Has a new state of matter been observed at RHIC?
T. Csörgő, PHENIX Collaboration

RHIC Accelerator Complex and Detectors

What's in a name? What is RHIC?

Relativistic: something traveling at nearly the speed of light

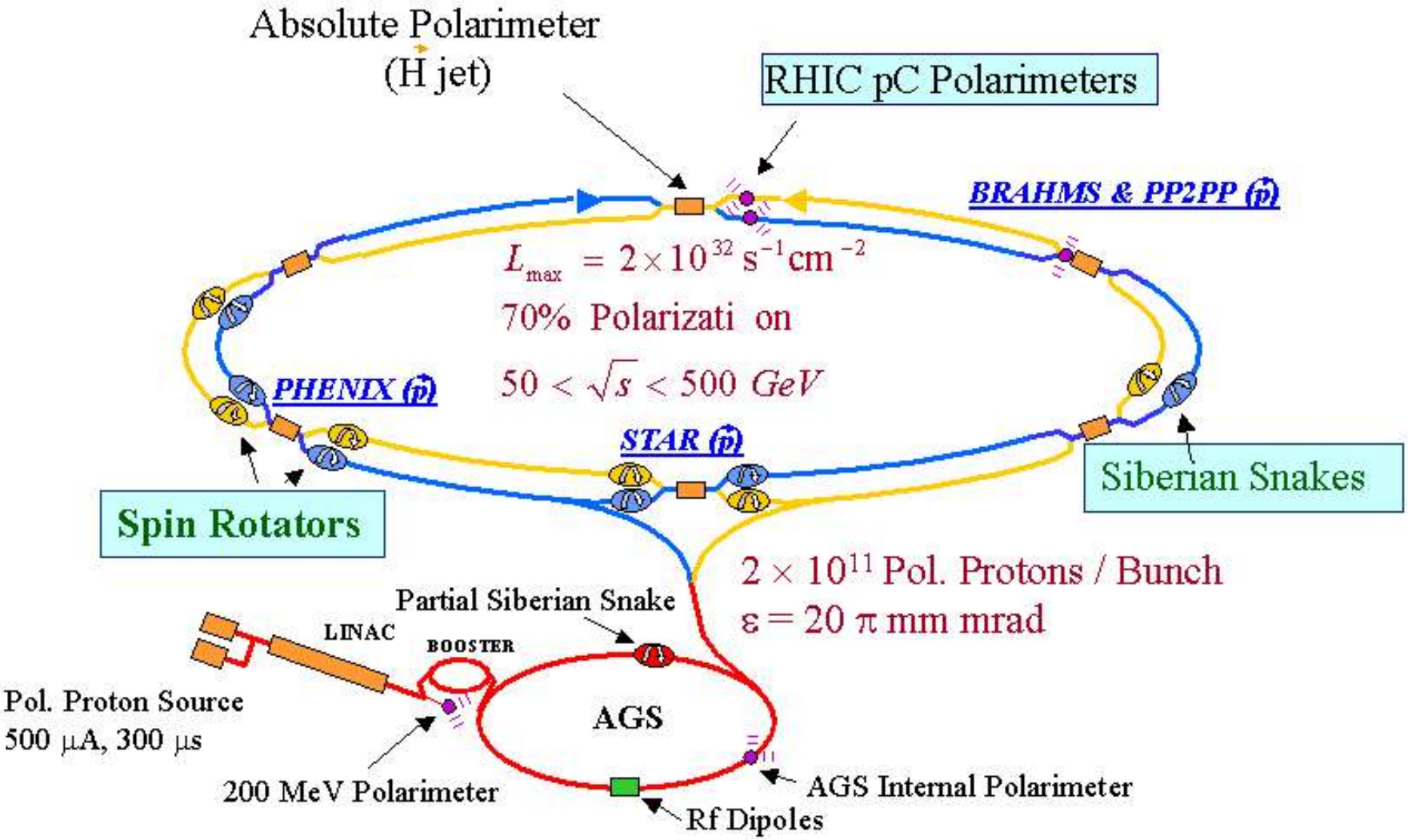
Heavy Ion: Typically fully-stripped gold ions (bare gold nucleii)

Collider: Two ion beams aimed at each other to hit head-on.

First four years of operation and plans for current run:

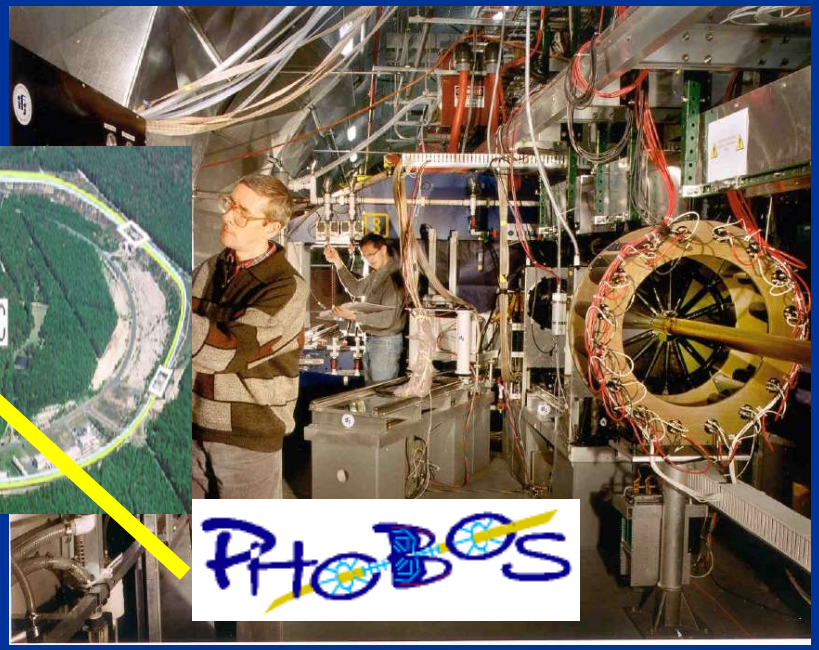
	Heavy-Ion Collisions	Polarized p (spin physics)
Run-1 (2000)	Au + Au at 130 GeV	
Run-2 (2001-2)	Au + Au at 200 GeV	p + p at 200 GeV
Run-3 (2002-3)	d + Au at 200 GeV	p + p at 200 GeV
Run-4 (2003-4)	Au + Au at 200, 62.4 GeV;	p + p at 200 GeV
Run-5 (2004-5)	Cu + Cu at 200 GeV;	p + p at 200 GeV

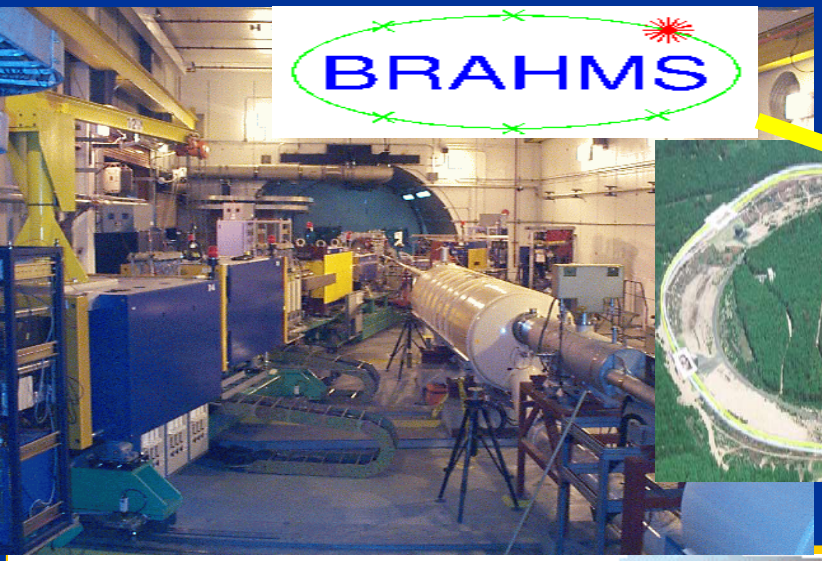
World's First Polarized Proton Collider

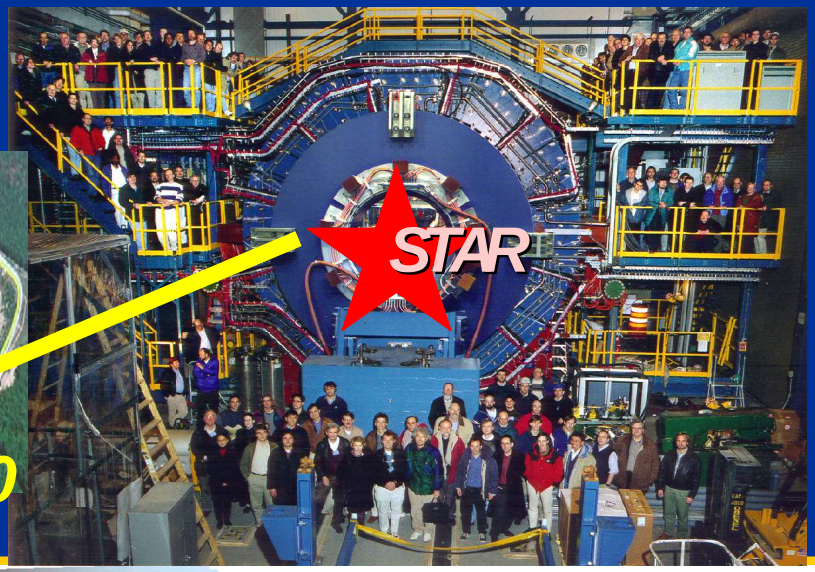


RHIC accelerates heavy ions to 100 GeV/A
and polarized protons to 250 GeV

RHIC Detectors (Collaborations): 2 large; 2 small

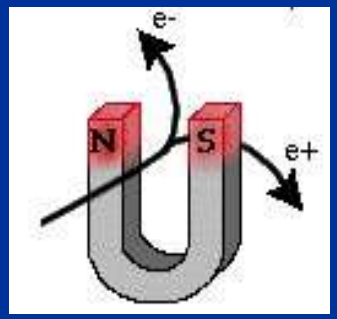




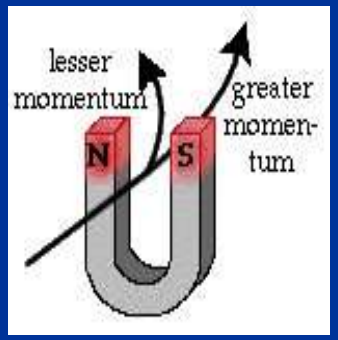


Tracking Detectors Measure Charge and Momentum

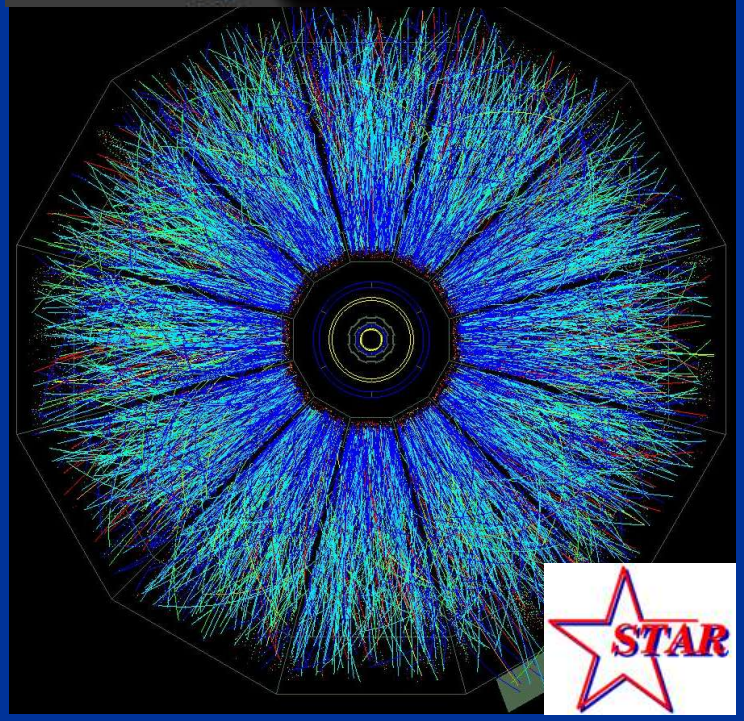
Event Displays



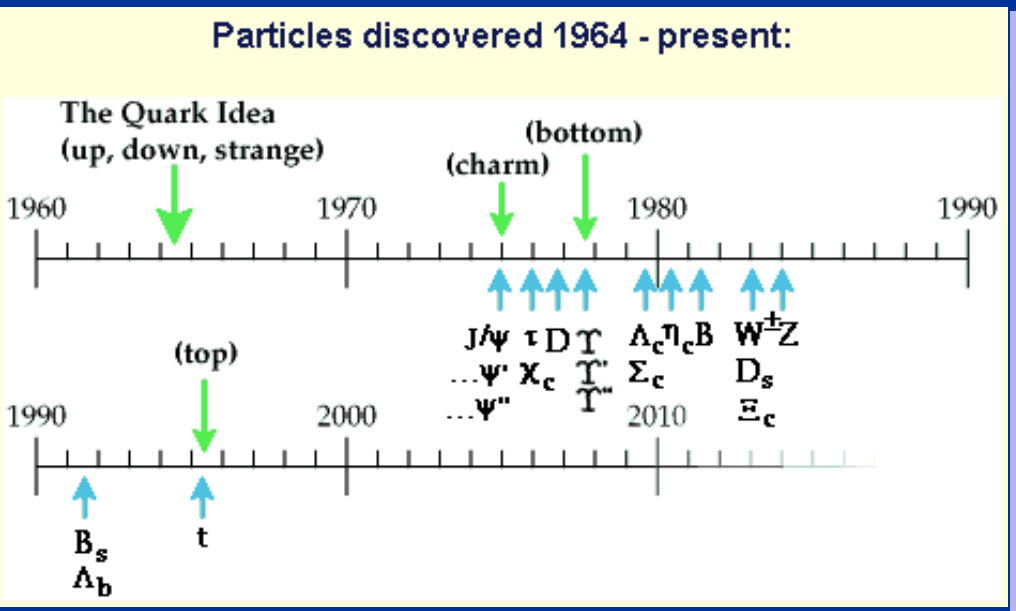
Left/Right tells charge

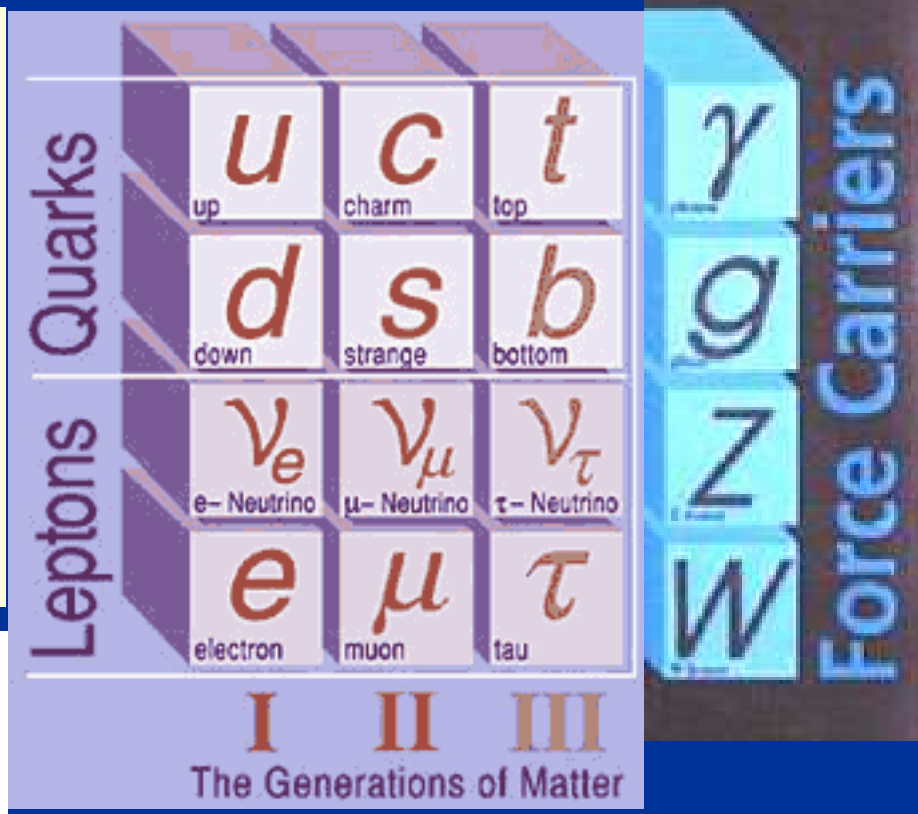


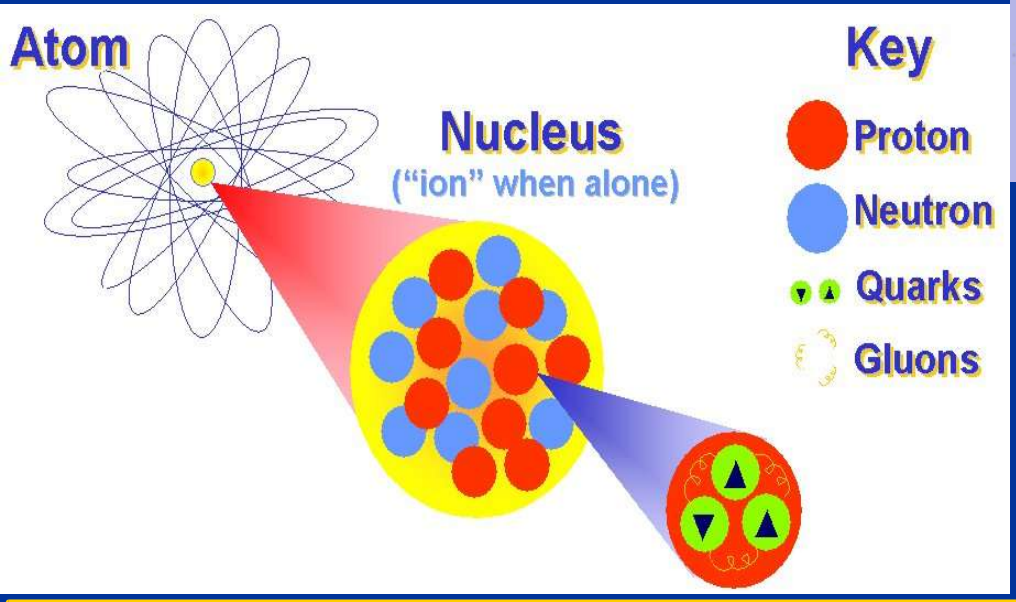
Curvature is proportional to 1/p



Quarks, Gluons, and Leptons







Proton

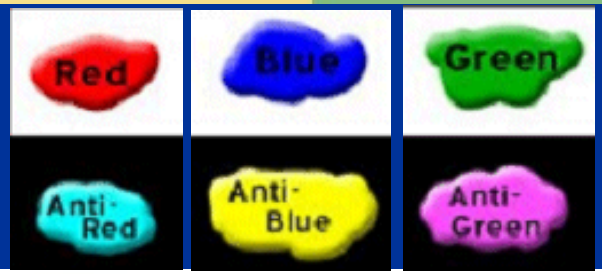
RHIC?

Hadrons: Baryons and Mesons

Sample Fermionic Hadrons
Baryons (qqq) and Anti-baryon ($\bar{q}\bar{q}\bar{q}$)

Symbol	Name	Quark Content	Electric Charge	Mass (GeV/c^2)	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	-1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2

	Fermions	Bosons	
Leptons and Quarks	Spin = $\frac{1}{2}$	Spin = 1*	Force Carrier Particles
Baryons (qqq)	Spin = $\frac{1}{2}$, $\frac{3}{2}$, $\frac{5}{2}$...	Spin = 0, 1, 2...	Mesons ($q\bar{q}$)



Sample Bosonic Hadrons
Mesons ($q\bar{q}$)

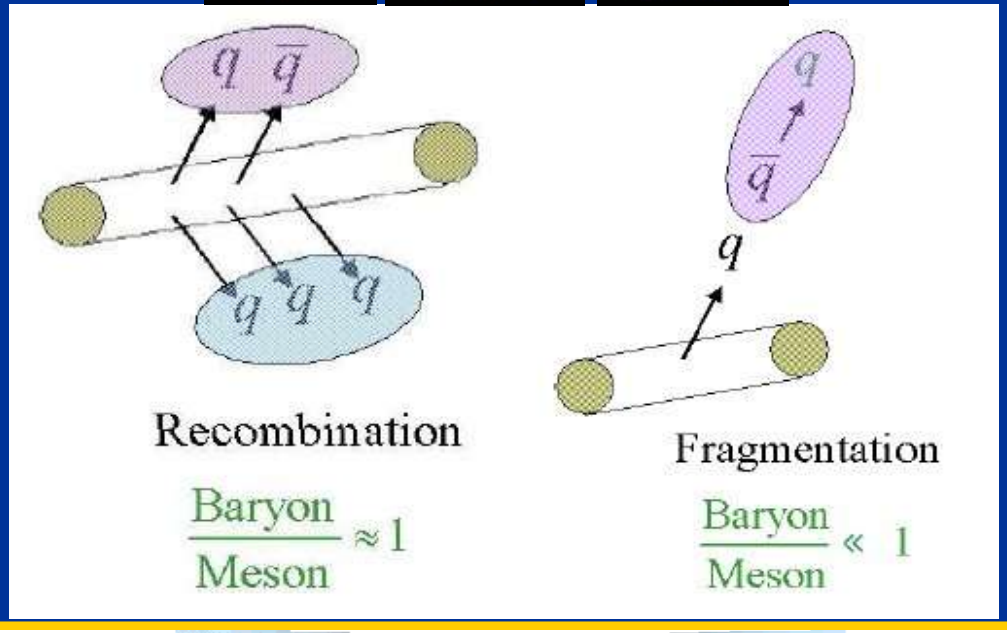
Symbol	Name	Quark Content	Electric Charge	Mass (GeV/c^2)	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	-1	0.494	0

Mesons

($q\bar{q}$)

Baryons

(qqq or $\bar{q}\bar{q}\bar{q}$)



2004 Nobel Prize in Physics for Asymptotic Freedom

http://www.physicstoday.org/vol-57/iss-10/nobel.html

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2004 jointly to

David J. Gross

David J. Gross
Kavli Institute for Theoretical Physics, University of California
Santa Barbara, CA, USA

H. David Politzer

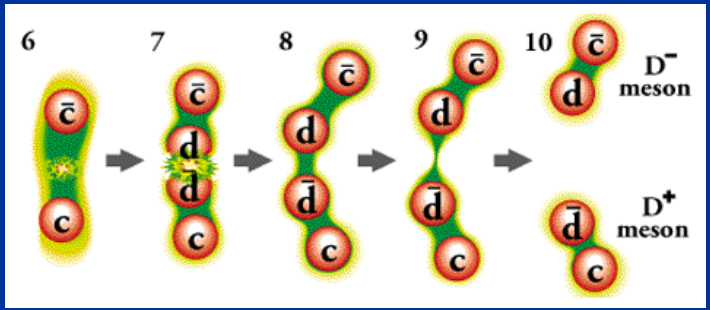
H. David Politzer
California Institute of Technology
Pasadena, CA, USA

Frank Wilczek
Massachusetts Institute of Technology (MIT)
Cambridge, MA, USA

Frank Wilczek

"for the discovery of asymptotic freedom in the theory of the strong interaction"

What Have We Learned From the Relativistic Heavy Ion Collider?
Thomas Ludlam and Larry McLerran
October 2003, page 48.



Disclaimer: slides are borrowed "whole hog"

Many of my much more expert colleagues have given similar talks.

Rather than borrow bits and pieces and give the impression that I have created all of the slides for this talk, I have chosen to borrow "whole hog" many of the slides from three excellent recent talks:

Recent Discoveries at RHIC:
Do They Indicate a New State of Matter?
Professor *William (Bill) Zajc*, Columbia University
(PHENIX Spokesperson)
General RHIC Colloquium, Fermilab (FNAL), July 30, 2003.

RHIC Colloquium, FNAL, July 30, 2003 ***W. A. (Bill) Zajc, Columbia***

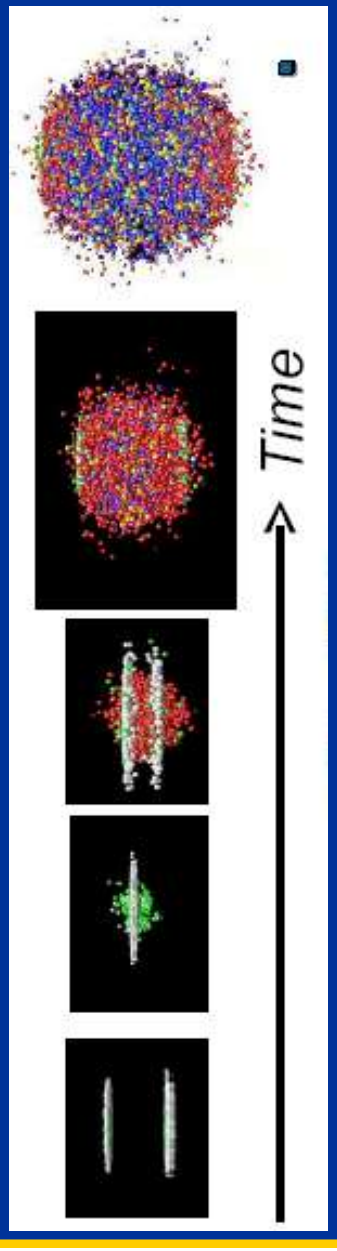
Status of QGP Search at RHIC: A PHENIX Perspective
Dr. *David d'Enterria*, Nevis Labs, Columbia University
Institute fur Kernphysik, Frankfurt, September 30, 2004

Inst. Kernphysik, Frankfurt, Sept. 30, 2004 ***David d'Enterria, Columbia***

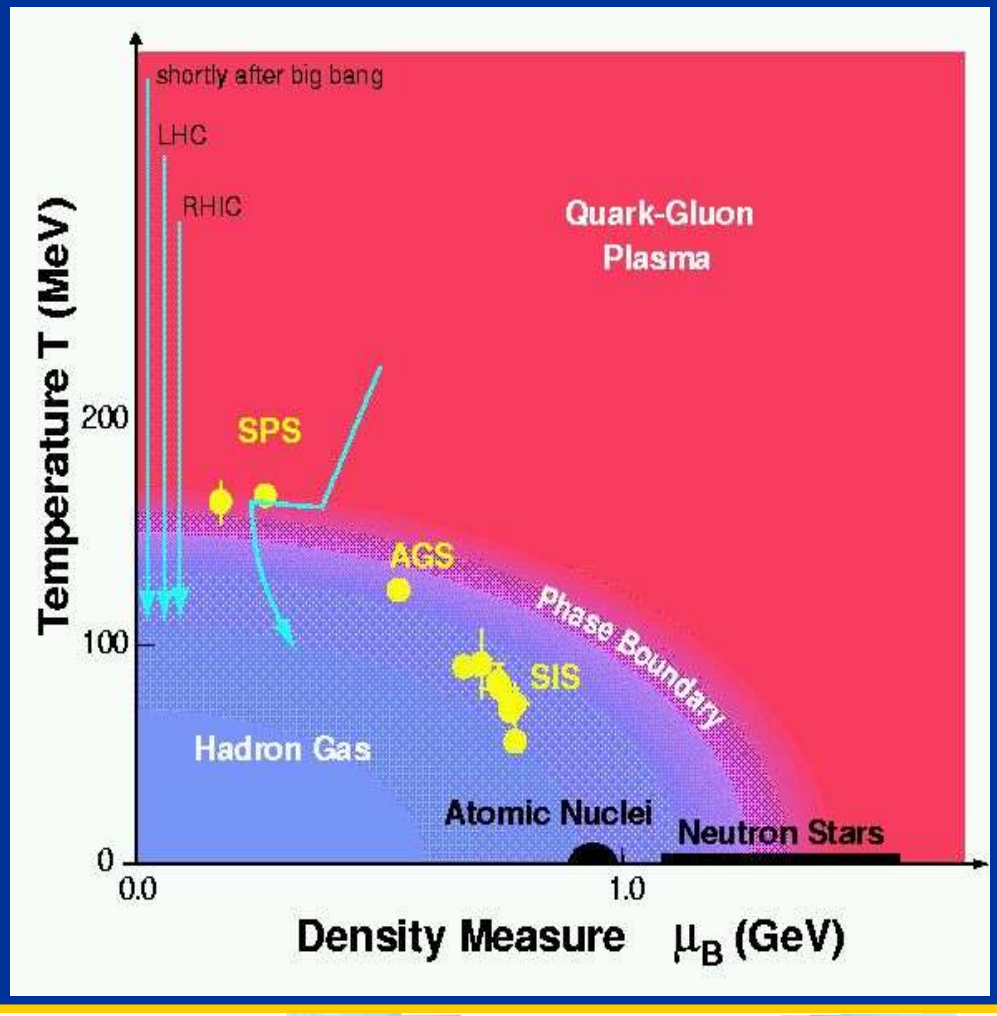
Has a new state of matter been observed at RHIC?
Professor *Brant M. Johnson* for the PHENIX Collaboration, BNL

CAARI, Oct 11, 2004 *Brant M. Johnson, BNL*

What is a Quark Gluon Plasma?



Phases of Matter: ***Quarks and gluons become deconfined as the temperature and/or density is increased through and beyond a phase boundary***

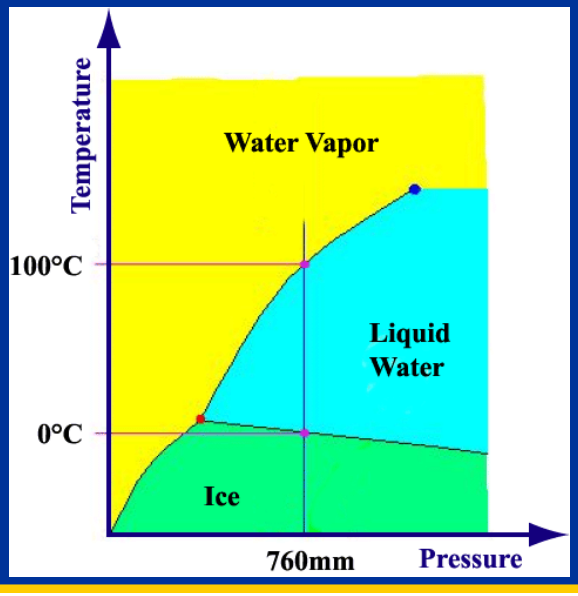


Phases of Water:

...Water Vapor

...Liquid Water

Ice ...



How did the universe come to be?

The U.S. High Energy Physics Advisory Panel (HEPAP) asked in

Quantum Universe: The Revolution in 21st Century Particle Physics:

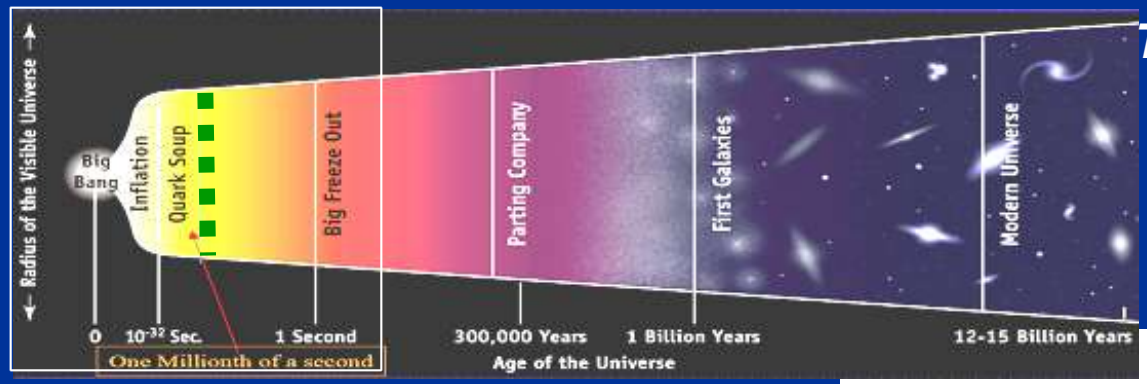
Question 8: How did the universe come to be?

Currently, the most intensely studied cosmic phase transition is connected with quantum chromodynamics (QCD), the theory of the nuclear force. During the QCD phase transition, the baryonic matter in the present universe condensed from a plasma-like state of quarks and gluons. The Relativistic Heavy Ion Collider (RHIC) facility at BNL is currently creating collisions of heavy ions to study quark-gluon plasma; the laboratory plans upgrades to enhance these studies.

The completion of RHIC at Brookhaven has ushered in a new era. Studies are now possible of the most basic interactions predicted by QCD in bulk nuclear matter at temperatures and densities great enough to excite the expected phase transition to a quark-gluon plasma.

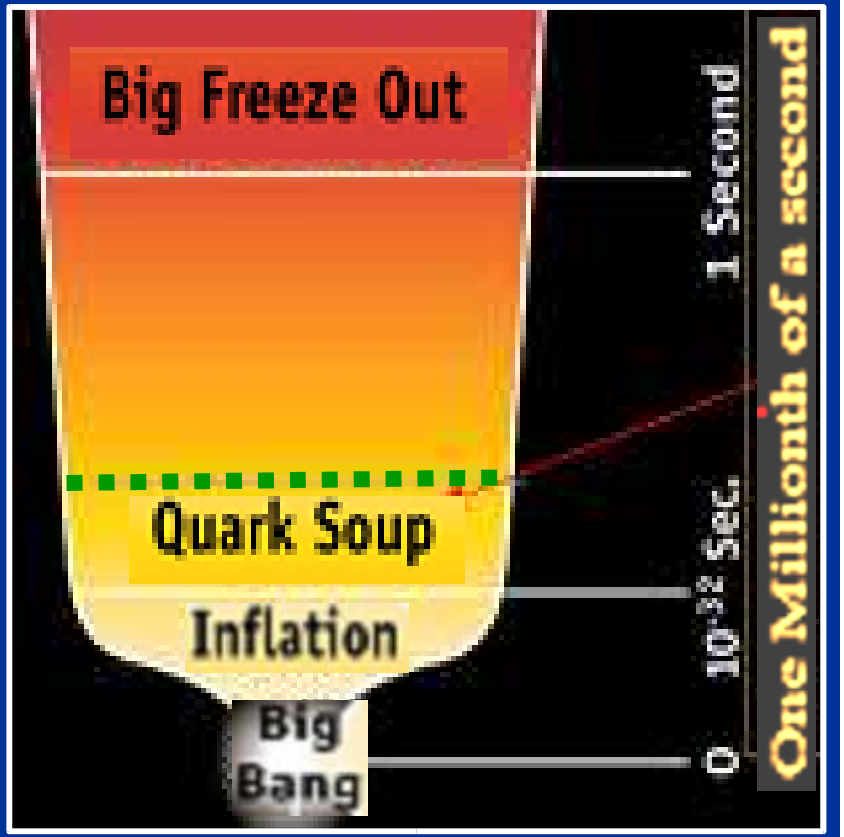
By colliding beams of ions from protons to gold, with center- of-mass energies from 20 to 200 GeV per nucleon pair, RHIC will create conditions favorable for melting the normal vacuum and creating states of matter unknown in the universe since the Big Bang.

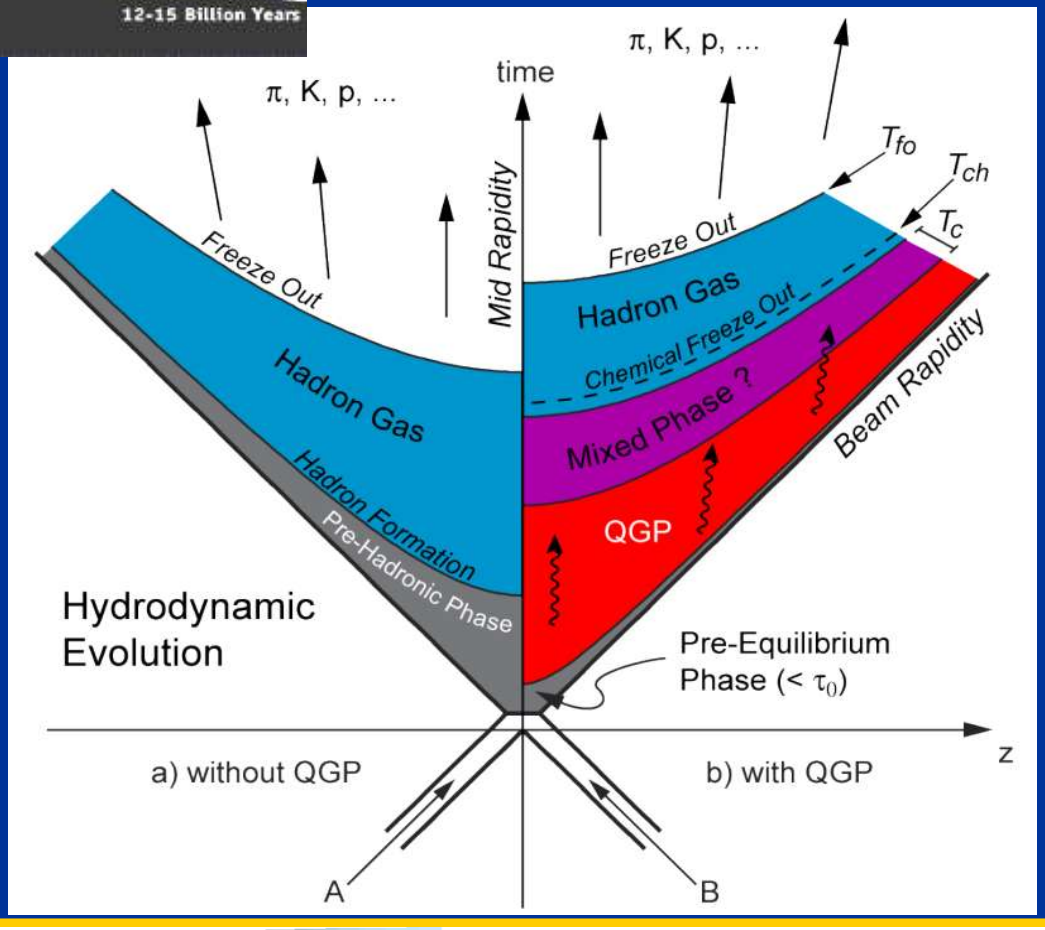
Physics at One Millionth of a Second After the Big Bang



Today is ~14 billion years later.

Most particles detected are hadrons after Freeze Out

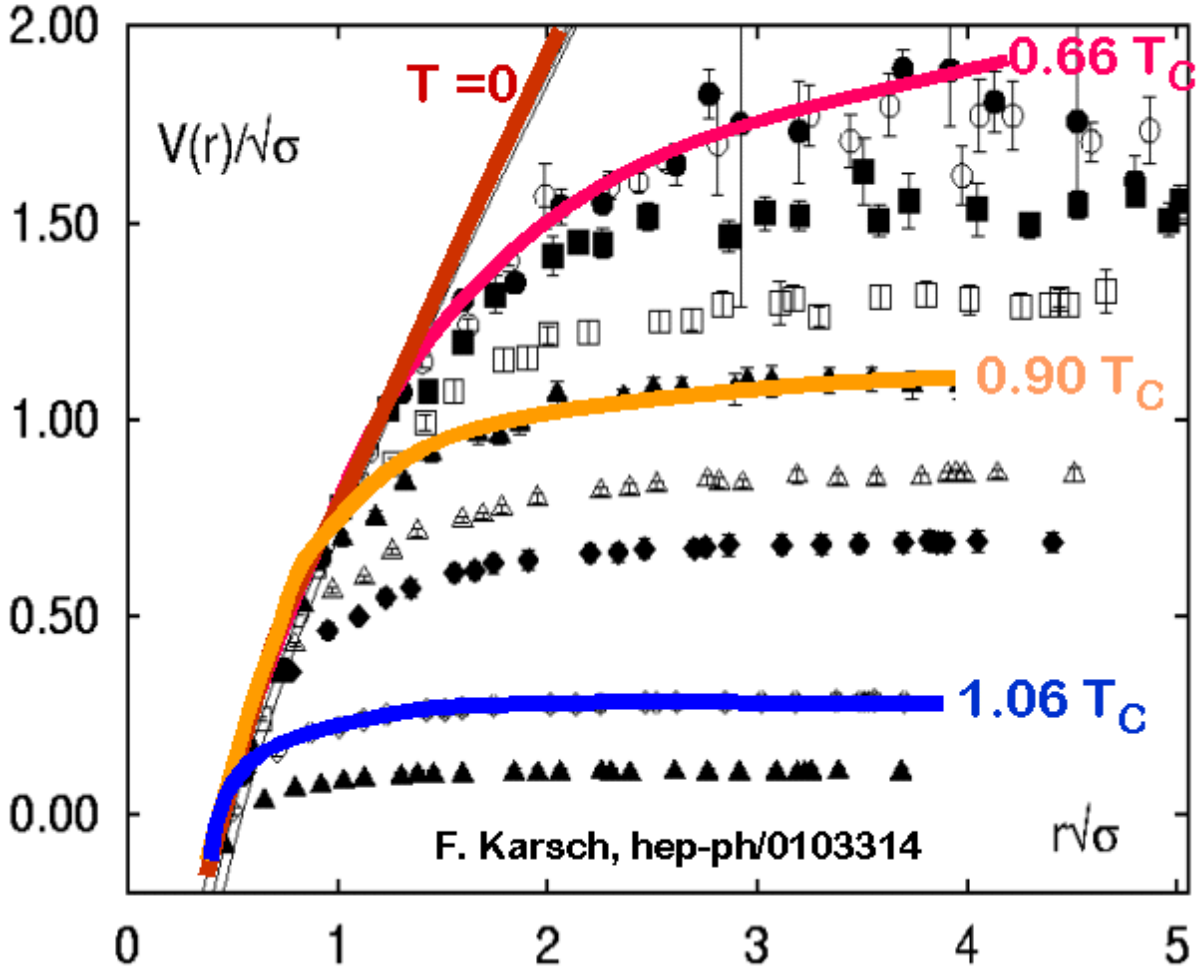




Theoretical Guidance

At a critical temperature (T_c) quarks and gluons become deconfined as the confining potential drops to zero

T_C = *Phase transition temperature* of QCD



Study confining potential in Lattice QCD at various temperatures

Current estimates from lattice calculations:

T_C ~ 150-170 MeV

L ~ 0.7±0.3 GeV / fm^3
(latent heat)

Questions Related to Formation of "New" State of Matter

- Are the Temperature and Energy Density High Enough?
- Are There Strong (Collective) Pressure Gradients?
- Is There Evidence of a Dense Final-State System?
- Is the Thermalization Time Realistic?
- Is the System Chemically Equilibrated?
- Is There Evidence for Quark Recombination?

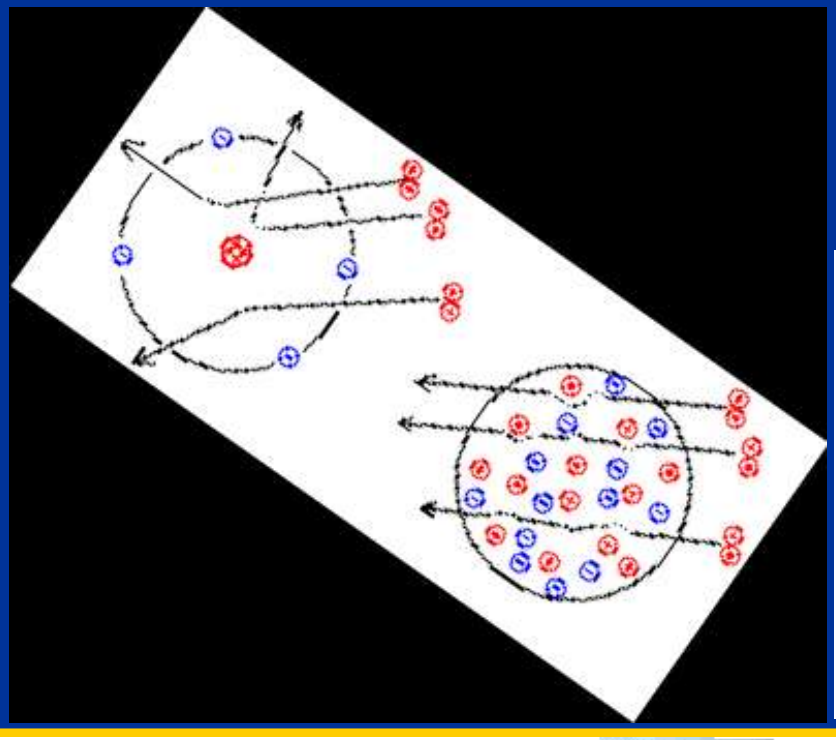
Experiment: Sole Judge of Scientific Truth

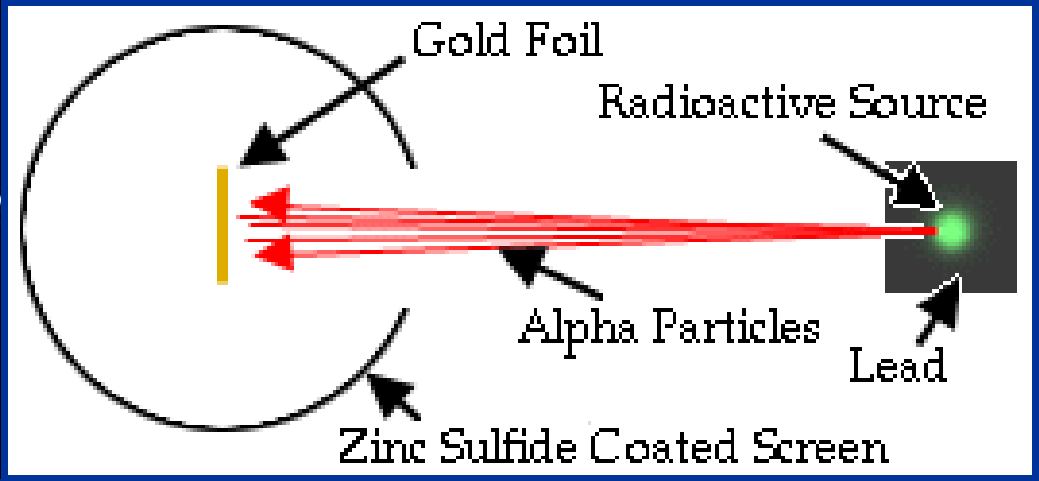
The test of all knowledge is experiment.
EXPERIMENT is the SOLE JUDGE of SCIENTIFIC TRUTH.

-- Richard P. Feynman

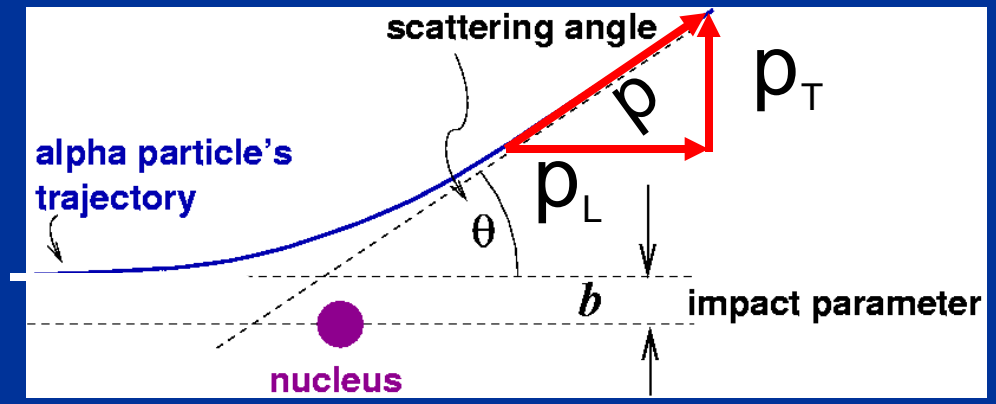
This is especially true when a model or theory is falsified.

Example: Rutherford Scattering Falsified the Plum Pudding Model





Soft and Hard Scattering



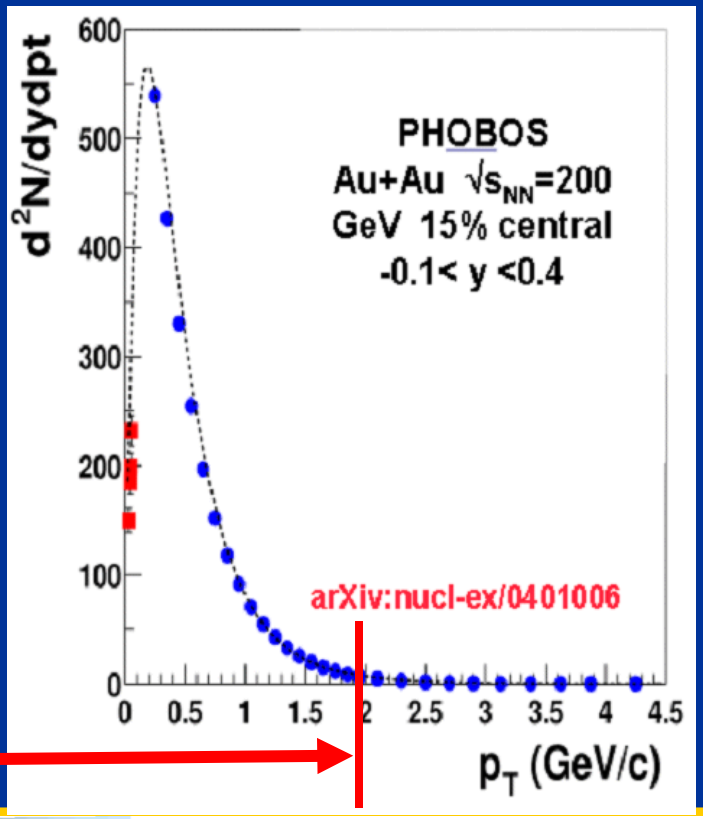
Transverse Momentum p_T

Longitudinal Momentum

Soft Scattering:
Low p_T like in plum pudding model prediction.

Hard Scattering:
High p_T, like in Rutherford scattering results.

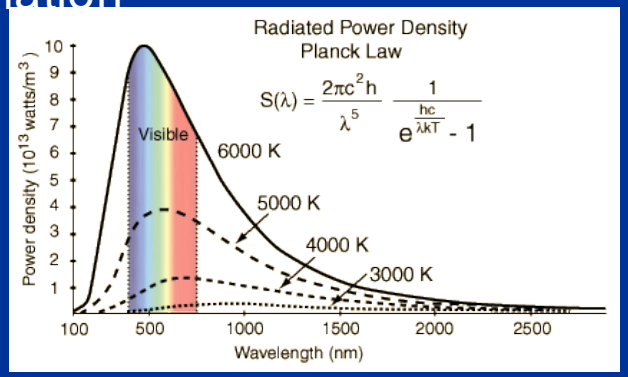
⇒Hard scattering implies substructure

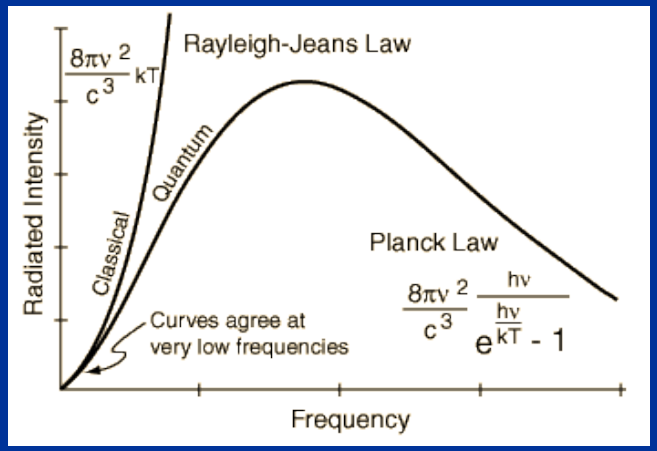


Most particles Produced at RHIC are "Soft" (Low p_T)

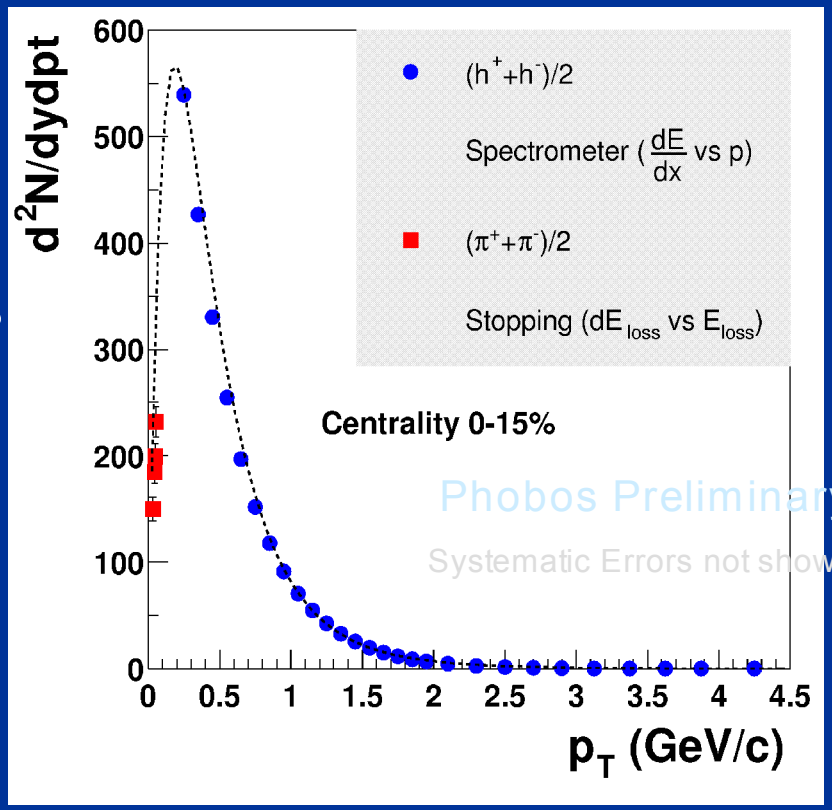
Is the Temperature (T) High Enough? Yes!

Planck distribution describes intensity as a function of the wavelength of emitted radiation





"Blackbody" radiation is the spectrum of radiation emitted by an object at temperature T



From transverse momentum distribution deduce temperature of 120 MeV or 1 trillion K

$$T = \frac{2E}{3k} = \frac{2 \times 120 \times 10^6 eV}{3 \times 1.4 \times 10^{-23} J/K} \times \frac{1.6 \times 10^{-19} J}{1 eV} = 930 \times 10^9 K$$

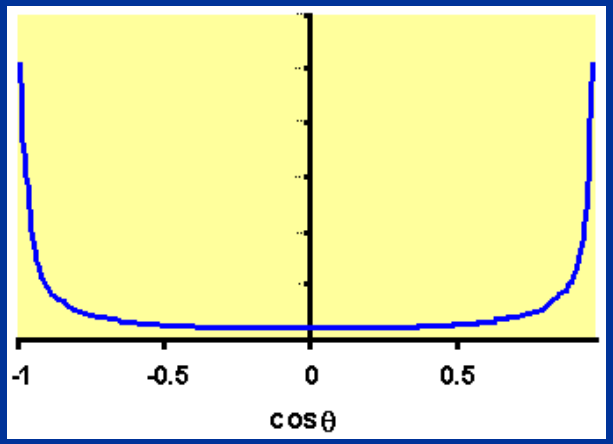
Courtesy: Dave Morrison, BNL

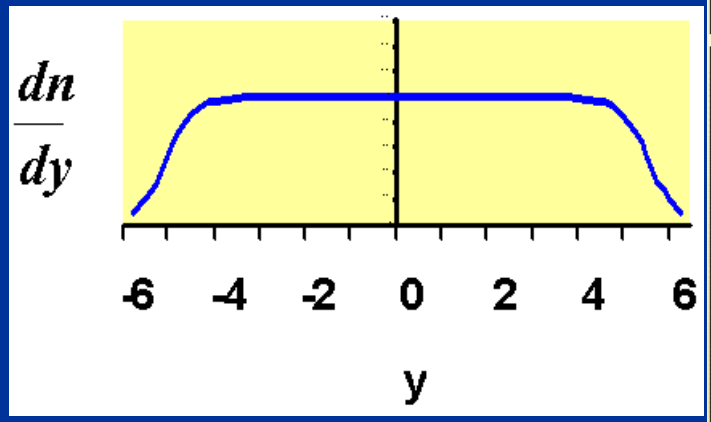
Kinematics: Angle (θ), Rapidity (y), Psuedorapidity (η)

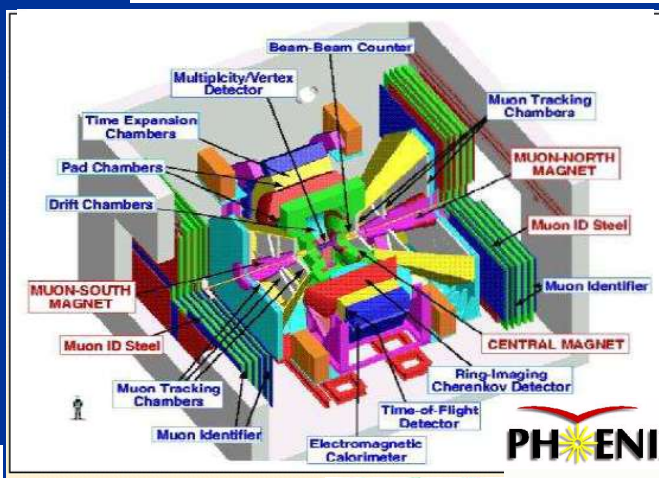
$$y \equiv \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right) \approx \frac{1}{2}\ln\left(\frac{1+\cos\vartheta}{1-\cos\vartheta}\right) \equiv \eta$$

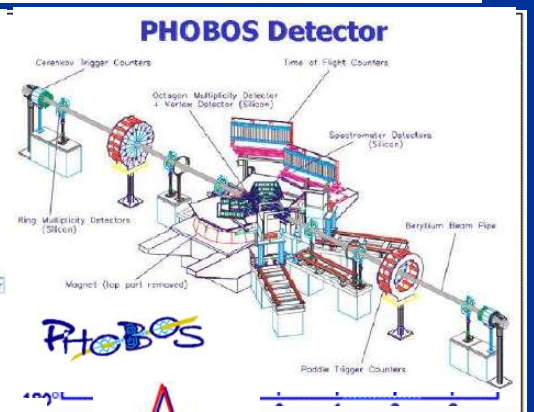
$$\Rightarrow \frac{dn}{d(\cos\vartheta)} \rightarrow \frac{dn}{dy} \approx \frac{dn}{d\eta}$$

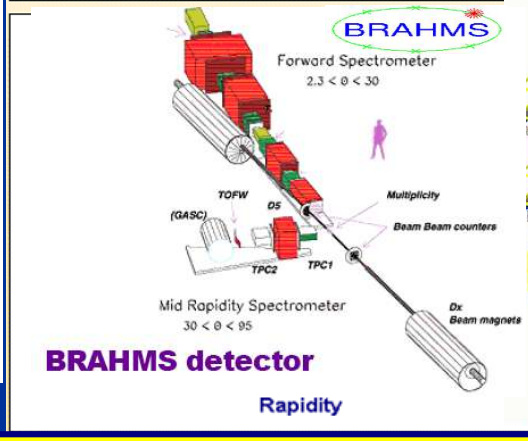
$$\frac{dn}{d(\cos\theta)}$$

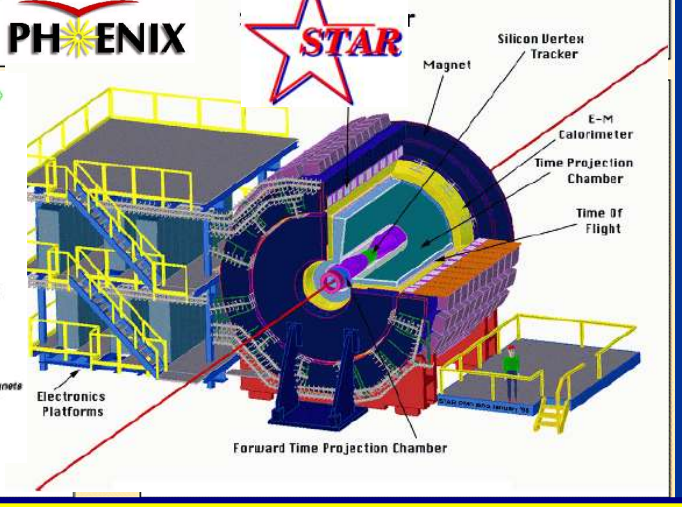






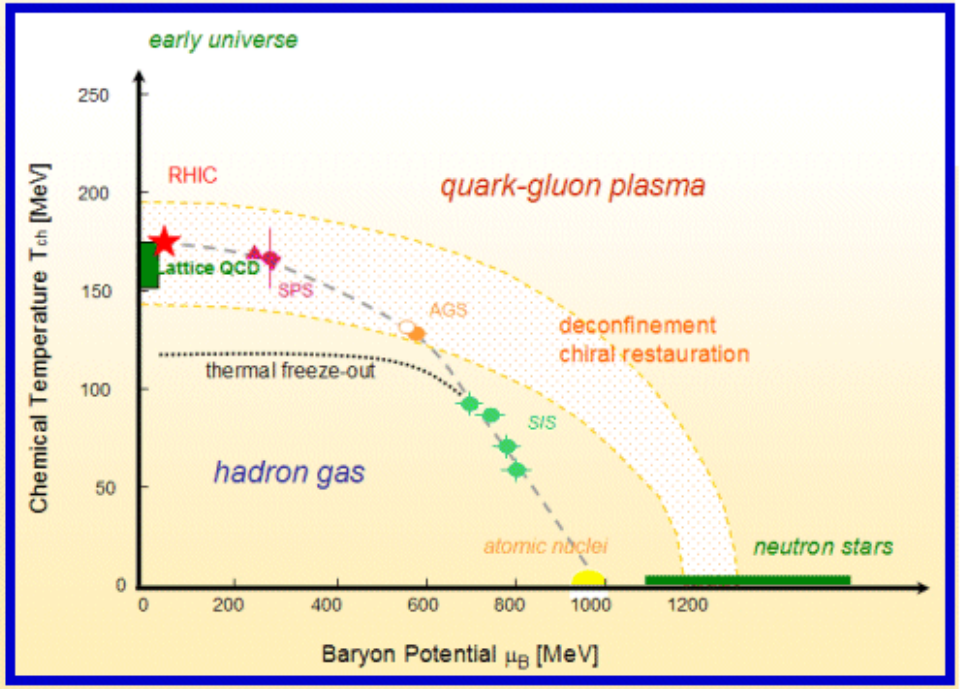


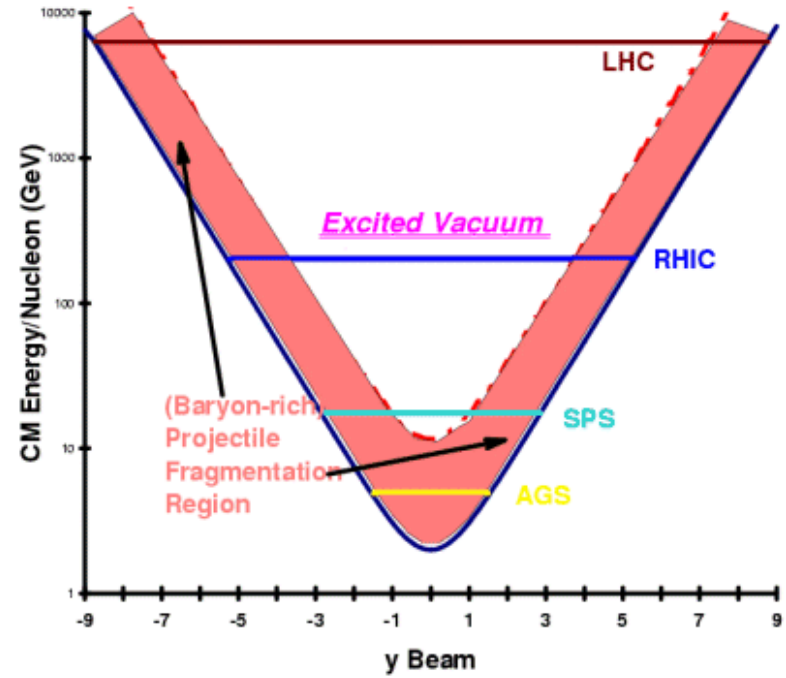


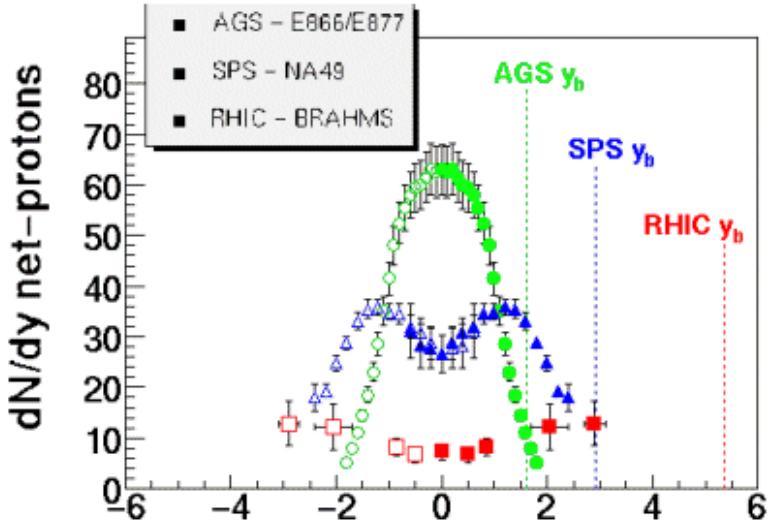


Longitudinal Dynamics

- From the RHIC design manual:
  - Emphasis on higher beam energy needed to develop "baryon-free" central region
  - This theoretical argument is nicely confirmed by measurements from BRAHMS

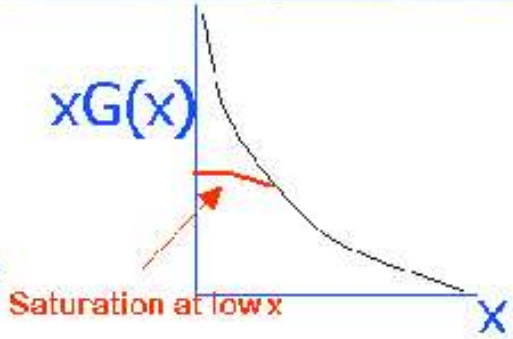


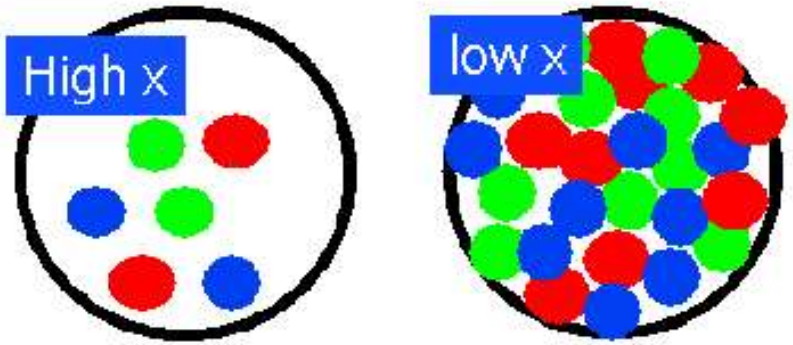


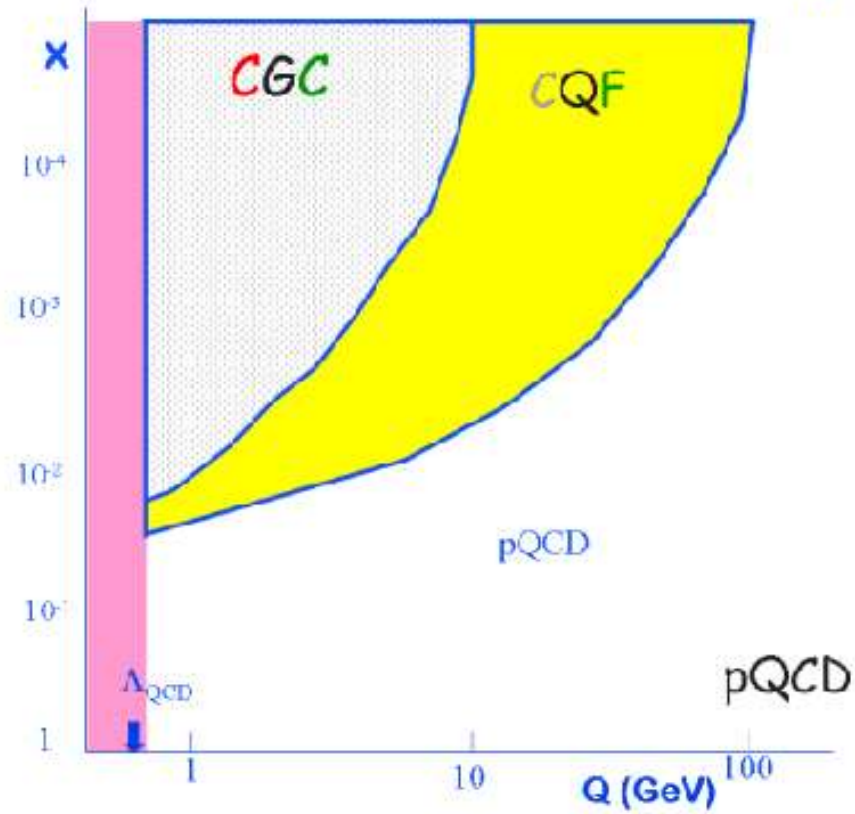


High Parton Densities in Nuclear Matter

- ✓ QCD - High Gluon Densities at low-x
  - » Onset of gluon saturation?
  - » Initial conditions in Au+Au?
- ✓ Classical Approx → Color glass condensate
  - » McLerran, Venugopalan, et al.
  - » Depends on a single scale
    - – $Q_s^2 \propto A^{1/3} \sim (1\text{-}2\ \text{GeV})^2$ at RHIC
  - » Is this the correct theory at RHIC?
  - » Where are the boundaries?







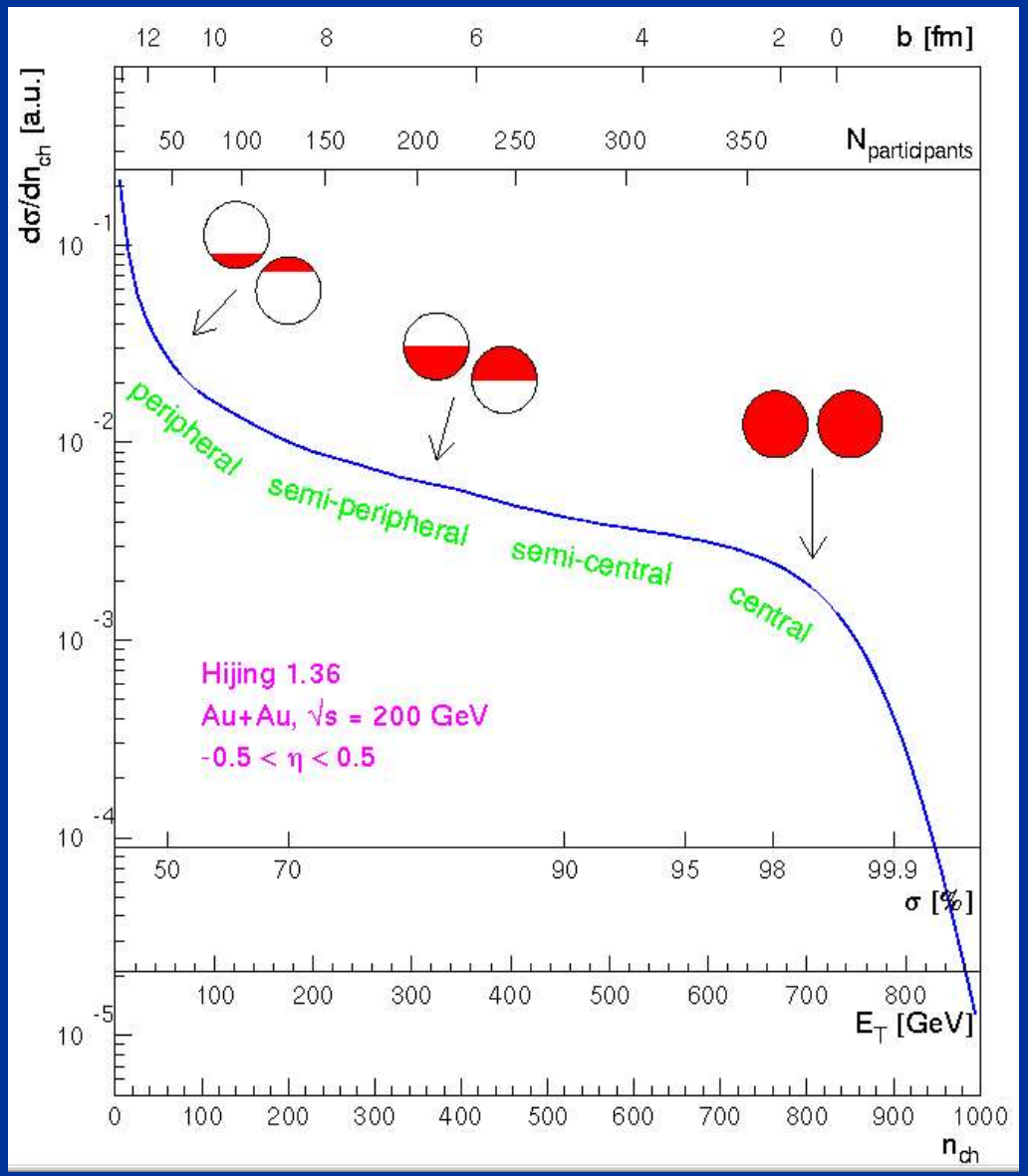
PHENIX

K. Barish

Multiplicity and Centrality

Multiplicity:

A large number or wide range (of something). At RHIC: the something is particles



Centrality:

The state of being central; tendency towards a center.

RHIC collisions are:

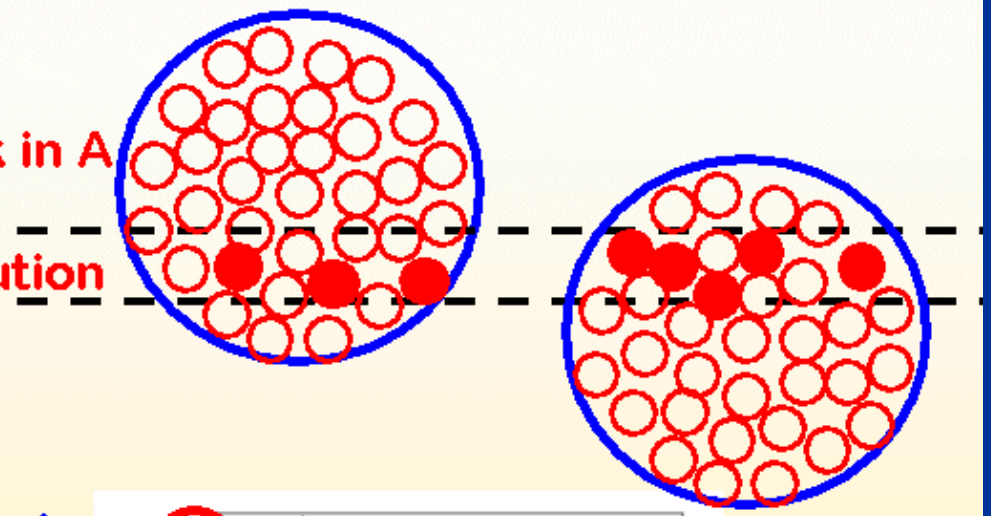
peripheral

semi-central

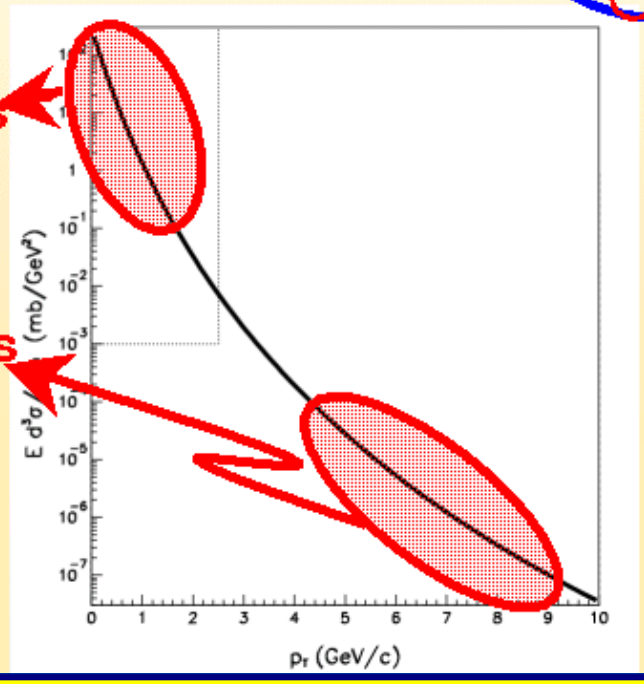
most central.

Number of Participants (N_{part}) and Collisions ($_{Ncoll}$)

- Focus on some slice of collision:
  - Assume 3 nucleons struck in A and 5 in B
  - Do we weight this contribution as
    - N_{part} (= 3 + 5) ?
    - N_{coll} (= 3 x 5) ?



- Answer is a function of p_T :
  - Low p_T ➡ large cross sections ➡ yield ~N_{part}
    - Soft, non-perturbative, "wounded nucleons", …
  - High p_T ➡ small cross sections ➡ yield ~N_{coll}
    - Hard, perturbative, "binary scaling", point-like, A*B, …

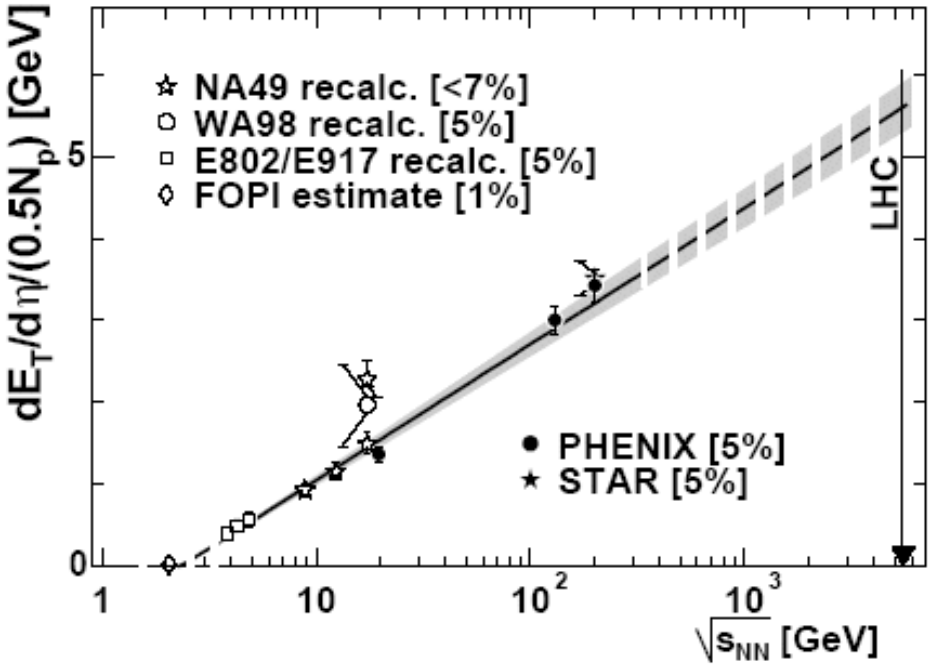


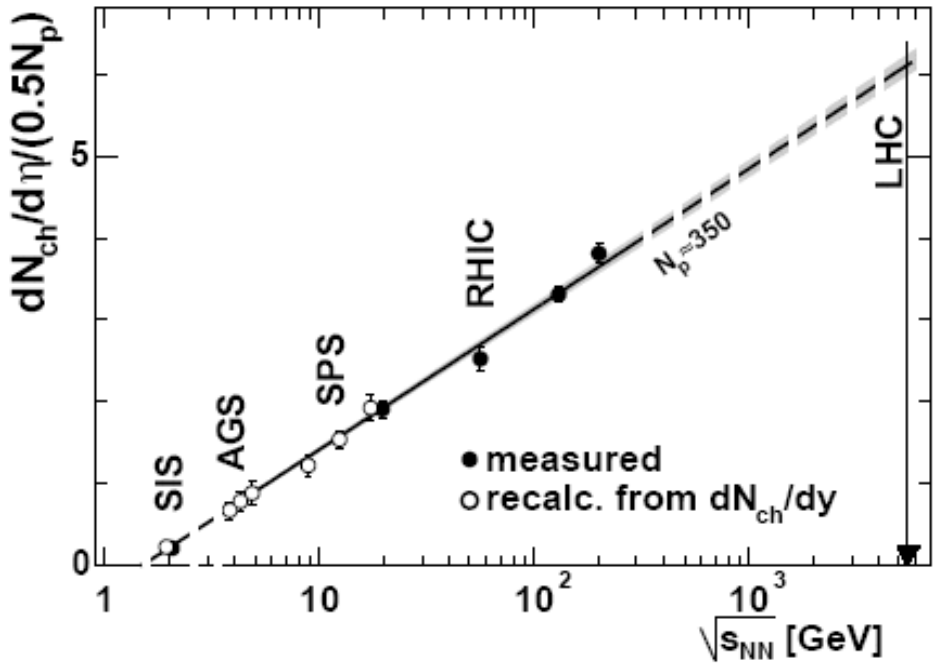
30-Jul-03

W.A. Zajc

Gobal Measurements: E_T and N_{ch}

Total Transverse Energy (E_T) and No. of Charged Particles (N_{ch})





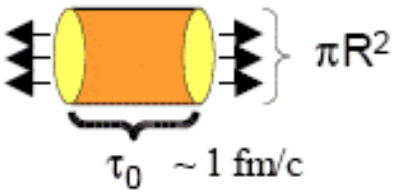
Systematic Studies of the Centrality and $\sqrt{s_{NN}}$ Dependence of $dE_T/d\eta$ and $dN_{ch}/d\eta$ in Heavy Ion Collisions at Mid-Rapidity, S.S. Adler, et. al, PHENIX Collaboration

Submitted to Physical Review C **nucl-ex/0409015**

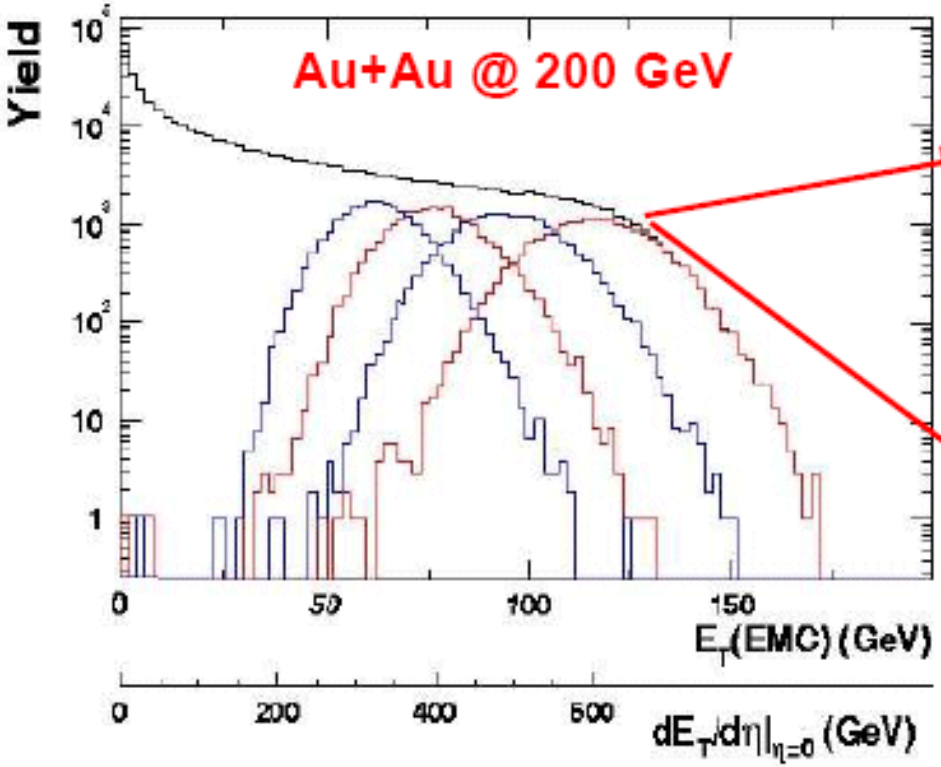
Is the Energy Density (ε) High Enough? Yes!

- Bjorken estimate: $\epsilon_{Bj} = \frac{dE_T}{dy}\frac{1}{\tau_0 \pi R^2}$

  (longitudinally expanding plasma)



- $dE_T/d\eta$ at mid-rapidity measured by calorimetry (using PHENIX EMCal as *hadronic* calorimeter: $E_T^{had} = (1.17 \pm 0.05)\, E_T^{EMCal}$)



$\langle dE_T/d\eta \rangle$ ~ 600 GeV (top 5% central)

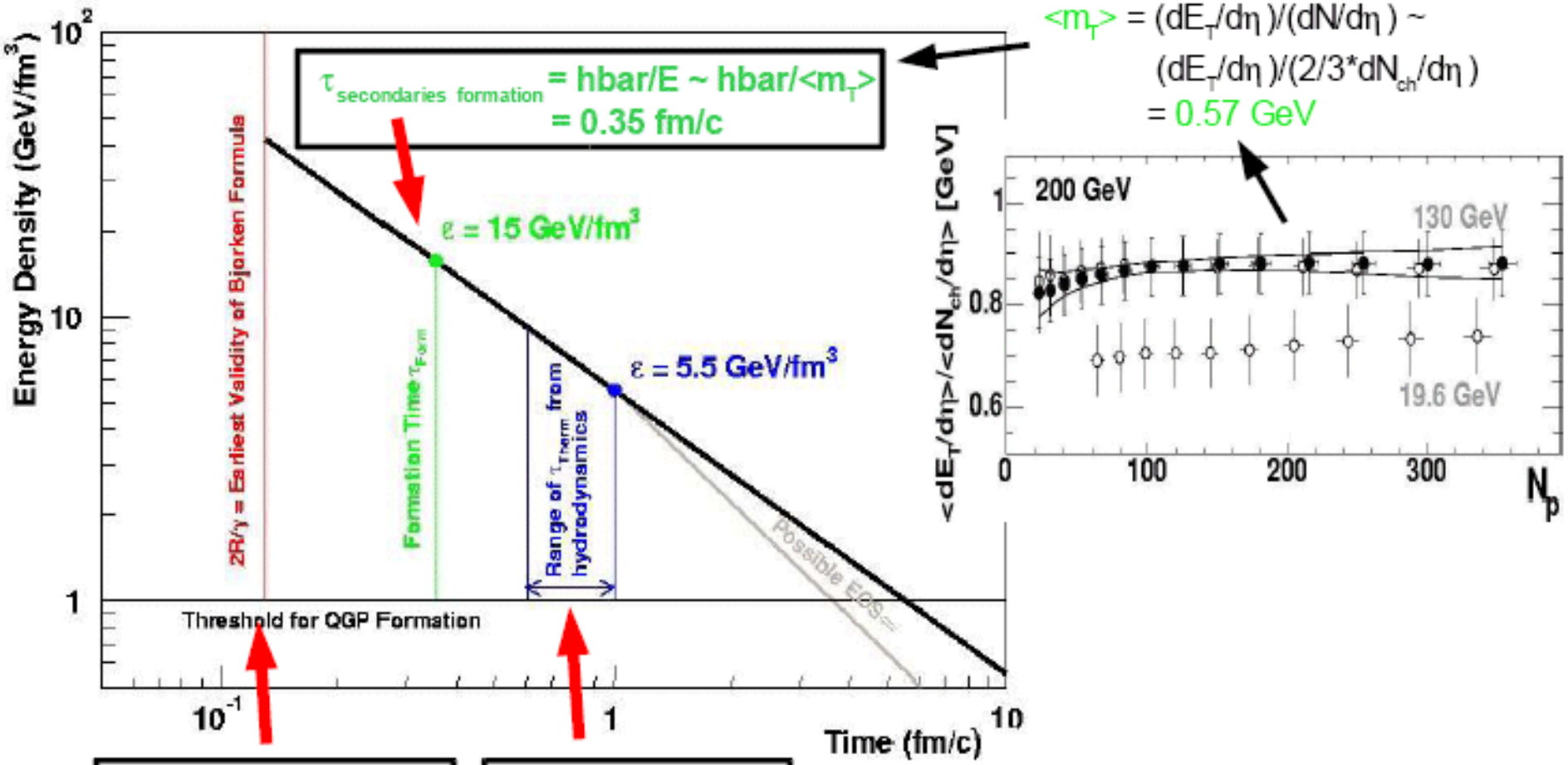
(~70% larger than at SPS)

$\boxed{\varepsilon_{Bjorken} \sim 5.0\ \mathrm{GeV/fm^3}}$

> QCD critical density (~1 GeV/fm^3)

Is the Thermalization Time Realistic? Yes

- Not unrealistic at RHIC… (for the 1st time: $\tau_{therm} > \tau_{cross} = 2R/\gamma = 0.13$ fm/c)
- Energy density time evolution in long. expanding system: $\varepsilon \sim 1/\tau$



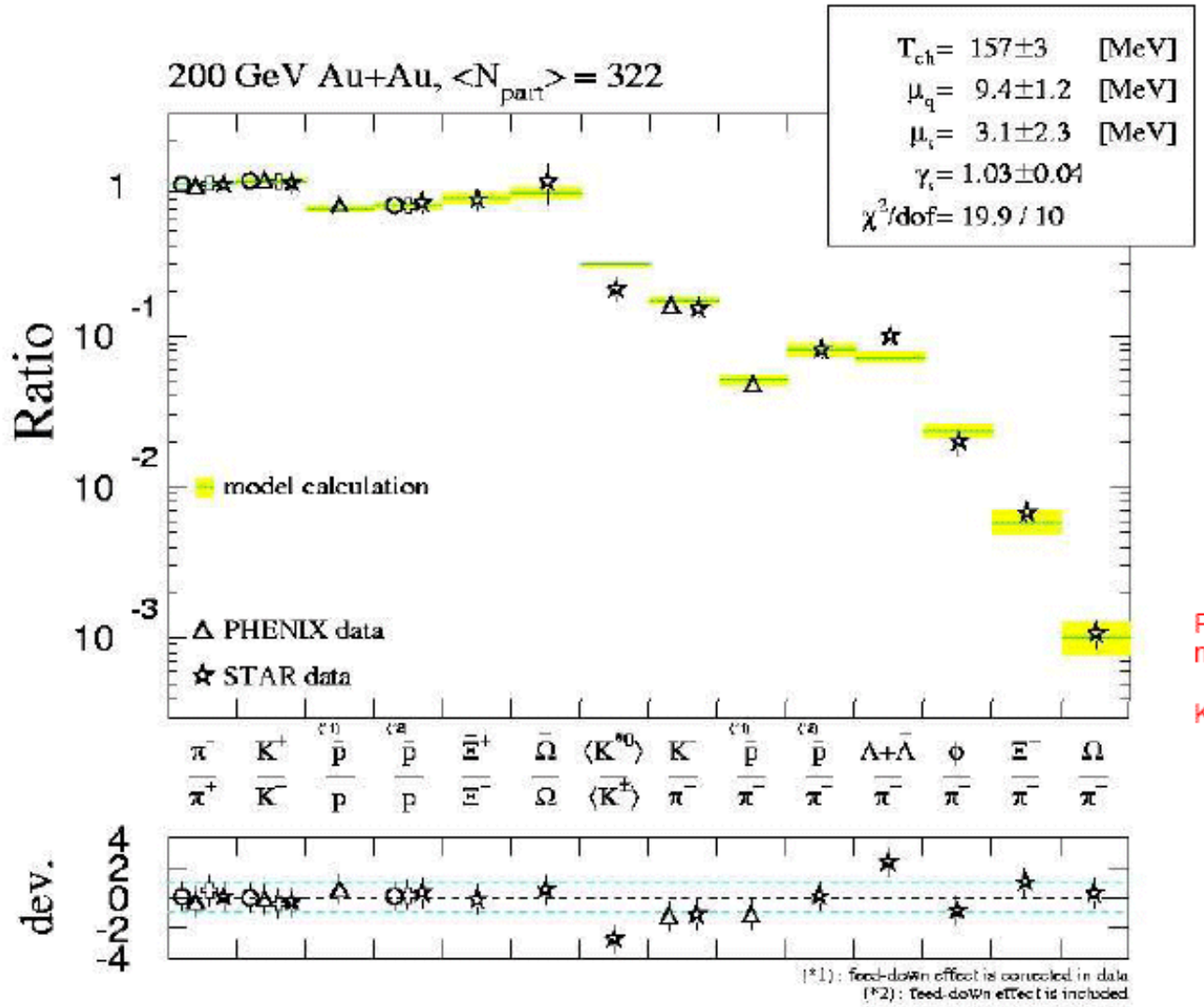
$\tau_{cross} = 2R/\gamma = 0.13$ fm/c

$\tau_{therm} \sim 0.6 - 1$ fm/c

(from hydrodynamics, see next)

Is the System Chemically Equilibrated? Yes

- Ratios of hadron yields consistent w/ system at chemical equilibrium (strangeness saturation factor γ_s=1) before hadronization ($T_{chem.freeze\text{-}out} \sim T_{crit}$) :



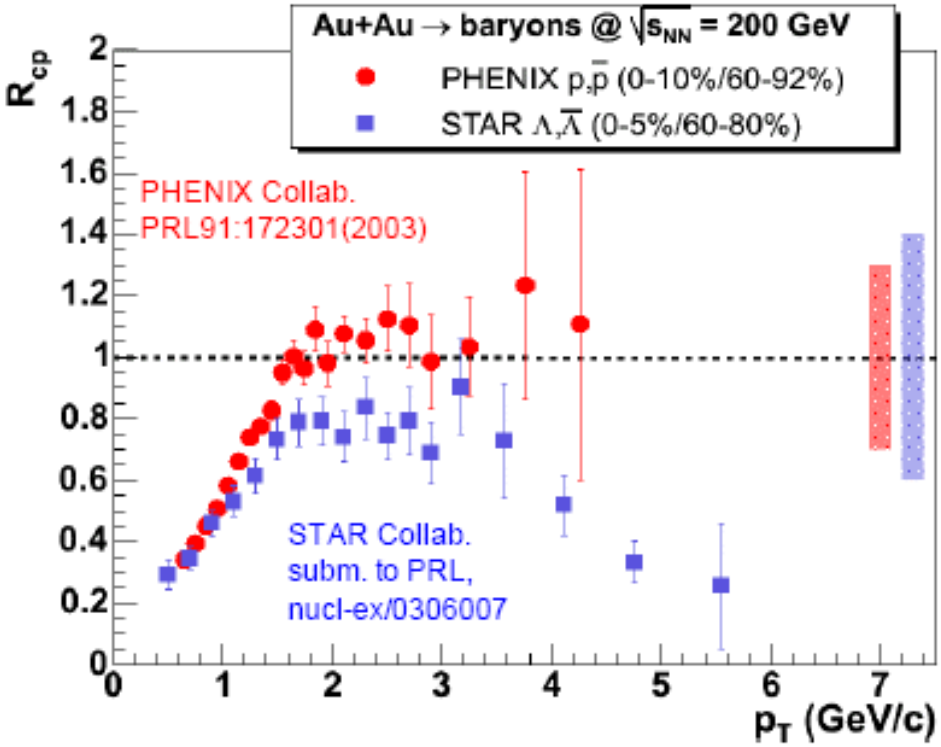
PBM, Redlich, Stachel nucl-th/0304013

Kaneta, Xu nucl-th/0405068

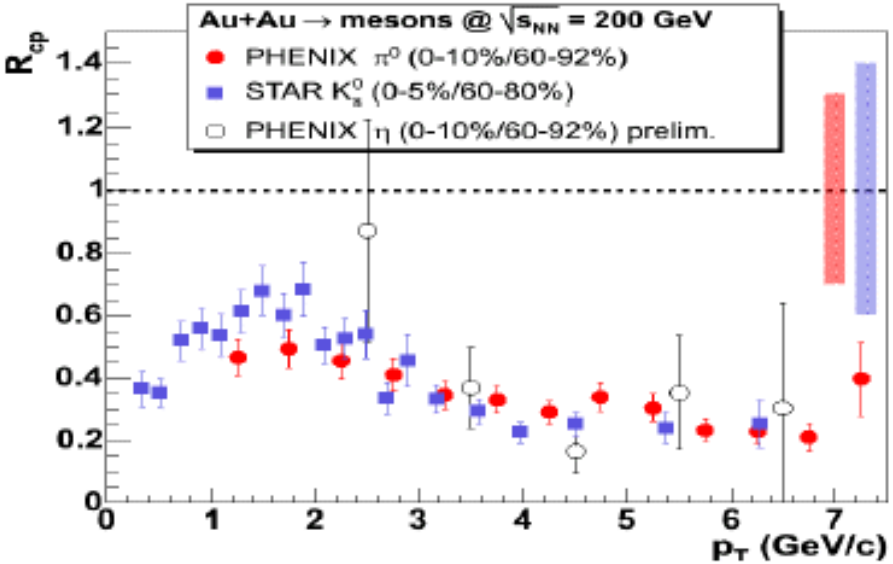
Intermediate p_T: Unsuppressed Baryon Production

- R_{cp} (ratio central/peripheral) at intermediate p_T = 2 – 4 GeV/c:

Baryons: p, $\bar{p}$, Λ, $\bar{\Lambda}$ **NOT** (or much less) suppressed in central Au+Au.



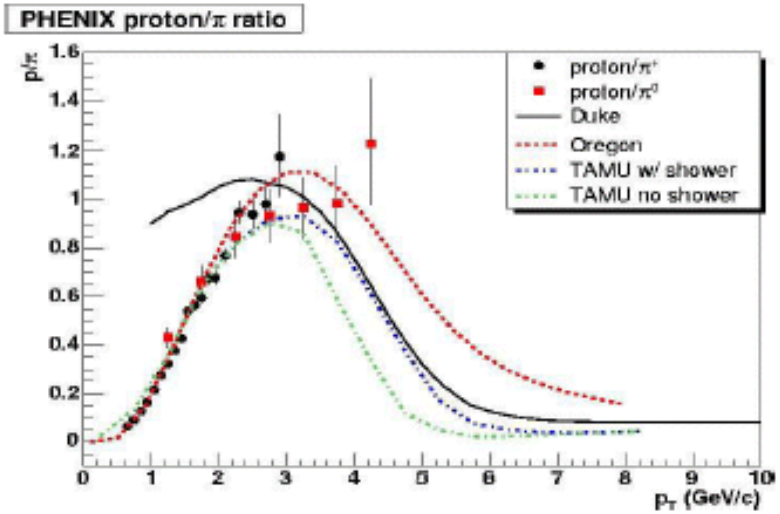
Mesons: π^0, k^0_s, η, equally suppressed.

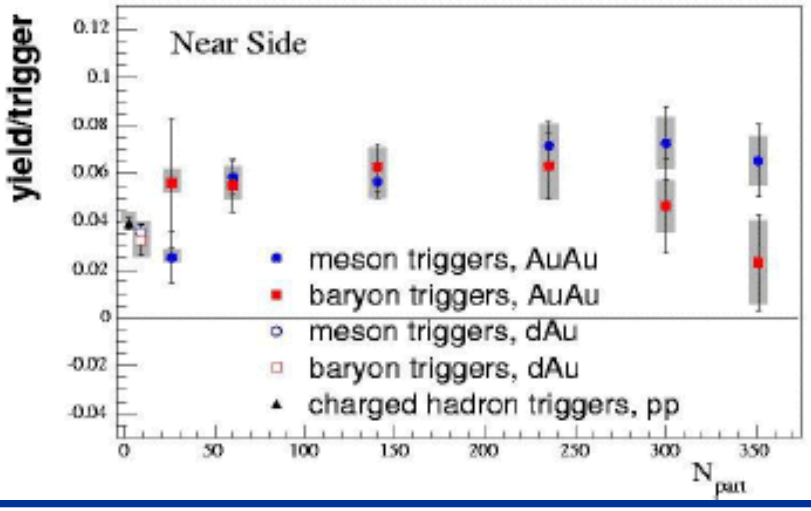


- Particle composition inconsistent with known (universal) fragmentation functions.
- Additional production mechanism for baryons in the intermediate p_T range

Is There Evidence of Quark Recombination? Yes

- Quark recombination (coalescence) mechanisms provide a simple explanation of anomalous baryon enhancement & v_2 at p_T= 2-5 GeV/c:





- Via quark momenta addition, recombination dominates for p_T ~ 1- 4 GeV/c:

  p_T(baryons) > p_T(mesons) > p_T(quarks)

- Fragmentation dominates for p_T > 5 GeV/c: p_T(hadrons)= z p_T(partons) , with z<1

- Constituent-quark scaling of v_2 naturally explained

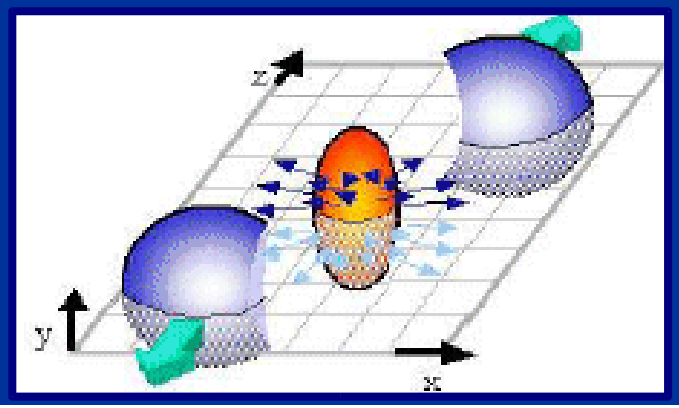
- However ... pure thermal + thermal parton recombination inconsistent w/ jet-like (baryon and meson) near-side azimuthal correlations. Simple recomb. does not work.

Are There Strong Collective Pressure Gradients? Yes!

- Initial anisotropy in x-space in non-central collisions (overlap) translates into final azimuthal asymmetry in p-space (transverse to react. plane)

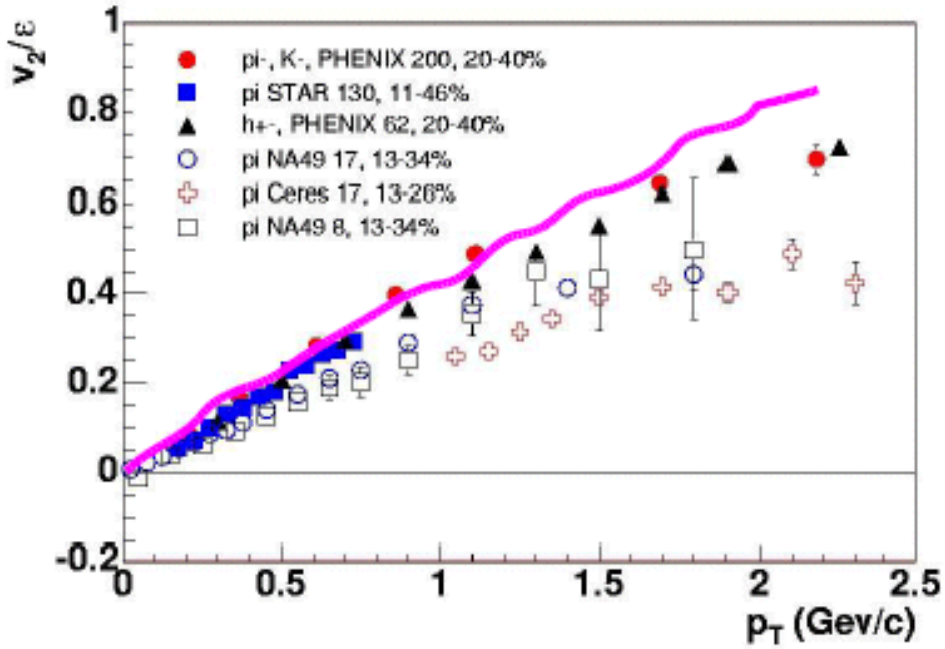
1. Truly collective effect (absent in p+p collisions).

2. Early-state phenomenon:
   develops only in 1st instants of reaction,
   strongly self-quenches after t~2 fm/c



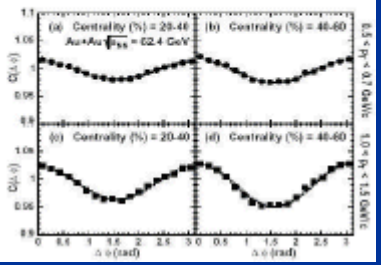
- Large v_2 signal at RHIC:

Exhausts hydro limit for p_T<1.5 GeV/c



$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos 2(\phi - \Phi_{RP})$$

Elliptic flow = v_2
(2nd Fourier coefficient)

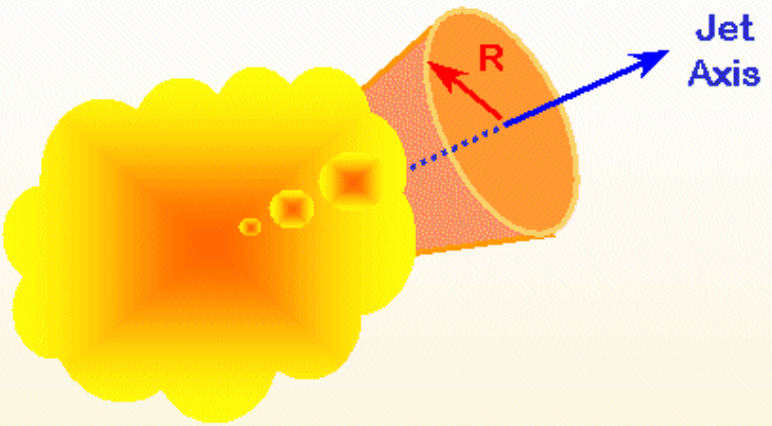


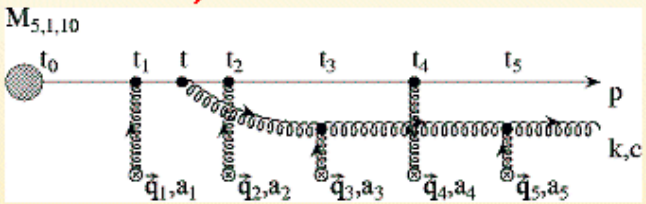
⇒ Strong (collective) pressure grads.
⇒ Large & fast parton rescattering: early thermalization.

- √s-dependence of v_2:
  ~50% increase from SPS
  Apparent saturation within 62-200 GeV

Dense Final State? Jets at RHIC

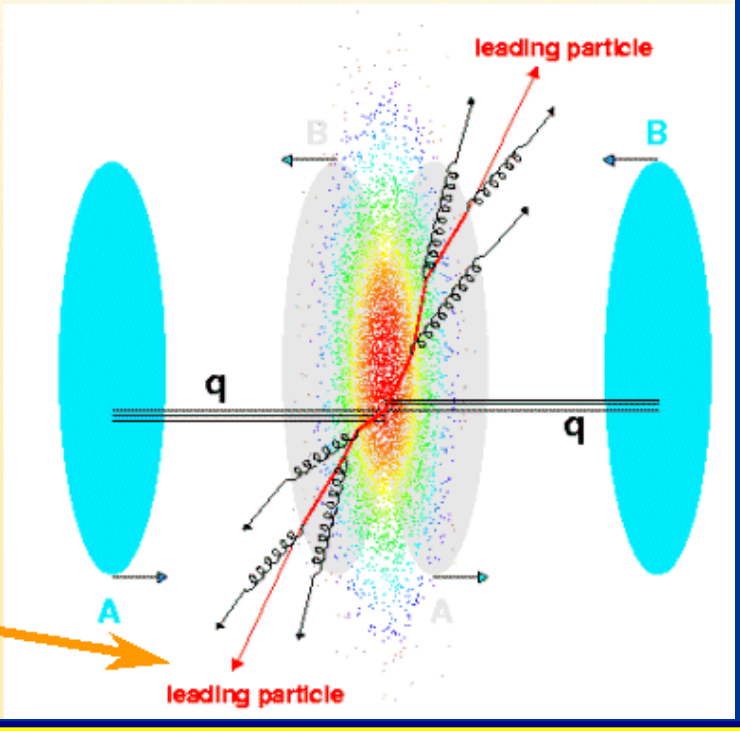
- **Tremendous interest in hard scattering (and subsequent energy loss in QGP) at RHIC**
  - Production rate calculable in pQCD
  - But strong reduction predicted due to dE/dx ~ path-length (due to non-Abelian nature of medium)





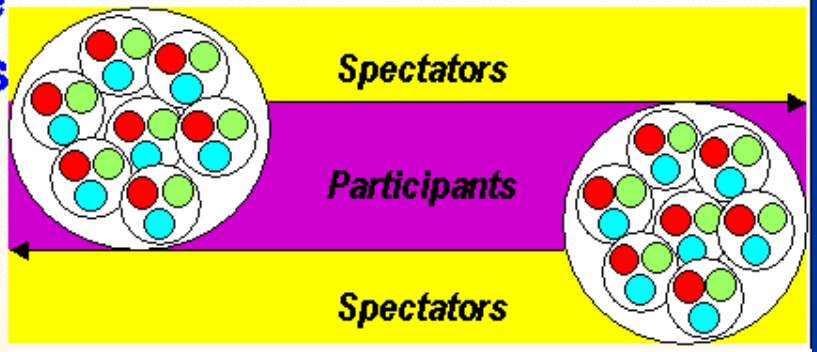
- ***However:***
  - "Traditional" jet methodology very difficult at RHIC
  - Dominated by the soft background

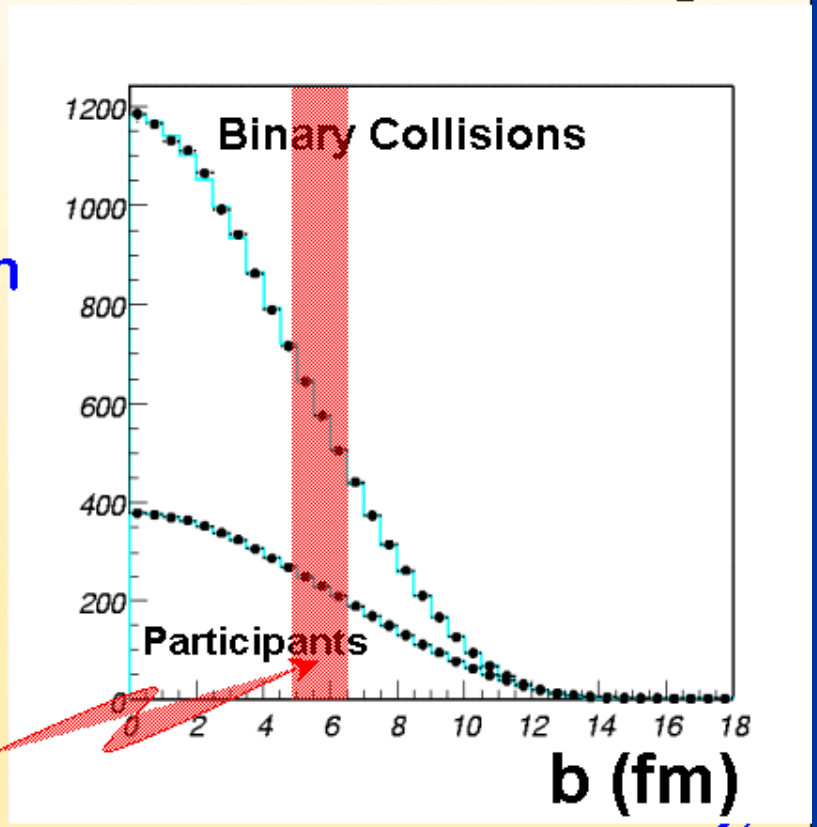
➔ **Investigate by (systematics of)** ***high-p_T single particles***



Systematizing RHIC Knowledge

- All four RHIC experiments have carefully developed techniques for determining
  - the number of participating nucleons N_{PART} in each collision (and thus the impact parameter)
  - The number of binary nucleon-nucleon collisions N_{COLL} as a function of impact parameter
- This effort has been essential in making the QCD connection
  - Soft physics ~ N_{PART}
  - Hard physics ~ N_{COLL}
- Often express impact parameter b in terms of "centrality", e.g., 10-20% most central collisions



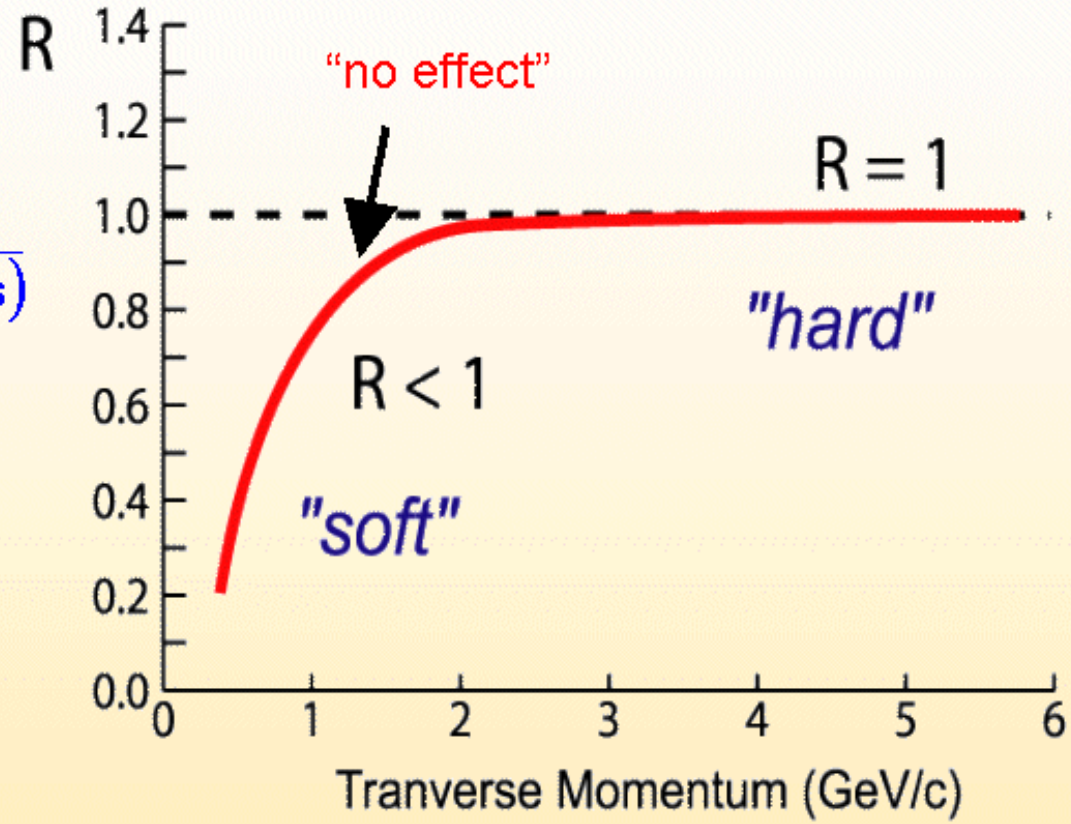


Systematizing Our Expectations

- Describe in terms of *scaled ratio* R_{AA}

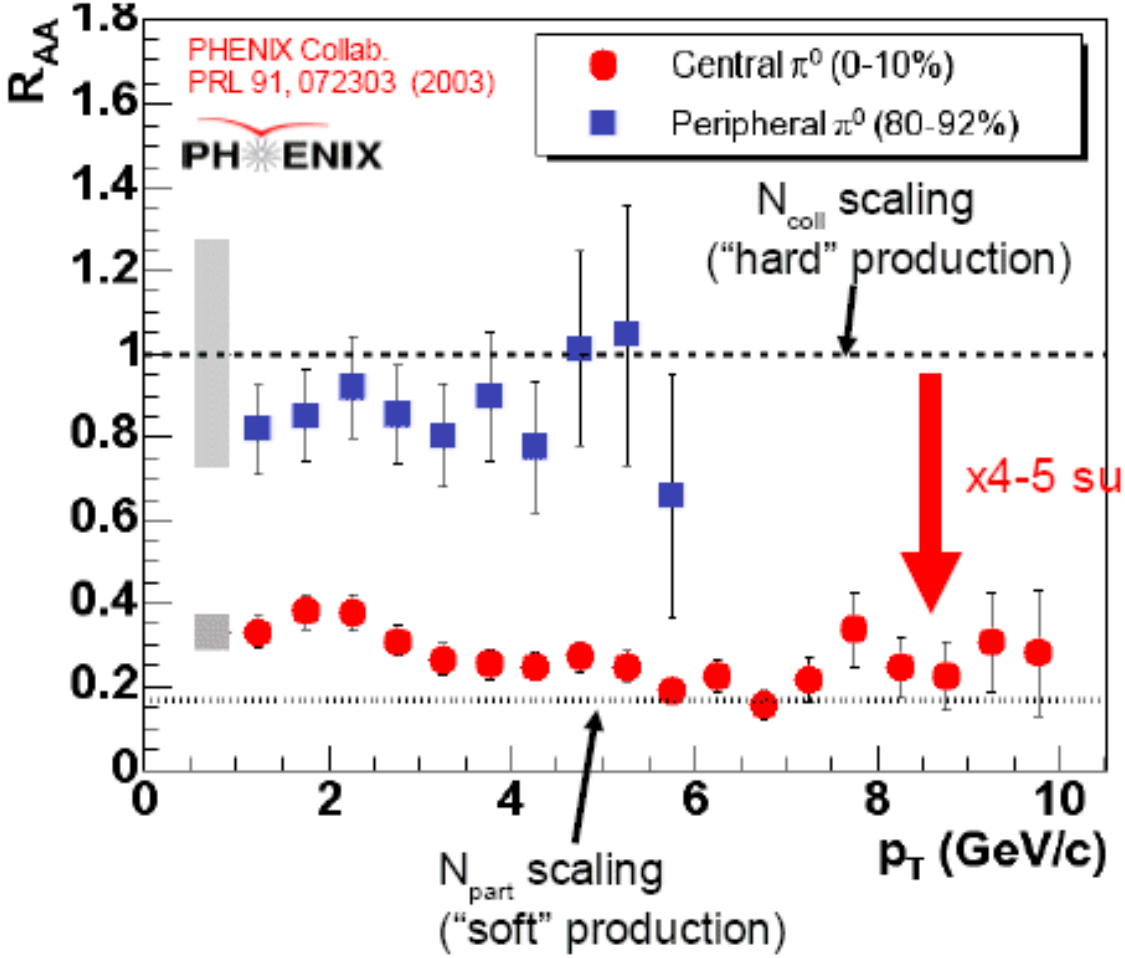
$$\equiv \frac{\text{Yield in Au}-\text{Au Events}}{\langle A \bullet B \rangle (\text{Yield in p}-\text{p Events})}$$

= 1 for "baseline expectations"

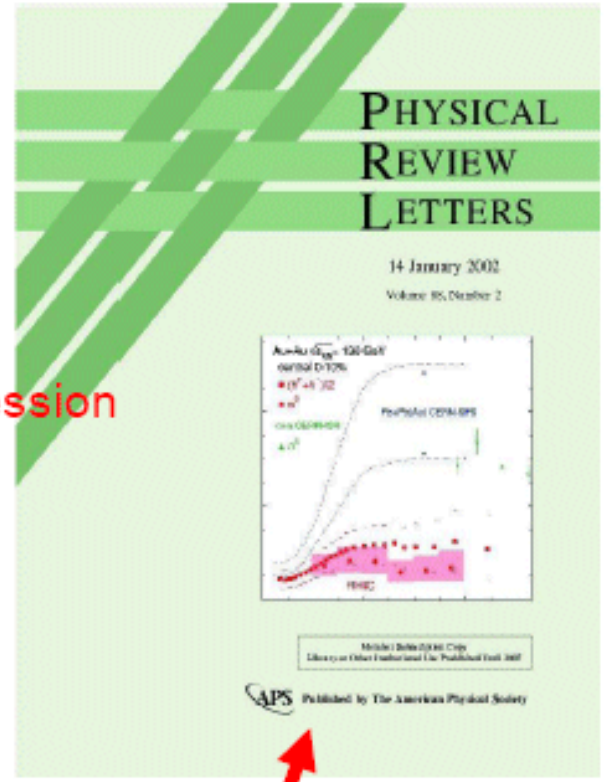


- Will present most of remaining plots on suppression in terms of this ratio

Is There Evidence of a Dense System? Yes!



PRL Cover – 14 January 2002



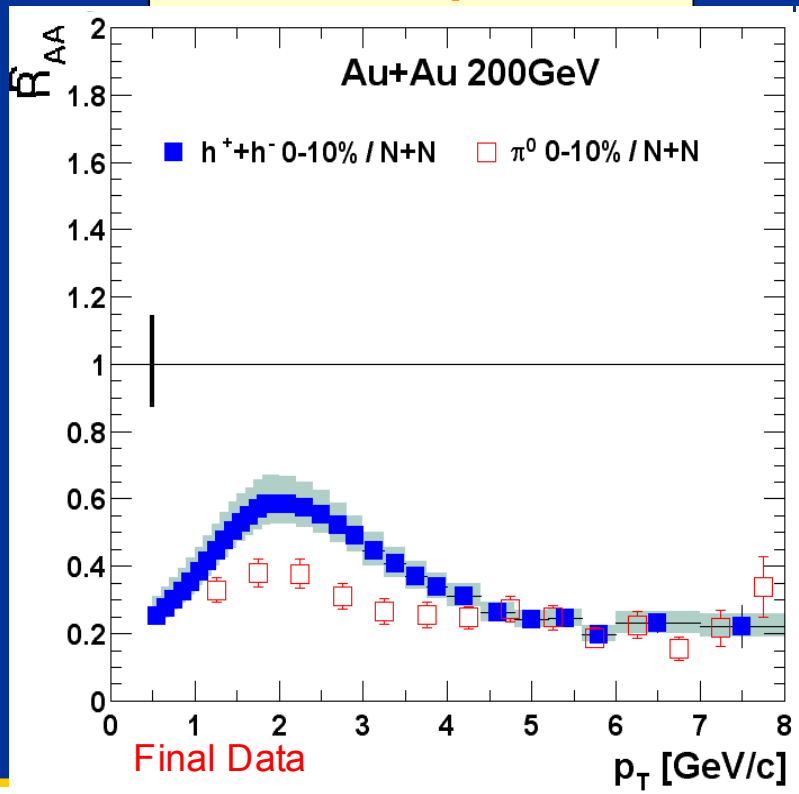
Discovery of high p_T suppression (one of most significant results @ RHIC so far)

$R_{AA} << 1$: well below pQCD (collinear factorization) expectations for hard scattering cross-sections

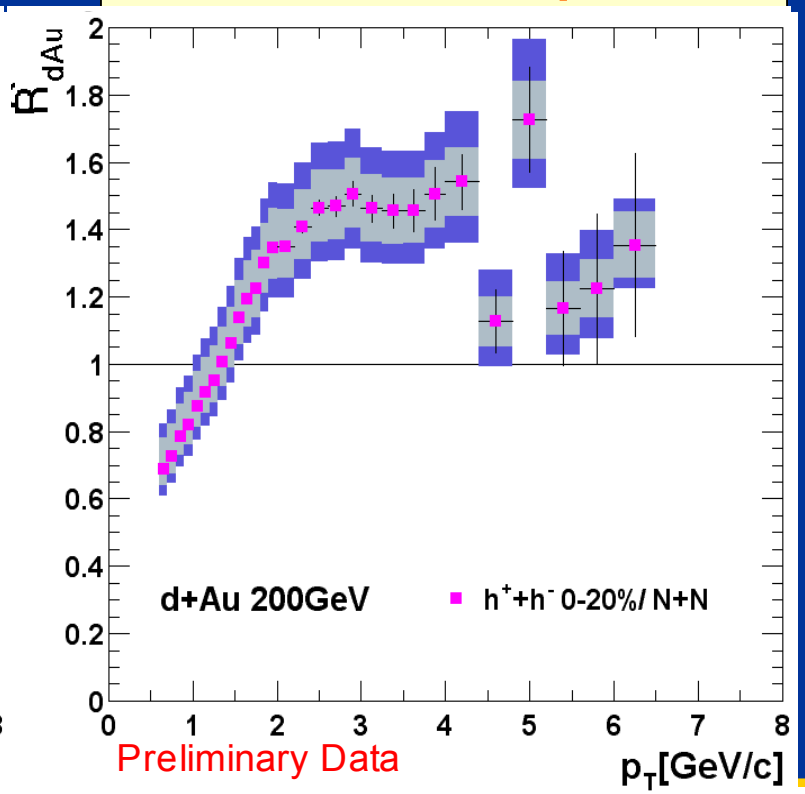
Control Experiment: d + Au (cold nucleus)

Some theorists suggested that the observed high p_T suppression in Au+Au central events was an initial state effect. If so, then at least some suppression should also be seen in d + Au collisions. Experimental results falsified the initial-state conjecture. Conclusion: *Au+Au result is a final-state effect.*

Au + Au Experiment

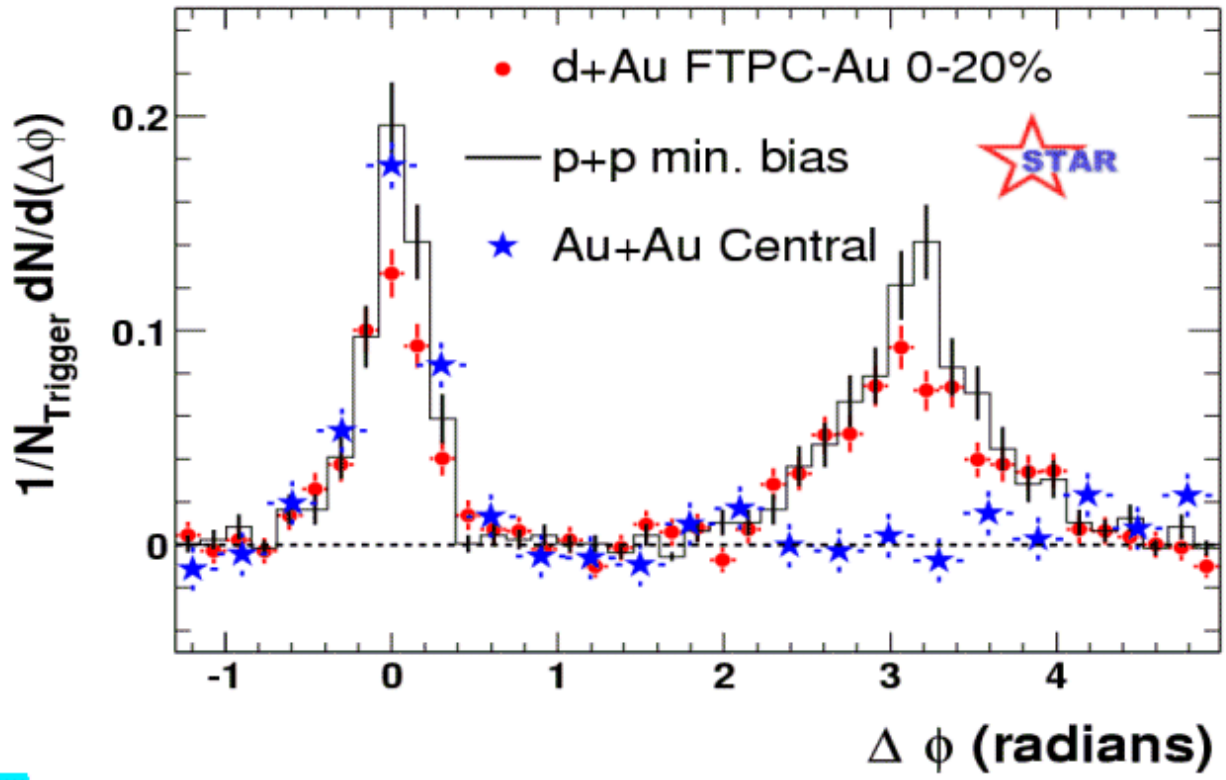


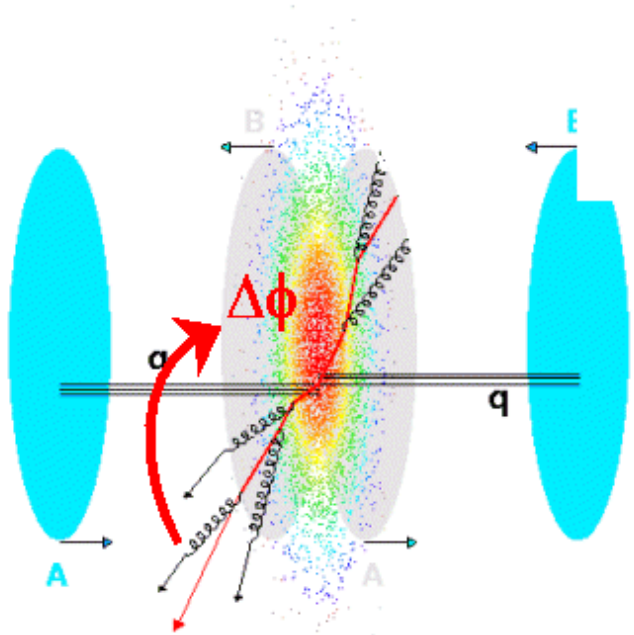
d + Au Control Experiment



Further Evidence of Final State Effect

- STAR azimuthal correlation function shows ~ complete absence of "away-side" jet





$$C_2(Au+Au) = C_2(p+p) + A*(1+2v_2^2\cos(2\Delta\phi))$$

➡ Surface emission only (?)

- That is, "partner" in hard scatter is absorbed in the dense medium

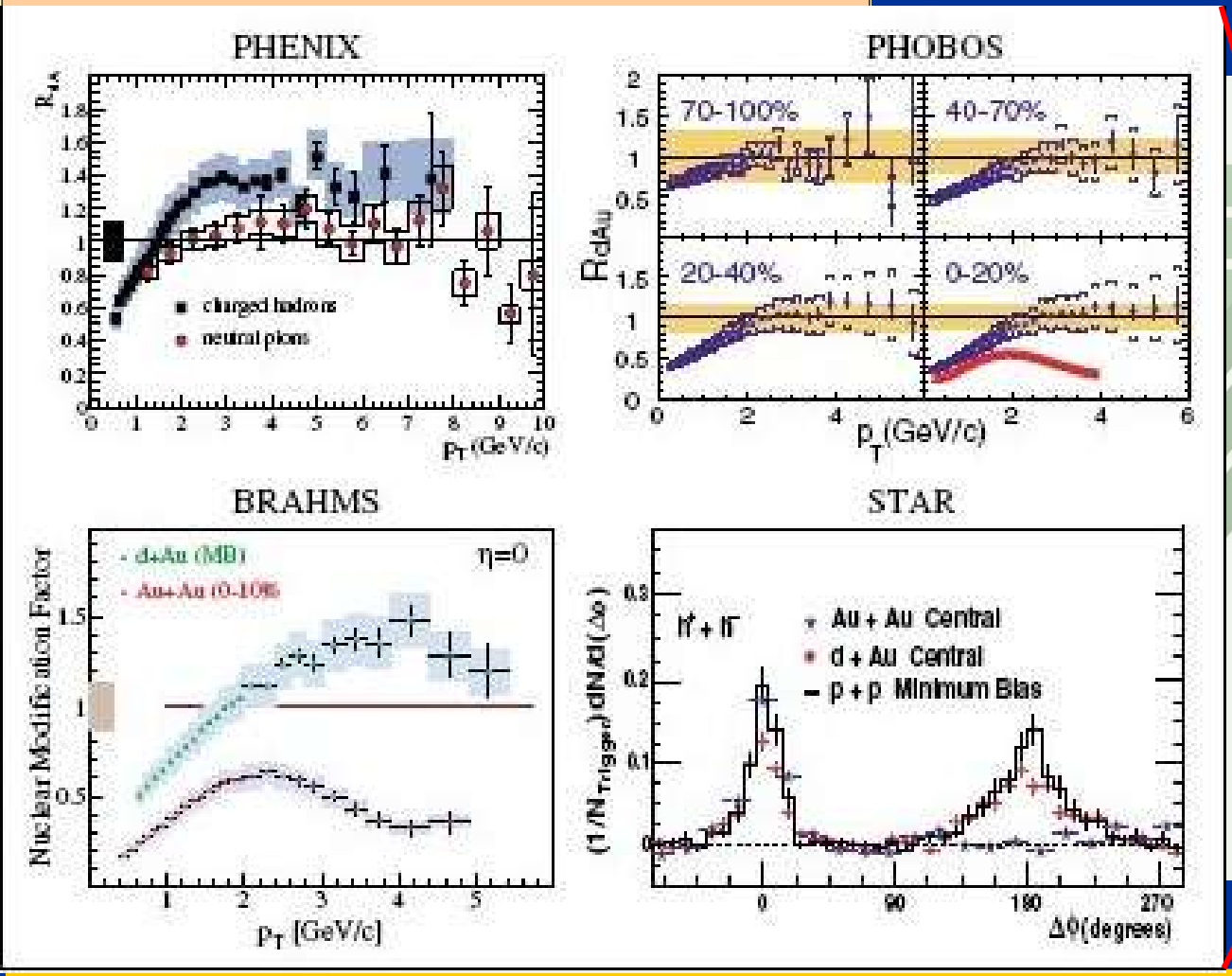
Is There Evidence of a Dense Final State System? Yes!

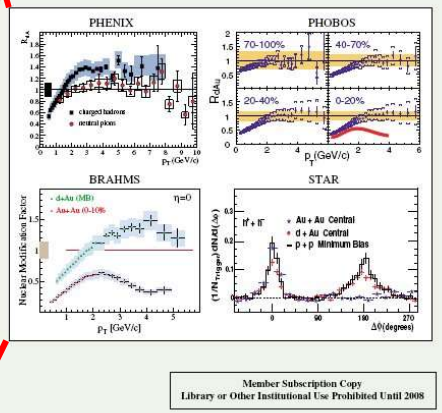
d+Au results from

BRAHMS PHENIX PHOBOS STAR

Presented at a BNL "Press Event"
18 June 2003.

PRL Cover
15 August 2003



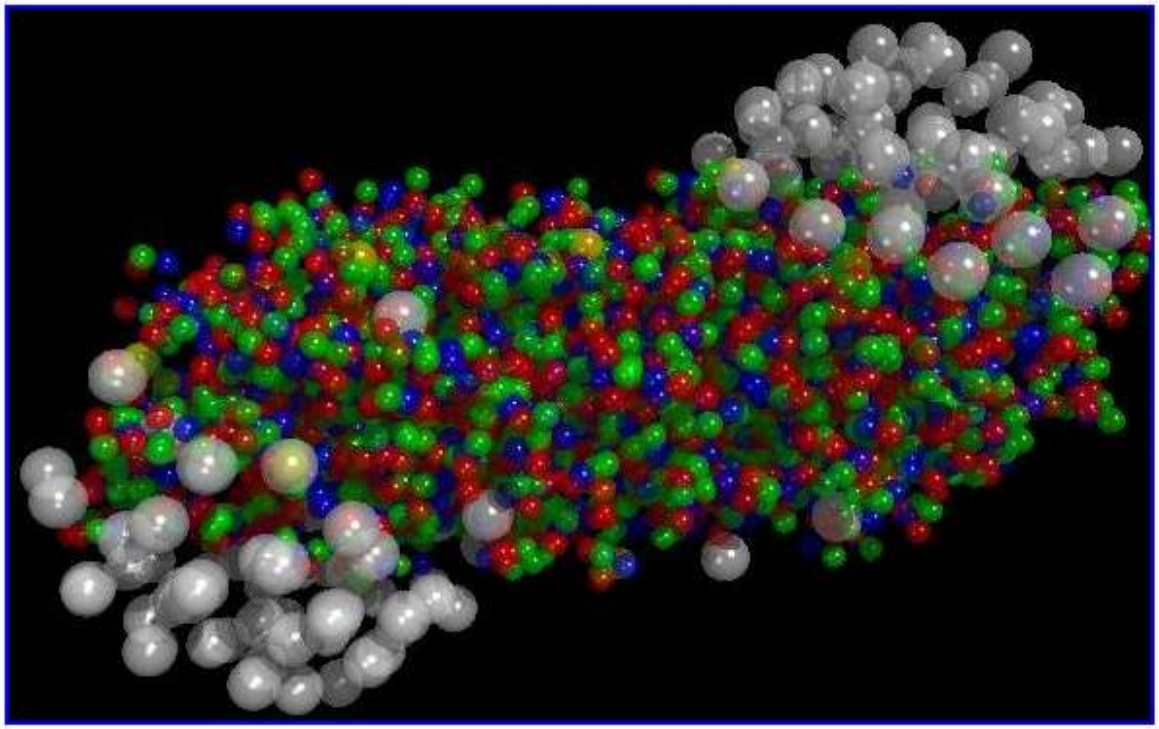


CERN Press Release, February 10, 2000

PRESS RELEASE

Organisation Européenne pour la Recherche Nucléaire
European Organization for Nuclear Research

New State of Matter created at CERN



At a special seminar on 10 February, spokespersons from the experiments on CERN* 's Heavy Ion programme presented compelling evidence for the existence of a new state of matter in which quarks, instead of being bound up into more complex particles such as protons and neutrons, are liberated to roam freely.

Question:

If we have seen a New State of Matter at RHIC, then how does it differ from the one CERN claimed to have discovered in 2000?

Students are welcome to join the age of discoveries!

PHOENIX

Experimental Evaluations by RHIC Collaborations

BRAHMS: nucl-ex/0410020	Quark Gluon Plasma and Color Glass Condensate at RHIC? The perspective from the BRAHMS experiment.
PHENIX: nucl-ex/0410003	Formation of dense partonic matter in relativistic nucleus nucleus collisions at RHIC: Experimental evaluation by the PHENIX collaboration
PHOBOS: nucl-ex/0410022	The PHOBOS Perspective on Discoveries at RHIC
STAR: (to be released)	Are We There Yet? The STAR Collaboration's Critical Evaluation of the Evidence Regarding Formation of a Quark Gluon Plasma in RHIC Collisions.

Answers to the Questions at RHIC

- Are the Energy Density and Temperature High?
  - Yes at RHIC
- Are There Strong (Collective) Pressure Gradients?
  - Yes at RHIC;
- Is There Evidence of a Dense Final-State System?
  - Yes at RHIC;
- Is the Thermalization Time Realistic?
  - Yes at RHIC;
- Is the System Chemically Equilibrated?
  - Yes at RHIC;
- Is There Evidence for Quark Recombination?
  - Yes at RHIC;