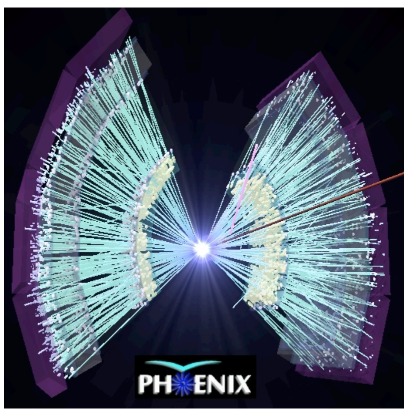
PHENIX

Hot and Dense Matter at RHIC

- From a hadron production viewpoint -



Tatsuya Chujo (BNL)
for the PHENIX Collaboration

BROOKHAVEN
NATIONAL LABORATORY

Outline

- **Physics at the Relativistic Heavy Ion Collider (RHIC)**
- **PHENIX experiment**

- **Experimental Results**
  - **What have we learned so far from hadron production?**

1. Bulk properties : Energy density and charged multiplicity.
2. Hydrodynamical behavior and chemical properties in AuAu.
3. High p_T particle production and jet quenching effect.
4. The control experiment: new results from d+Au.
5. Particle compositions at high p_T.

- **Conclusions**

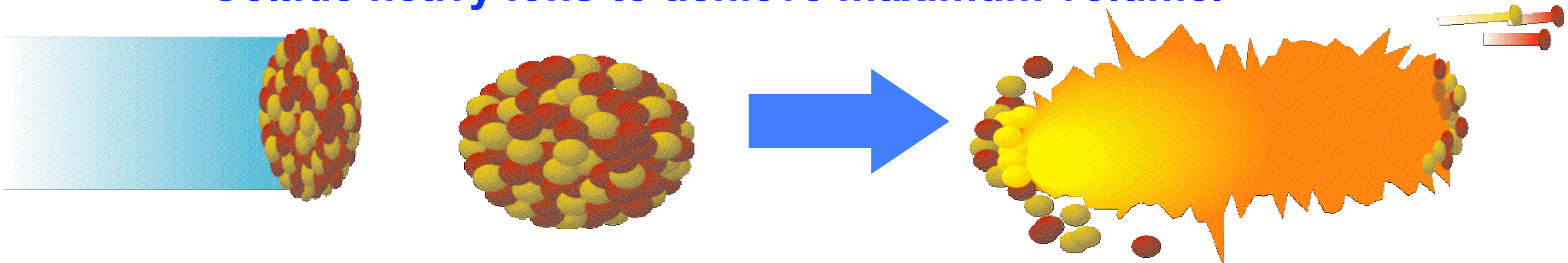
Physics at RHIC

- Lattice QCD predicts transition to deconfinement sate of quarks and gluons occurs at:

  $T_c \sim 170 \pm 10$ MeV (10^{12} °K) and $\varepsilon \sim 3$ GeV/fm^3.

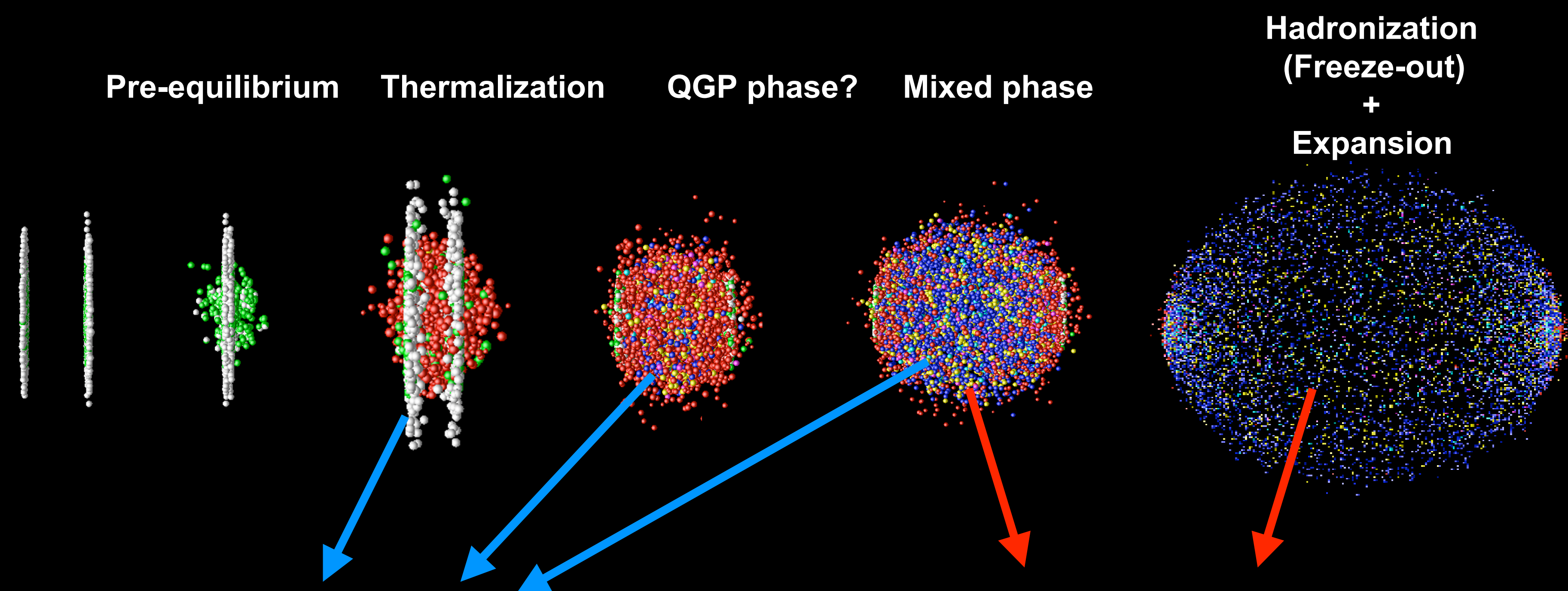
  - **As existed ~1 μsec after the Big Bang.**
  - **Inter-hadron distances comparable to that in neutron stars.**

- RHIC is designed to create very high temperature and density matter in the laboratory.
  - **Collide heavy ions to achieve maximum volume.**



- Experiments can study the hot, dense medium.
  - **Is thermal equilibrium reached?**
  - **What is the equation of state of the matter?**
  - **Do the nuclei dissolve into a quark gluon plasma (QGP)?**

History of Heavy Ion Collisions



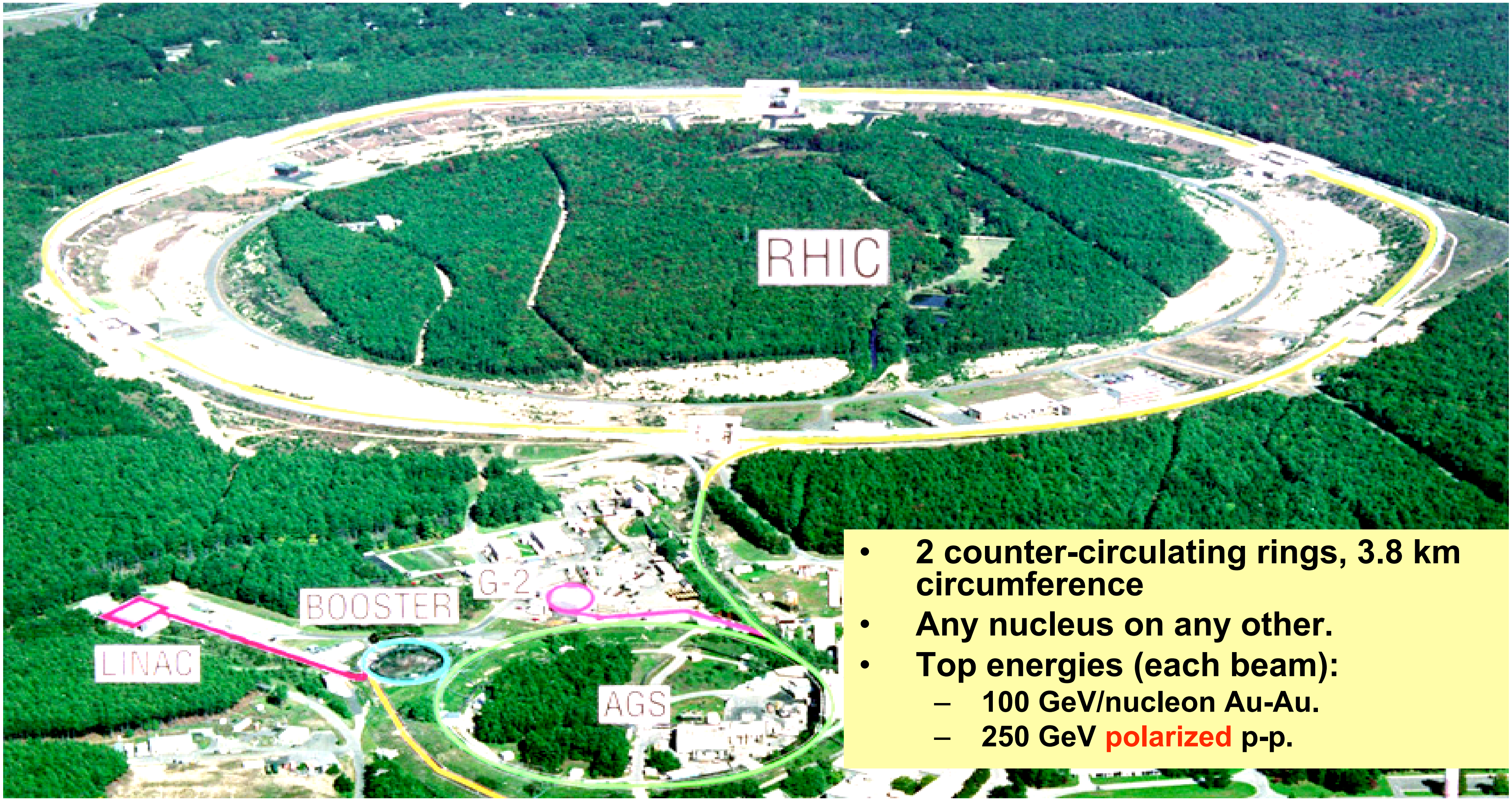
□, □□□ e^+e^-, $□^+□^□$

□, K, p, n, □, □, □, □, □, d,…

Real and virtual photons from q scattering sensitive to the early stages (penetrative probes).

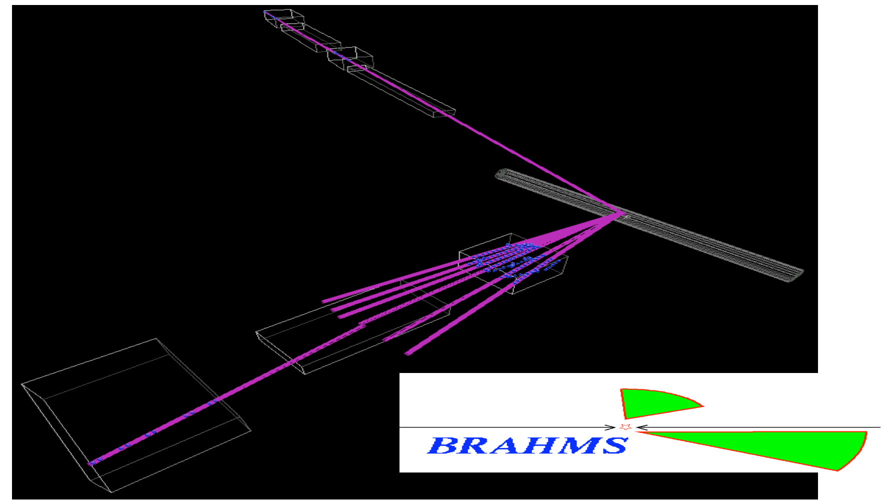
Hadrons reflect medium properties when inelastic collisions stop (chemical freeze-out).

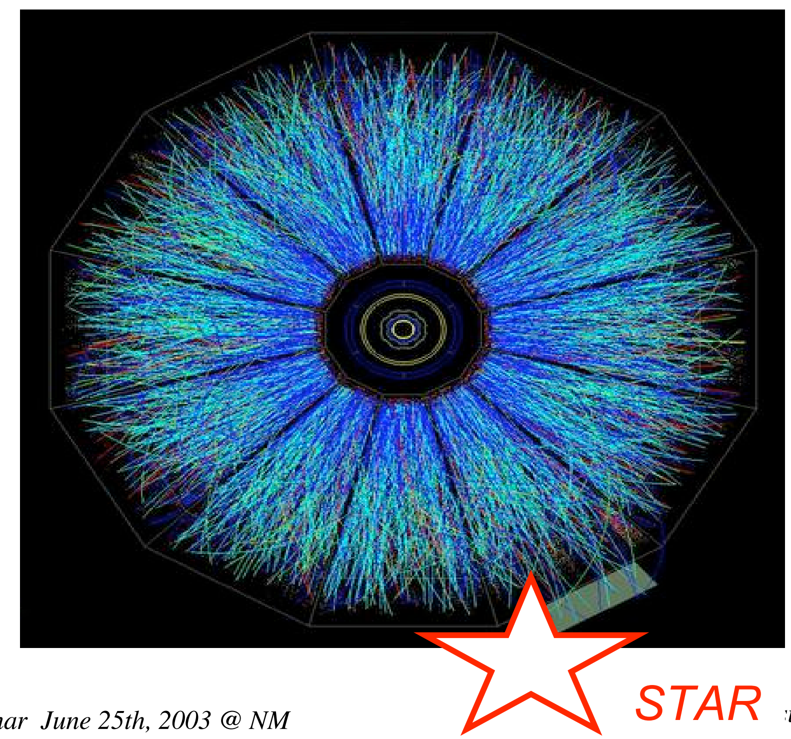
RHIC @ BNL

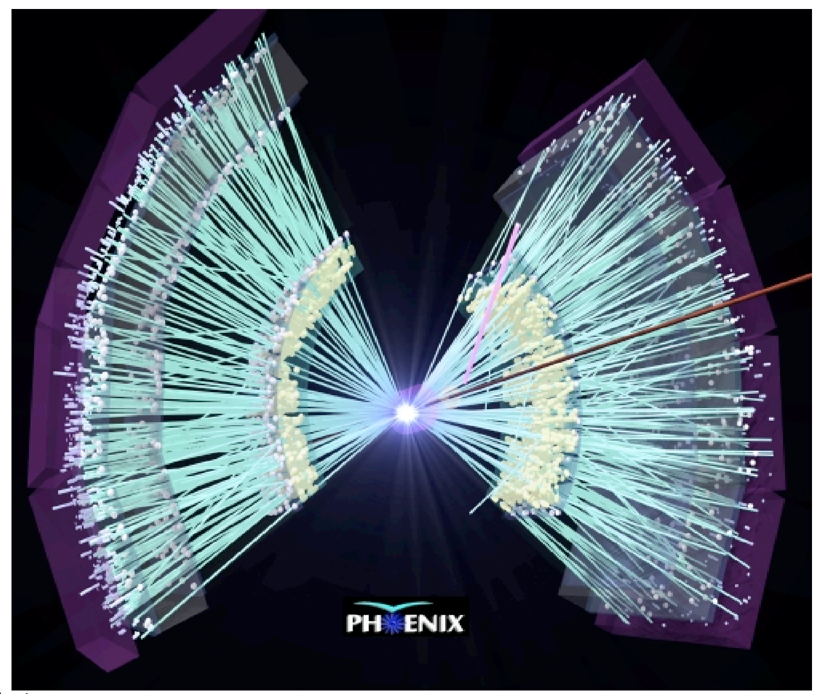


- 2 counter-circulating rings, 3.8 km circumference
- Any nucleus on any other.
- Top energies (each beam):
  - 100 GeV/nucleon Au-Au.
  - 250 GeV polarized p-p.

Four Complementary Experiments



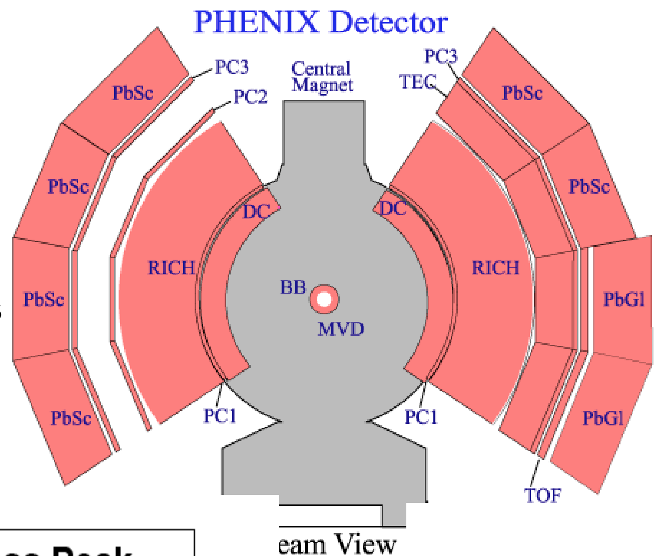




PHENIX Experiment

ID-

PHENIX Hadron PID



π^0 PID by EMCal

via $\pi^0 \rightarrow \gamma\gamma$ ($1<p_T<10$GeV/c)

6 lead- Scintillator (PbSc) sectors

2 lead- glass (PbGl) sectors

$\Delta\phi = \pi$

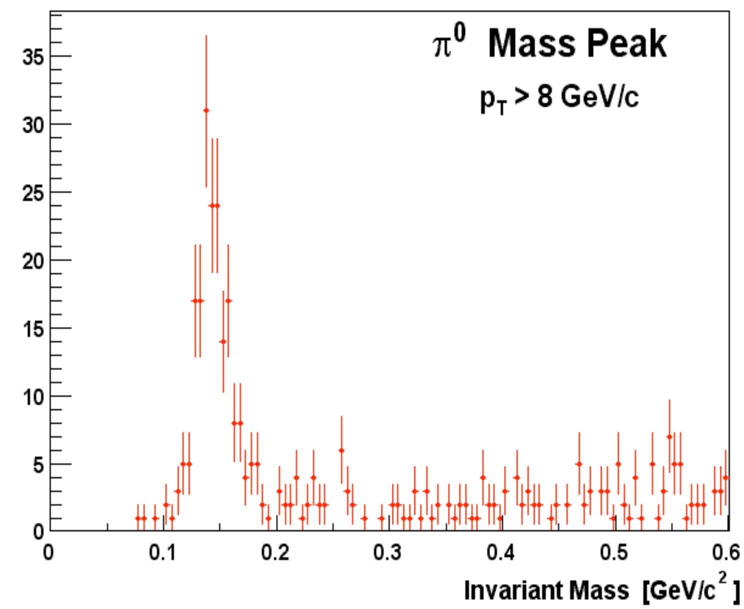
$\Delta\eta = 0.7$

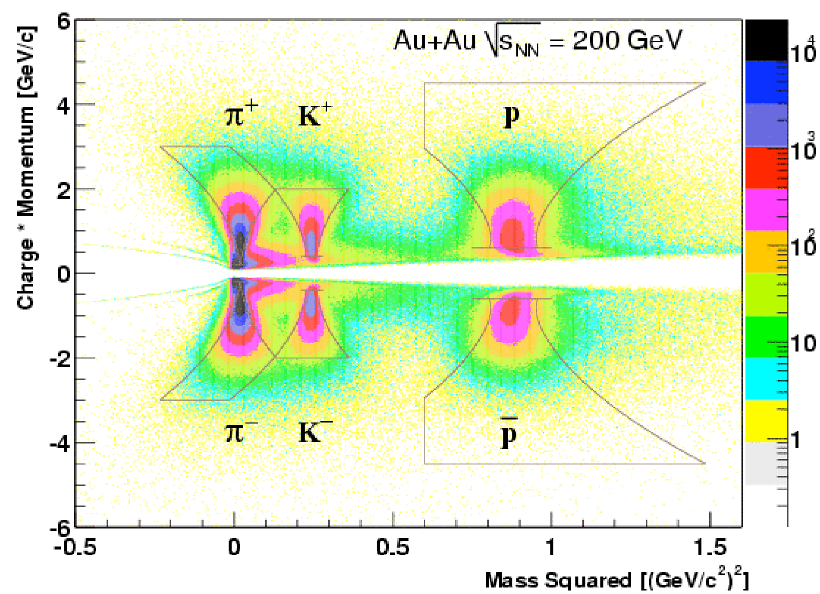
Charged PID by TOF

(DCH+PC1+TOF+BBC)

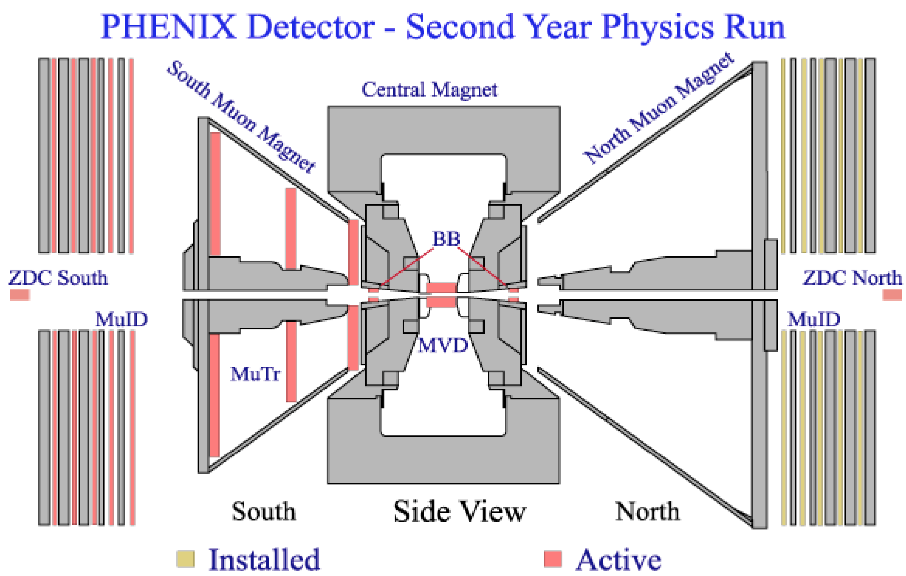
π/K < 2 GeV/c, K/p < 4 GeV/c

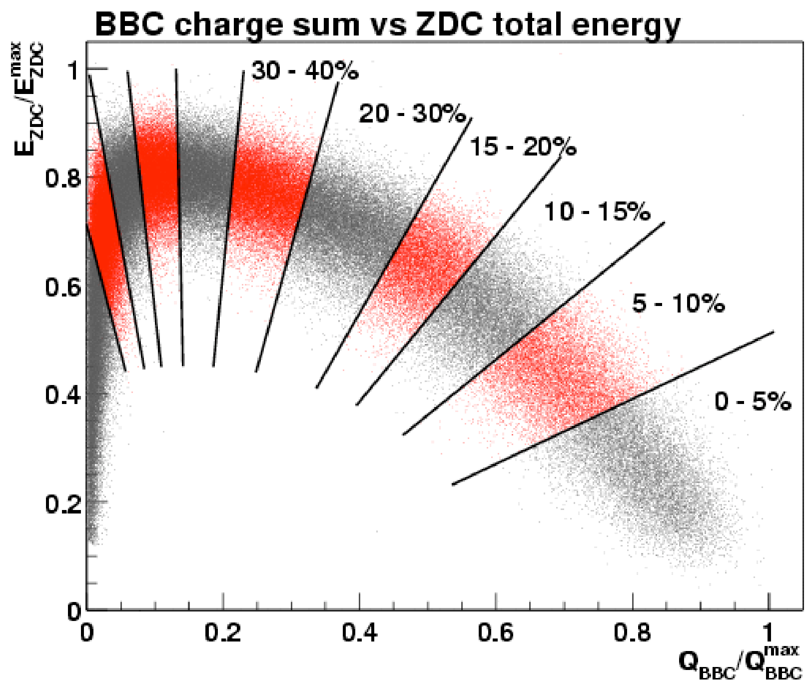
$\Delta\phi = \pi/8$





Collision Centrality Determination



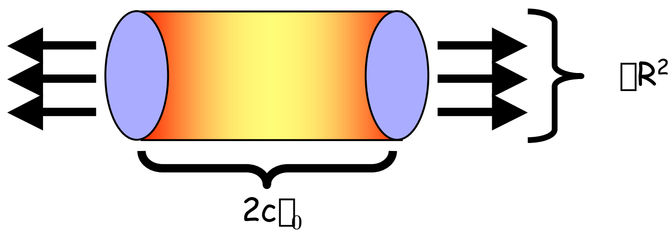


- Centrality selection : Used charge sum of Beam-Beam Counter (**BBC**, |□|=3~4) and energy of Zero-degree calorimeter (**ZDC**) in minimum bias events (92% of total inelastic cross sections).
- Extracted $\mathbf{N}_{\mathbf{coll}}$ and $\mathbf{N}_{\mathbf{part}}$ based on Glauber model.

(1) Global Observables
- $dN_{ch}/d\eta$, $dE_T/d\eta$ -

Is the Energy Density High Enough?

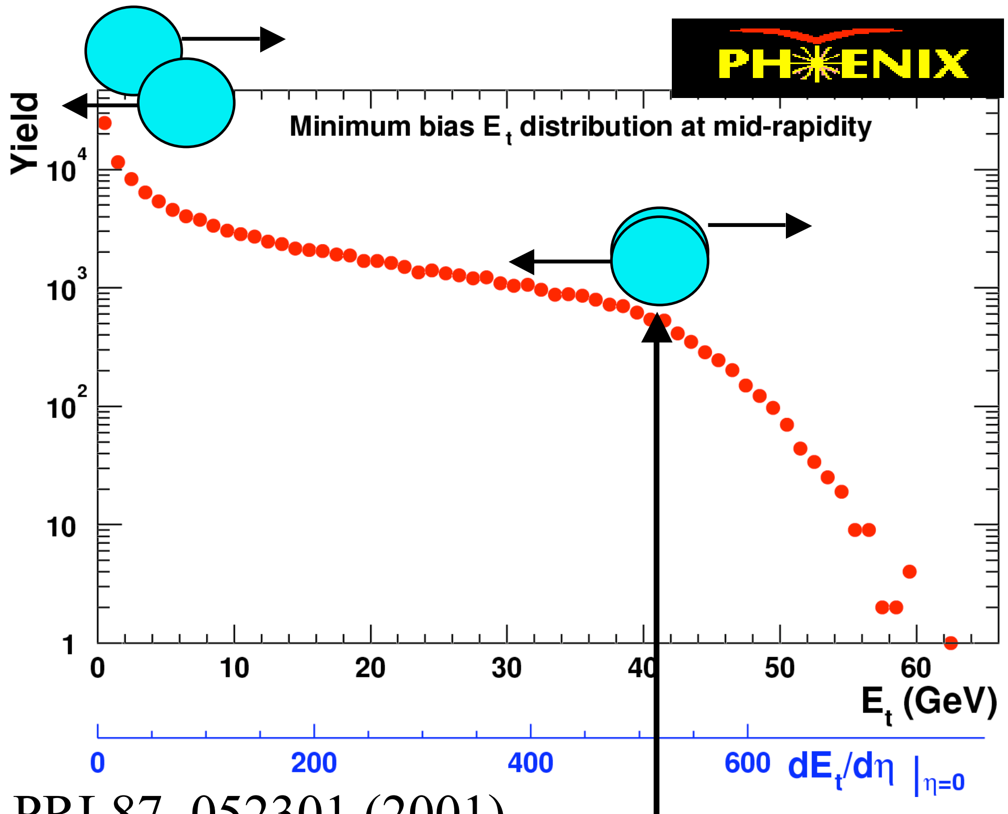
Colliding system expands:



Energy ⊥ to beam direction

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

per unit velocity || to beam



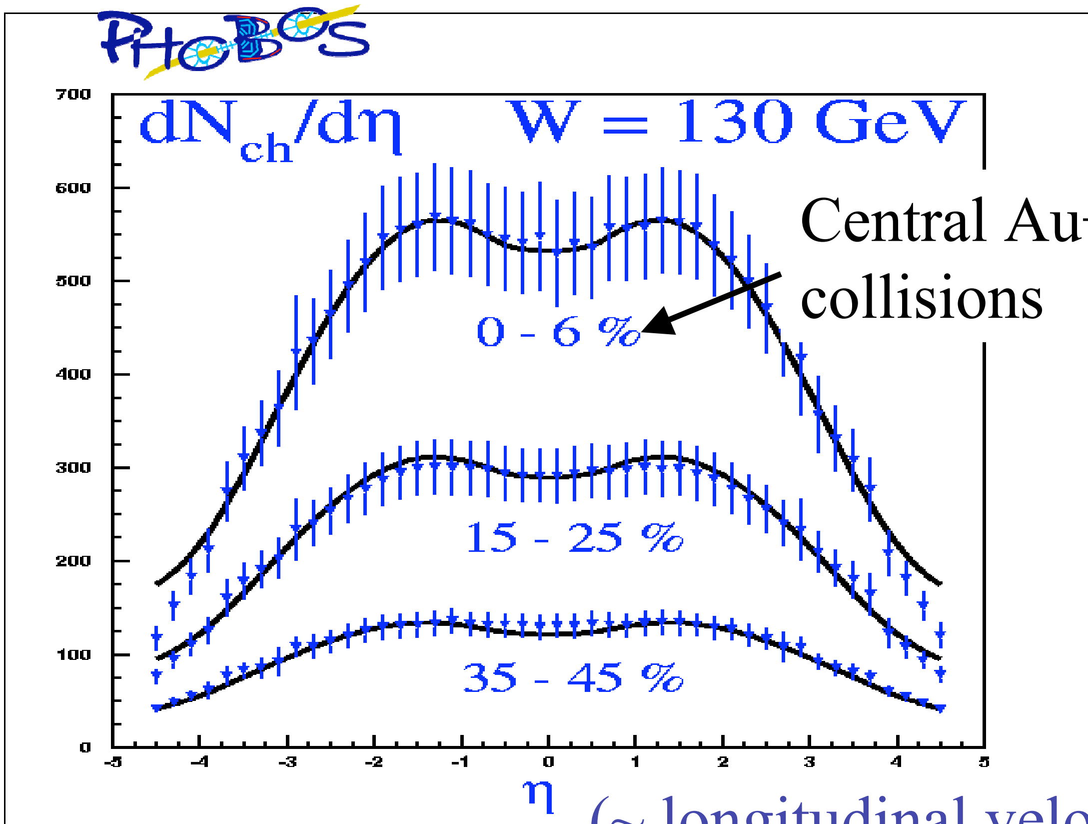
PRL87, 052301 (2001)

$\Rightarrow \varepsilon \geq$ 4.6 GeV/fm^3 (130 GeV Au+Au)

5.5 GeV/fm^3 (200 GeV Au+Au)

Well above predicted transition!

Charged Particle Multiplicity



Central Au+Au collisions

(~ longitudinal velocity)

Sum particles under the curve, find ~ 5000 charged particles in collision final state

(6200 in 200 GeV/A central Au+Au)

In initial volume ~ $V_{nucleus}$
Rescattering should be important!

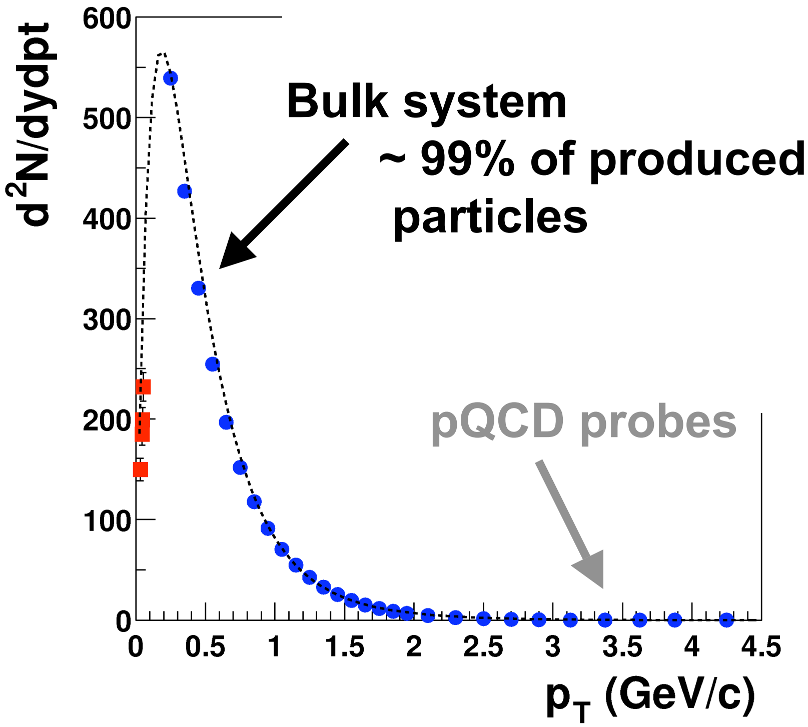
(2) Particle Production - Soft Physics -

Bulk Effects

- Equilibration
- Equation of State

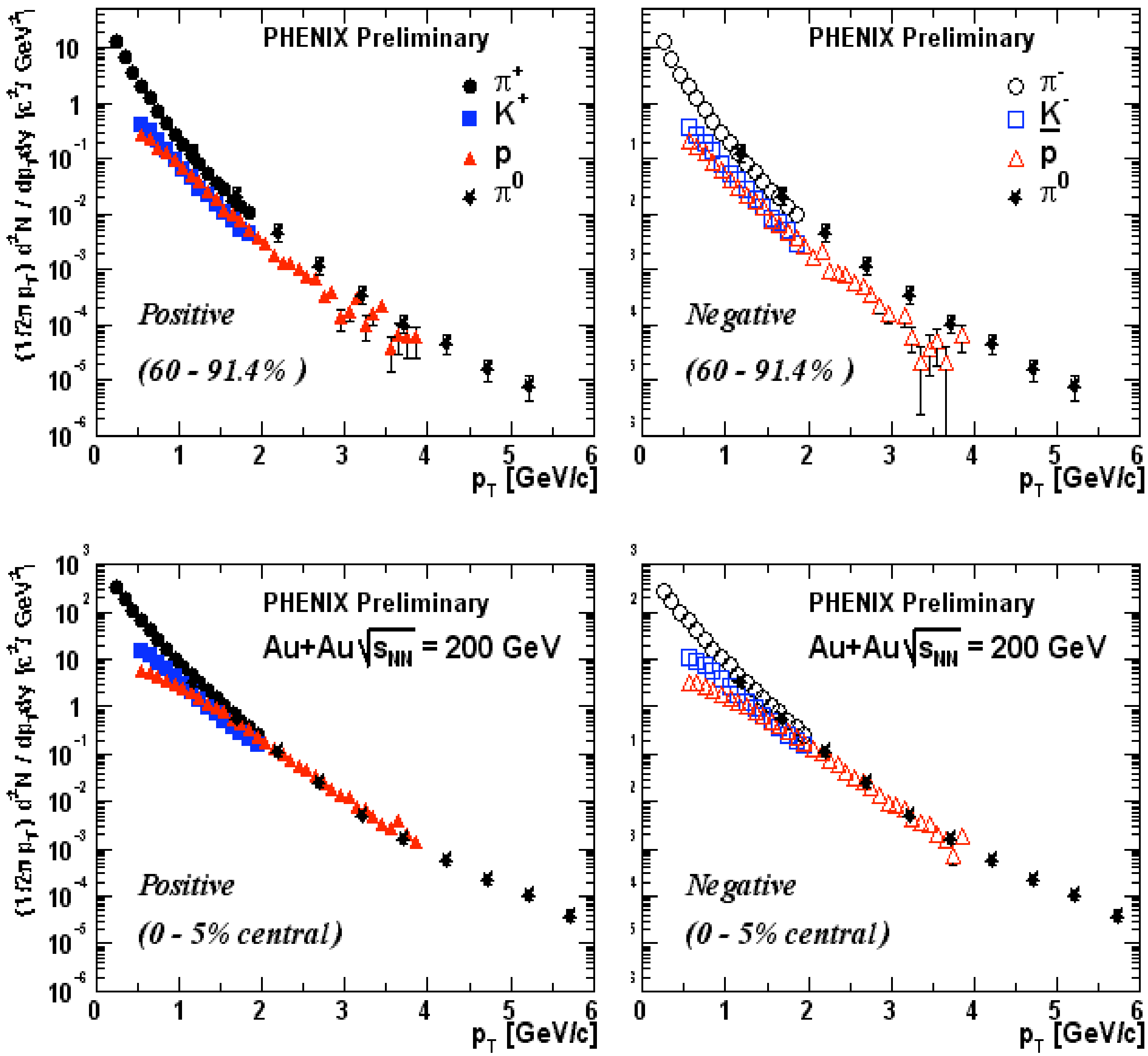
Probes of the System

- Hard scattered partons
- Heavy quarks



p_T Spectra (central vs. peripheral)

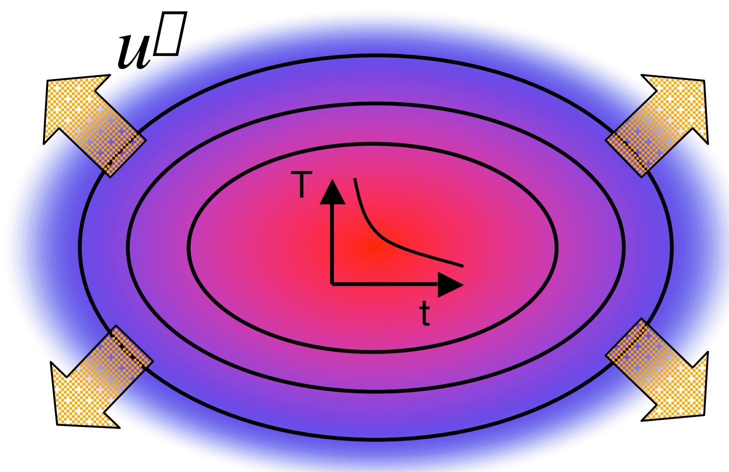
- **Peripheral**
  - ➢ similar to pp



- **Central**
  - ➢ low-pt slopes increase with particle mass
  - ➢ proton and anti-proton yields equal the pion yield at high p_T.

Hydro-dynamical Model

macroscopic view

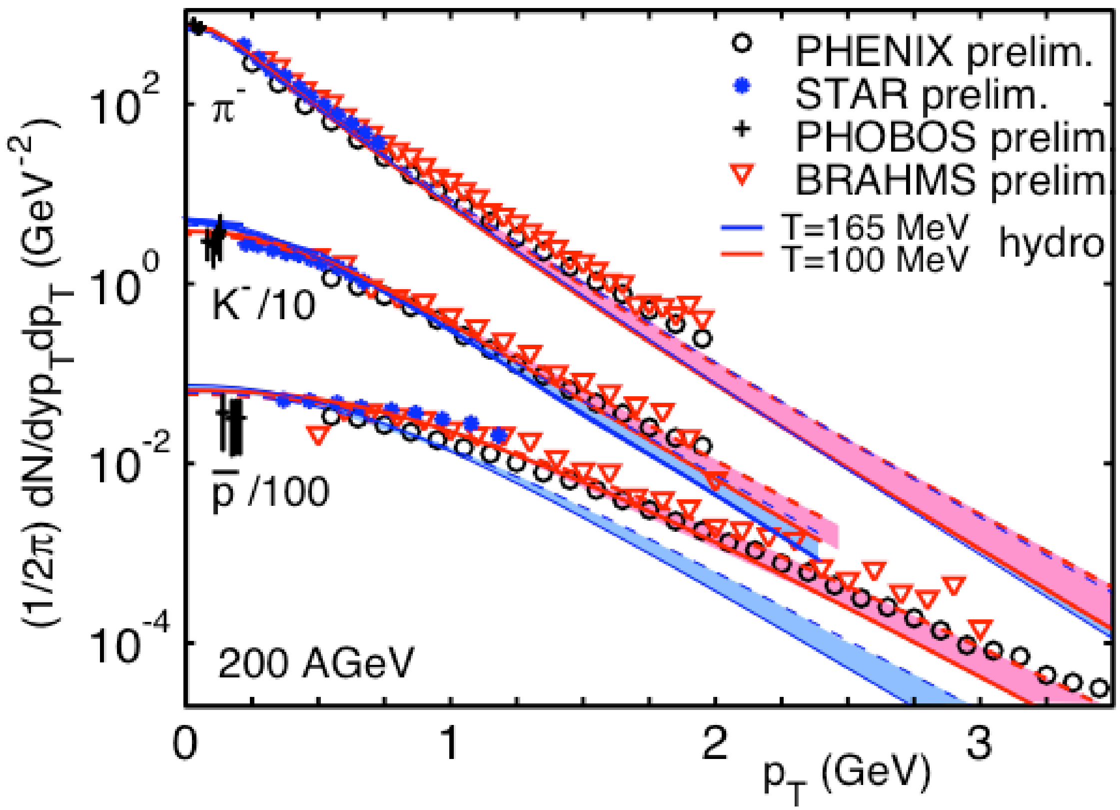


Hydro-dynamical Model Formalism:

continuity equations energy, momentum conservation equation of state

p_T Spectra for All 4 Experiments

Data: PHENIX: NPA715(03)151; STAR: NPA715(03)458; PHOBOS: NPA715(03)510; BRAHMS: NPA715(03)478
Hydro-calculations including chemical potentials: PFK and R. Rapp, Phys. Rev. C 67 (03) 044903



Calculations → too long a system lifetime
Enormous initial pressure, but decouples quickly (~10 fm/c)

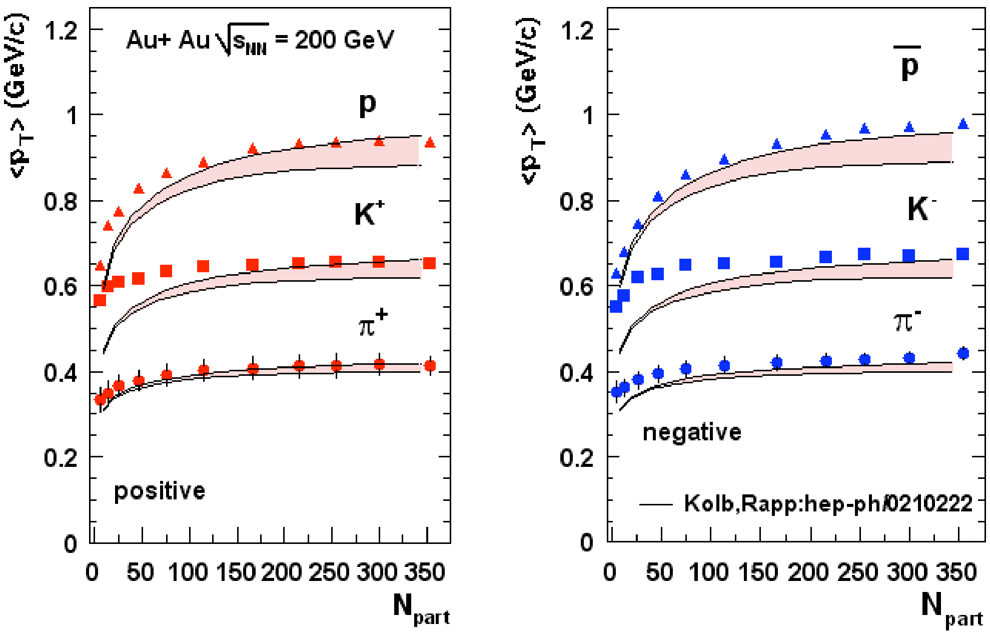
Hydrodynamics describes bulk particle momentum distributions

EOS is <u>not</u> hadronic

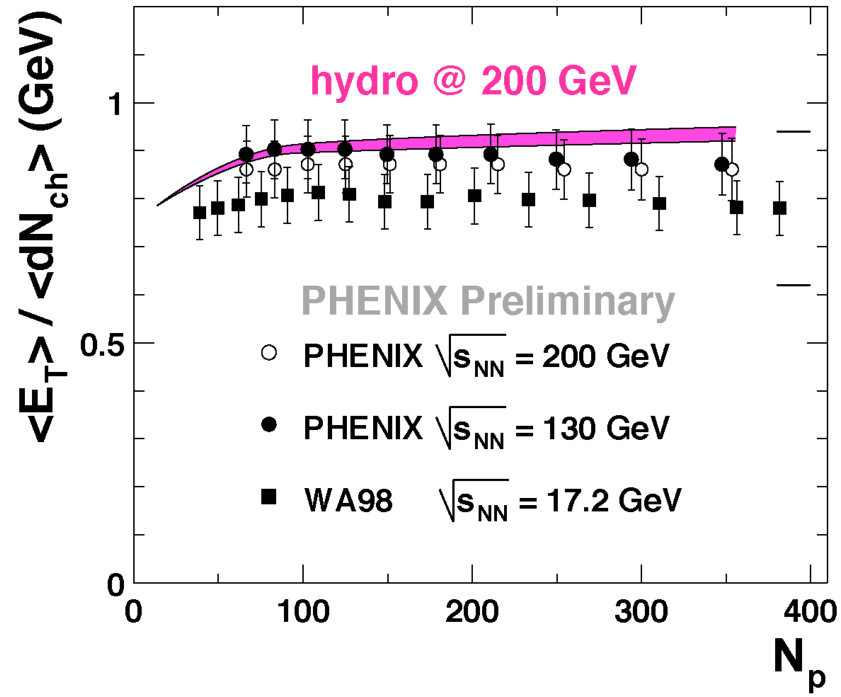
Transverse Momentum and Transverse Energy

PHENIX collab., Nucl. Phys. A 715 (2003) 151c

PHENIX preliminary



PHENIX collab., Nucl. Phys. A 715 (2003) 151c

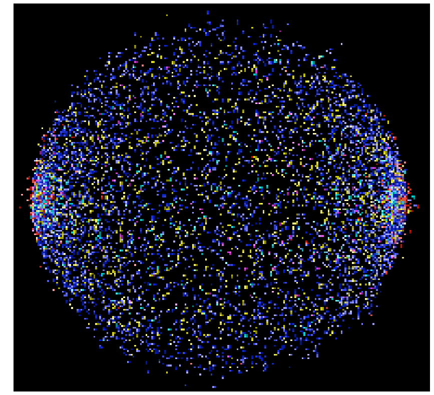


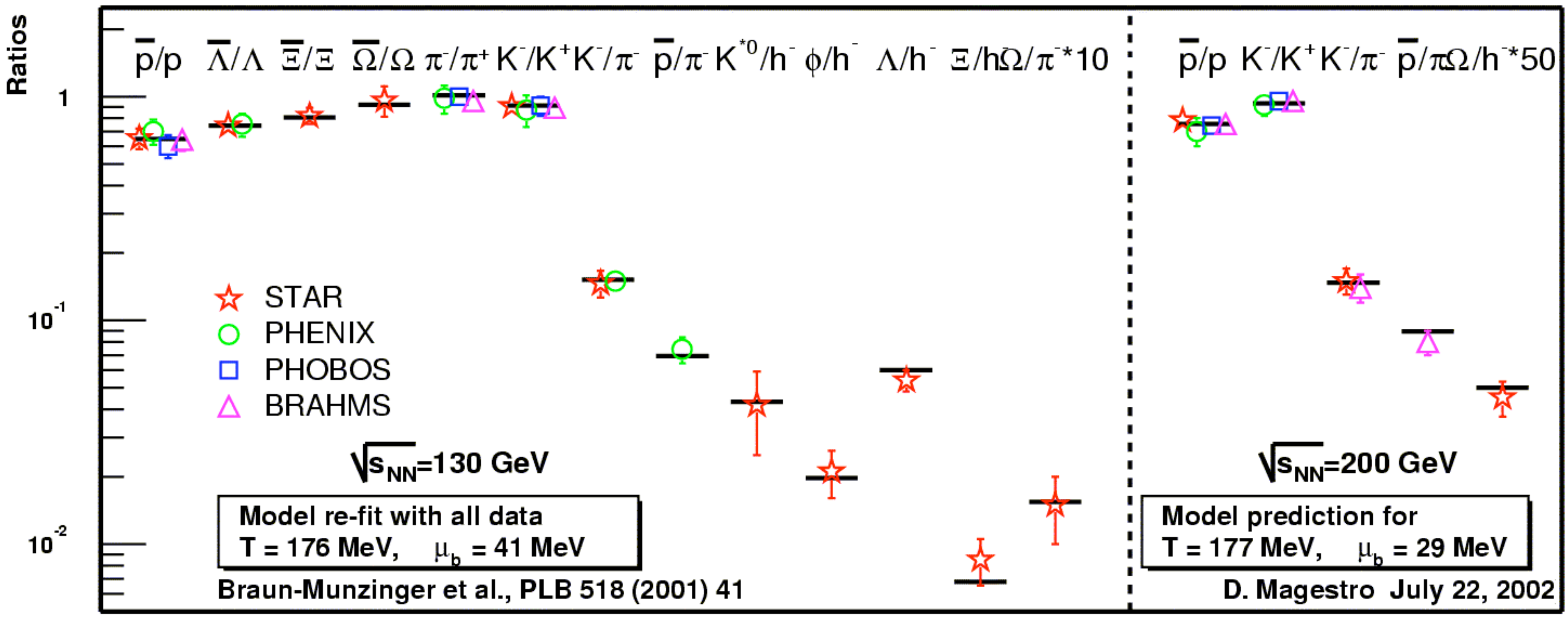
Transverse momenta as function of centrality are well under control as long as the collisions are not too peripheral. Transverse energy agrees for all centralities.

Evidence for equilibrated final state

- Almost complete reconstruction of hadronic state when system decouples by the statistical thermal model.

- Fit yields vs. mass (grand canonical ensemble)
  - ➢ T_{ch} = 177 MeV, μ_B = 29 MeV @ 200 GeV central AuAu.

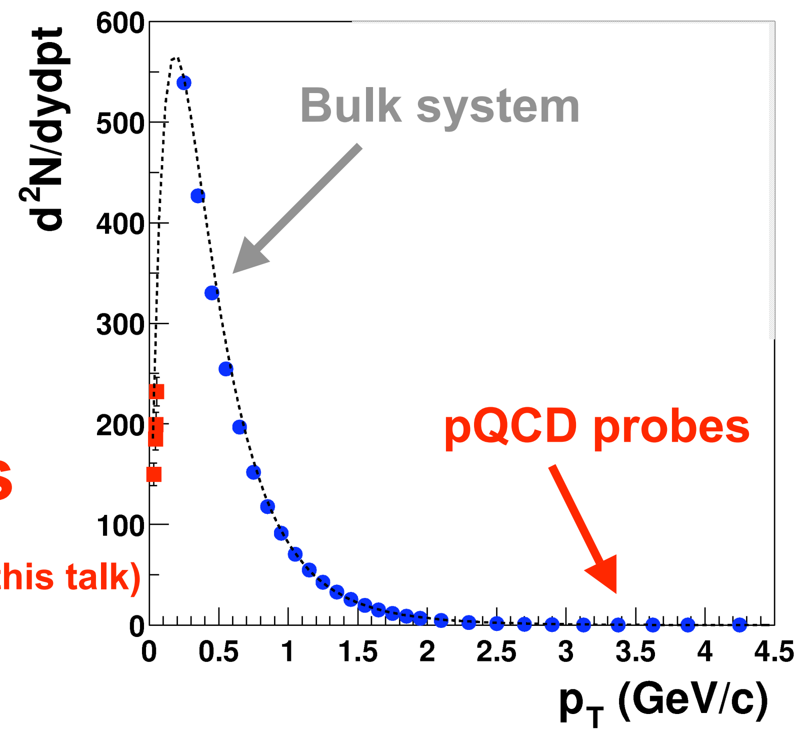




(3) High p_T Particle Production
- Hard Process -

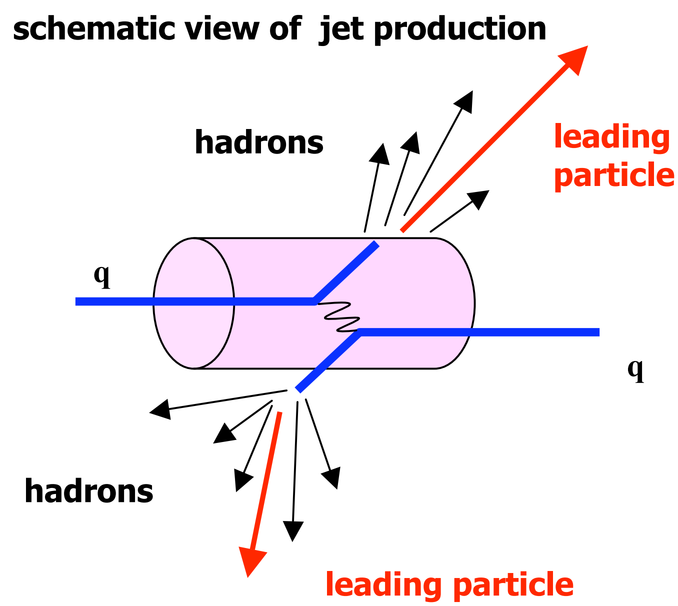
Bulk Effects
- Equilibration
- Equation of State

Probes of the System
- **Hard scattered partons**
- **Heavy quarks** (not included in this talk)



Hard Scattered Partons

- Hard scatterings in nucleon collisions produce jets of particles.
- In the presence of a color-deconfined medium, the partons strongly interact (~GeV/fm) losing much of their energy.
- **"Jet Quenching"**



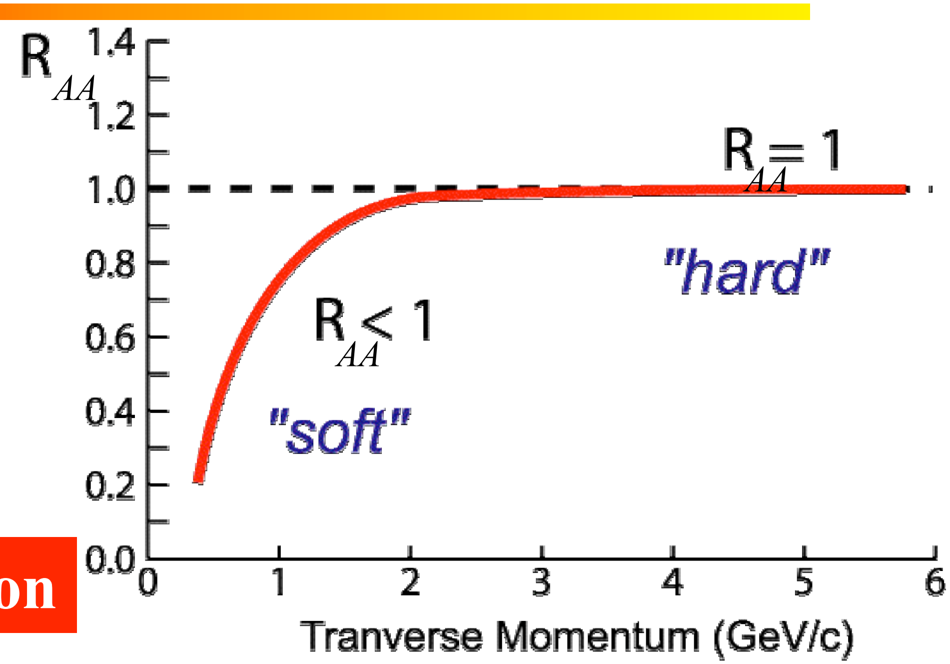
How Quantify the Nuclear Modification

Nuclear Modification Factor

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

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

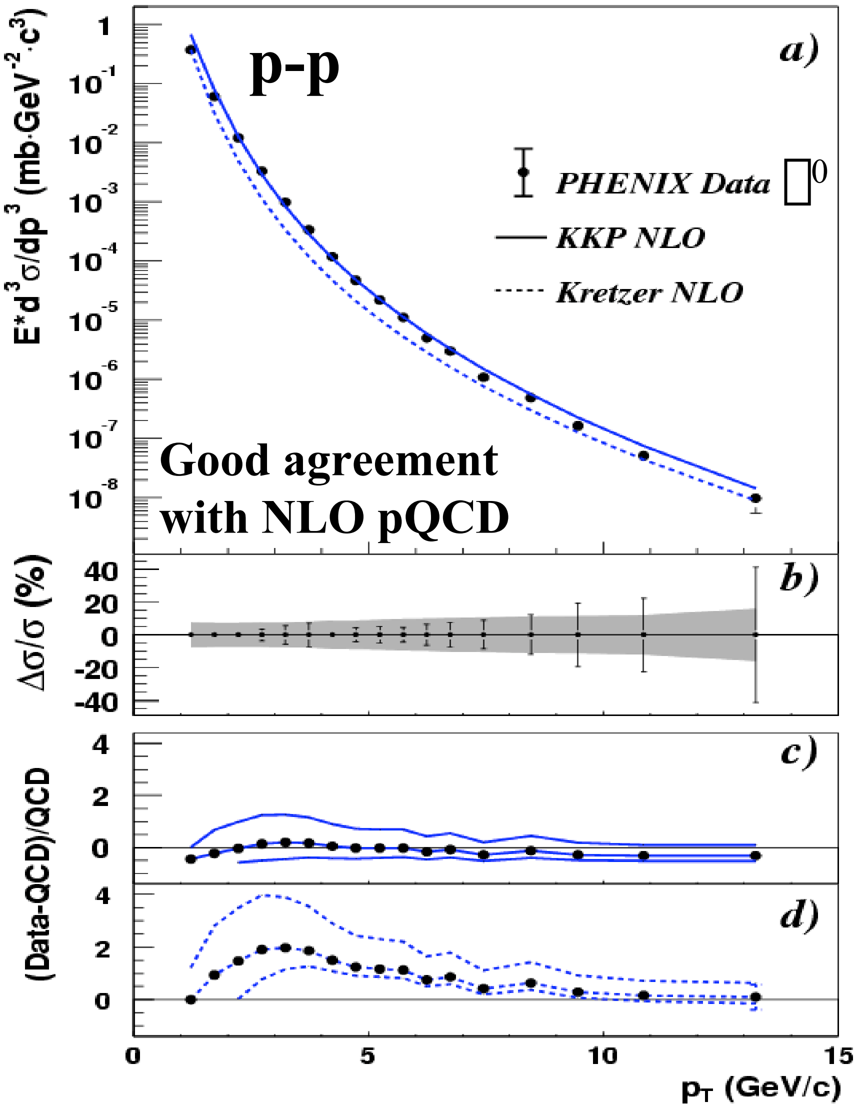
NN cross section



- **Scenario 1 : R_{AA} =1 : Scale with # of binary collisions (N_{coll}).**
- **Scenario 2 : R_{AA} >1 : Cronin effect (observed in ISR and SPS).**
- **Scenario 3 : R_{AA} <1 : Suppression.**

• Any departures from the expected binary collision scaling (N_{coll}) behavior provide the information on the strong interacting medium in *AA* collisions.

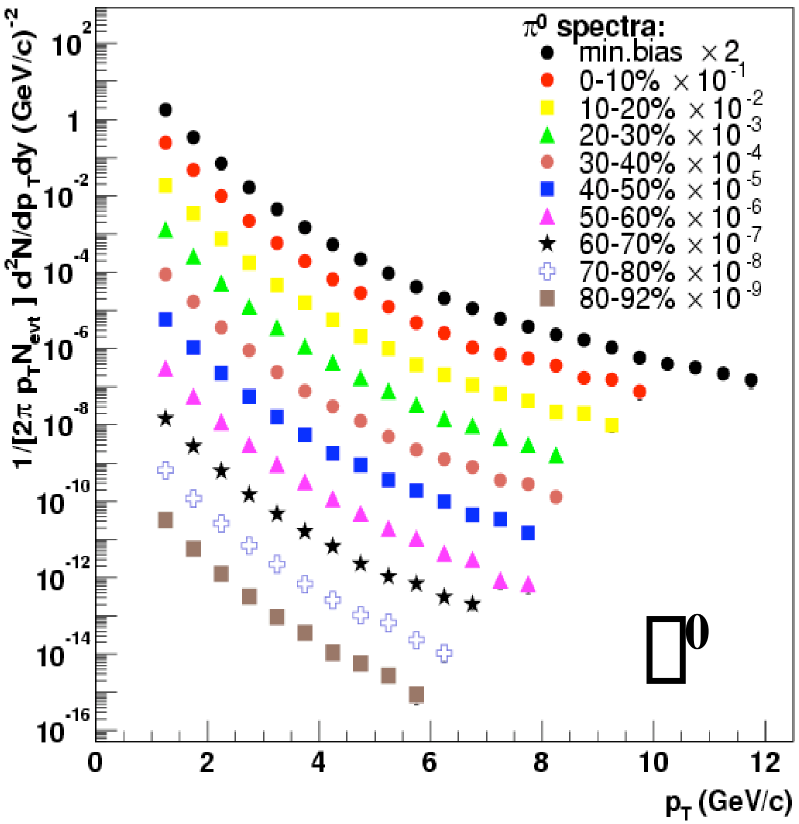
π⁰ spectra pp @ 200 GeV : Baseline

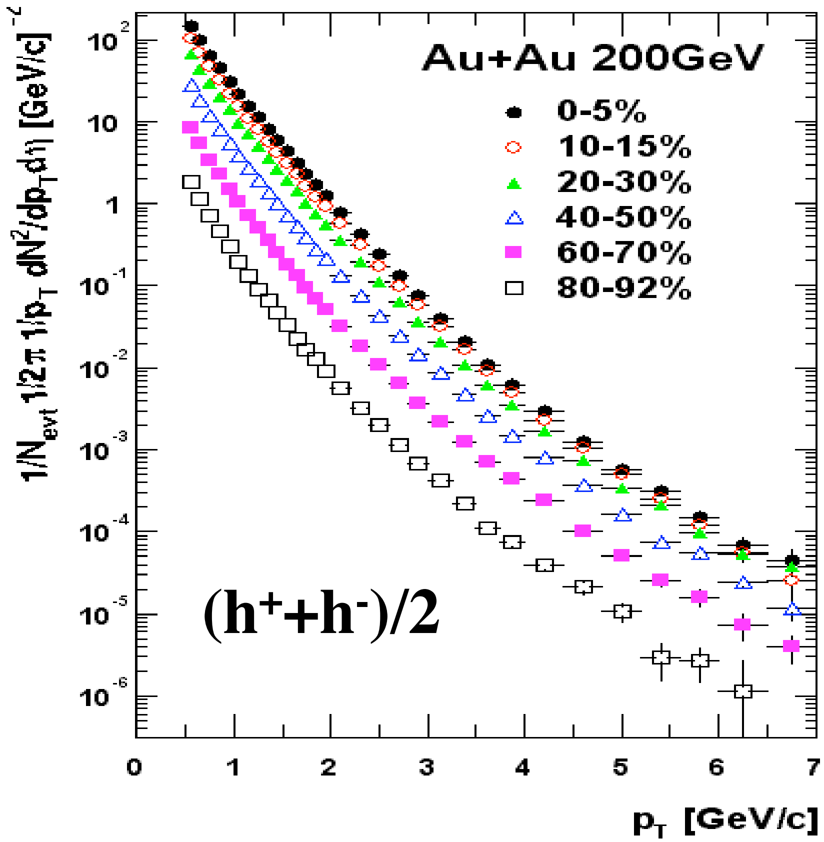


- π⁰ measurement in same experiment allows us the study of nuclear effect with less systematic uncertainties.
- Good agreement with NLO pQCD
- **Reference for Au+Au spectra**

PHENIX (p+p)
hep-ex/0304038

π^0 and *h* spectra AuAu @ 200 GeV





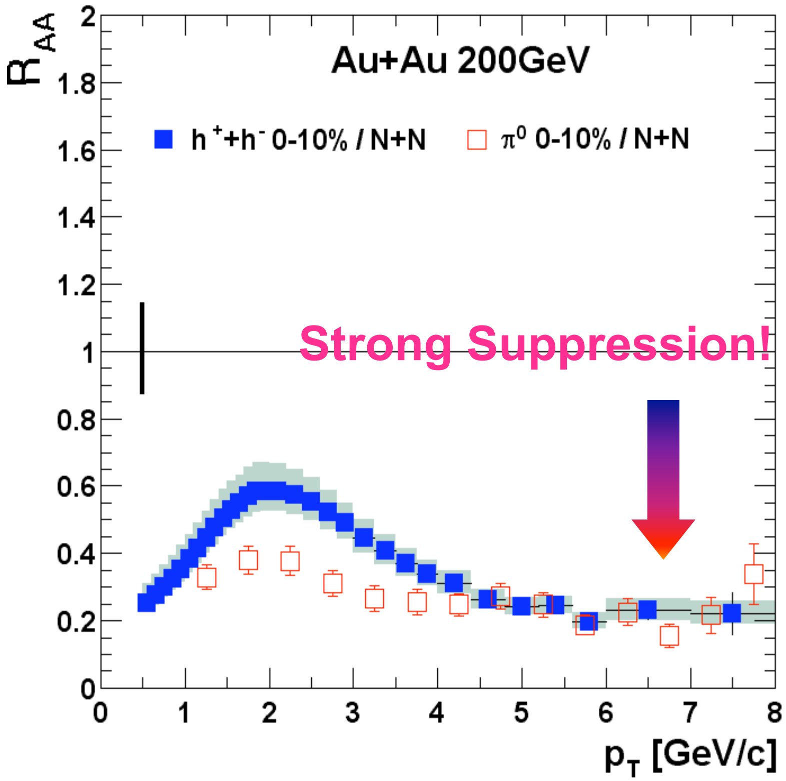
PHENIX AuAu 200 GeV

π^0 data: nucl-ex/0304022, submitted to PRL.

charged hadron (preliminary) : NPA715, 769c (2003).

R_{AA} for π^0 and charged hadron

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



- R_{AA} is **well below 1** for both charged hadrons and neutral pions.
- The neutral pions fall below the charged hadrons since they do not contain contributions from protons and kaons (will be discussed later).

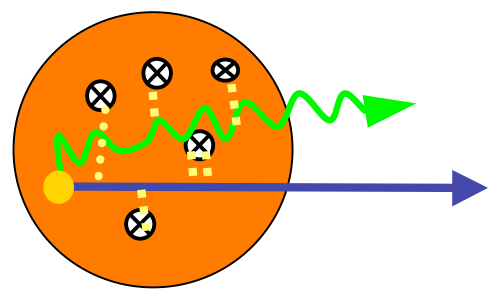
PHENIX AuAu 200 GeV
π^0 data: nucl-ex/0304022, submitted to PRL.
charged hadron (preliminary) : NPA715, 769c (2003).

(4) Initial state effect
or
Final state effect?

- d+Au Experiment -

Suppression: Final State Effect?

- **Hadronic absorption of fragments:**
  - Gallmeister, et al. PRC67,044905(2003)
  - Fragments formed inside hadronic medium
- **Parton recombination (up to moderate p_T)**
  - Fries, Muller, Nonaka, Bass nucl-th/0301078
  - Lin & Ko, PRL89,202302(2002)
- **Energy loss of partons in dense matter**
  - Gyulassy, Wang, Vitev, Baier, Wiedemann…



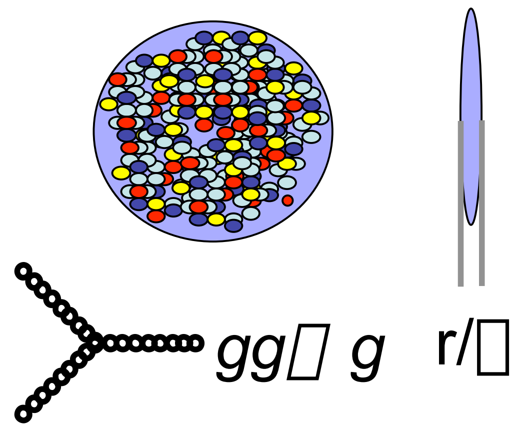
Alternative: Initial Effects

- **Gluon Saturation**
  - **(color glass condensate: CGC)**

  Wave function of low x gluons overlap; the self-coupling gluons fuse, saturating the density of gluons in the initial state.

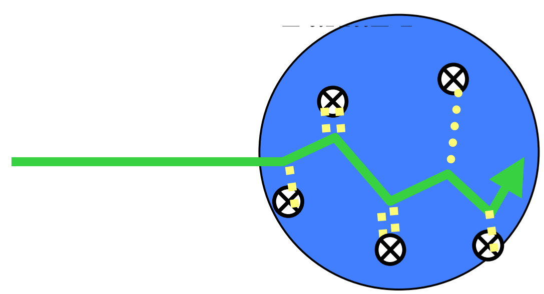
  (gets N_{ch} right!)

  hep-ph/0212316; D. Kharzeev, E. Levin, M. Nardi



D.Kharzeev et al., PLB 561 (2003) 93

Broaden p_T



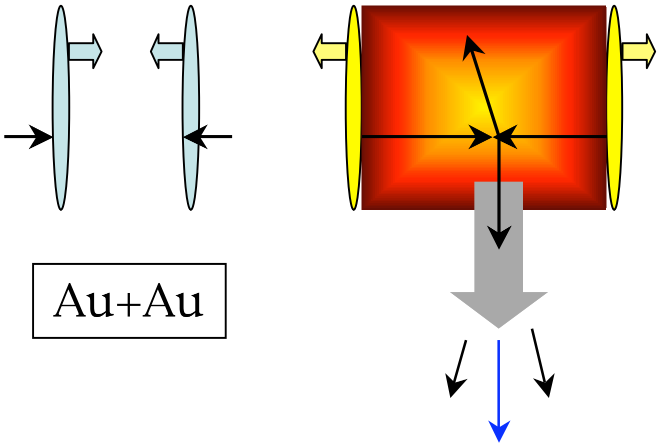
- **Multiple elastic scatterings (Cronin effect)**

  Wang, Kopeliovich, Levai, Accardi

- **Nuclear shadowing**

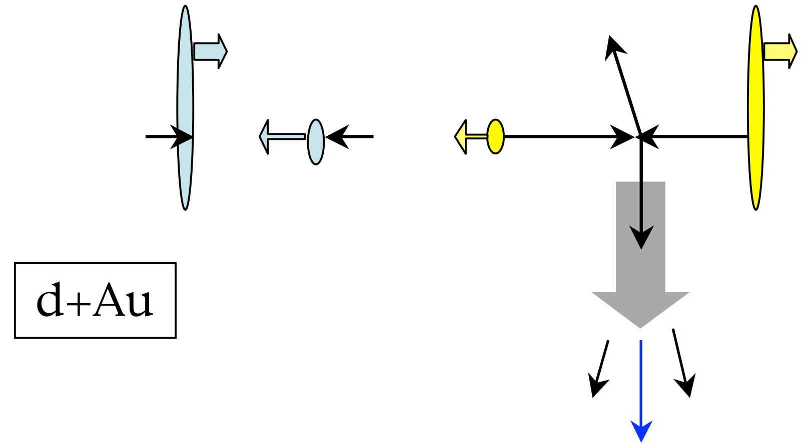
PHENIX

d+Au: Control Experiment



= hot and dense medium

Initial + Final State Effects

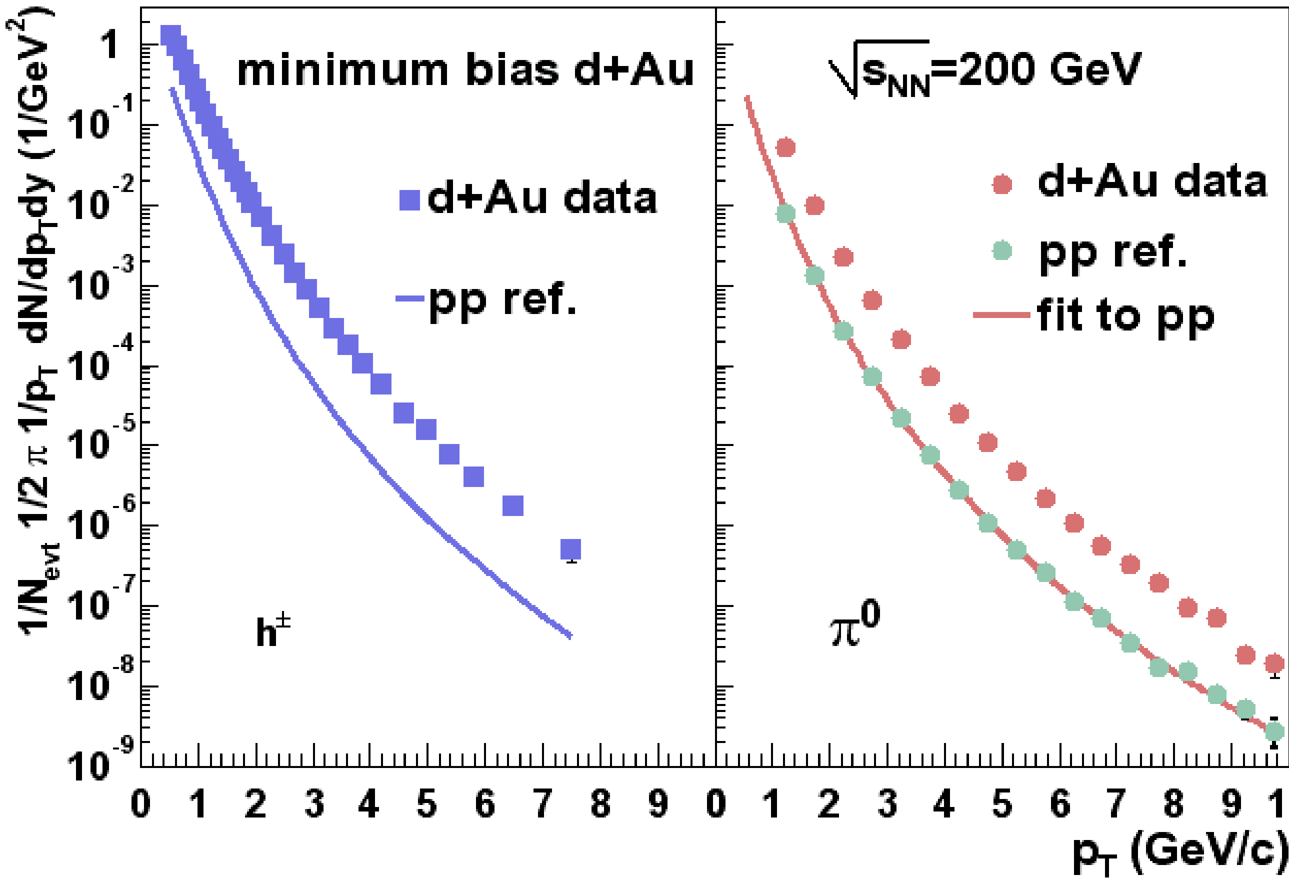


= cold medium

Initial State Effects Only

- The “Color Glass Condensate” model predicts the suppression in **both Au+Au and d+Au** (due to the initial state effect).
- **d+Au experiment can tell us whether the observed hadron suppression at high p_T central Au+A is the final state effect or initial state effect.**

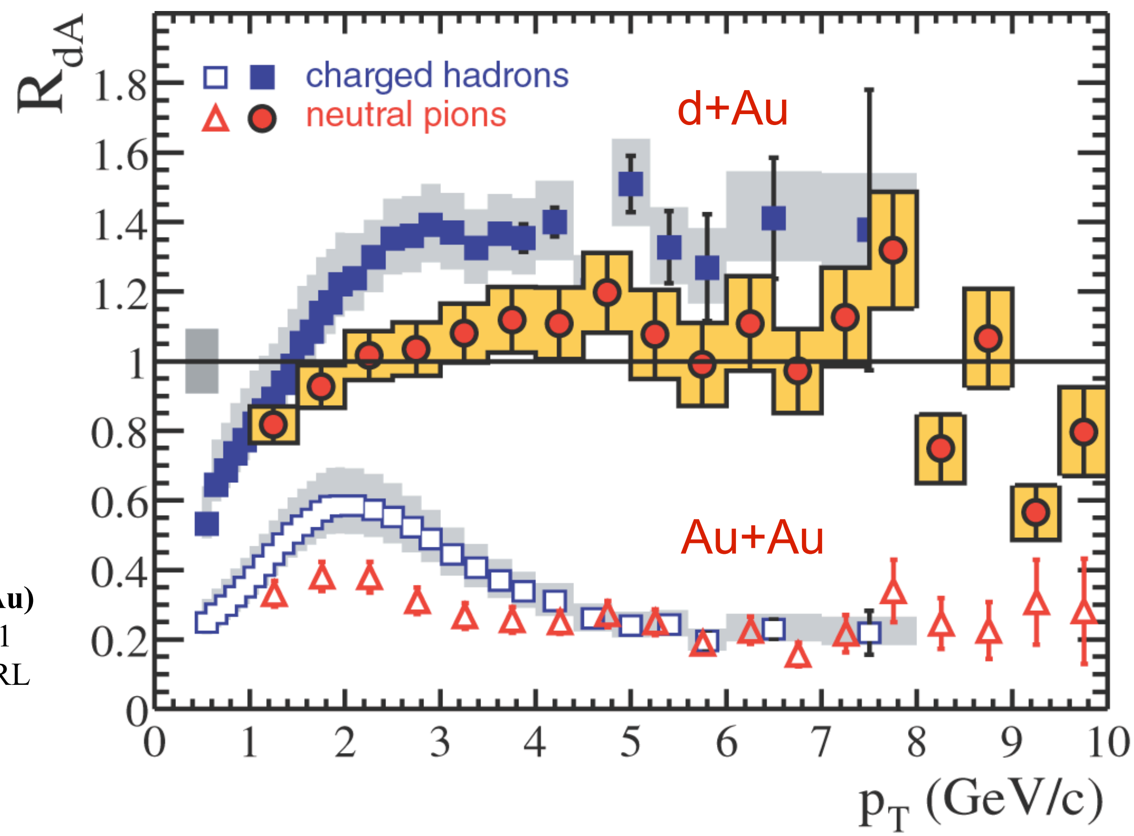
d+Au Spectra



PHENIX (d+Au)
hep-ex/0306021
submitted to PRL

- Final spectra for charged hadrons and identified pions.
- Data span 7 orders of magnitude.

R_{AA} vs. R_{dA} for charged hadrons and π^0



Initial State Effects Only

Initial + Final State Effects

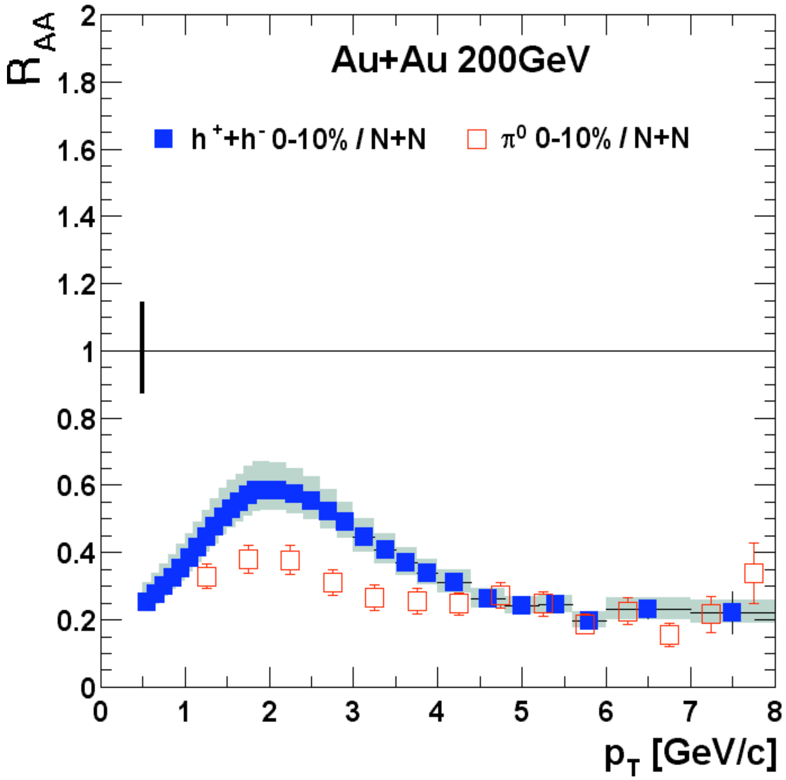
PHENIX (d+Au)
hep-ex/0306021
submitted to PRL

No Suppression in d+Au, instead small enhancement observed (Cronin effect)!!

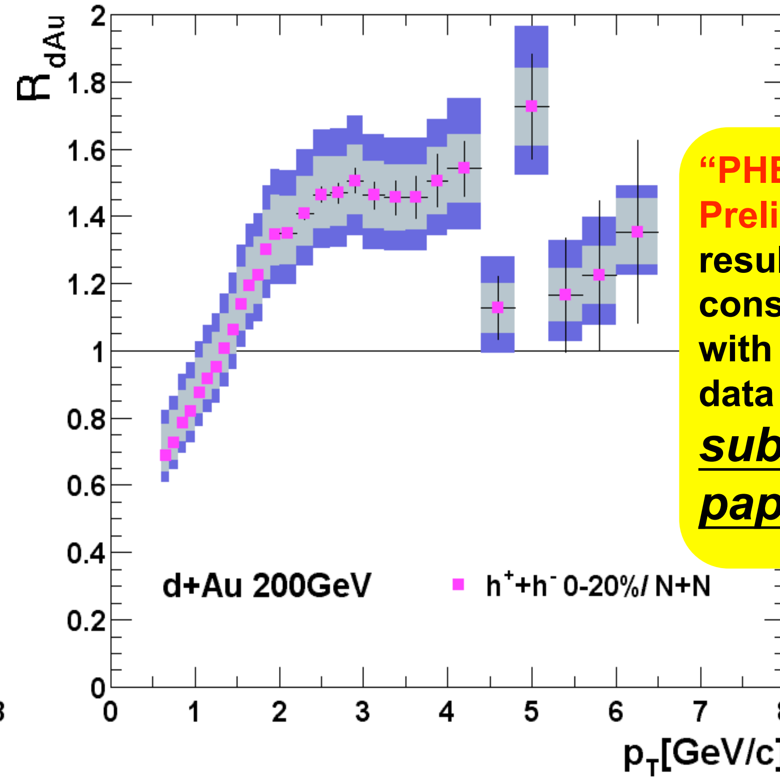
d-Au results rule out CGC as the explanation for high p_T Suppression of hadrons in AuAu central.

Centrality Dependence

Au + Au Experiment



d + Au Control Experiment



"PHENIX Preliminary" results, consistent with PHOBOS data in ***submitted paper***

- Dramatically different and opposite centrality evolution of Au+Au experiment from d+Au control.
- High p_T hadron suppression in AuAu is clearly a final state effect.

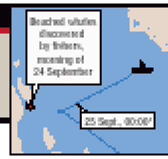
(5) Particle Compositions at High p_T

Article from SCIENCE

C.Seife, Science298, 718(2002)

THIS WEEK

NEWS



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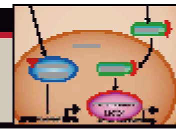
Whale of a problem



723
Hormones and bones

HIGH-ENERGY PHYSICS

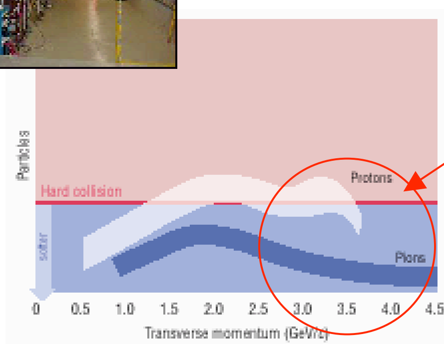
Wayward Particles Collide With Physicists' Expectations

EAST LANSING, MICHIGAN—Physicists' quest for a new state of matter has taken a bewildering turn. At a meeting here last week,* researchers from the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory in Upton, New York, announced results that, so far, nobody can explain. By slamming gold atoms together at nearly the speed of light, the physicists hoped to make gold nuclei melt into a novel phase of matter called a quark-gluon plasma. But although the experiment produced encouraging evidence that they had succeeded, it also left them struggling to account for the behavior of the particles that shoot away from the tremendously energetic smashups.

"The more I think about it, the more I think it's not completely wacko," William Zajc of Columbia University, spokesperson for one of the four particle detectors at RHIC, said privately at the conference. Zajc ruminated for a few moments and then corrected himself. "Well, it *is* completely wacko," he said. "We don't get it. I really don't know—on a fundamental level."

The confusion comes from PHENIX, one of the four detectors, which probed the differences between "hard" and "soft" nuclear collisions. Nuclei are collections of protons and neutrons, and at low energies, they behave

dicts that the particles in the smashup would no longer bounce cleanly off one another; the melted mess would be sloppier, the particles splashing off one another like droplets of water instead of rebounding like chunks of ice. By analyzing the sprays of particles created by colliding various atoms, the RHIC physicists hoped to determine whether collisions become softer as the nuclei get bigger and carry more energy—a sign of a quark-gluon plasma, a state of matter that



Hard riddle. At the Relativistic Heavy Ion Collider (*top*), protons and pions born from the same explosions inexplicably show earmarks of different origins.

rather than merely ricocheting off the components of the nucleus.

This tidy picture has just become considerably messier. With the higher energies and better statistics of RHIC's second year of running, physicists could classify the particles zooming away from the collisions. What they saw was a shock.

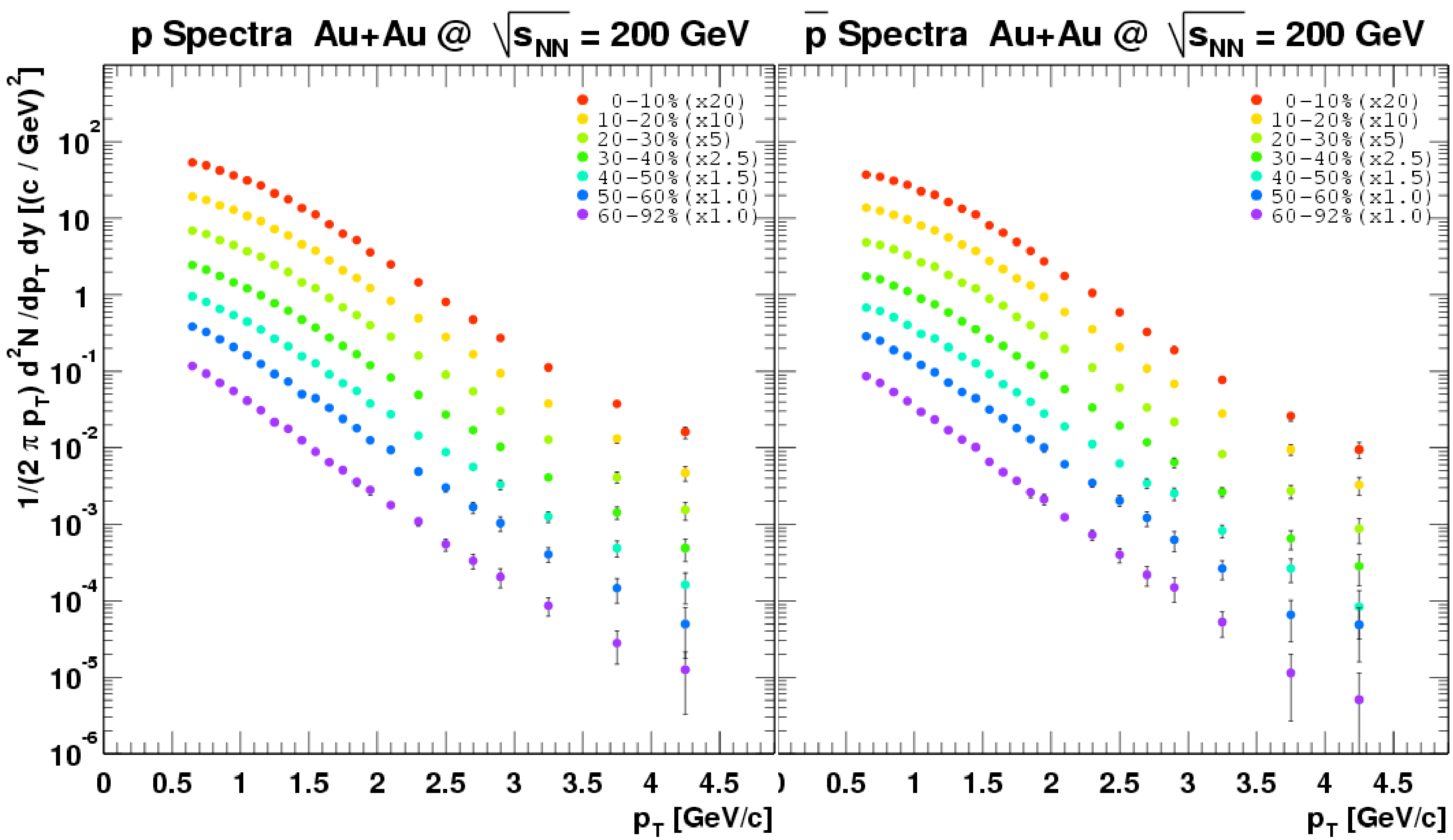
Measurements at PHENIX indicate that some of the particles flying away from the smashup are moving more slowly than normal, as one would expect in a soft collision, but others are caroming out of the wreck as if from a hard collision (see figure). Scientists know of no plausible mechanism for this discrepancy. "It's a true puzzle," says Zajc.

Part of the problem is that most of the particles PHENIX detects are born after the collision—spawned from more or less identical quarks and gluons (collectively dubbed "partons") that scatter off one another at the moment the two atoms crash together. The flying partons only then recombine into two-quark or three-quark ensembles ("hadrons," such as protons and neutrons). Because identical partons are doing the scattering, the hadrons they produce should all look as if they were born in the same sort of collision, soft or hard.

But that isn't what PHENIX sees, says Julia Velkovska, a Brookhaven physicist who is also associated with the PHENIX experiment. Pions, two-quark ensembles made of up and down quarks and antiquarks (and a handful of gluons) bound in an uneasy package, "behave more or less exactly like predicted" for a particle traveling through a sticky medium like a quark-gluon plasma, she says, whereas pro-

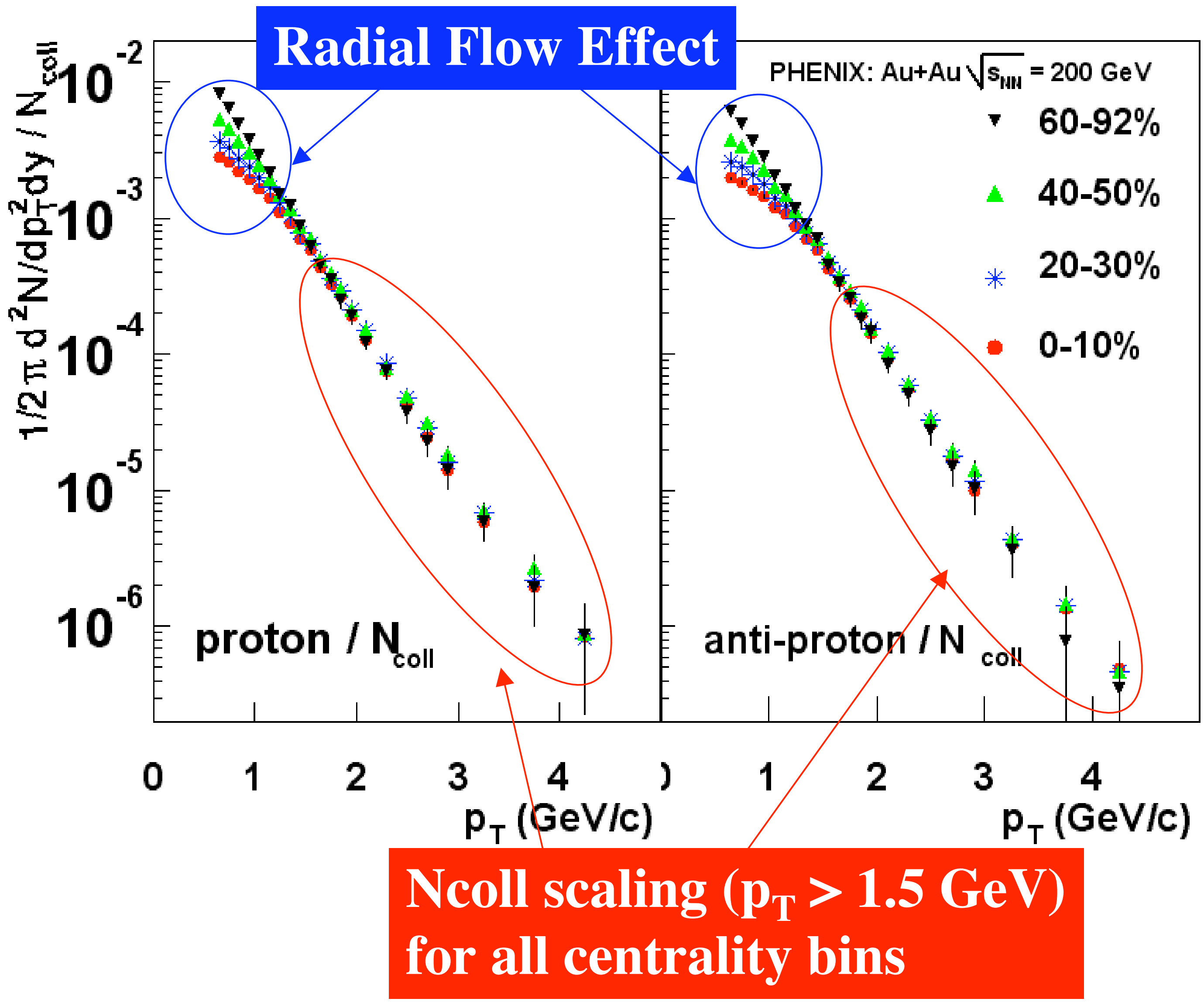
!

Proton and anti-proton spectra in AuAu at 200 GeV



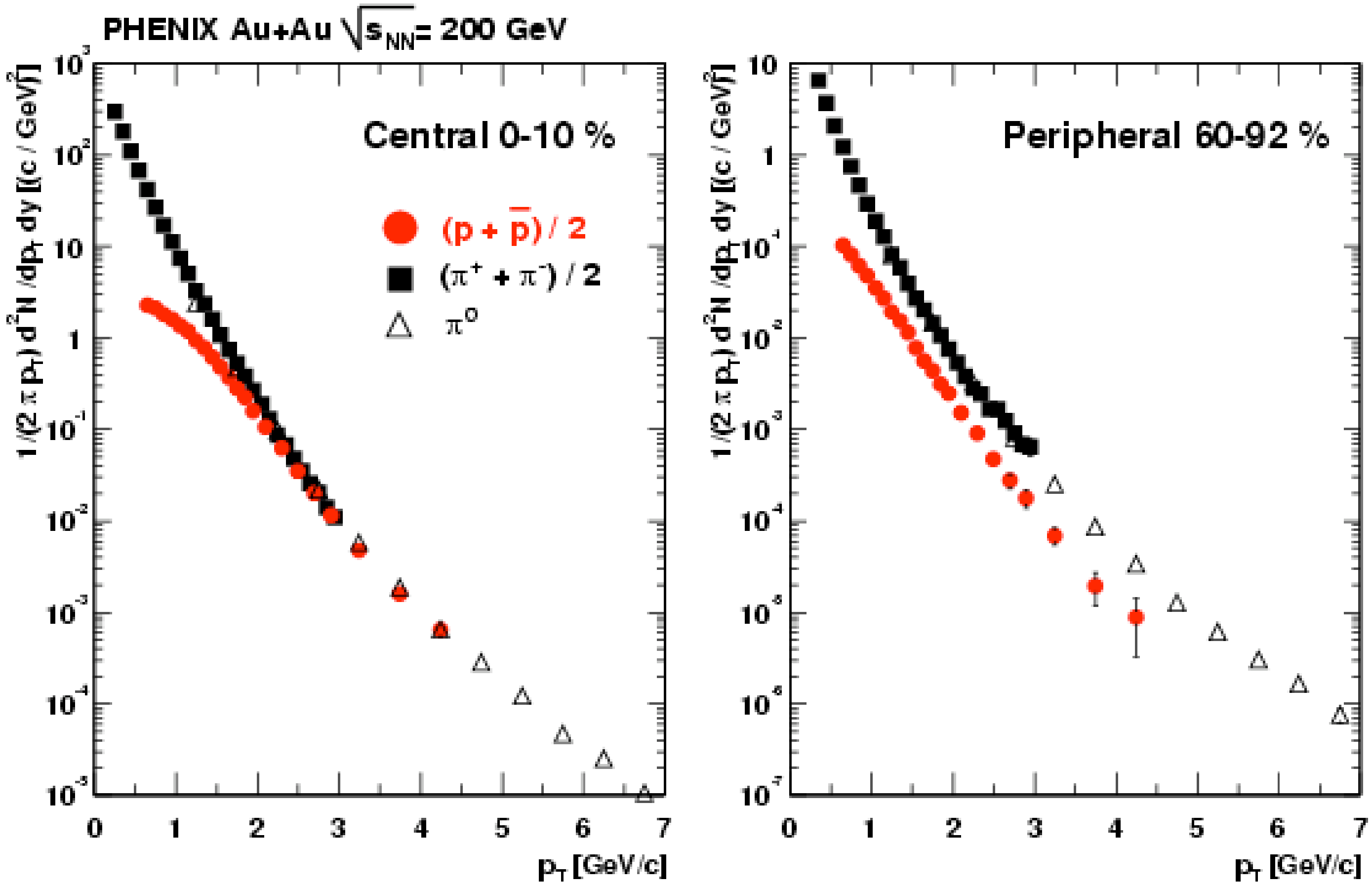
- Corrected for weak decay feed-down effect (~40% at 0.6 GeV/c, ~25% at 4 GeV/c).
- **Strong centrality dependence in spectra shape at low p_T (< 1.5 GeV/c).**

N_{coll} scaled p_T spectra for p and pbar



PHENIX (Au+Au)
hep-ex/0305036
submitted to PRL

p_T spectra (p vs. π) in Au+Au @ 200 GeV



- Clearly seen p-π merging at p_T ~ 2 GeV/c in central.
- No p-π merging in peripheral.
- Suggested significant fraction of p, pbar at pt = 1.5 - 4.5 GeV/c in central.

Central-to-Peripheral Ratio (R_{CP}) vs. p_T

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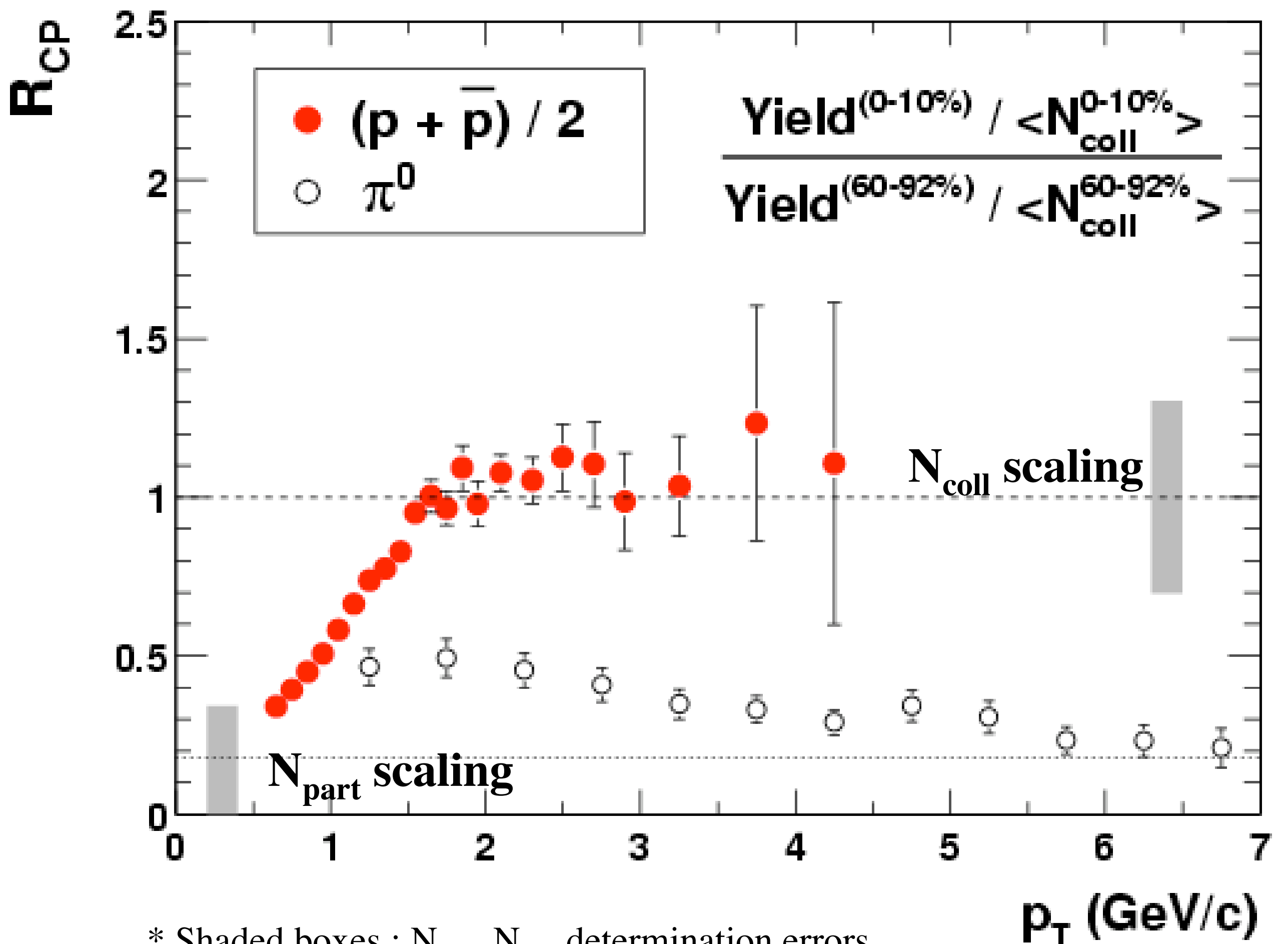


$= R_{CP} \approx R_{AA}$

p : N_{coll} scaling at 1.5 GeV - 4.5 GeV

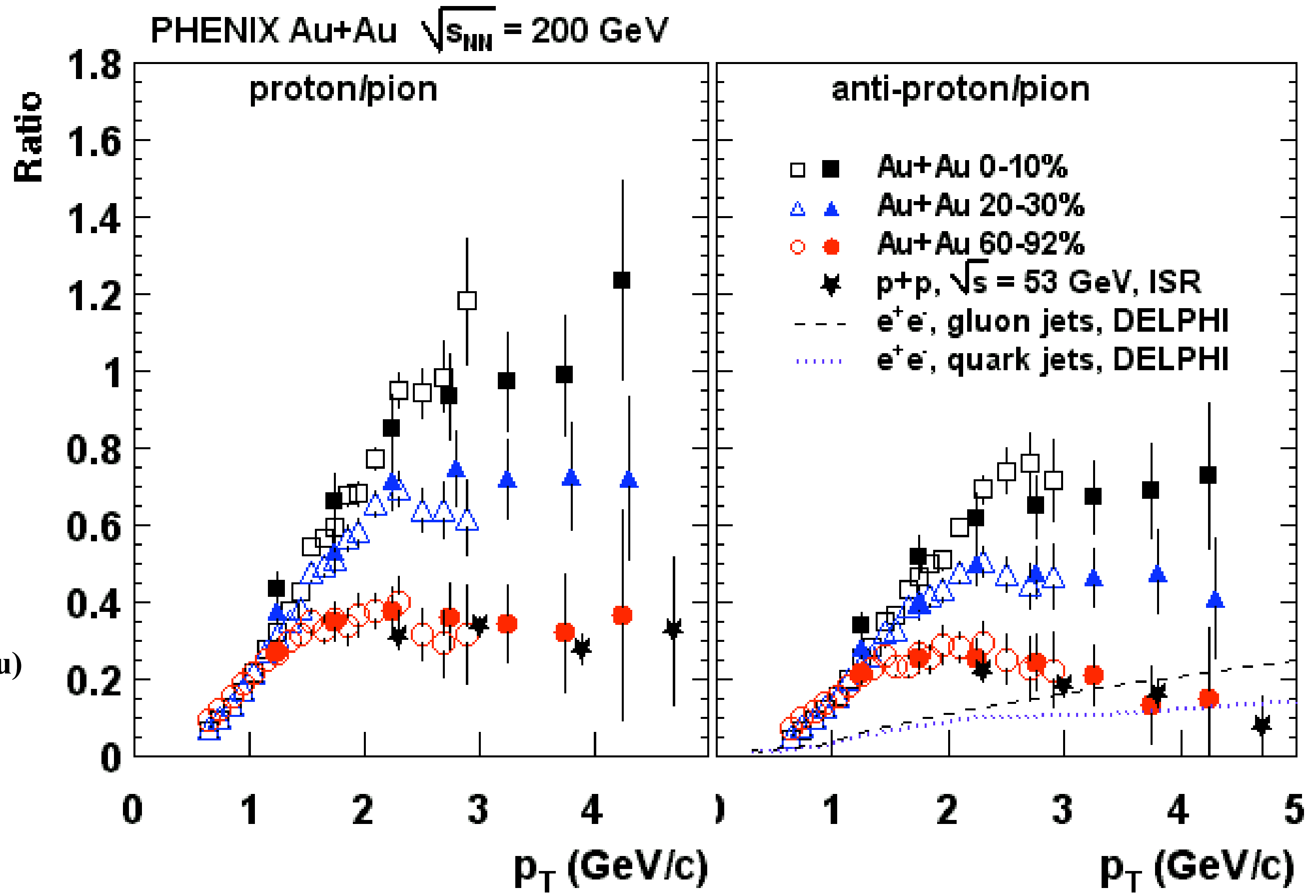
(Not suppressed for all centralities)

π^0: Suppression

(central > peripheral)

* Shaded boxes : N_{part}, N_{coll} determination errors.

p/π ratio vs. p_T and centrality



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- **Both p/π and pbar/π ratios are enhanced compared to peripheral Au+Au, p+p and e^+e^- at p_T = 1.5 ~ 4.5 GeV/c.**
- **Consistent with gluon/quark jet fragmentation in peripheral AuAu (> 3 GeV/c).**

Particle composition beyond 5 GeV …

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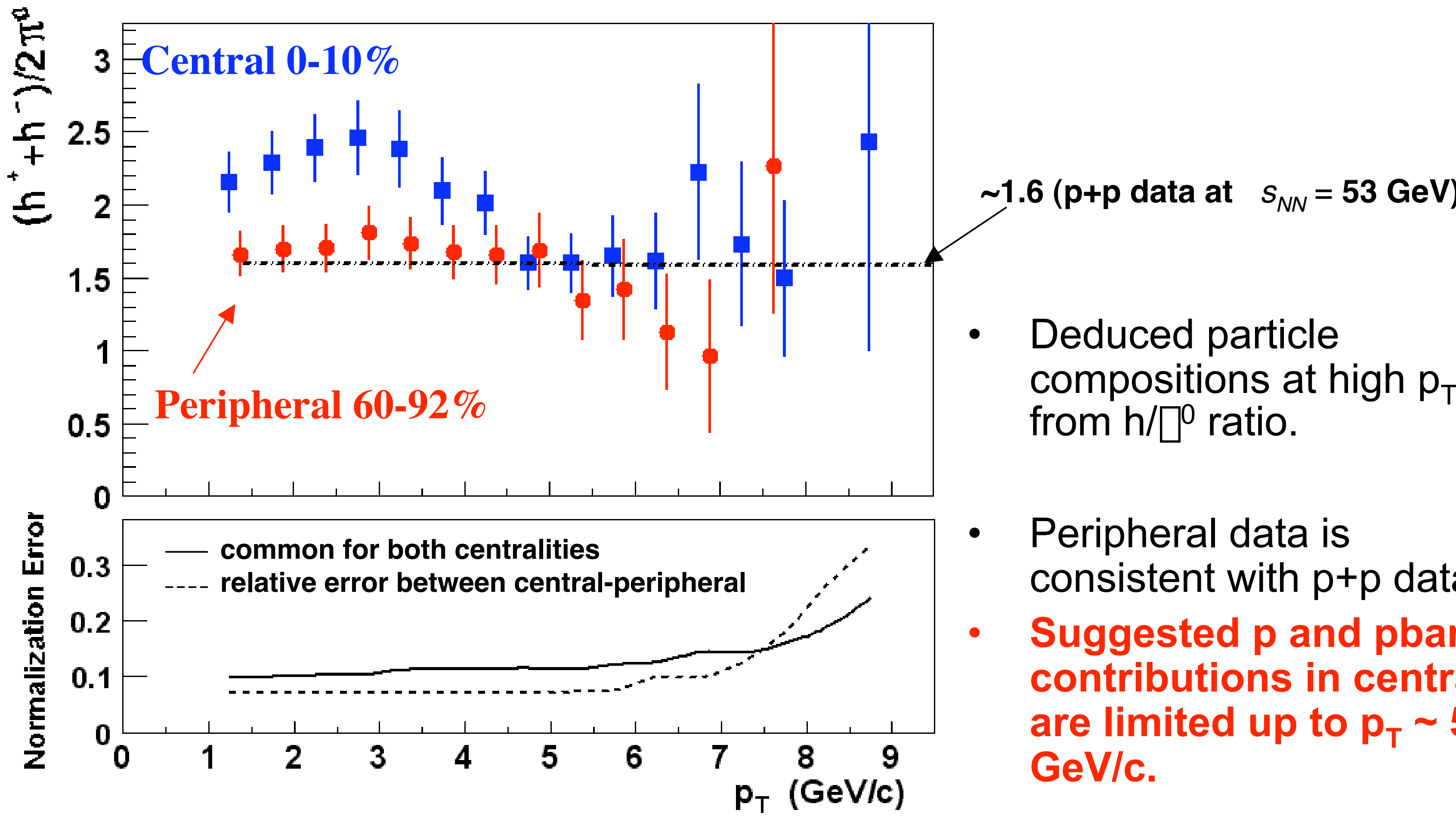
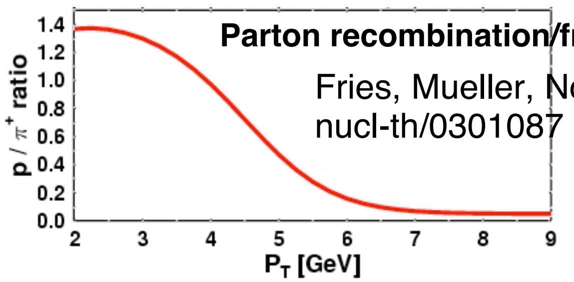
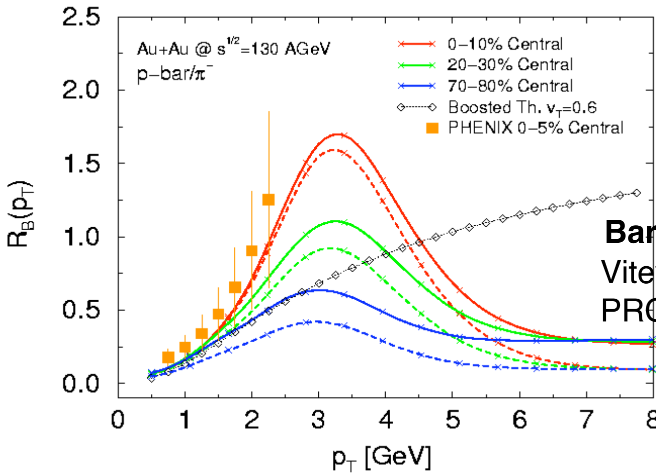


- Deduced particle compositions at high p_T from h/π^0 ratio.
- Peripheral data is consistent with p+p data.
- **Suggested p and pbar contributions in central are limited up to p_T ~ 5 GeV/c.**

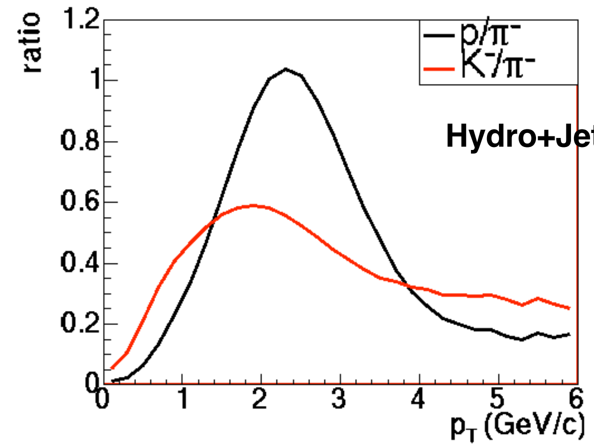
What is the PHYSICS behind?





Baryon Junction
Vitev, Gyulassy
PRC 65, 041902, 2002

Hirano, Nara
(Transverse Dynamics
workshop@ BNL)



- Both **Parton Recombination/Coalescence** and **Baryon Junction** models reproduce p/π ratio (p_T and centrality dep.) qualitatively.
- Both models predict p/π enhancement is limited < 5 GeV/c.
- Another scenarios: Different formation time between baryons and mesons ?
  or Strong radial flow + hard scattering ?

Summary

1. Energy density in central AuAu is well above the critical density of deconfined state predicted by the lattice QCD.
2. **In low p_T region (< 2 GeV/c),** the single particle spectra in AuAu central are well described by hydrodynamic model, and particle abundance is well reproduced by the statistical thermal model.
3. **At high p_T,** both neutral and inclusive charged hadrons are largely suppressed in AuAu central collisions.
4. However, **these suppressions are not observed in d+Au,** instead there is an enhancement (Cronin effect), which suggests the **suppression in AuAu is the final state effect.**
5. **At the intermediate p_T (2 - 4 GeV/c),** the proton and anti-proton spectra show the different scaling behavior from pions (Ncoll scaling), and a strong centrality dependence of p/□ ratio has been observed.
   – Various theoretical models (recombination, baryon junction, flow+jet) reproduce the data qualitatively.

What's Next

- **We must investigate other probes that look deeply into the medium to characterize it.**
- **The Rare Processes Probe the Medium:**
  - **Heavy Quark States**
    - Dissolution of J/ψ & ψ', the bound states of charm-anticharm quarks probes quark deconfinement.
  - **Electromagnetic Probes (no strong interaction)**
    - Lack of strong interaction allows them to penetrate the black medium and see through the hadronic veil
    - Direct Photons, e^+e^-, $\mu^+\mu^-$
- **PHENIX plans to make these measurements in the next high luminosity Au+Au run.**

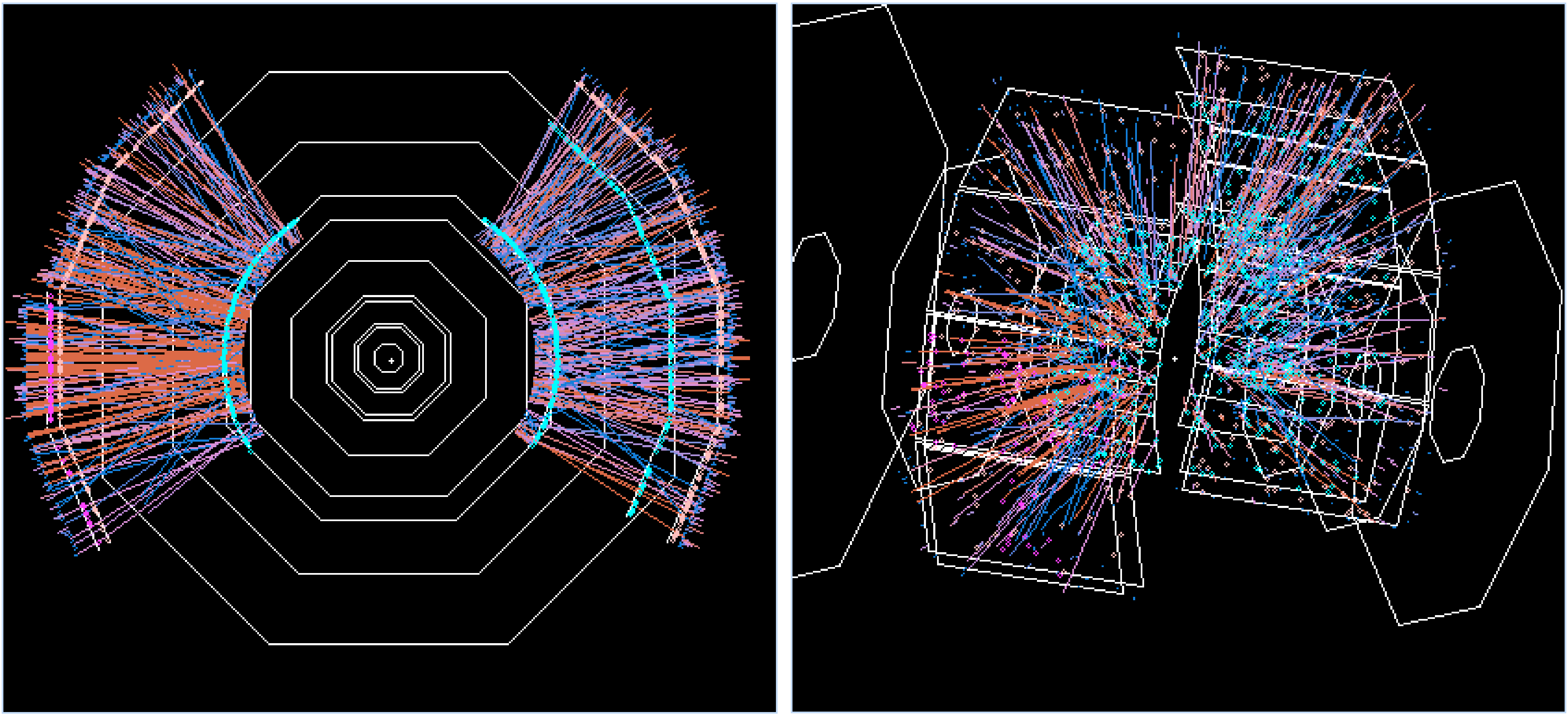
PHENIX

12 Countries; 57 Institutions; 460 Participants*

Brazil	University of São Paulo, São Paulo
China	Academia Sinica, Taipei, Taiwan
	China Institute of Atomic Energy, Beijing
	Peking University, Beijing
France	LPC, University de Clermont-Ferrand, Clermont-Ferrand
	Dapnia, CEA Saclay, Gif-sur-Yvette
	IPN-Orsay, Universite Paris Sud, CNRS-IN2P3, Orsay
	LLR, Ecòle Polytechnique, CNRS-IN2P3, Palaiseau
	SUBATECH, Ecòle des Mines at Nantes, Nantes
Germany	University of Münster, Münster
Hungary	Central Research Institute for Physics (KFKI), Budapest
	Debrecen University, Debrecen
	Eötvös Loránd University (ELTE), Budapest
India	Banaras Hindu University, Banaras
	Bhabha Atomic Research Centre, Bombay
Israel	Weizmann Institute, Rehovot
Japan	Center for Nuclear Study, University of Tokyo, Tokyo
	Hiroshima University, Higashi-Hiroshima
	KEK, Institute for High Energy Physics, Tsukuba
	Kyoto University, Kyoto
	Nagasaki Institute of Applied Science, Nagasaki
	RIKEN, Institute for Physical and Chemical Research, Wako
	RIKEN-BNL Research Center, Upton, NY
	University of Tokyo, Bunkyo-ku, Tokyo
	Tokyo Institute of Technology, Tokyo
	University of Tsukuba, Tsukuba
	Waseda University, Tokyo
S. Korea	Cyclotron Application Laboratory, KAERI, Seoul
	Kangnung National University, Kangnung
	Korea University, Seoul
	Myong Ji University, Yongin City
	System Electronics Laboratory, Seoul Nat. University, Seoul
	Yonsei University, Seoul
Russia	Institute of High Energy Physics, Protovino
	Joint Institute for Nuclear Research, Dubna
	Kurchatov Institute, Moscow
	PNPI, St. Petersburg Nuclear Physics Institute, St. Petersburg
	St. Petersburg State Technical University, St. Petersburg
Sweden	Lund University, Lund
USA	Abilene Christian University, Abilene, TX
	Brookhaven National Laboratory, Upton, NY
	University of California - Riverside, Riverside, CA
	University of Colorado, Boulder, CO
	Columbia University, Nevis Laboratories, Irvington, NY
	Florida State University, Tallahassee, FL
	Georgia State University, Atlanta, GA
	University of Illinois Urbana Champaign, Urbana-Champaign, IL
	Iowa State University and Ames Laboratory, Ames, IA
	Los Alamos National Laboratory, Los Alamos, NM
	Lawrence Livermore National Laboratory, Livermore, CA
	University of New Mexico, Albuquerque, NM
	New Mexico State University, Las Cruces, NM
	Dept. of Chemistry, Stony Brook Univ., Stony Brook, NY
	Dept. Phys. and Astronomy, Stony Brook Univ., Stony Brook, NY
	Oak Ridge National Laboratory, Oak Ridge, TN
	University of Tennessee, Knoxville, TN
	Vanderbilt University, Nashville, TN

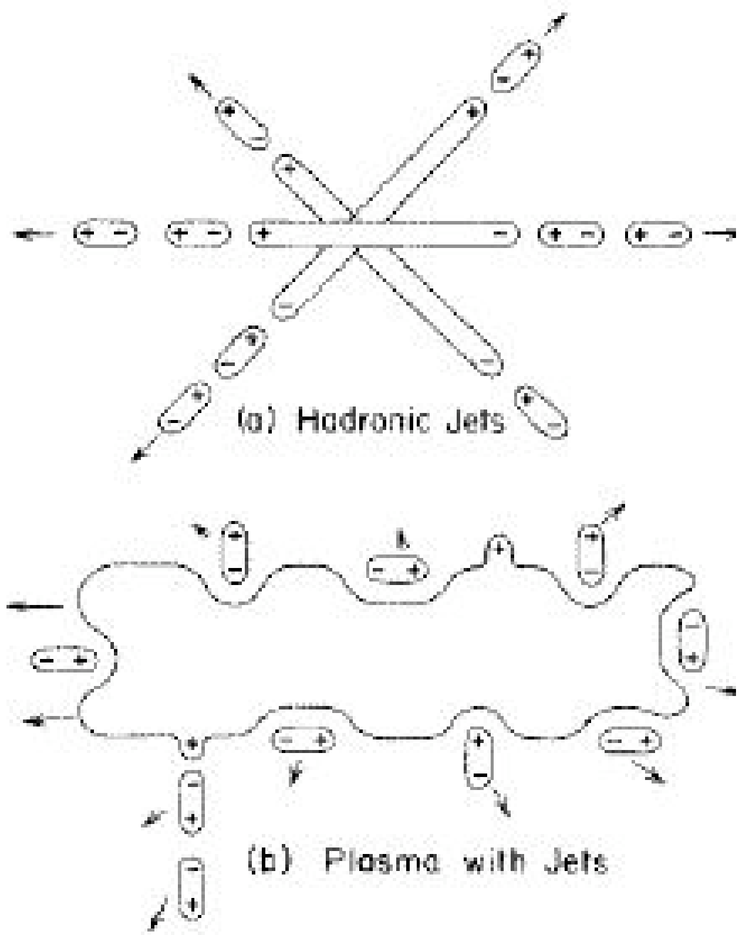
*as of July 2002

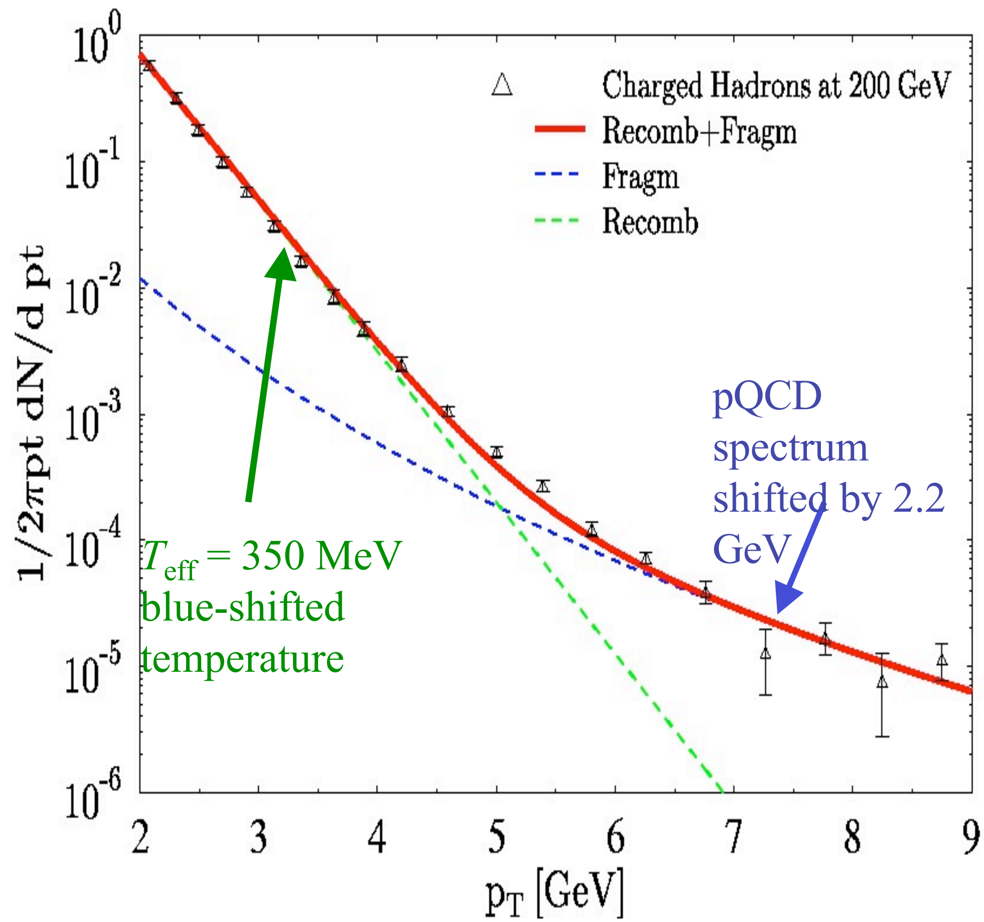
Au+Au 200 GeV

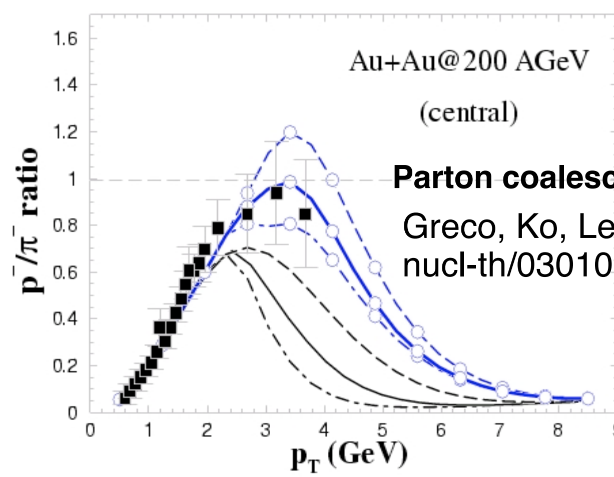


PHENIX Event Display

Parton Recombination







Parton coalescence

Greco, Ko, Levai
nucl-th/0301093