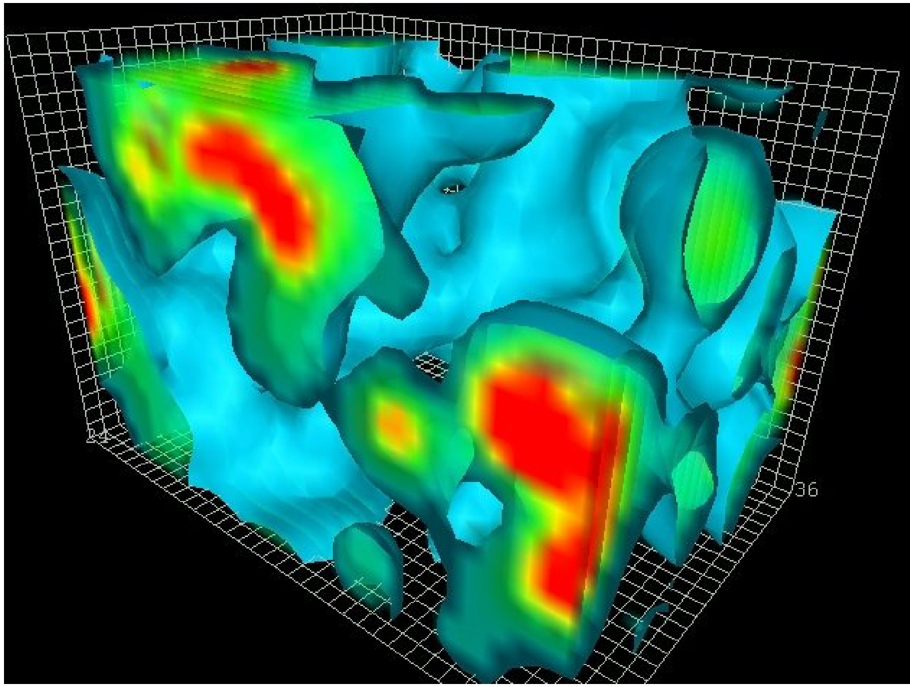
Recent Results from PHENIX



Kenneth N. Barish
UC Riverside

Datong, China
Sep. 3, 2001

RHIC Physics Program

Why high energy heavy ions?

(*Relativistic Heavy Ions*)

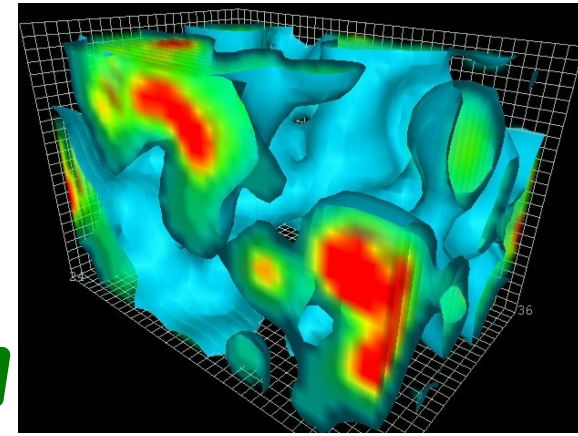
Characterize nuclear matter at high temperatures

- ➢Understand transitions between phases
- ➢Determine equation of state

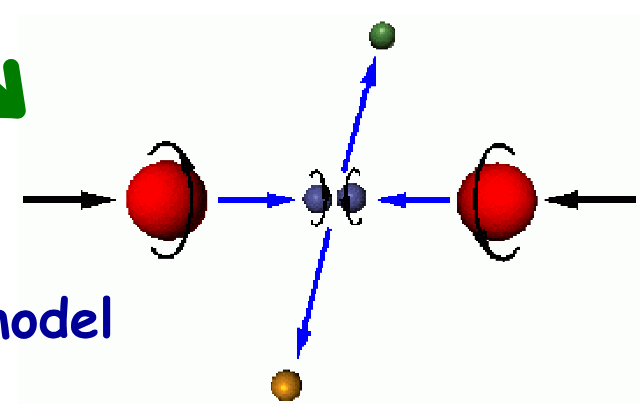
Or

Excite vacuum and see what happens:

- ➢Deconfinement
- ➢Chiral symmetry restoration



$$\mathcal{L}_{QCD} = -\frac{1}{4}\mathrm{Tr}\,\mathbf{F}_{\mu\nu}^2 + \sum_{flavors} \bar{q}\left(i\gamma_\mu \mathbf{D}^\mu - m\right)q$$



Spin Physics Program

ΔG, $\Delta q/q$, δq, physics beyond standard model

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Relativistic Heavy Ion Collider

Year-1 Data Taking

- ✓ PHENIX Recorded ~5M minimum bias events
  ~ 3TB of data !
- ➢ Collisions from 15-Jun-00 to 04-Sep-00

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

RHIC Capabilities

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

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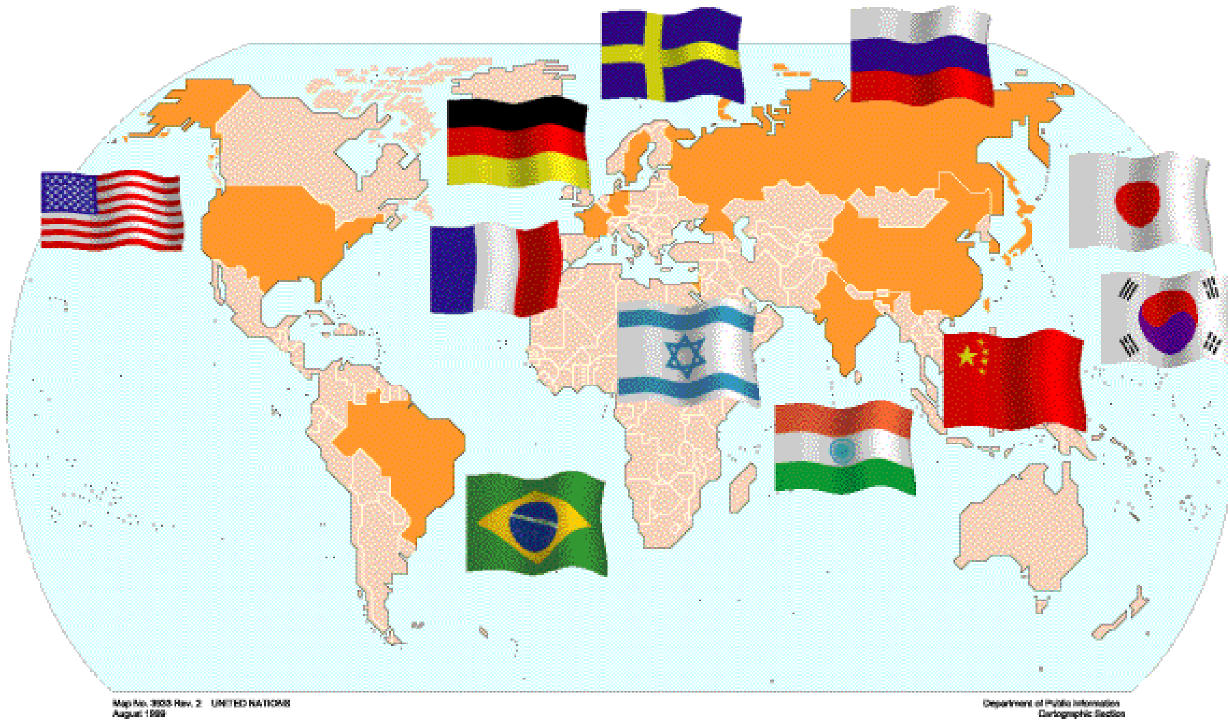
PHENIX

11 Countries

51 Institutions

~450 Collaborators

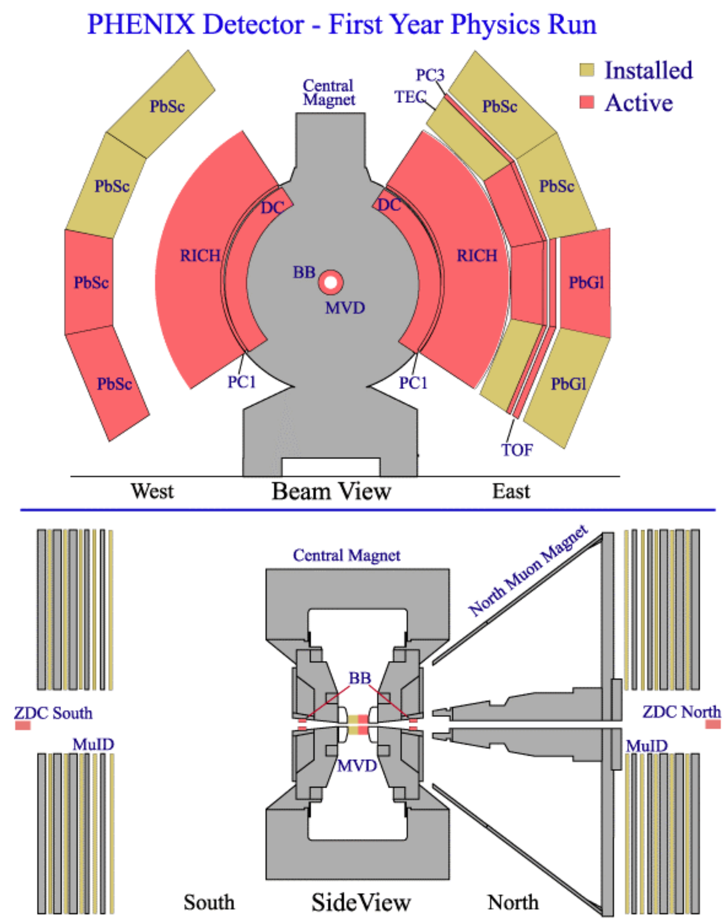


University of São Paulo, São Paulo, Brazil
Academia Sinica, Taipei 11529, China
China Institute of Atomic Energy (CIAE), Beijing, P. R. China
Laboratoire de Physique Corpusculaire (LPC), Universite de Clermont-Ferrand, 63170 Aubiere, Clermont-Ferrand, France
Dapnia, CEA Saclay, Bat. 703, F-91191, Gif-sur-Yvette, France
IPN-Orsay, Universite Paris Sud, CNRS-IN2P3, BP1, F-91406, Orsay, France
LPNHE-Palaiseau, Ecole Polytechnique, CNRS-IN2P3, Route de Saclay, F-91128, Palaiseau, France
SUBATECH, Ecole des Mines at Nantes, F-44307 Nantes, France
University of Muenster, Muenster, Germany
Banaras Hindu University,Banaras, India
Bhabha Atomic Research Centre (BARC),Bombay, India
Weizmann Institute, Rehovot, Israel
Center for Nuclear Study (CNS-Tokyo), University of Tokyo, Tanashi, Tokyo 188, Japan
Hiroshima University, Higashi-Hiroshima 739, Japan
KEK, Institute for High Energy Physics,Tsukuba, Japan
Kyoto University, Kyoto, Japan
Nagasaki Institute of Applied Science, Nagasaki-shi, Nagasaki, Japan
RIKEN, Institute for Physical and Chemical Research, Hirosawa, Wako, Japan
University of Tokyo, Bunkyo-ku, Tokyo 113, Japan
Tokyo Institute of Technology, Ohokayama, Meguro, Tokyo, Japan
University of Tsukuba, Tsukuba, Japan
Waseda University, Tokyo, Japan
Cyclotron Application Laboratory, KAERI, Seoul, South Korea
Kangnung National University, Kangnung 210-702, South Korea
Korea University, Seoul, 136-701, Korea
Myong Ji University, Yongin City 449-728, Korea
System Electronics Laboratory, Seoul National University, Seoul, South Korea
Yonsei University, Seoul 120-749, KOREA
Institute of High Energy Physics (IHEP-Protvino or Serpukhov), Protovino, Russia
Joint Institute for Nuclear Research (JINR-Dubna), Dubna, Russia
Kurchatov Institute, Moscow, Russia
PNPI: St. Petersburg Nuclear Physics Institute, Gatchina, Leningrad, Russia
Lund University, Lund, Sweden
Abilene Christian University, Abilene, Texas, USA
Brookhaven National Laboratory (BNL), Upton, NY 11973
University of California - Riverside (UCR), Riverside, CA 92521, USA
Columbia University, Nevis Laboratories, Irvington, NY 10533, USA
Florida State University (FSU), Tallahassee, FL 32306, USA
Georgia State University (GSU), Atlanta, GA, 30303, USA
Iowa State University (ISU) and Ames Laboratory, Ames, IA 50011, USA
LANL: Los Alamos National Laboratory, Los Alamos, NM 87545, USA
LLNL: Lawrence Livermore National Laboratory, Livermore, CA 94550, USA
University of New Mexico, Albuquerque, New Mexico, USA
New Mexico State University, Las Cruces, New Mexico, USA
Department of Chemistry, State University of New York at Stony Brook (USB), Stony Brook, NY 11794, USA

The PHENIX Detector

Philosophy:

- ✓ High rate capability & granularity
- ✓ Good mass resolution and particle ID
- ➢ Sacrifice acceptance



Two central arms: Tracking & particle ID

- ✓ Drift Chamber,
- ✓ Pixel Pad Chambers, &
- ✓ Time Expansion Chamber
- ❑ PbSc and PbGl Electromagnetic Calorimetry
- ❑ Time-of-Flight Detector
- ❑ Ring Imaging Cerenkov Counter
- ❑ Time Expansion Chamber

Forward Detectors: Muons

- ✓ Cathode Strip Muon Tracker
- ✓ Muon Identifier

Global Detectors: Event characterization, vertex measure, and triggering

- ✓ Beam-Beam Counter, Zero Degree Calorimeters, and Multiplicity and Vertex Detector

Initial Conditions

What is the initial density of created partons?

» Does this density saturate?

What is the net baryon density at RHIC?

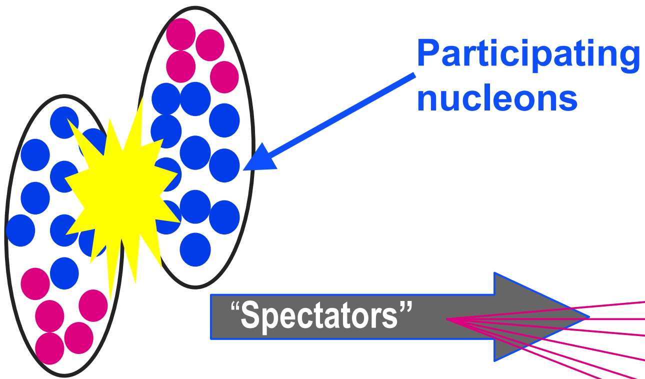
What is the energy density achieved?

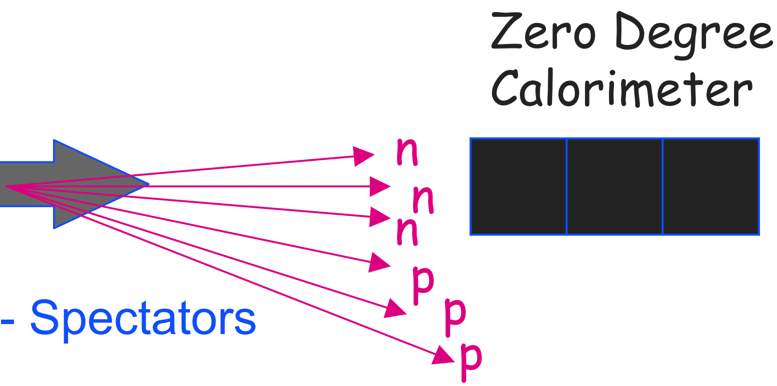
» How does it compare to the expect phase transition value from lattice QCD?

» Is this energy density thermalized? If so, what is the energy density at thermalization?

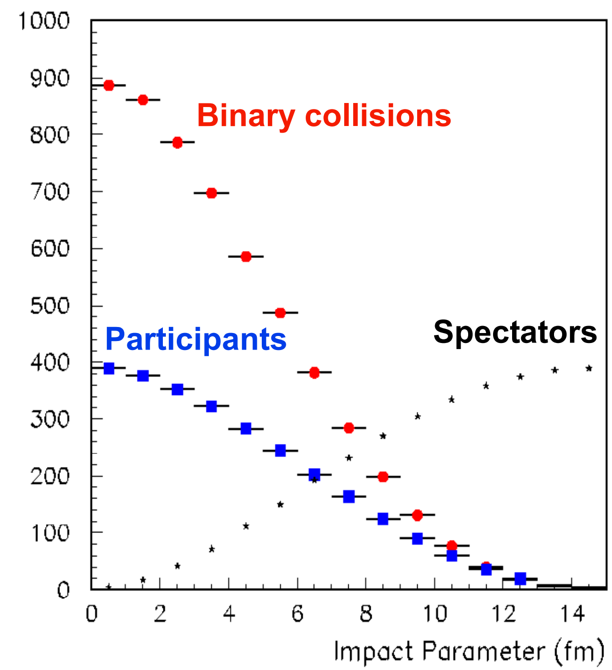
Collision Characterization

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





Participants = 2 x 197 - Spectators



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Many models of particle production identify two components.

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

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

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

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

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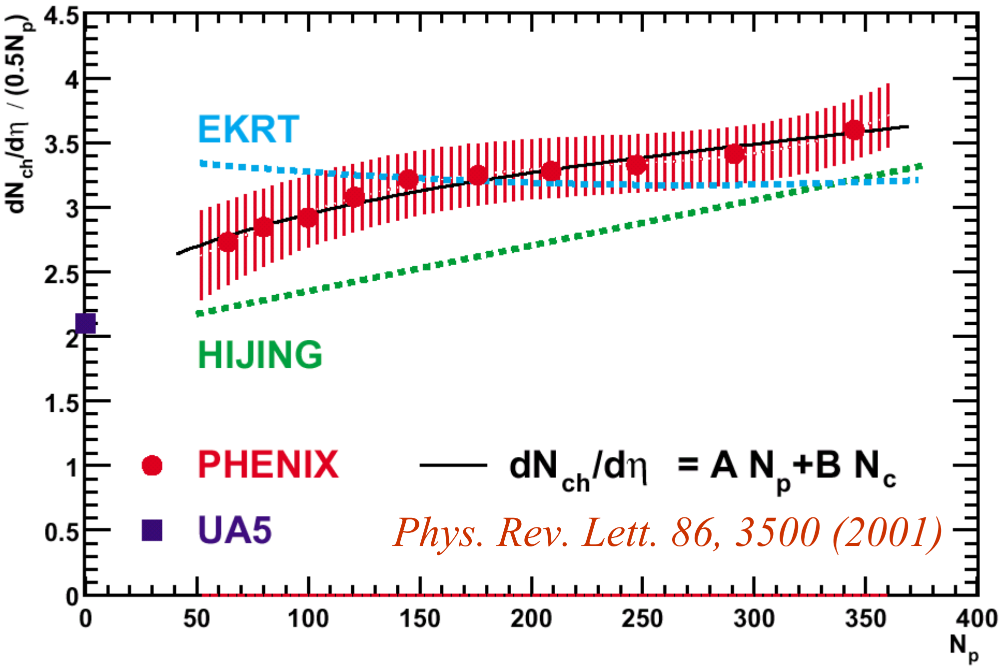
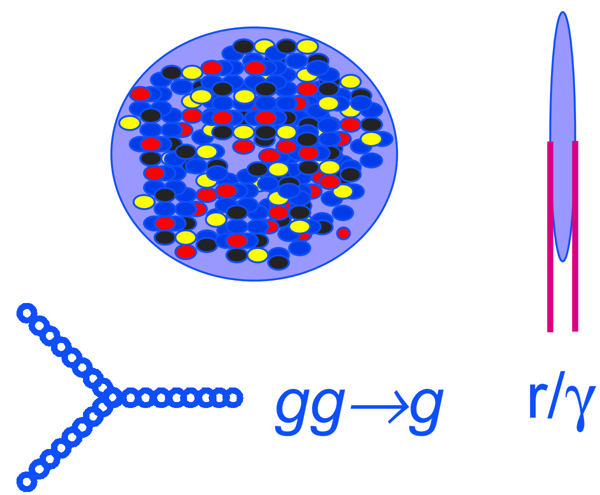
Gluon Saturation?

- Gluons can begin to fuse with high enough gluon density.
- Saturation will limit parton production
  - Final state charged particle yields per collision limited?

Eskola, Kajantie, and Tuominen: hep-ph/0009246
Kharzeev, Nandi: nucl-th/0012025





- ✓ Gluon Saturation does not appear to set in for peripheral collisions
- ✓ Cannot yet rule out Eskola's saturation for central collisions
- ✓ Kharzeev's initial-state saturation picture is consistent with data

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Baryon Density at RHIC

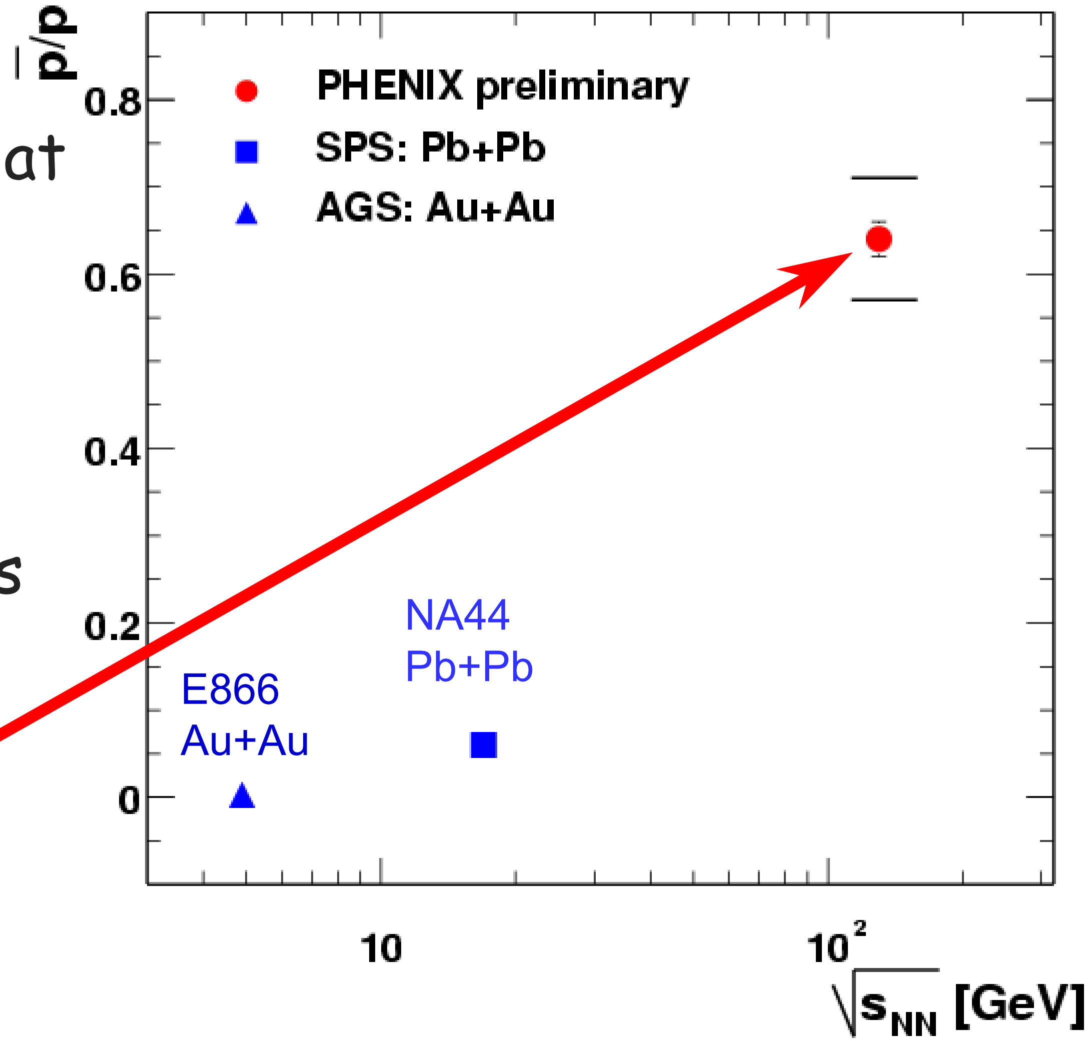
Antiproton/proton Ratio:

» Much lower net baryon density than at SPS

» Approaching early universe value

» More *produced* than *participating* baryons at midrapidity

$$\frac{\bar{p}}{p} = 0.64 \pm 0.01 \pm 0.08$$



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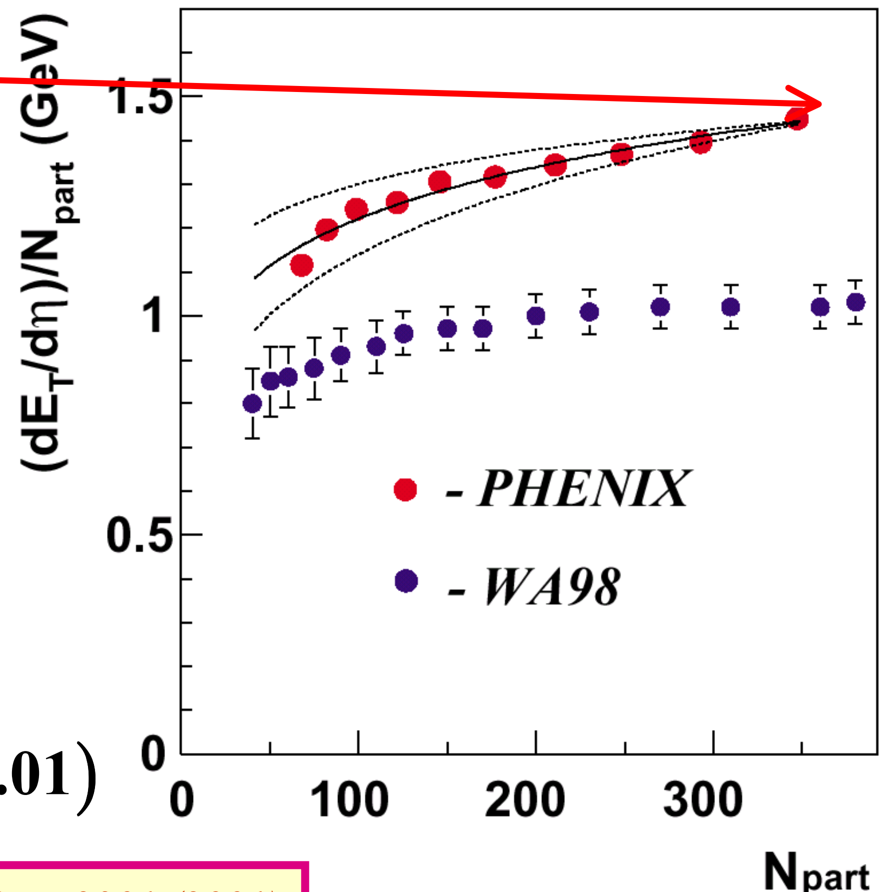
Energy density

Bjorken formula for energy density in terms of measured transverse energy assuming a thermalized system at time τ_0.

$$\varepsilon_{Bj} = \frac{1}{\pi R^2}\frac{1}{c\tau_0}\left(\frac{dE_T}{dy}\right)$$

6.88 fm
(hard sphere radius)

Time to thermalize the system (~ 1.0 - 0.2 fm/c?)



PHENIX: Central Au-Au yields

$$\left\langle\frac{dE_T}{dy}\right\rangle_{y=0}^{2\%} = \left(578^{+26}_{-39}\,\mathrm{GeV}\right)\times\left(1.19\pm0.01\right)$$

Phys. Rev. Lett. 87, 52301 (2001)

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Is the energy density high enough?

The PHENIX EMCal measures transverse energy

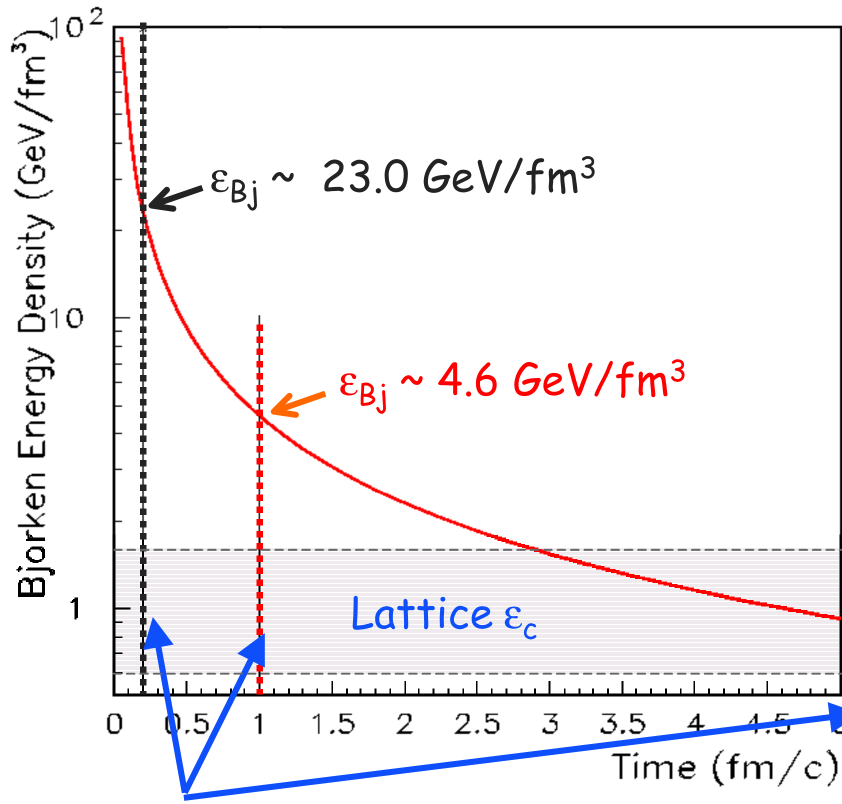
For the most central events:

$\varepsilon_{Bjorken} \sim 4.6\text{-}23\ GeV/fm^3$

Lattice phase transition:

$\varepsilon_{critical} \sim 0.6\text{-}1.8\ GeV/fm^3$

Roughly 1.5 to 2 times higher than previous experiments if assume same formation time



thermalization time?

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Energy deposition is certainly adequate, but does it create a thermalized new phase of matter while $\varepsilon > \varepsilon_{crit}$?

PHENIX Multiplicity Data

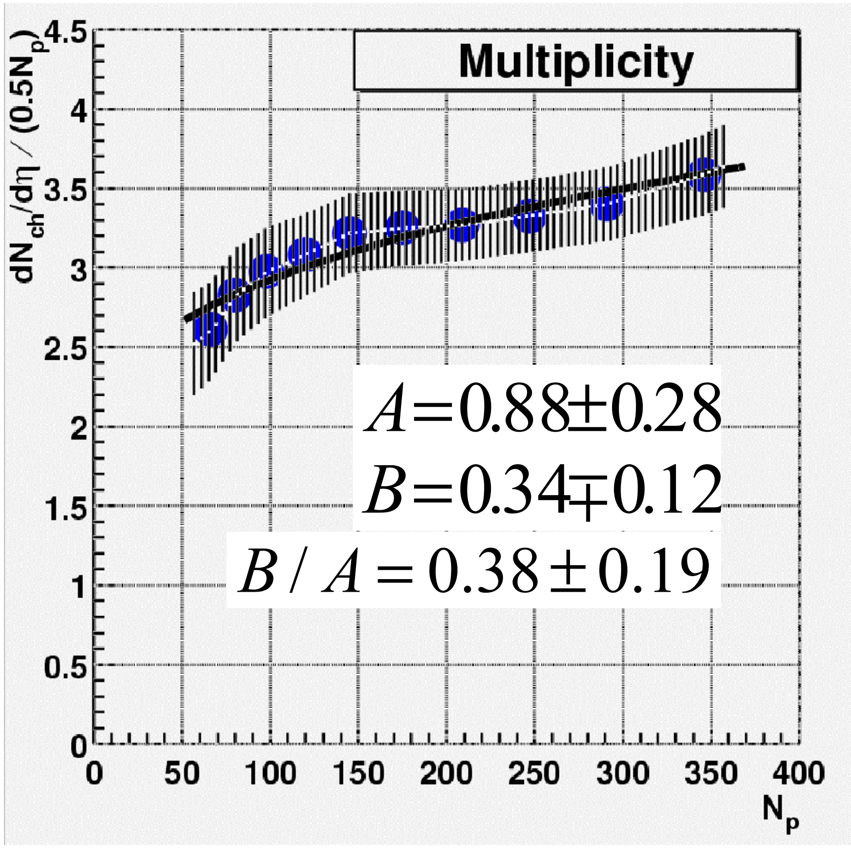
$$dN_{ch}/d\eta\big|_{\eta=0} = A \times N_{part} + B \times N_{bin}$$

$$\frac{dN_{ch}/d\eta\,|_{\eta=0}}{0.5 \times N_{part}} = 2 \times \left(A + B \times \frac{N_{bin}}{N_{part}} \right)$$

First PHENIX paper published !

"Centrality Dependence of Charged Particle Multiplicity in Au-Au Collisions at $\sqrt{s_{NN}}$ = 130 GeV"

Phys. Rev. Lett. 86, 3500 (2001)



Evidence for term in growth ~ number of collisions

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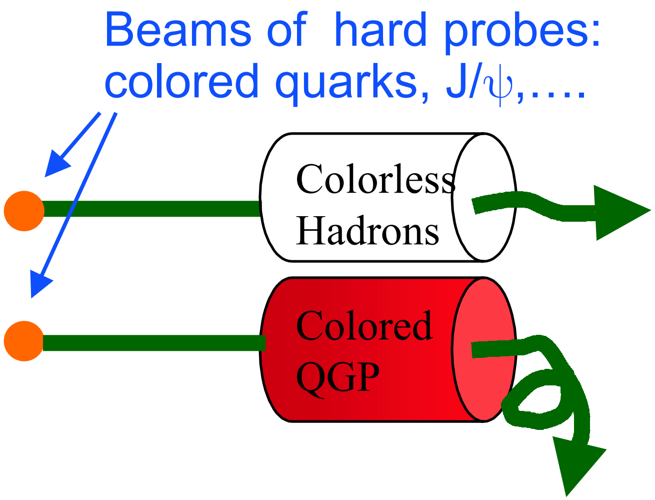
How can we Probe the QGP?

We expect quarks and quarkonium states to ***respond differently*** to a plasma compared to ordinary nuclear matter



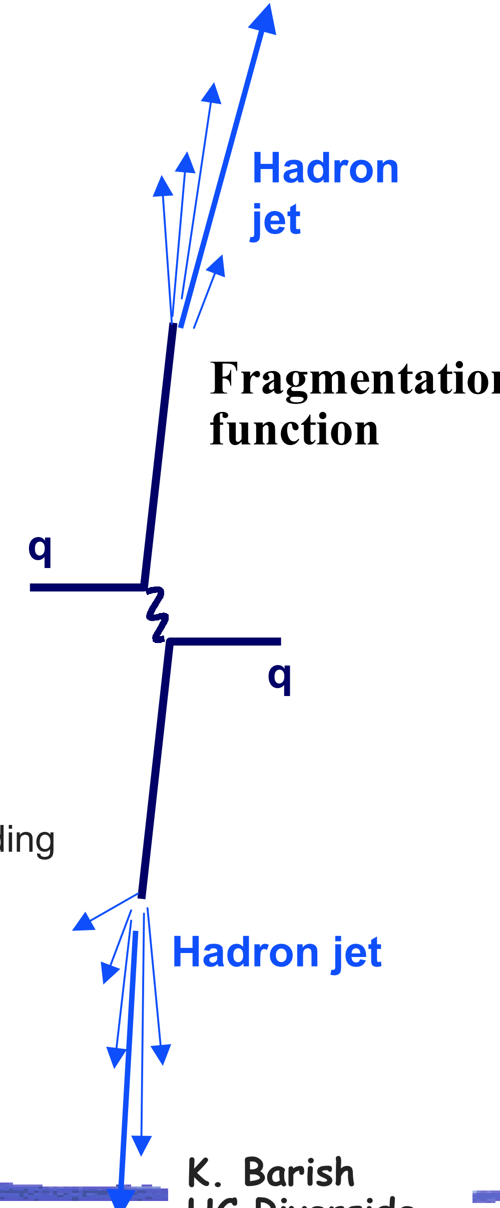
In year-1 we got our first glimpse at **hard probes**.

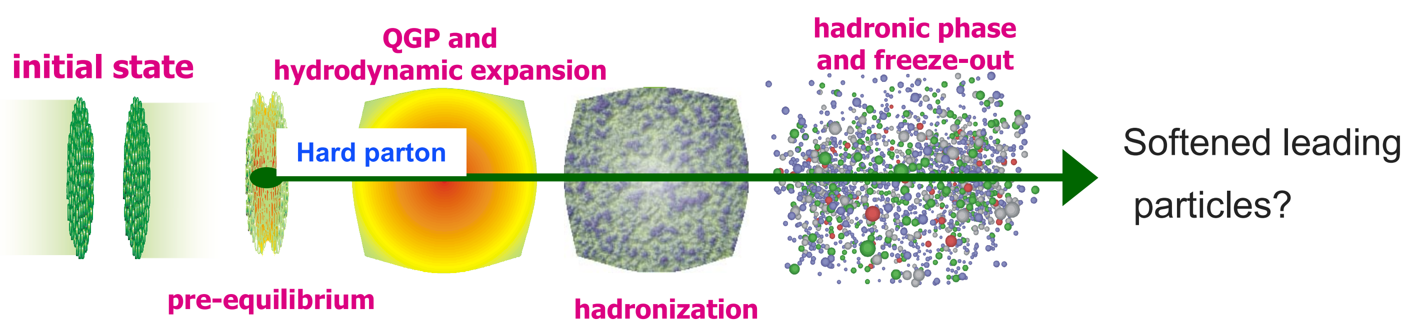
In year-2 we will get our first glimpse of "onium" probes.

Hard Probes in Heavy Ion Collisions

"Hard" probes

- » Formed in initial collision with high Q^2
- » Have predictable rates given:
  - Parton distribution functions
  - pQCD hard scattering rates
  - Fragmentation functions





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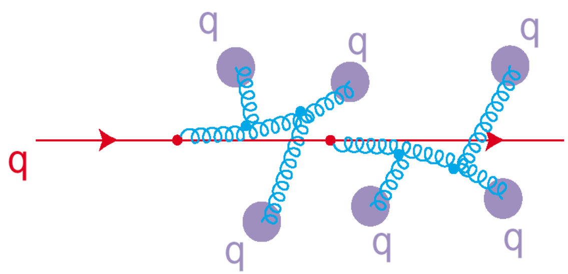
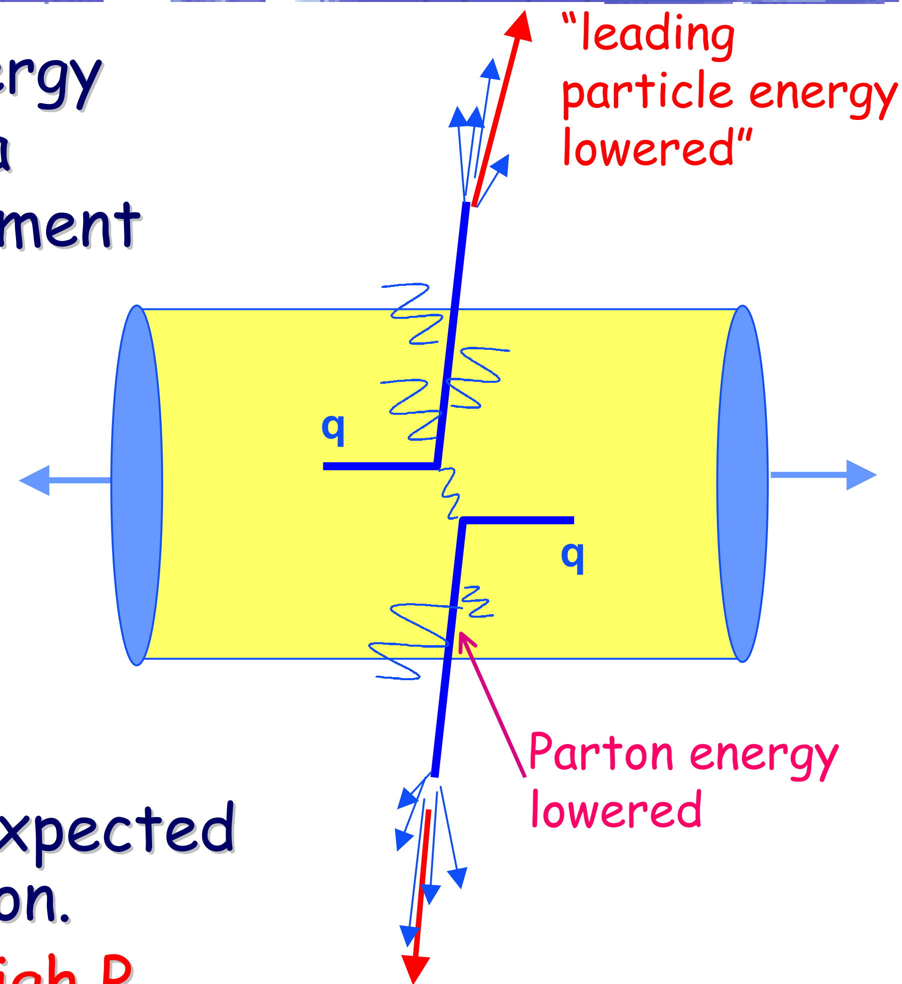
Partonic Energy Loss

Partons are expected to lose energy via gluon radiation in traversing a quark-gluon plasma. Partons fragment into hadrons, which we measure.





Leading Particle

» Energy is lowered

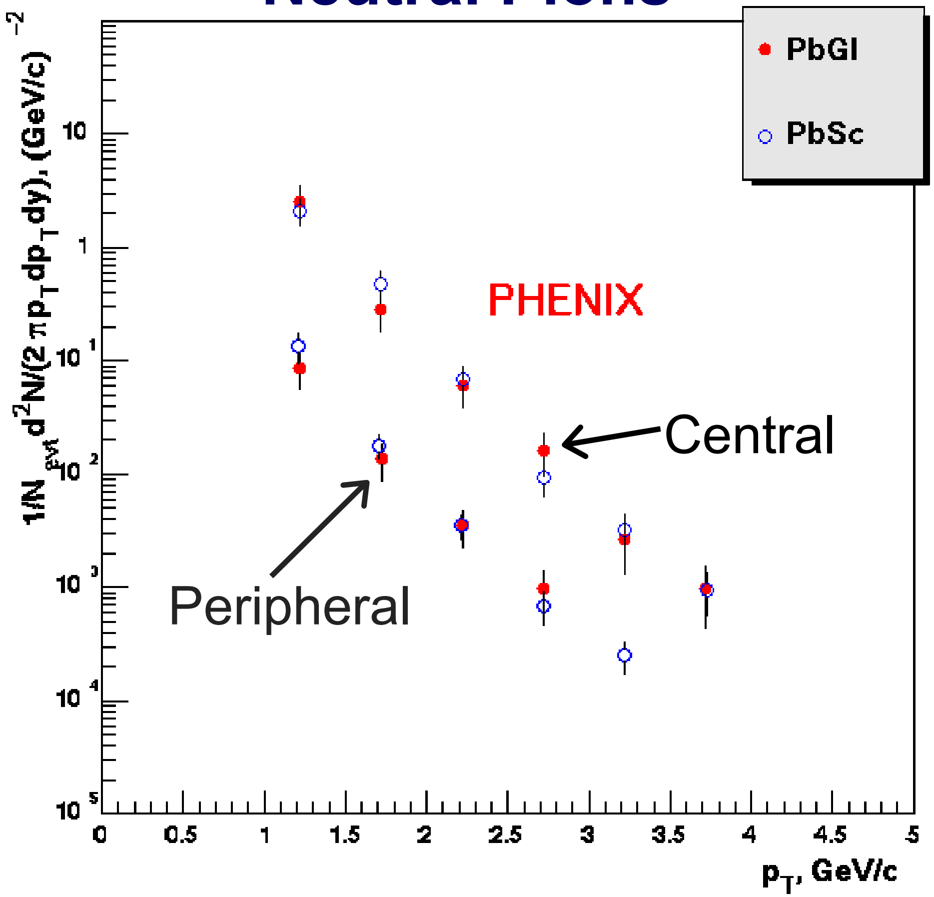
» Hadrons above P_T > 2 GeV expected to be from jet fragmentation.

» Look for a suppression of high P_T leading particles

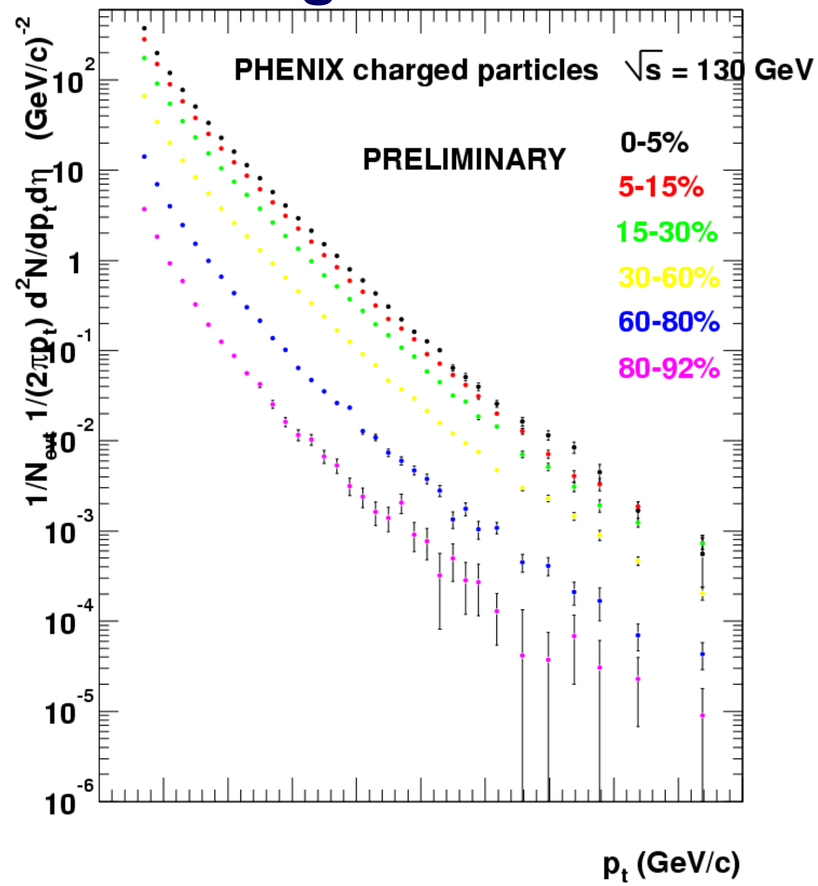
Baier, Dokshitzer, Mueller, Schiff, hep-ph/9907267
Gyulassy, Levai, Vitev, hep-pl/9907461
Wang, nucl-th/9812021
and many more…..

PHENIX Spectra ~1.4M minbias events

Neutral Pions



Charged Hadrons



Consistency between PbGL & PbSc

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How do we compare with NN baseline?

Currently, there is no NN data at 130 GeV. Therefore, we
- parameterize pp & $p\bar{p}$ charged hadron spectra
- interpolate to 130GeV

Scale by the number of binary collisions $\langle N_{coll} \rangle$

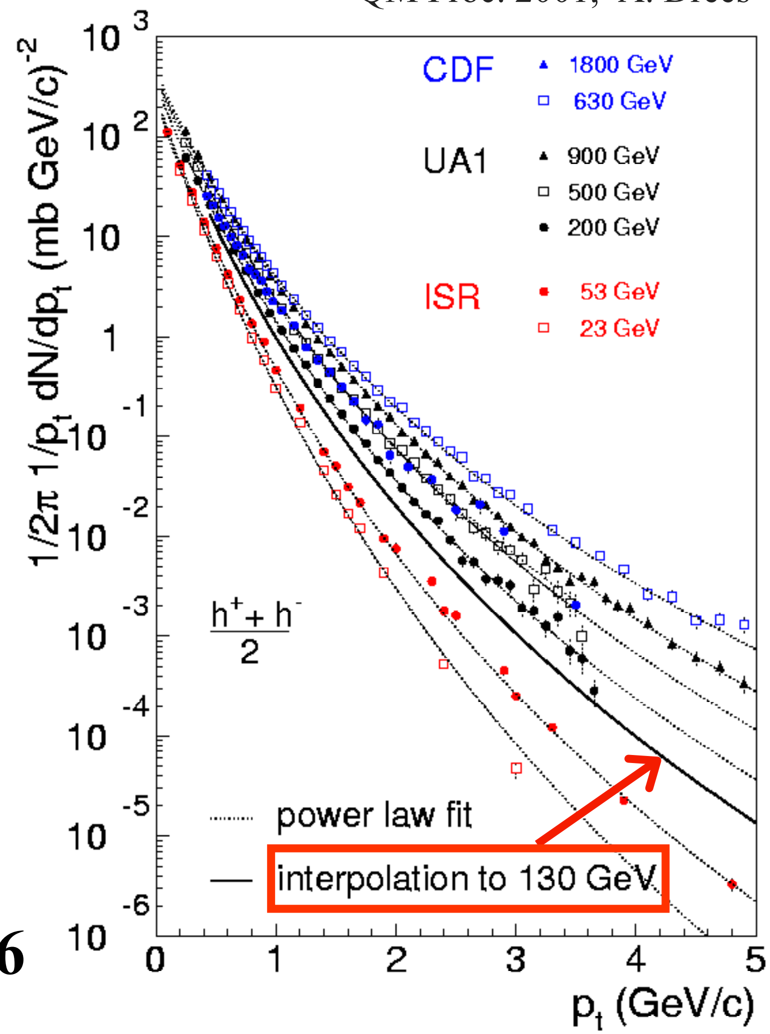
$$N_{collisions}^{60-80\%} = 20 \pm 6 \quad \text{(peripheral)}$$

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

For π^0 baseline, make additional correction due to h/π ratio at ISR

$$(\pi / h)^{ISR}_{p_T > 1.5 GeV/c} = 0.63 \pm 0.06$$

QM Proc. 2001, A. Drees



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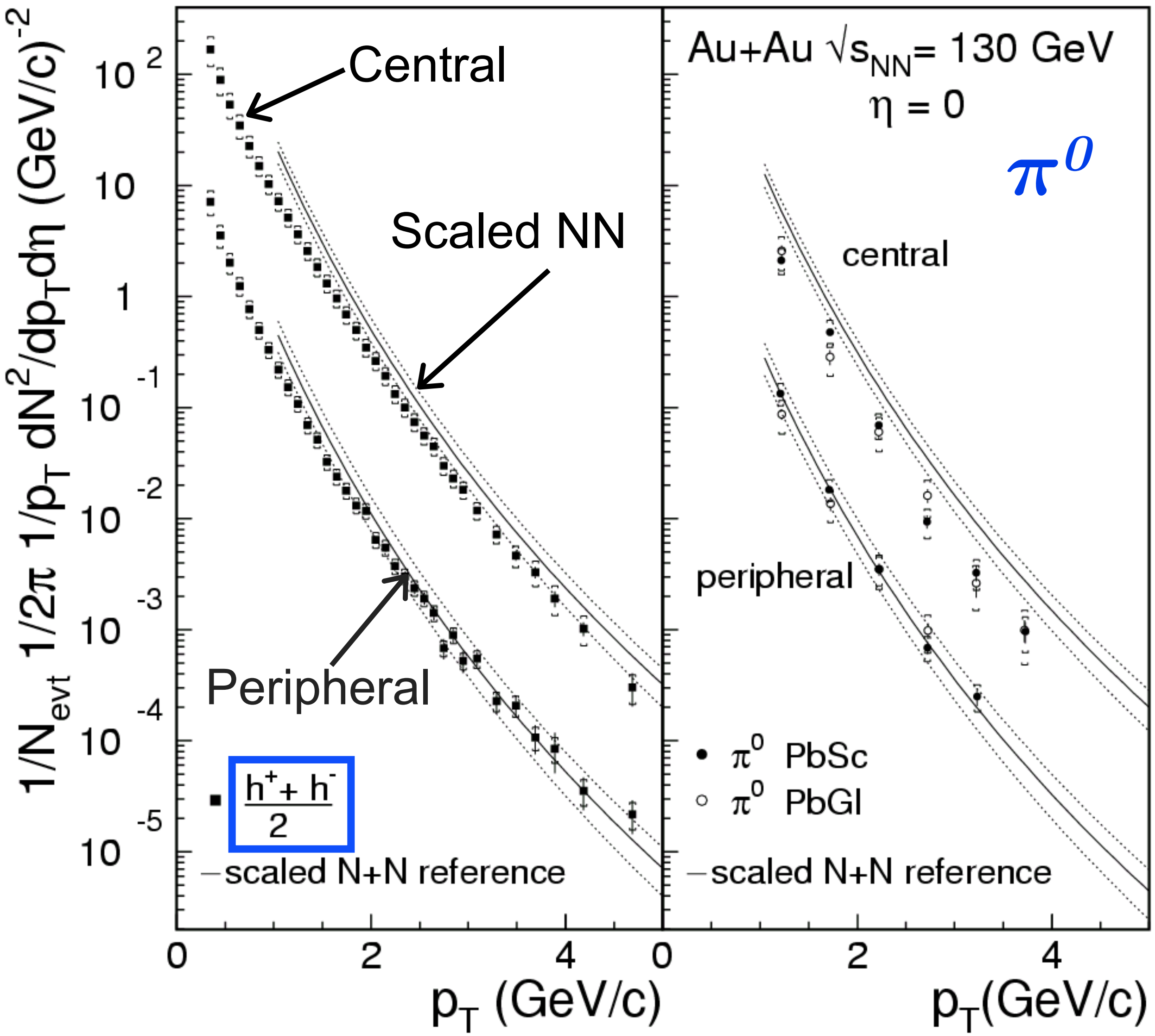
Comparison with pp baseline



Peripheral

consistent with NN scaled by number of collisions

Central

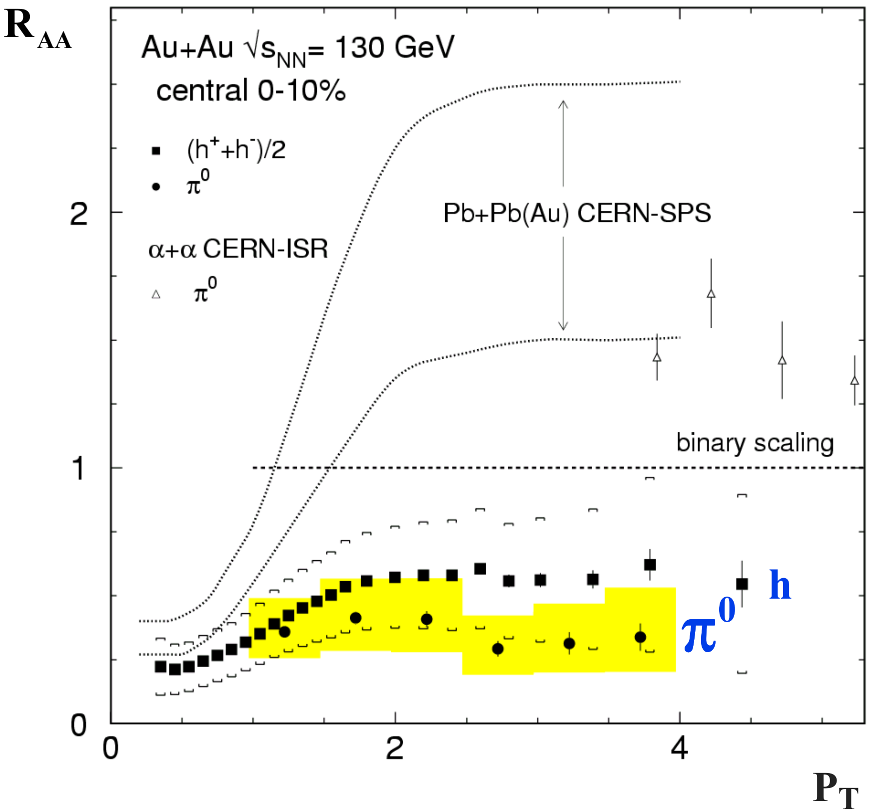
below scaled NN spectrum

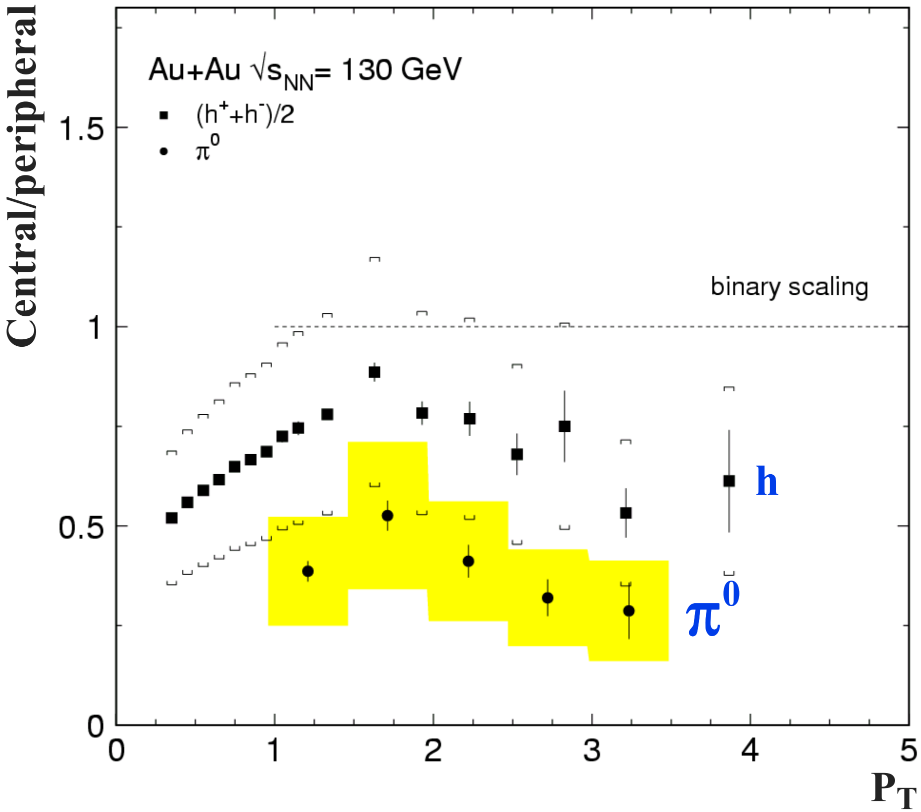
π^0 larger deficit than unidentified hadrons

π^0 ratio's with pp and peripheral

$$R_{AA} = \frac{Yield_{central} / \langle N_{binary} \rangle_{central}}{Yield_{pp}}$$

$$\frac{Yield_{central} / \langle N_{binary} \rangle_{central}}{Yield_{peripheral} / \langle N_{binary} \rangle_{peripheral}}$$





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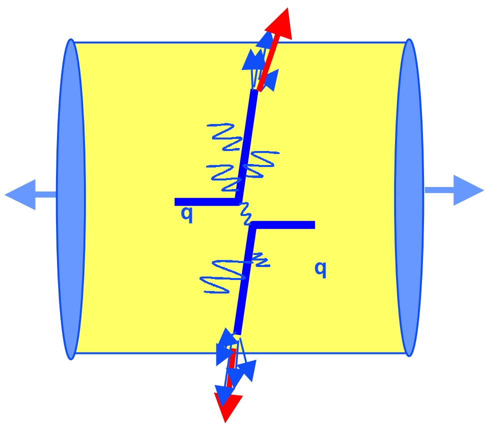
Complications

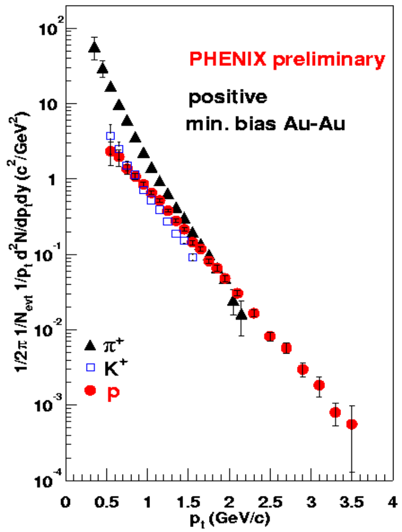
"Ordinary" Nuclear effects:

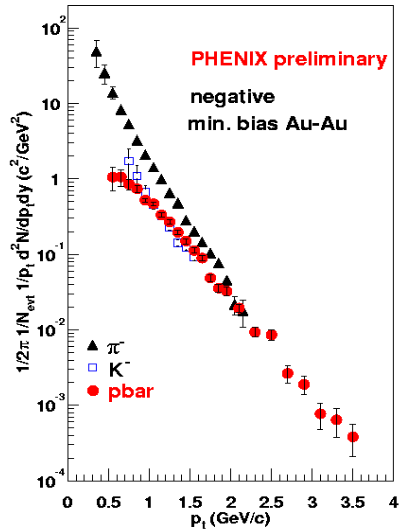
- Cronin Effect and P_T broadening
- Nuclear shadowing of gluon structure functions

Issues:

- Does the parton fragment inside the medium?
- Particle composition is a strong function of p_T
- Other unknown effects?







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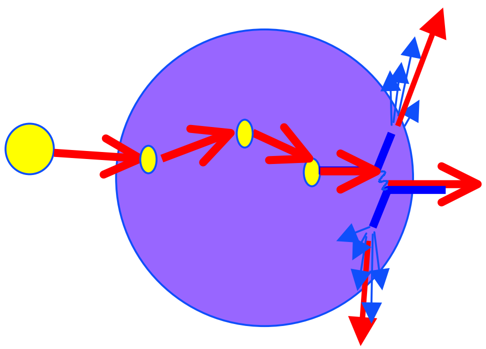
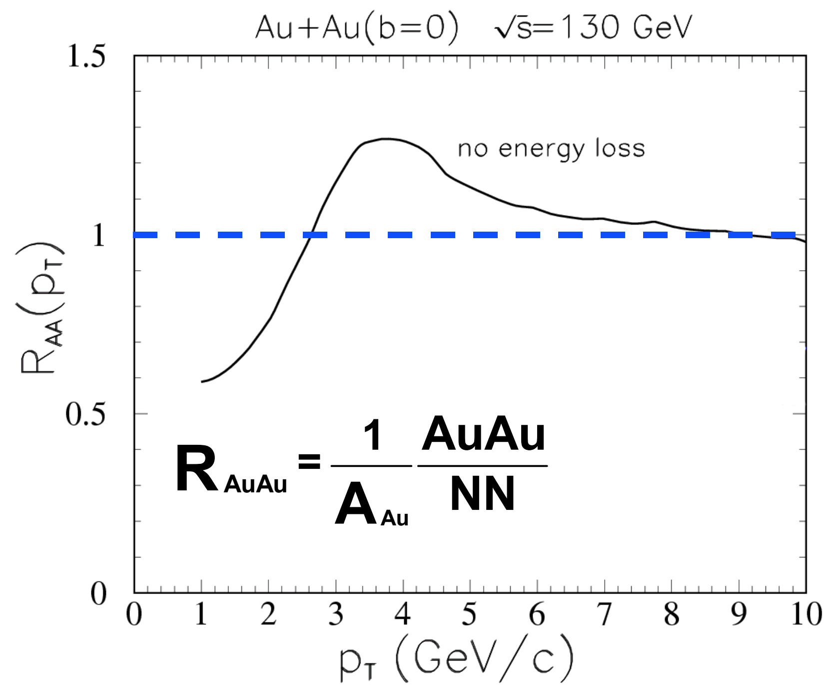
Cronin Effect

Prior parton scattering broadens the transverse momentum spectrum ("Cronin effect" or "p_T broadening").



- ✓ ***Enhances*** high p_T
- ✓ Effect small above 6 GeV/c.
- ✓ Would like pp run at appropriate energy to confirm

Calculation for RHIC



Xin-Nian Wang: (nucl-th/0104031)

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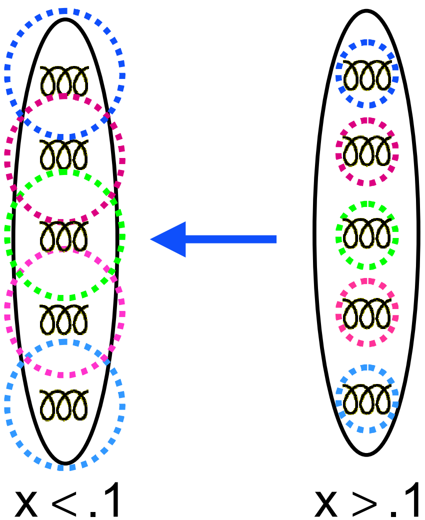
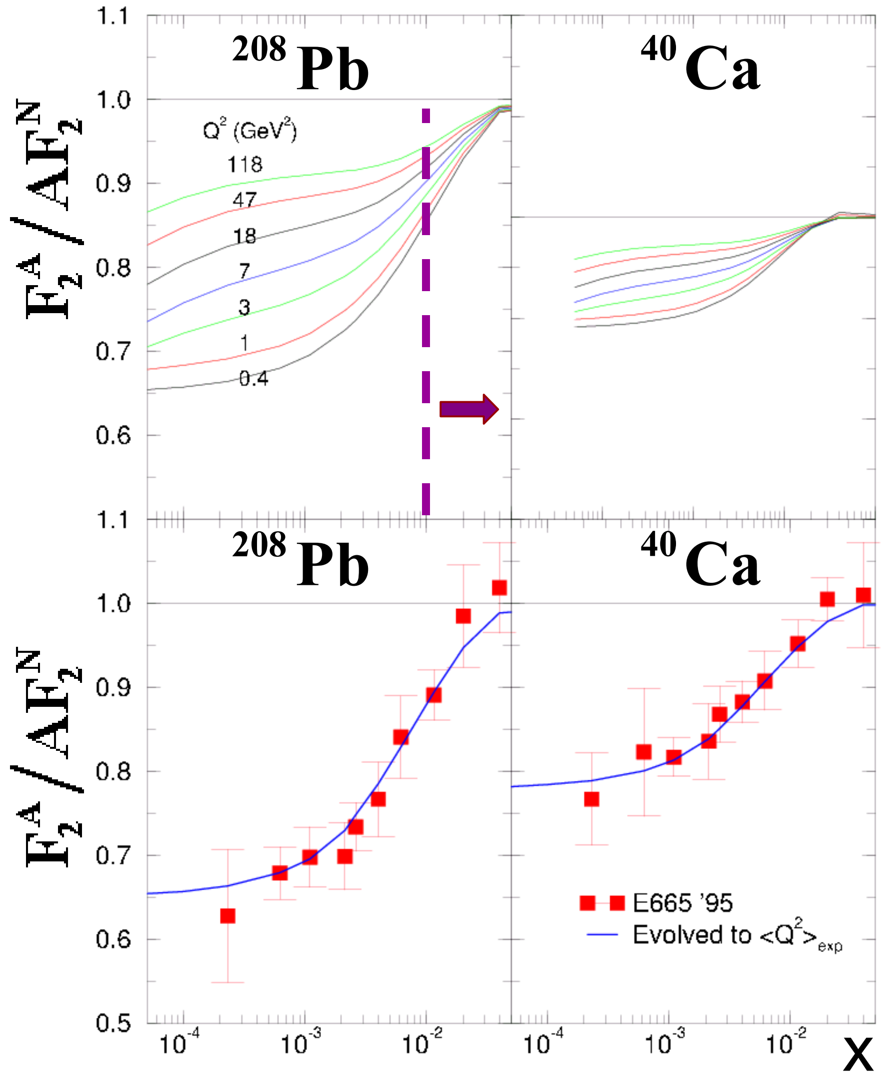
Nuclear Shadowing of Quarks

- Nucleon structure functions are known to be modified in nuclei.
- Can be modeled as a recombination effect due to high gluon # density at low x (in frame where nucleon is moving fast)



$$x \simeq \frac{1}{2m\ell_c} \approx 0.1$$



Zheng Huang, Hung Jung Lu, Ina Sarcevic: Nucl.Phys.A637:79-106,1998 (hep-ph/9705250)

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

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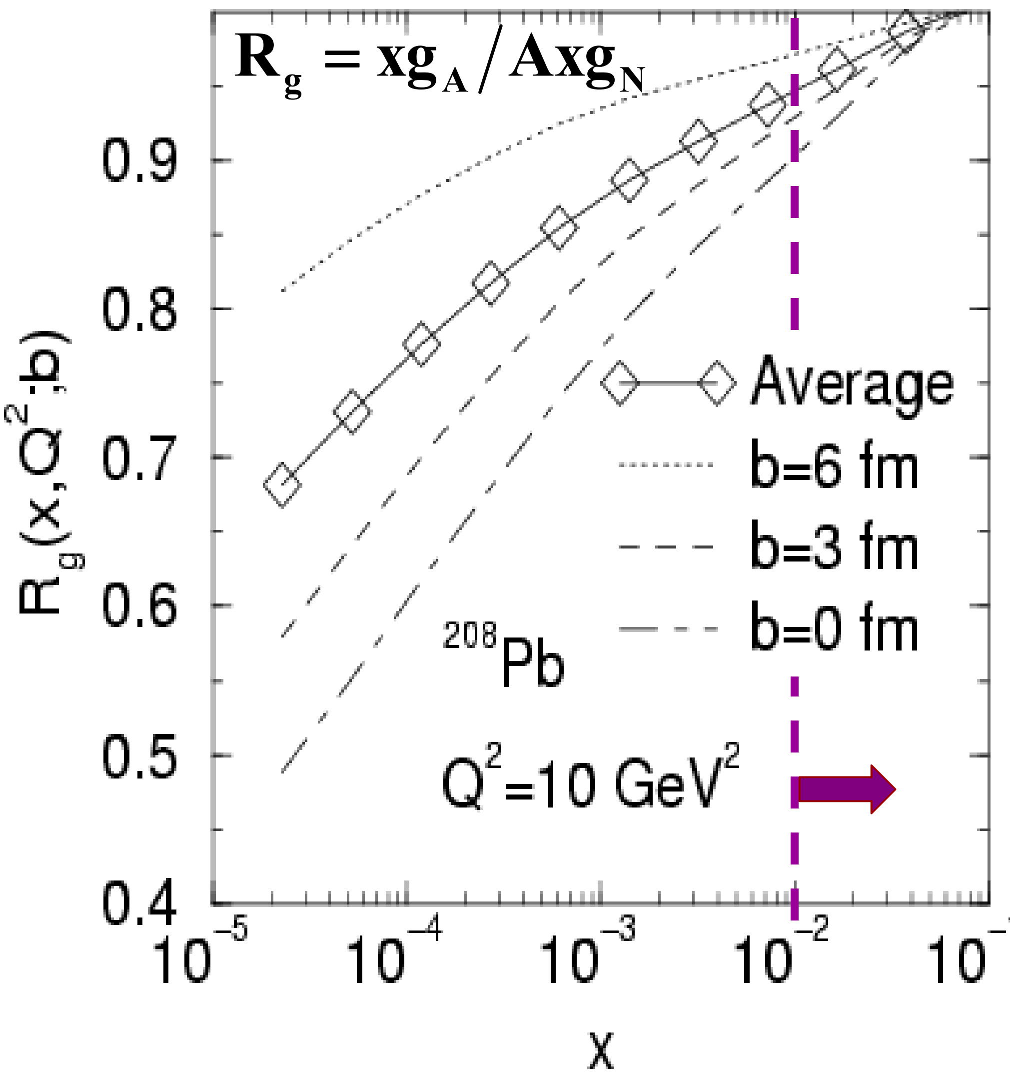
Nuclear Shadowing of Gluons

- Gluon scattering will be important at RHIC
- Gluon shadowing is not measured, but will clearly play a large role.
- Approximately 10% fewer high P_T particles expected RHIC

✓ pA running is needed

✓ Higher P_T (Q^2) reach important



Zheng Huang, Hung Jung Lu, Ina Sarcevic: Nucl.Phys.A637:79-106,1998 (hep-ph/9705250)

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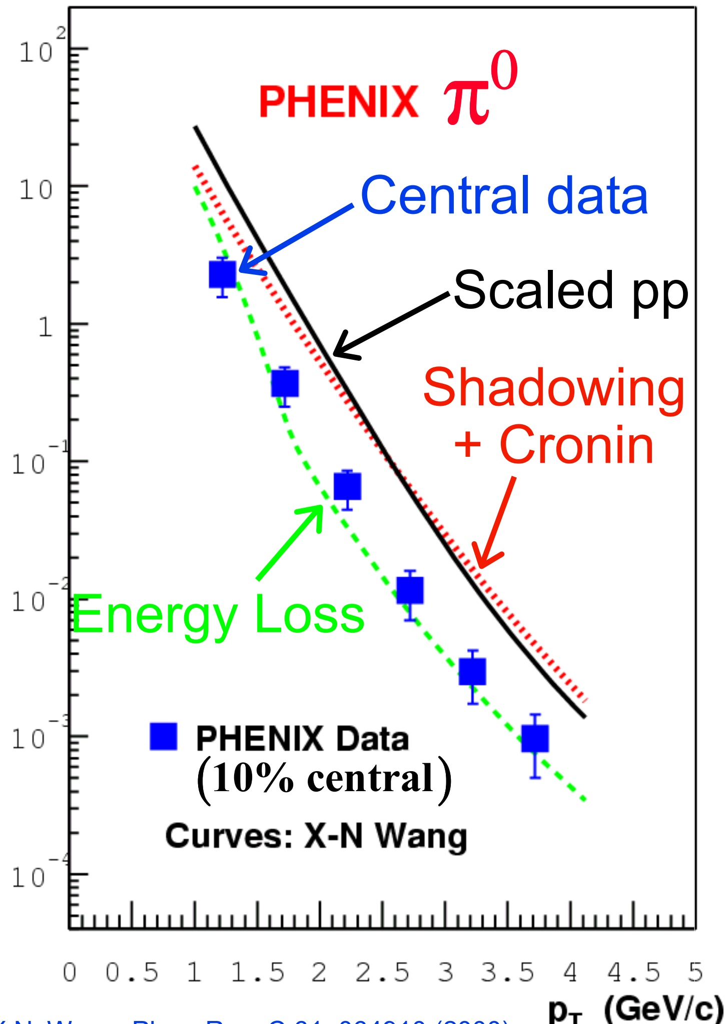
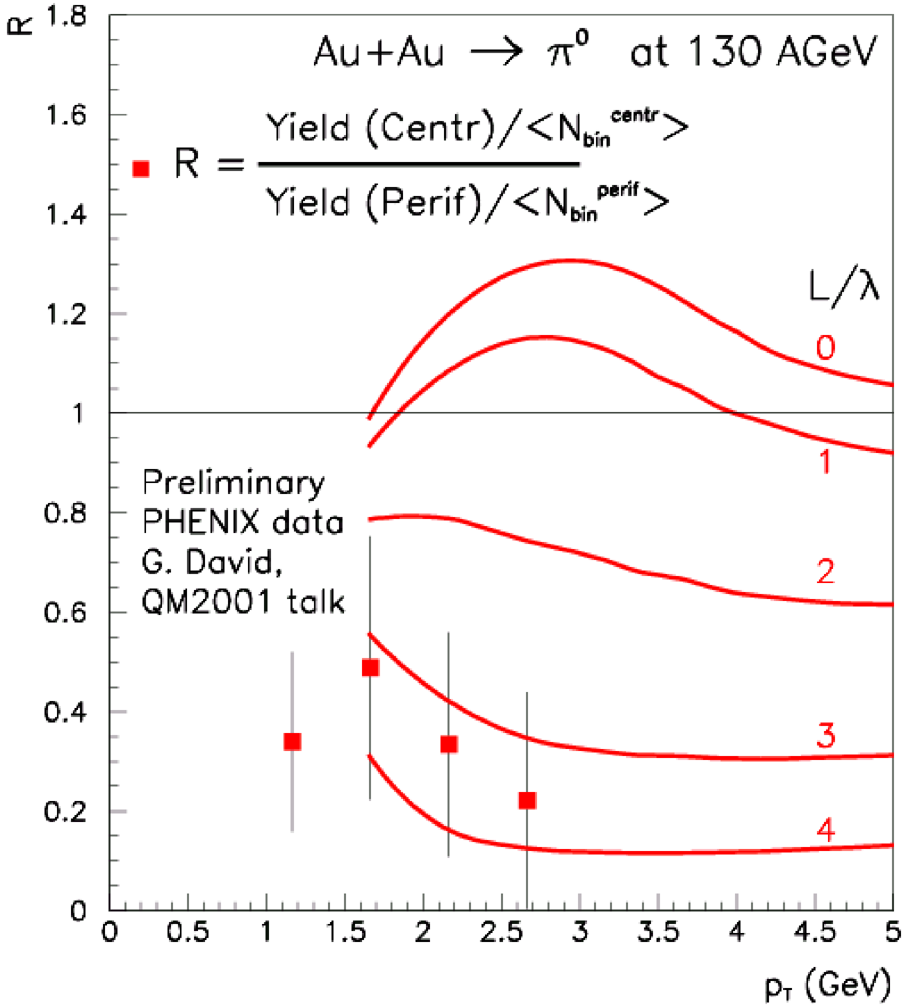
Theoretical Calculations



X.N. Wang, Phys. Rev. C 61, 064910 (2000) (nucl-th/9812021)



P.Levai, G. Fai, G. Papp, MG (QM01)

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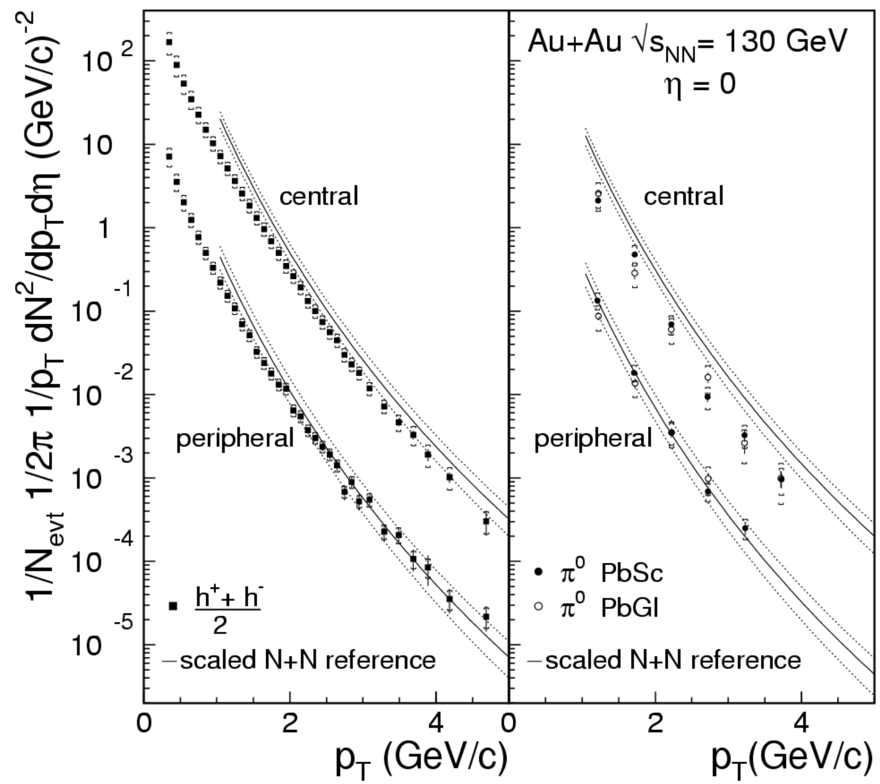
Year-1 High P_T Conclusions

Central collision data shows significant suppression relative to prediction without energy loss.

Indicates a novel effect: deviation from point like scaling

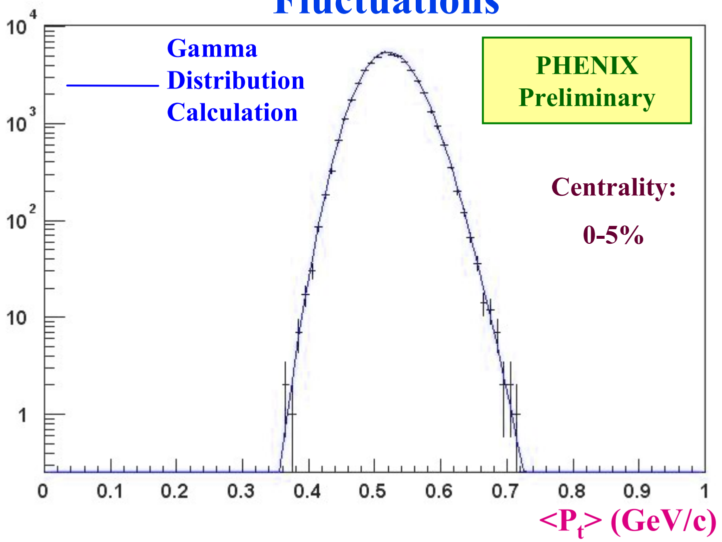
It is consistent with parton energy loss , but <u>too early</u> to make definitive conclusion.



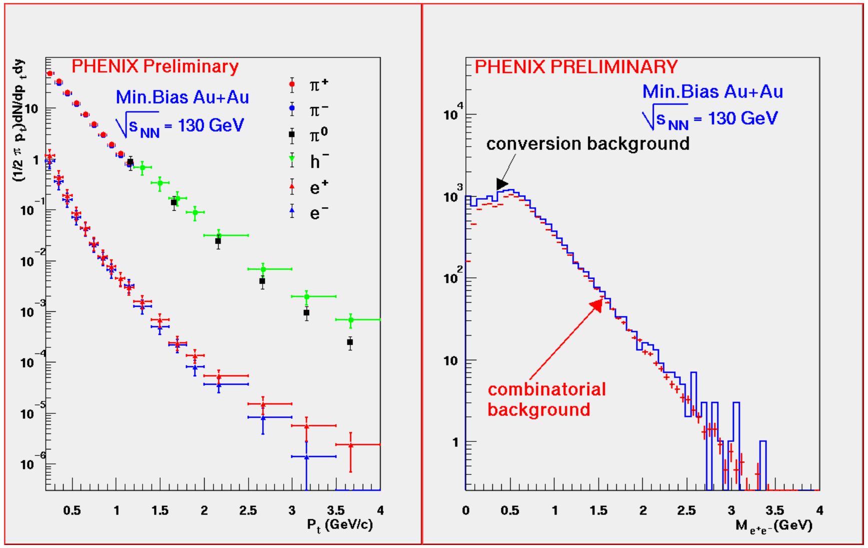
A systematic study including pA and higher P_T reach is needed. Stay tuned …

“Other” Year-1 PHENIX results

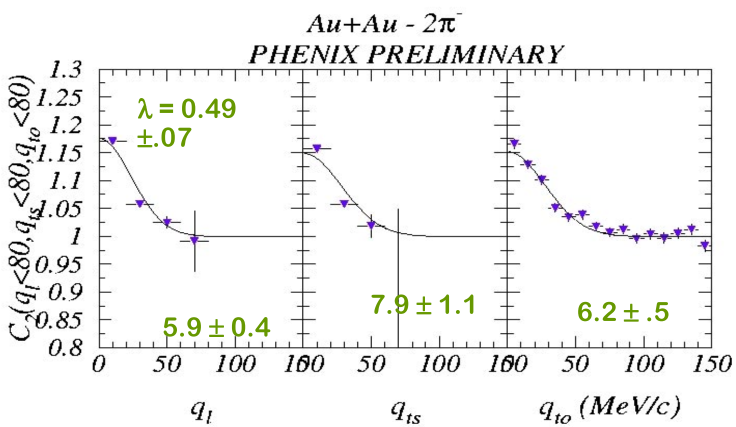
Fluctuations



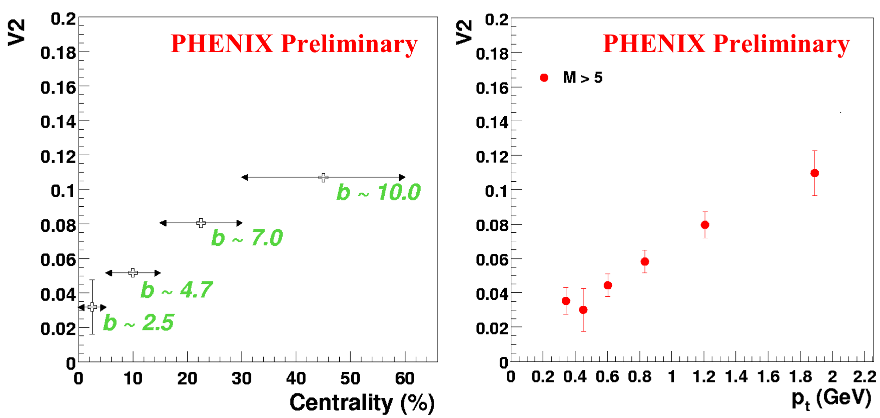
Electrons



HBT



Elliptic Flow



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Year 2: Jet Preview

π^0 production out to $P_T > 10$ GeV !

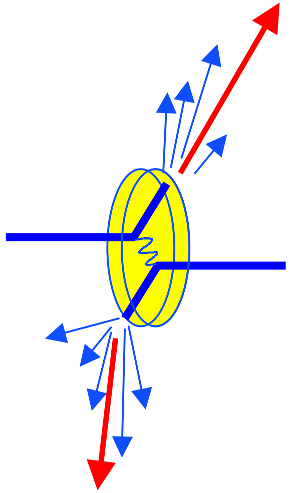
No questions about soft contributions

Greater sensitivity to exact energy loss

Better statistics for identified hadrons π,k,p

Back-to-Back correlation studies.

Possible d-A running.



Year 2: Heavy Vector Mesons

Confined

» Gluons confined to thermally distributed π's

Structure functions

$\langle P_o \rangle = 3T$

☞ $\langle P_g \rangle = 1/5 \langle P_\pi \rangle = 3/5\ T$

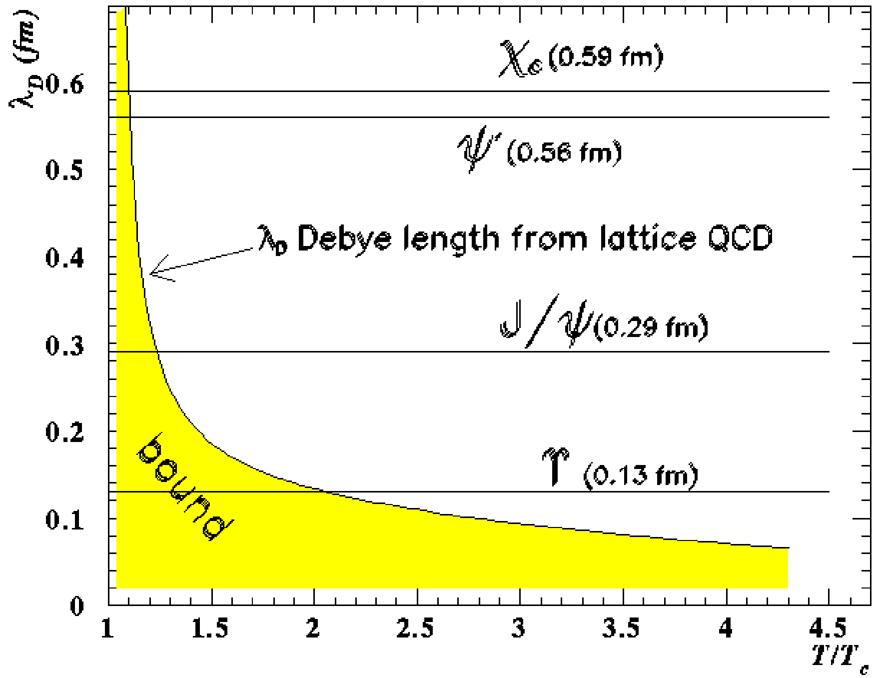
(For T=200MeV, $\langle P_g \rangle$ = 0.1 GeV)

Deconfined

» Gluons are distributed thermally

☞ $\langle P_g \rangle_{deconf} = 3T$

(T=200, $\langle P_g \rangle_{deconf}$ = 0.6 GeV)



Gluon distribution is hardened in a deconfined medium.
"Onium" bound states are a "Temperature" gauge due their small radii.

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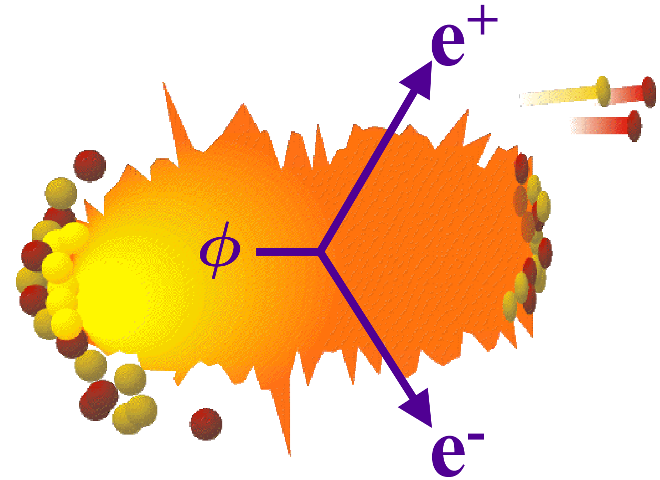
Year 2: Chiral Symmetry Restoration

- Recreate "Simple" Vacuum
- Look at narrow resonances
  - » Look for changes of masses and width's of light vector mesons (ρ, ω, ϕ)
  - » Leptonic Channels most sensitive
  - » Need excellent mass resolution



Measure ρ, ω, ϕ as a function of transverse momentum and centrality for different beam energies.

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Year 2: 1st Spin Physics Run!

Establish Stable Asymmetry Measurements

- » Beam Polarization > 50%
- » Luminosity ~5E30$cm^{-2}s^{-1}$

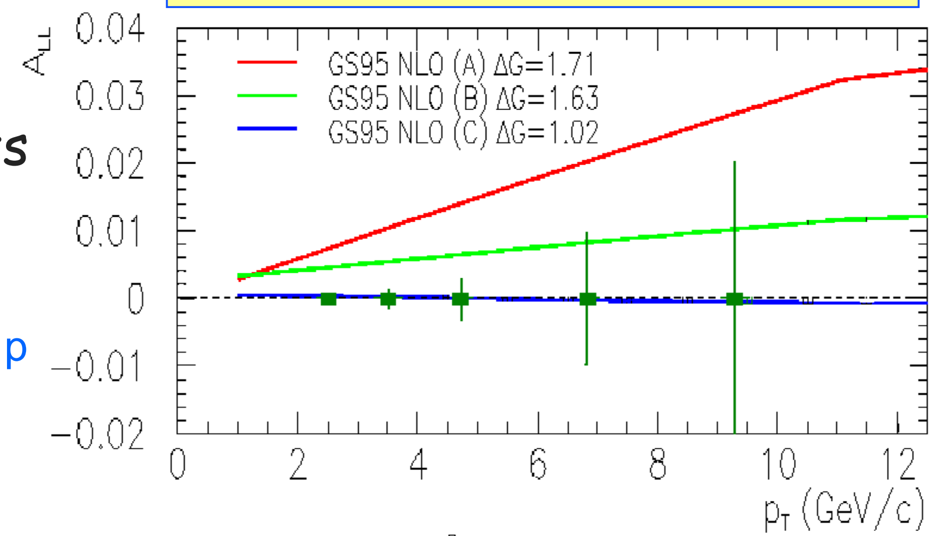
1 week of transverse polarization (~0.75 pb^{-1})

- » A_N ~ Higher Twist Effects

4 weeks of longitudinal polarization (~3 pb^{-1})

- » A_{LL} for pion ~ Δg Measurements
- » A_{LL} for J/ψ in muon Arm

5 pb^{-1} and 50% polarization



π^0 Asymmetry

proton spin | quark spin | gluon spin | Angular p

$$1/2 = \Delta\Sigma + \Delta G + L_q$$

$\Delta\Sigma$ ~ .25 measured in Deep Inelastic Scattering Experiments

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First PHENIX run is a **HUGE** success !

Commissioned detector, 2 prl published, 1 prl to be submitted Sep. 5th, more on the way …

- ✓ Charged Particle Multiplicity results constrain models
- ✓ Energy Density well above phase transition level
- ✓ Suggestive high transverse momentum measurement

- ➢ RHIC second data taking run is underway
- ➢ RHIC expected to achieve design luminosity
- ➢ First polarized proton run to measure spin structure
- ➢ Jet quenching measurements beyond $P_T > 10$ GeV !
- ➢ $J/\psi, \Upsilon, \rho, \omega, \phi$, direct γ measurements at RHIC !

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