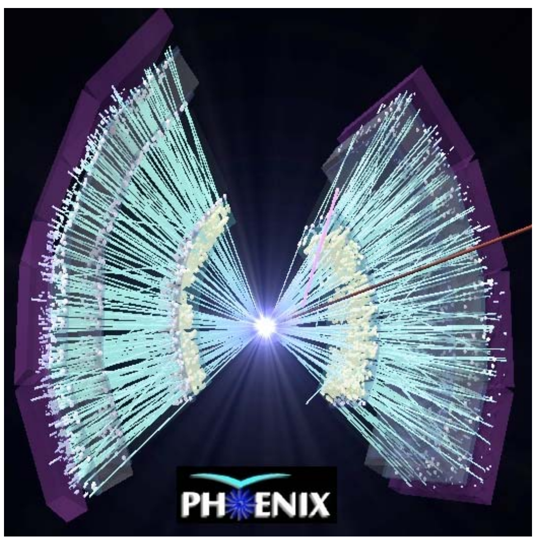
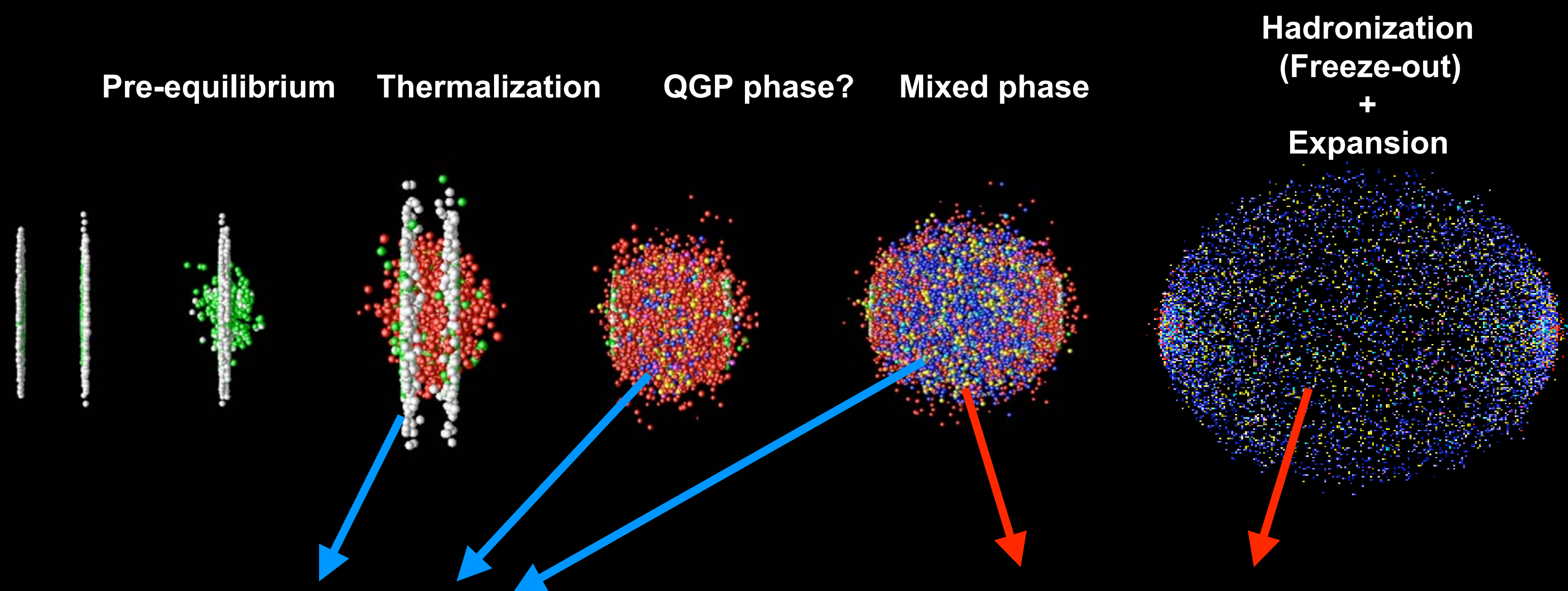
Particle Production at High p_T and Jet Quenching Effect at RHIC



Tatsuya Chujo (KEK)
for the PHENIX Collaboration

History of Heavy Ion Collisions



$\gamma, \gamma^* \rightarrow e^+e^-, \mu^+\mu^-$

π, K, p, n, ϕ, Λ, Δ, Ξ, Ω, 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).

Probes of hot and dense medium in Au+Au

PHENIX

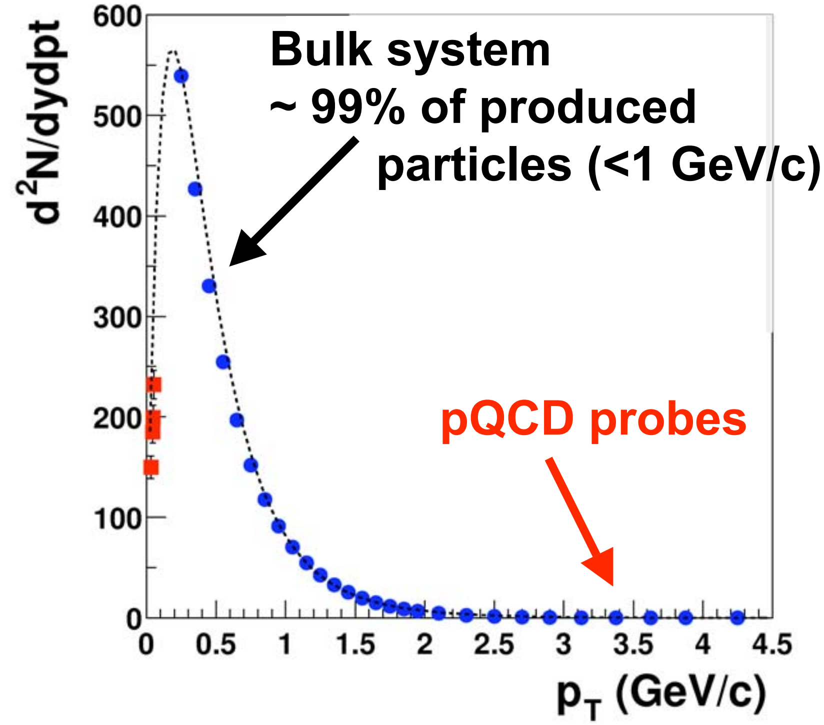
Bulk Effects (previous talk, M. Kaneta)

- Equilibration
- Equation of State
- Space-time Evolution

Probes of the System

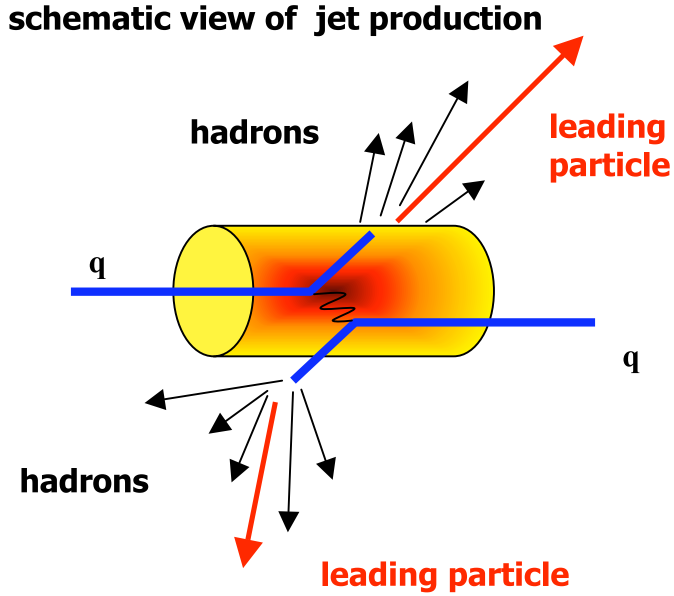
- **Hard scattered partons**
- **Heavy quarks**

(not included in this talk)



Hard Scattered Partons

- Needed **“calibrated”** probe.
- Hard scatterings in nucleon collisions produce jets of particles.
  - hadron structure function
  - hard scattering parton (pQCD)
  - fragmentation of partons
- In the presence of a color-deconfined medium, the partons lose their energy(~GeV/fm) via gluon bremsstrahlung.



  - **“Jet Quenching”**
    ∝ Color Charge Density
    “gluonometer”

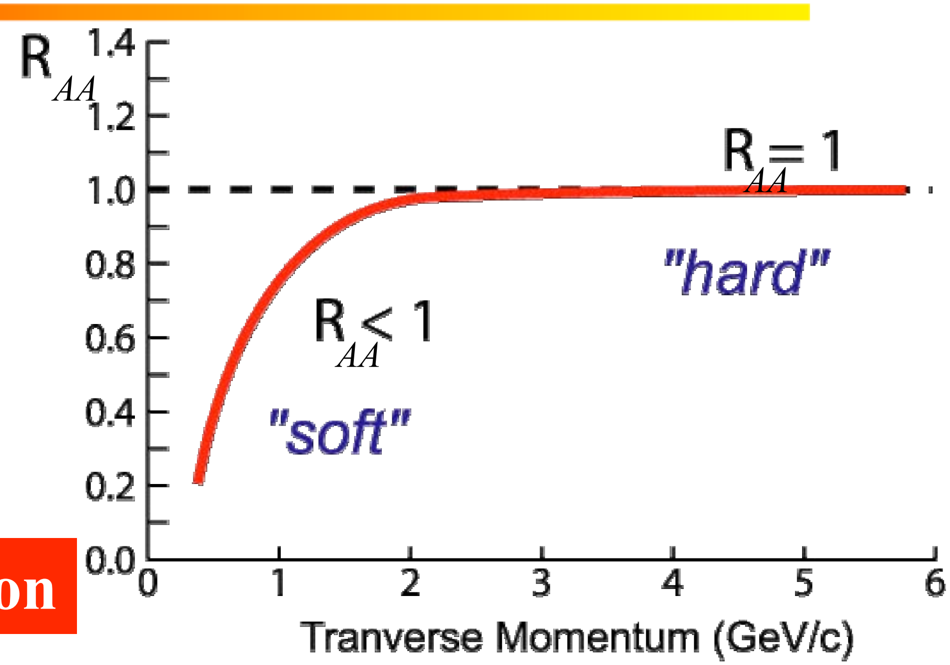
How Quantify the Nuclear Modification

Nuclear Modification Factor

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

$<N_{binary}>/\sigma_{inel}^{p+p}$

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.

Outline

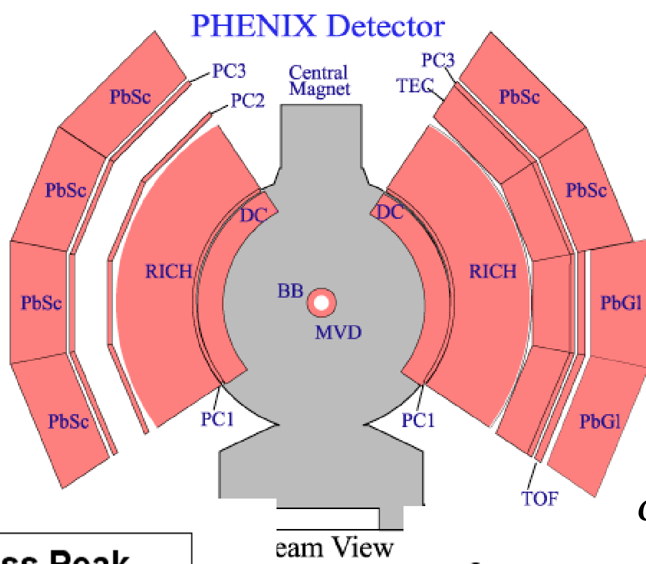
We present the most recent results of high p_T particle production measured by PHENIX experiment @ $\sqrt{s_{NN}}$ = 200 GeV in Au+Au, p+p, and d+Au collisions.

- *π^0 /inclusive charged particle production and their nuclear modification in Au+Au.*
- *Azimuthal two-particle distributions at high p_T (STAR results).*
- *Control experiment - d+Au results.*
- *Particle compositions at high p_T.*
- *Upgrade plan.*
- *Summary.*

PHENIX Hadron PID

π^0 PID by EMCal

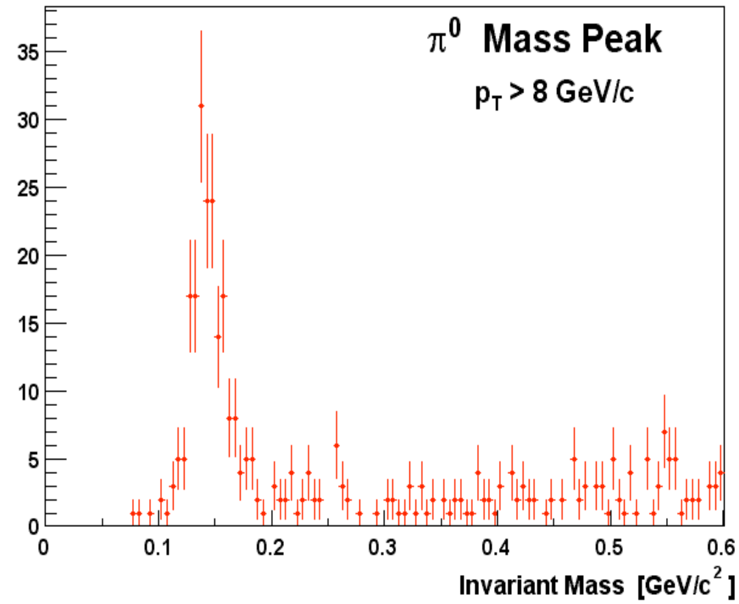
via $\pi^0 \rightarrow \gamma\gamma$ ($1 < p_T < 10$ GeV/c)
6 lead- Scintillator (PbSc) sectors
2 lead- glass (PbGl) sectors
$\Delta\phi = \pi$
$\Delta\eta = 0.7$

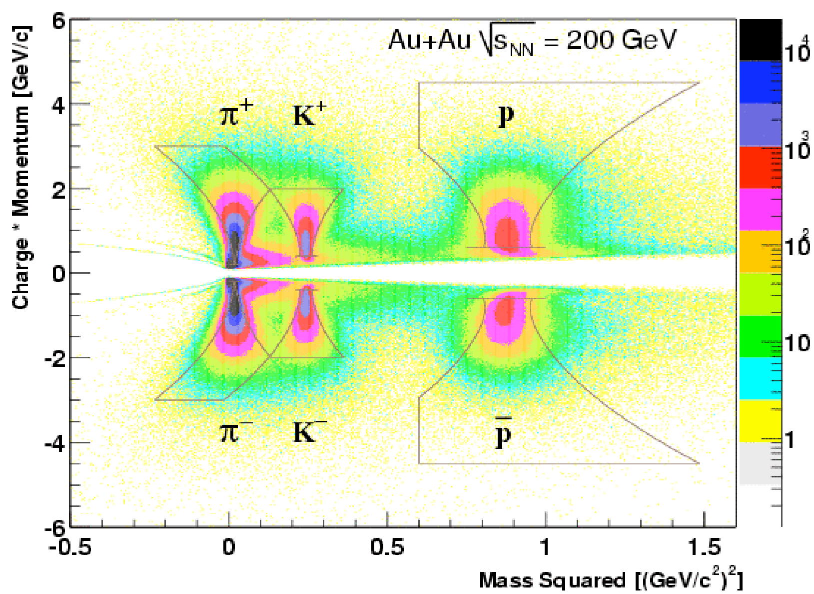


Charged PID by TOF

(DCH+PC1+TOF+BBC)
π/K < 2 GeV/c, K/p < 4 GeV/c
$\Delta\phi = \pi/8$

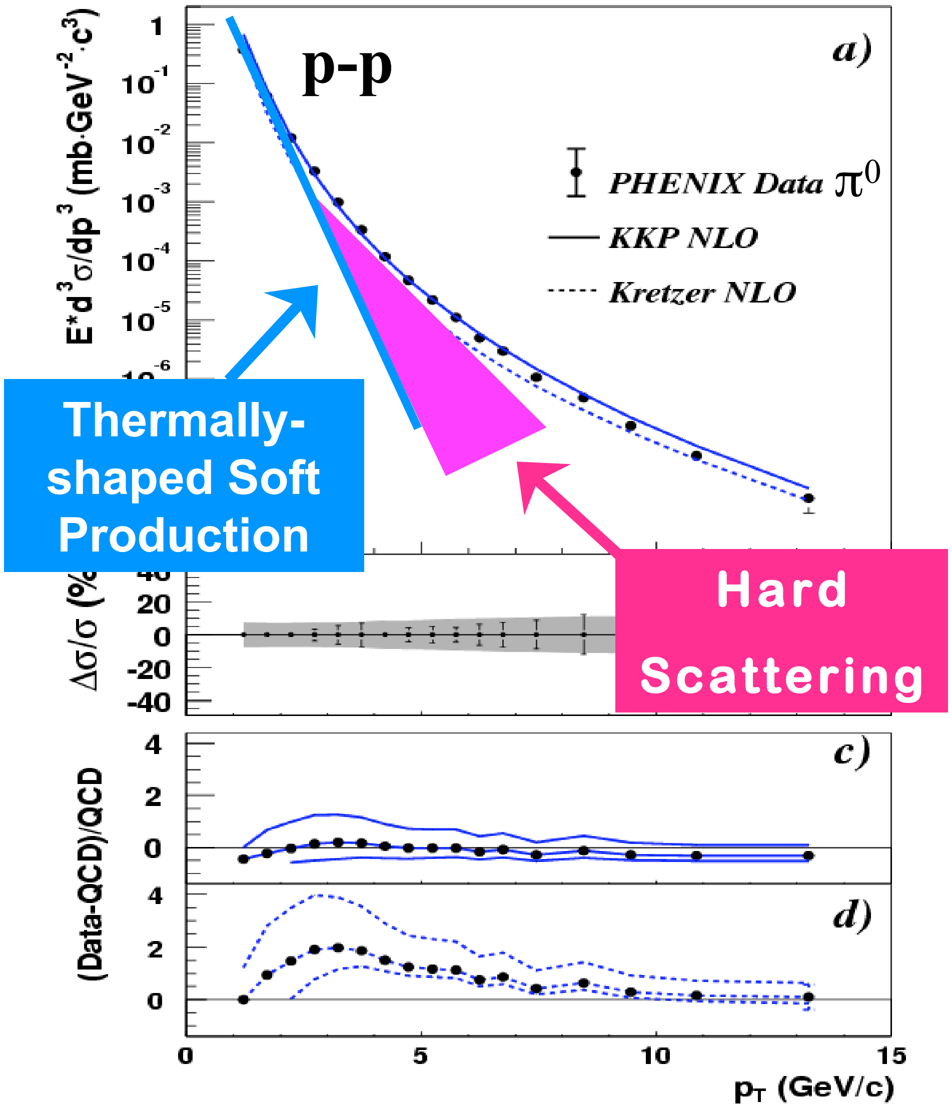
$$\delta p / p \approx 0.7\% \oplus 1.0\% \times p \text{ (GeV/}c\text{)}$$





High p_T Particle Production in Au+Au Collisions

π^0 spectra pp @ 200 GeV : Baseline

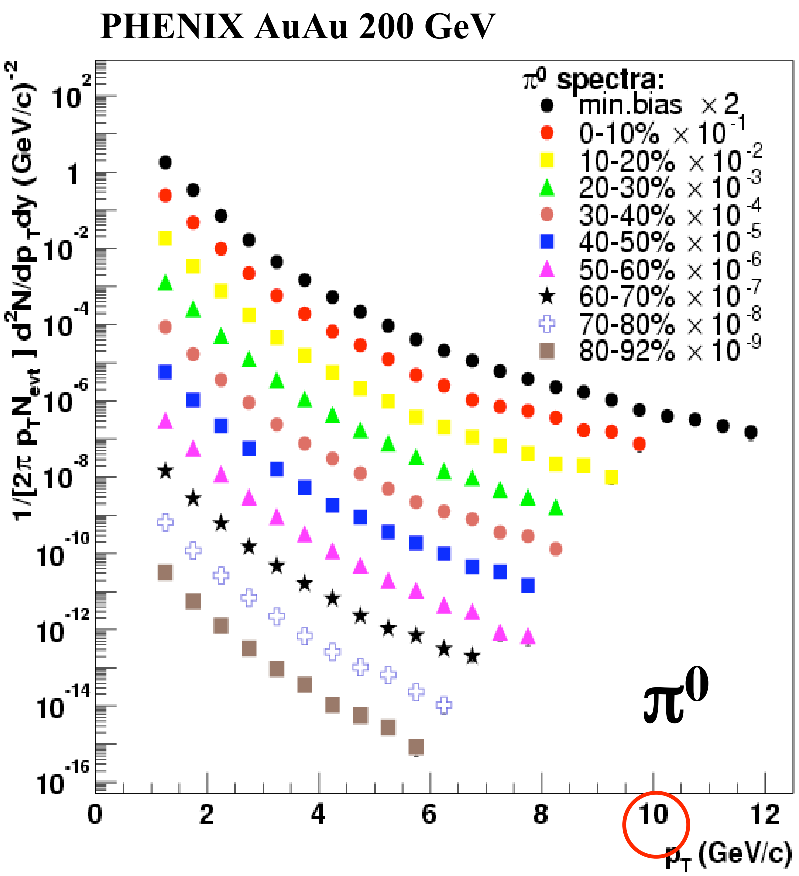


- π^0 measurement in same experiment allows us the study of nuclear effect with less systematic uncertainties.

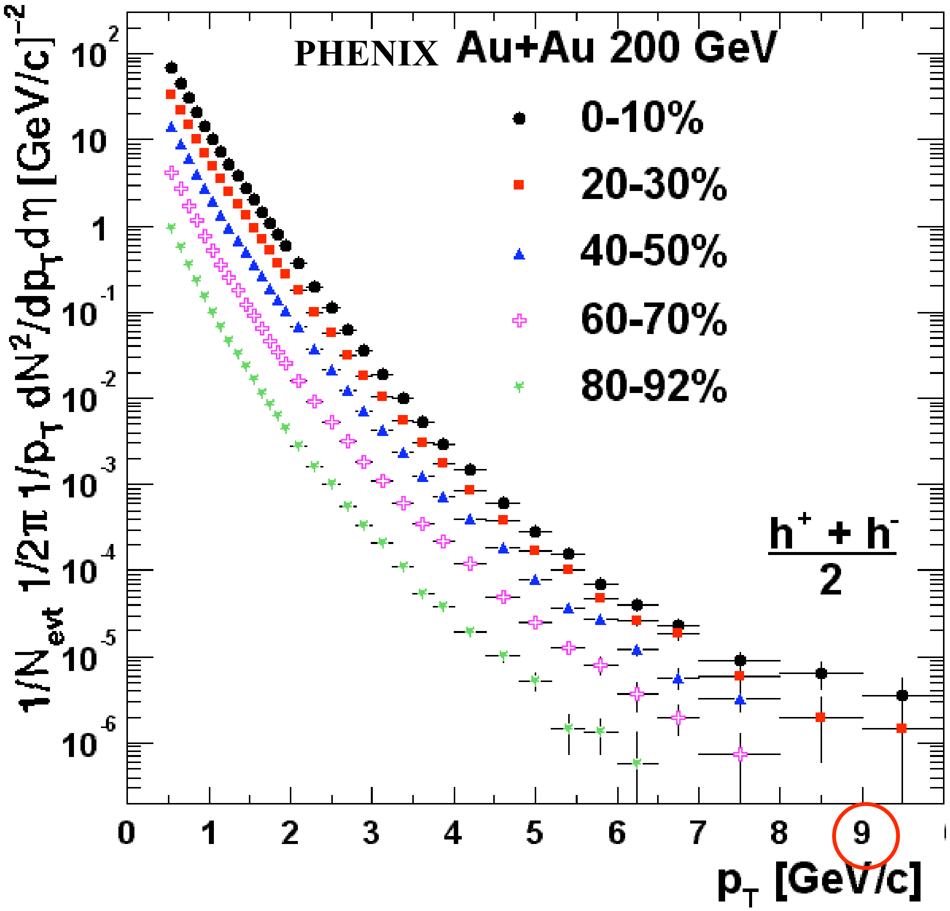
- Characteristic power law shape ($1/p_T^n$)
- Good agreement with NLO pQCD
- **Reference for Au+Au spectra**

PHENIX (p+p) hep-ex/0304038

π^0 and *h* spectra AuAu @ 200 GeV



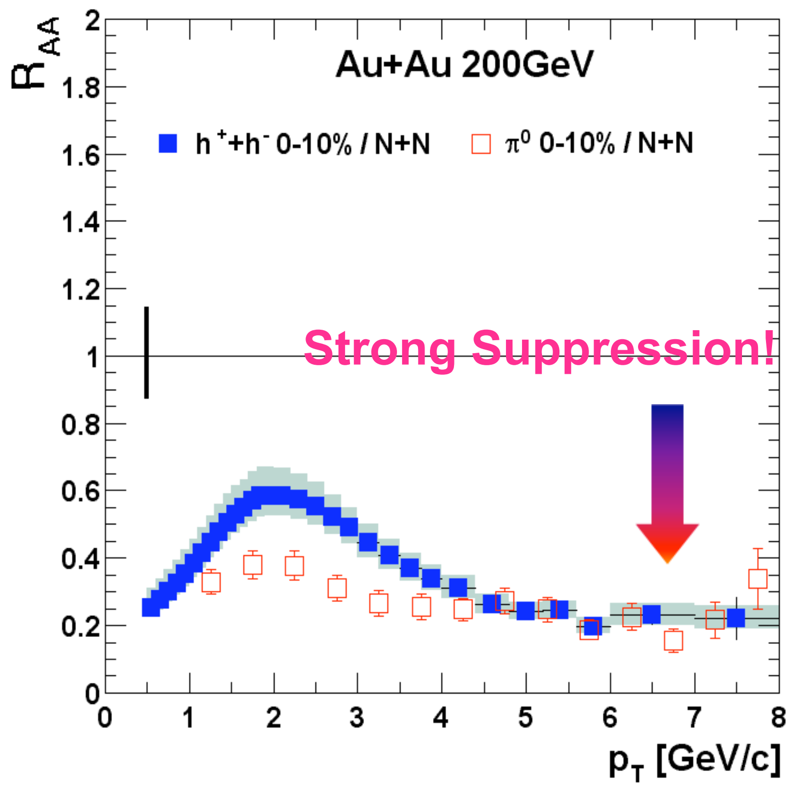
π^0 data:PRL 91, 072301 (2003) [nucl-ex/0304022]



Charged hadron : submitted to PRC, nucl-ex/0308006

R_{AA} for π^0 and charged hadron

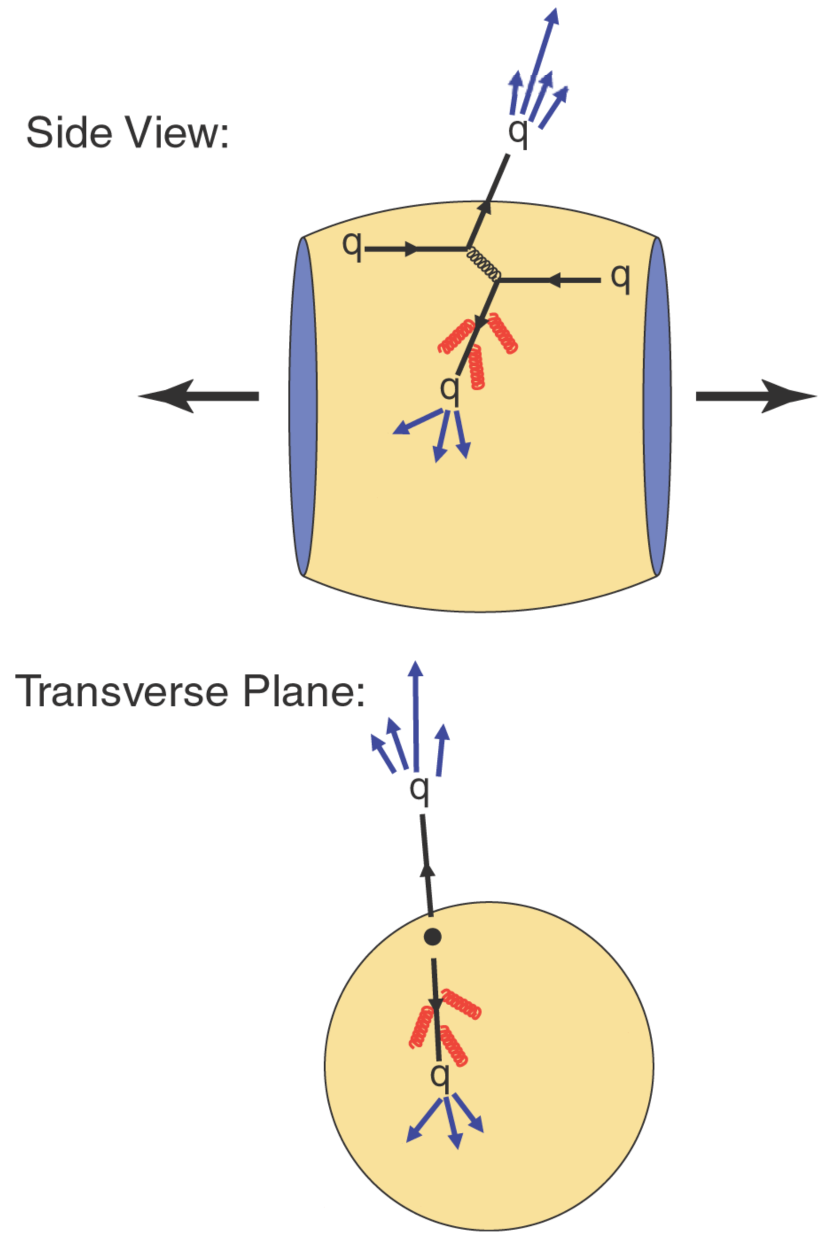
$$R_{AA} = \frac{Yield_{AuAu} / \langle N_{binary} \rangle_{AuAu}}{Yield_{pp}}$$



PHENIX AuAu 200 GeV
π^0 data: PRL 91 072301 (2003), nucl-ex/0304022.
charged hadron (preliminary) : NPA715, 769c (2003).

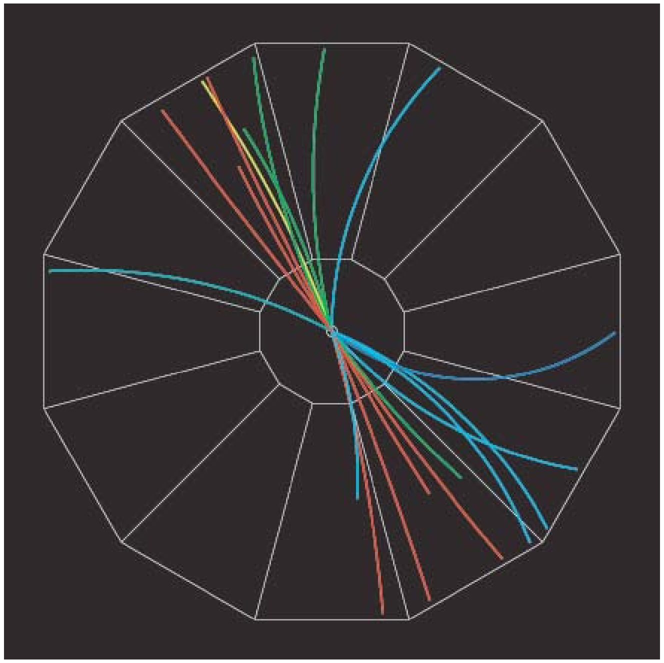
- **R_{AA} is well below 1 for both charged hadrons and neutral pions.**
- **Suppression is larger in central events.**
- **The neutral pions fall below the charged hadrons since they do not contain contributions from protons and kaons (discussed later).**

Azimuthal Two-Particle Correlation (Jet)

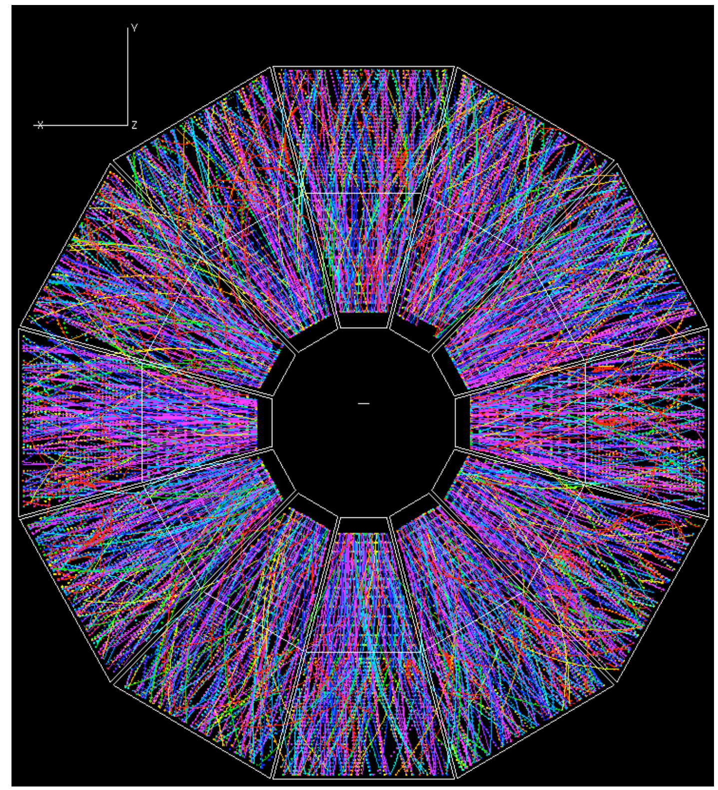


Jet Event in STAR

Find this……….in this



p+p →jet+jet
(STAR@RHIC)

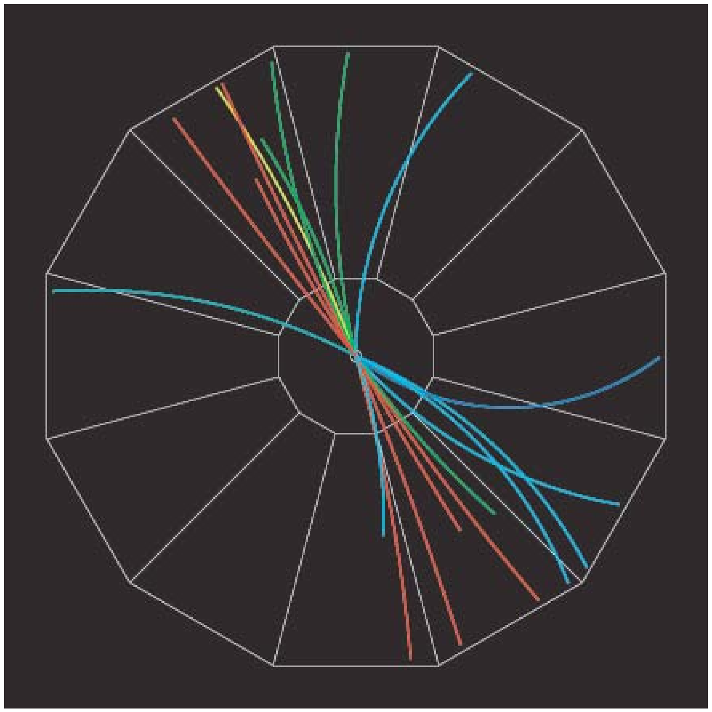


Au+Au →???
(STAR@RHIC)

- **Experimental challenge to find jet and study its property in central Au+Au.**
- **Use "statistical" method to quantify the Au+Au event instead.**

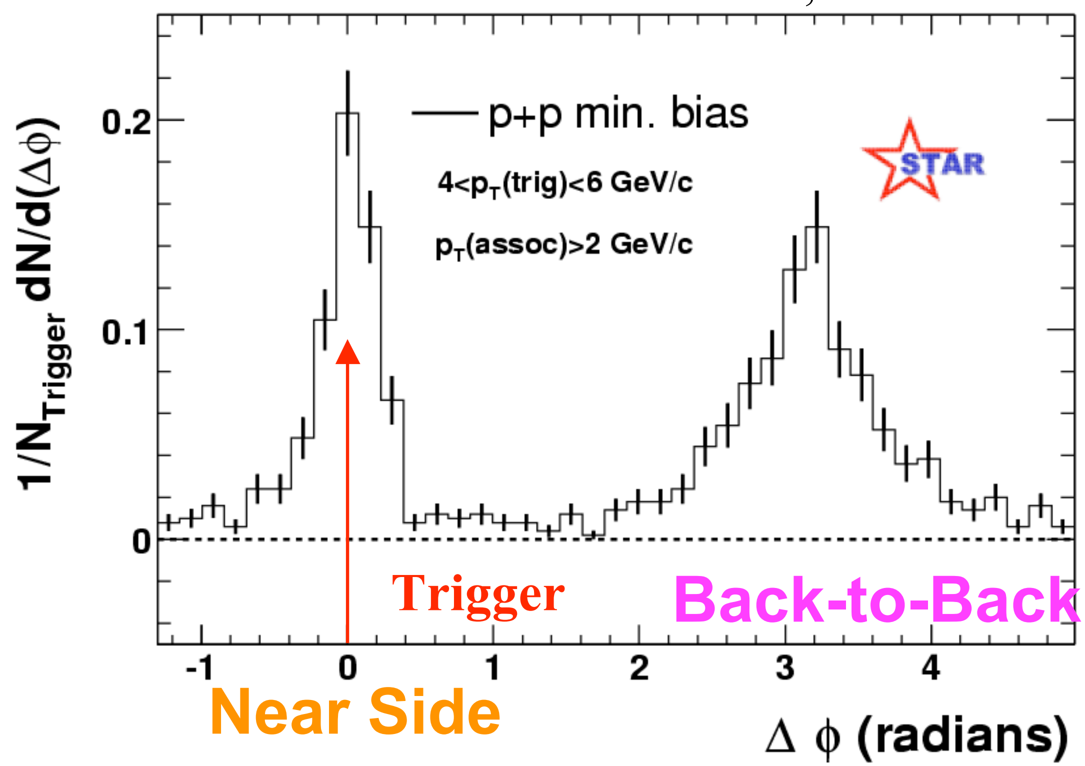
Jet and Two-particle Azimuthal Distribution

p+p → di-jet



- trigger: highest p_T track, p_T>4 GeV/*c*
- $\Delta\phi$ distribution: 2 GeV/*c* < p_T < $p_T^{\,trigger}$
- normalize to number of triggers

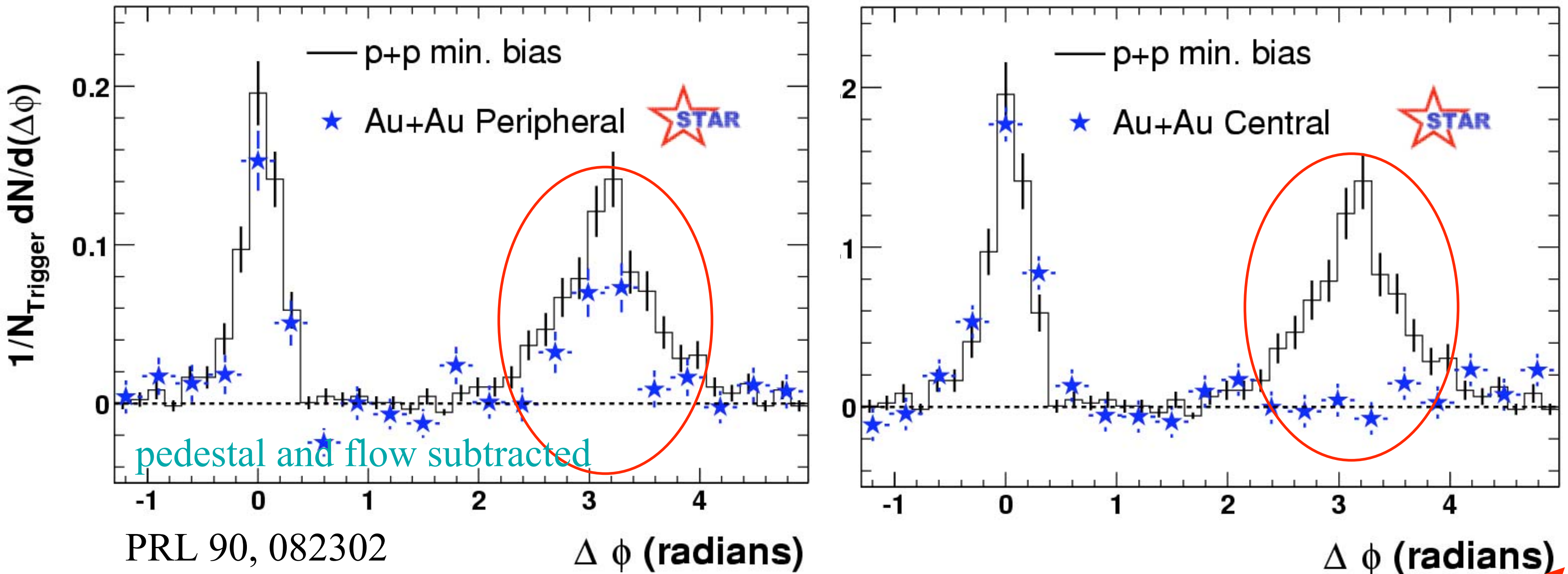
PRL 90, 082302



Azimuthal distribution in Au+Au

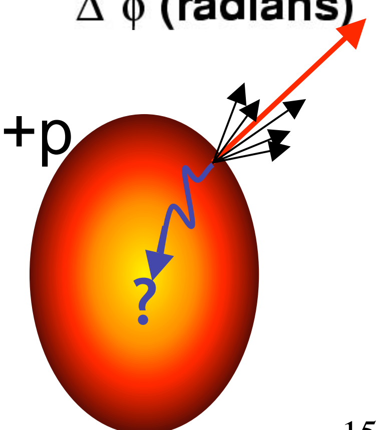
Au+Au peripheral

Au+Au central



PRL 90, 082302

Near-side: peripheral and central Au+Au similar to p+p

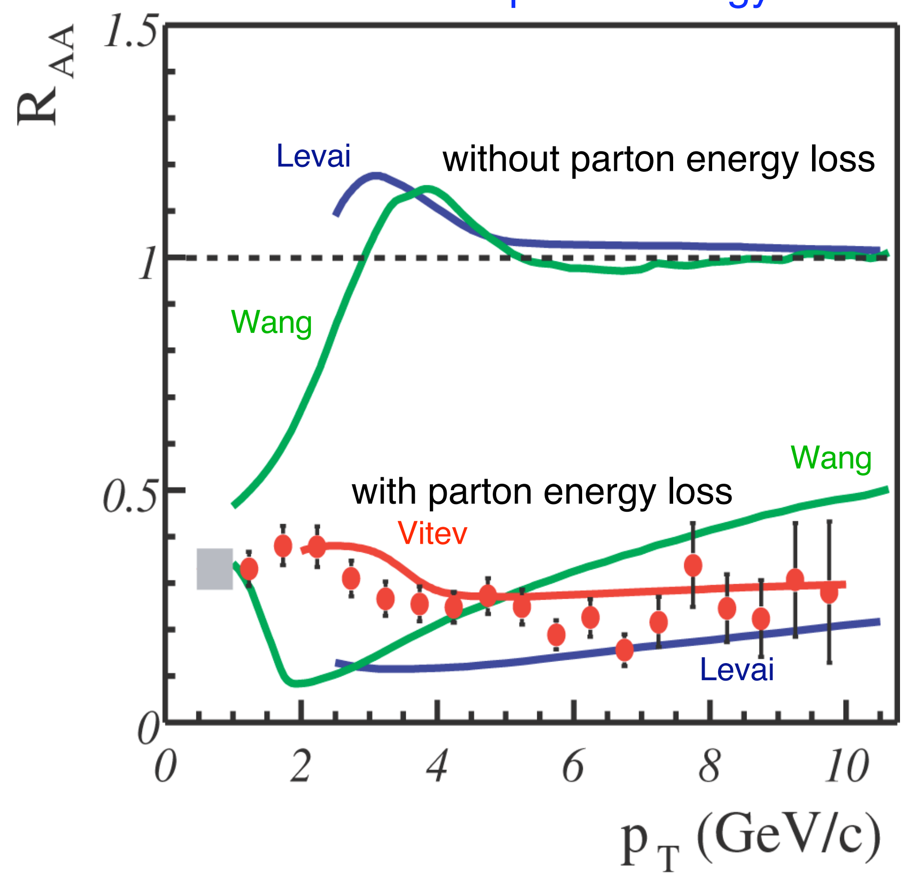


Strong suppression of back-to-back correlations in central Au+Au

Jet Quenching?

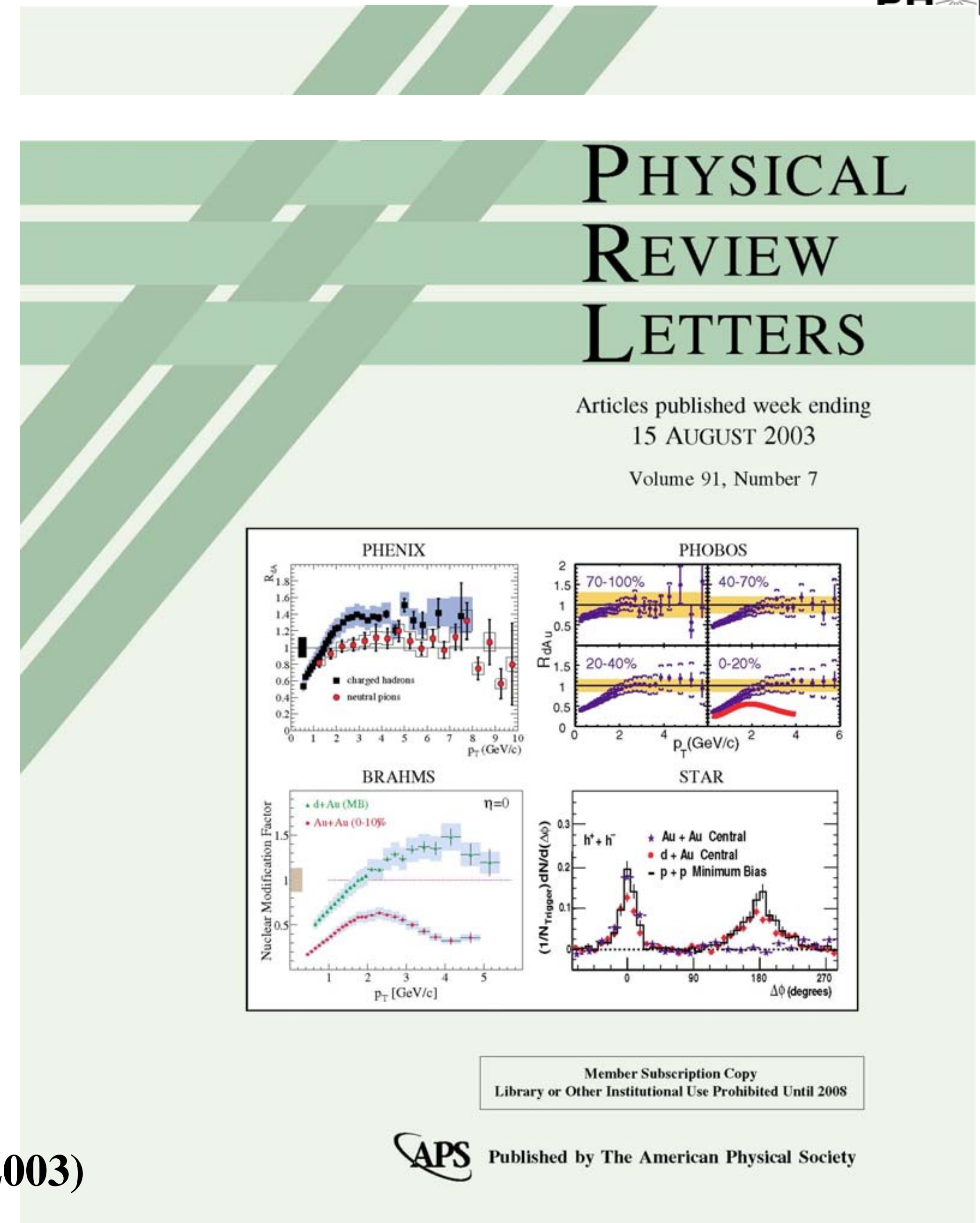
- Pion suppression reproduced by models with parton energy loss.
- other explanations not ruled out.

Comparison with model calculations with and without parton energy loss



Au+Au→π^0+X at $\sqrt{s_{NN}}$ = 200 GeV

d+Au Experiment

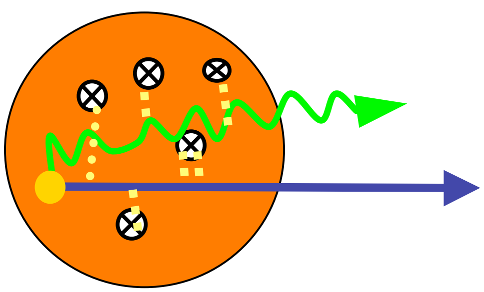


PRL 91, Number7 (2003)

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)

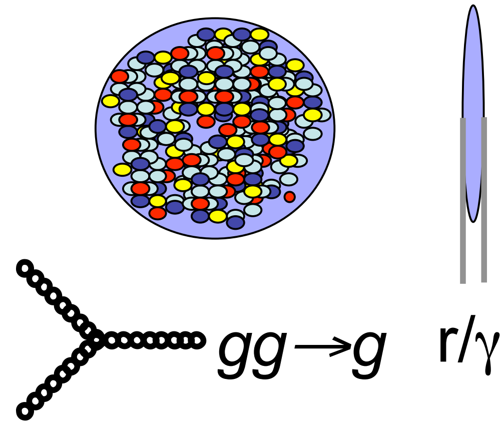


- **Energy loss of partons in dense matter**
  - Gyulassy, Wang, Vitev, Baier, Wiedemann…

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.



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

Braking QCD factorization!

→gets N_{ch} right!

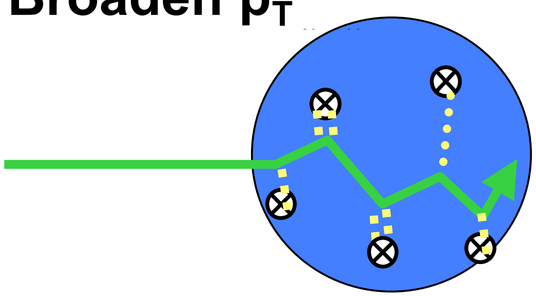
hep-ph/0212316; D. Kharzeev, E. Levin, M. Nardi

- **Multiple elastic scatterings**

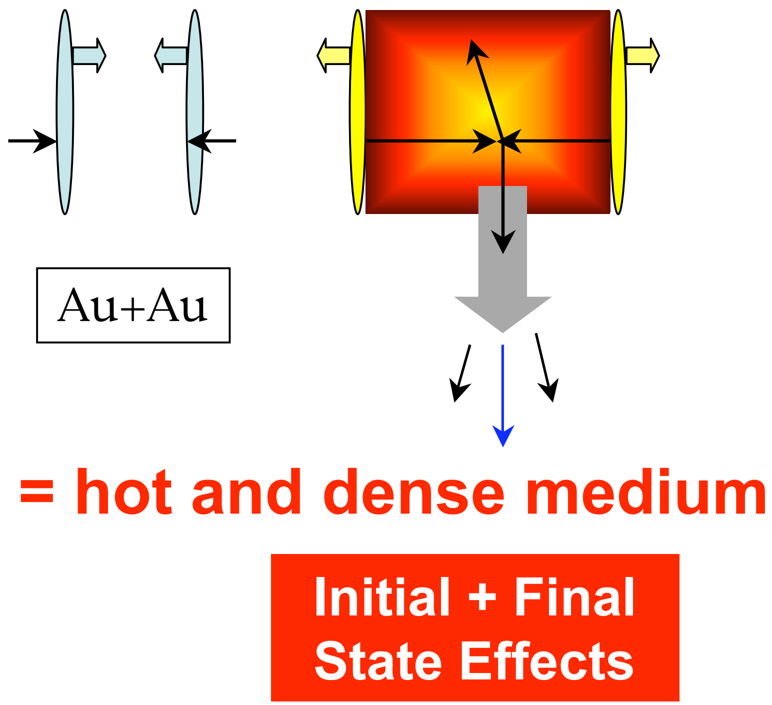
(Cronin effect)

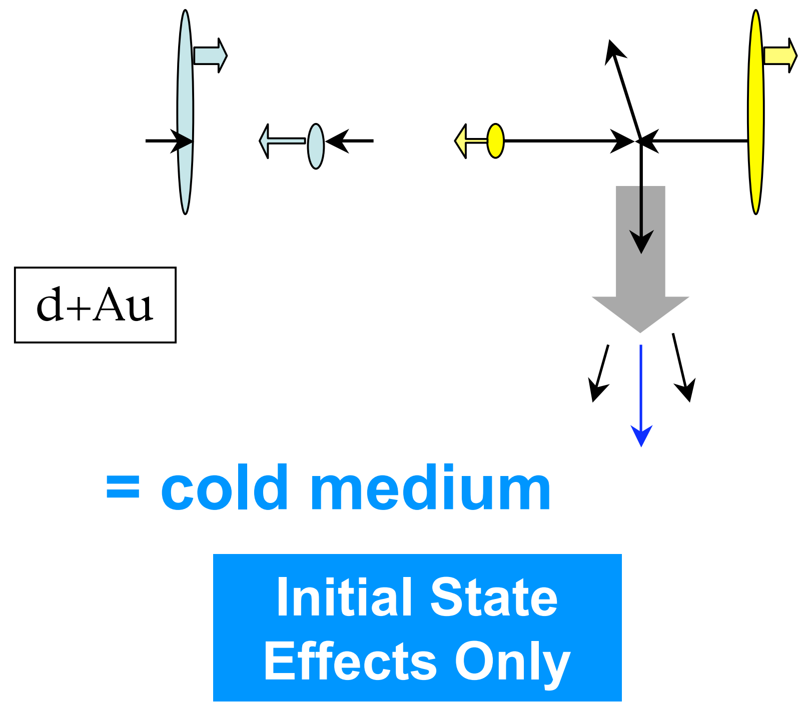
Wang, Kopeliovich, Levai, Accardi

Broaden p_T



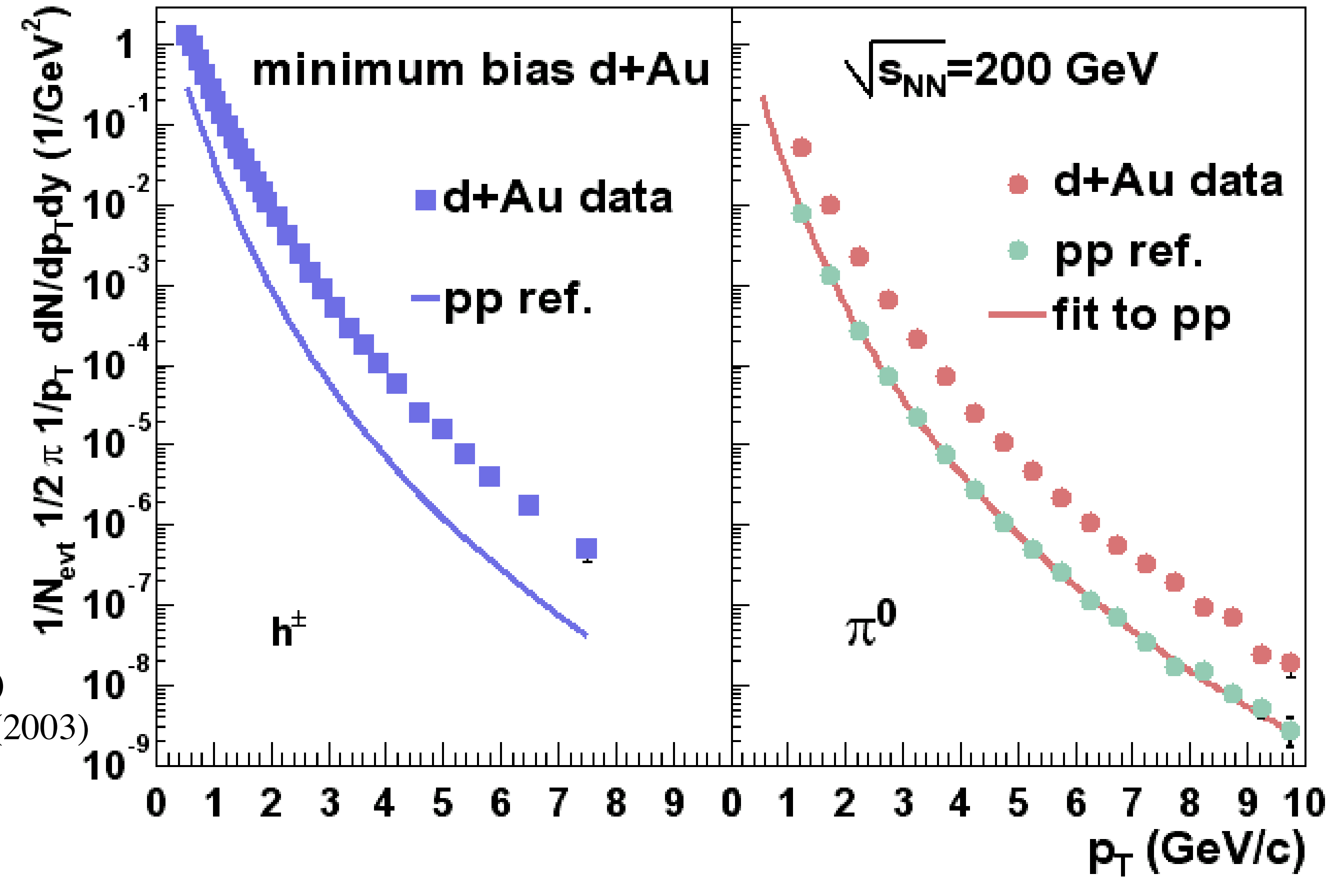
d+Au: Control Experiment





- 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.**

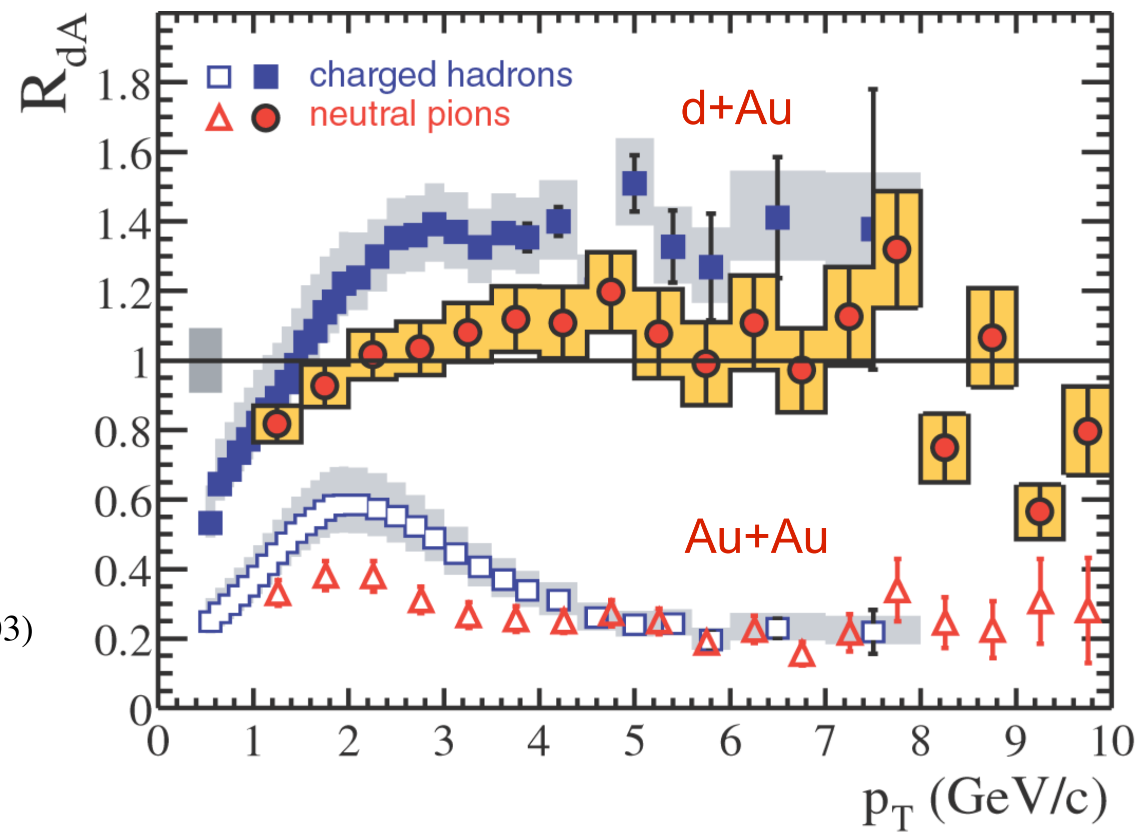
d+Au Spectra



PHENIX (d+Au)
PRL 91, 072303 (2003)
hep-ex/0306021

- **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

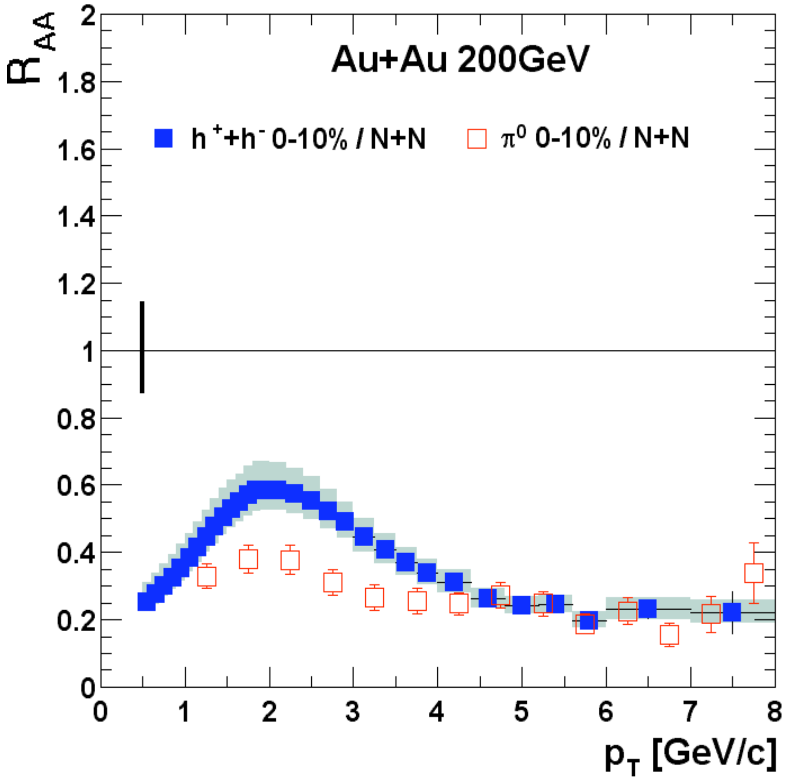
Initial + Final State Effects

PHENIX (d+Au)
PRL 91, 072303 (2003)
hep-ex/0306021

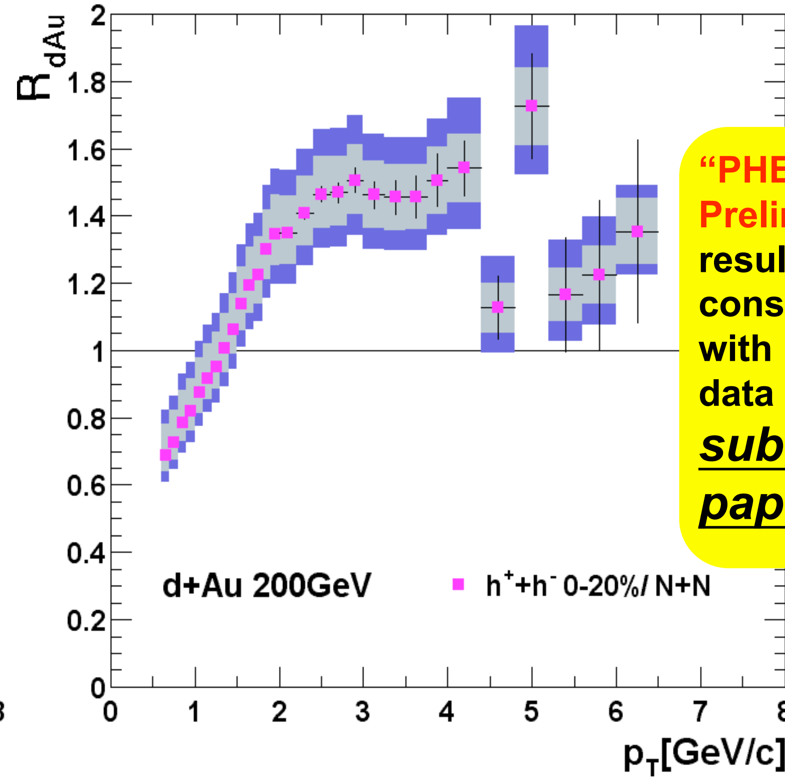
- **No Suppression in d+Au, instead small enhancement observed (Cronin effect)!!**
- **d-Au results rule out CGC as the explanation for high p_T Suppression of hadrons in AuAu central.**

Centrality Dependence

Au + Au Experiment



d + Au Control Experiment

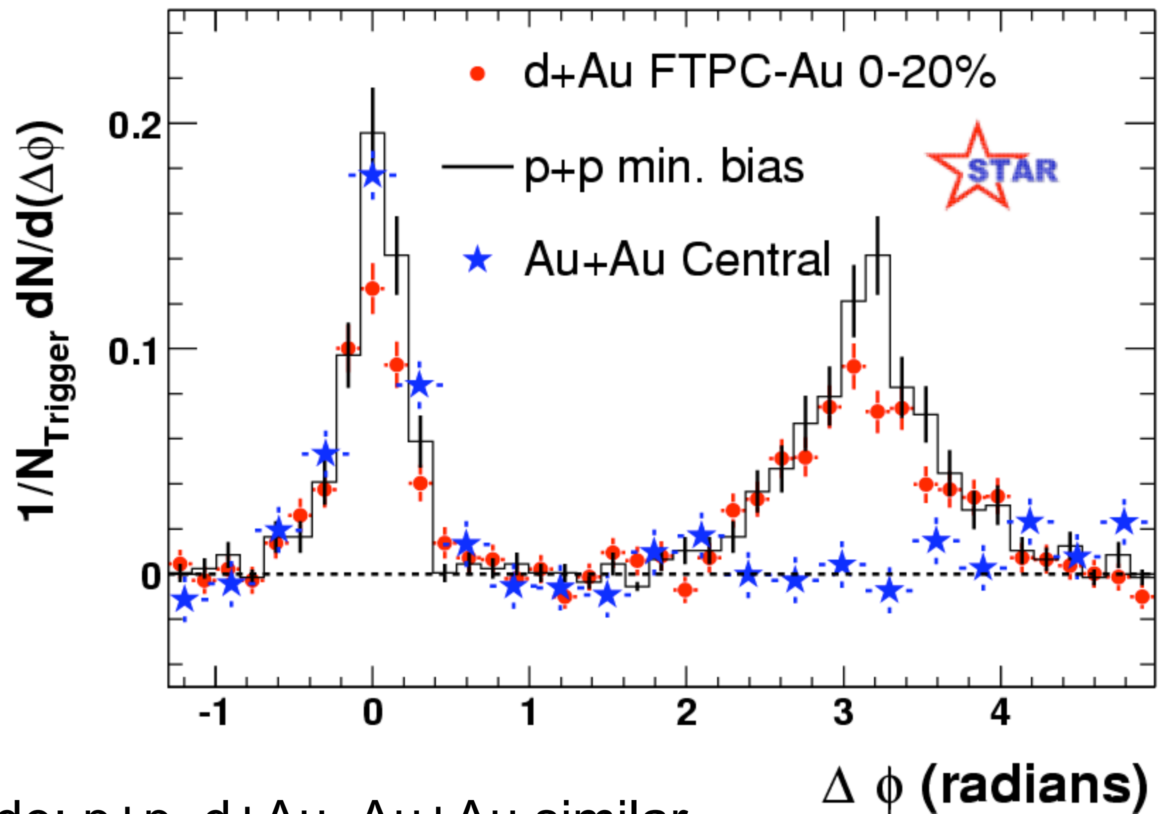


"PHENIX Preliminary" results, consistent with PHOBOS data in ***submitted paper***

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

See Talk by T. Sakaguchi, Sep. 11 (11aSF-9) for details.

Azimuthal Distributions in d+Au (STAR)

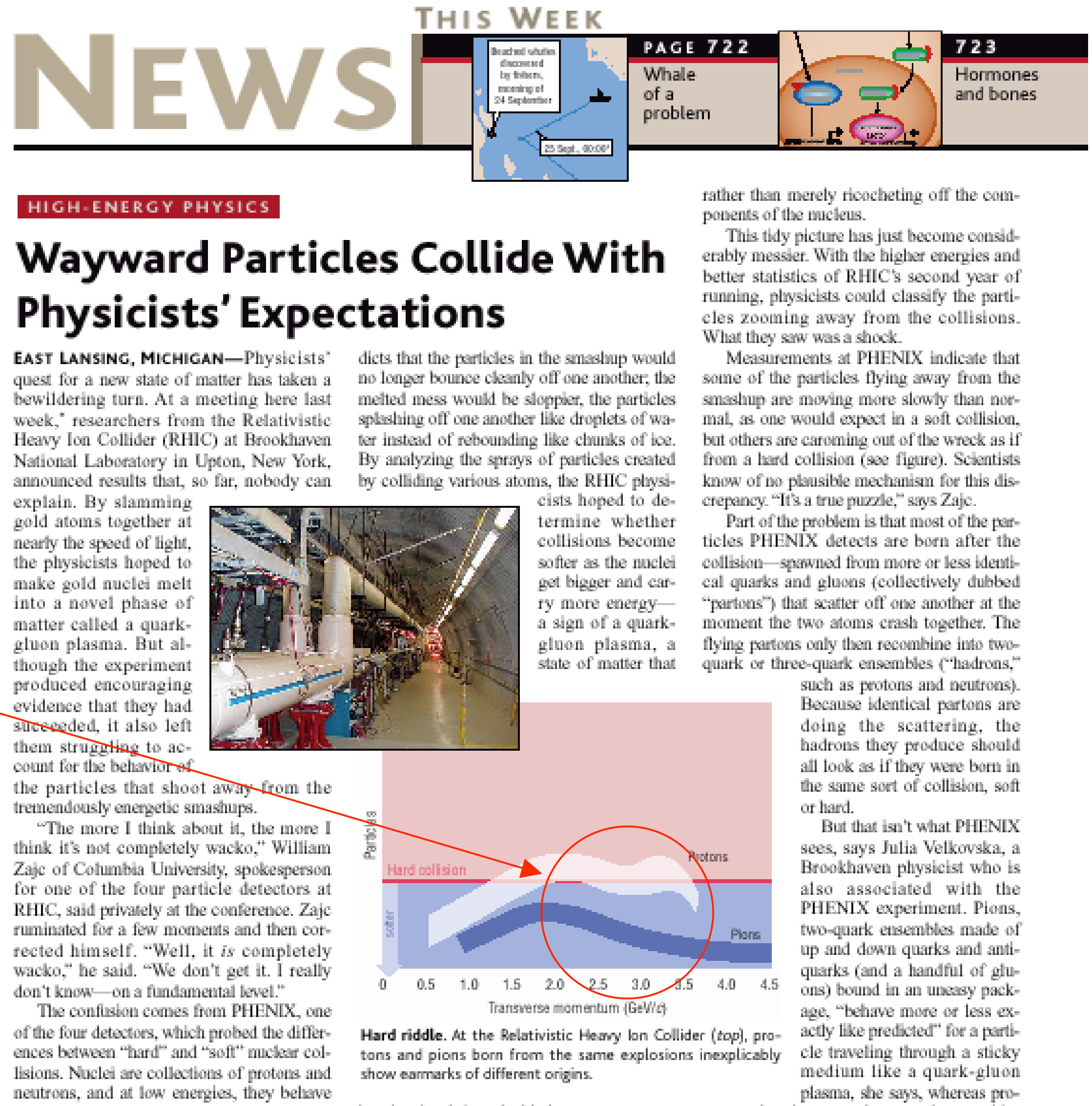


* Pedestal and flow subtracted

- Near-side: p+p, d+Au, Au+Au similar
- Back-to-back: Au+Au strongly suppressed relative to p+p and d+Au

Suppression of the back-to-back correlation in central Au+Au is a final-state effect

Particle Composition at High p_T



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.

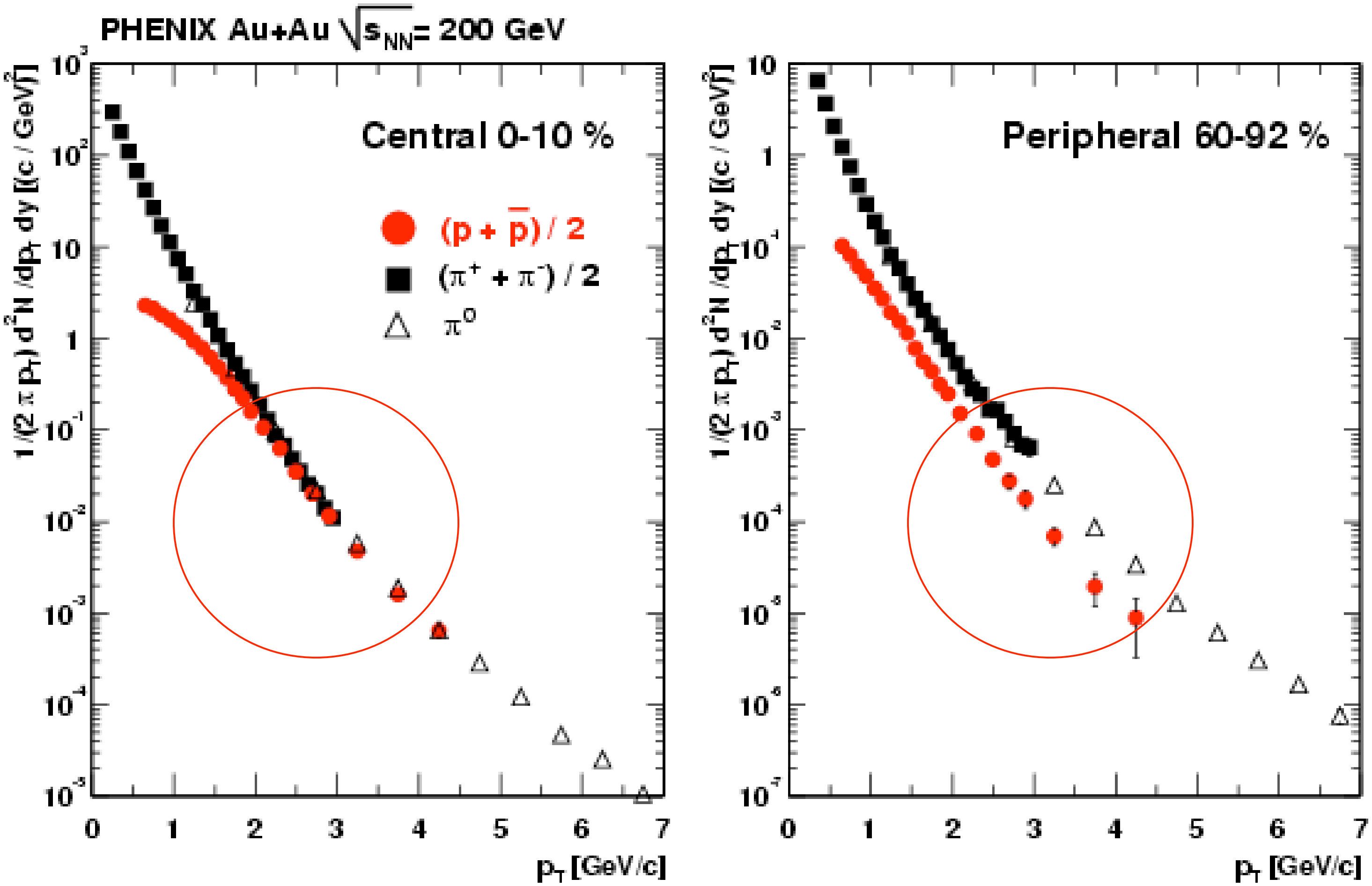
Part of the problem is that most of the particles PHENIX detects are born after the collision—spawned from more or less identical quarks and gluons (collectively dubbed "partons") that scatter off one another at the moment the two atoms crash together. The flying partons only then recombine into two-quark 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-

C.Seife, Science298, 718(2002)

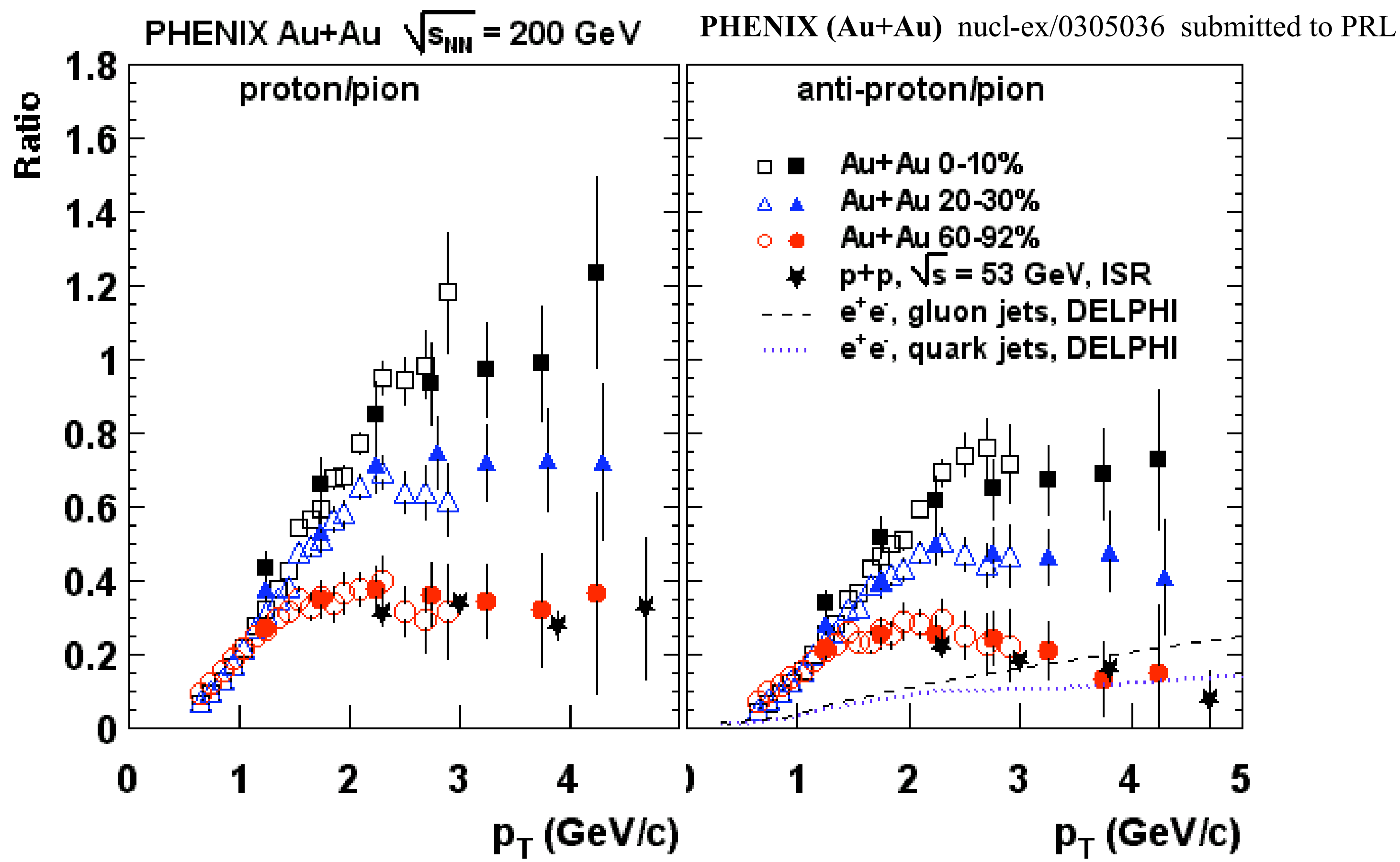
p_T spectra (p vs. π) in Au+Au @ 200 GeV

PHENIX



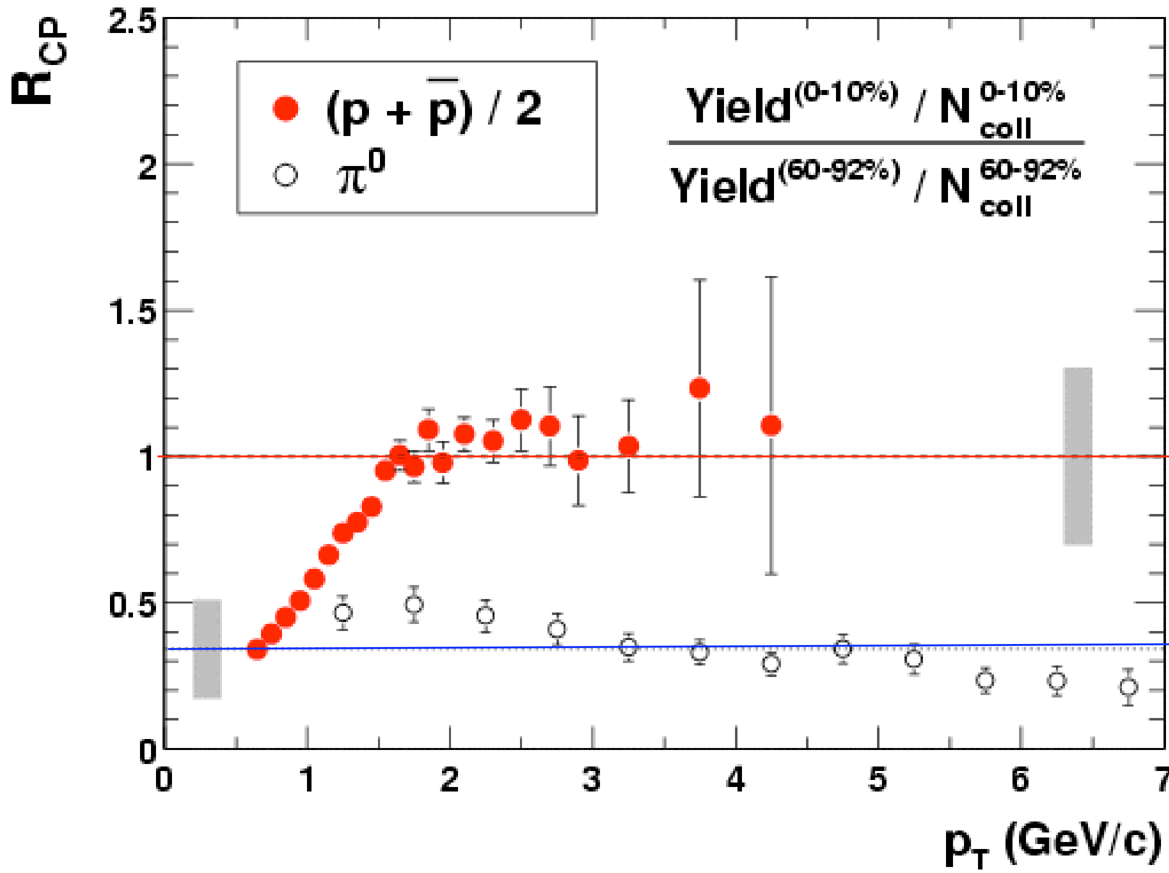
- Clearly seen p-π merging at p_T ~ 2 GeV/c in central.
- No p-π merging in peripheral.
- Suggested significant fraction of p, pbar at pt = 1.5 - 4.5 GeV/c in central.

p/π ratio vs. p_T and centrality



- 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).

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



$\approx R_{AA}$

N_{coll} scaling

N_{part} scaling

nucl-ex/0305036 submitted to PRL
nucl-ex/0307022 submitted to PRC

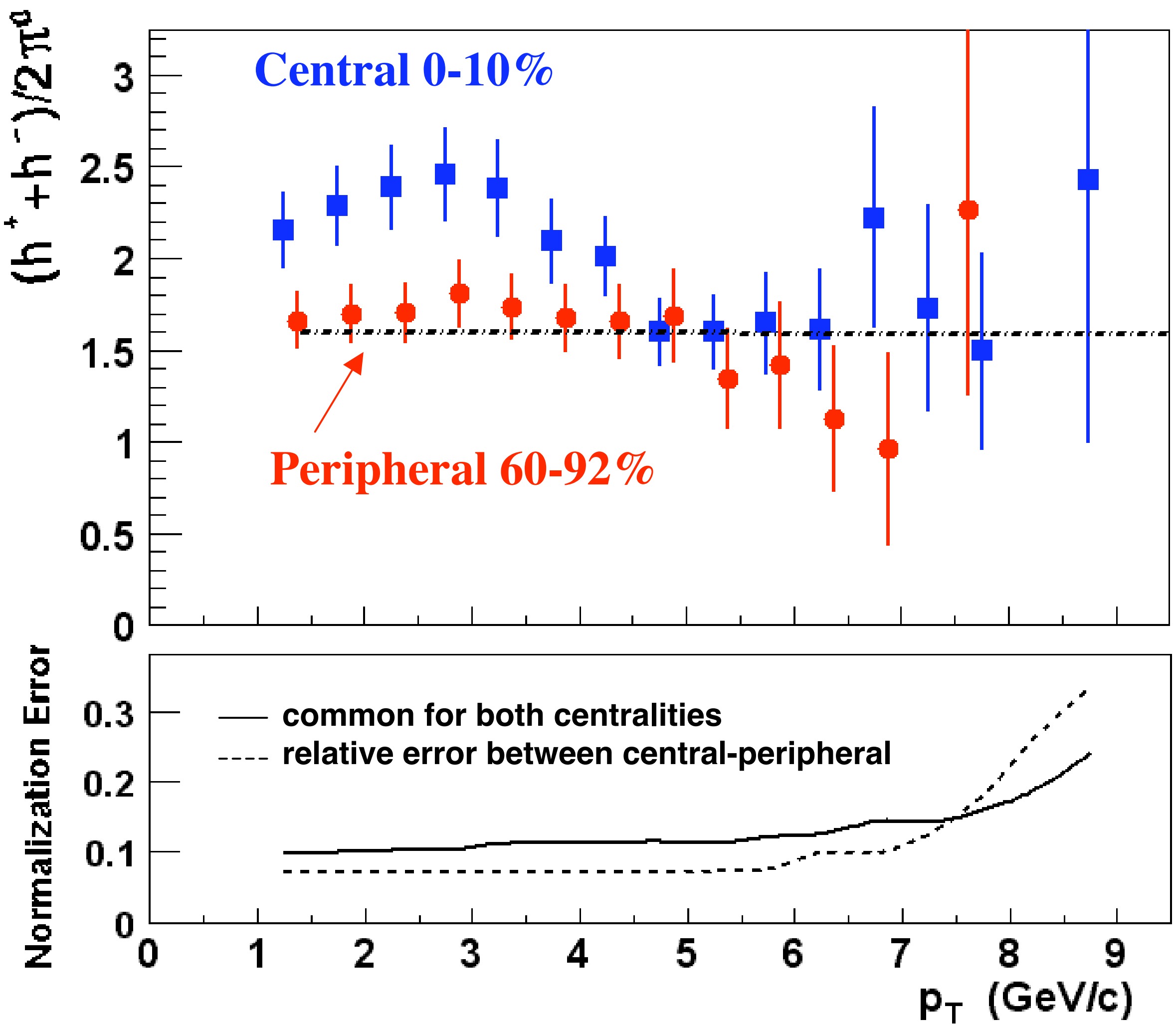
* Shaded boxes : N_{part}, N_{coll} determination errors.

p : No suppression,
N_{coll} scaling at
1.5 GeV - 4.5 GeV

π^0: Suppression
(central > peripheral)

Particle composition beyond 5 GeV …

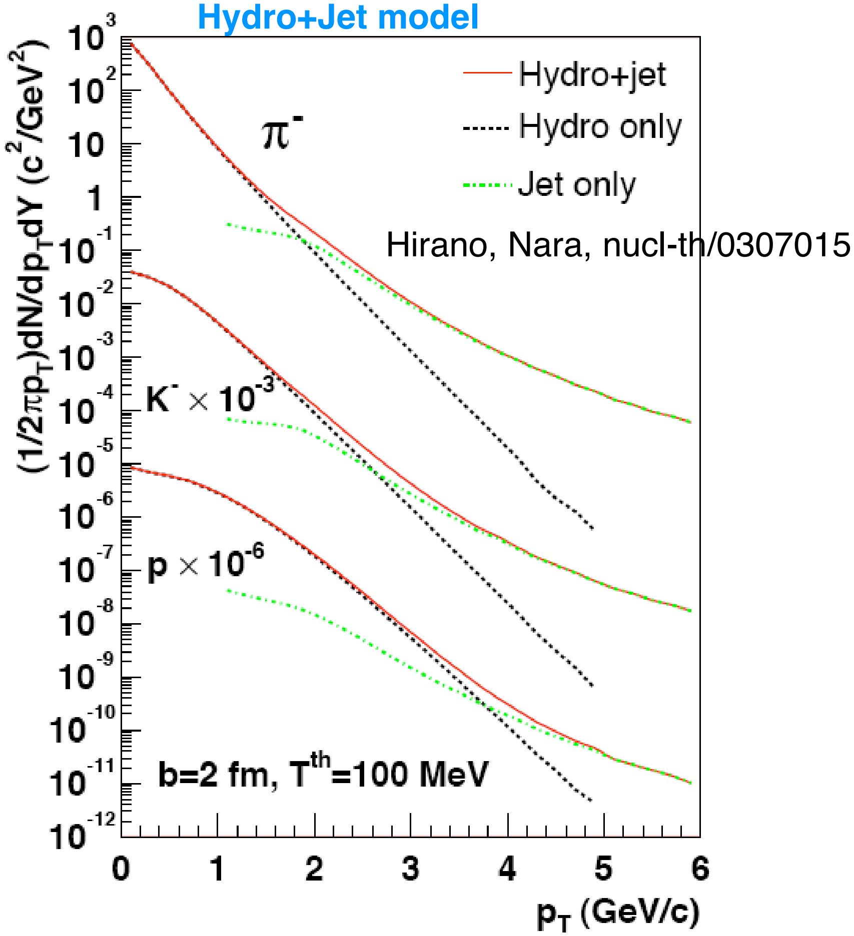
PHENIX (Au+Au) nucl-ex/0305036 submitted to PRL

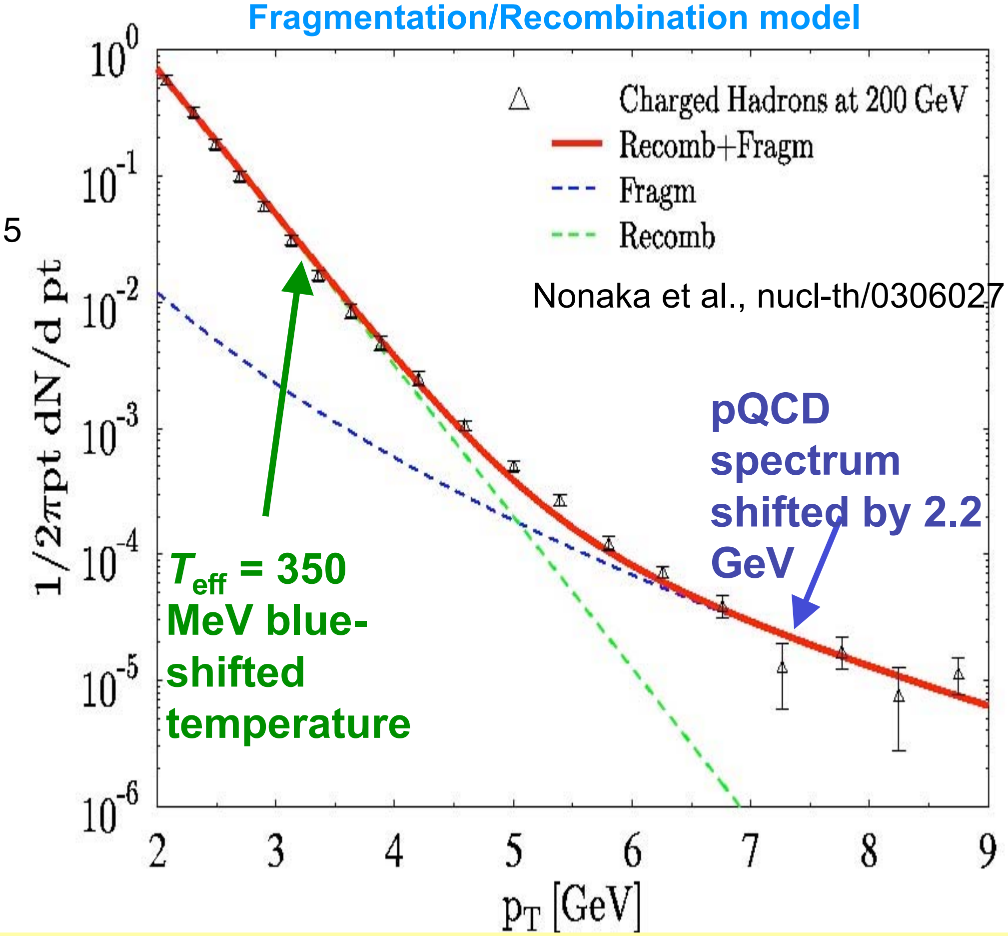


~1.6 (p+p data at $\sqrt{s_{NN}}$ = 53 GeV)

- 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.**
- **Similar behavior has seen in Λ measurement by STAR.**

What is the physics behind?





- **The origin of this baryon behavior is at present not well understood…**
- **Recombination model, Hydro-jet model, Baryon Junction model,**

  ⇒ Predicted baryon enhancement is limited up to ~ 4-5 GeV/c.

(See next talks by Nonaka and Hirano)

Summary

In last 3 years, RHIC provided a wealth of new exciting experimental data and theoretical progress in this new energy frontier for nuclear physics!

1. At high p_T, both neutral and inclusive charged hadrons are largely suppressed in Au+Au central collisions.
2. The away-side jet in Au+Au central collisions is also suppressed.
3. 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** *(ruled out CGC model).*
4. 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/π ratio has been observed.

- *Theoretical interlunations (Parton recombination, Hydro+Jet, Baryon junction)*

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 - anti-charm 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^-, $\mu^+\mu^-$
  - **Hadronic Probes**
    - High p_T identified charged particle.

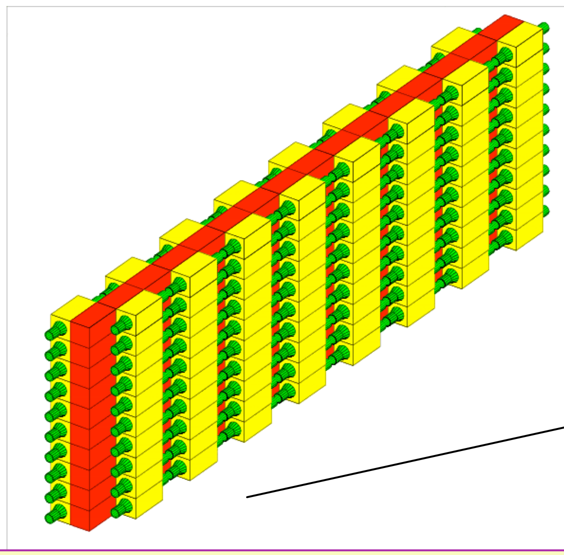
- **PHENIX plans to make these measurements in the next high luminosity Au+Au run.**

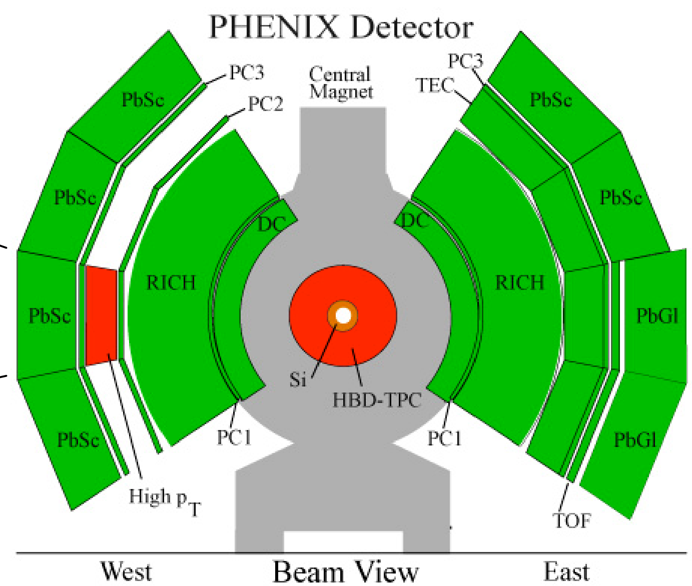
High p_T Particle Identification Upgrade

		Pion-Kaon separation	Kaon-Proton separation
TOF	σ~100 ps	0 - 2.5	- 5
RICH	n=1.00044 γth~34	5 - 17	17 -
Aerogel	n=1.01 γth~8.5	1 - 5	5 - 9

Aerogel Cherenkov

- Together with the Aerogel, TOF and RICH, we can extend the PID **beyond 5 GeV/c.**
- **Coverage: ~ 4 m^2 in west arm.**



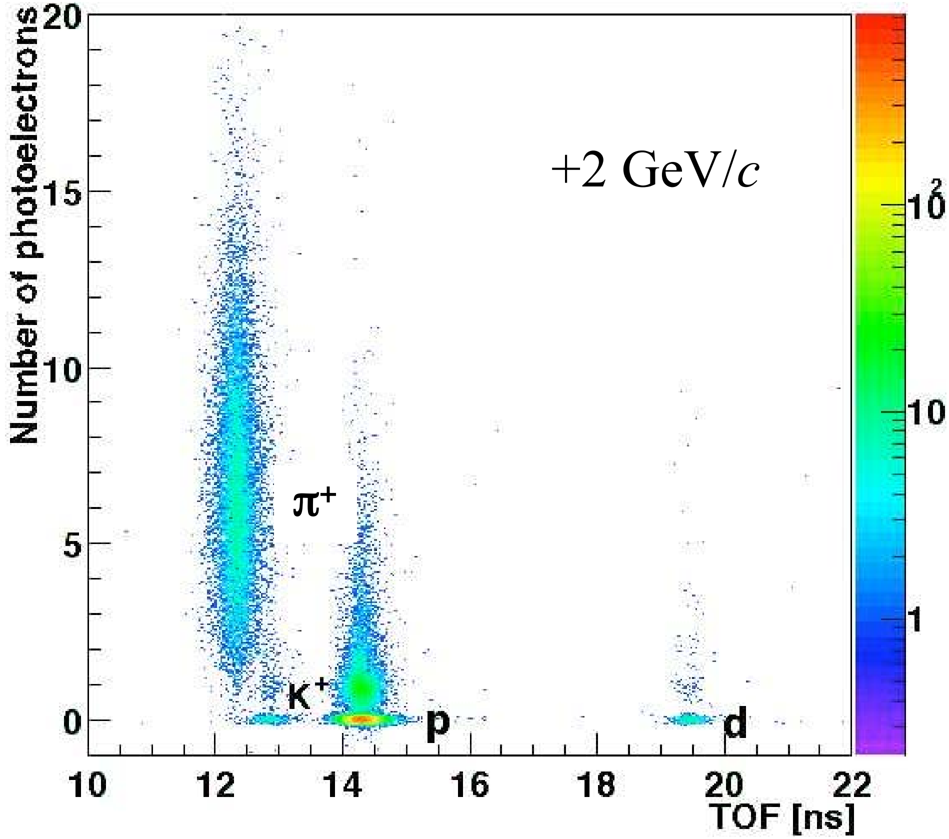


Prototype test during RUN-3
Installation in 2003 for Au-Au run

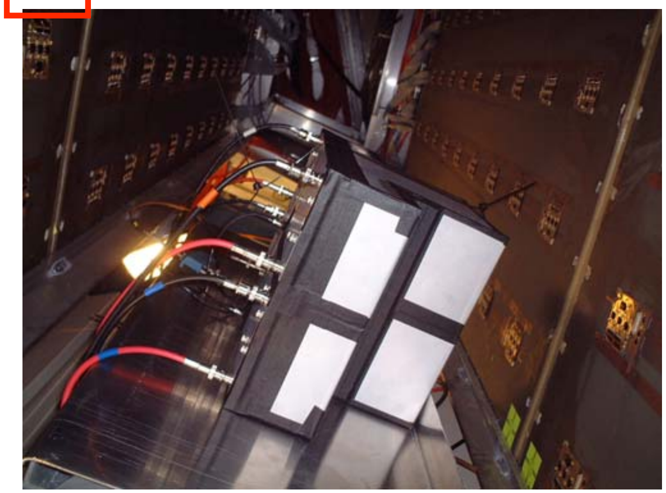
Participating institutions:
BNL, Dubna, Tokyo, Tsukuba

Aerogel Prototype Test

Final Prototype Test @ KEK



Prototype test @ PHENIX



Clean separation of π/(K,p)

(See talk by M. Konno, 10pSF6)

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

Backup Slides

PHENIX Publications

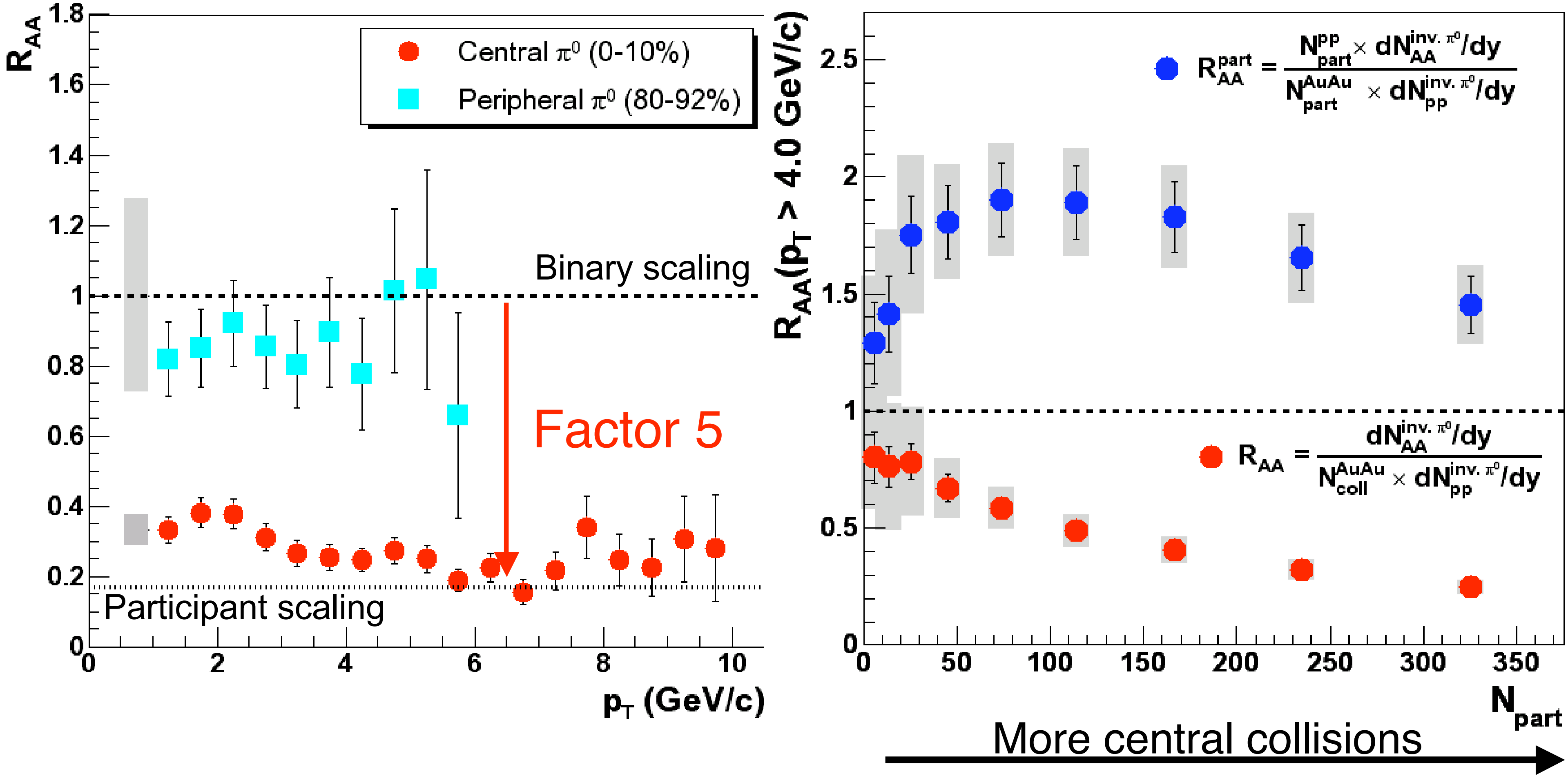
~ single particle spectra (hadron) only ~

PHENIX

- K. Adcox *et al.*, PHENIX Collaboration, “Suppression of Hadrons with Large Transverse Momentum in Central Au+Au Collisions at $\sqrt{s_{NN}}$ =130 GeV”, Phys. Rev. Lett. 88, 022301 (2002).
- K. Adcox *et al.*, PHENIX Collaboration, “Centrality dependence of $\pi^{\pm}$, $K^{\pm}$, p and p-bar production from $\sqrt{s_{NN}}$ =130 GeV Au+Au collisions at RHIC, Phys. Rev. Lett. 88, 242301 (2002).
- K. Adcox *et al.*, PHENIX Collaboration, “Measurement of Lambda and Lambda-bar particles in Au+Au collisions at $\sqrt{s_{NN}}$ =130 GeV”, Phys. Rev. Lett. 89, 092302 (2002).
- K. Adcox *et al.*, PHENIX Collaboration, “Centrality Dependence of the High p_T Charged Hadron Suppression in Au+Au collisions at $\sqrt{s_{NN}}$ =130 GeV”, Phys. Lett. B 561, 82-92 (2003).
- S.S. Adler *et al.*, PHENIX Collaboration, “Suppressed π^0 Production at Large Transverse Momentum in Central Au+Au Collisions at $\sqrt{s_{NN}}$=200 GeV”, Phys. Rev. Lett. 91, 072301 (2003) [nucl-ex/0304022].
- S.S. Adler *et al.*, PHENIX Collaboration, “Scaling properties of proton and anti-proton production in =200 GeV Au+Au collisions”, to be appeared in Phys. Rev. Lett., nucl-ex/0305036.
- S.S. Adler *et al.*, PHENIX Collaboration, “Midrapidity Neutral Pion Production in Proton-Proton Collisions at $\sqrt{s}$ = 200 GeV”, to be appeared in Phys. Rev. Lett., hep-ex/0304038.
- S.S. Adler *et al.*, PHENIX Collaboration, “Absence of Suppresion in Particle Production at Large Transverse Momentum in $\sqrt{s_{NN}}$ = 200 GeV d+Au Collisions”, Phys. Rev. Lett. 91, 072303 (2003) [nucl-ex/0306021].
- K. Adcox, et al, PHENIX Collaboration, “Single Identified Hadron Spectra from $\sqrt{s_{NN}}$ = 130 GeV Au+Au Collisions”, to be appeared in Phys. Rev. C, nucl-ex/0307010.
- S.S. Adler *et al.*, PHENIX Collaboration, “Identified Charged Particle Spectra and Yields in Au+Au Collisions at $\sqrt{s_{NN}}$ = 200 GeV”, to be appeared in Phys. Rev. C, nucl-ex/0307022.
- S.S. Adler *et al.*, PHENIX Collaboration, “High p_T Charged Hadron Suppression in Au+Au Collisions at $\sqrt{s_{NN}}$ = 200 GeV”, to be appeared in Phys. Rev. C, nucl-ex/0308006.

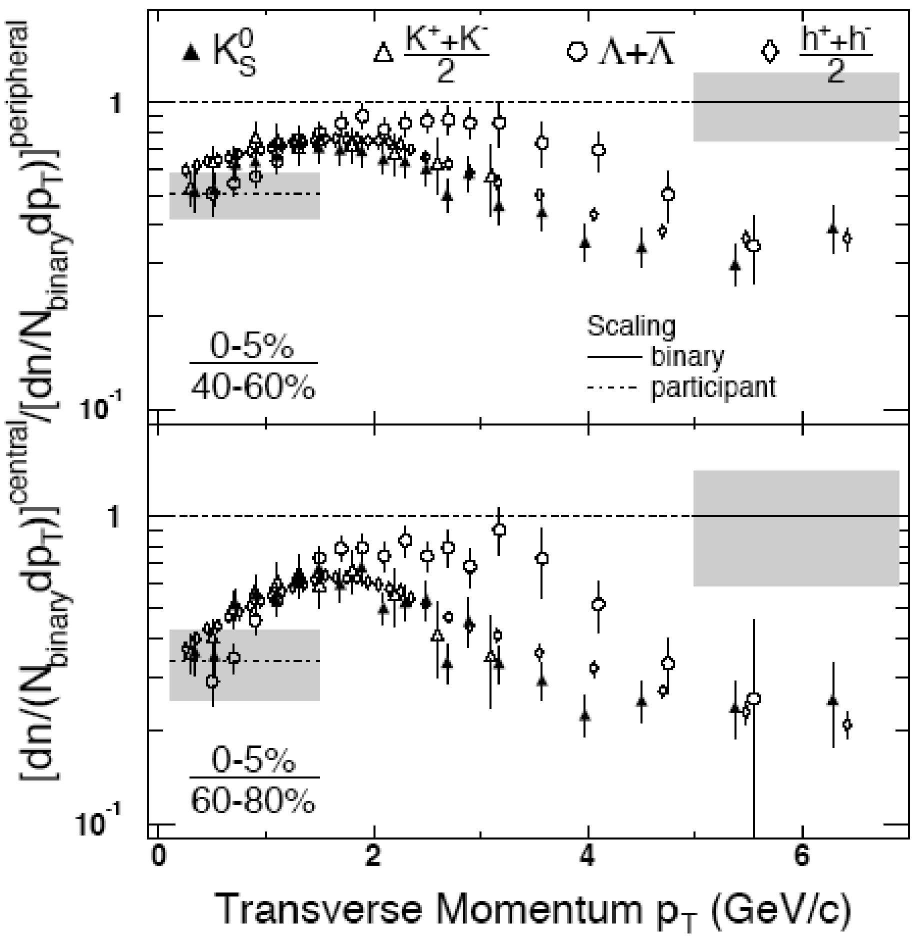
R_{AA} in Au+Au : suppression

PRL 91, 072301 (2003), nucl-ex/0304022



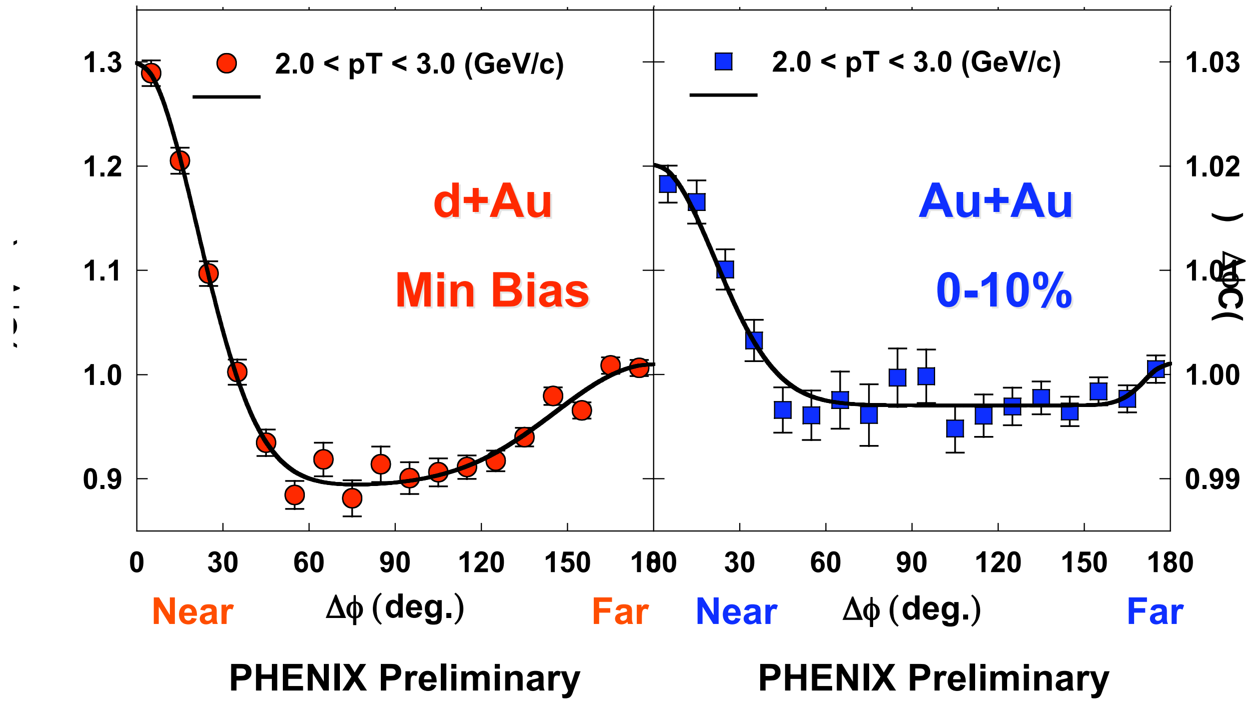
STAR Results

STAR nucl-ex/0306007



- **Similar behavior has been observed in Λ.**
- **Limited behavior of baryon enhancement (< ~4 GeV/c).**

Azimuthal Distributions in d+Au (PHENIX)



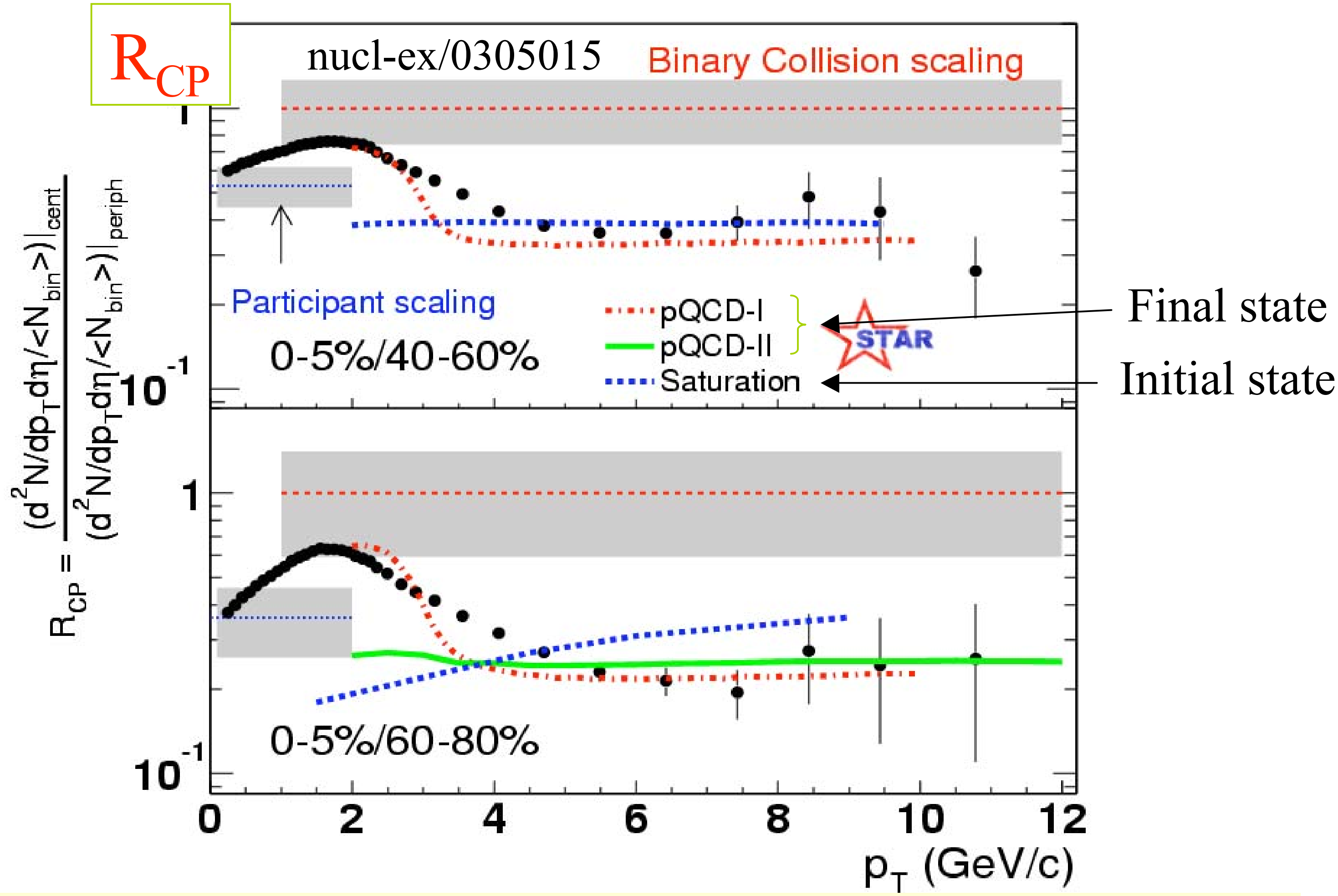
- Peripheral Au+Au similar to d+Au
- Central Au+Au shows distinct reduction in far side correlation.
- Away-side Jet is missing in Au+Au

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

PHENIX Experiment

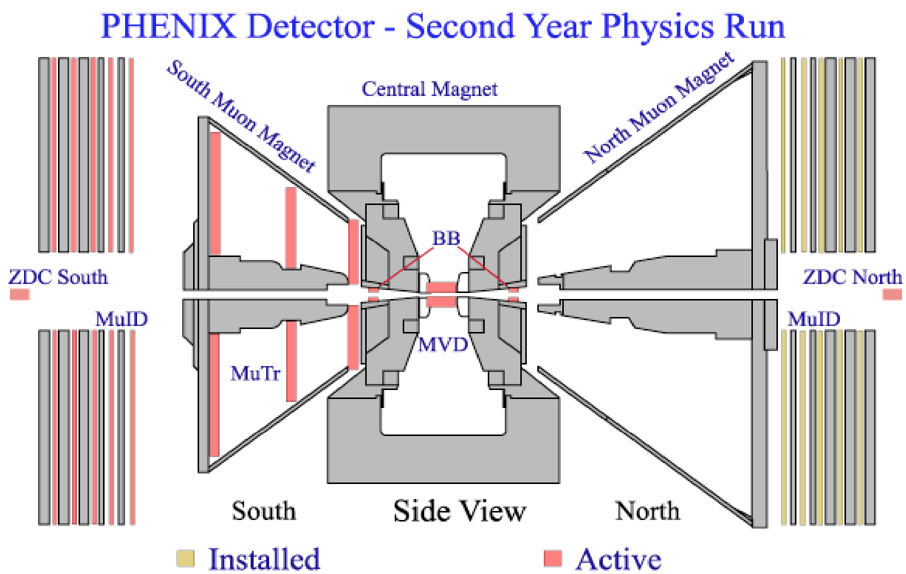
Inclusive suppression: theory vs. data

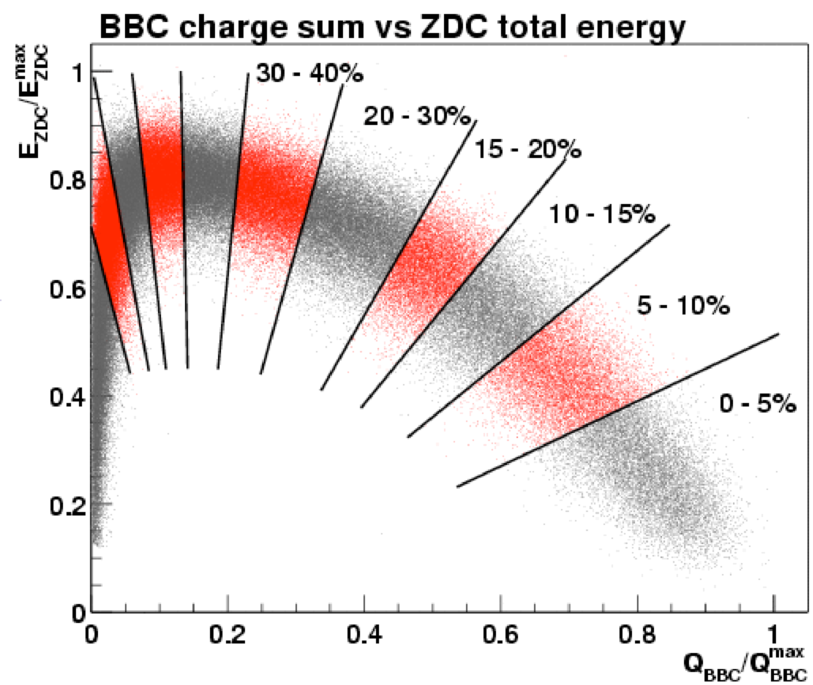
pQCD-I: Wang, nucl-th/0305010
pQCD-II: Vitev and Gyulassy, PRL 89, 252301
Saturation: KLM, Phys Lett B561, 93



p_T>5 GeV/c: well described by KLM saturation model (up to 60% central) and pQCD+jet quenching

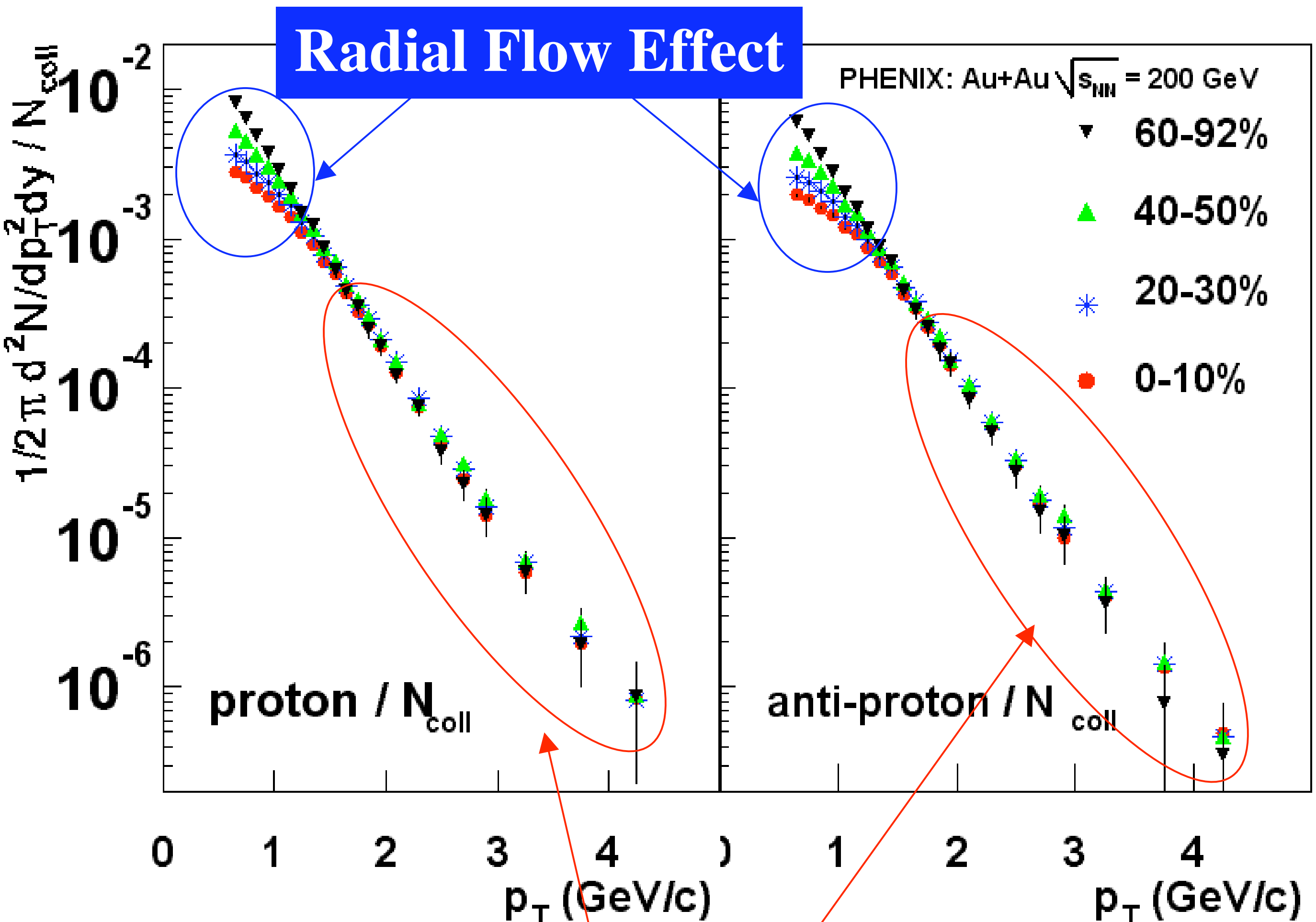
Collision Centrality Determination





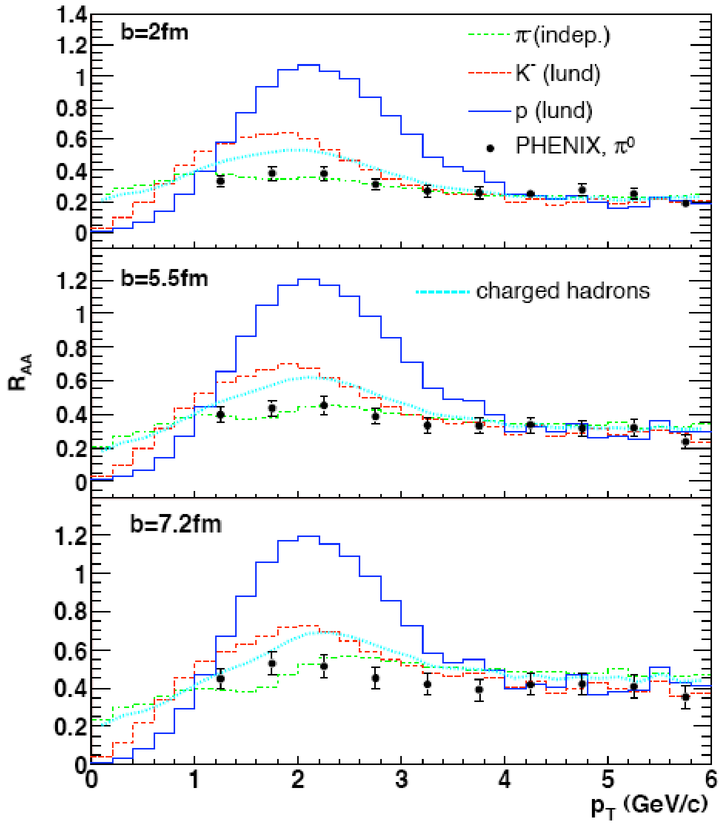
- Centrality selection : Used charge sum of Beam-Beam Counter (**BBC**, |η|=3~4) and energy of Zero-degree calorimeter (**ZDC**) in minimum bias events (92% of total inelastic cross sections).
- Extracted $\mathbf{N_{coll}}$ and $\mathbf{N_{part}}$ based on Glauber model.

N_{coll} scaled p_T spectra for p and pbar

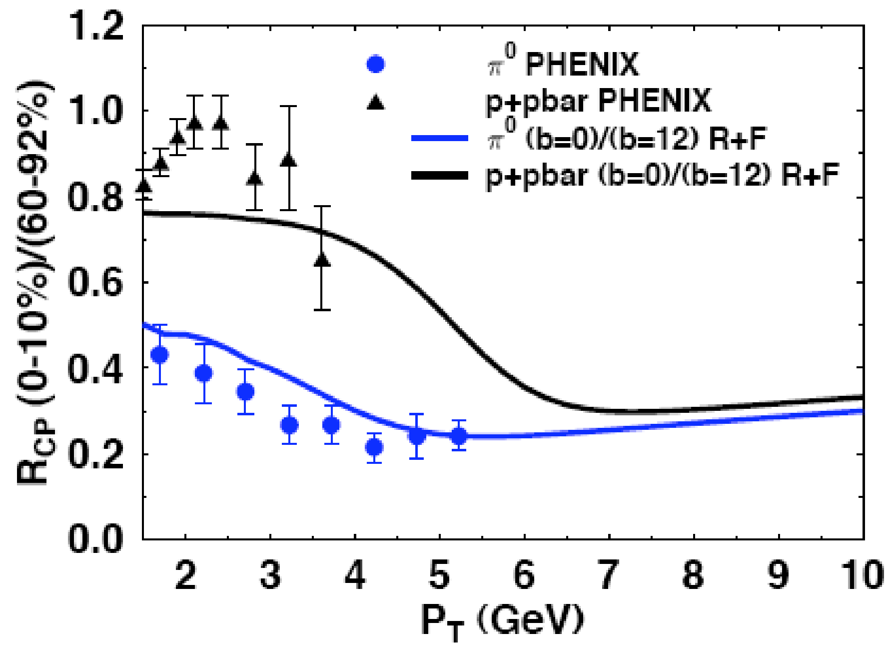


Ncoll scaling (p_T > 1.5 GeV) for all centrality bins

Model Comparison



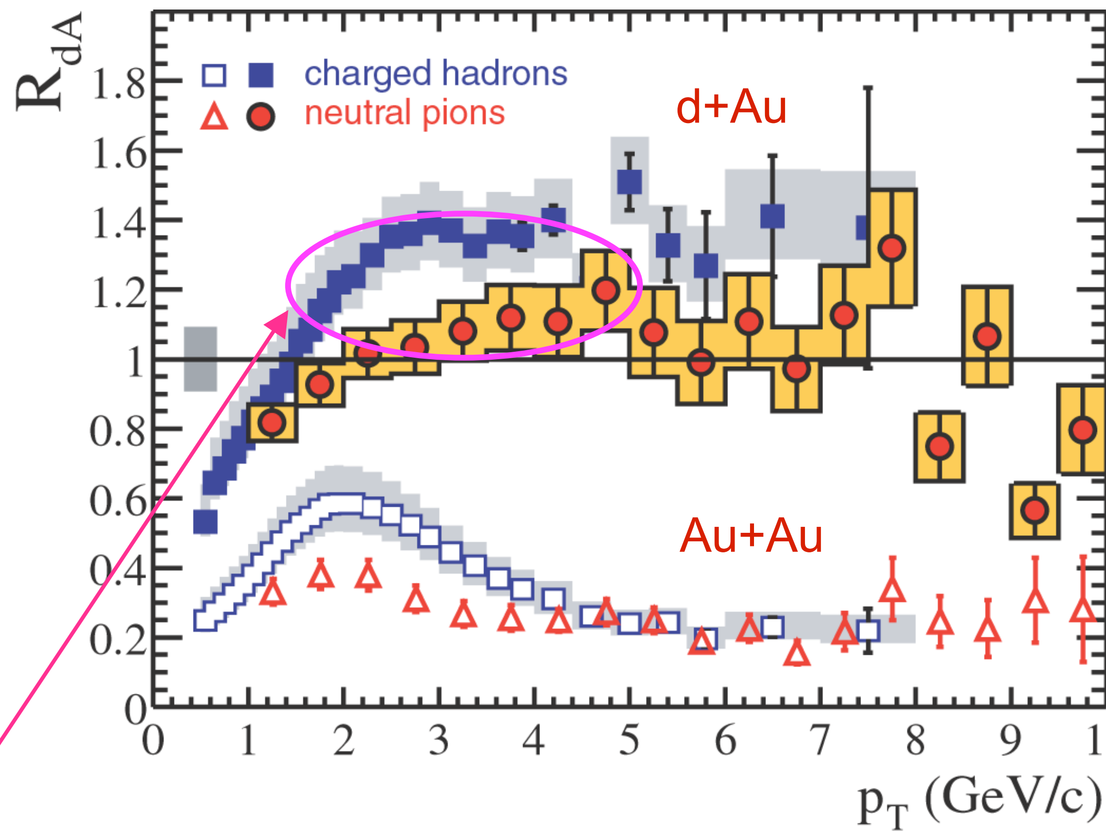
Hirano, Nara (Hydro+Jet model)
nucl-th/0307015



Fries, Muller, Nonaka, Bass
(Fragmentation/Recombination model)
nucl-th/0306027

- **Baryon Junction model, Recombination model, Hydro-jet model**
  ⇒ Predicted baryon enhancement is limited up to ~ 4-5 GeV/c.
- **Qualitative agreement with data for all these models.**

R_{dA} for charged hadrons and π^0



PHENIX (d+Au)
PRL 91 072303 (2003)
nucl-ex/0306021

- Different behavior between π^0 and charged again at p_T = 1.5 - 5.0 GeV/c!
- d+Au data suggests the flavor dependent Cronin effect.