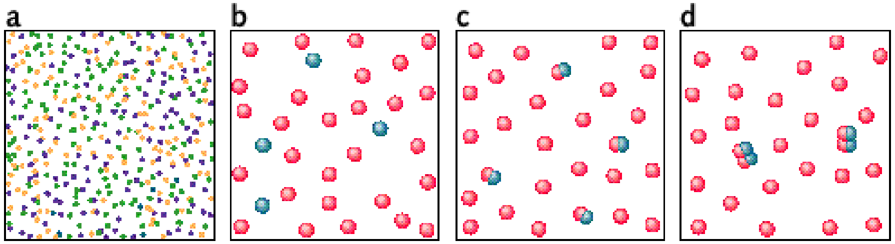
Nagle Ph.D. Thesis

Supercooling and Bubbles

If the plasma-to-hadrons transition were strongly first order, bubble formation could lead to an inhomogeneous early universe, thus impacting big bang nucleosynthesis (BBN).

Are the bubbles too small and close together such that diffusion before nucleosynthesis erases the inhomogeneities? (200 MeV to 2 MeV)

This line of investigation was quite active when the dark matter issue raised questions about the implied baryon content in the universe from BBN.

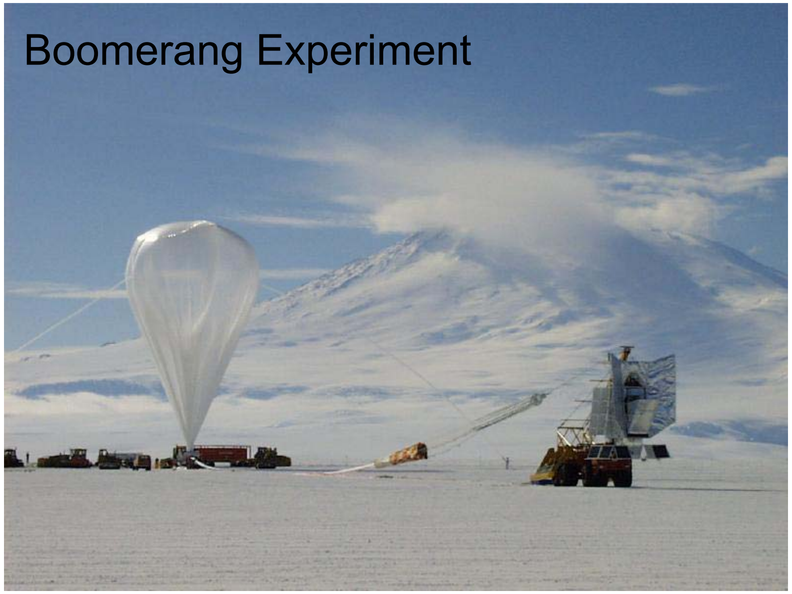


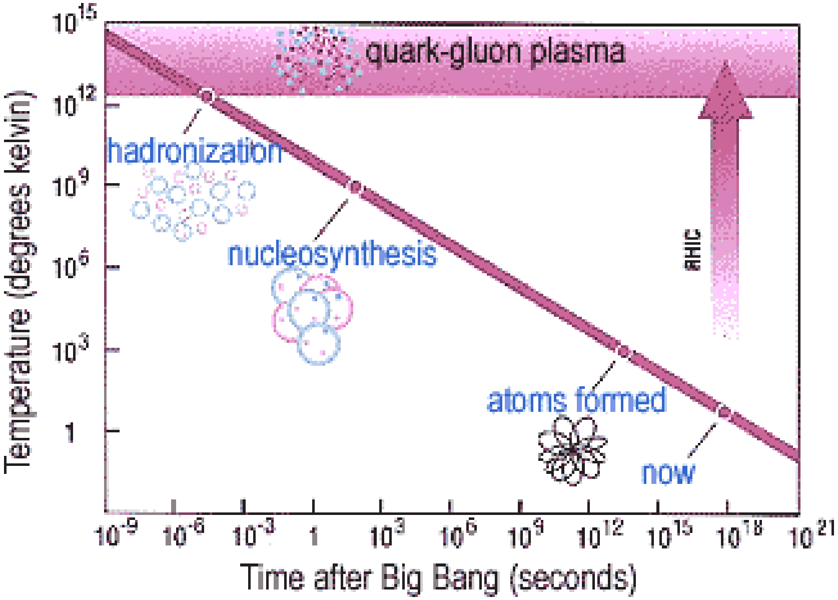
Microwave Background

Physics Today, July 2001: Cosmic Microwave Background Observations

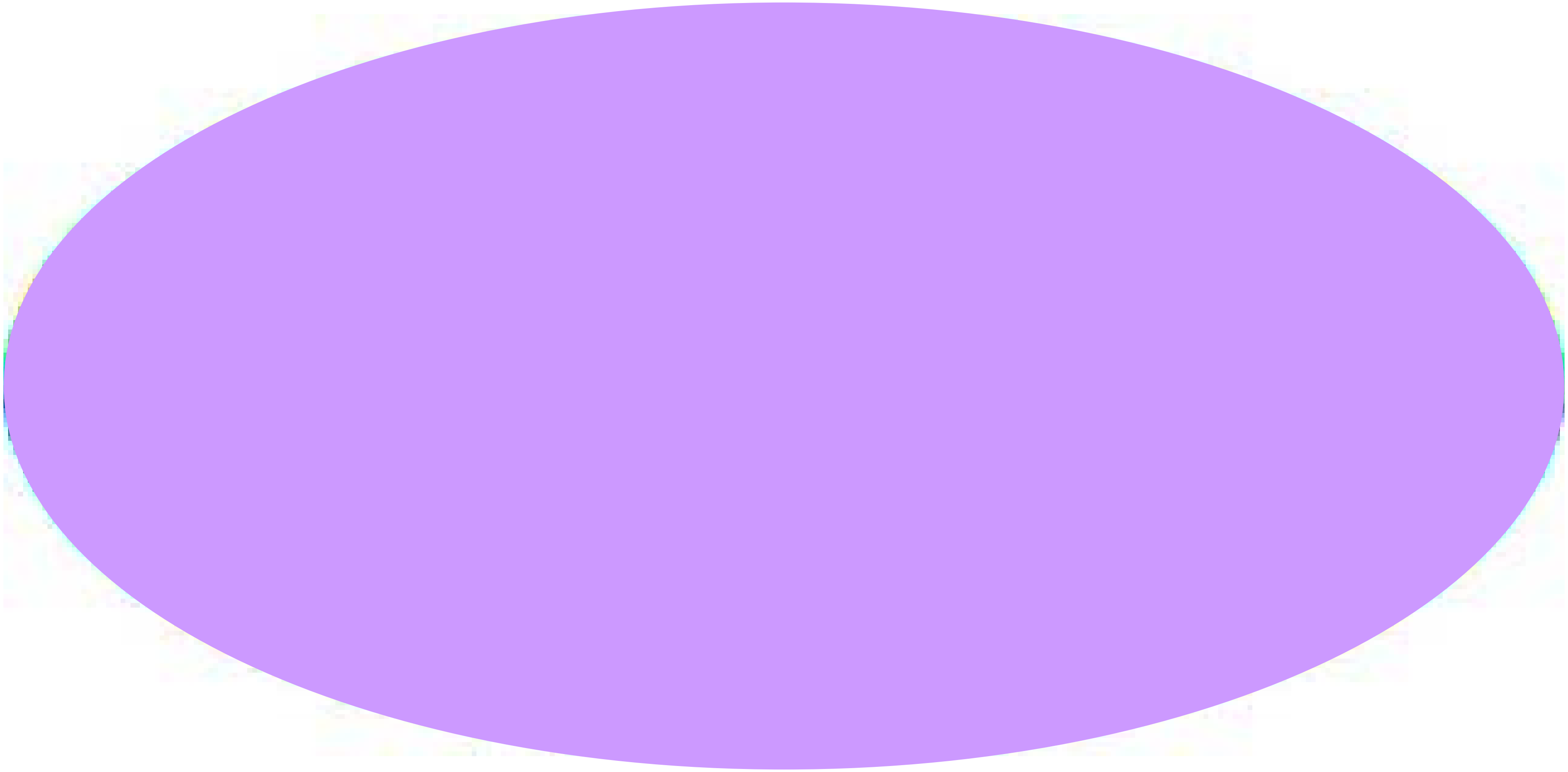
"The value deduced from the second harmonic in the acoustic oscillations for Ω_B=0.042 ± 0.008 (cosmic baryon mass density) is in very good agreement with the value one gets by applying the theoretical details of primordial big bang nucleosynthesis to the observations of cosmic abundances of deuterium."

However, this confirmation of BBN does not rule out a first order phase transition in QCD because of the diffusion issue.





Universe at 300,000 Years Old



WMAP Results
Age of the Universe = 13.8 billion years
Isotropic (1:100,000)
Total Energy = 0 (Universe is flat!)

Quantum Chromodynamics (QCD)

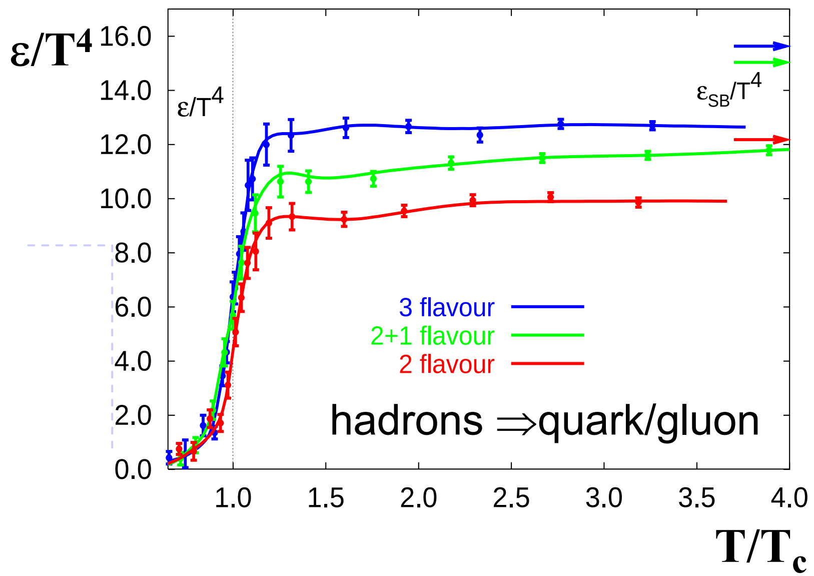
Lattice QCD calculations predict a phase transition to a Quark-Gluon Plasma at high temperature where the number of degrees of freedom is significantly increased.

Phase Transition:

T = 150-200 MeV ~ 10^{12} ^{0}F

ε ~ 0.6-1.8 GeV/fm^3

Assumes thermal system.



Only early universe transition with a temperature achievable in the lab.

(F. Karsch, hep-lat/0106019)

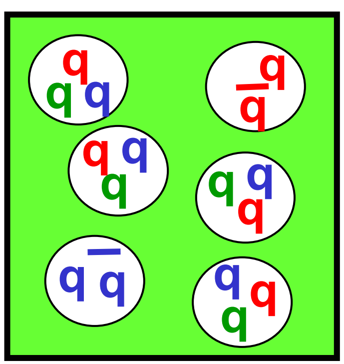
Deconfinement

QCD in Vacuum

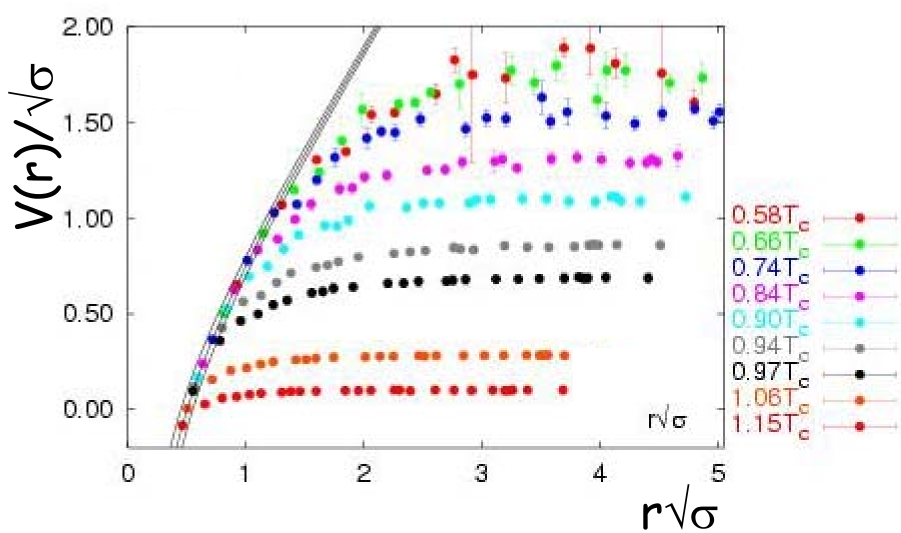
- linear increase with distance from color charge
- strong attractive force
- **confinement of quarks** to hadrons baryons (qqq) and mesons ($q\bar{q}$)

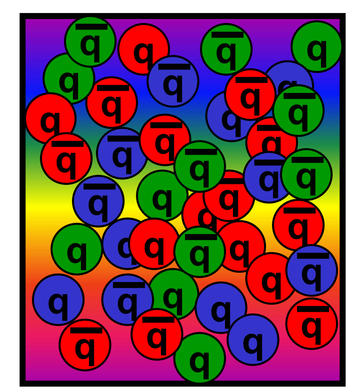
QCD in dense and hot matter

- screening of color charges
- potential vanishes for large distance scales
- restoration of approximate chiral symmetry
- **deconfinement of quarks and gluons !**



Lattice QCD calculation

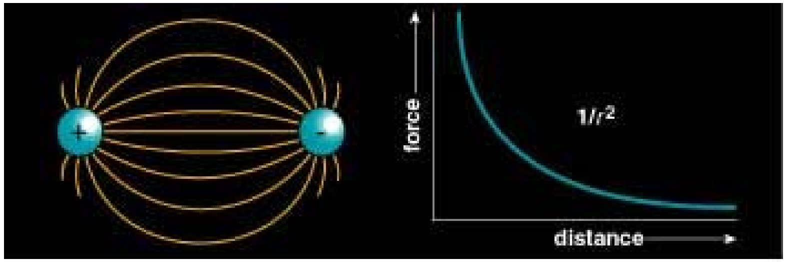


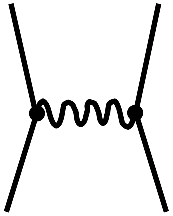


Quantum Chromodynamics

Quantum Electrodynamics (QED)

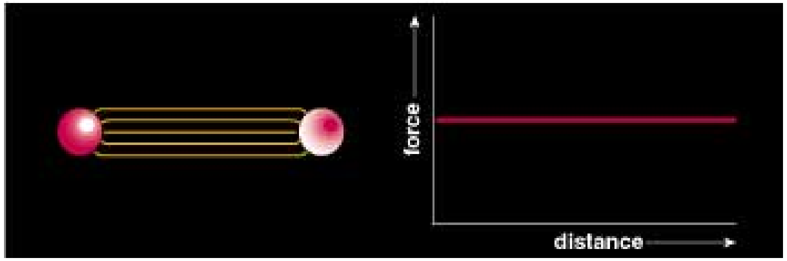
Field theory for electromagnetic interactions
Exchange particles (photons) do not have electric charge
Flux is not confined - U(r) α 1/r and F(r) a $1/r^2$

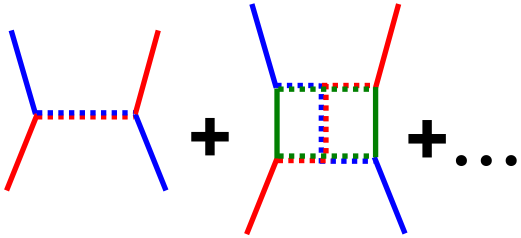




Quantum Chromodynamics (QCD)

Field theory for strong (nuclear) interactions
Exchange particles (gluons) do have "color" charge
Flux is confined - U(r) α r and F(r) = constant

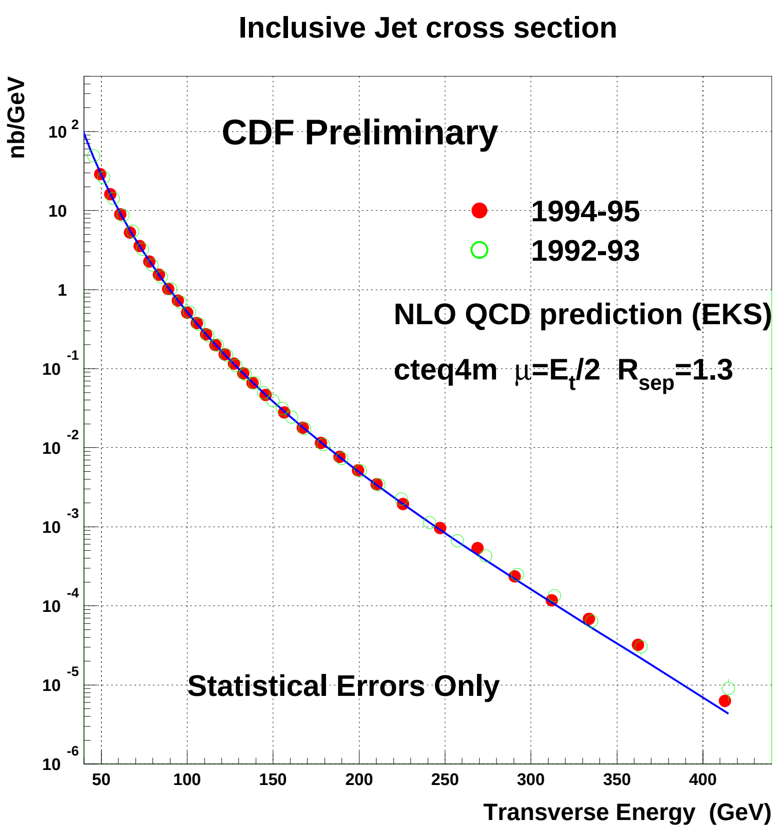




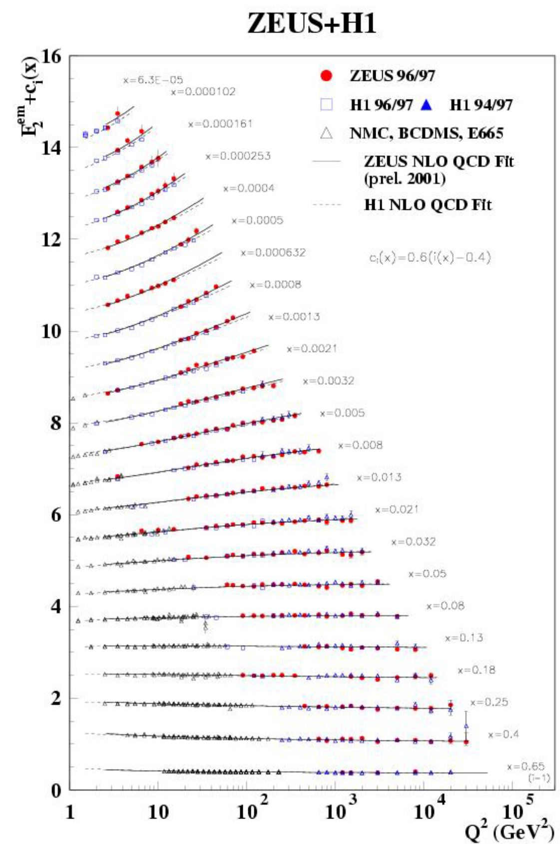
Quantum Chromodyanmics

Most of us believe that QCD is the correct theory of strong interactions. Why do we believe this?

High Energy Jet Observations



Deep Inelastic Scattering Observations



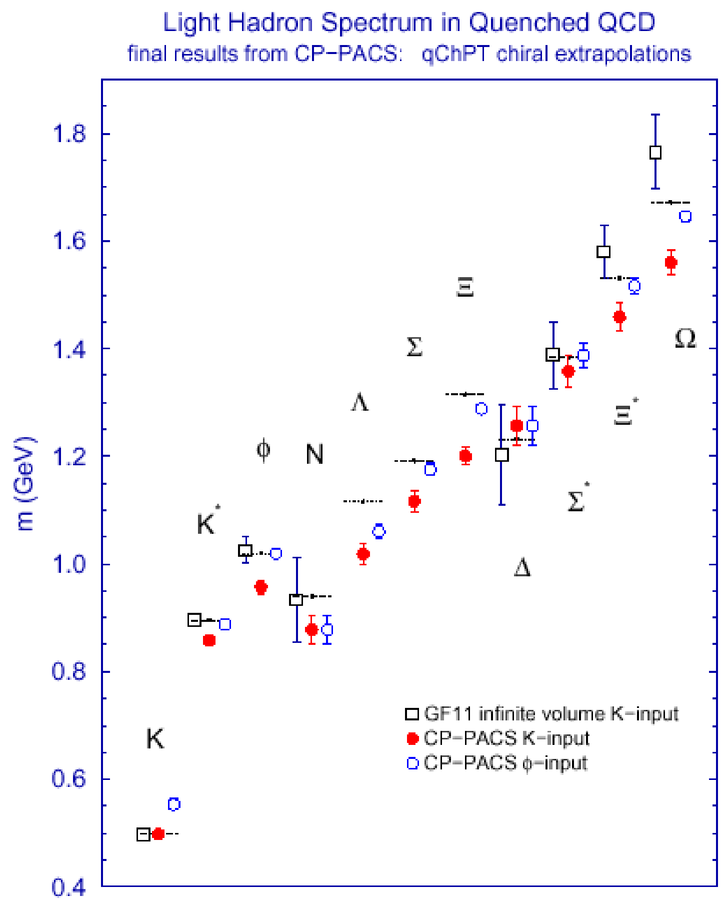
Quantum Chromodynamics II

The previous examples were Next-to-Leading-Order (NLO) perturbative calculations that are applicable at large Q^2.

What about the non perturbative world around us?

Using lattice QCD we can calculate the various hadron masses.

Agreement at 10% level, excluding π^0.

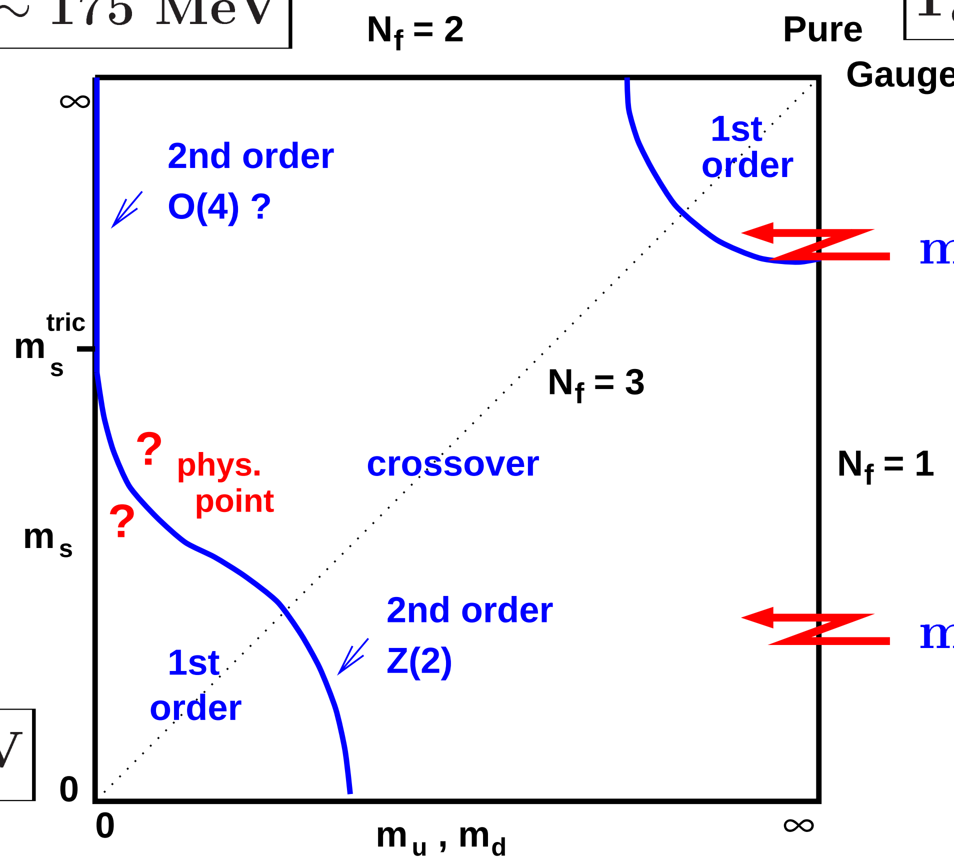


What Order?

3-flavour phase diagram

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

$T_d \sim 270$ MeV

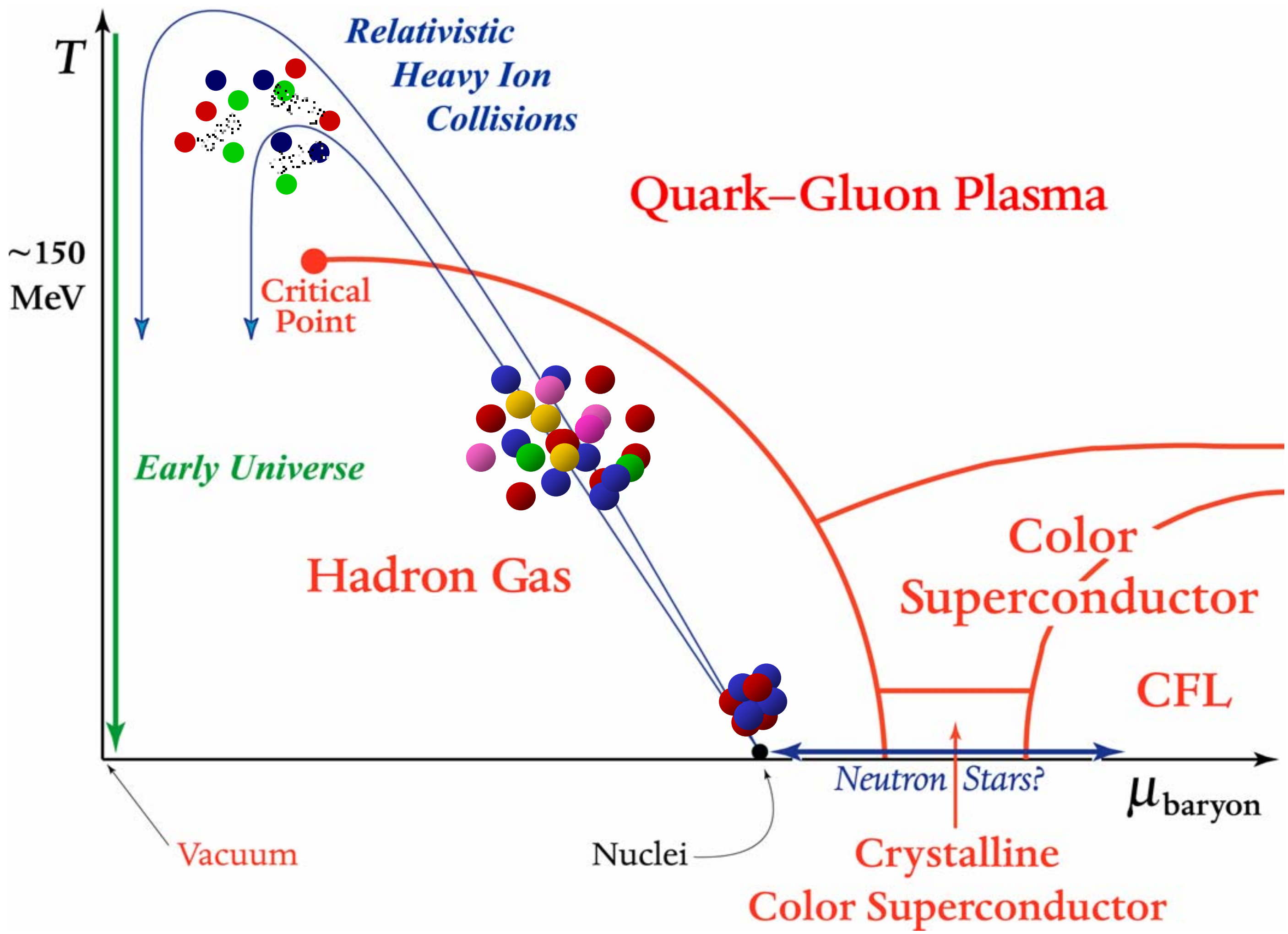


$m_{PS}^{crit} \simeq 2.5$ GeV

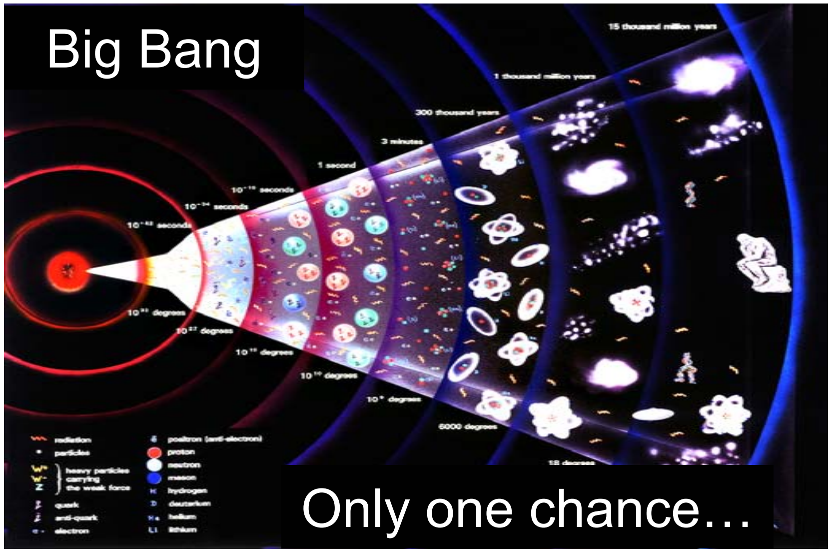
$m_{PS}^{crit} \simeq 300$ MeV

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

Phase Diagram



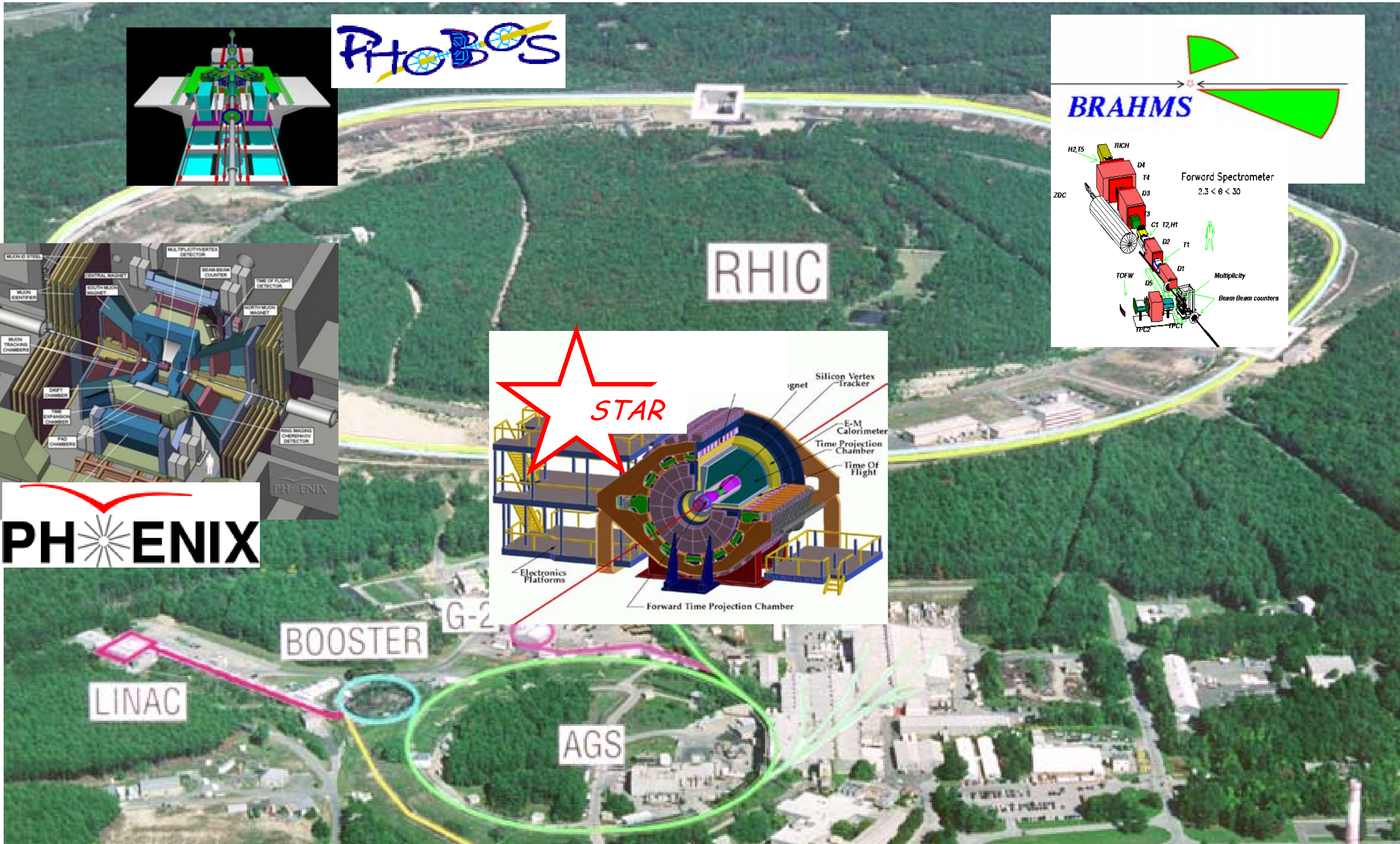
Where to Study Extreme QCD?



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



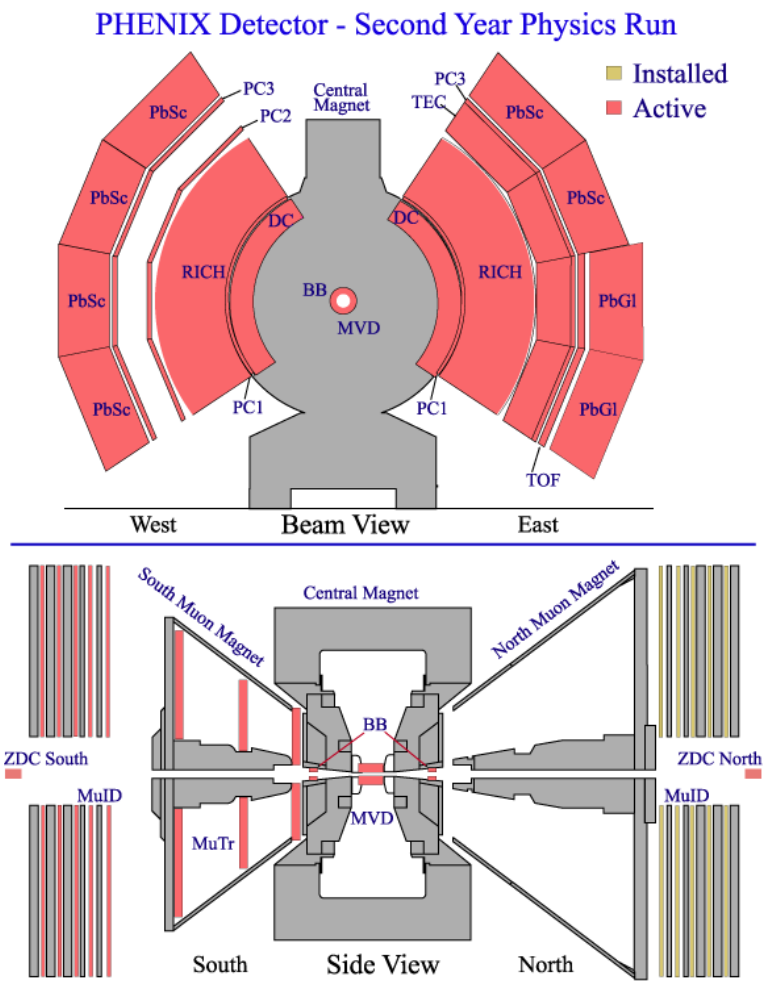
PHENIX

Pioneering High Energy Nuclear Ion eXperiment

Designed to measure electrons, muons, photons and hadrons.

Complex set of four separate particle spectrometers.

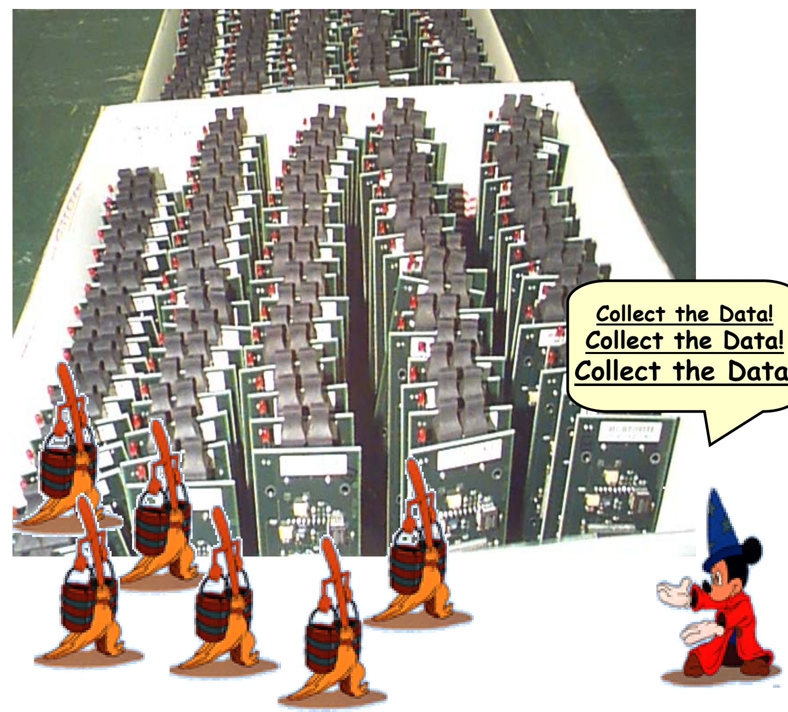
This requires many different types of detector technologies and an integrated electronics readout.



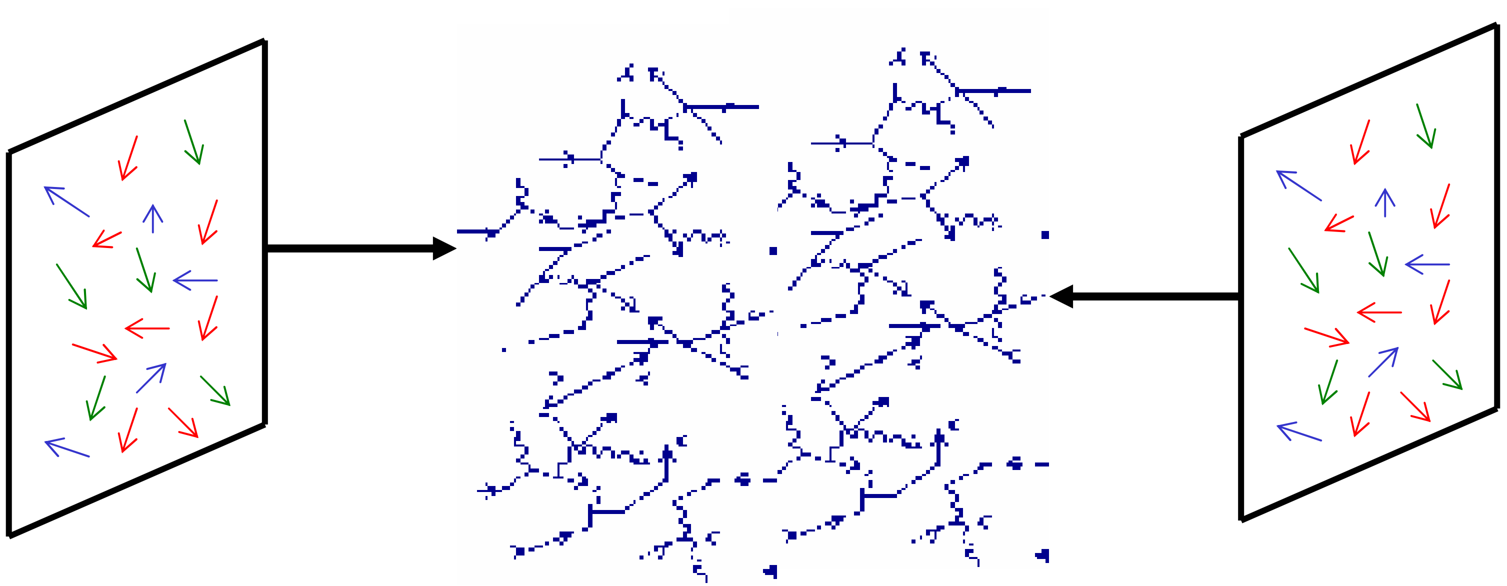
Scale of the Problem

Uncovering nature's secrets is not easy.

- over 500 people, over 10 countries
- tons of steel, specialized detectors
- thousands of custom electronic chips and boards
- transmitting over 5 Gigabytes per second

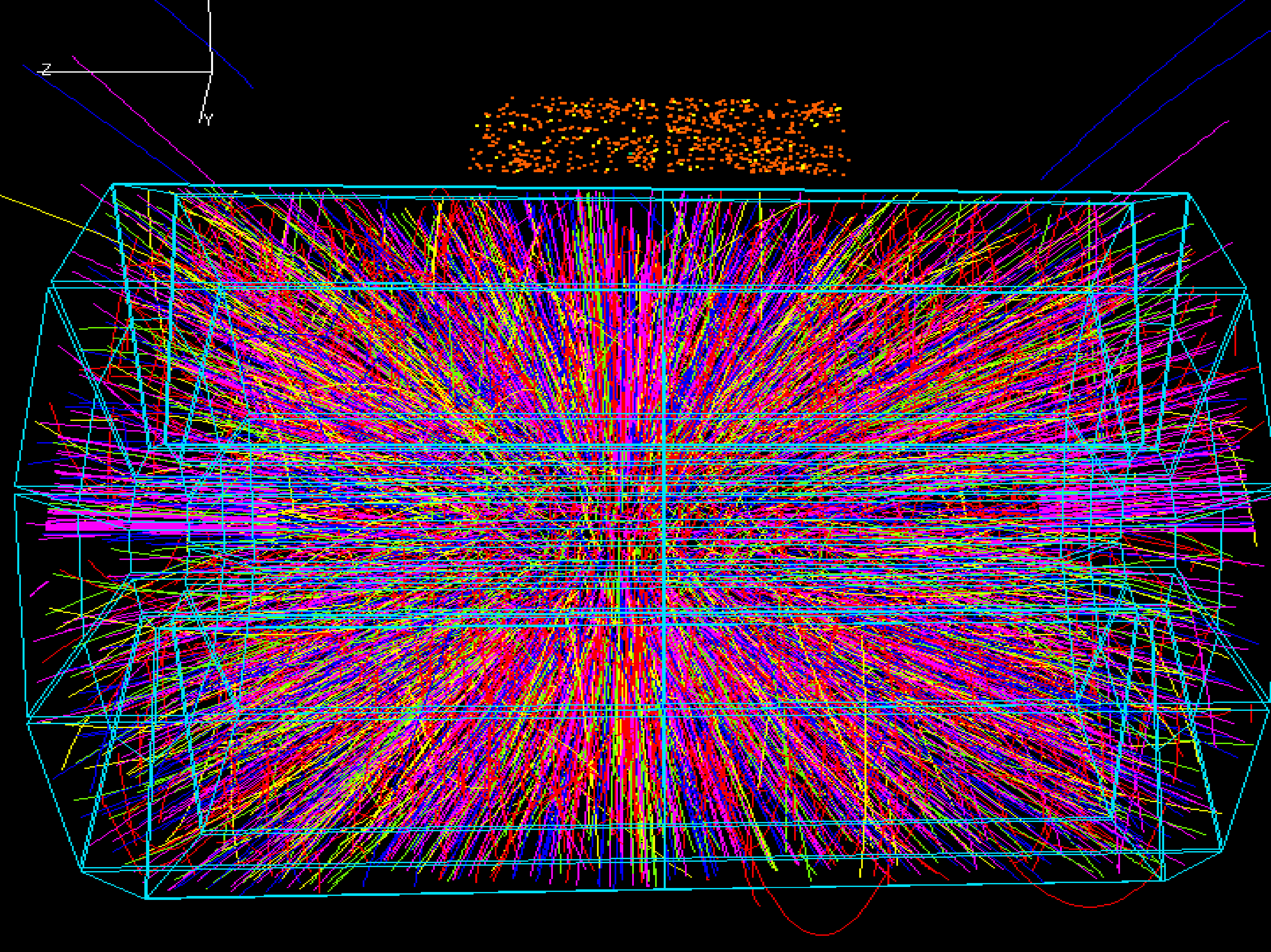


Complex System



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?


Z
Y

Creating Black Holes ? !

Can be dismissed with some basic General Relativity

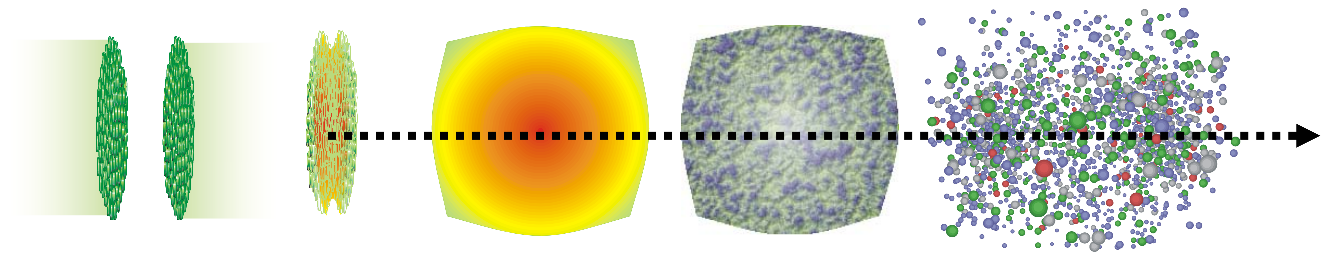
$$R_S = {2GM}/{c^2} = 10^{-49}\ meters$$

much less than Planck length !

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

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

How to Study QCD in this Environment?

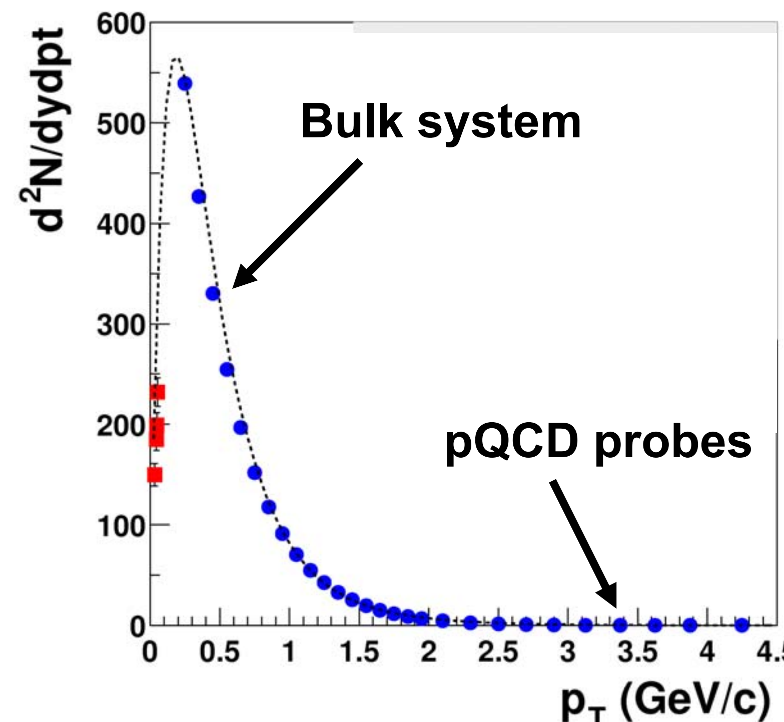


Bulk Effects (QGP)

- 10,000 Gluons Freed
- Equilibration
- Equation of State

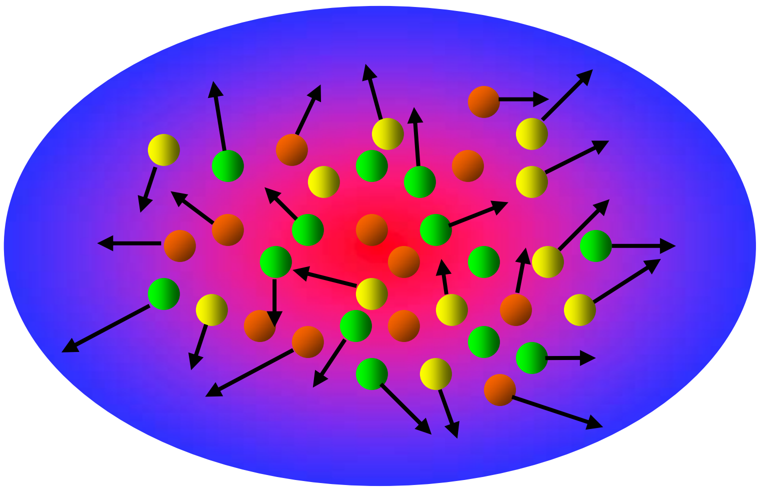
Probes of the System

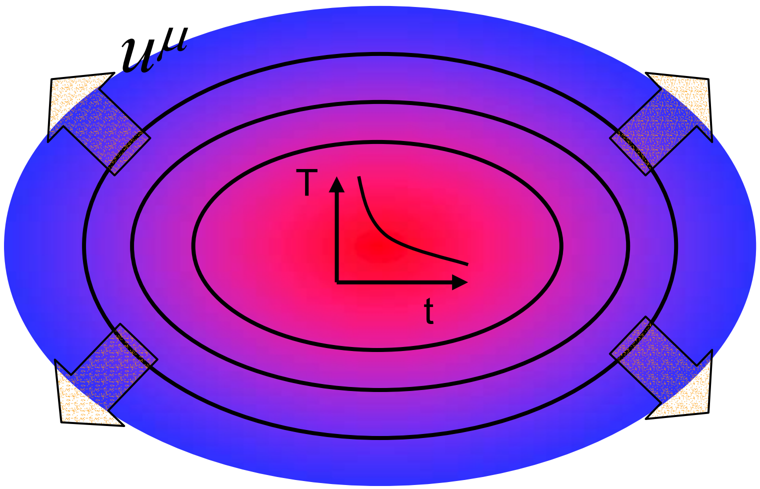
- Hard scattered quarks
- Heavy quarkonia



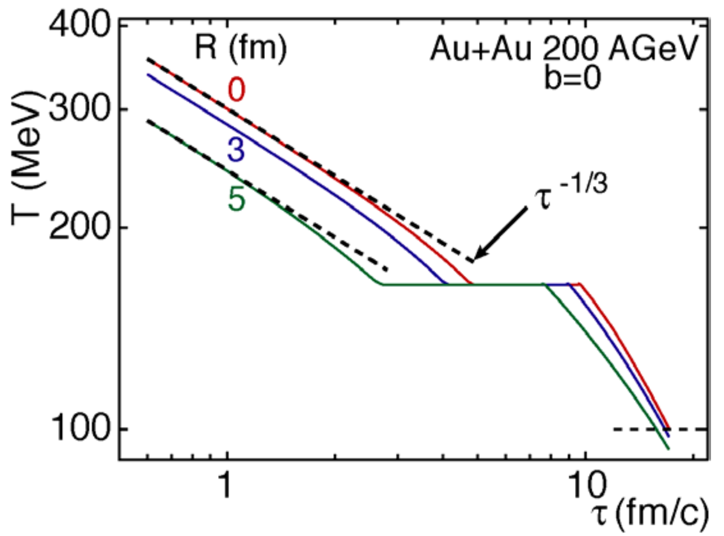
PHOBOS Experiment

Hydrodynamics





Hadronic re-scattering is insufficient to describe the data. Implies strong partonic re-scattering and high initial density

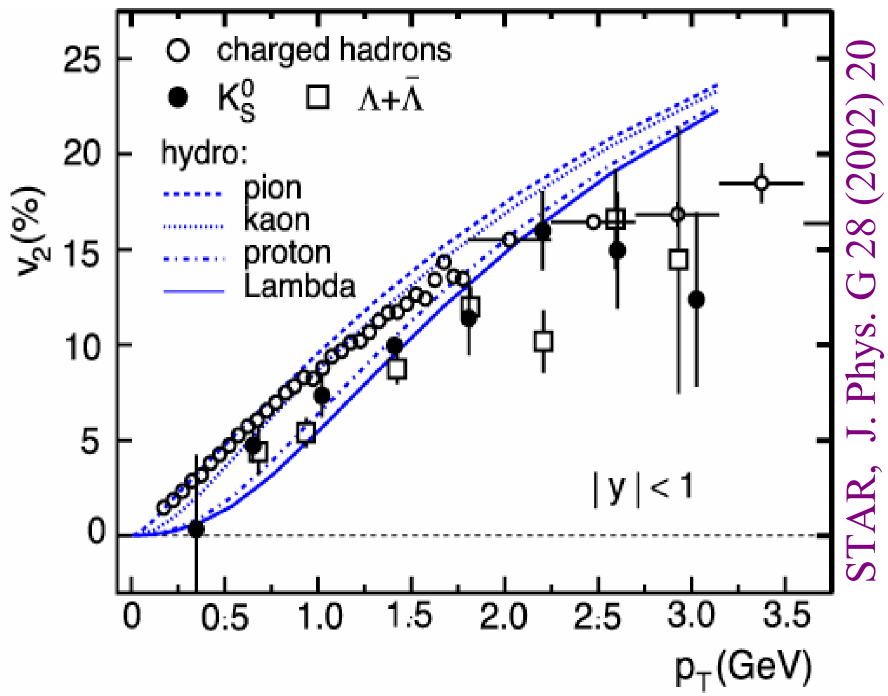


ε = 20 GeV/fm^3 and τ = 0.6 fm/c

Calculation by P. Kolb

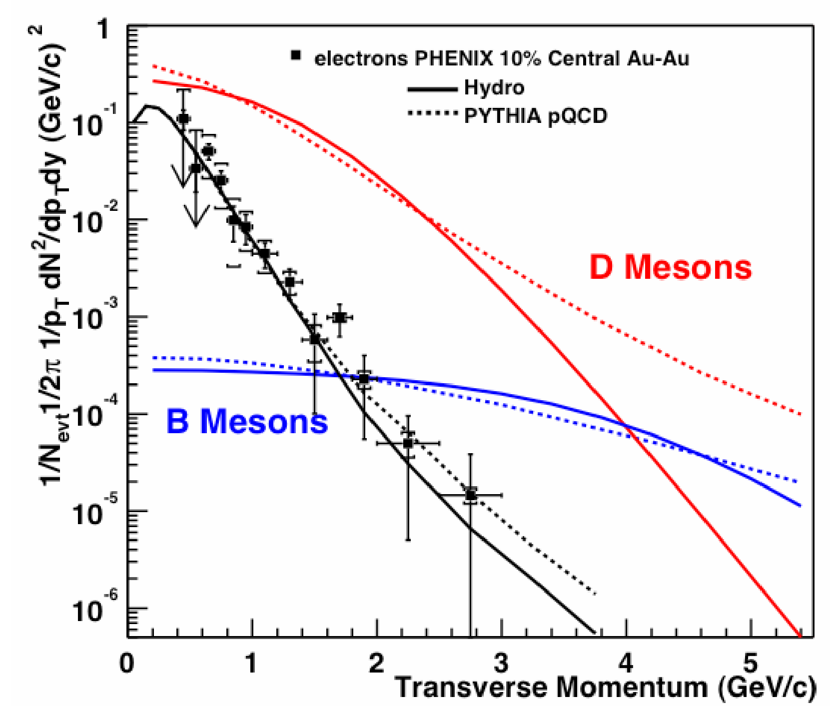
Good Data Agreement

Over 99 % of the emitted particles follow hydrodynamics systematics



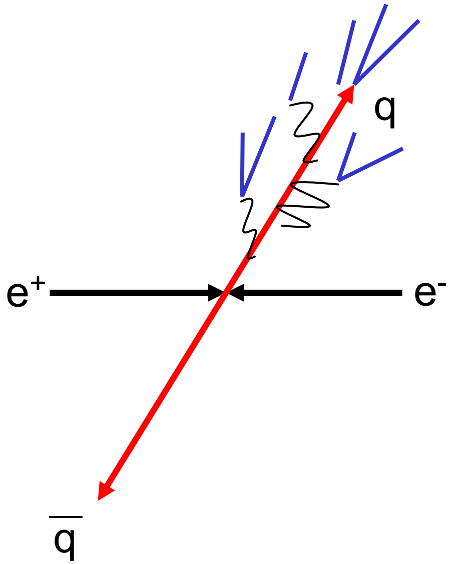
Peter Kolb and collaborators

Perhaps even charm quarks follow hydrodynamics?



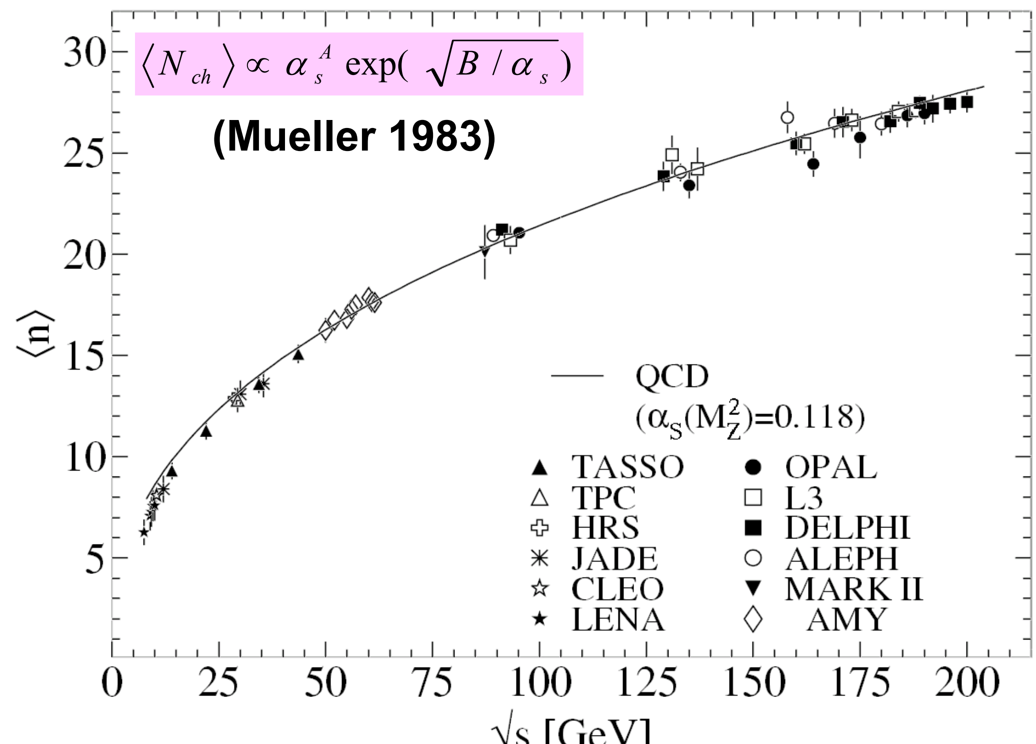
PLB 2002, Batsouli, Kelly, Gyulassy, Nagle

Quark Probes of the Plasma



Quark radiates gluons and eventually forms hadrons in a jet cone.

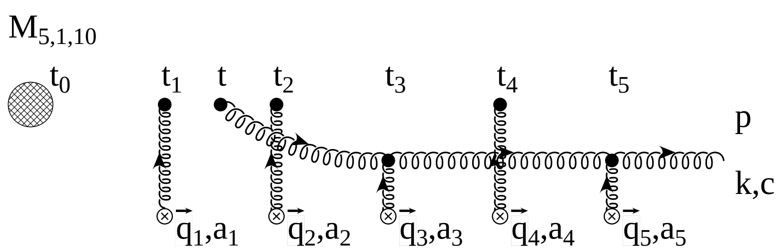
QCD calculation of gluon multiplicity times a hadron scale factor gives excellent agreement with data.



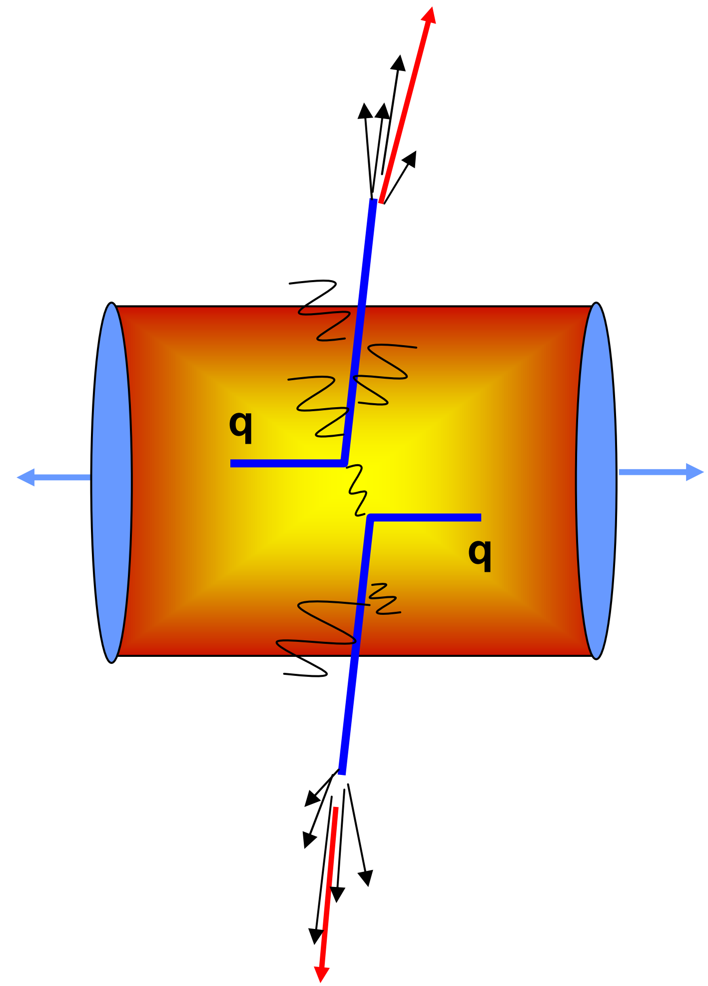
Induced Gluon Radiation

Partons are expected to lose additional energy via induced gluon radiation in traversing a dense partonic medium.

Coherence among these radiated gluons leads to ΔE a L^2

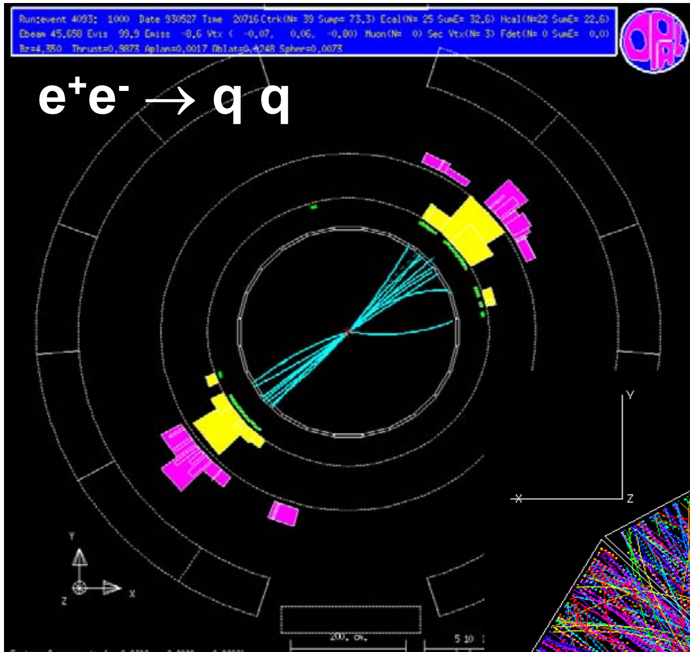


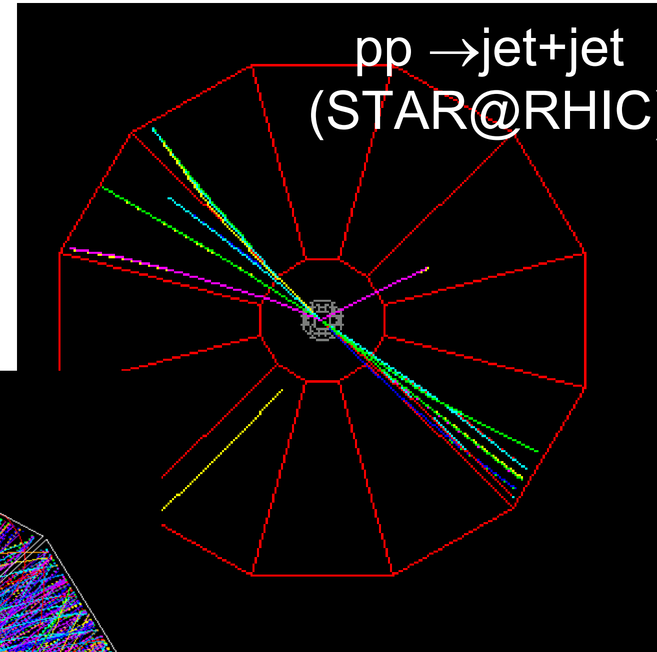
Look for an increase in multiplicity and a suppression of high z (momentum fraction) hadrons from jet fragmentation.

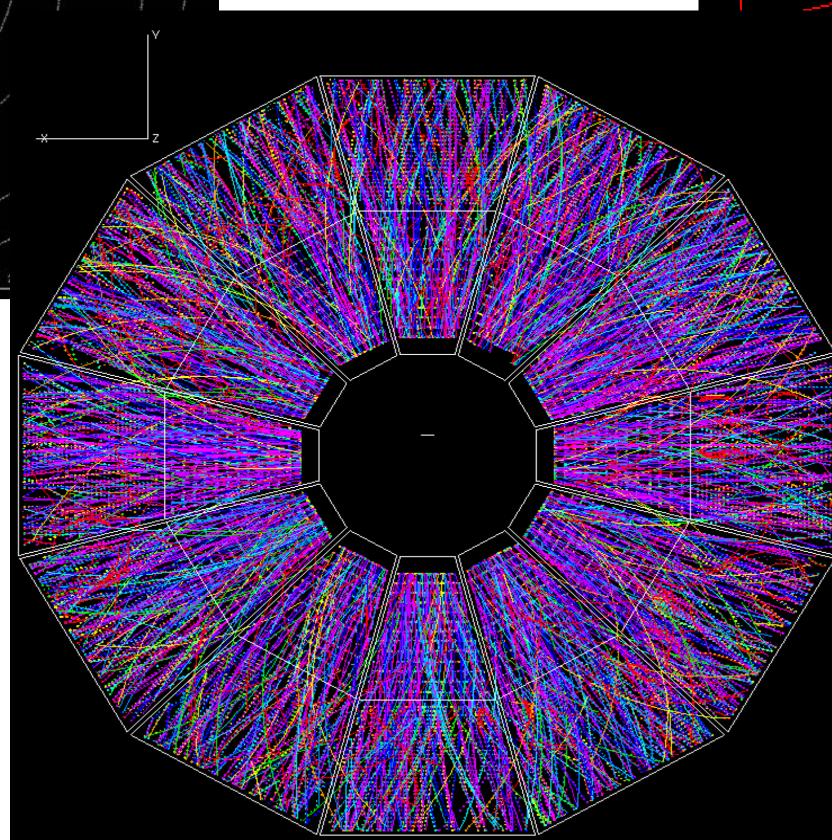


Baier, Dokshitzer, Mueller, Schiff, hep-ph/9907267
Gyulassy, Levai, Vitev, hep-pl/9907461
Wang, nucl-th/9812021
and many more…..

What about in Hot Nuclear Matter?



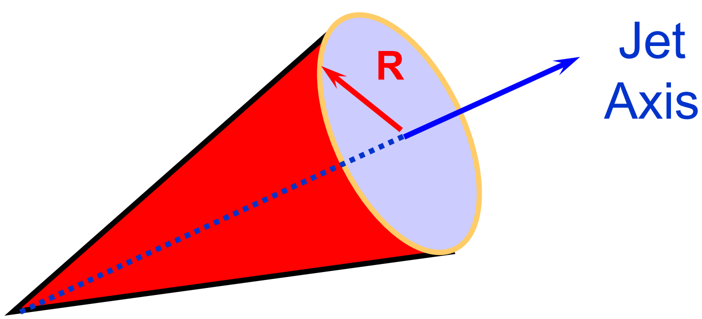


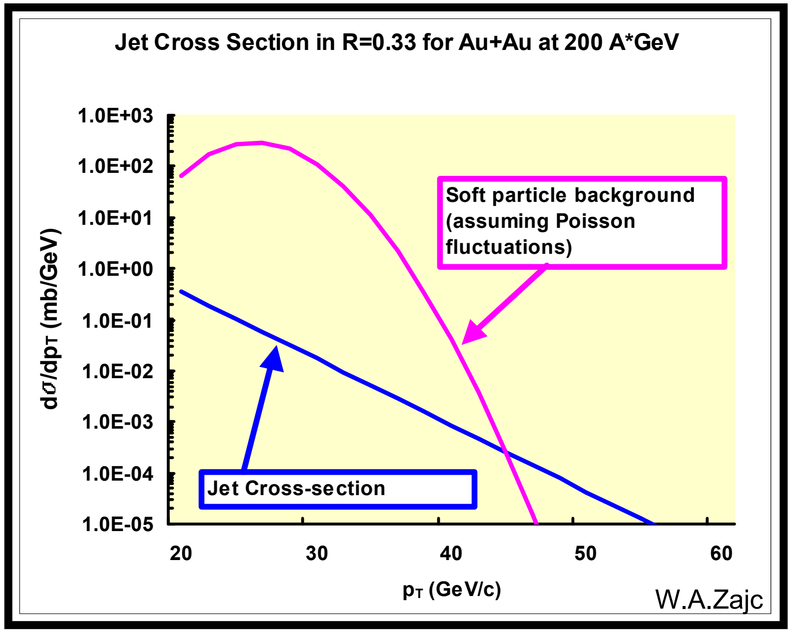


Jets and Underlying Event

“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 p_T < ~ 40 GeV

Note that Jet measurements in proton-antiproton reactions at Fermilab Tevatron below 50 GeV are still very challenging.

Factorization to Final Hadrons

In hadron-hadron, we can calculate the yield of high p_T hadrons

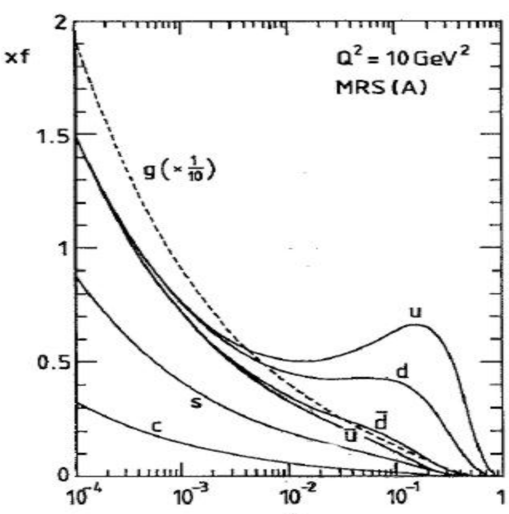
$$E_h \frac{d\sigma_h^{pp}}{d^3p} = K \sum_{abcd} \int dz_c\, dx_a\, dx_b \int d^2\mathbf{k}_{Ta} d^2\mathbf{k}_{Tb} f(\mathbf{k}_{Ta}) f(\mathbf{k}_{Tb}) f_{a/p}(x_a, Q_a^2) f_{b/p}(x_b, Q_b^2)\, D_{h/c}(z_c, Q_c^2) \frac{\hat{s}}{\pi z_c^2} \frac{d\sigma^{(ab\to cd)}}{d\hat{t}} \delta(\hat{s}+\hat{u}+\hat{t})$$

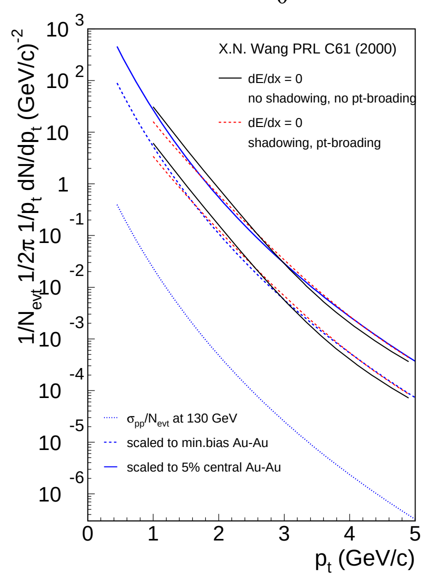
Flux of incoming partons (structure functions) from Deep Inelastic Scattering

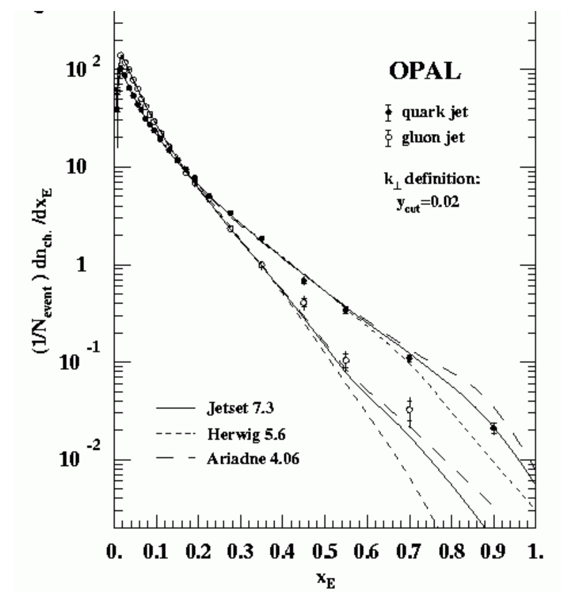
Perturbative QCD

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

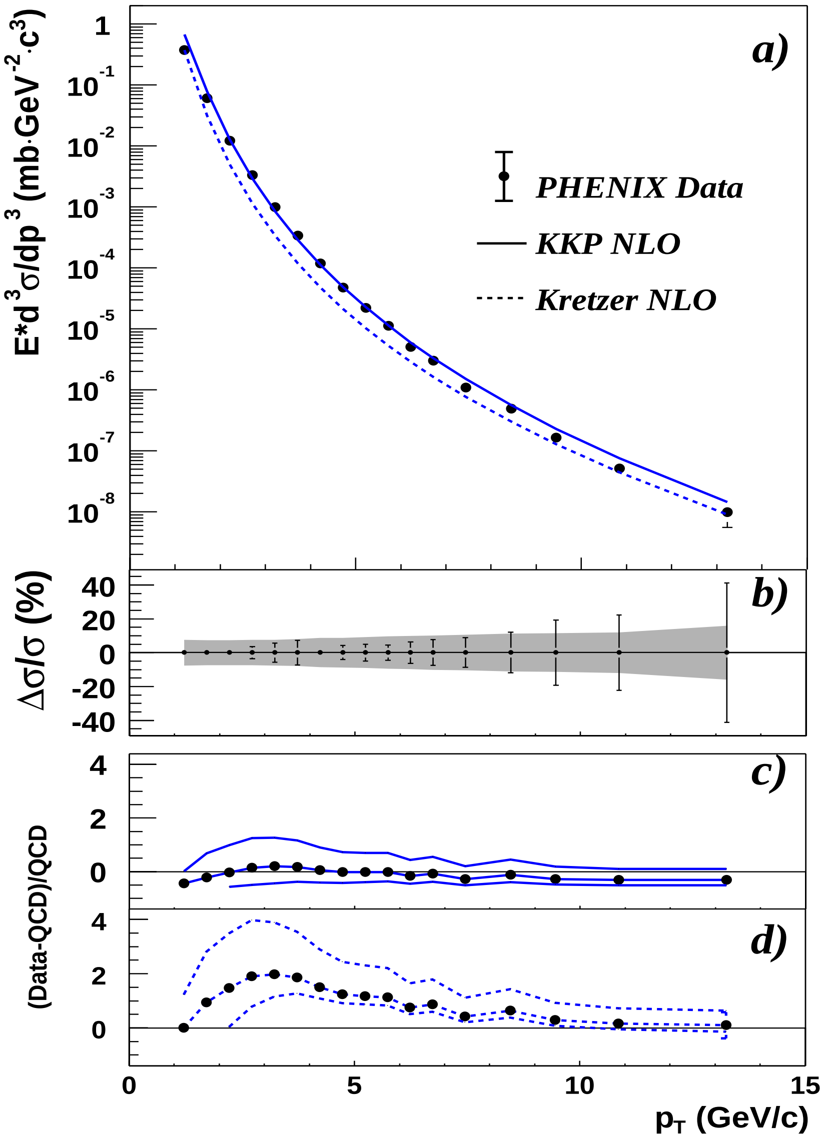
Fragmentation functions D(z) in order to relate jets to observed hadrons







PHENIX pp→ π^0 + X Baseline

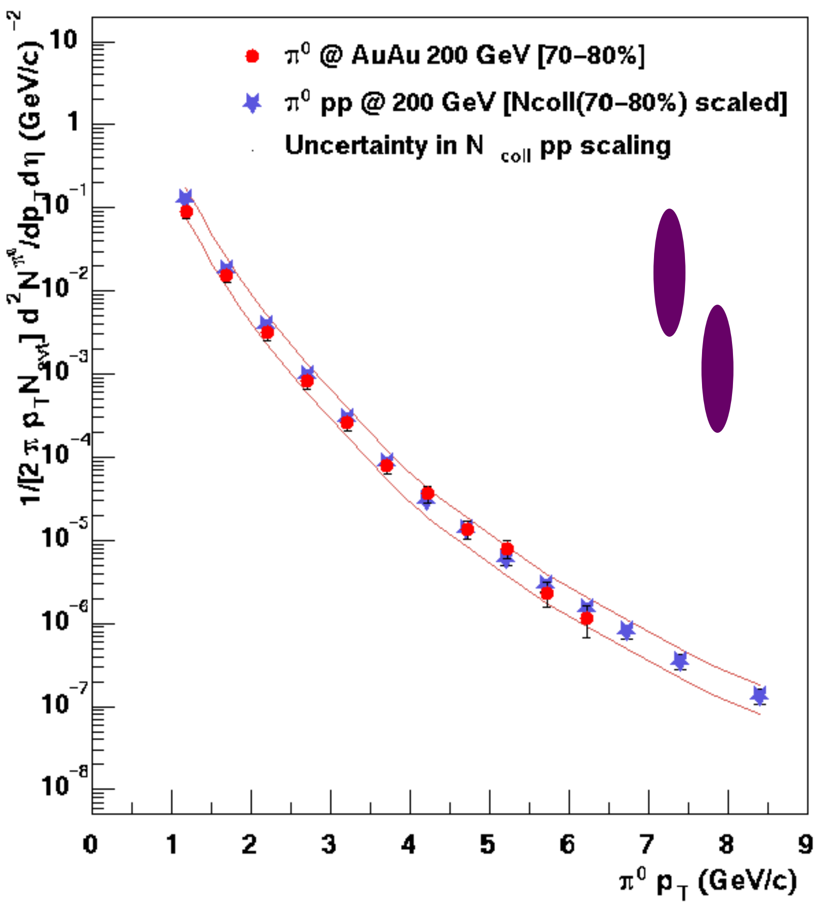


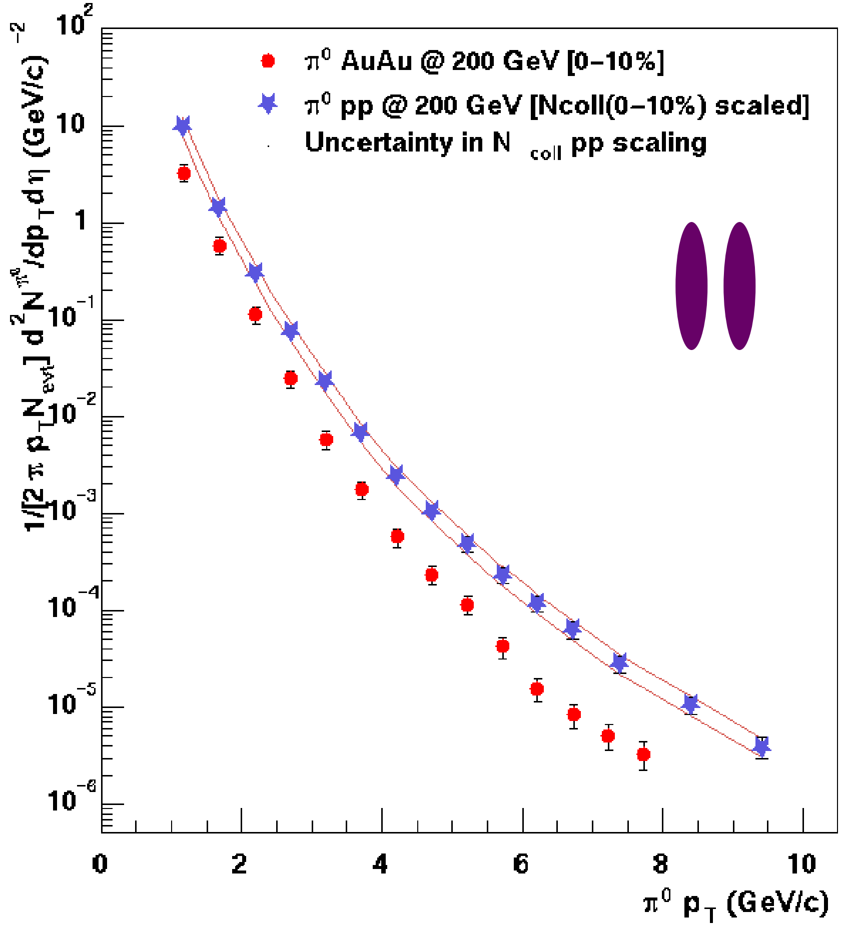
No big surprise...

perturbative QCD works!

Au+Au → π^0 + X

Peripheral Au+Au collisions appear as superposition of proton-proton reactions. Central Au+Au collisions show a significant suppression relative to naïve expectations (binary collision scaling of hard processes).





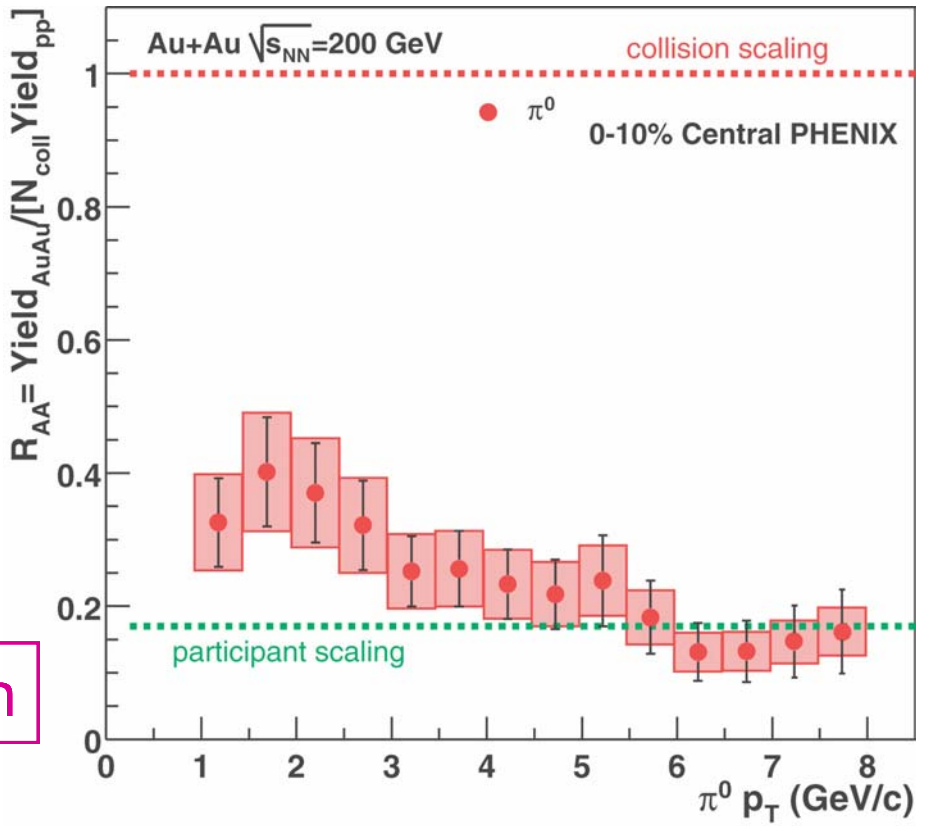
Very Large (x5)
Final or Initial State Effect !

Nuclear Modification Factor:

$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{T_{AA}\, d^2\sigma^{NN}/dp_T d\eta}$$

$\langle N_{binary}\rangle / \sigma_{inel}^{p+p}$

N-N cross section



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

Induced Parton Energy Loss

<u>Energy Loss Calcultions:</u>

X.N. Wang, Phys. Rev. C61, 064910 (2000).

dE/dx = 0

<u>dE/dx = 0.25 GeV/fm</u>

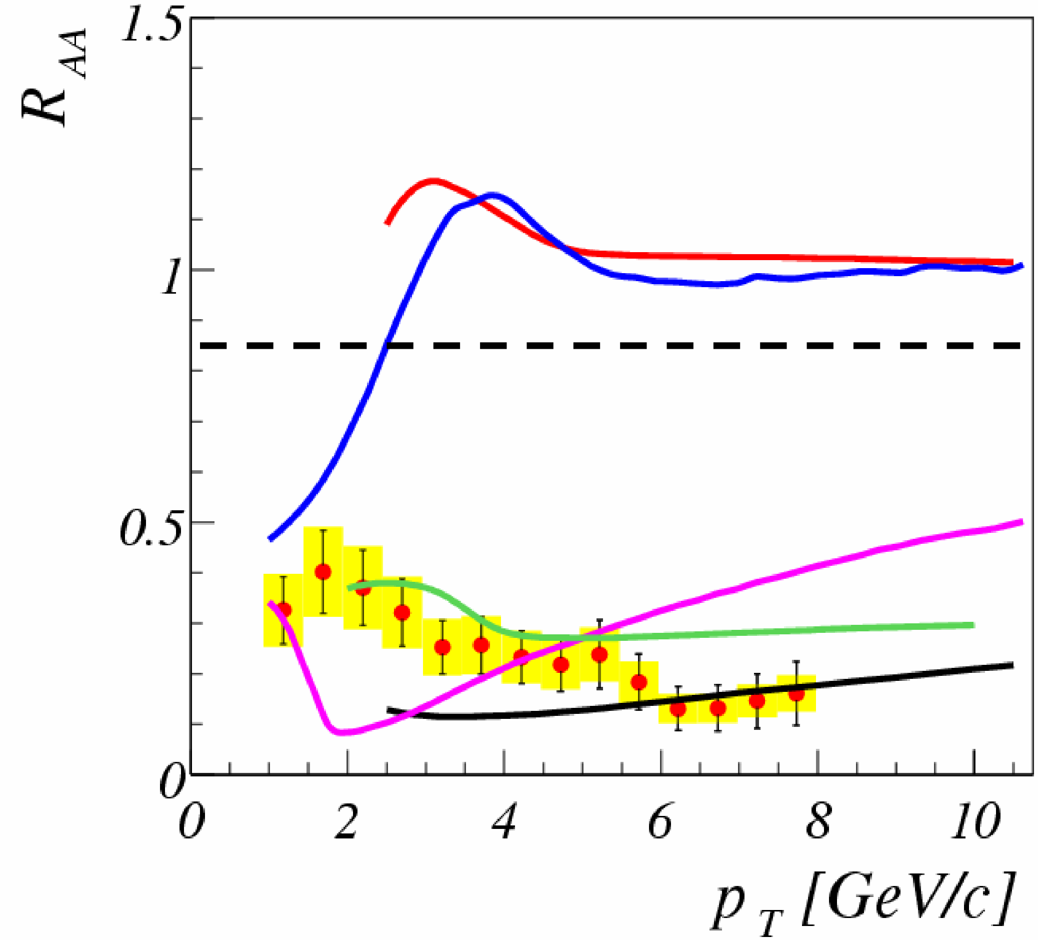
Gyulassy, Levai, Vitev: Nuclear Physics A698 (2002) 631.

Levai L/λ = 0

L/λ = 4

GLV, Nucl. Phys. B 594, p. 371 (2001) + work in preparation.

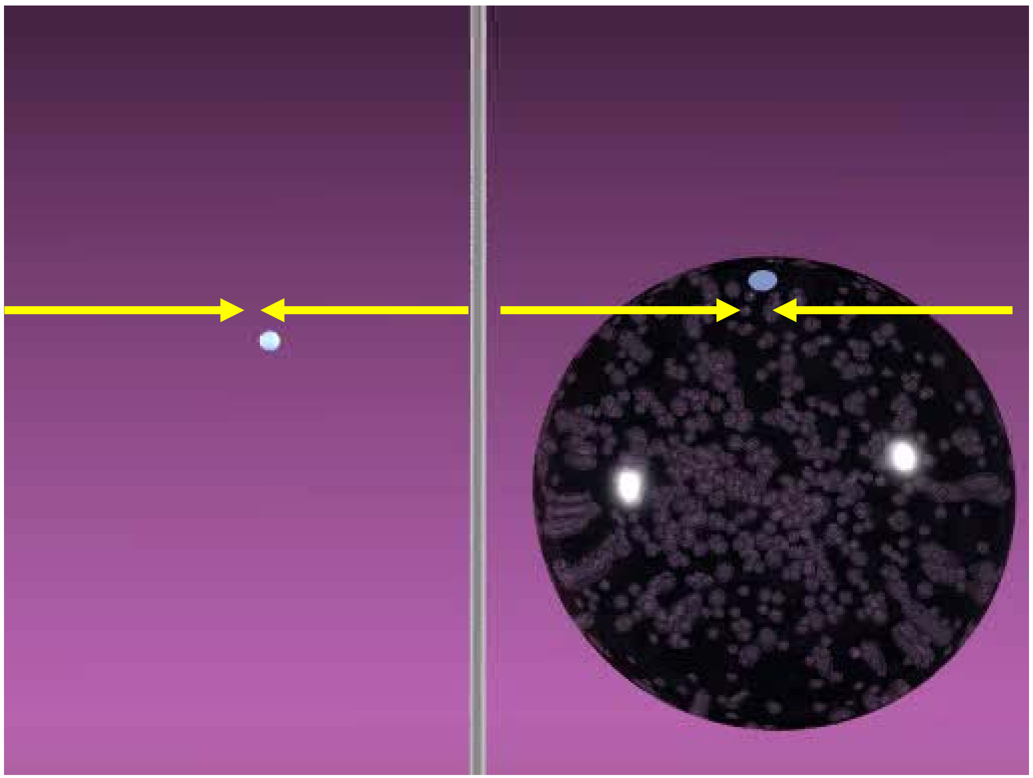
dN/dy(gluon) = 900



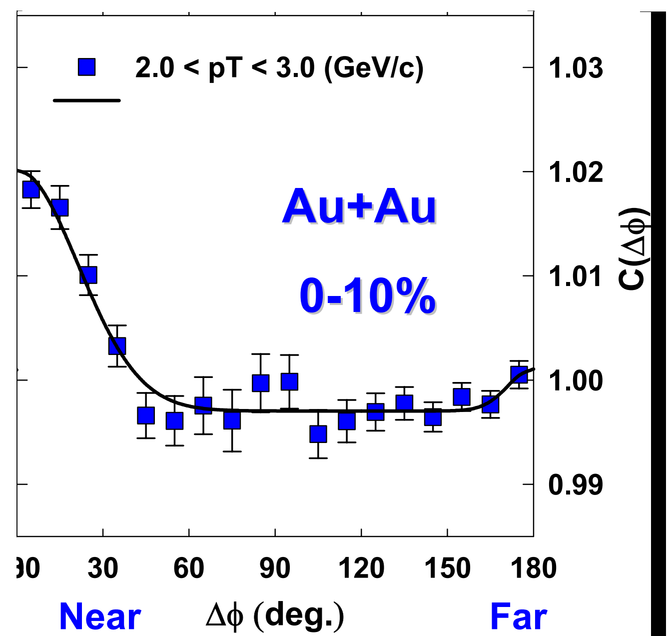
- Calculations sensitive to infrared cutoff (Mueller *et al.*)
- Only indicative of gluon density, no quark-gluon plasma

Parton Energy Loss

Jets in Proton-Proton   Jets in Gold-Gold



We observe a disappearance of the “away” side jet.

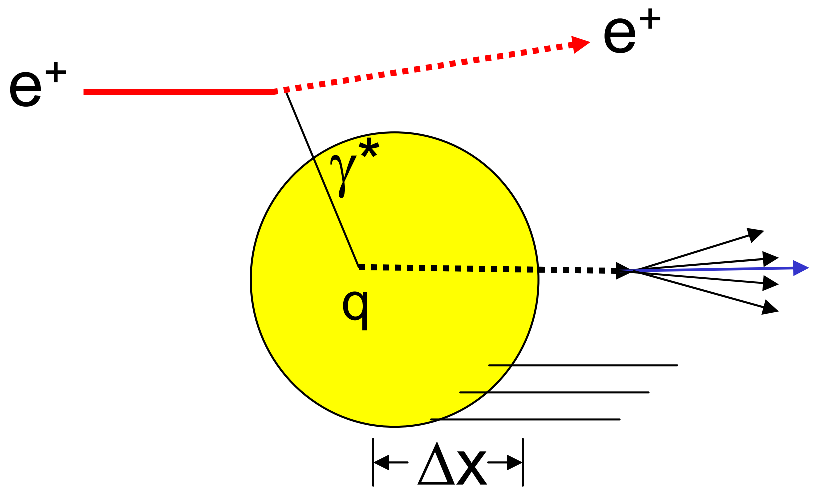


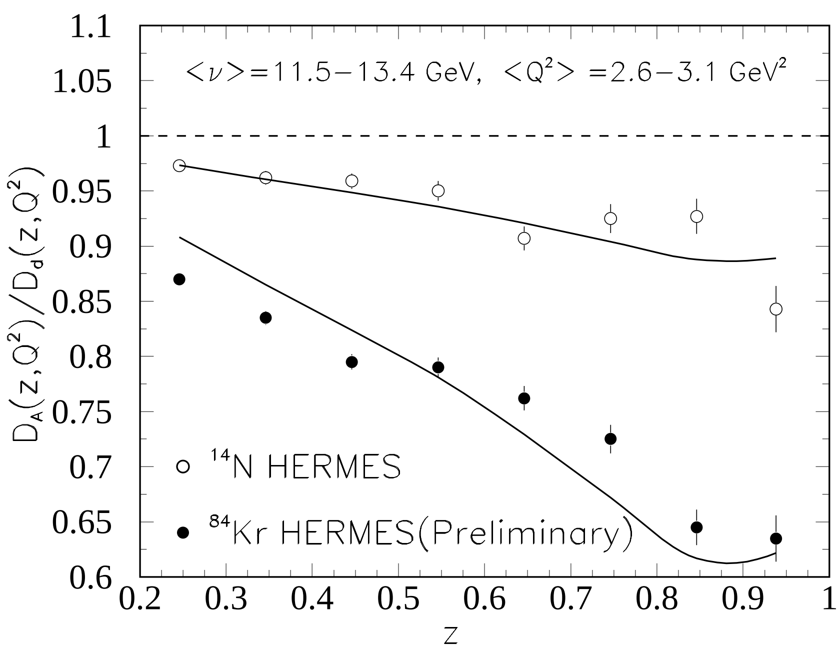
PHENIX Preliminary

Animation by Jeffery Mitchell

Partons in Cold Nuclear Matter

HERMES Experiment





Measure quark energy from electron scattering off nuclei.

Measure hadron fragmentation function D(z).

<u>Larger nuclei show fewer high z hadrons in fragmentation</u>.

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 Effects

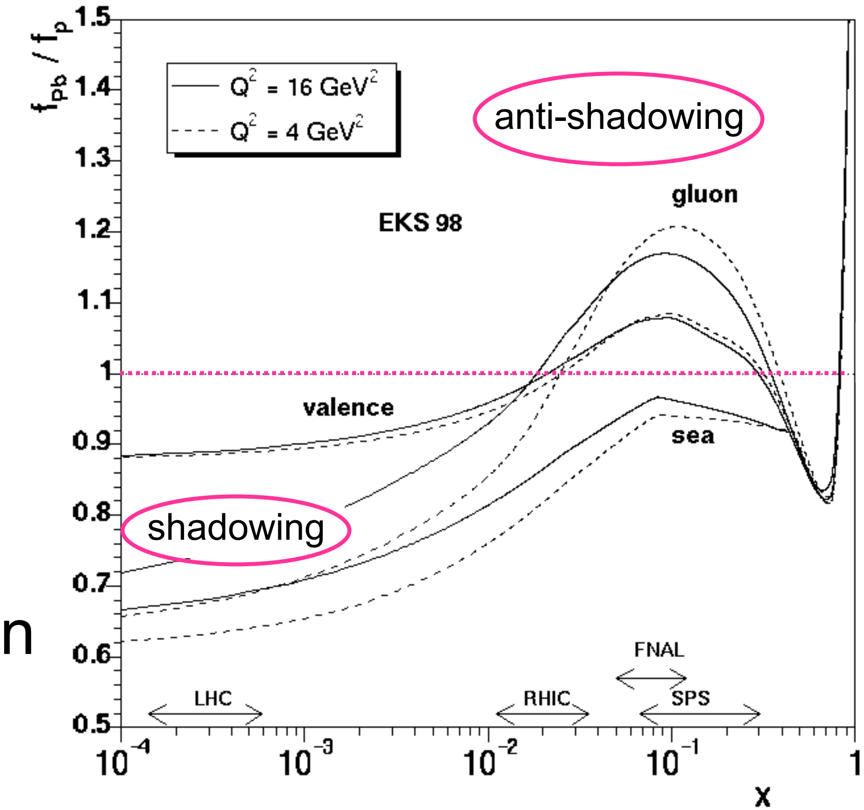
The probabilities of finding a parton at a given *x* are different if the proton is inside a nucleus.

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

Nuclear shadowing naturally leads to a suppression of high p_T hadrons.

However, at $p_T \sim 7$ GeV, the dominant $x \sim 2\, p_T/\mathrm{sqrt}(s) \sim 0.1$ which is in the anti-shadowing region.

Extreme shadowing called parton saturation has been proposed.
Color Glass Condensate!



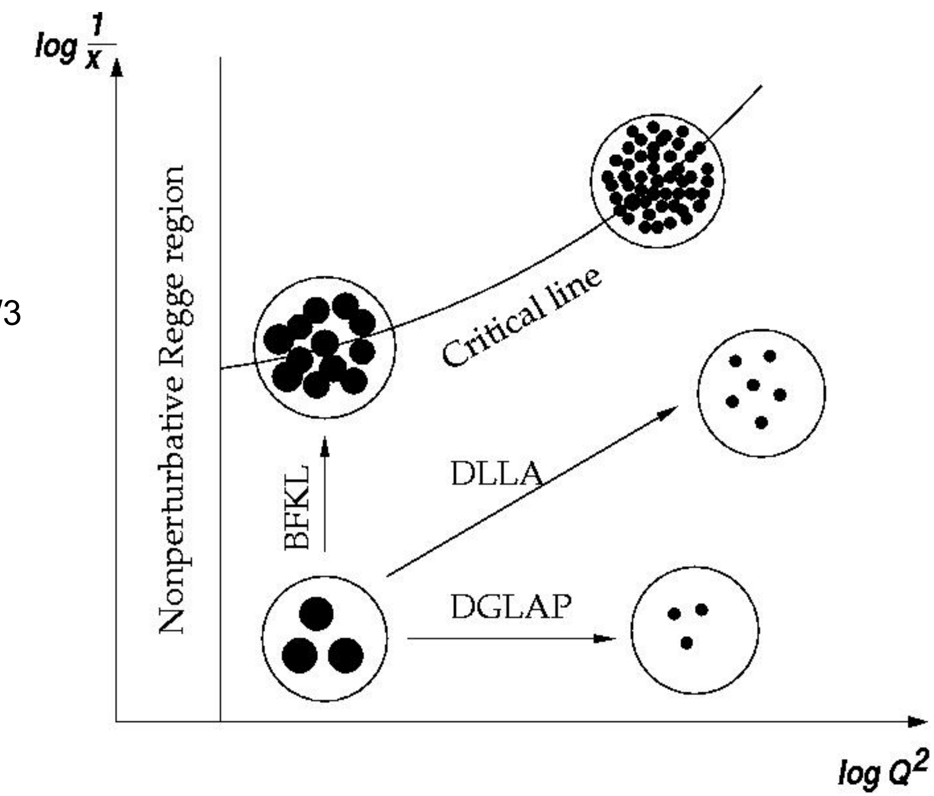
Extreme Initial State Effects

At low x the gluon density may be so high that it saturates.

Gluon density is increased in a nucleus relative to the proton by $A^{1/3}$

McLerran *et al.* show that in this limit, factorization breaks down and one can describe the proton or nucleus in terms of classical gluon fields (Color Glass Condensate).

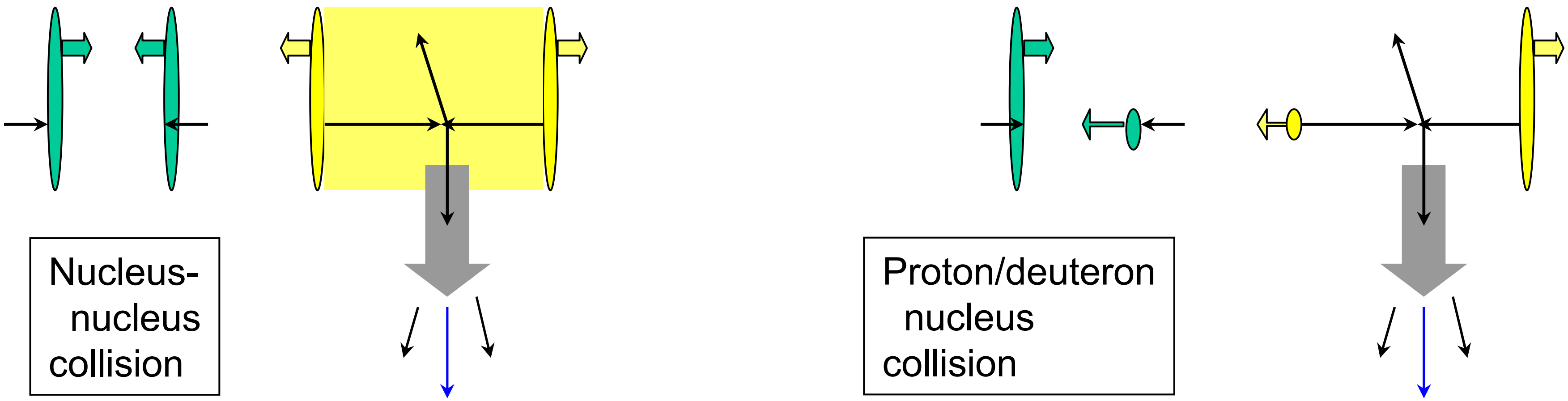
Mueller has shown that this is isomorphic to the color dipole cross section approaching the unitarity limit in DIS.



Critical line indicates region above which saturation will occur – gluons overlap – nonlinear evolution

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

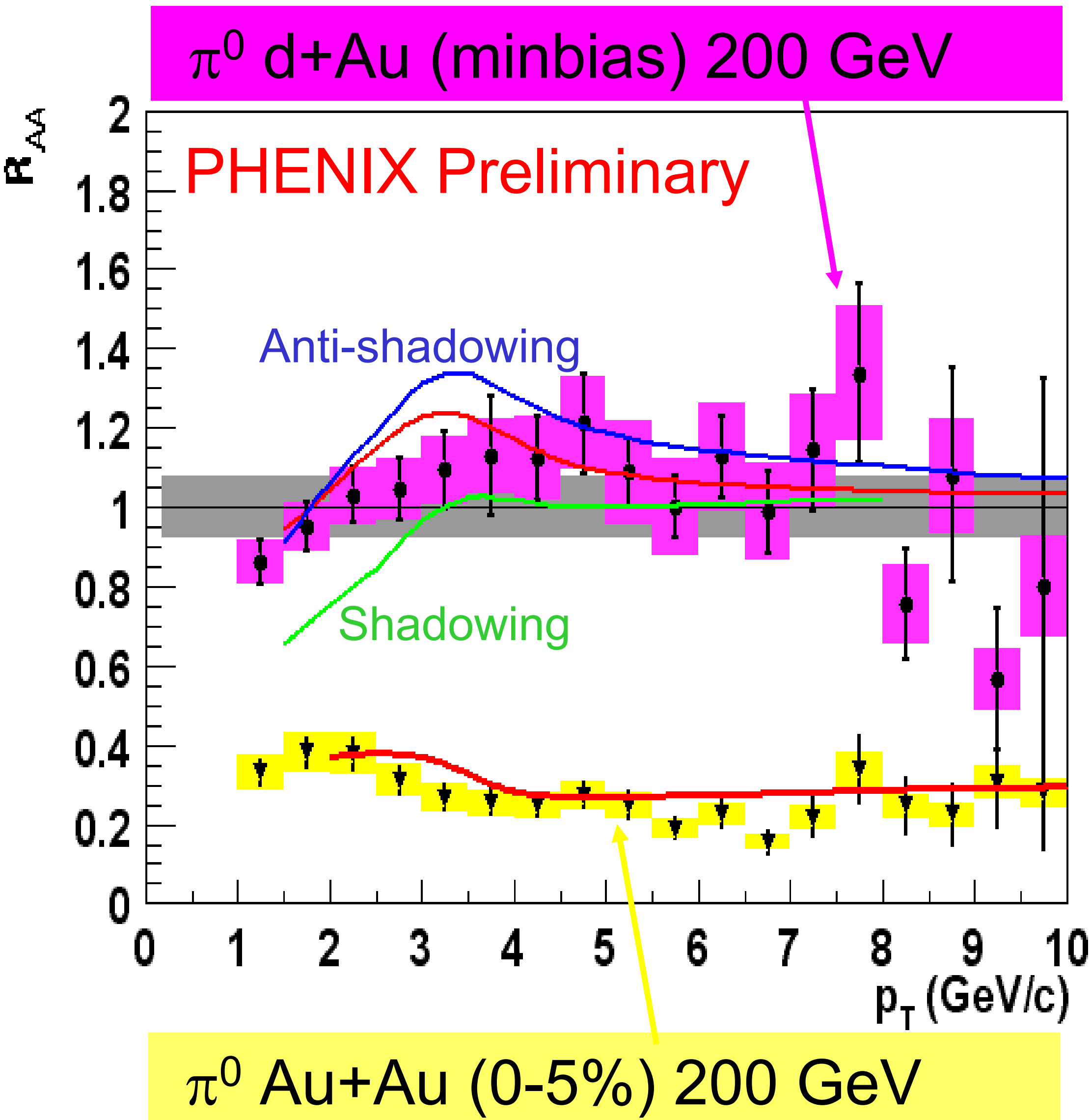
Control Experiment



If the suppression is from lower incident parton flux (initial state effect), then we should still see suppression in deuteron-nucleus collisions.

If the suppression is from an opaque medium, then we should see no suppression in the control experiment with deuteron-nucleus collisions.

Very Opaque Gluon Medium!



Deuteron-Gold data should only have initial state effects.

No Large Effect Seen!

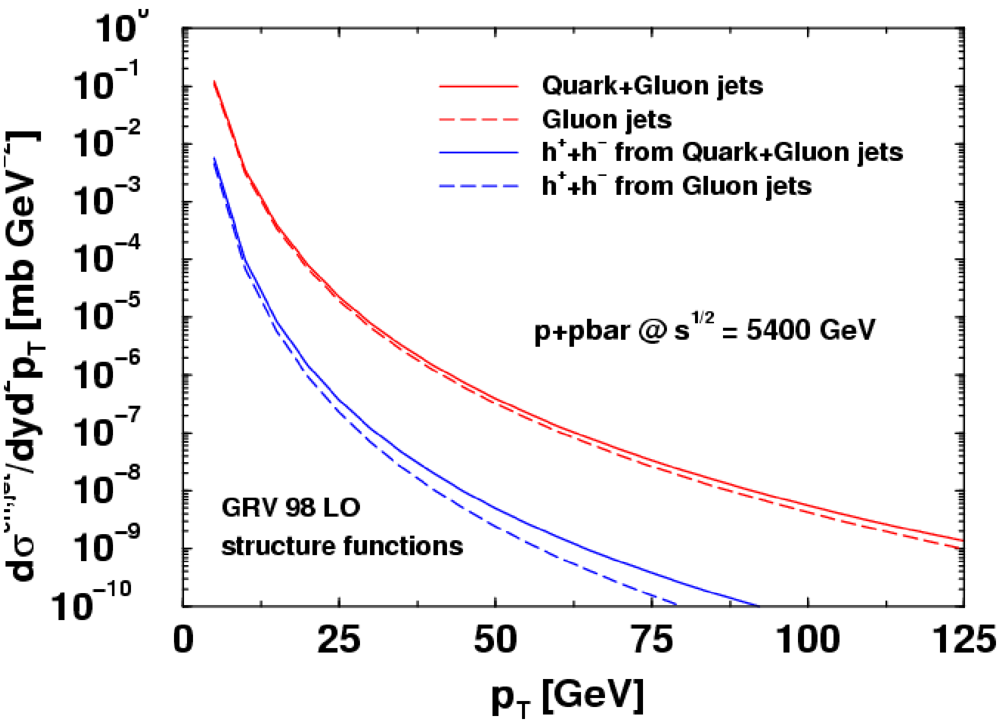
<u>Thus, Gold-Gold suppression is due to very opaque gluon medium !</u>

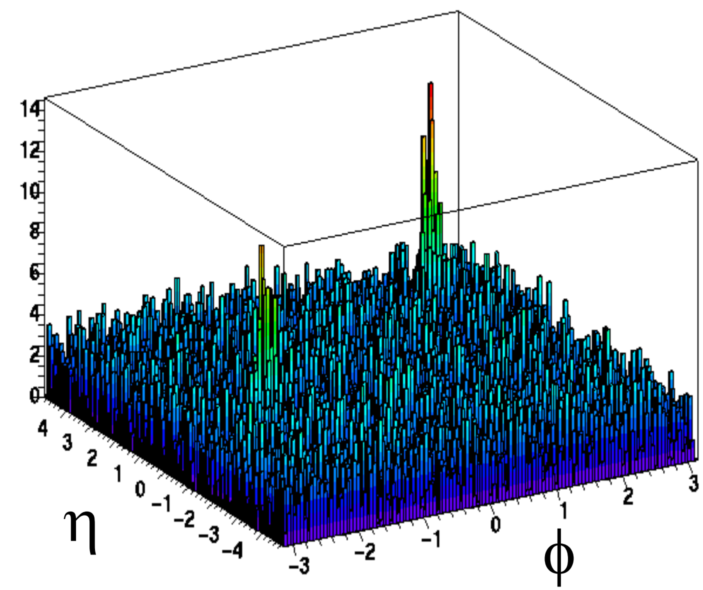
Over ten times density of normal nuclear matter.

d+Au: calculations I. Vitev, nucl-th/0302002

Jets in ATLAS at LHC

Although the soft background is increased at LHC energies, the jet cross sections are so large that truly high p_T (> 70 GeV) jets may be observed.



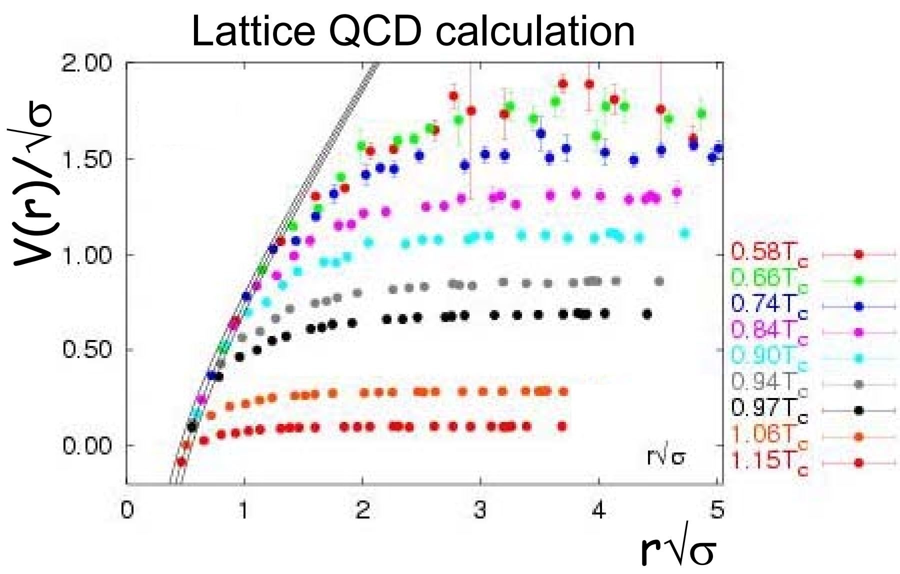


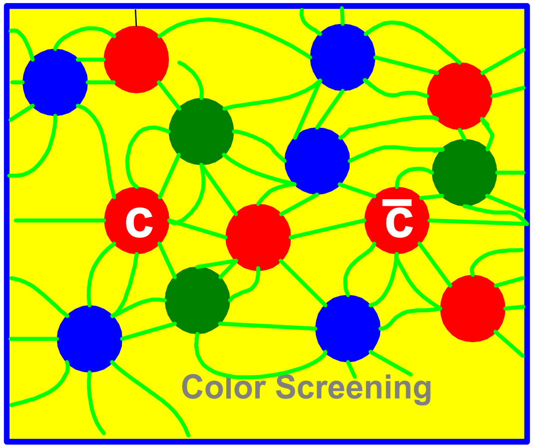
200 GeV jet event overlay on central Pb-Pb event with ATLAS calorimter segmentation

ATLAS Heavy Ion Letter of Intent [nucl-ex/0212016]

Studying Quark Deconfinement

Lattice QCD results show that the confining potential between heavy quarks is screened at high temperature.



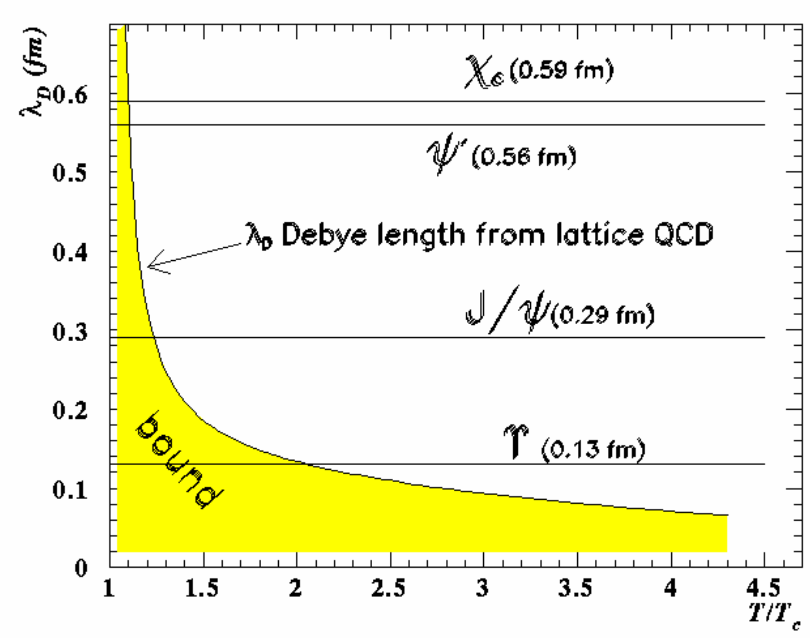


This screening should suppress bound states such as J/ψ.

Quark-Antiquark Pairs

Different states "melt" at different temperatures due to different binding energies.

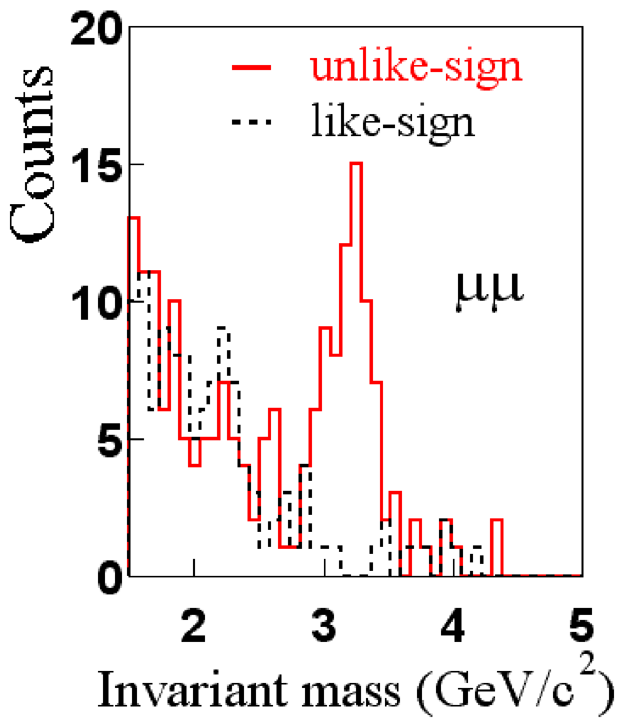
The ψ' and χ_c melt below or at T_c
the J/ψ melts above T_c and
eventually the ϒ(1s) melts.

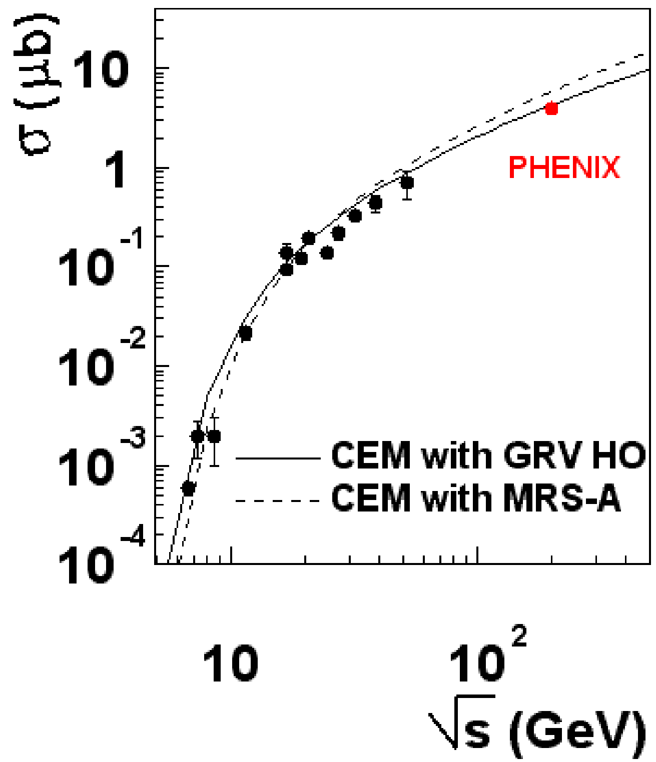


state	J/ψ	χ_c	ψ'	ϒ(1s)	χ_b	ϒ(2s)	χ_b'	ϒ(3s)
Mass [GeV}	3.096	3.415	3.686	9.46	9.859	10.023	10.232	10.355
B.E. [GeV]	0.64	0.2	0.05	1.1	0.67	0.54	0.31	0.2
T_d/T_c	---	0.74	0.15	---	---	0.93	0.83	0.74

hep-ph/0105234

Highest Energy J/ψ Cross Section





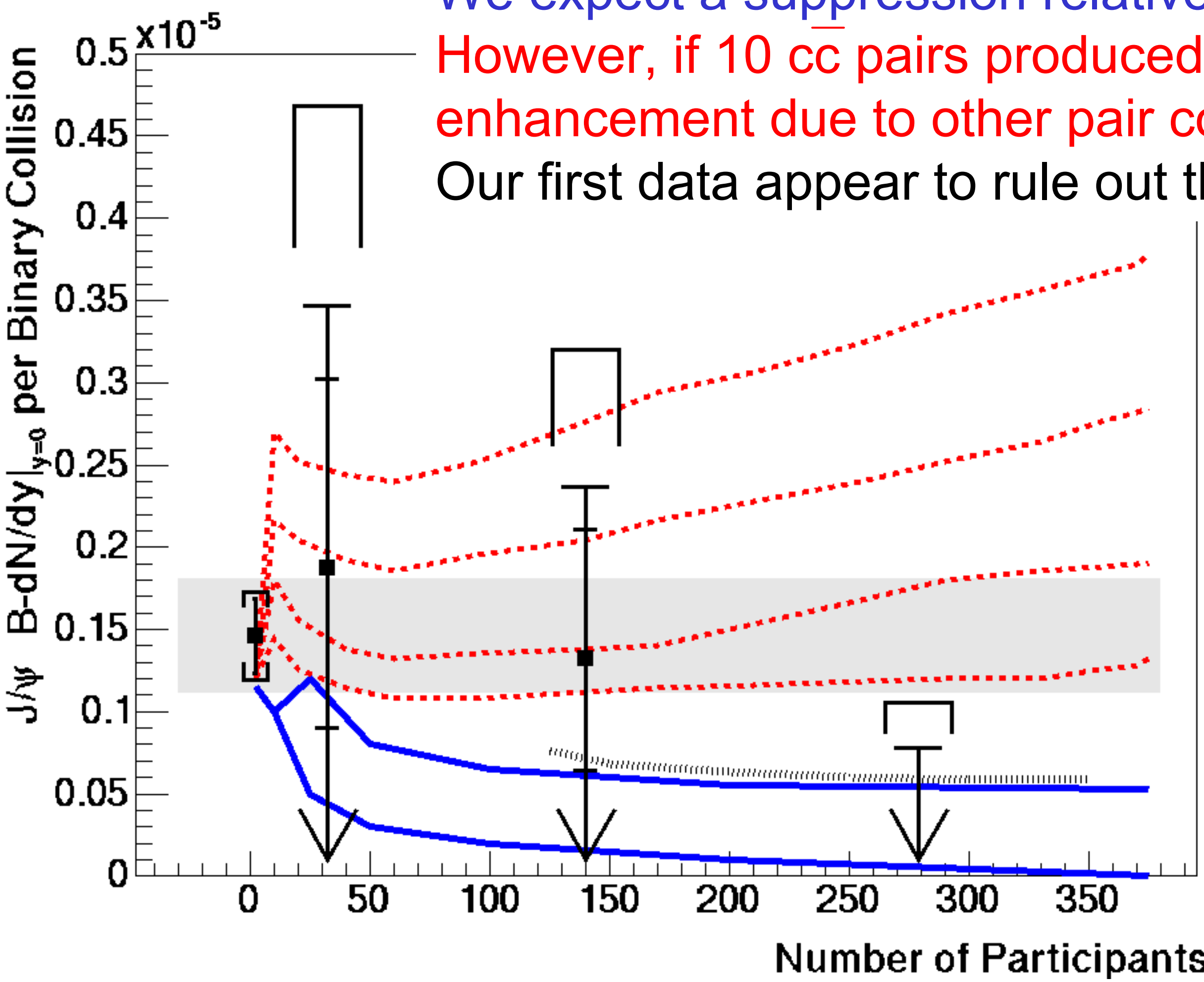
Gold-Gold J/ψ First Results

Each charm-anticharm pair has ~ 1% chance to form J/ψ.

We expect a suppression relative to this rate.

However, if 10 $c\bar{c}$ pairs produced, high mobility could allow enhancement due to other pair combinations.

Our first data appear to rule out this enhancement!



R.L. Thews, M. Schroedter, J. Rafelski Phys. Rev. C63 054905 (2001): Plasma coalesence model for T=400MeV and y_{charm}=1.0,2.0, 3.0 and 4.0.

L. Grandchamp, R. Rapp Nucl. Phys. A&09, 415 (2002) and Phys. Lett. B 523, 50 (2001): Nuclear Absorption+ absoption in a high temperature quark gluon plasma

Understanding QCD

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. 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 interacting plasma of quarks and gluons until some of the predictions are confirmed by experiment."

The challenge is out there to the people in the field to have this hope fully realized.

Conclusions

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 exciting observations of very dense gluonic medium from jet quenching results. Gluon density well above predicted phase transition level.

The third phase is next.
Quarkonia measurements to test deconfinment.
The spin physics program in PHENIX is starting, and will further address basic QCD questions being asked (and hopefully answered).

PHENIX

Brazil
University of São Paulo, São Paulo

China
Academia Sinica, Taipei, Taiwan
China Institute of Atomic Energy, Beijing
Peking University, Beijing

France
LPC, University de Clermont-Ferrand, Clermont-Ferrand
Dapnia, CEA Saclay, Gif-sur-Yvette
IPN-Orsay, Universite Paris Sud, CNRS-IN2P3, Orsay
LLR, Ecole Polytechnique, CNRS-IN2P3, Palaiseau
SUBATECH, Ecole des Mines de Nantes, CNRS-IN2P3, Univ. Nantes

Germany
University of Münster, Münster

Hungary
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Debrecen University, Debrecen
Eötvös Loránd University (ELTE), Budapest

India
Banaras Hindu University, Banaras
Bhabha Atomic Research Centre, Bombay

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Center for Nuclear Study, University of Tokyo, Tokyo
Hiroshima University, Higashi-Hiroshima
KEK, Institute for High Energy Physics, Tsukuba
Kyoto University, Kyoto
Nagasaki Institute of Applied Science, Nagasaki
RIKEN, Institute for Physical and Chemical Research, Wako
RIKEN-BNL Research Center, Upton, NY
University of Tokyo, Bunkyo-ku, Tokyo
Tokyo Institute of Technology, Tokyo
University of Tsukuba, Tsukuba
Waseda University, Tokyo

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Cyclotron Application Laboratory, KAERI, Seoul
Kangnung National University, Kangnung
Korea University, Seoul
Myong Ji University, Yongin City
System Electronics Laboratory, Seoul Nat. University, Seoul
Yonsei University, Seoul

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PNPI, St. Petersburg Nuclear Physics Institute, St. Petersburg
St. Petersburg State Technical University, St. Petersburg

Sweden
Lund University, Lund

12 Countries; 57 Institutions; 460 Participants

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Oak Ridge National Laboratory, Oak Ridge, TN
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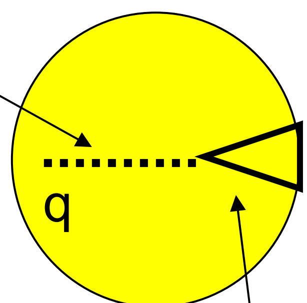
Hadronization Time

Alternative description also considered by HERMES.

Suppression due to quark-nucleon scattering ($t < t^{\pi}_{f}$) and hadron-nucleon scattering ($t > t^{\pi}_{f}$).

$$t_f^{\pi} = c_{\pi}(1-z)\nu$$

$$\sigma_{q-N} = 0.0 \pm 0.2 mb$$



$$\sigma_{h-N} = 25.0 mb$$

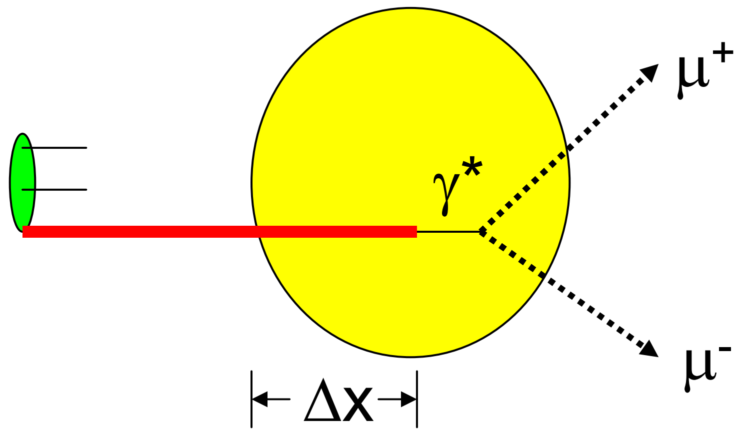
A hadron with large z originates from a quark emitting only a few gluons. The emission of only a few gluons corresponds to a small formation time.

They consider good agreement with N^{14} data in a model in which the "interaction of the struck quark with the nuclear medium is very small."

hep-ex/0012049

Incoming Parton Energy Loss

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



Must carefully separate nuclear shadowing effects and energy loss effects both of which lead to suppression of Drell-Yan pairs.

E772 and E866 at Fermilab

$dE/dx = 2.73 \pm 0.37 \pm 0.5$ GeV/fm (from hadronization due to confinement)
$dE/dx \sim 0.2$ GeV/fm (from gluon radiation due to nuclear environment)

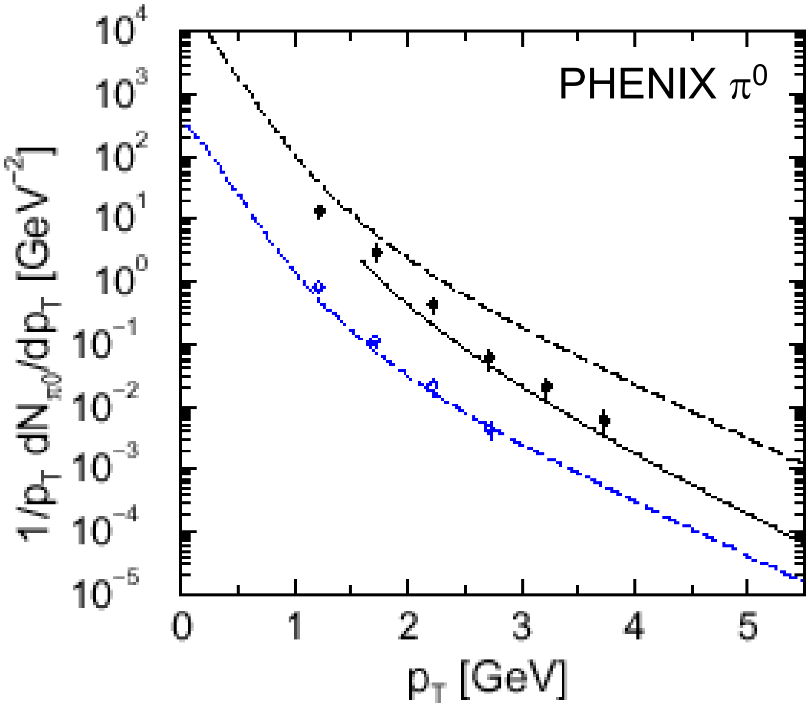
"This is the first observation of a non-zero energy loss effect in such experiments."

Johnson, Kopeliovich, Potashnikova, E772 et al.
Phys. Rev.C 65, 025203 (2002) hep-ph/0105195
Phys. Rev. Lett. 86, 4487 (2001) hep=ex/0010051

Formation Time

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

Then the fragmented hadrons can interact with other hadrons and thus suppress high momentum hadrons.



Gallmeister model:
Formation time is the time to build up the hadronic wavefunction and is proportional to energy from γ boost

$\tau_f \sim 1.2$ (E/GeV) * fm/c

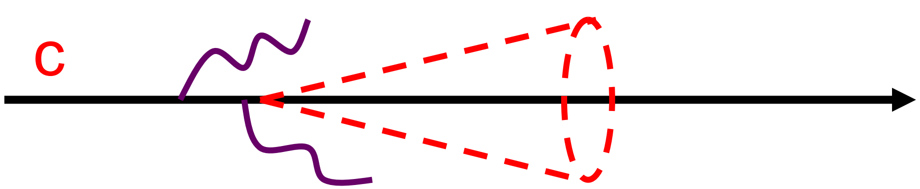
This model should see the suppression go away at high p_T.
As one moves up in p_T, z is always ~ 0.6-0.7, but γ boost increases. $t_f^\pi = c_\pi (1-z)\nu$

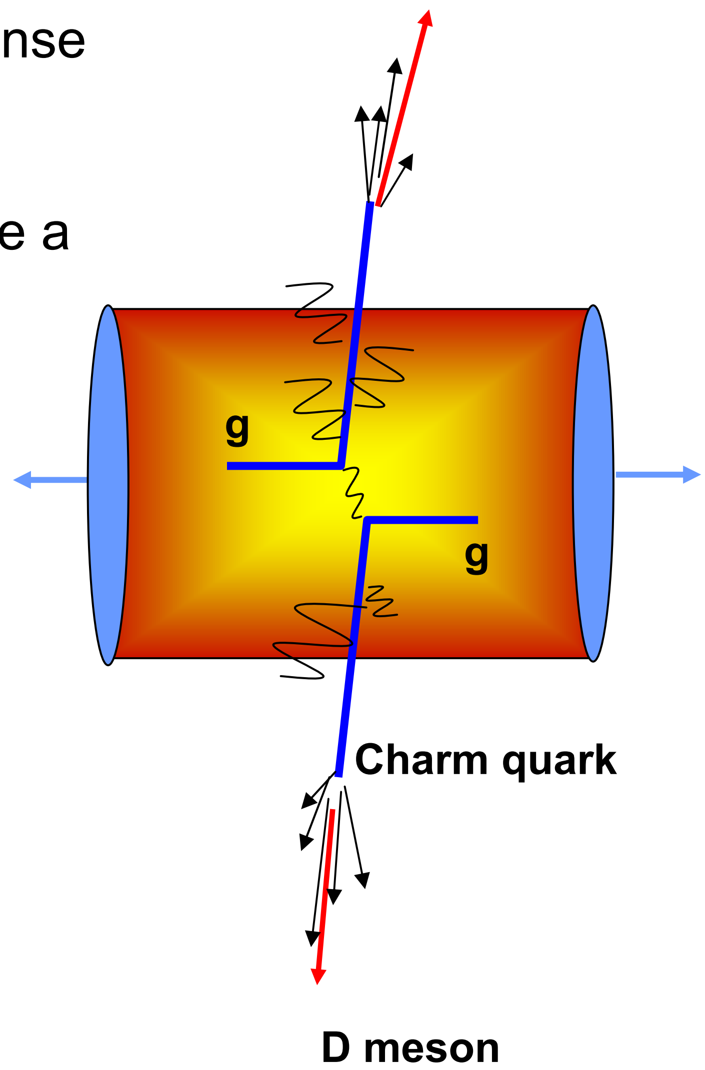
Gallmeister et al., nucl-th/0202051

Heavy Quark Propagating

Heavy quarks should also lose energy in a dense gluonic medium.

However, due to their finite velocity, they have a forward “dead-cone” where gluon radiation is not allowed.

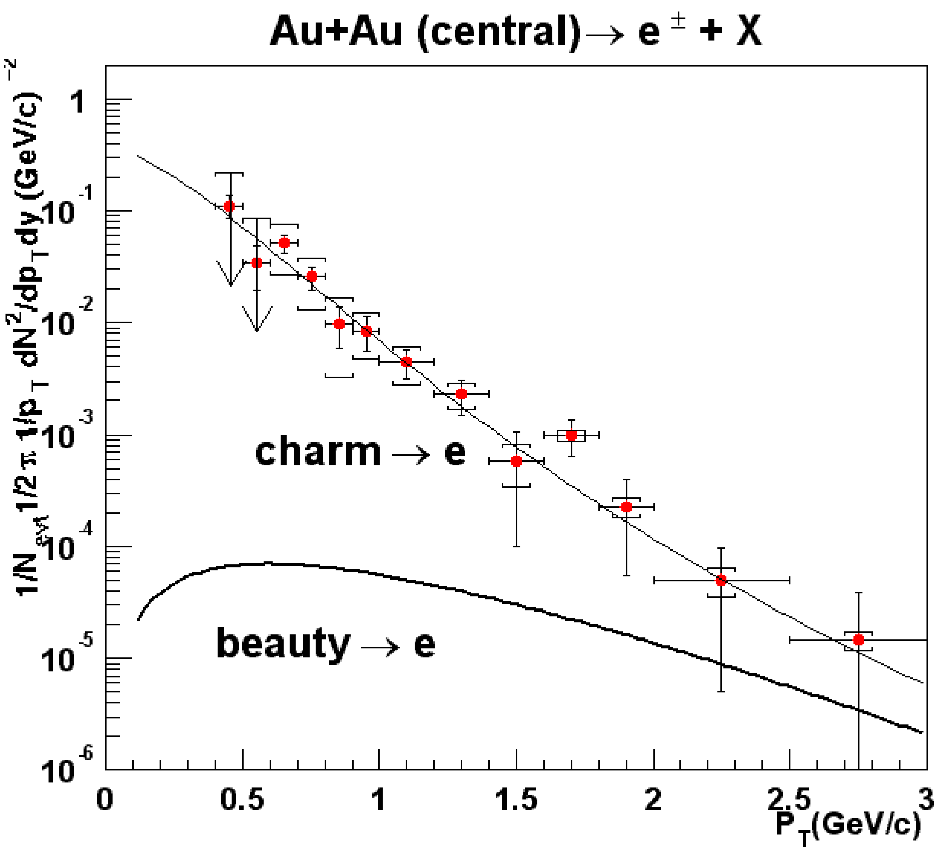




Z. Lin et al., Phys. Rev. C 57, 899, 1992.
Y.L. Dokshitzer and D.E. Kharzeev, hep-ph/0106202
M. Djordjevic and M. Gyulassy, nucl-th/0302069
Baier, Dokshitzer, Mueller, Schiff, hep-ph/9907267
Gyulassy, Levai, Vitev, hep-pl/9907461
X.N. Wang, nucl-th/9812021

Charm Results

PHENIX measures single electrons, and after subtracting off Dalitz, conversion and other decay contributions, the remaining signal is dominated by D and B meson semi-leptonic decays.

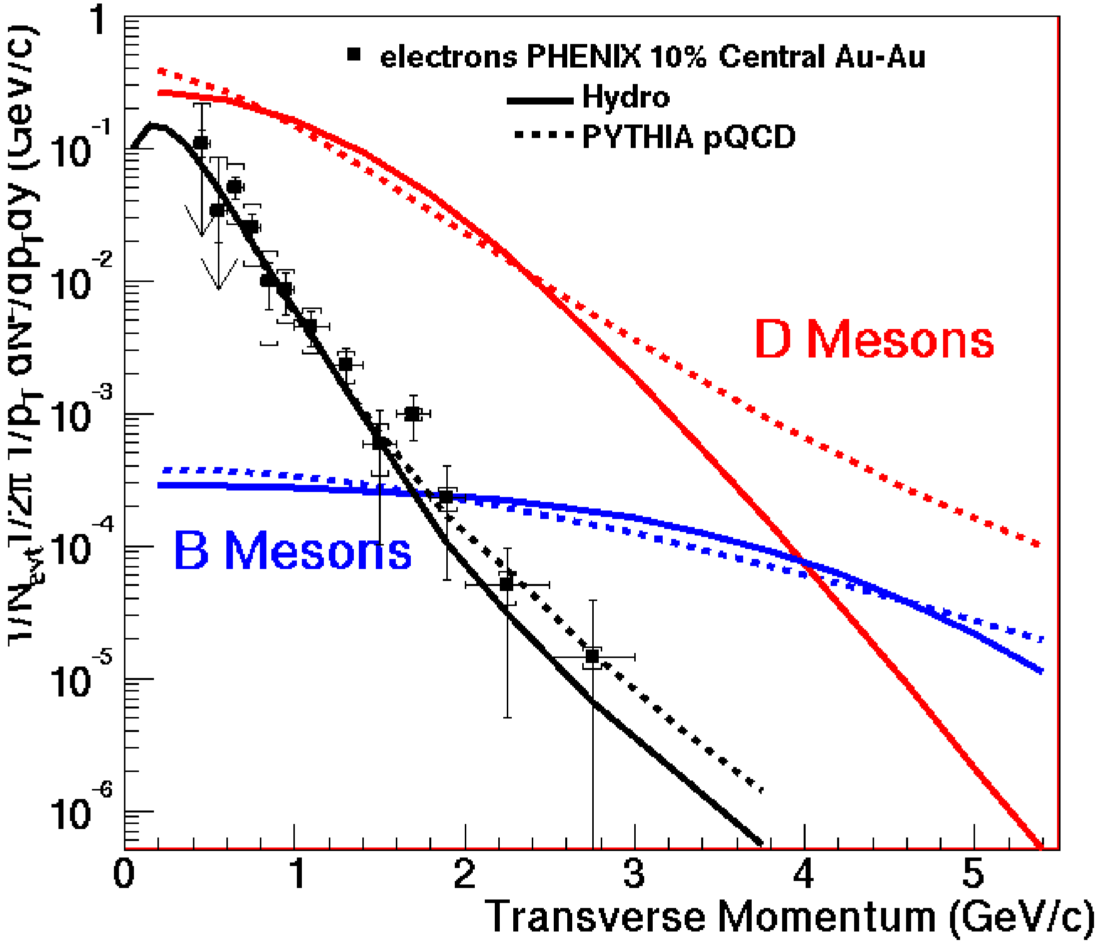


Results are consistent with PYTHIA calculation for charm and beauty tuned to lower energy FNAL data.

Apparent scaling with binary collisions.

No indication of factor of 5 suppression as seen in pions!

Charm Recombination and Flow



What if charm partons hadronize in medium and form D mesons via recombination?

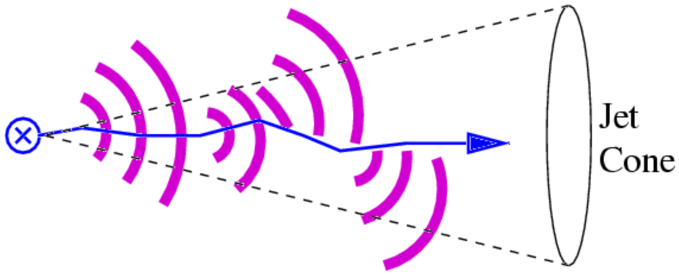
Outward pressure from re-scattering as observed in π, K, protons allows us to predict D, B meson p_T spectra and thus resulting electron spectra.

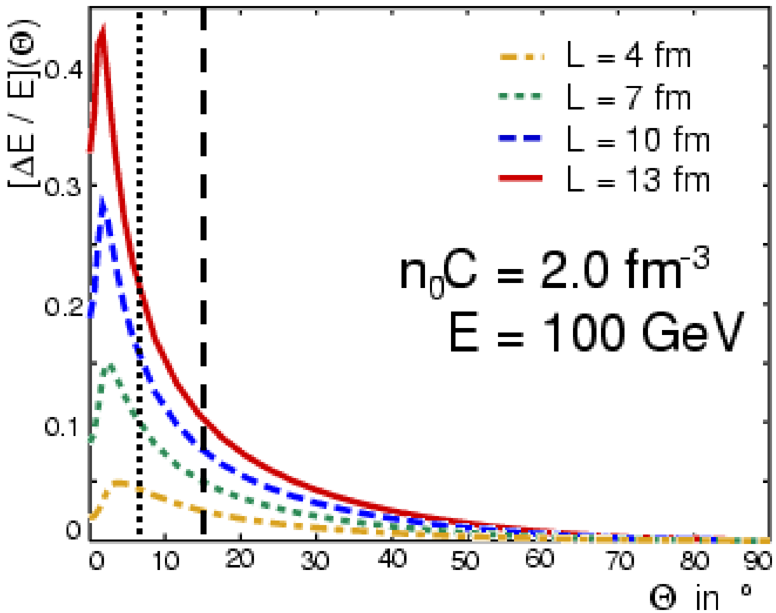
Amazing ambiguity with previous vacuum fragmentation (PYTHIA) result.

S. Batsouli, S. Kelly, M. Gyulassy, JN, Phys. Lett. B 557, pp 26-32.

Jet Broadening

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

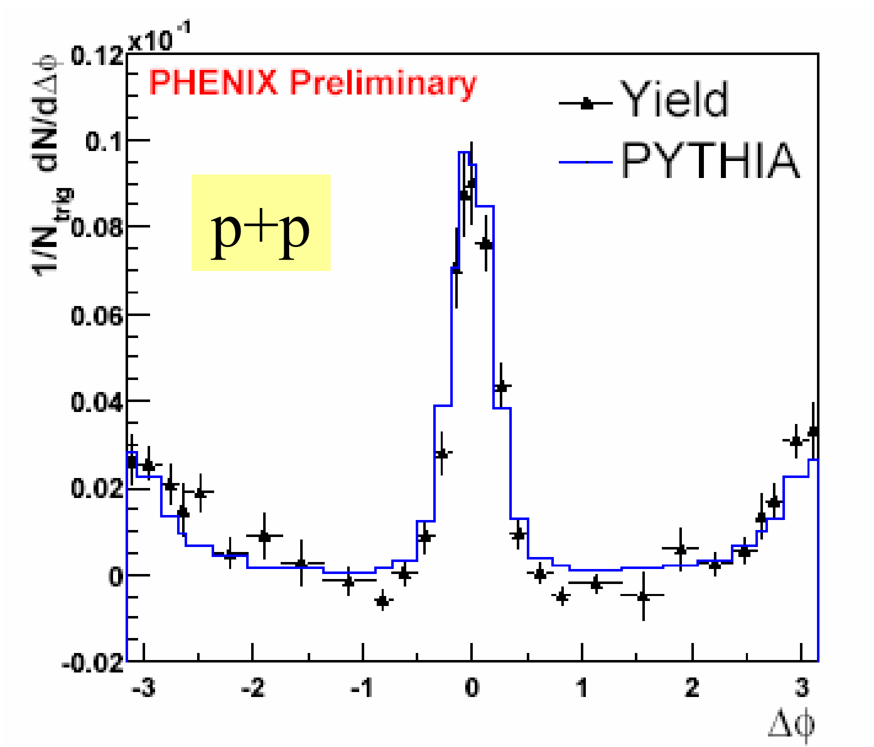
$\theta<12^0$ - 70% of jet energy contained
8% loss of energy outside

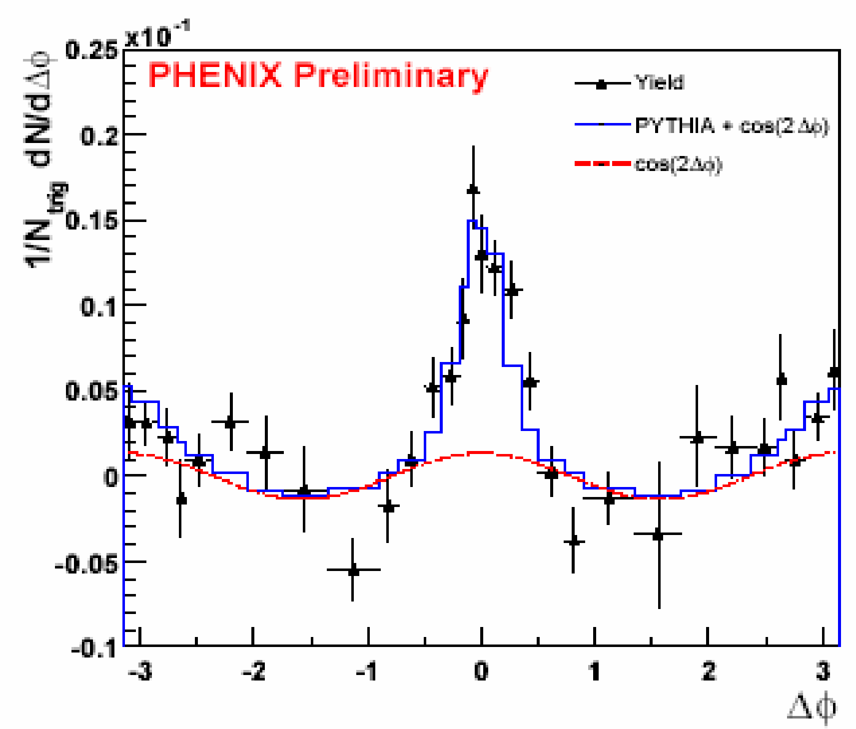
Possible observation of reduced "jet" cross section from this effect. This is not going to be easy at RHIC or LHC.

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

Jet Correlations

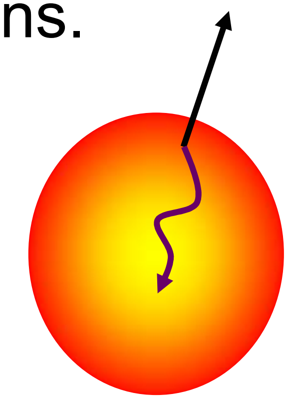
Although complete jet reconstruction does not work, we can measure angular correlations from jets.
Agreement between PYTHIA model and forward cone ($\Delta\phi \sim 0$) and opposite set cone ($\Delta\phi \sim \pi$) in proton-proton.
Similar behavior in Au-Au. Not sensitive to jet broadening at this level.

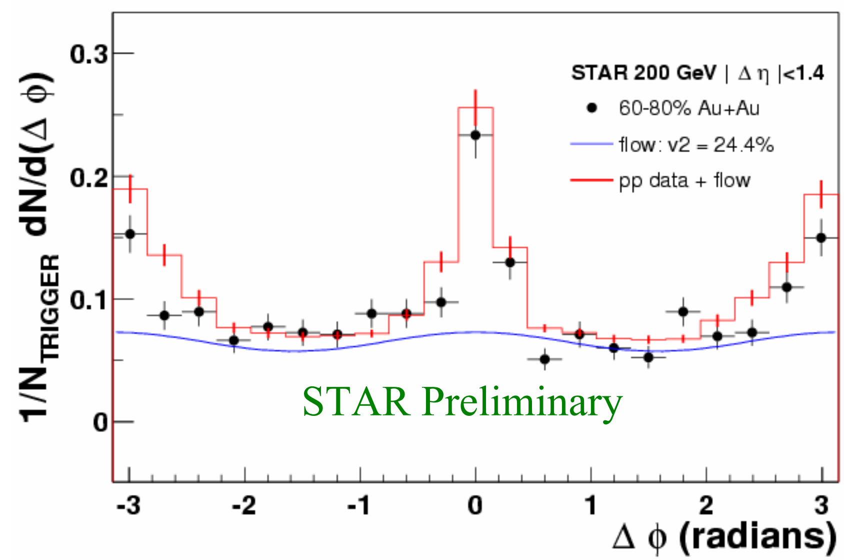


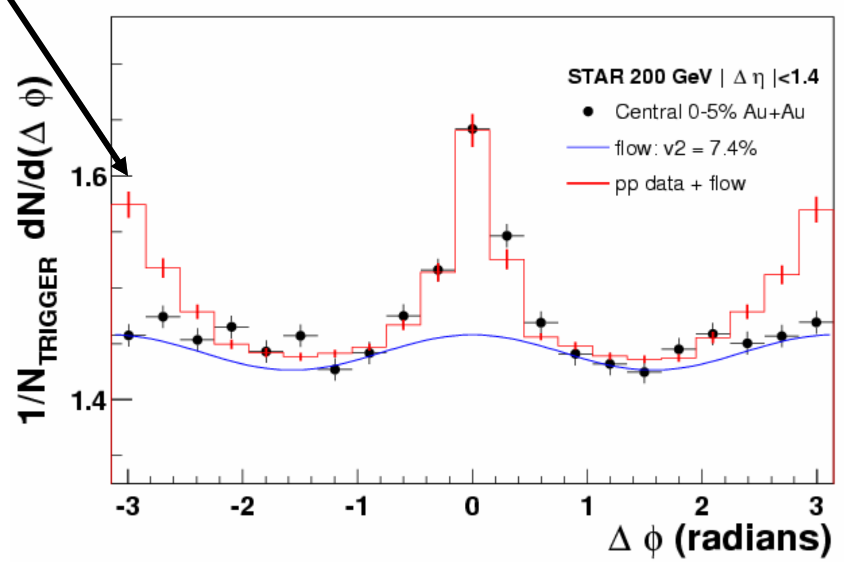


STAR Jet Correlations

STAR with better η and ϕ coverage sees clear disappearance of away side correlation in central Au-Au reactions.



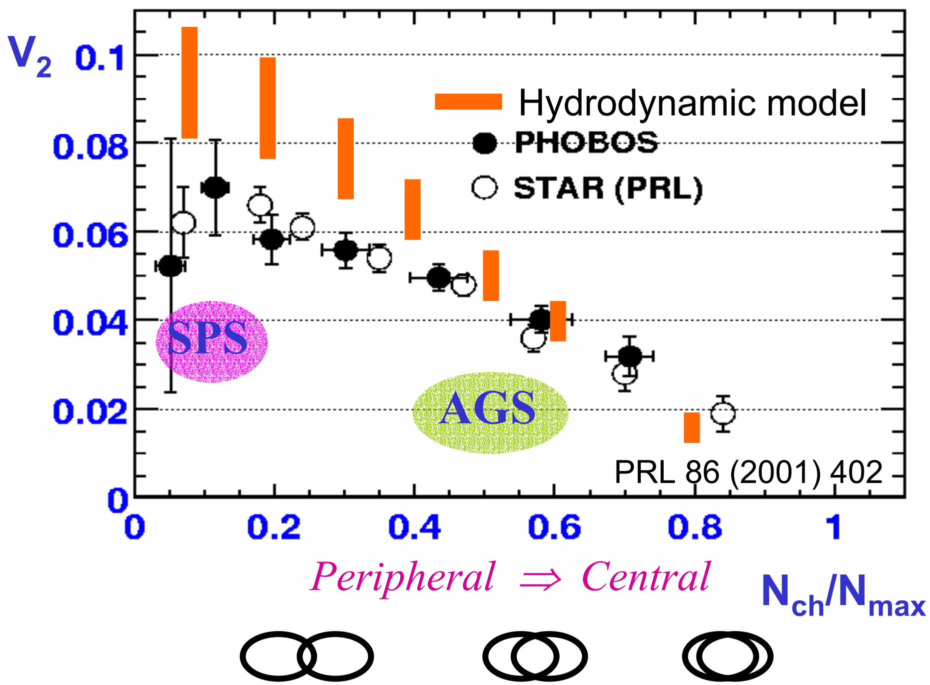


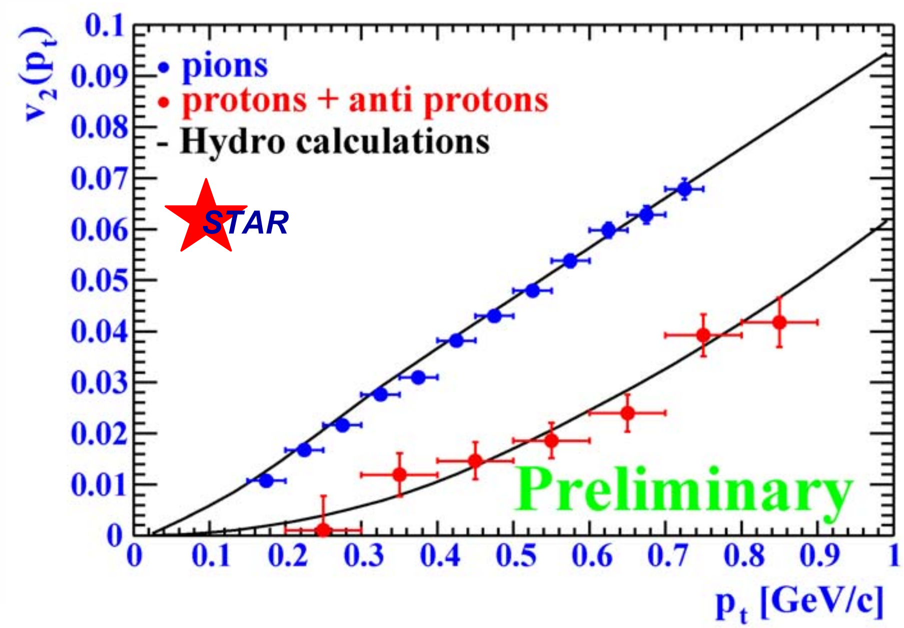


Perhaps the opposite side parton does not emerge?
Or no back-to-back jets at all from saturation model picture?

Large Parton Re-Scattering

Strong elliptic flow near the hydrodynamic limit





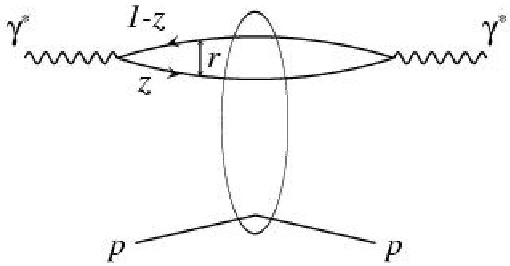
Hadronic re-scattering is insufficient to describe the data.

Implies strong partonic re-scattering and high initial density

ε = 20 GeV/fm^3 and τ = 0.6 fm/c

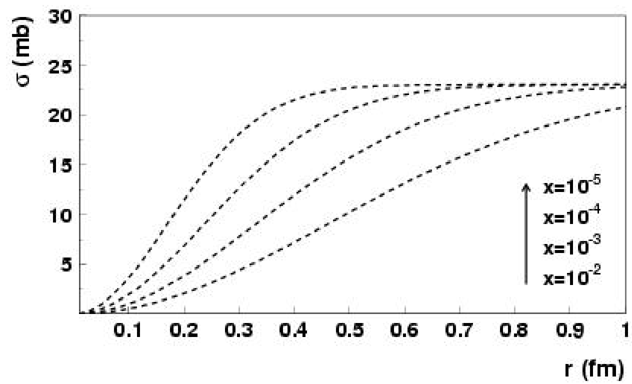
Hydro calculations: P. Huovinen, P. Kolb and U. Heinz

Saturation Effects in the Proton



$$\sigma_{\gamma^* P} = \int d^2r\, dz\, \Psi^*_{\gamma^*}(r,z,Q^2)\, \sigma_{qq}(x,r)\, \Psi_{\gamma^*}(r,z,Q^2)$$

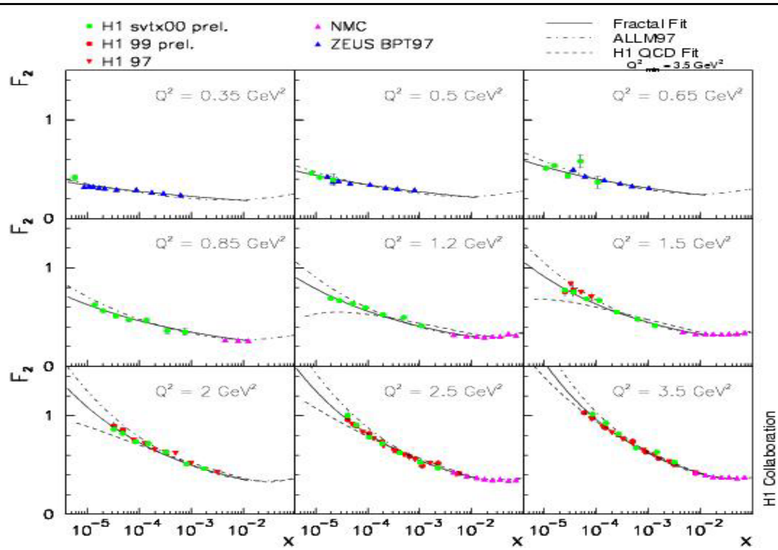
$$\sigma_{qq}(x,r) = \sigma_0 \left\{ 1 - \exp(-r^2 / 4R_0^2(x)) \right\}; \qquad R_0(x) = (x/x_0)^{\lambda/2}$$



$r << R_0 \qquad \sigma_{qq} \propto r^2 x^{-\lambda}$

$r >> R_0 \qquad \sigma_{qq} \propto \sigma_0$

Unitarity bound built in and approach controlled by $R_0(x)$ – saturation radius



Jury is still out….

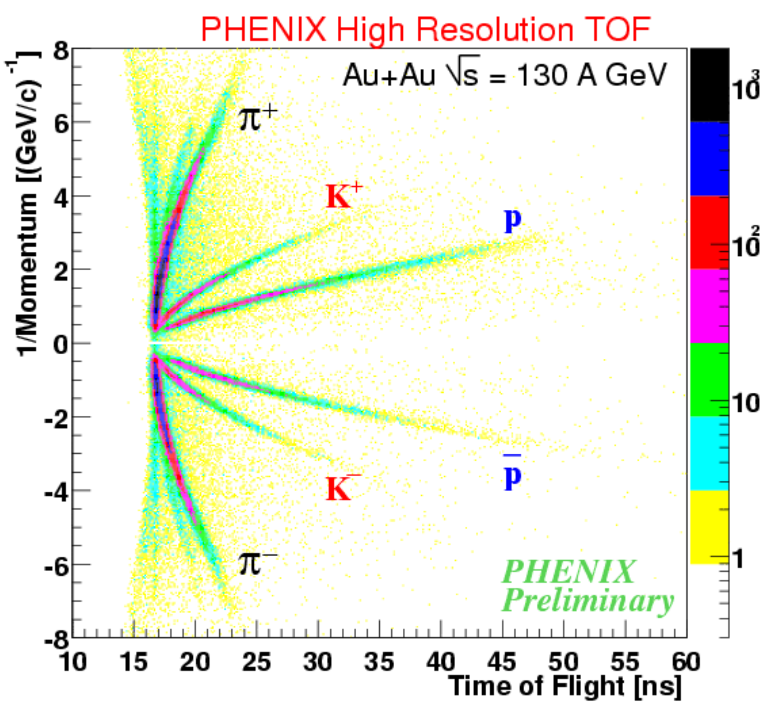
Color Dipole Model with Saturation shows excellent agreement with data, but

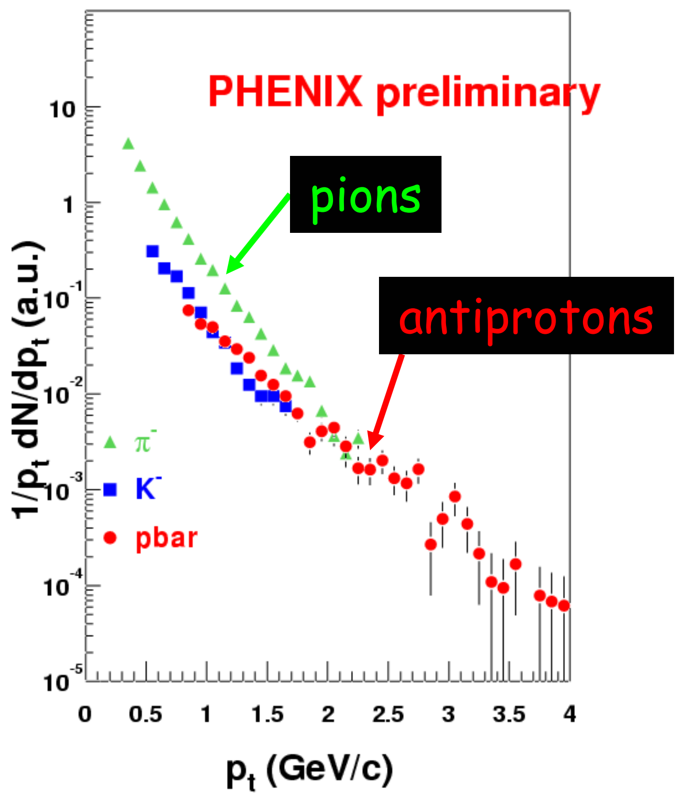
Standard NLO DGLAP fits also describe data at low *x* down to $Q^2 \sim 1.5\ GeV^2$

Golec-Biernat and Wuesthoff

Other Observations: Jet Fragmentation?

PHENIX identifies other hadrons via their time-of-flight. Pions are suppressed as seen before, but protons and antiprotons are not.



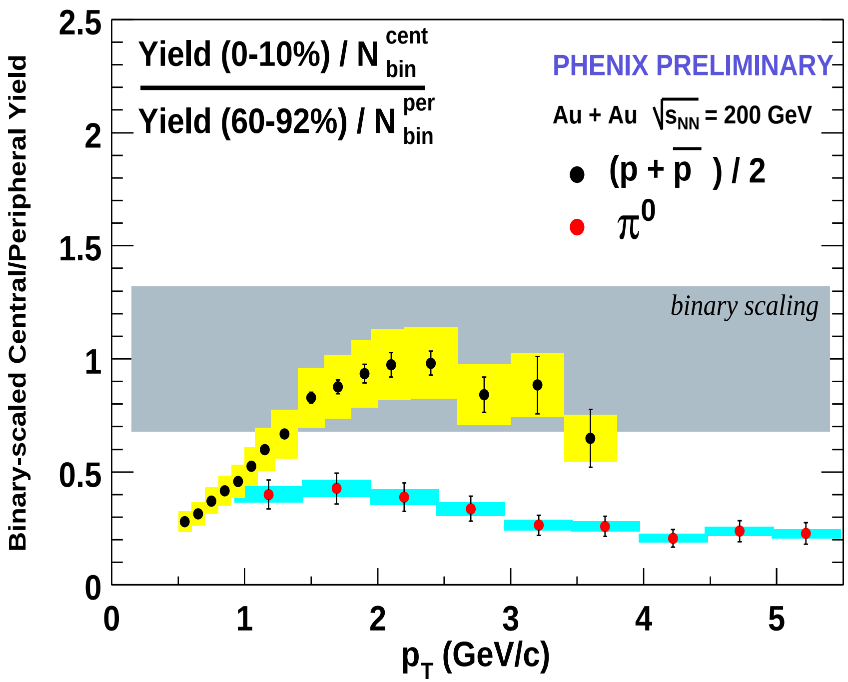


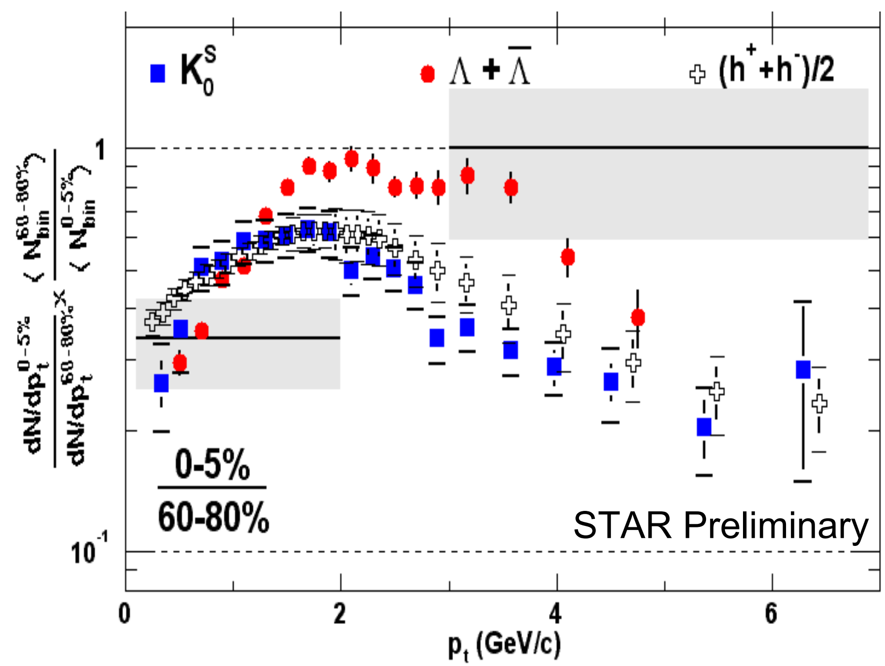
This is not the expected jet fragmentation function D(z).

Excess of Baryons at p_T ~ 1-4 GeV

Large ratio of baryons to mesons in the intermediate p_T
Opposite of fragmentation functions in e^+e^- and p-p(bar).

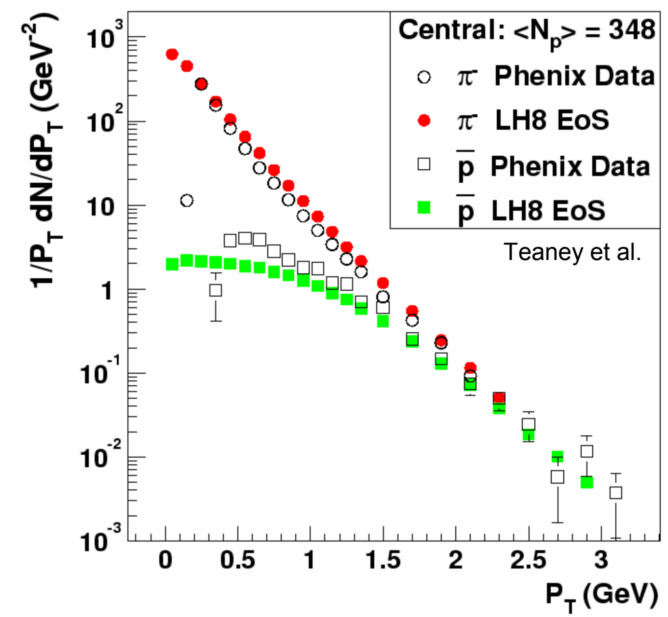
This baryon excess appears to go away at higher p_T.

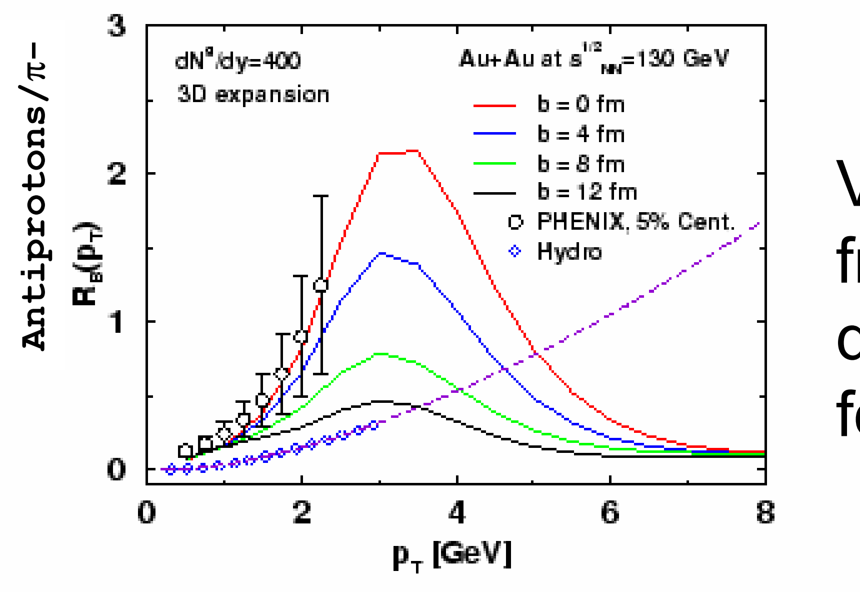




Boosted "Soft" Physics

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





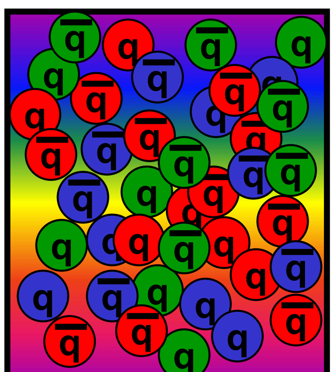
Vitev *et al.* predict that "hard" jet fragmentation eventually dominates over hydrodynamics for antiprotons above p_T~6 GeV

Recombination vs. Fragmentation

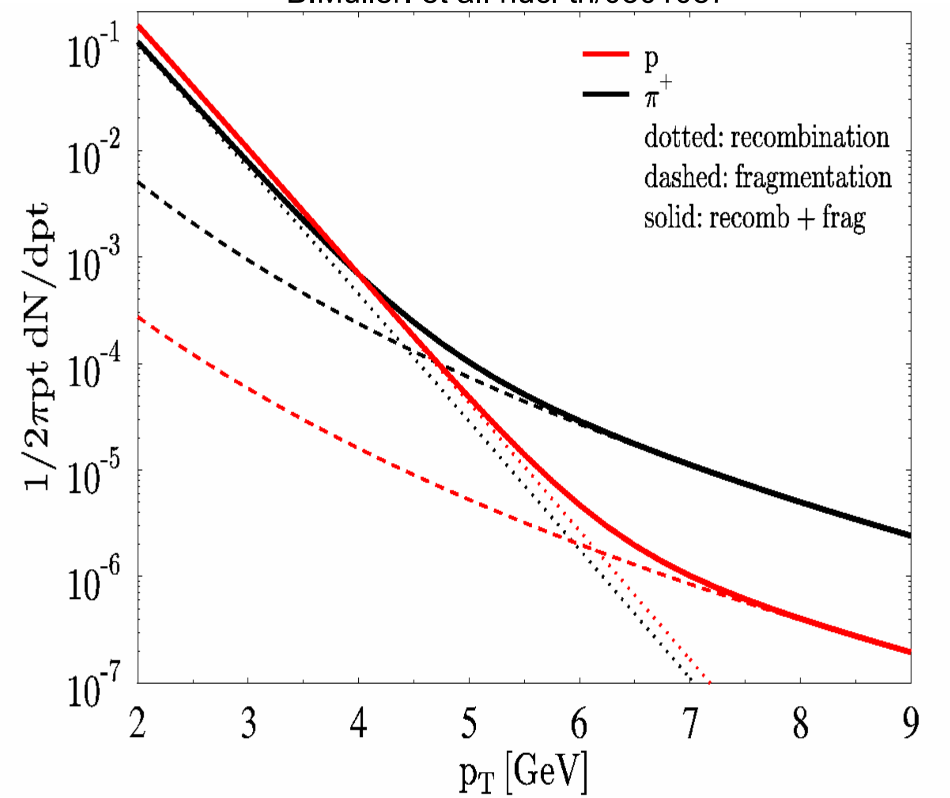
New picture put forth by D.Molnar *et al.* and B. Muller *et al.* speculate that in this dense partonic medium, color recombination dominates over hadron formation via fragmentation at intermediate p_T.

Fragmentation has scattered quark pairing with quark-antiquark or diquark-antidiquark pair from vacuum (B/M << 1).

Recombination has scattered quark pairing with other partons in medium (B/M ~ 1).



B.Muller. et al. nucl-th/0301087



Similar recombination models used to describe forward D meson production at FNAL. Not conclusive yet due to excited D state feed-down.

Deuteron-Nucleus Collisions

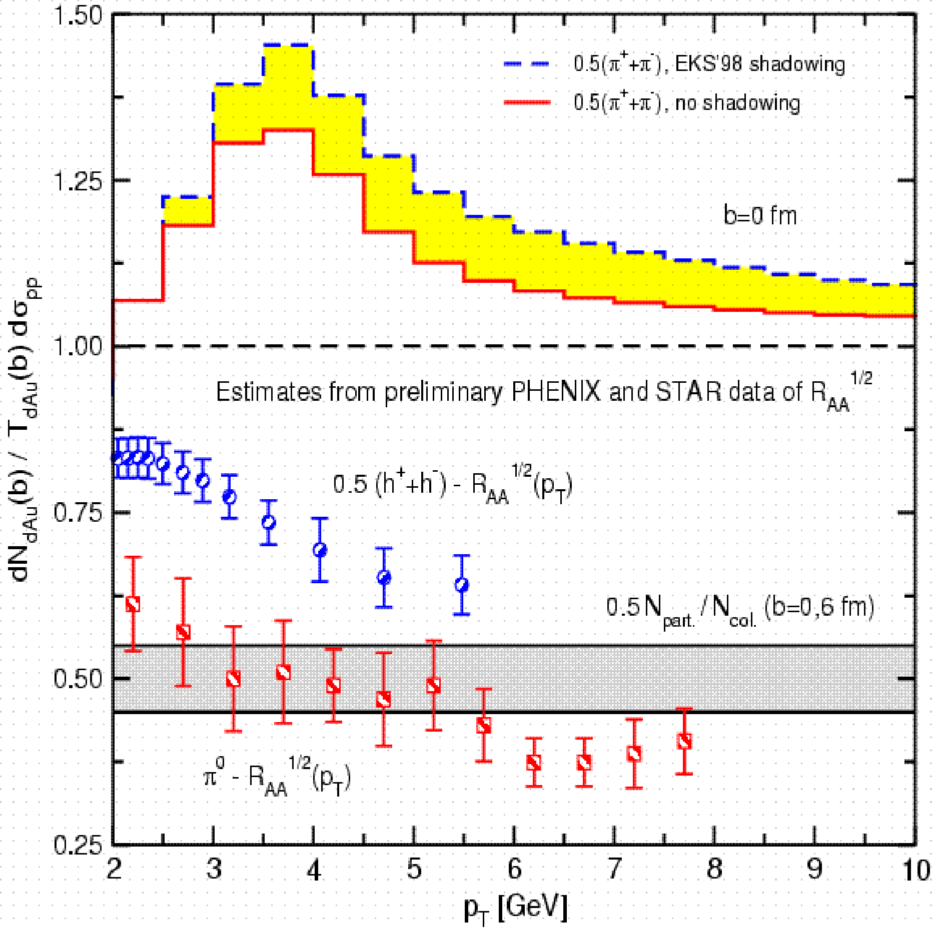
Two extreme opposite interpretations of RHIC data exists:

1) Evidence for opaque
   100 x nuclear density matter

2) Evidence for deep gluon
   shadowing (saturation)

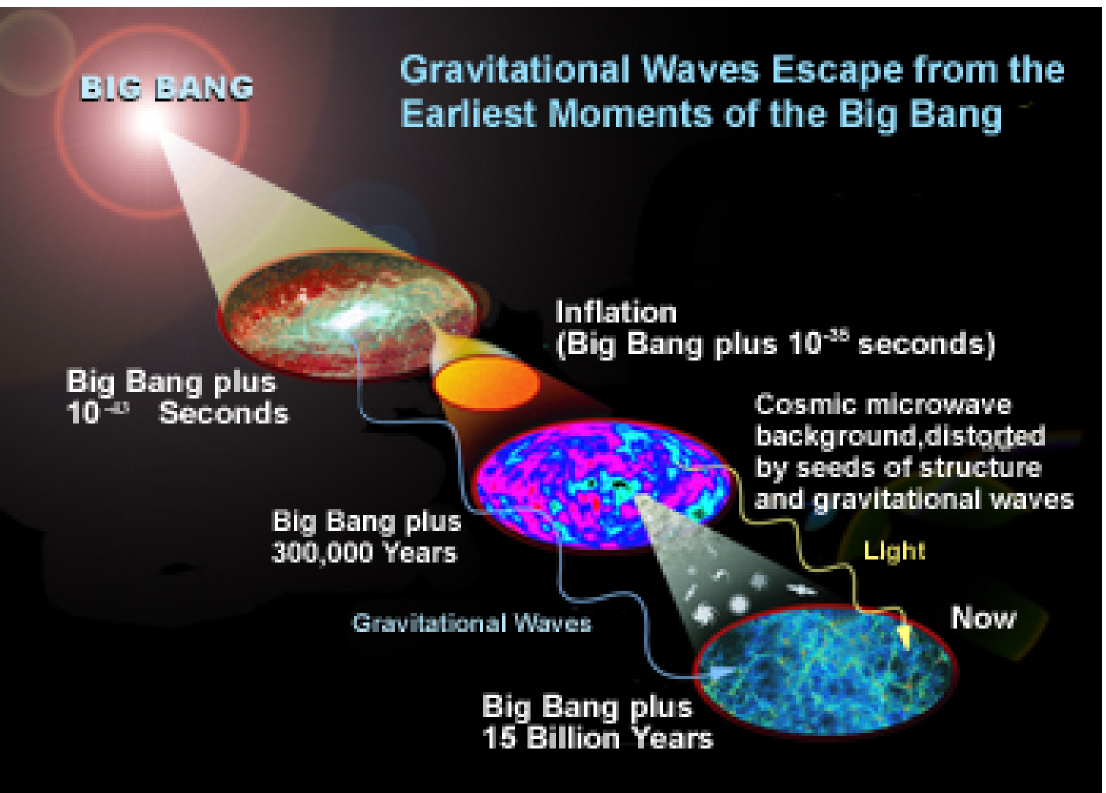
Deuteron-Nucleus data taken by PHENIX this winter should resolve the issue.

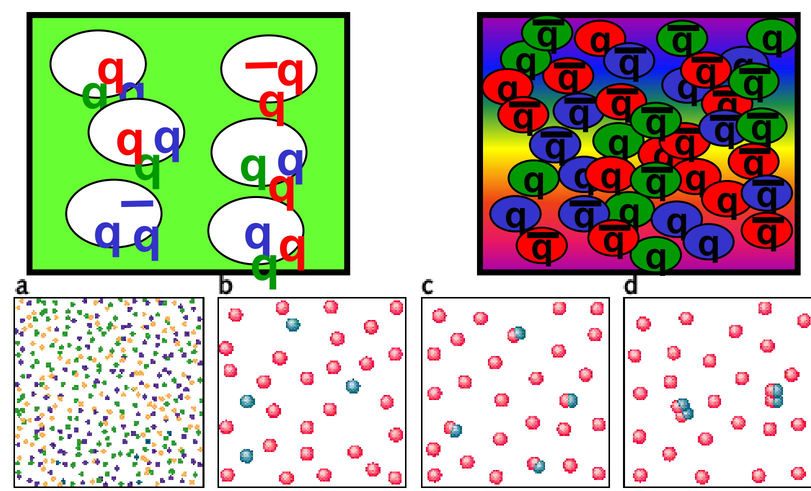
Another discriminator are direct photons (Justin Frantz thesis work).



Very Brief History of Time

Strong Interaction Transition
(Quarks and Gluons → Hadrons)
Big Bang Nucleosynthesis
Atom Formation

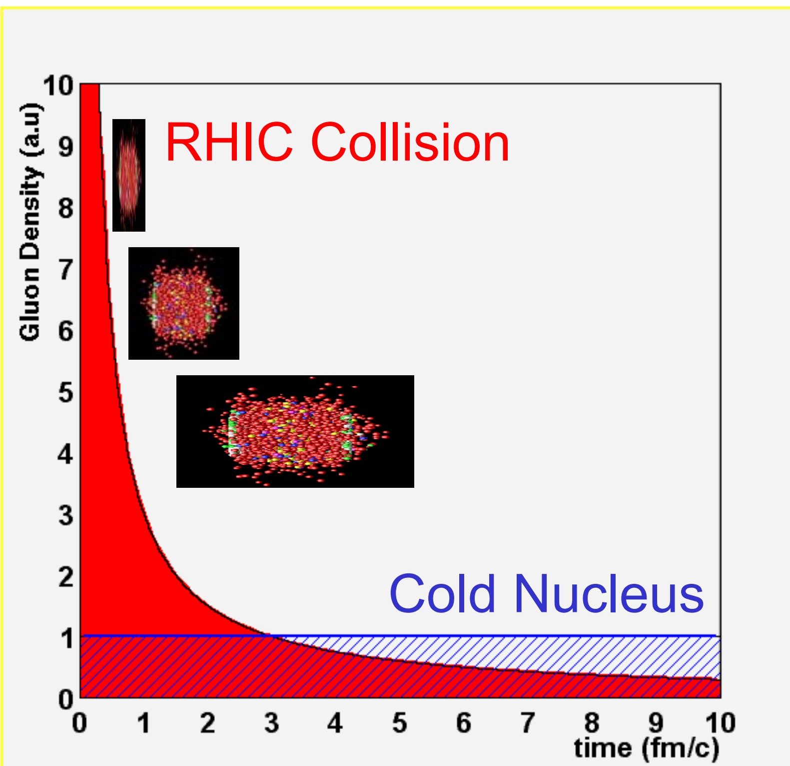




Expanding System Problem

Calculation of X.N. Wang implies <dE/dx> = 0.25 GeV/fm in hot nuclear matter (RHIC) and <dE/dx> = 0.3 GeV/fm in cold nuclear matter (HERMES)

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

<dE/dx> ~ 7 GeV/fm

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

Should it worry us that the large energy loss does not occur, but would have occurred if the system were static?