RHIC Experimental Overview:

What we have (not) learned

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17-Nov-04

Outline

- Pre-history
  - Early efforts to understand hadronic *matter*
  - pre-RHIC murky experiments (not covered)
- RHIC as a revolution
  - Dedicated machine
  - Dedicated experiments
  - Access to perturbative phenomena
- RHIC as a discovery machine
  - Thermal hadronic matter
  - Hydrodynamic behavior
  - Precision via perturbative probes
- What remains

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Pre-History I

- Fermi (1950)
  - "High Energy Nuclear Events", Prog. Theor. Phys. 5, 570 (1950)
  - Lays groundwork for statistical approach to particle production in strong interactions:
    - "Since the interactions of the pion field are strong, we may expect that rapidly this energy will be distributed among the various degrees of freedom present in this volume according to statistical laws."

790 241. – *High Energy Nuclear Events*

241.

HIGH ENERGY NUCLEAR EVENTS

« Progr. Theor. Theoret. Phys. », 5, 570–583 (1950).

ABSTRACT

A statistical method for computing high energy collisions of protons with multiple production of particles is discussed. The method consists in assuming that as a result of fairly strong interactions between nucleons and mesons the probabilities of formation of the various possibile numbers of particles are determined essentially by the statistical weights of the various possibilities.

1. INTRODUCTION.

The meson theory has been a dominant factor in the development of physics since it was announced fifteen years ago by Yukawa. One of its outstanding achievements has been the prediction that mesons should be produced in high energy nuclear collisions. At relatively low energies only one meson can be emitted. At higher energies multiple emission becomes possible.

In this paper an attempt will be made to develop a crude theoretical approach for calculating the outcome of nuclear collisions with very great energy. In particular, phenomena in which two colliding nucleons may give rise to several π–mesons, briefly called hereafter pions, and perhaps also to some anti-nucleons, will be discussed.

In treating this type of processes the conventional perturbation theory solution of the production and destruction of pions breaks down entirely. Indeed, the large value of the interaction constant leads quite commonly to situations in which higher approximations yield larger results than do lower approximations. For this reason it is proposed to explore the possibilities of a method that makes use of this fact. The general idea is the following:

When two nucleons collide with very great energy in their center of mass system this energy will be suddenly released in a small volume surrounding the two nucleons. We may think pictorially of the event as of a collision in which the nucleons with their surrounding retinue of pions hit against each other so that all the portion of space occupied by the nucleons and by their surrounding pion field will be suddenly loaded with a very great amount of energy. Since the interactions of the pion field are strong we may expect that rapidly this energy will be distributed among the various degrees of freedom present in this volume according to statistical laws. One can then compute statistically the probability that in this tiny volume a certain number of pions will be created with a given energy distribution. It is then assumed that the

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Pre-History II

- Landau (1955) significant extension of Fermi's approach
- Considers fundamental roles of
  - hydrodynamic evolution
  - entropy
    - "The defects of Fermi's theory arise mainly because the expansion of the compound system is not correctly taken into account…(The) expansion of the system can be considered on the basis of relativistic hydrodynamics."

88. A HYDRODYNAMIC THEORY OF MULTIPLE FORMATION OF PARTICLES

1. INTRODUCTION

Experiment shows that in collisions of very fast particles a large number of new particles are formed in multi-prong stars. The energy of the particles which produce such stars is of the order of 10^{12} eV or more. A characteristic feature is that such collisions occur not only between a nucleon and a nucleus but also between two nucleons. For example, the formation of two mesons in neutron–proton collisions has been observed at comparatively low energies, of the order of 10^{9} eV, in cosmotron experiments[1].

Fermi[2,3] originated the ingenious idea of considering the collision process at very high energies by the use of thermodynamic methos. The main points of his theory are as follows.

(1) It is assumed that, when two nucleons of very high energy collide, energy is released in a very small volume V in their centre of mass system. Since the nuclear interaction is very strong and the volume is small, the distribution of energy will be determined by statistical laws. The collision of high-energy particles may therefore be treated without recourse to any specific theories of nuclear interaction.

(2) The volume V in which energy is released is determined by the dimensions of the meson cloud around the nucleons, whose radius is $\hbar/\mu c$, μ being the mass of the pion. But since the nucleons are moving at very high speeds, the meson cloud surrounding them will undergo a Lorentz contraction in the direction of motion. Thus the volume V will be, in order of magnitude,

$$V = \frac{4\pi}{3}\left(\frac{\hbar}{\mu c}\right)^3 \frac{2Mc^2}{E'}, \qquad (1.1)$$

where M is the mass of a nucleon and E' the nucleon energy in the centre of mass system.

(3) Fermi assumes that particles are formed, in accordance with the laws of statistical equilibrium, in the volume V at the instant of collision. The particles formed do not interact further with one another, but leave the volume in a "frozen" state.

С. З. Беленький и Л. Д. Ландау, Гидродинамическая теория множественного образования частиц, *Успехи Физических Наук*, **56**, 309 (1955).
S. Z. Belenkij and L. D. Landau, Hydrodynamic theory of multiple production of particles, *Nuovo Cimento*, Supplement, **3**, 15 (1956).

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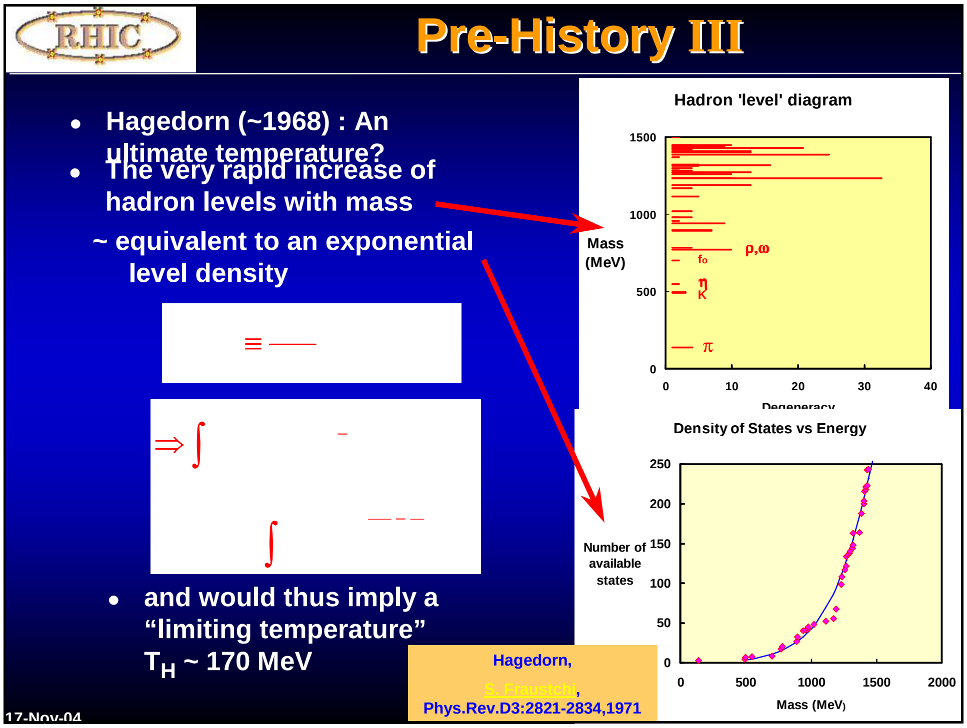
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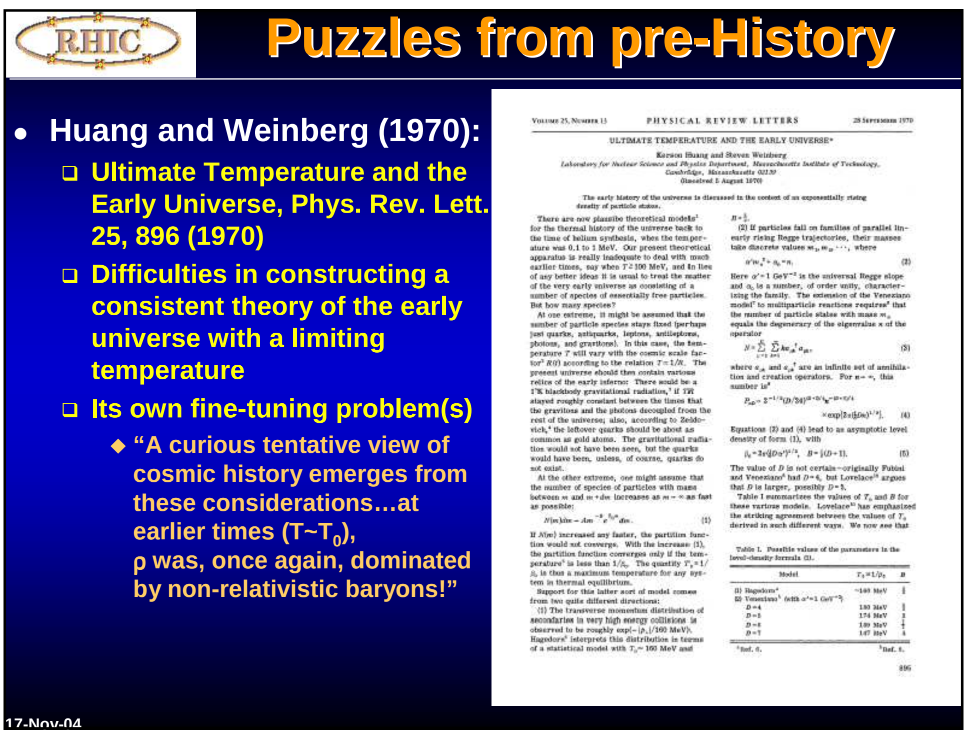
Pre-History III
Hagedorn (~1968) : An ultimate temperature?
The very rapid increase of hadron levels with mass
~ equivalent to an exponential level density
and would thus imply a "limiting temperature"
T_H ~ 170 MeV
Hadron 'level' diagram
Mass (MeV)
Degeneracy
ρ,ω
f₀
η
K
π
Density of States vs Energy
Number of available states
Mass (MeV)
Hagedorn, S. Frautschi, Phys.Rev.D3:2821-2834,1971
17-Nov-04


RHIC
Puzzles from pre-History
Huang and Weinberg (1970):
Ultimate Temperature and the Early Universe, Phys. Rev. Lett. 25, 896 (1970)
Difficulties in constructing a consistent theory of the early universe with a limiting temperature
Its own fine-tuning problem(s)
"A curious tentative view of cosmic history emerges from these considerations…at earlier times (T~T₀), ρ was, once again, dominated by non-relativistic baryons!"
VOLUME 25, NUMBER 13 PHYSICAL REVIEW LETTERS 28 SEPTEMBER 1970
ULTIMATE TEMPERATURE AND THE EARLY UNIVERSE*
Kerson Huang and Steven Weinberg
17-Nov-04

History!

- 1973: "Puzzles" resolved
- Gross, Politzer, Wilczek
- Miraculous year, Miraculous theory

VOLUME 30, NUMBER 26 PHYSICAL REVIEW LETTERS 25 JUNE 1973

[14]Y. Nambu and G. Jona-Lasino, Phys. Rev. 122, 345 (1961); S. Coleman and E. Weinberg, Phys. Rev. D 7, 1888 (1973).
[15]K. Symanzik (to be published) has recently suggested that one consider a $\lambda\varphi^4$ theory with a negative λ to achieve UV stability at $\lambda = 0$. However, one can show, using the renormalization-group equations, that in such theory the ground-state energy is unbounded from below (S. Coleman, private communication).
[16]W. A. Bardeen, H. Fritzsch, and M. Gell-Mann, CERN Report No. CERN-TH-1538, 1972 (to be published).
[17]H. Georgi and S. L. Glashow, Phys. Rev. Lett. 28, 1494 (1972); S. Weinberg, Phys. Rev. D 5, 1962 (1972).
[18]For a review of this program, see S. L. Adler, in Proceedings of the Sixteenth International Conference on High Energy Physics, National Accelerator Laboratory, Batavia, Illinois, 1972 (to be published).

Reliable Perturbative Results for Strong Interactions?*

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(Received 3 May 1973)

An explicit calculation shows perturbation theory to be arbitrarily good for the deep Euclidean Green's functions of any Yang-Mills theory and of many Yang-Mills theories with fermions. Under the hypothesis that spontaneous symmetry breakdown is of dynamical origin, these symmetric Green's functions are the asymptotic forms of the physically significant spontaneously broken solution, whose coupling could be strong.

Renormalization-group techniques hold great promise for studying short-distance and strong-coupling problems in field theory.[1,2] Symanzik[2] goes to zero, compensating for the fact that there are more and more of them. But the large-p^2 divergence represents a real breakdown of

PHYSICAL REVIEW D VOLUME 8, NUMBER 10 15 NOVEMBER 1973

Asymptotically Free Gauge Theories. I*

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Frank Wilczek
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08540
(Received 23 July 1973)

Asymptotically free gauge theories of the strong interactions are constructed and analyzed. The reasons for doing this are recounted, including a review of renormalization-group techniques and their application to scaling phenomena. The renormalization-group equations are derived for Yang-Mills theories. The parameters that enter into the equations are calculated to lowest order and it is shown that these theories are asymptotically free. More specifically the effective coupling constant, which determines the ultraviolet behavior of the theory, vanishes for large spacelike momenta. Fermions are incorporated and the construction of realistic models is discussed. We propose that the strong interactions be mediated by a "color" gauge group which commutes with SU(3) × SU(3). The problem of symmetry breaking is discussed. It appears likely that this would have a dynamical origin. It is suggested that the gauge symmetry might not be broken and that the severe infrared singularities prevent the occurrence of noncolor singlet physical states. The deep-inelastic structure functions, as well as the electron-positron total annihilation cross section are analyzed. Scaling obtains up to calculable logarithmic corrections, and the naive light-cone or parton-model results follow. The problems of incorporating scalar mesons and breaking the symmetry by the Higgs mechanism are explained in detail.

Hagedorn Temperature → QCD Phase Transition

- *Compare*

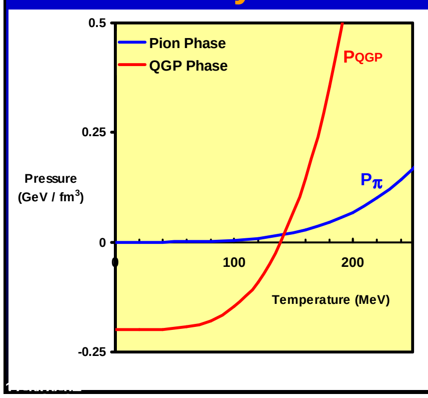
$$P_\pi = 3\frac{\pi^2}{90}T^4$$

Pressure of "pure" pion gas at temperature T

$$P_{QGP} = g\frac{\pi^2}{90}T^4 - B, \quad g = 37$$

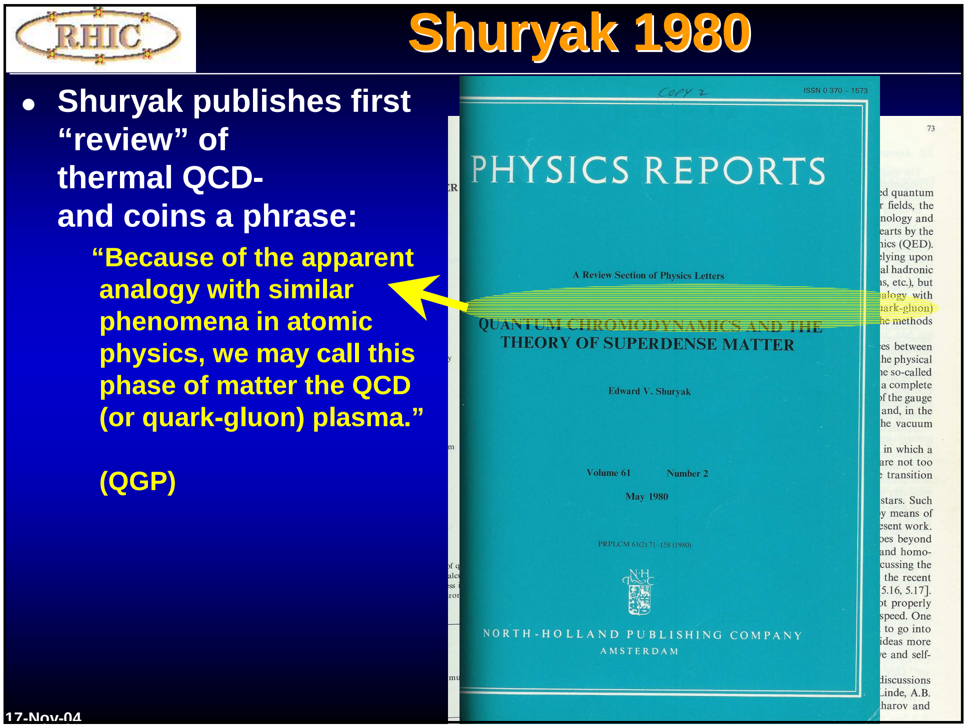
Pressure in plasma phase with "Bag constant" B ~ 0.2 GeV / fm^3

- *Select* system with higher pressure:



➔ Phase transition at T ~ 140 MeV with latent heat ~0.8 GeV / fm^3

Compare to best estimates (Karsch, QM01) from lattice calculations:
T ~ 150-170 MeV
latent heat ~ 0.7±0.3 GeV / fm^3


Shuryak 1980
RHIC
• Shuryak publishes first "review" of thermal QCD- and coins a phrase:
"Because of the apparent analogy with similar phenomena in atomic physics, we may call this phase of matter the QCD (or quark-gluon) plasma."
(QGP)
PHYSICS REPORTS
A Review Section of Physics Letters
QUANTUM CHROMODYNAMICS AND THE THEORY OF SUPERDENSE MATTER
Edward V. Shuryak
Volume 61 Number 2
May 1980
NORTH-HOLLAND PUBLISHING COMPANY
AMSTERDAM
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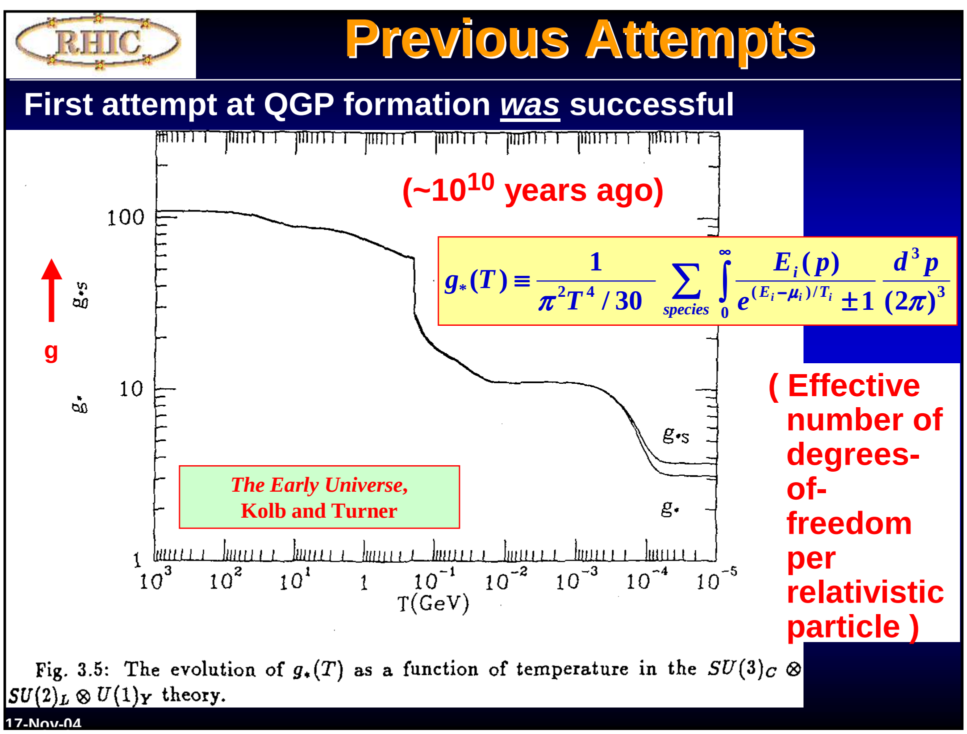
Previous Attempts
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First attempt at QGP formation was successful
(~10^10 years ago)
$g_*(T) \equiv \frac{1}{\pi^2 T^4/30} \sum_{species} \int_0^\infty \frac{E_i(p)}{e^{(E_i-\mu_i)/T_i} \pm 1} \frac{d^3p}{(2\pi)^3}$
(Effective number of degrees-of-freedom per relativistic particle)
The Early Universe, Kolb and Turner
g
g_{*S}
g_*
100
10
1
10^3 10^2 10^1 1 10^{-1} 10^{-2} 10^{-3} 10^{-4} 10^{-5}
T(GeV)
Fig. 3.5: The evolution of $g_*(T)$ as a function of temperature in the $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ theory.
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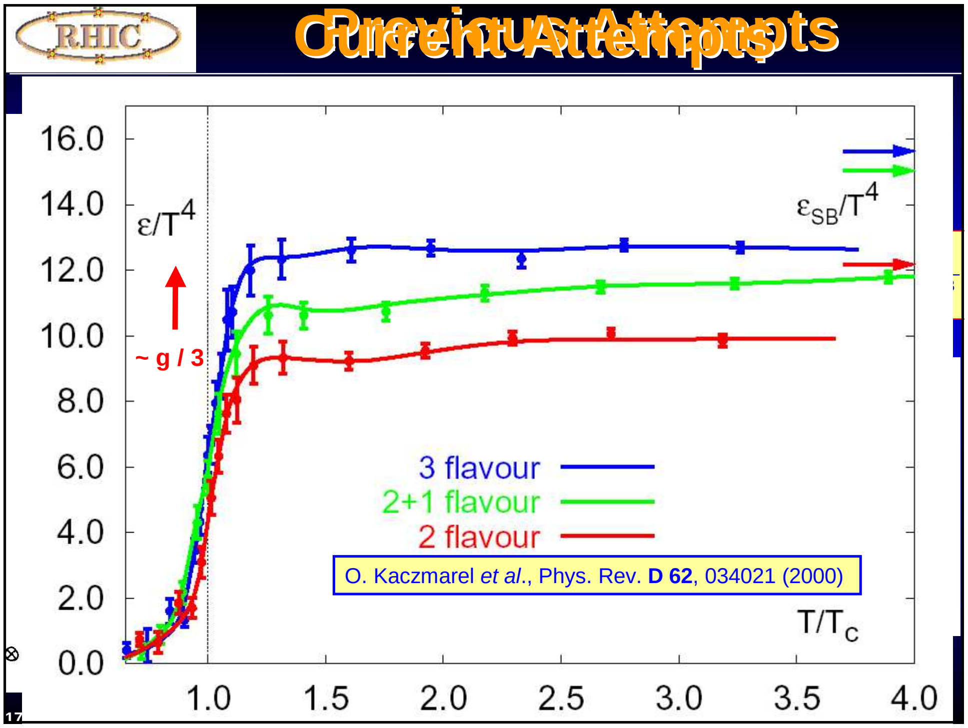
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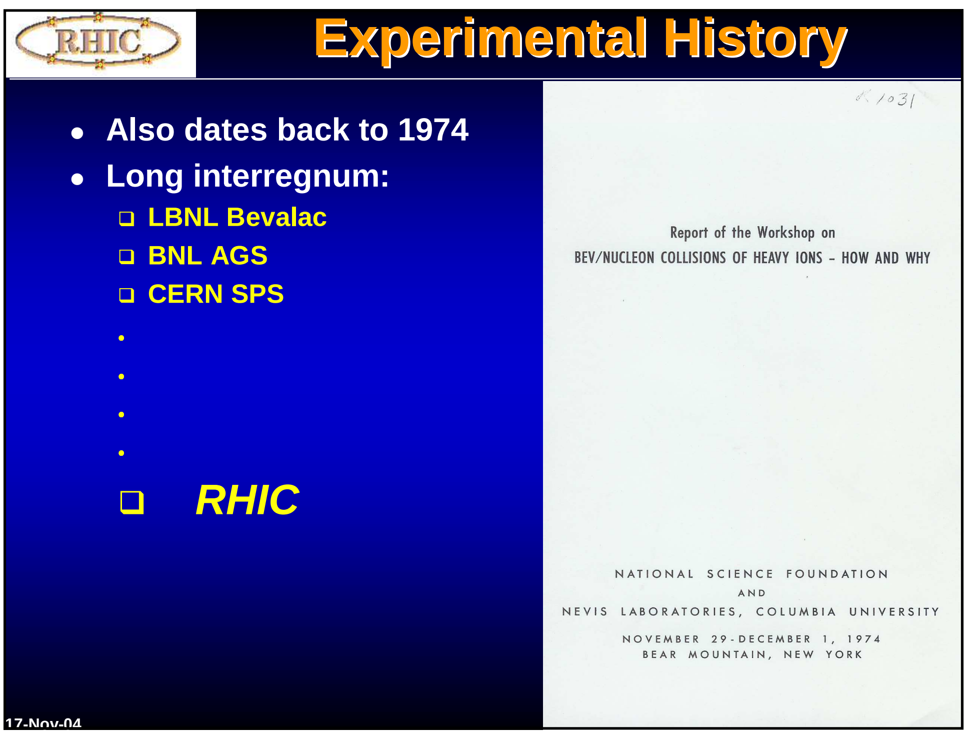
Current Attempts
Previous Attempts
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
ε/T4
~ g / 3
εSB/T4
3 flavour
2+1 flavour
2 flavour
O. Kaczmarel et al., Phys. Rev. D 62, 034021 (2000)
T/Tc
1.0
1.5
2.0
2.5
3.0
3.5
4.0


RHIC
Experimental History
Also dates back to 1974
Long interregnum:
LBNL Bevalac
BNL AGS
CERN SPS
RHIC
Report of the Workshop on
BEV/NUCLEON COLLISIONS OF HEAVY IONS – HOW AND WHY
NATIONAL SCIENCE FOUNDATION
AND
NEVIS LABORATORIES, COLUMBIA UNIVERSITY
NOVEMBER 29 - DECEMBER 1, 1974
BEAR MOUNTAIN, NEW YORK
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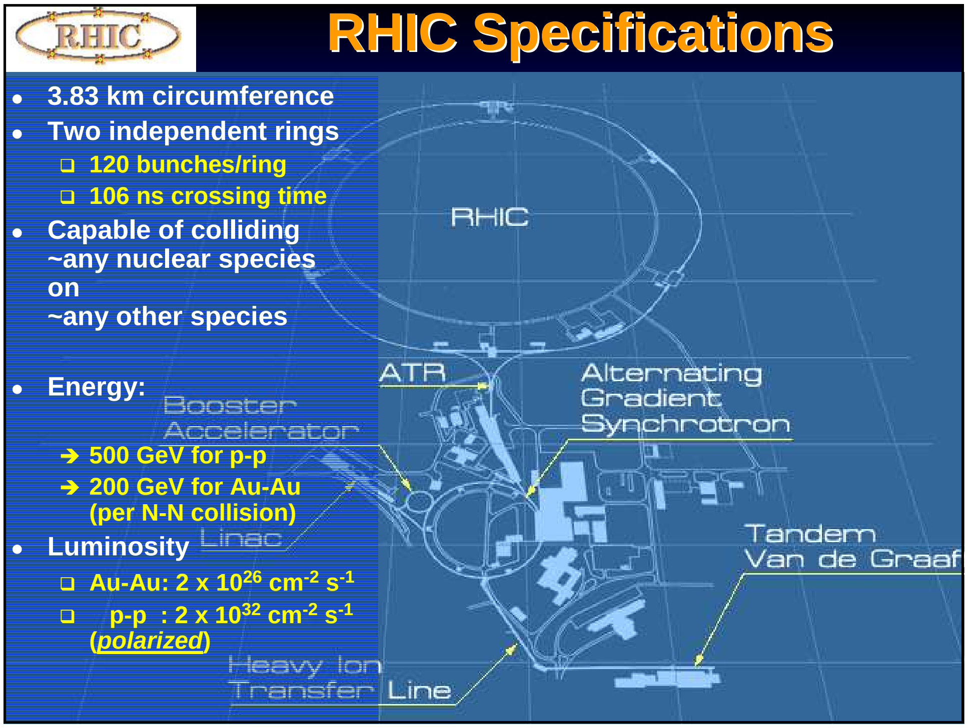
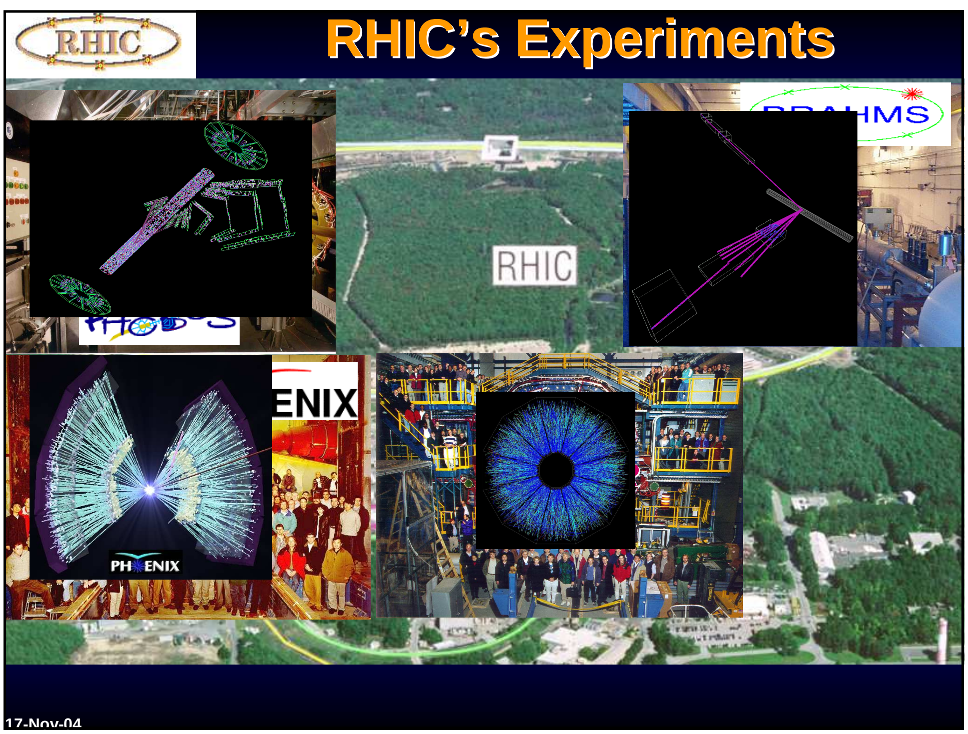

RHIC
RHIC Specifications
• 3.83 km circumference
• Two independent rings
❑ 120 bunches/ring
❑ 106 ns crossing time
• Capable of colliding ~any nuclear species on ~any other species
• Energy:
➔ 500 GeV for p-p
➔ 200 GeV for Au-Au (per N-N collision)
• Luminosity
❑ Au-Au: 2 x 10^{26} cm^{-2} s^{-1}
❑ p-p : 2 x 10^{32} cm^{-2} s^{-1} (polarized)
RHIC
ATR
Alternating Gradient Synchrotron
Booster Accelerator
Linac
Tandem Van de Graaf
Heavy Ion Transfer Line


RHIC
RHIC's Experiments
RHIC
ENIX
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RHIC Achievements to Date

- Machine :
  - Runs 1-4 (Calendar Years 2000-2004):
    - Au+Au: operation at 4 energies (19, 62, 130, 200 GeV)
    - d+Au comparison run (200 GeV)
    - p+p baseline (200 GeV)
  - Routine operation in excess of twice design luminosity !
  - First polarized hadron collider !
- Experimental Operations:
  - Routine collection, analysis of 100 Tb datasets
  - >50 publications in Physical Review Letters
  - Excellent control of systematics and inter-experiment comparisons
- Experimental Results:
  - Record densities created ~100 times normal nuclear density
  - New phenomena clearly observed (“jet” quenching)
  - Strong suggestions of a new state of matter

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RHIC Data to Date

- What have the four RHIC experiments (BRAHMS, PHENIX, PHOBOS, STAR) measured in the first 4 RHIC runs?
- “Only”

γ’s, $\pi^{\pm}$, π^0, $K^{\pm}$, K^{*0}(892), K_s^0, η, p, d, ρ^0, ϕ, Δ,

Λ, Σ^*(1385), Λ^*(1520), $\Xi^{\pm}$, Ω, D^0, $D^{\pm}$, J/Ψ’s,

(+ anti-particles) …

- How to characterize this embarrassment of riches?

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Summary

- The experiments work
- The *initial nuclear geometry* is determined event-by-event
  - Impact parameter
  - Reaction plane

  } Essentially all signals studied as function of $N_{participants}$ and $N_{collisions}$
- Multiplicities are "low"
- Abundances are thermal
- Motion is hydrodynamic
- New phenomena observed } "jet" quenching, baryon/pion "anomaly"
- Evidence for partonic recombination
- Hints of the extraordinary

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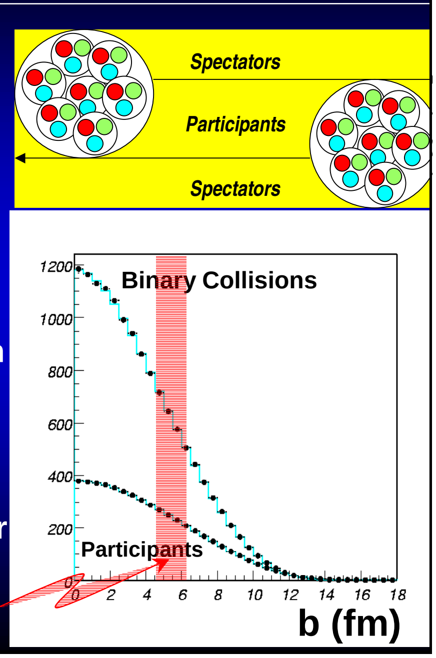
Determining the Initial Geometry

- 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



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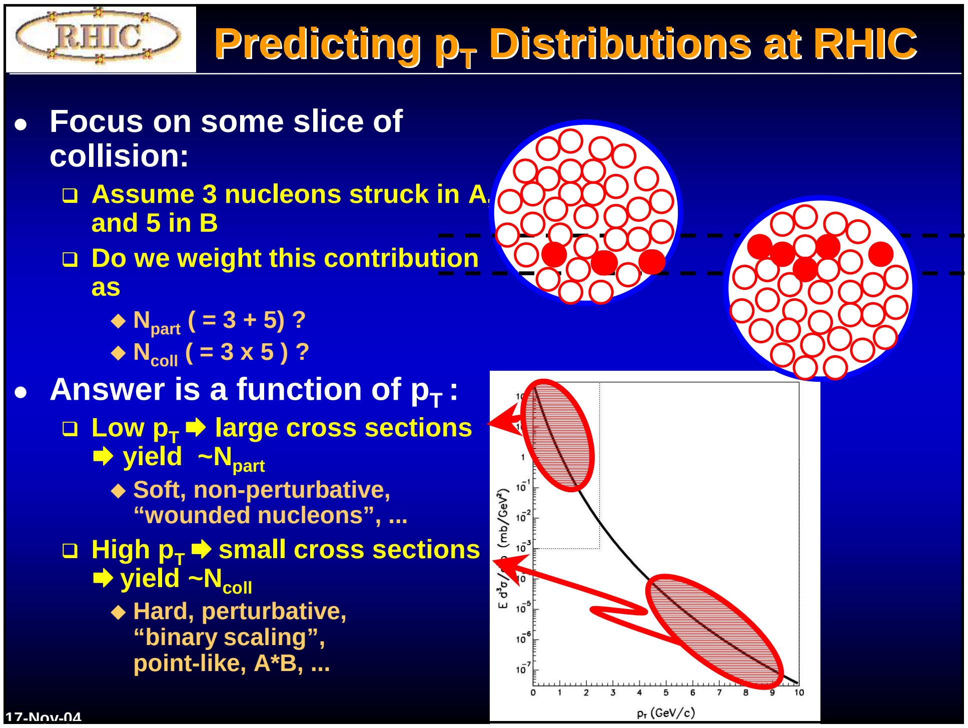
RHIC
Predicting p_T Distributions at RHIC
• Focus on some slice of collision:
❑ Assume 3 nucleons struck in A, and 5 in B
❑ Do we weight this contribution as
◆ N_{part} (= 3 + 5) ?
◆ N_{coll} (= 3 x 5) ?
• Answer is a function of p_T :
❑ Low p_T ➡ large cross sections ➡ yield ~N_{part}
◆ Soft, non-perturbative, “wounded nucleons”, ...
❑ High p_T ➡ small cross sections ➡ yield ~N_{coll}
◆ Hard, perturbative, “binary scaling”, point-like, A*B, ...
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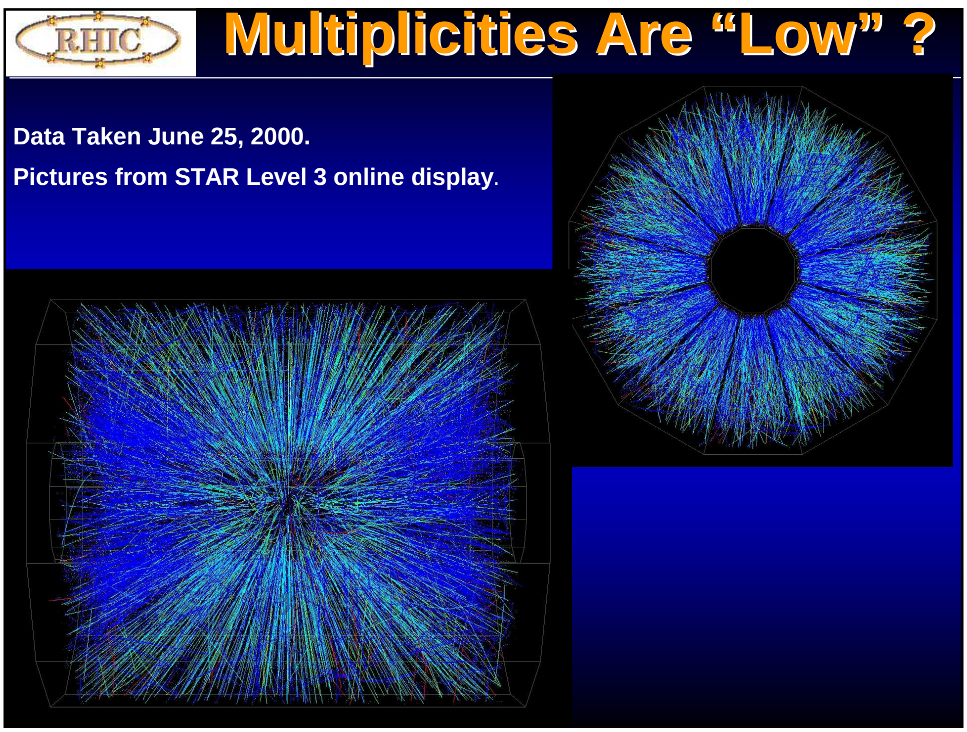
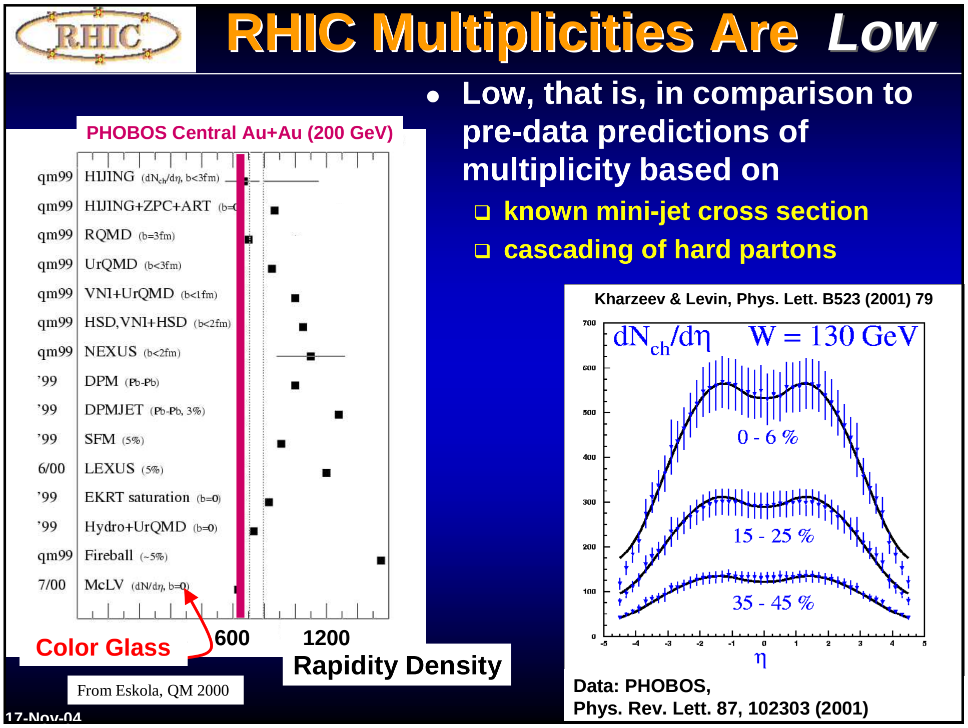
p_T (GeV/c)


RHIC
Multiplicities Are “Low” ?
Data Taken June 25, 2000.
Pictures from STAR Level 3 online display.


RHIC
RHIC Multiplicities Are Low
Low, that is, in comparison to pre-data predictions of multiplicity based on
known mini-jet cross section
cascading of hard partons
PHOBOS Central Au+Au (200 GeV)
qm99 HIJING
qm99 HIJING+ZPC+ART
qm99 RQMD (b=3fm)
qm99 UrQMD (b<3fm)
qm99 VNI+UrQMD
qm99 HSD,VNI+HSD (b<2fm)
qm99 NEXUS (b<2fm)
'99 DPM (Pb-Pb)
'99 DPMJET (Pb-Pb, 3%)
'99 SFM (5%)
6/00 LEXUS (5%)
'99 EKRT saturation (b=0)
'99 Hydro+UrQMD (b=0)
qm99 Fireball (~5%)
7/00 McLV
Color Glass
600
1200
Rapidity Density
From Eskola, QM 2000
Kharzeev & Levin, Phys. Lett. B523 (2001) 79
dN_ch/dη W = 130 GeV
0 - 6 %
15 - 25 %
35 - 45 %
η
Data: PHOBOS,
Phys. Rev. Lett. 87, 102303 (2001)
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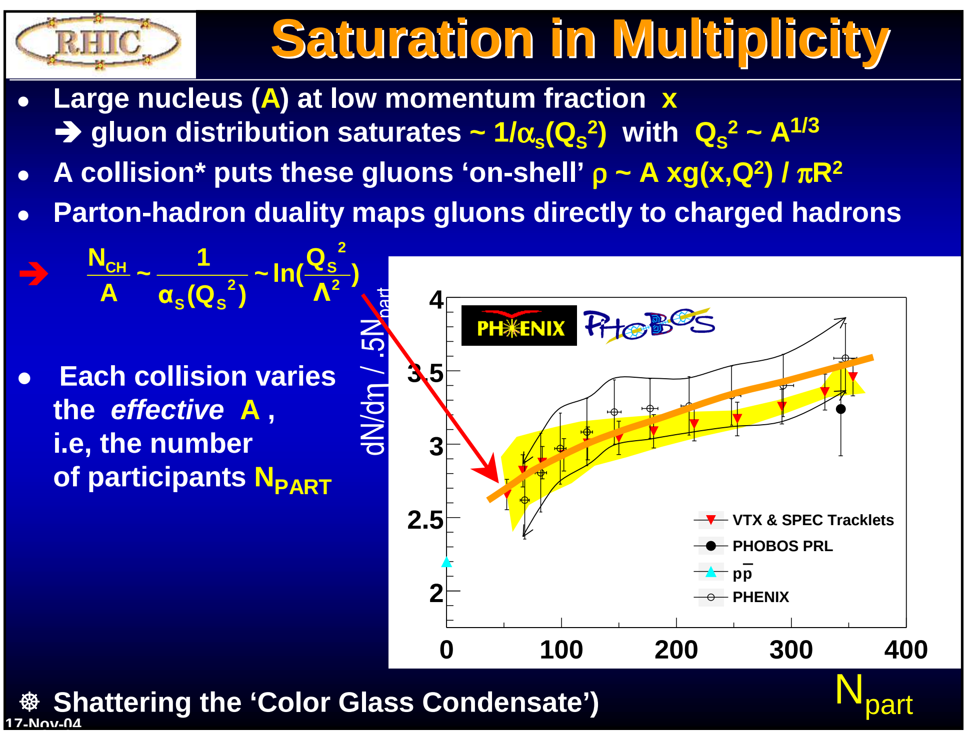
RHIC
Saturation in Multiplicity
Large nucleus (A) at low momentum fraction x
➔ gluon distribution saturates ~ 1/αs(Qs²) with Qs² ~ A^1/3
A collision* puts these gluons 'on-shell' ρ ~ A xg(x,Q²) / πR²
Parton-hadron duality maps gluons directly to charged hadrons
N_CH / A ~ 1 / αs(Qs²) ~ ln(Qs² / Λ²)
Each collision varies the effective A, i.e, the number of participants N_PART
dN/dη / .5N_part
PHENIX
PHOBOS
VTX & SPEC Tracklets
PHOBOS PRL
pp
PHENIX
4
3.5
3
2.5
2
0
100
200
300
400
N_part
Shattering the 'Color Glass Condensate')
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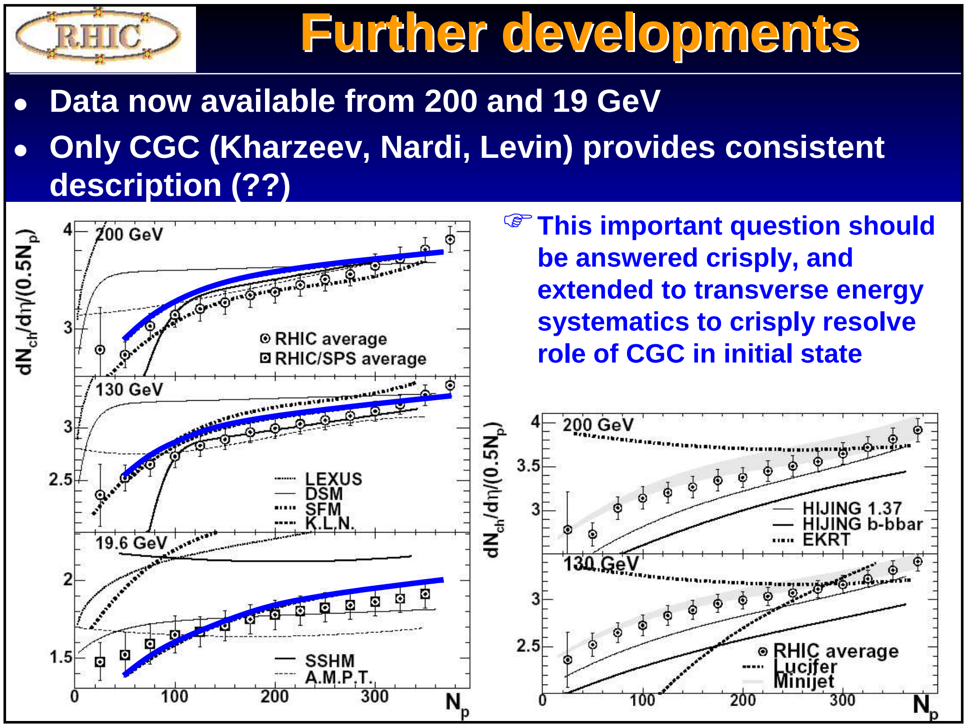
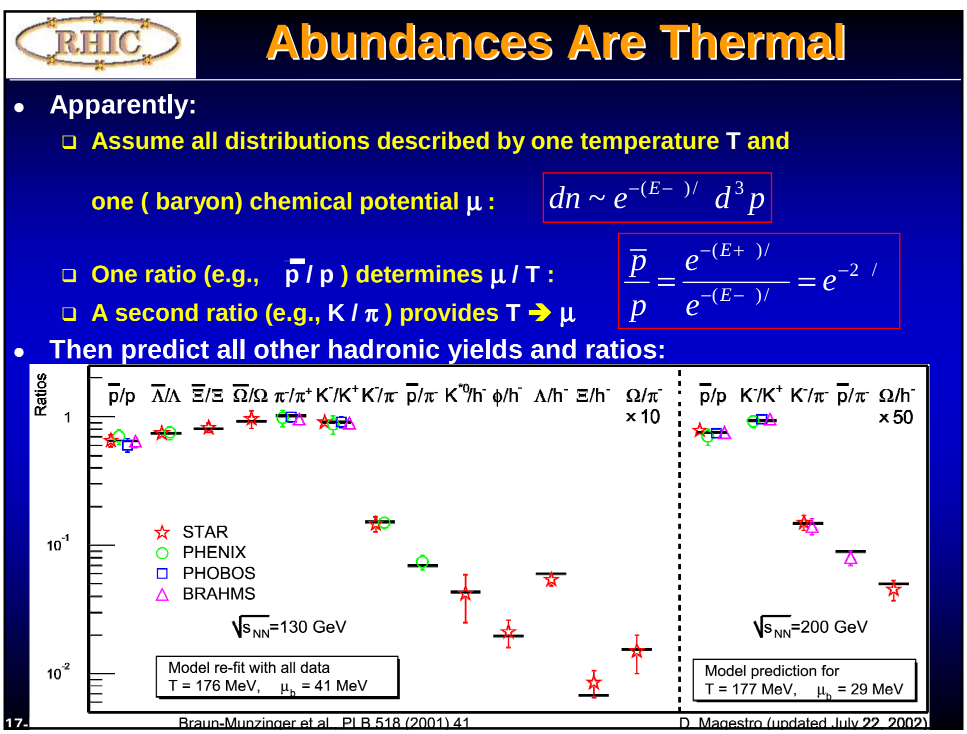
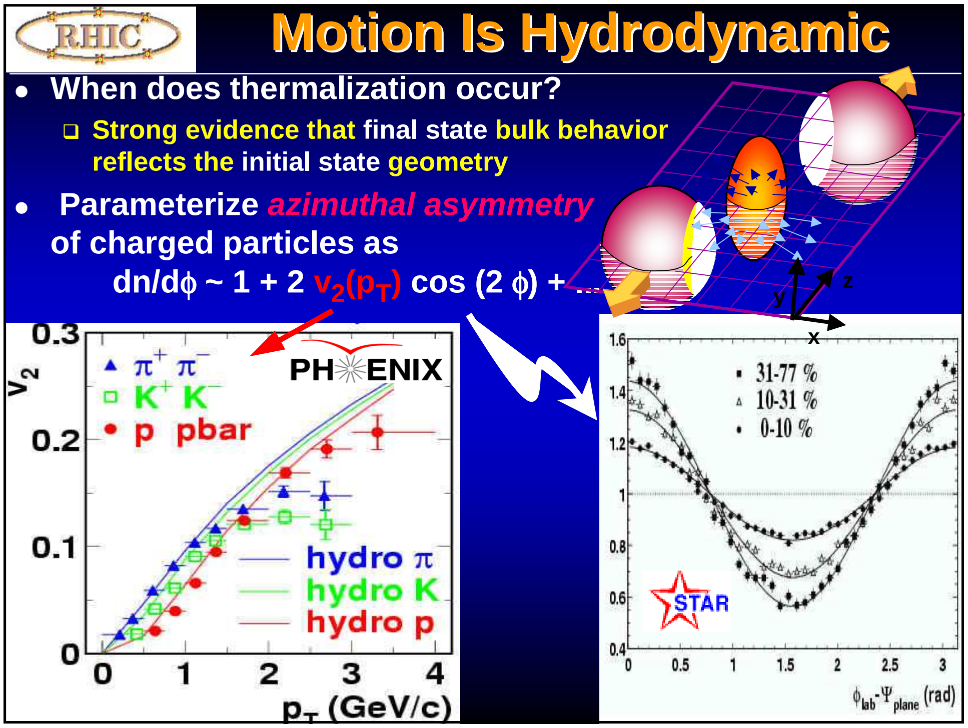
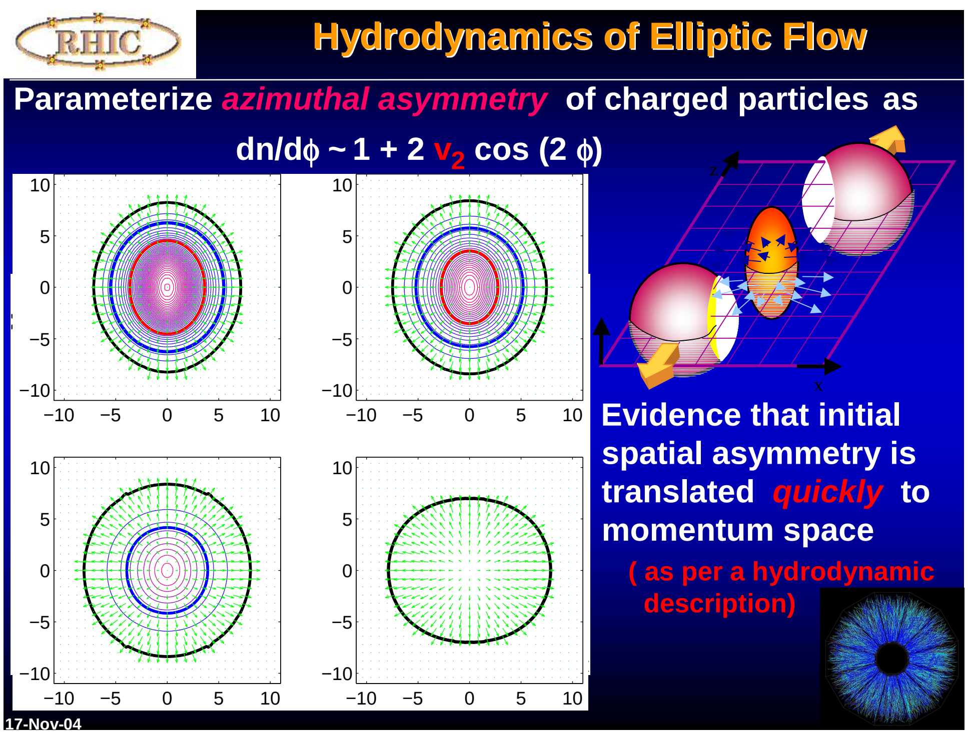

RHIC
Further developments
Data now available from 200 and 19 GeV
Only CGC (Kharzeev, Nardi, Levin) provides consistent description (??)
This important question should be answered crisply, and extended to transverse energy systematics to crisply resolve role of CGC in initial state
200 GeV
130 GeV
19.6 GeV
RHIC average
RHIC/SPS average
LEXUS
DSM
SFM
K.L.N.
SSHM
A.M.P.T.
HIJING 1.37
HIJING b-bbar
EKRT
Lucifer
Minijet
dN_ch/dη/(0.5N_p)
N_p


RHIC
Abundances Are Thermal
Apparently:
Assume all distributions described by one temperature T and
one (baryon) chemical potential μ :
One ratio (e.g., p̄ / p) determines μ / T :
A second ratio (e.g., K / π) provides T → μ
Then predict all other hadronic yields and ratios:
STAR
PHENIX
PHOBOS
BRAHMS
Ratios
√s_NN=130 GeV
√s_NN=200 GeV
Model re-fit with all data
T = 176 MeV, μ_b = 41 MeV
Model prediction for
T = 177 MeV, μ_b = 29 MeV
Braun-Munzinger et al., PLB 518 (2001) 41
D. Magestro (updated July 22, 2002)


RHIC
Motion Is Hydrodynamic
When does thermalization occur?
Strong evidence that final state bulk behavior reflects the initial state geometry
Parameterize azimuthal asymmetry of charged particles as
dn/dφ ~ 1 + 2 v2(pT) cos (2 φ) + ...
v2
π+ π−
K+ K−
p pbar
PHENIX
hydro π
hydro K
hydro p
pT (GeV/c)
31-77 %
10-31 %
0-10 %
STAR
x
y
z


RHIC
Hydrodynamics of Elliptic Flow
Parameterize azimuthal asymmetry of charged particles as
dn/dφ ~ 1 + 2 v2 cos (2 φ)
Evidence that initial spatial asymmetry is translated quickly to momentum space
(as per a hydrodynamic description)
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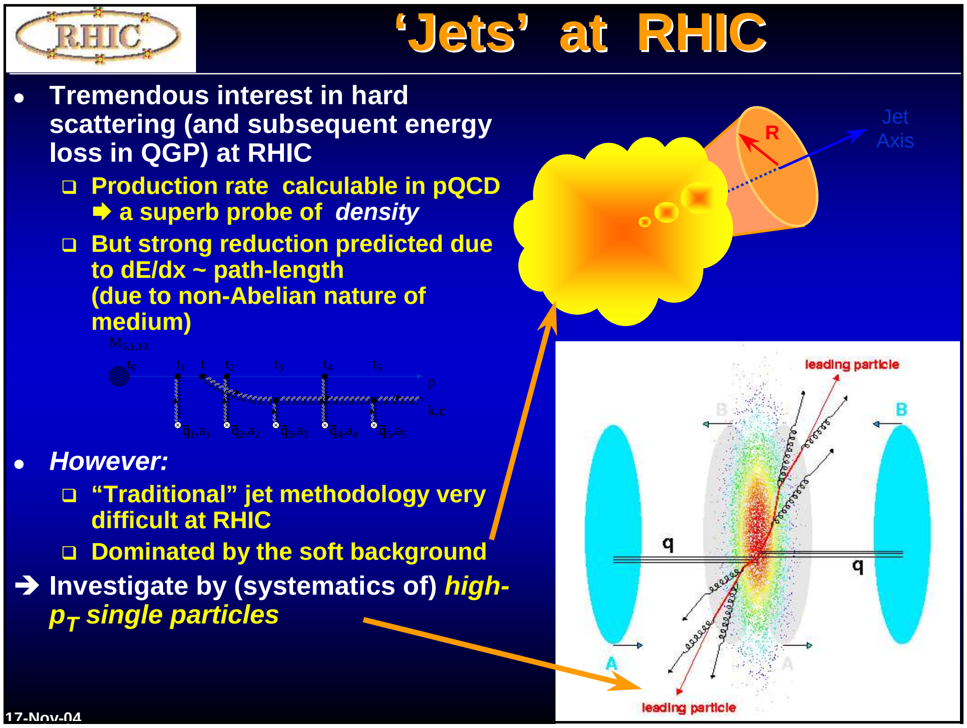
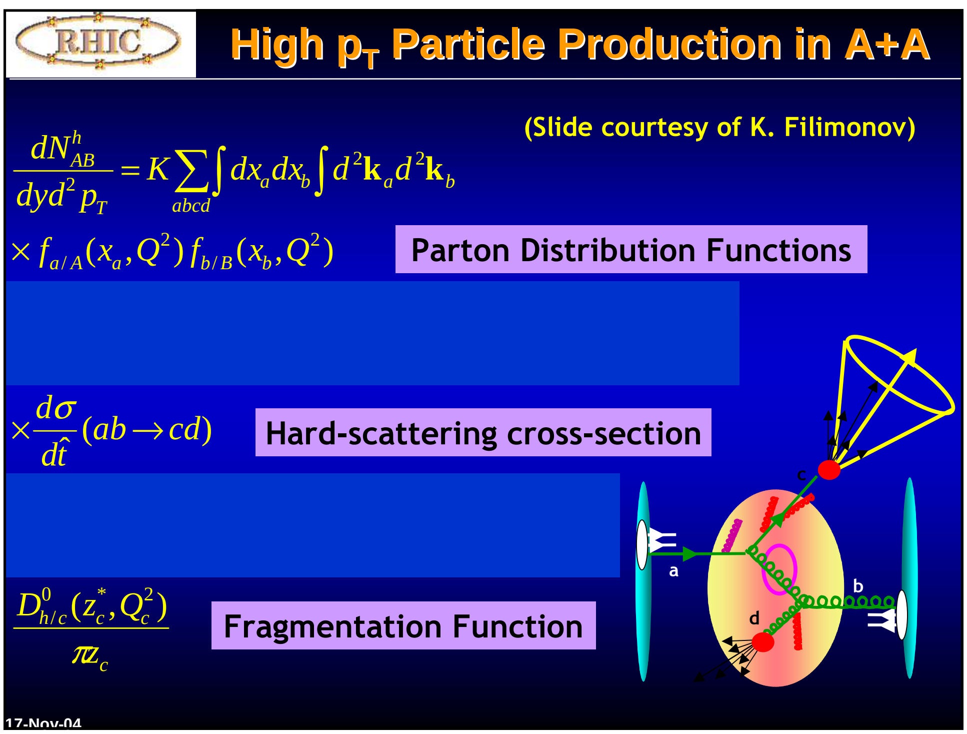
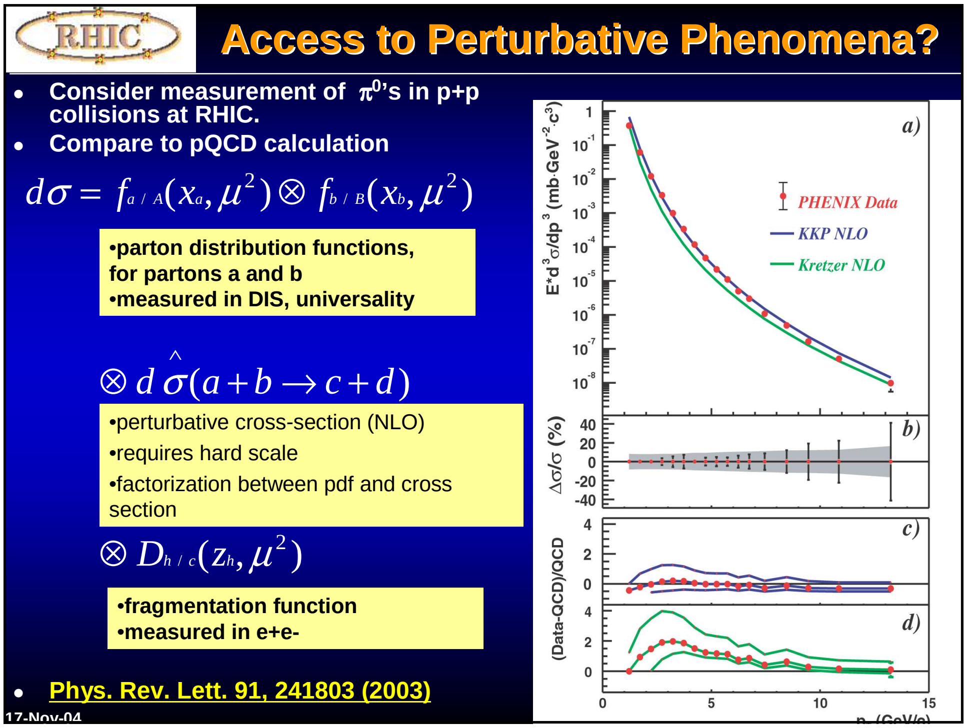
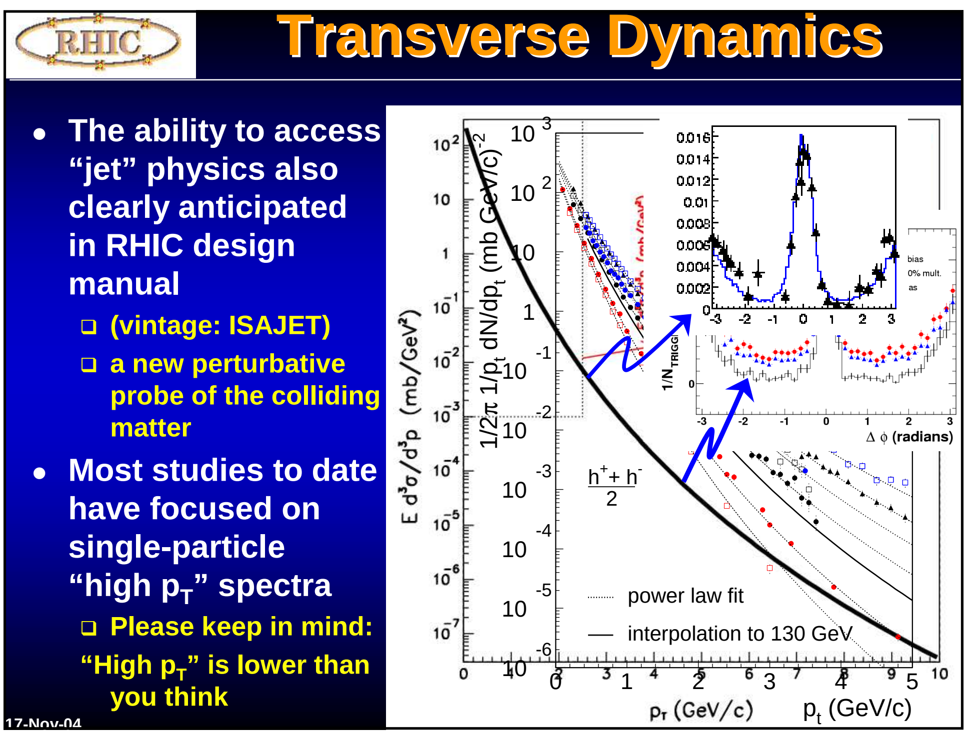
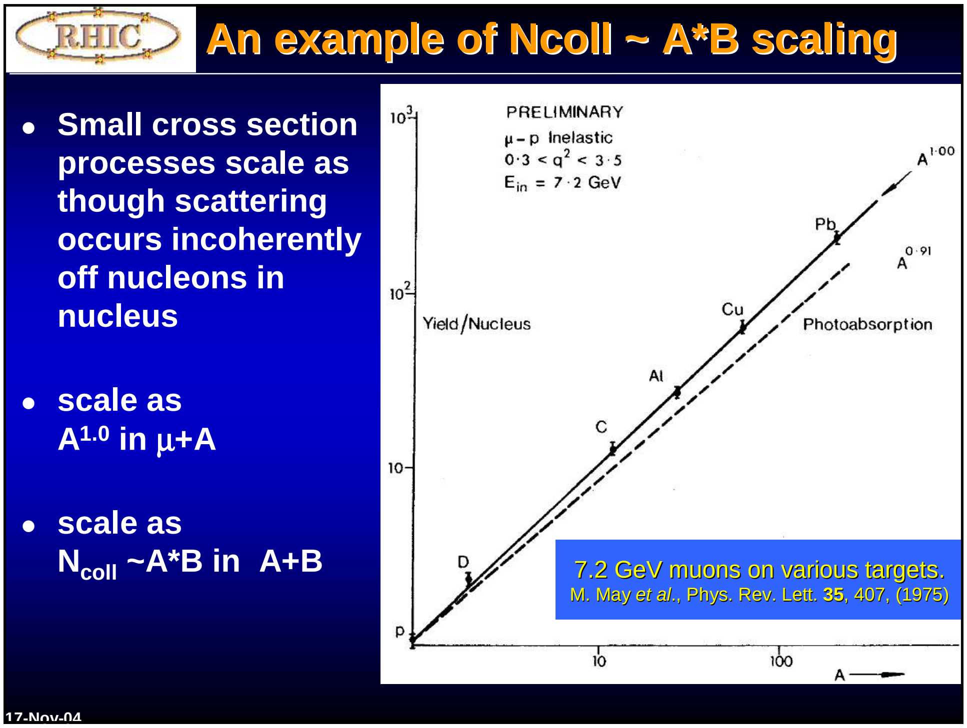
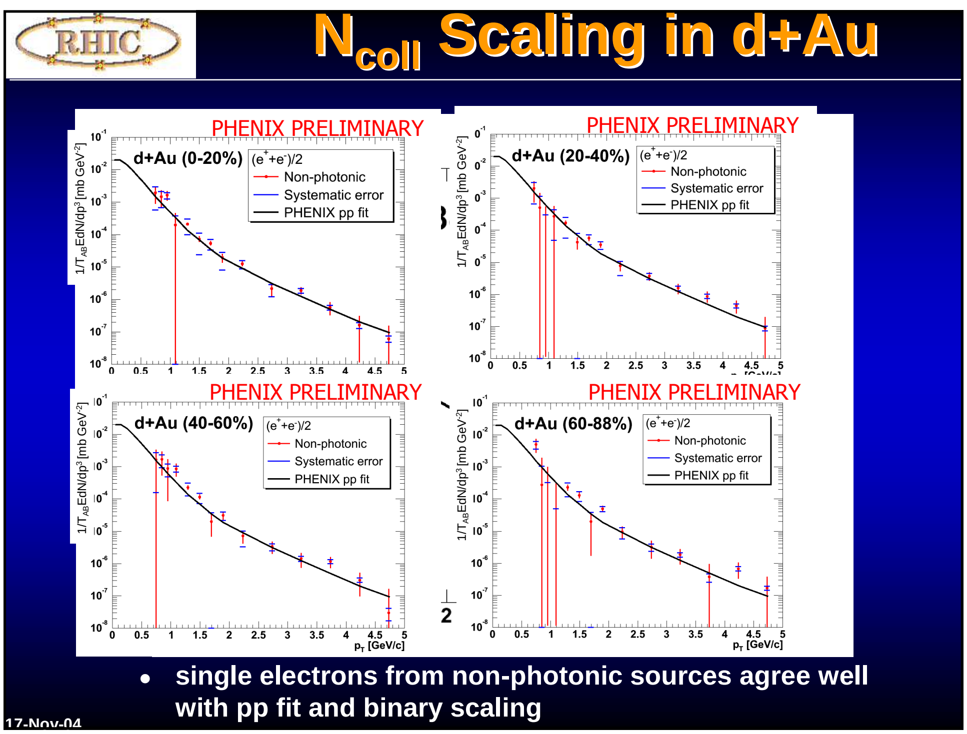

RHIC
'Jets' at RHIC
• Tremendous interest in hard scattering (and subsequent energy loss in QGP) at RHIC
❑ Production rate calculable in pQCD ➡ a superb probe of density
❑ But strong reduction predicted due to dE/dx ~ path-length (due to non-Abelian nature of medium)
• However:
❑ "Traditional" jet methodology very difficult at RHIC
❑ Dominated by the soft background
➔ Investigate by (systematics of) high-p_T single particles
R
Jet Axis
leading particle
B
q
q
A
leading particle
17-Nov-04

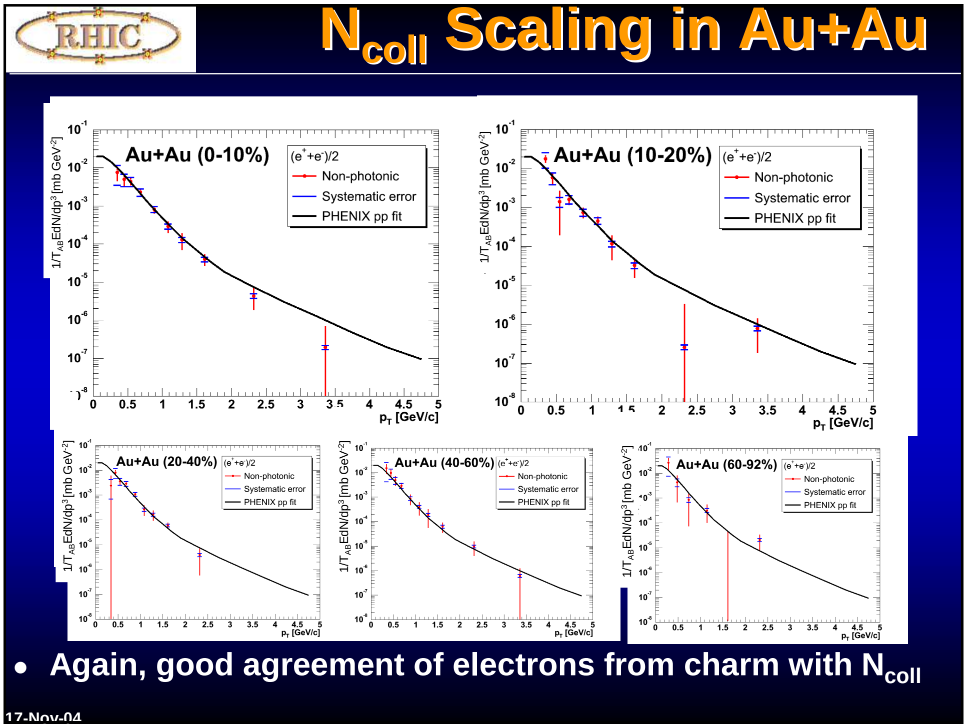

RHIC
High p_T Particle Production in A+A
(Slide courtesy of K. Filimonov)
$\frac{dN^h_{AB}}{dyd^2p_T} = K \sum_{abcd} \int dx_a dx_b \int d^2\mathbf{k}_a d^2\mathbf{k}_b$
$\times f_{a/A}(x_a, Q^2) f_{b/B}(x_b, Q^2)$
Parton Distribution Functions
$\times \frac{d\sigma}{d\hat{t}}(ab \to cd)$
Hard-scattering cross-section
$\frac{D^0_{h/c}(z^*_c, Q^2_c)}{\pi z_c}$
Fragmentation Function
c
a
b
d
17-Nov-04

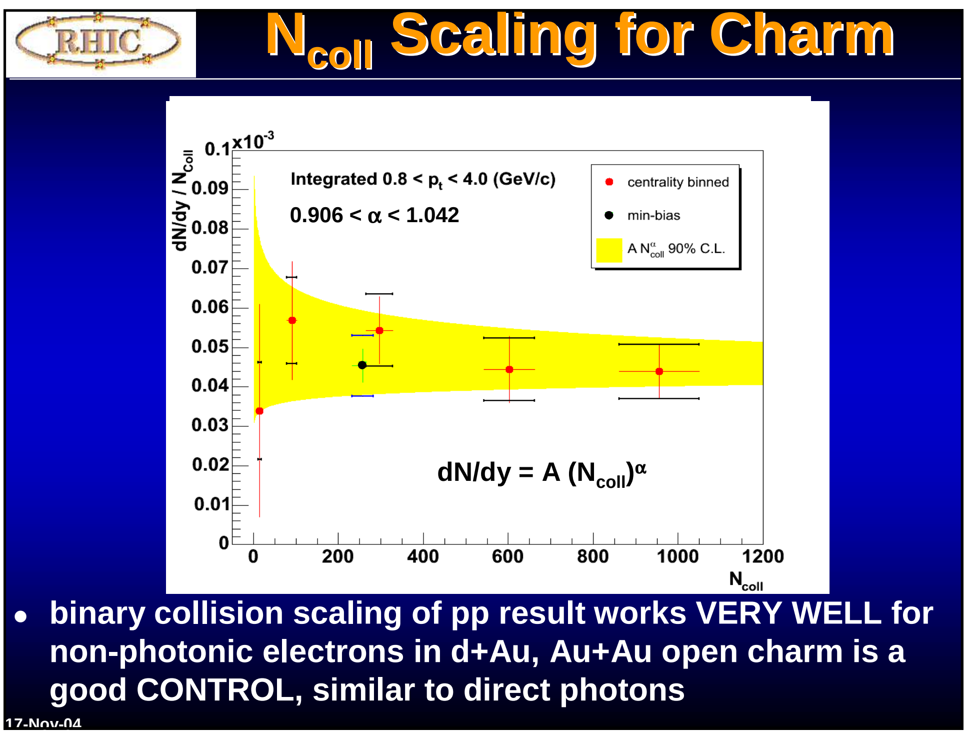

RHIC
Access to Perturbative Phenomena?
Consider measurement of π0's in p+p collisions at RHIC.
Compare to pQCD calculation
$d\sigma = f_{a/A}(x_a,\mu^2) \otimes f_{b/B}(x_b,\mu^2)$
•parton distribution functions, for partons a and b
•measured in DIS, universality
$\otimes\, d\hat{\sigma}(a+b \rightarrow c+d)$
•perturbative cross-section (NLO)
•requires hard scale
•factorization between pdf and cross section
$\otimes\, D_{h/c}(z_h,\mu^2)$
•fragmentation function
•measured in e+e-
Phys. Rev. Lett. 91, 241803 (2003)
17-Nov-04
PHENIX Data
KKP NLO
Kretzer NLO
E*d3σ/dp3 (mb·GeV-2·c3)
Δσ/σ (%)
(Data-QCD)/QCD
a)
b)
c)
d)

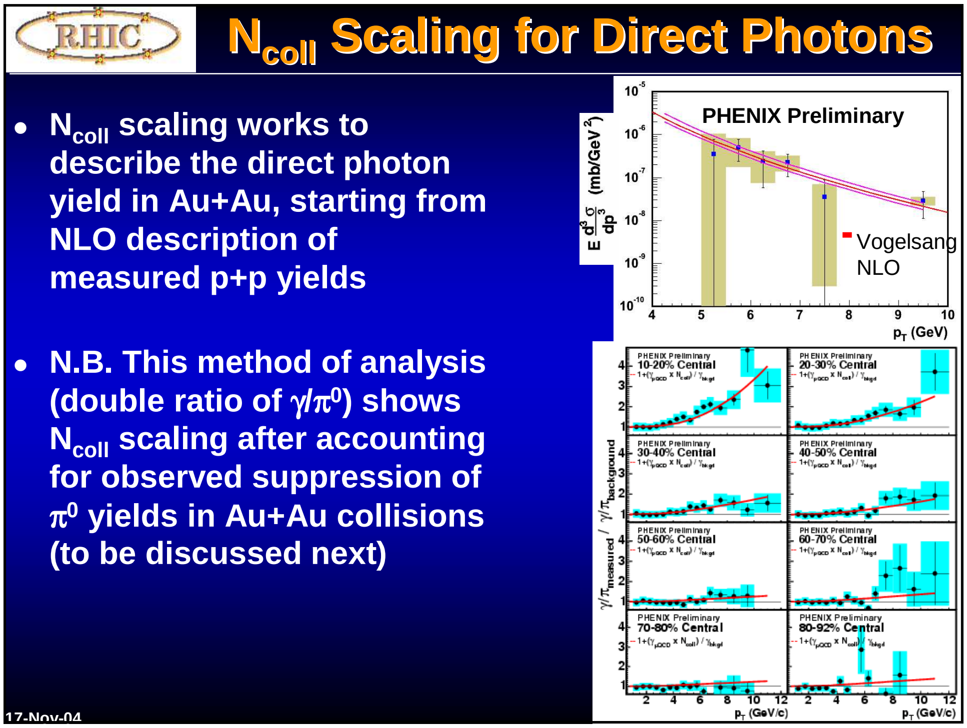

RHIC
Transverse Dynamics
The ability to access "jet" physics also clearly anticipated in RHIC design manual
(vintage: ISAJET)
a new perturbative probe of the colliding matter
Most studies to date have focused on single-particle "high pT" spectra
Please keep in mind:
"High pT" is lower than you think
17-Nov-04
E d3σ/d3p (mb/GeV2)
1/2π 1/pt dN/dpt (mb GeV/c)-2
h+ + h-
2
power law fit
interpolation to 130 GeV
pT (GeV/c)
pt (GeV/c)
Δ φ (radians)

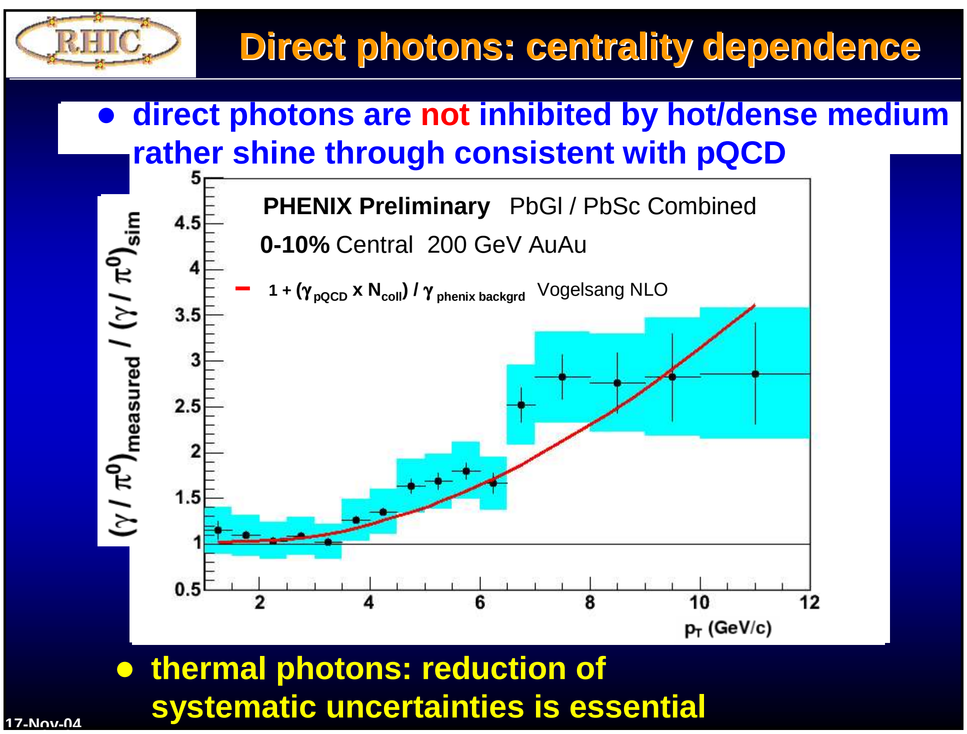

An example of Ncoll ~ A*B scaling
• Small cross section processes scale as though scattering occurs incoherently off nucleons in nucleus
• scale as A^1.0 in μ+A
• scale as N_coll ~A*B in A+B
PRELIMINARY
μ – p Inelastic
0·3 < q² < 3·5
E_in = 7·2 GeV
Yield/Nucleus
Photoabsorption
A^1·00
A^0·91
p
D
C
Al
Cu
Pb
A
7.2 GeV muons on various targets.
M. May et al., Phys. Rev. Lett. 35, 407, (1975)
17-Nov-04

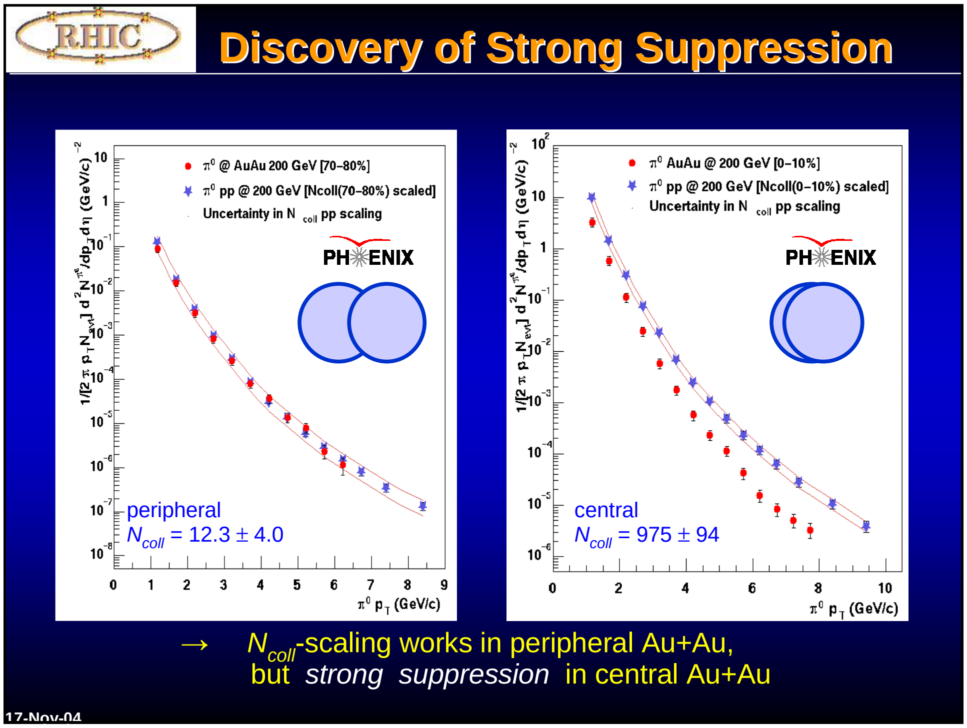

N_coll Scaling in d+Au
PHENIX PRELIMINARY
d+Au (0-20%)
d+Au (20-40%)
d+Au (40-60%)
d+Au (60-88%)
(e⁺+e⁻)/2
Non-photonic
Systematic error
PHENIX pp fit
1/T_AB EdN/dp³ [mb GeV⁻²]
p_T [GeV/c]
• single electrons from non-photonic sources agree well with pp fit and binary scaling
17-Nov-04

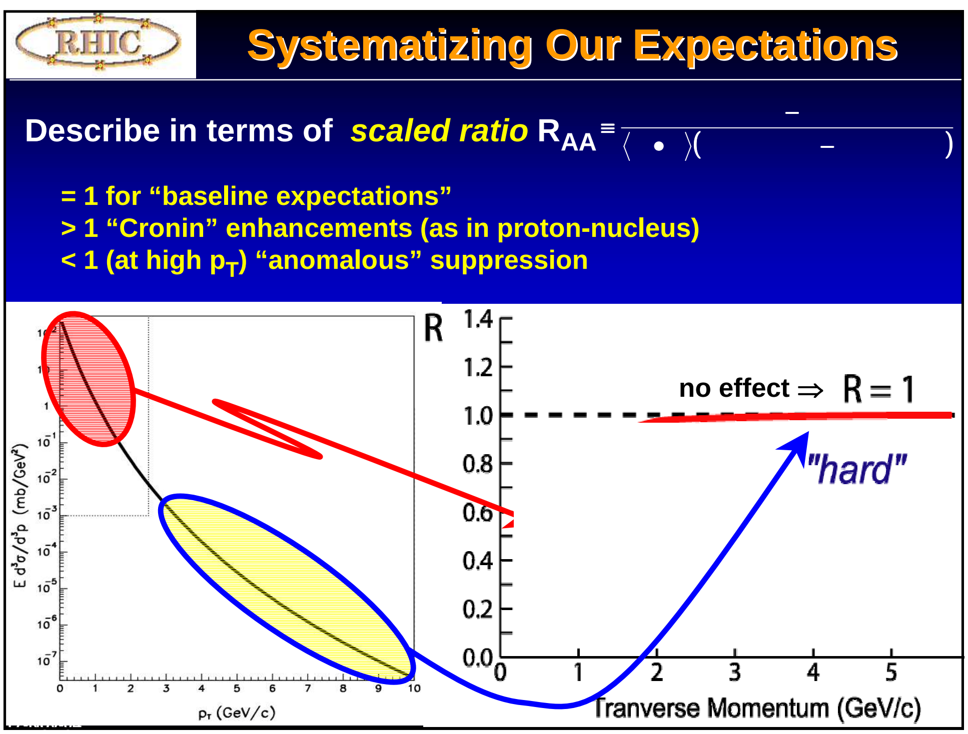

RHIC
N_{coll} Scaling in Au+Au
Au+Au (0-10%)
Au+Au (10-20%)
Au+Au (20-40%)
Au+Au (40-60%)
Au+Au (60-92%)
$(e^+ + e^-)/2$
Non-photonic
Systematic error
PHENIX pp fit
$1/T_{AB} EdN/dp^3$ [mb GeV^{-2}]
p_T [GeV/c]
• Again, good agreement of electrons from charm with N_{coll}
17-Nov-04

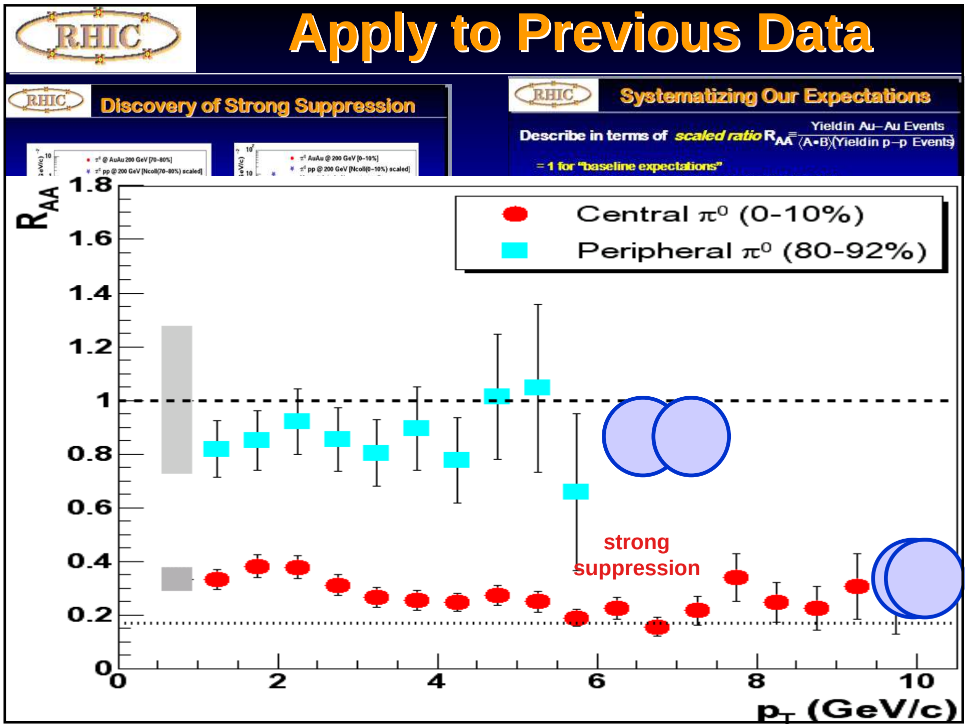

RHIC
N_{coll} Scaling for Charm
Integrated 0.8 < p_t < 4.0 (GeV/c)
0.906 < α < 1.042
centrality binned
min-bias
A N_{coll}^{α} 90% C.L.
dN/dy / N_{coll}
$\times 10^{-3}$
$dN/dy = A (N_{coll})^{\alpha}$
N_{coll}
• binary collision scaling of pp result works VERY WELL for non-photonic electrons in d+Au, Au+Au open charm is a good CONTROL, similar to direct photons
17-Nov-04

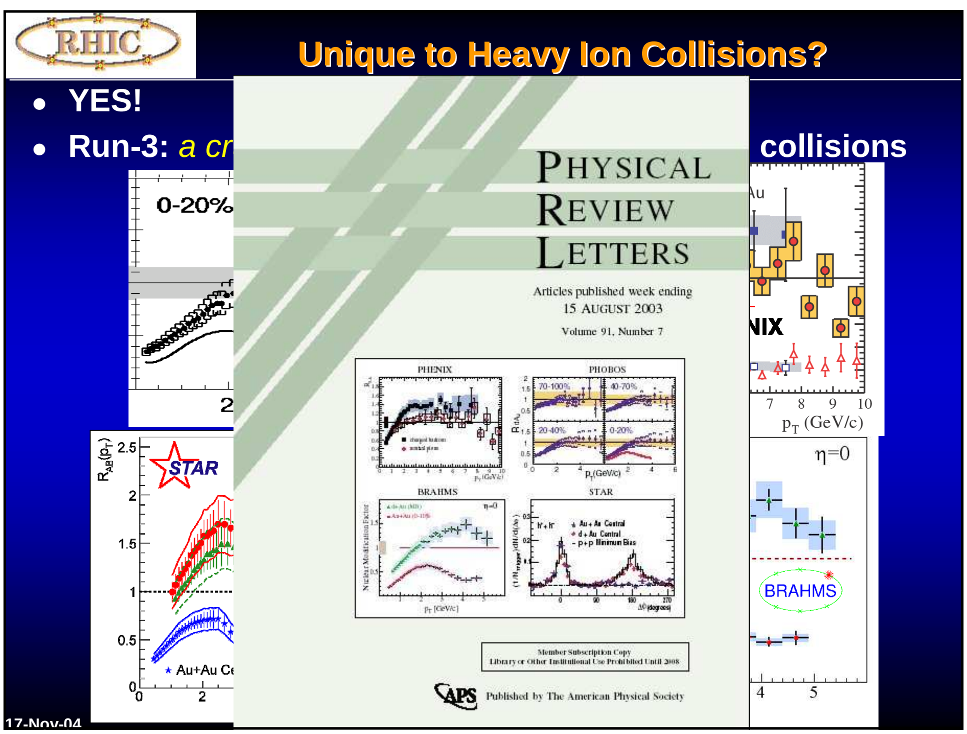

RHIC
N_{coll} Scaling for Direct Photons
• N_{coll} scaling works to describe the direct photon yield in Au+Au, starting from NLO description of measured p+p yields
• N.B. This method of analysis (double ratio of γ/π^0) shows N_{coll} scaling after accounting for observed suppression of π^0 yields in Au+Au collisions (to be discussed next)
PHENIX Preliminary
Vogelsang NLO
$E\frac{d^3\sigma}{dp^3}$ (mb/GeV^2)
p_T (GeV)
10-20% Central
20-30% Central
30-40% Central
40-50% Central
50-60% Central
60-70% Central
70-80% Central
80-92% Central
p_T (GeV/c)
17-Nov-04

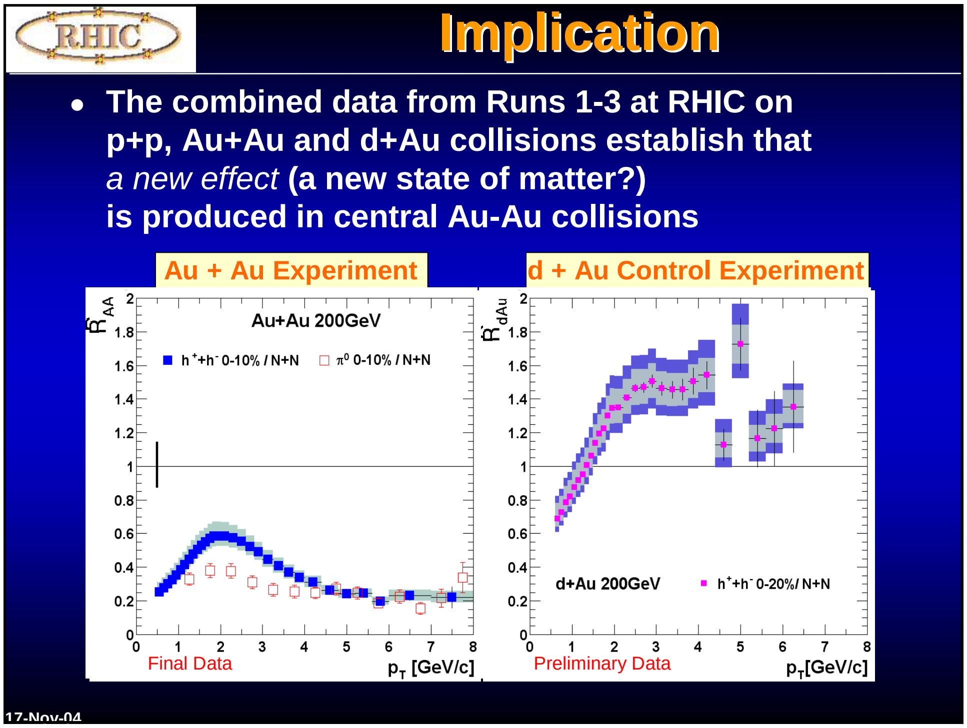

RHIC
Direct photons: centrality dependence
• direct photons are not inhibited by hot/dense medium rather shine through consistent with pQCD
PHENIX Preliminary PbGl / PbSc Combined
0-10% Central 200 GeV AuAu
$1 + (\gamma_{pQCD} \times N_{coll}) / \gamma_{phenix\ backgrd}$ Vogelsang NLO
$(\gamma/\pi^0)_{measured} / (\gamma/\pi^0)_{sim}$
p_T (GeV/c)
• thermal photons: reduction of systematic uncertainties is essential
17-Nov-04

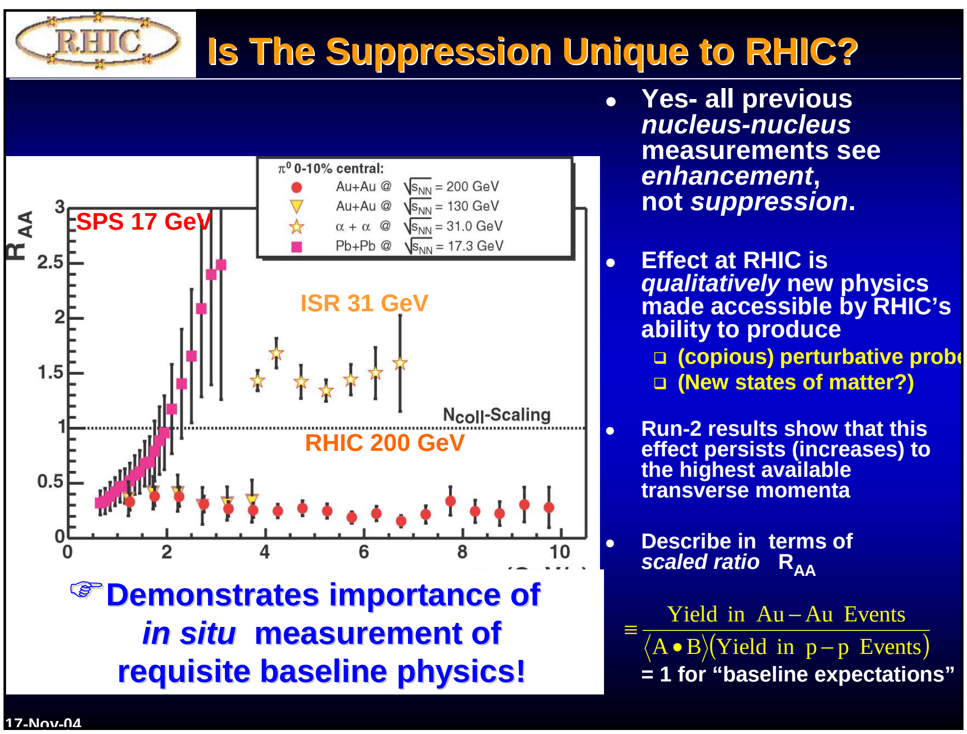

RHIC
Discovery of Strong Suppression
π⁰ @ AuAu 200 GeV [70–80%]
π⁰ pp @ 200 GeV [Ncoll(70–80%) scaled]
Uncertainty in N coll pp scaling
PHENIX
peripheral
Ncoll = 12.3 ± 4.0
π⁰ pT (GeV/c)
π⁰ AuAu @ 200 GeV [0–10%]
π⁰ pp @ 200 GeV [Ncoll(0–10%) scaled]
Uncertainty in N coll pp scaling
PHENIX
central
Ncoll = 975 ± 94
π⁰ pT (GeV/c)
→ Ncoll-scaling works in peripheral Au+Au,
but strong suppression in central Au+Au
17-Nov-04

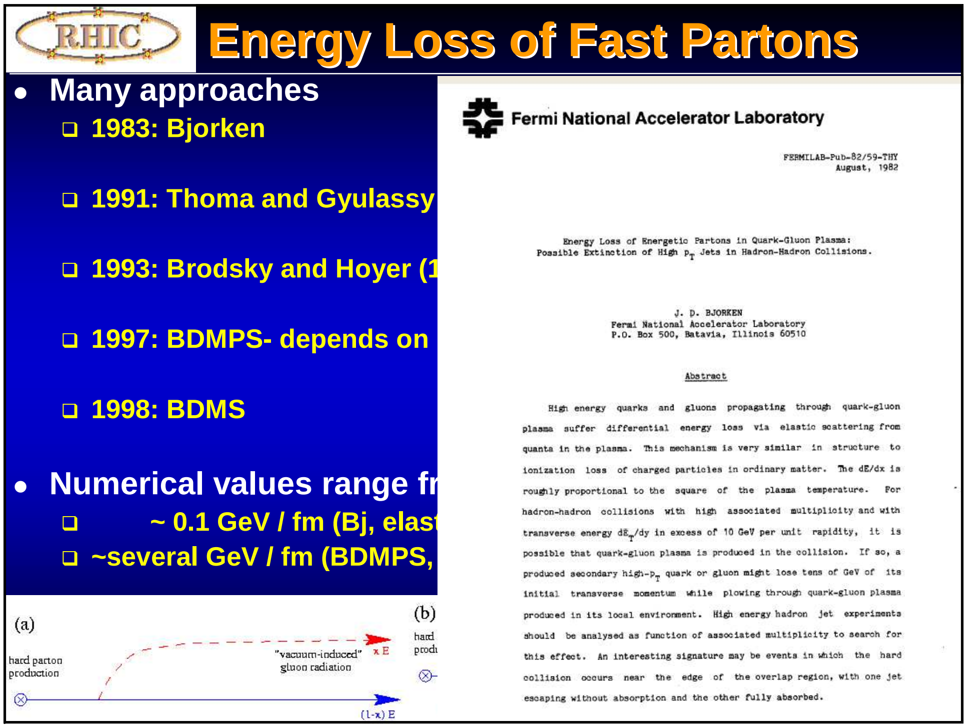

RHIC
Systematizing Our Expectations
Describe in terms of scaled ratio RAA ≡
= 1 for "baseline expectations"
> 1 "Cronin" enhancements (as in proton-nucleus)
< 1 (at high pT) "anomalous" suppression
R
no effect ⇒ R = 1
"hard"
Tranverse Momentum (GeV/c)
pT (GeV/c)

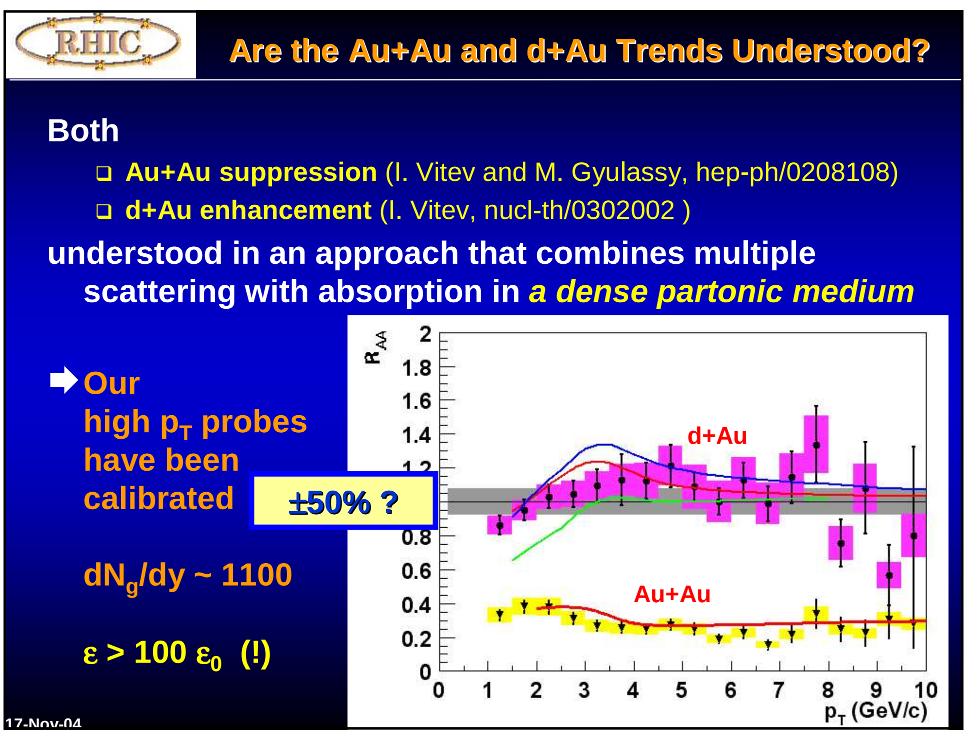

RHIC
Apply to Previous Data
Discovery of Strong Suppression
Systematizing Our Expectations
Describe in terms of scaled ratio R_AA = Yieldin Au–Au Events / ⟨A•B⟩(Yieldin p–p Events)
= 1 for "baseline expectations"
Central π⁰ (0-10%)
Peripheral π⁰ (80-92%)
strong suppression
R_AA
p_T (GeV/c)

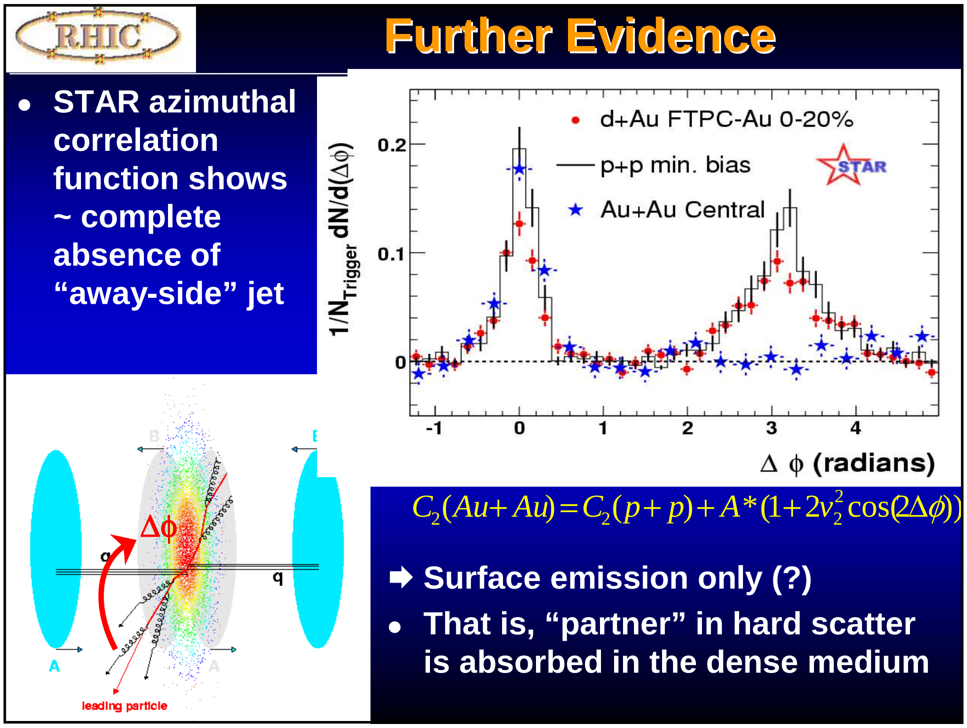

RHIC
Unique to Heavy Ion Collisions?
YES!
Run-3: a cr
collisions
0-20%
STAR
Au+Au Ce
PHYSICAL REVIEW LETTERS
Articles published week ending 15 AUGUST 2003
Volume 91, Number 7
PHENIX
PHOBOS
BRAHMS
STAR
Member Subscription Copy
Library or Other Institutional Use Prohibited Until 2008
APS Published by The American Physical Society
η=0
BRAHMS
p_T (GeV/c)
17-Nov-04

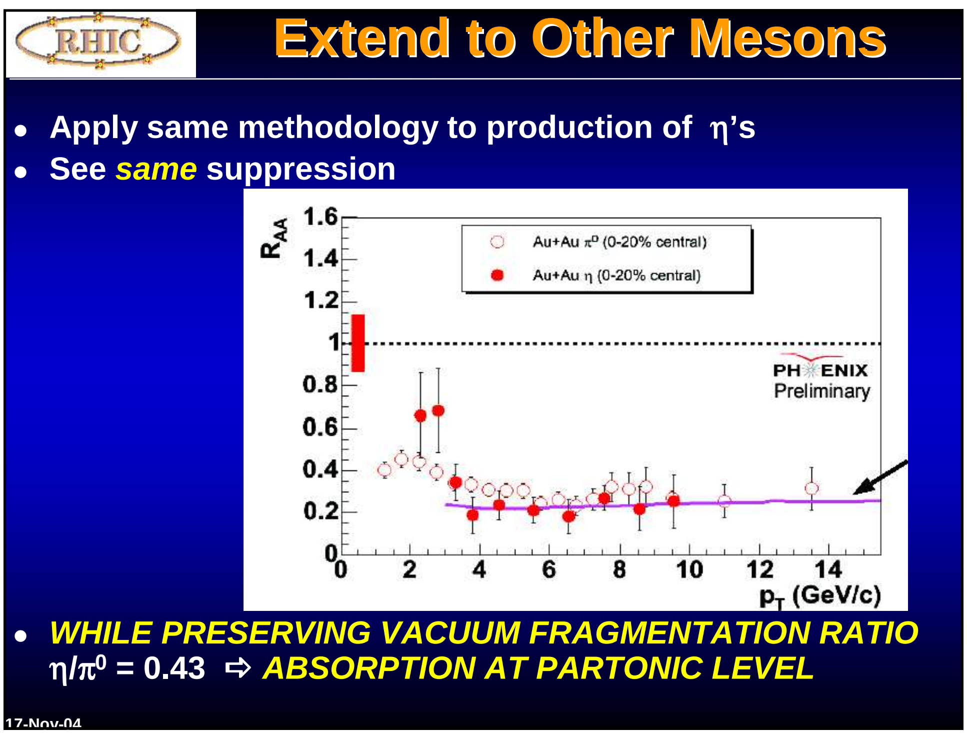

RHIC
Implication
The combined data from Runs 1-3 at RHIC on p+p, Au+Au and d+Au collisions establish that a new effect (a new state of matter?) is produced in central Au-Au collisions
Au + Au Experiment
d + Au Control Experiment
Au+Au 200GeV
h+h- 0-10% / N+N
π0 0-10% / N+N
d+Au 200GeV
h+h- 0-20%/ N+N
Final Data
Preliminary Data
pT [GeV/c]
17-Nov-04

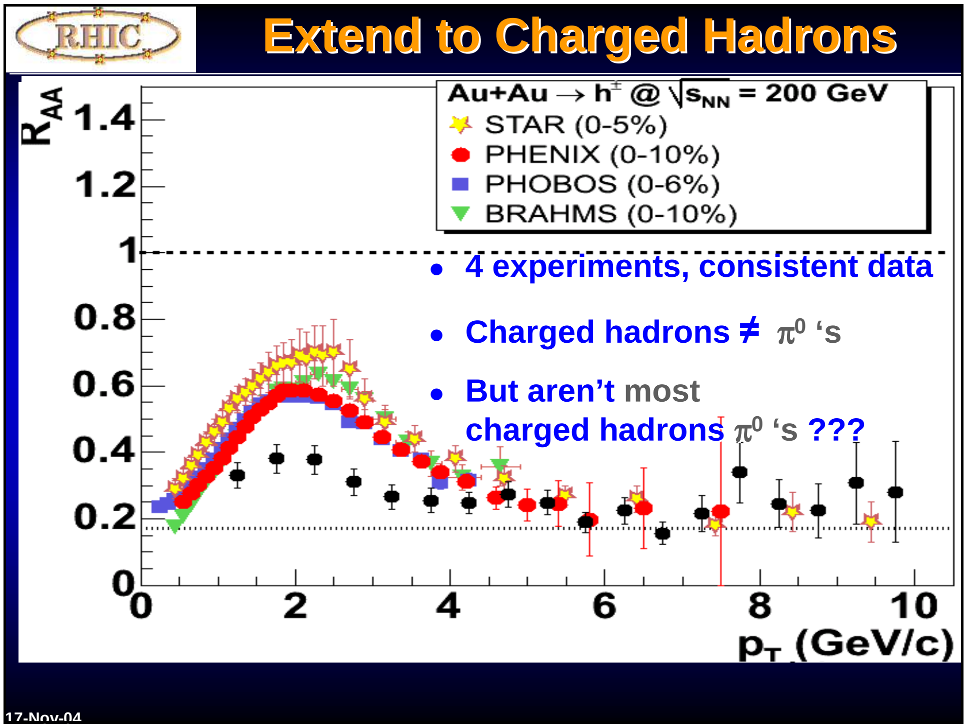

RHIC
Is The Suppression Unique to RHIC?
Yes- all previous nucleus-nucleus measurements see enhancement, not suppression.
Effect at RHIC is qualitatively new physics made accessible by RHIC's ability to produce
(copious) perturbative probe
(New states of matter?)
Run-2 results show that this effect persists (increases) to the highest available transverse momenta
Describe in terms of scaled ratio RAA
≡ Yield in Au−Au Events / ⟨A•B⟩(Yield in p−p Events)
= 1 for "baseline expectations"
π0 0-10% central:
Au+Au @ √sNN = 200 GeV
Au+Au @ √sNN = 130 GeV
α + α @ √sNN = 31.0 GeV
Pb+Pb @ √sNN = 17.3 GeV
SPS 17 GeV
ISR 31 GeV
RHIC 200 GeV
Ncoll-Scaling
Demonstrates importance of in situ measurement of requisite baseline physics!
17-Nov-04

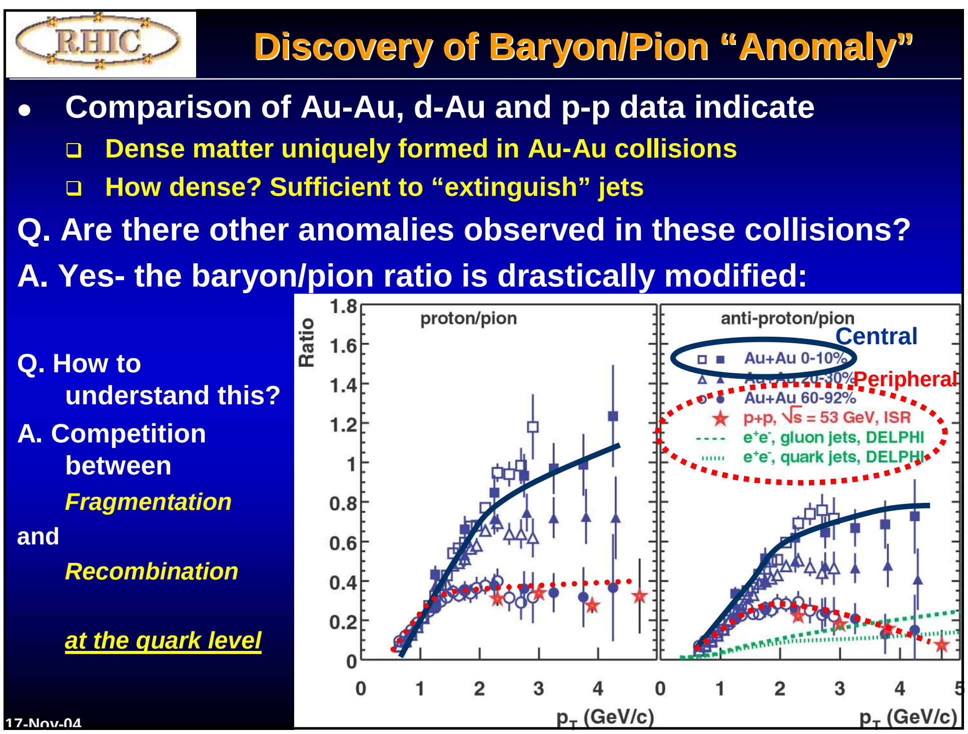

RHIC
Energy Loss of Fast Partons
• Many approaches
❑ 1983: Bjorken
❑ 1991: Thoma and Gyulassy
❑ 1993: Brodsky and Hoyer (1
❑ 1997: BDMPS- depends on
❑ 1998: BDMS
• Numerical values range fr
❑ ~ 0.1 GeV / fm (Bj, elast
❑ ~several GeV / fm (BDMPS,
(a)
hard parton production
"vacuum-induced" gluon radiation
x E
(1-x) E
(b)
hard prod
Fermi National Accelerator Laboratory
FERMILAB-Pub-82/59-THY
August, 1982
Energy Loss of Energetic Partons in Quark-Gluon Plasma:
Possible Extinction of High p_T Jets in Hadron-Hadron Collisions.
J. D. BJORKEN
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510
Abstract
High energy quarks and gluons propagating through quark-gluon plasma suffer differential energy loss via elastic scattering from quanta in the plasma. This mechanism is very similar in structure to ionization loss of charged particles in ordinary matter. The dE/dx is roughly proportional to the square of the plasma temperature. For hadron-hadron collisions with high associated multiplicity and with transverse energy dE_T/dy in excess of 10 GeV per unit rapidity, it is possible that quark-gluon plasma is produced in the collision. If so, a produced secondary high-p_T quark or gluon might lose tens of GeV of its initial transverse momentum while plowing through quark-gluon plasma produced in its local environment. High energy hadron jet experiments should be analysed as function of associated multiplicity to search for this effect. An interesting signature may be events in which the hard collision occurs near the edge of the overlap region, with one jet escaping without absorption and the other fully absorbed.

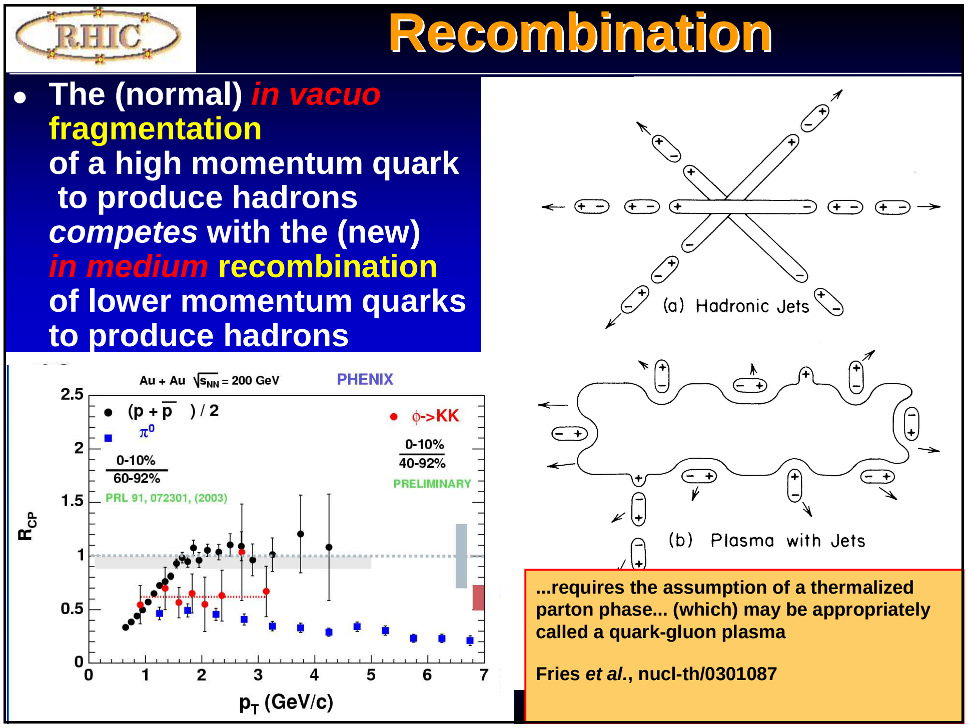

RHIC
Are the Au+Au and d+Au Trends Understood?
Both
❑ Au+Au suppression (I. Vitev and M. Gyulassy, hep-ph/0208108)
❑ d+Au enhancement (I. Vitev, nucl-th/0302002)
understood in an approach that combines multiple scattering with absorption in a dense partonic medium
➡ Our high p_T probes have been calibrated
±50% ?
$dN_g/dy \sim 1100$
$\varepsilon > 100\ \varepsilon_0$ (!)
R_{AA}
d+Au
Au+Au
p_T (GeV/c)
17-Nov-04

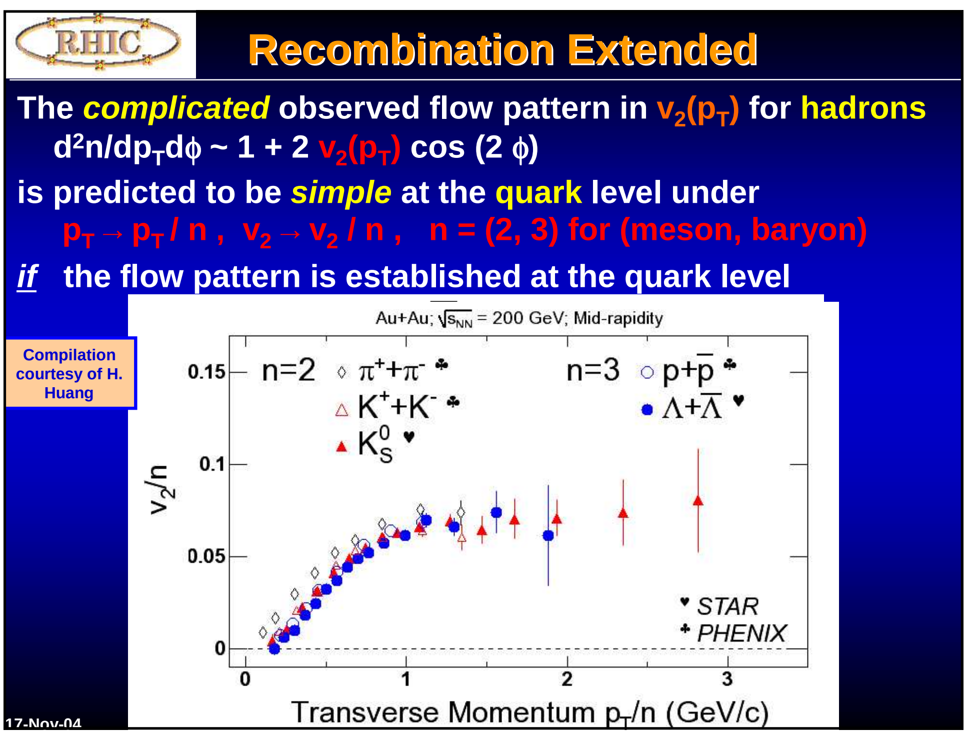

RHIC
Further Evidence
• STAR azimuthal correlation function shows ~ complete absence of "away-side" jet
d+Au FTPC-Au 0-20%
p+p min. bias
Au+Au Central
STAR
0.2
0.1
0
-1
0
1
2
3
4
$1/N_{Trigger}\ dN/d(\Delta\phi)$
$\Delta\ \phi$ (radians)
$C_2(Au+Au) = C_2(p+p) + A*(1+2v_2^2\cos(2\Delta\phi))$
Δφ
q
A
B
leading particle
➡ Surface emission only (?)
• That is, "partner" in hard scatter is absorbed in the dense medium

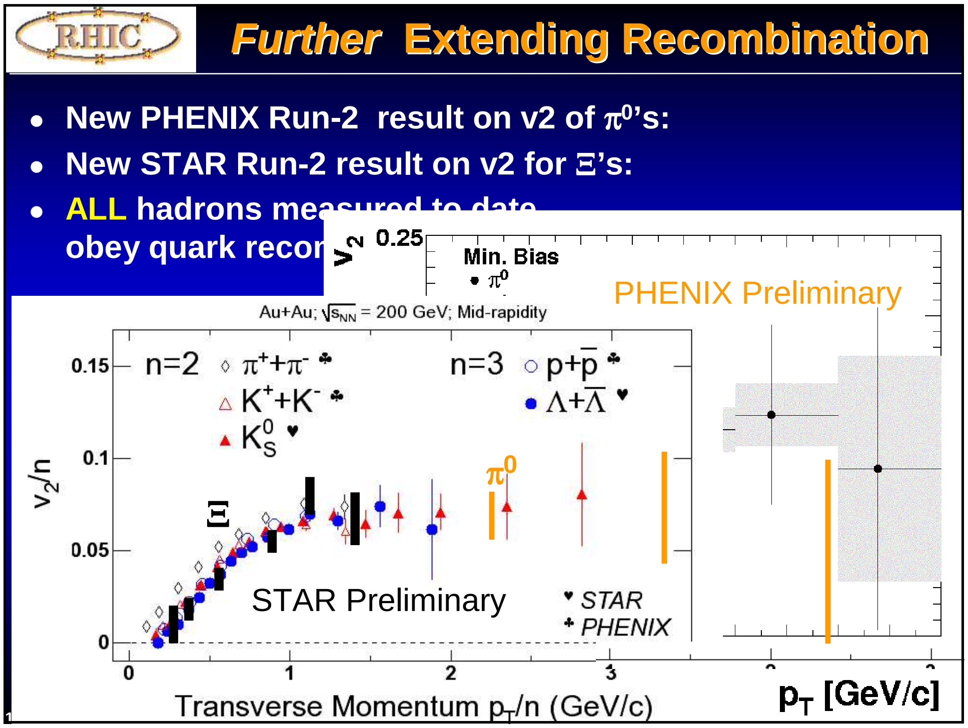

RHIC
Extend to Other Mesons
• Apply same methodology to production of η's
• See *same* suppression
R_{AA}
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Au+Au π^0 (0-20% central)
Au+Au η (0-20% central)
PHENIX
Preliminary
0
2
4
6
8
10
12
14
p_T (GeV/c)
• *WHILE PRESERVING VACUUM FRAGMENTATION RATIO* $\eta/\pi^0 = 0.43$ ⇨ *ABSORPTION AT PARTONIC LEVEL*
17-Nov-04


RHIC
Extend to Charged Hadrons
R_{AA}
Au+Au → $h^{\pm}$ @ $\sqrt{s_{NN}}$ = 200 GeV
STAR (0-5%)
PHENIX (0-10%)
PHOBOS (0-6%)
BRAHMS (0-10%)
• 4 experiments, consistent data
• Charged hadrons ≠ π^0 's
• But aren't most charged hadrons π^0 's ???
0 0.2 0.4 0.6 0.8 1 1.2 1.4
0 2 4 6 8 10
p_T (GeV/c)
17-Nov-04


RHIC
Discovery of Baryon/Pion "Anomaly"
• Comparison of Au-Au, d-Au and p-p data indicate
❑ Dense matter uniquely formed in Au-Au collisions
❑ How dense? Sufficient to "extinguish" jets
Q. Are there other anomalies observed in these collisions?
A. Yes- the baryon/pion ratio is drastically modified:
Q. How to understand this?
A. Competition between
Fragmentation
and
Recombination
at the quark level
Ratio
proton/pion
anti-proton/pion
Central
Au+Au 0-10%
Au+Au 20-30%
Peripheral
Au+Au 60-92%
p+p, √s = 53 GeV, ISR
e+e-, gluon jets, DELPHI
e+e-, quark jets, DELPHI
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8
0 1 2 3 4 0 1 2 3 4 5
p_T (GeV/c)
p_T (GeV/c)
17-Nov-04


RHIC
Recombination
• The (normal) in vacuo fragmentation
of a high momentum quark
to produce hadrons
competes with the (new)
in medium recombination
of lower momentum quarks
to produce hadrons
(a) Hadronic Jets
(b) Plasma with Jets
Au + Au √sNN = 200 GeV
PHENIX
(p + p̄) / 2
π0
0-10%
60-92%
PRL 91, 072301, (2003)
φ->KK
0-10%
40-92%
PRELIMINARY
RCP
pT (GeV/c)
...requires the assumption of a thermalized parton phase... (which) may be appropriately called a quark-gluon plasma
Fries et al., nucl-th/0301087


RHIC
Recombination Extended
The complicated observed flow pattern in v2(pT) for hadrons
d2n/dpTdφ ~ 1 + 2 v2(pT) cos (2 φ)
is predicted to be simple at the quark level under
pT → pT / n , v2 → v2 / n , n = (2, 3) for (meson, baryon)
if the flow pattern is established at the quark level
Compilation courtesy of H. Huang
Au+Au; √sNN = 200 GeV; Mid-rapidity
n=2 π++π- ♣
K++K- ♣
K0S ♥
n=3 p+p̄ ♣
Λ+Λ̄ ♥
♥ STAR
♣ PHENIX
v2/n
Transverse Momentum pT/n (GeV/c)
17-Nov-04



Current State

- What we do know
  - Densities formed well in excess of ~ 1 GeV/fm³ required (according to lattice) for QGP formation
  - Strong evidence for thermalization and hydrodynamic flow of matter
  - Strong suppression at high p_T; almost certainly of partonic origin
  - Indications (recombination) that flow pattern is also established at partonic level
- What we don't know
  - How do reconcile recombination with jet yields?
  - What is the equation of state of the produced matter?
  - What is the state of the produced matter?
  - Is the flow truly non-dissipative?

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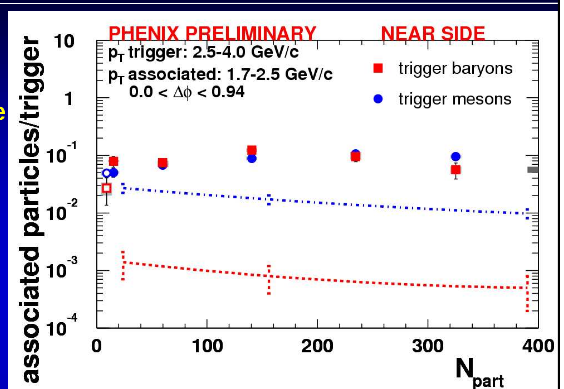
Recombination Challenged

- **Successes:**
  - **Accounts for p_T dependence of baryon/meson yields**
  - **Unifies description of $v_2(p_T)$ for baryons and mesons**
- **Challenged by**
  - **"Associated emission" at high p_T (there shouldn't be any in a pure thermal model of recombination)**
  - **Can the simple appeal of Thermal-Thermal correlations survive extension to Jet-Thermal ?**



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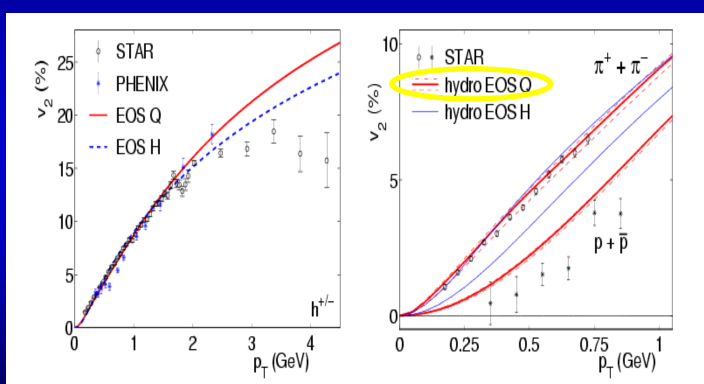
State of Matter

- **The systematics of the flow pattern can be tested for various equations of state (EOS)**
- **At RHIC, the QGP EOS for P(T) is preferred:**



STAR Coll., PRL 86 (2001) 402; 87 (2001) 182301; PHENIX Coll., nucl-ex/020400512 and QM 2001

- **How to move from this qualitative to quantitative understanding?**

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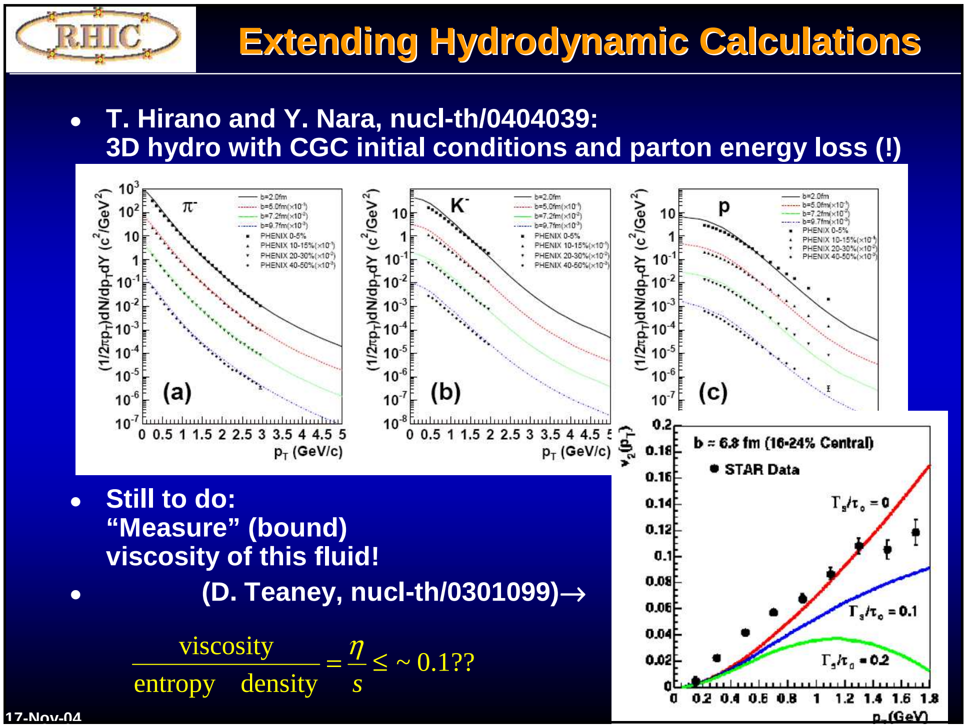
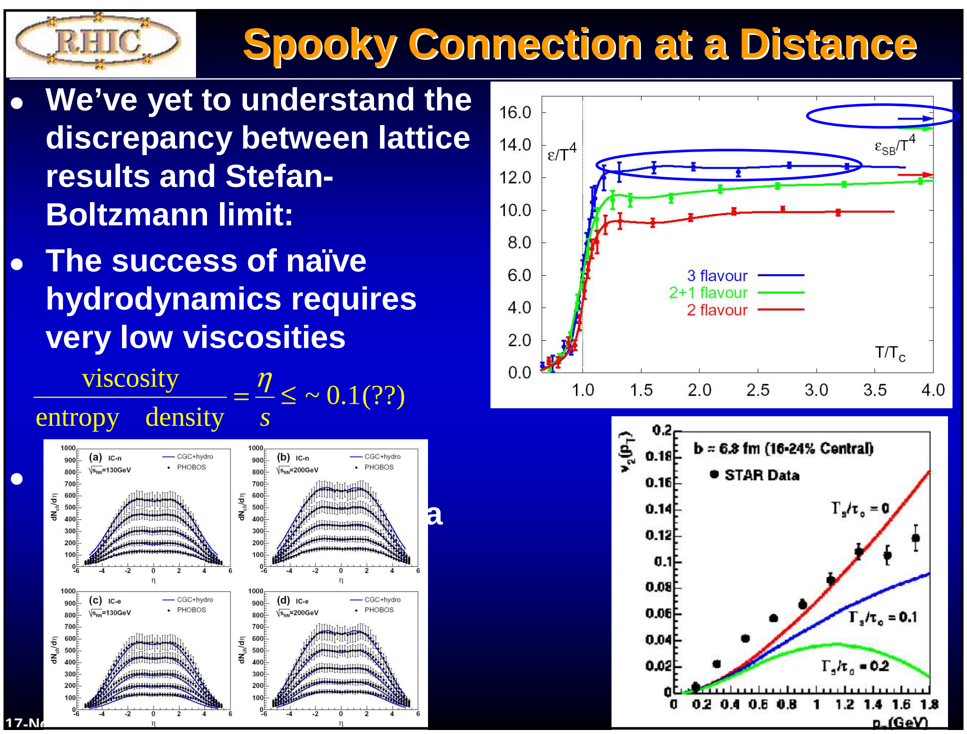

RHIC
Extending Hydrodynamic Calculations
T. Hirano and Y. Nara, nucl-th/0404039:
3D hydro with CGC initial conditions and parton energy loss (!)
(a)
(b)
(c)
p_T (GeV/c)
Still to do:
"Measure" (bound)
viscosity of this fluid!
(D. Teaney, nucl-th/0301099)→
$\frac{\text{viscosity}}{\text{entropy density}} = \frac{\eta}{s} \leq \sim 0.1??$
b = 6.8 fm (16-24% Central)
STAR Data
$\Gamma_s/\tau_o = 0$
$\Gamma_s/\tau_o = 0.1$
$\Gamma_s/\tau_o = 0.2$
17-Nov-04


RHIC
Spooky Connection at a Distance
We've yet to understand the discrepancy between lattice results and Stefan-Boltzmann limit:
The success of naïve hydrodynamics requires very low viscosities
$\frac{\text{viscosity}}{\text{entropy density}} = \frac{\eta}{s} \leq \sim 0.1(??)$
ε/T^4
ε_{SB}/T^4
3 flavour
2+1 flavour
2 flavour
T/T_c
b = 6.8 fm (16-24% Central)
STAR Data
$\Gamma_s/\tau_o = 0$
$\Gamma_s/\tau_o = 0.1$
$\Gamma_s/\tau_o = 0.2$

Strongly Coupled Plasmas

- Recently, much interest in the “strongly interacting” (i.e., non-ideal) behavior of the matter produced at RHIC
- This property has been known long enough to be forgotten several times:
  - 1982: Gordon Baym, proceedings of Quark Matter ‘82:
    - A hint of trouble can be seem from the first order result for the entropy density (N_f = 3)

      $s(T) = \frac{19\pi^2}{9}\{\ 1 - \frac{54}{19\pi}\alpha_S(T)\ + ...\ \} T^4$

      which turns negative for $\alpha_s > 1.1$
  - 1992: Berndt Mueller, Proc. of NATO Advanced Study Institute
    - For plasma conditions realistically obtainable in the nuclear collisions (T ~250 MeV, g = √(4πα$_s$) = 2) the effective gluon mass m_g* ~ 300 MeV. We must conclude, therefore, that the notion of almost free gluons (and quarks) in the high temperature phase of QCD is quite far from the truth. Certainly one has m_g* << T when g <<1, but this condition is never really satisfied in QCD, because g ~ 1/2 even at the Planck scale (10^{19} GeV), and g<1 only at energies above 100 GeV.
  - 2002: Ulrich Heinz, Proceedings of PANIC conference:
    - Perturbative mechanisms seem unable to explain the phenomenologically required very short thermalization time scale, pointing to strong non-perturbative dynamics in the QGP even at or above 2Tc.... The quark-hadron phase transition is arguably the most strongly coupled regime of QCD.
  - Atomic plasmas:
    - Strongly coupled ⇒ Γ ≡<Coulomb>/<Kinetic> > 1

$$\Gamma = \langle \alpha_S(T)/r \rangle / 3T \sim \alpha_S(T) n^{1/3} / 3T \sim \alpha_S(T) [\,5T^3\,]^{1/3} / 3T = 0.6\alpha_S(T) \sim 1$$

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The Strongly Coupled Plasma

- Classical coupling parameter

$$\Gamma \equiv \frac{\text{Potential Energy}}{\text{Kinetic Energy}}$$

  - Strongly coupled when Γ > 1
  - Naïve estimate on previous slide

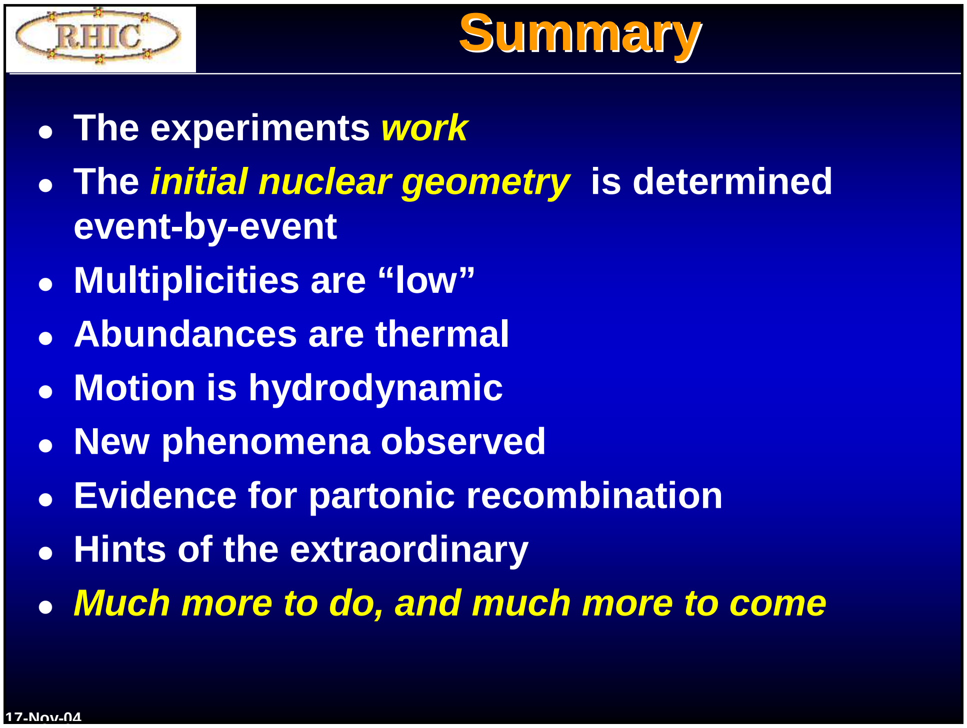
$$\Gamma = \frac{\langle \alpha_S(T)/r \rangle}{3T} = 0.6\alpha_S(T) \sim 1$$

  - Better (screening, Debye masses)

$$\Gamma \sim \frac{gT}{3T} \sim 1$$

- My personal view:
  - We should not be surprised by the strongly coupled nature of the QGP- it is an *intrinsic* property of *the* QCD plasma (for any accessible T)

17-Nov-04


RHIC
Summary
The experiments work
The initial nuclear geometry is determined event-by-event
Multiplicities are "low"
Abundances are thermal
Motion is hydrodynamic
New phenomena observed
Evidence for partonic recombination
Hints of the extraordinary
Much more to do, and much more to come
17-Nov-04