PHENIX at RHIC

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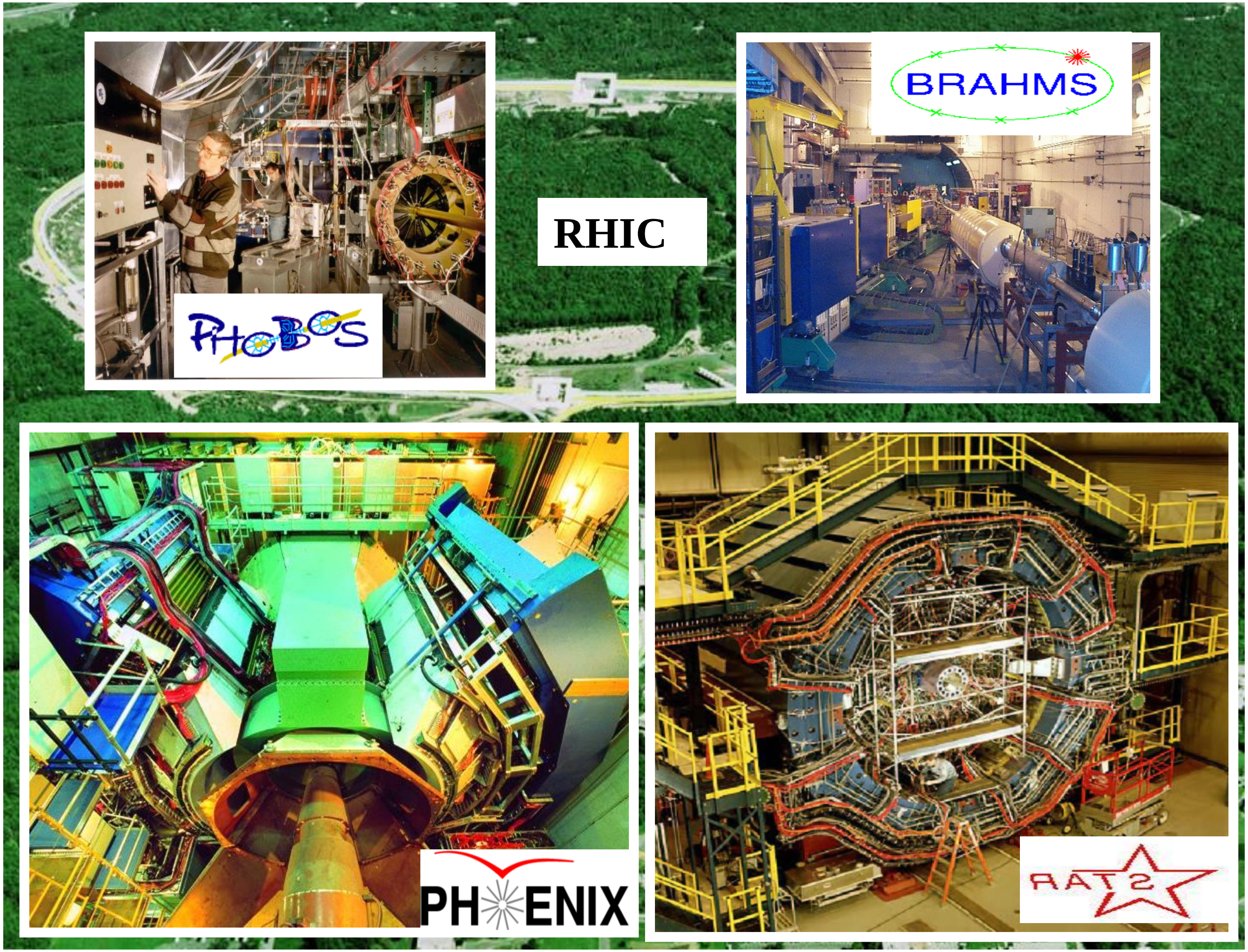
Mini Workshop for Korea-EU ALICE Collaboration
Yonsei & Hanyang University, Korea
October 8-9, 2004

The Relativistic Heavy Ion Collider at BNL

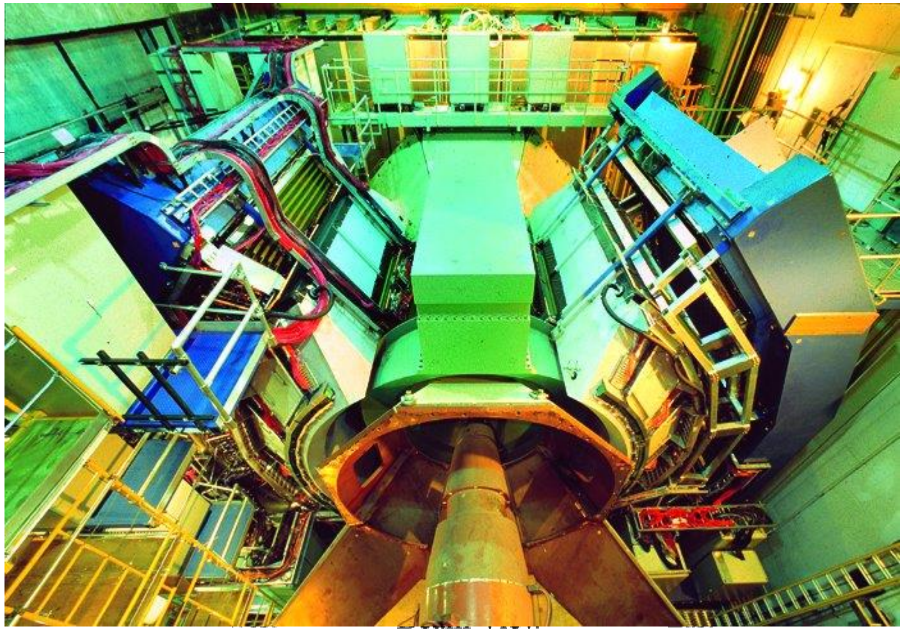
- **Two independent rings 3.83 k in circumference**
  - **120 bunches/ring**
  - **106 ns crossing time**
- **Maximum Energy**
  - **$s^{1/2}$ = 500 GeV p-p**
  - **$s^{1/2}$ = 200 GeV/N-N Au-Au**
- **Design Luminosity**
  - **Au-Au 2×10^{26} $cm^{-2}s^{-1}$**
  - **p - p 2×10^{32} $cm^{-2}s^{-1}$ (polarized)**
- **Capable of colliding any nuclear species on any other nuclear species**

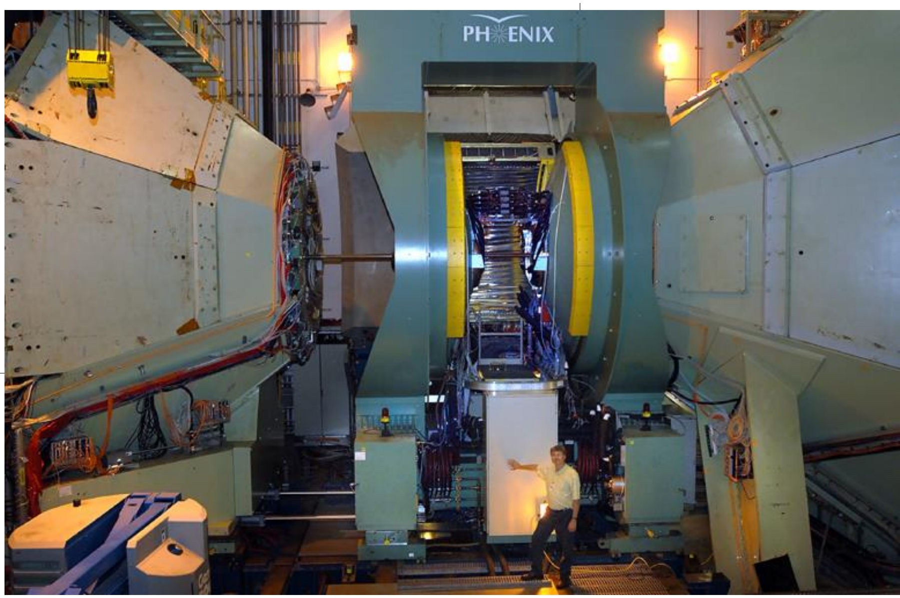
The RHIC Experiments



The PHENIX Detector

Detector Redundancy
Fine Granularity, Mass Resolution
High Data Rate
Good Particle ID
Limited Acceptance





Charged Particle Tracking:

- Drift Chamber
- Pad Chamber
- Time Expansion Chamber/TRD
- Cathode Strip Chambers

Particle ID:

- Time of Flight
- Ring Imaging Cerenkov Counter
- TEC/TRD
- Muon ID (PDT's)

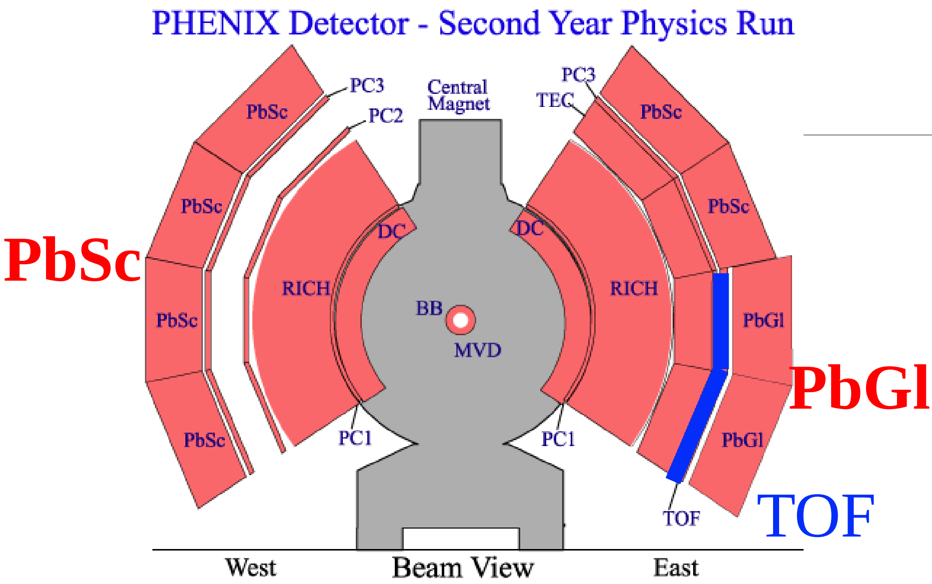
Calorimetry:

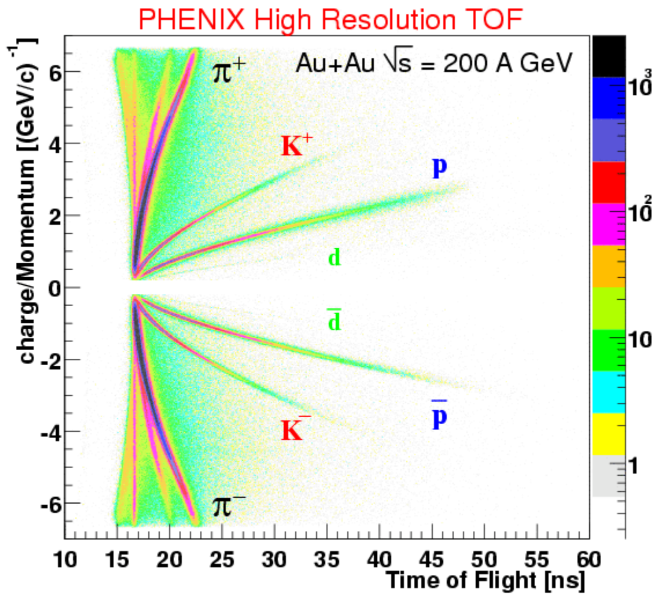
- Pb Scintillator
- Pb Glass

Event Characterization:

- Multiplicity Vertex Detector (Si Strip,Pad)
- Beam-Beam Counter
- Zero Degree Calorimeter/Shower Max Detector
- Forward Calorimeter

PHENIX Central Arm





PID by high resolution TOF

- π, K < 2 GeV/c
- proton, anti-proton < 4 GeV/c
- $\Delta\phi = \pi/4$

π^0 measurement by EMCal

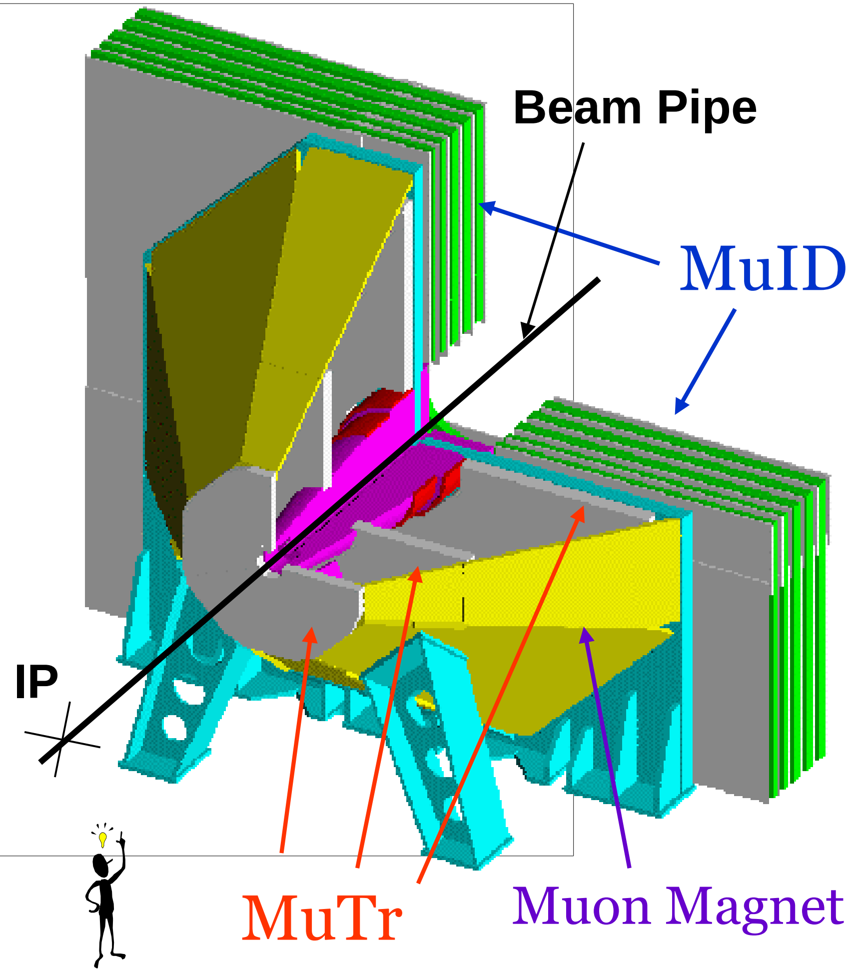
- 1<pt<10GeV/c (possibly ~20GeV)
- 6 lead- scintillator (PbSc) sectors
- 2 lead- glass (PbGl) sectors
- $|\eta|<0.38$ at midrapidity, $\Delta\phi = \pi$

Electron measurement

- Charged tracks: DC & PC
- RICH rings
- EM Calorimeter clusters

The PHENIX Muon Arms

- Detect muons with
  - p_{tot} > 2 GeV/c
  - -1.2 > η > -2.2 (South Arm) or
    1.2 < η < 2.4 (North Arm)
- Muon Tracker (MuTr)
  - Measure momentum of muons with cathode-readout strip chambers at 3 stations inside Muon Magnet
- Muon Identifier (MuID)
  - π/μ separation with 5-layer sandwich of chambers (Iarocci tubes) and steel
  - Trigger muons



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

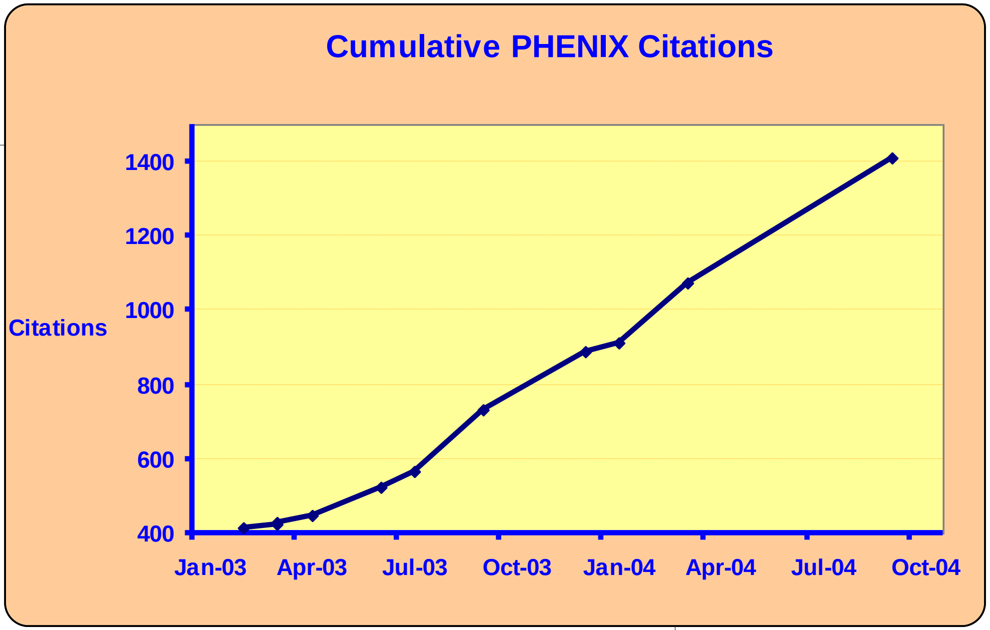
The RHIC machine performance has been very impressive:

- Machine is delivering design luminosity(+) for AuAu
- Collided 3 different species in 4 years
  - AuAu, dAu, pp
- 3 energies run
  - 19 GeV, 130 GeV, 200 GeV
- 1st operation of a polarized hadron collider

PHENIX	Year	Species	$s^{1/2}$ [GeV]	$\int L dt$	N_{tot} (sampled)	Data Size
Run1	2000	Au-Au	130	1 μb^{-1}	10M	3 TB
Run2	2001/02	Au-Au	200	24 μb^{-1}	170M	10 TB
		Au-Au	19	------	<1M	
		p-p	200	0.15 pb^{-1}	3.7G	20 TB
Run3	2002/03	d-Au	200	2.74 nb^{-1}	5.5G	46 TB
		p-p	200	0.35 pb^{-1}	6.6G	35 TB
Run4	2003/04	Au-Au	200(64)	241 μb^{-1}(9.1)	1.5G(58M)	200 TB
		p-p	200	352 μb^{-1}	360M	10 TB

Publication Summary

- Run-1
  - 12 publications
  - 8 are "TopCites"
    - 3 of these are "famous"
  - One "archival" summary
- Run-2
  - 12 publications to date
  - 4 are "TopCites"
    - 1 of these is "famous"
  - One "archival" summary
  - Several more nearing completion
    - Direct photons, open charm, energy survey…
- Run-3
  - 2 publications
    - d+Au suppression (a TopCite/famous)
    - First result on $A_{LL}(\pi^0)$ for spin study
  - Several in progress
- Run-4: > x 10 *data-size compared to Run-2 Au+Au*



PHENIX White Paper (I)

PHENIX just released White Paper which is a extensive review of its results up to Run3 (http://arXiv.org/abs/nucl-ex/0410003).

- Energy density; $\varepsilon_{Bj}=(1/\tau A)(dE_T/dy)$
  - For the Created particles at proper time (τ_{Form}=0.35fm/c); 15 GeV/fm^3.
  - Hydrodynamical calculation using elliptic flow (τ_{Therm}=1fm/c); 5.4 GeV/fm^3.
- Thermalization
  - Measured yields/spectra are consistent with thermal emission (T_{Therm}=157MeV, μ_B=23MeV, β=0.5).
  - Elliptic flow (v_2) is stronger at RHIH than at SPS, and $v_2(p) < v_2(\pi)$.
  - Currently do not have a consistent picture of the space-time dynamics of reactions at RHIC as revealed by p_t spectra, v_2 vs p_t for proton and pion; not yet possible to extract quantitative properties of QGP or mixed phase using those observables.
- Fluctuations
  - Net charge fluctuations has ruled out the most naïve model in a QGP by showing non-random fluctuations expected from high-p_t jets only.
  - A severe constraint on the critical fluctuations expected for a sharp phase transition but is consistent with the expectation from lattice QCD having a smooth transition.

PHENIX White Paper (II)

- Binary Scaling
  - To exclude final state medium effect, π from d+Au, γ/total charm yields from Au+Au collisions were used.
  - Experimental evidence for the binary scaling of point-like pQCD process in AuAu collisions.
  - Initial condition for hard-scattering at RHIC is an incoherent superposition of nucleon structure functions.
- High-P_t Suppression
  - The observed suppression of high-pt particle production at RHIC is a unique phenomenon not having been produced previously.
  - Medium induced energy lose is the only currently known physical mechanism that can fully explain the observed high-p_t suppression.
- Hadron production
  - The large (anti) baryon to pion excess relative to expectations from parton fragmentation functions at p_t=2-5GeV/c remains one of the most striking unpredicted experimental observations at RHIC.
  - At present, no theoretical framework provides a complete understanding of hadron formation in the intermediate P_t region.

PHENIX White Paper (III) ; Future Measurements

To further define and characterize the state of matter formed at RHIC, PHENIX is just starting the study of penetrating probes not experiencing strong interactions in the produced medium. By their very nature, penetrating probes are also rare probes and consequently require large value of the integrated luminosity.

- High-P_t Suppression and Jet Physics
  - Trace the suppression to much higher P_t to determine whether it disappears.
  - High momentum jet correlations using π, K, p to beyond 8GeV/c in P_t and γ.
- J/ψ Production
  - $\mu^+\mu^-$ decay channel at forward and backward rapidities, and e^+e^- decay channel in mid-rapidity for p+p, d+A/p+A, and A+A systems.
- Charm Production
  - Produced in the initial hard collisions between the incoming partons. Measure indirectly using high-p_t single leptons and directly with upgraded detector.
- Low-Mass dileptons
  - Sensitive prove of chiral symmetry restoration.
- Thermal Radiation
  - Through real photons or dileptons, a direct fingerprint of the matter formed.

More on High P_T Suppression

I would like to pick the most famous result for the rest of my talk. The following are topics related to the High P_T Suppression.

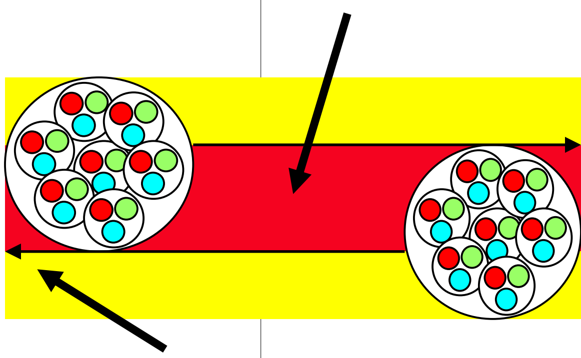
- Event Characterization in PHENIX
- Collision centrality, N_participants, N_collisions
- High p_T hadron suppression in Au+Au
- High p_T hadron suppression in d+Au (control exp.)
- Suppression of far-side jet in central Au+Au

Event characterization

AA collisions are not all the same, centrality (or impact parameter b) can be determined by measuring multiplicity (or transverse energy) near collision point combined with the number of free neutrons into beam directions.

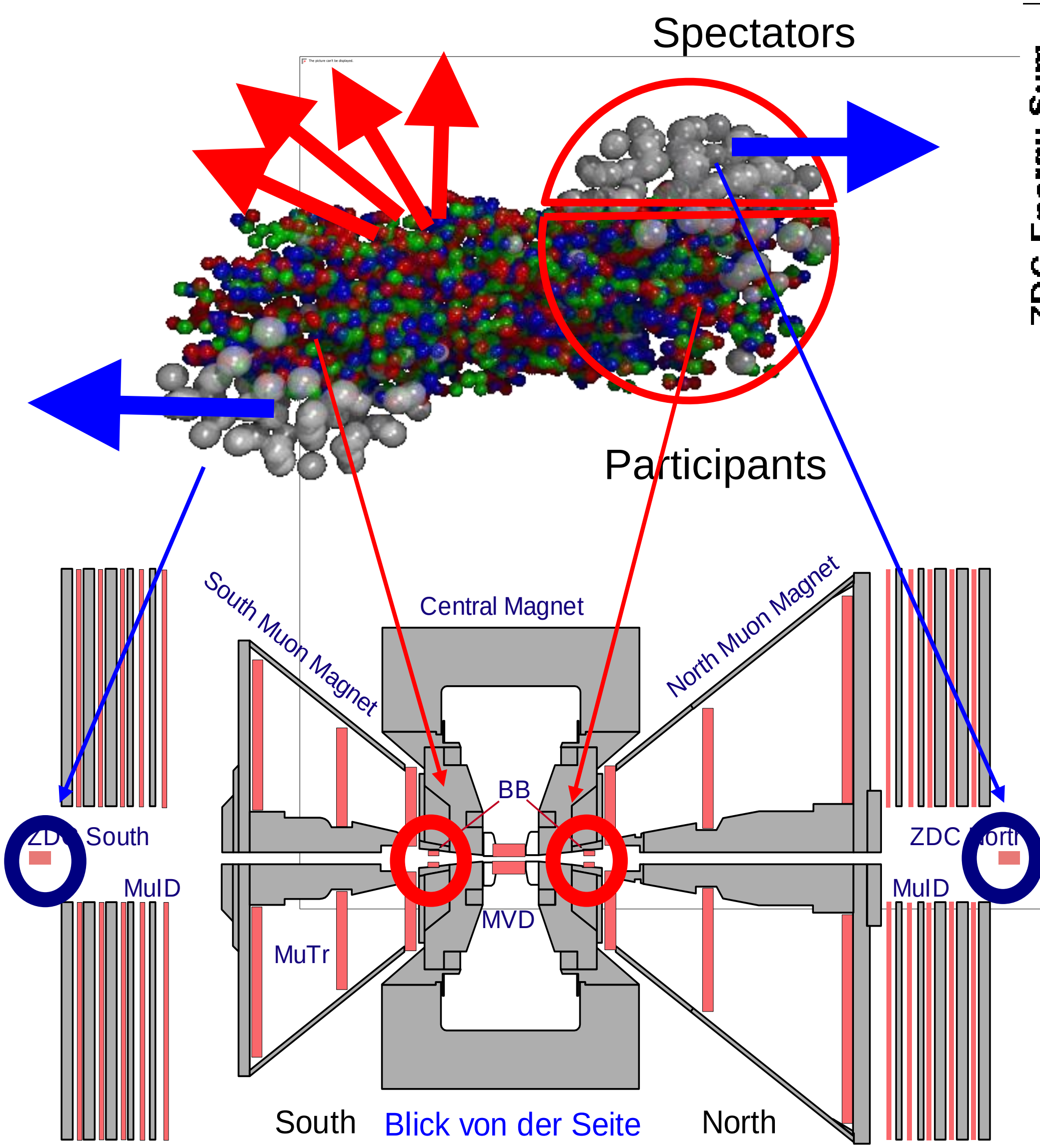
- *Npart*: Number of nucleons which suffered at least one inelastic nucleon-nucleon collision

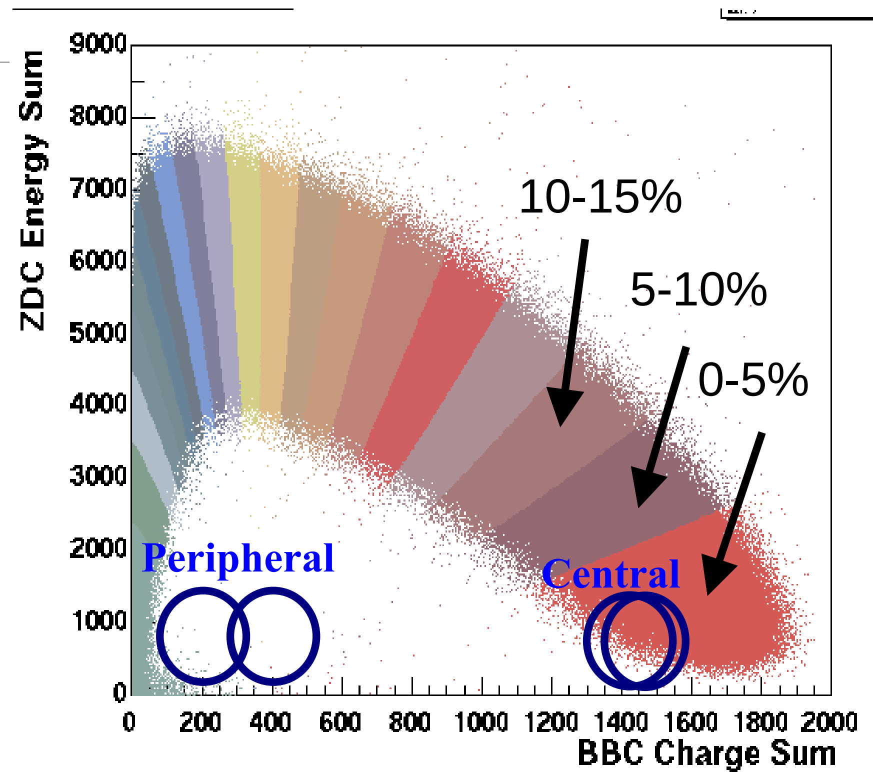
- *Ncoll*: Number of inelastic nucleon-nucleon collisions



Knowing the centrality using multiplicity of charged particles (BBC) and, number of free neutrons (ZDC), we can determine *Npart* and *Ncoll* from Glauber calculations; **Phys. Rev. 100 (1955) 242.**

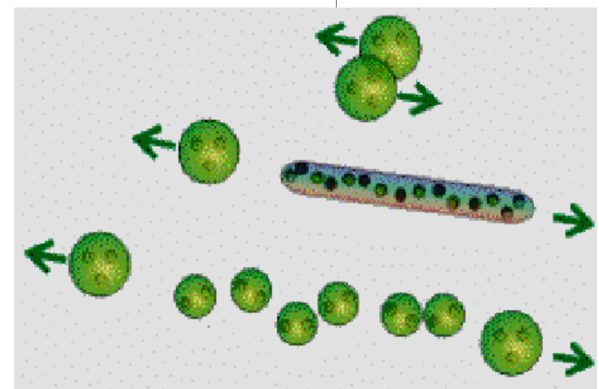
Collision Centrality Determination



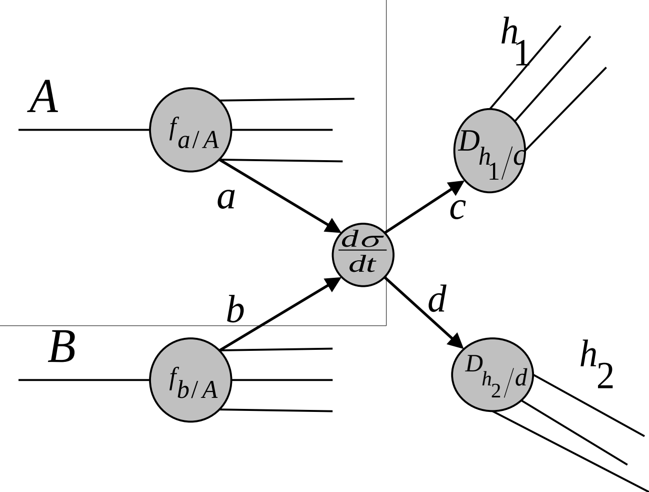


- Centrality selection : Sum of Beam-Beam Counter (BBC, |η|=3~4) and energy of Zero-degree calorimeter (ZDC)
- Extracted N_{coll} and N_{part} based on Glauber model.

AA as a superposition of pp



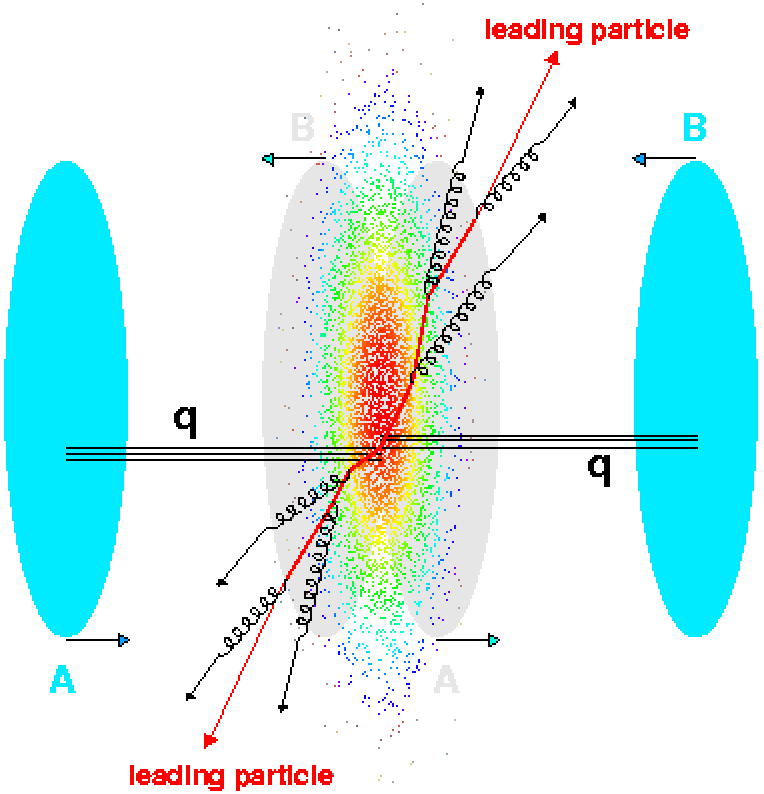
Probability for a "soft" collision is large (~99.5%). If it happens, the nucleon is "wounded" and insensitive to additional collisions as it needs some time (~1fm/c) to produce particles, thus yields of soft particles scale from pp to AA as the number of participants(*Npart*).



Probability for a "hard" collision for any two nucleons is small, thus yields of hard particles should scale with the number of binary nucleon-nucleon collisions(*Ncoll*).

Hard scattering in Heavy Ion collisions

schematic view of jet production



Jets:

- primarily from gluons at RHIC
- produced early (τ<1fm)
- sensitive to the QCD medium (dE/dx)

Observed via:

- fast leading (high pt) particles or
- azimuthal correlations between them

Mechanisms of energy loss in vacuum (*pp*) is understood in terms of formation time and static chromoelectric field regeneration* . Any nuclear modification of this process could provide a hint of QGP formation.

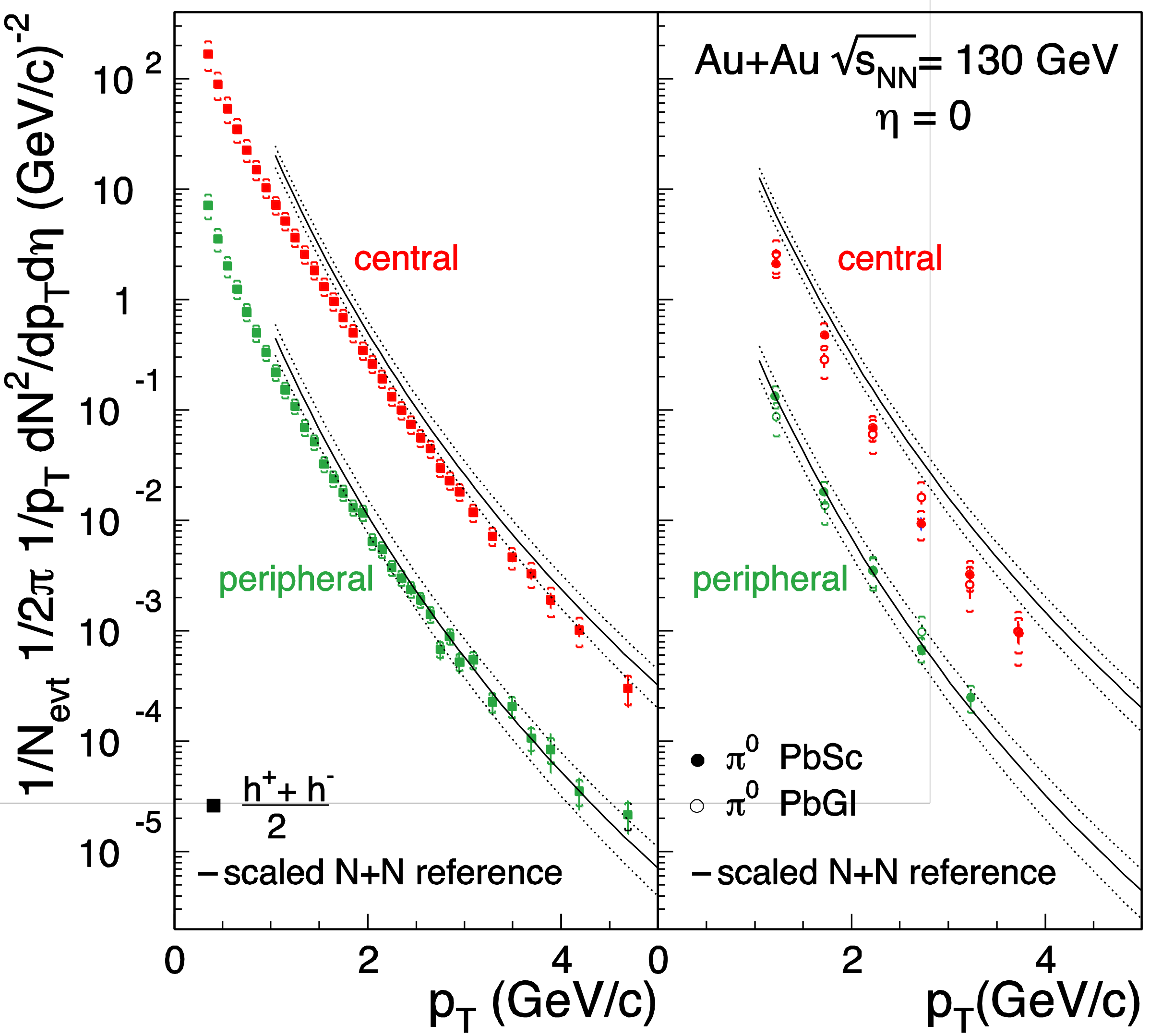
* *F.Niedermayer, Phys.Rev.D34:3494,1986.*

RHIC Year-1 High-PT Hadrons

Hadron spectra out to p_T~4-5 GeV/c

Nominally high p_T hardrons are from hard scattering; scale spectra from N+N by number of binary collisions

Peripheral reasonably well reproduced; but central significantly below binary scaling

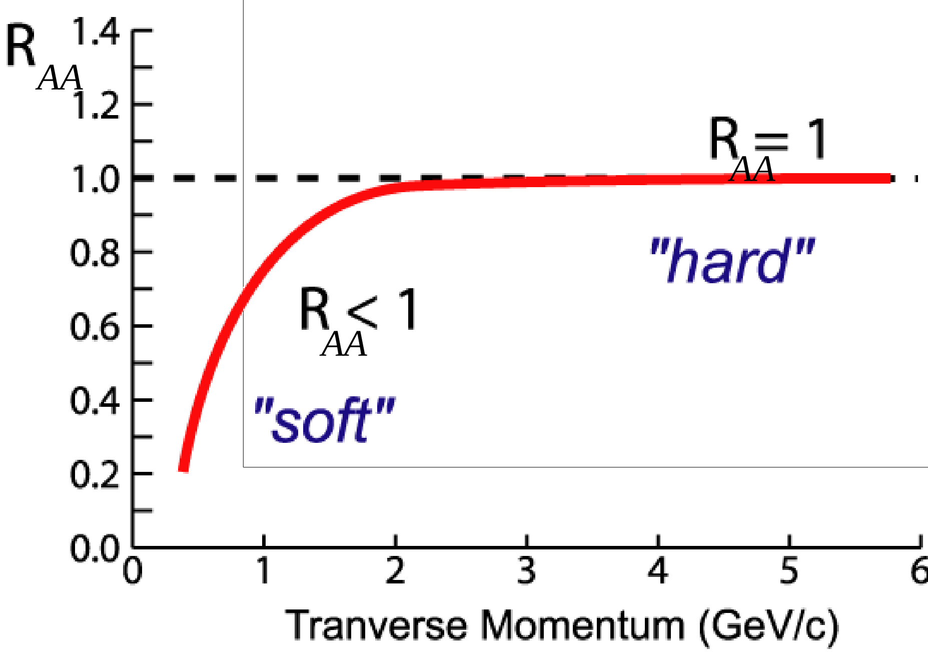


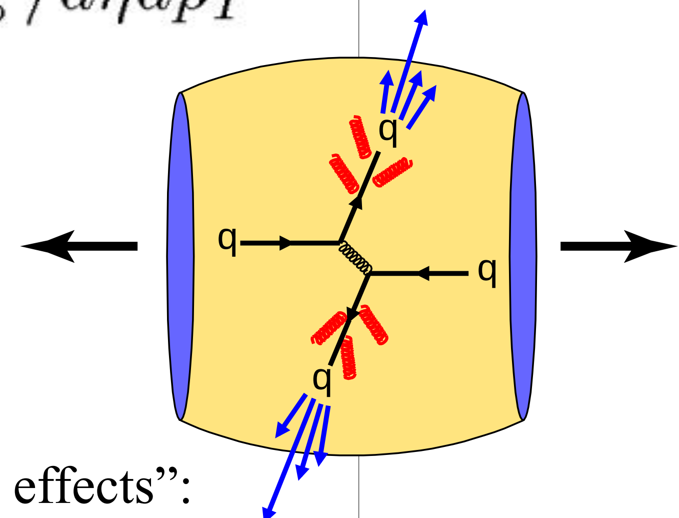
Closer look using the Nuclear Modification Factor RAA

Nuclear Modification Factor:

$$R_{AA}(p_T) = \frac{d^2N_{AA}/d\eta dp_T}{\langle N_{coll}\rangle d^2N_{pp}/d\eta dp_T}$$

Compare A+A to p-p cross sections





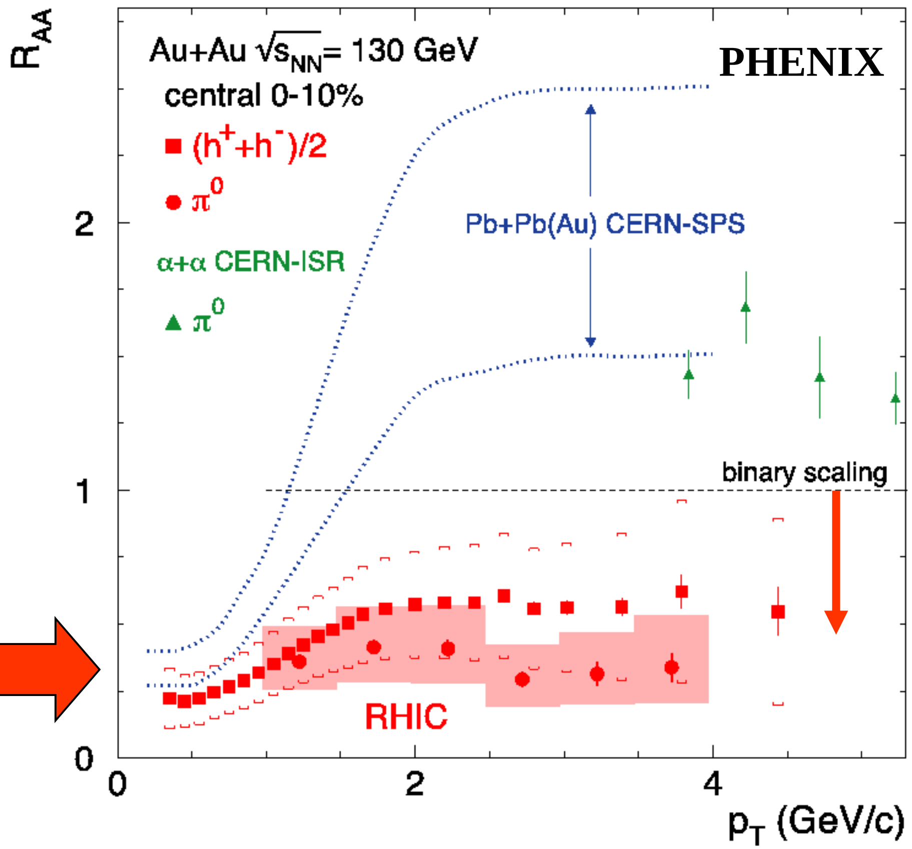
"Nominal effects":

- $R_{AA} < 1$ in regime of soft physics
- $R_{AA} = 1$ at high-p_T where hard scattering dominates
- $R_{AA} > 1$ due to k_T broadening (Cronin)

Suppression:

- $R_{AA} < 1$ at high-p_T

RHIC Headline News… January 2002



PHENIX PRL 88, 022301 (2002)

First observation of *large* suppression of high p_T hadron yields

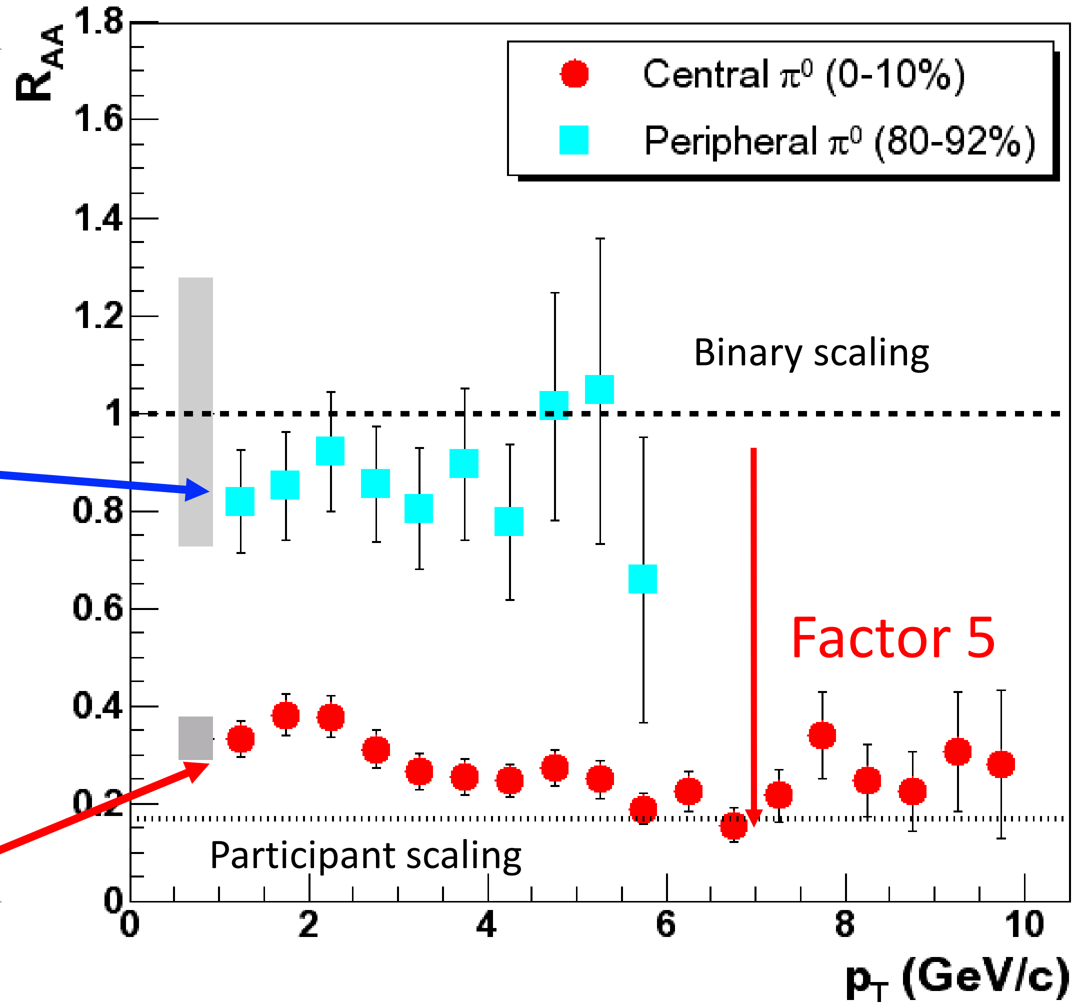
"Jet Quenching"? == Quark Gluon Plasma?

R_{AA} : High P_T Suppression to at least 10 GeV/c

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

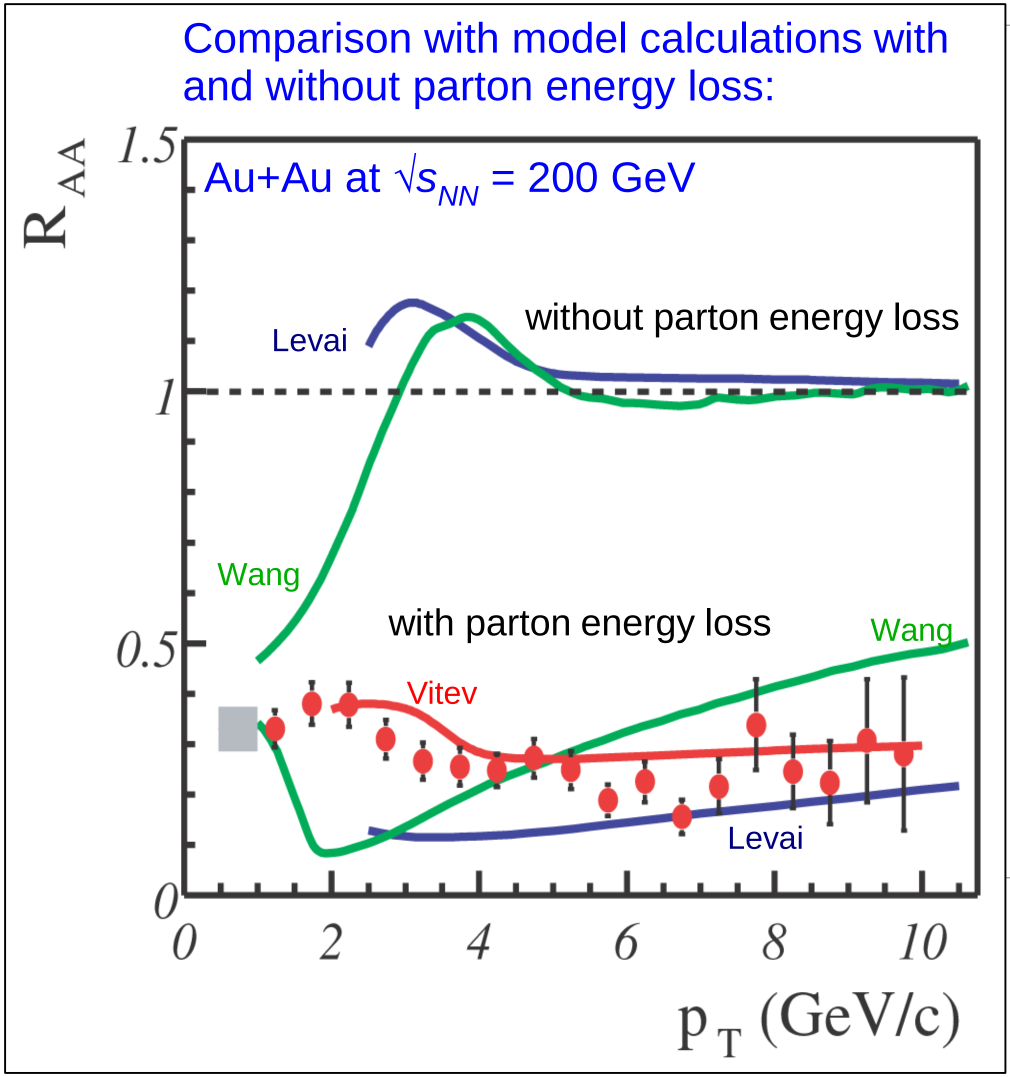
Peripheral AuAu - consistent with N_{coll} scaling (large systematic error)

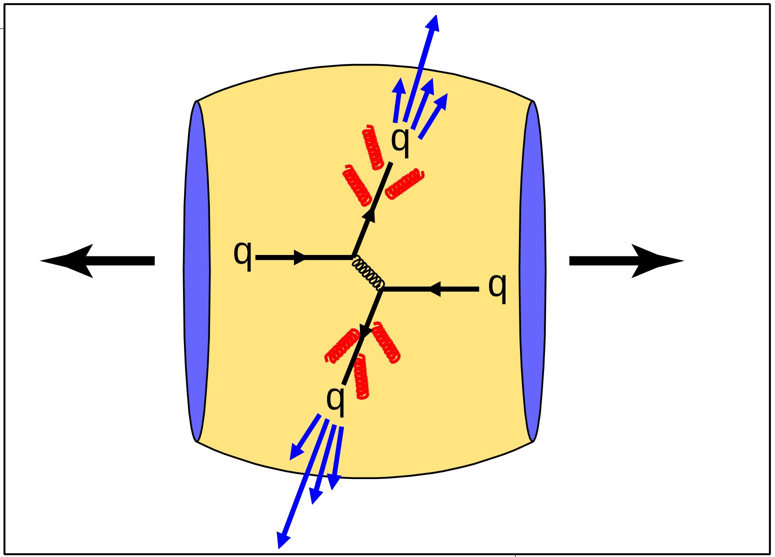
Large suppression in central AuAu - close to participant scaling at high P_T



PRL 91 (2003) 072301

Jet-Quenching?





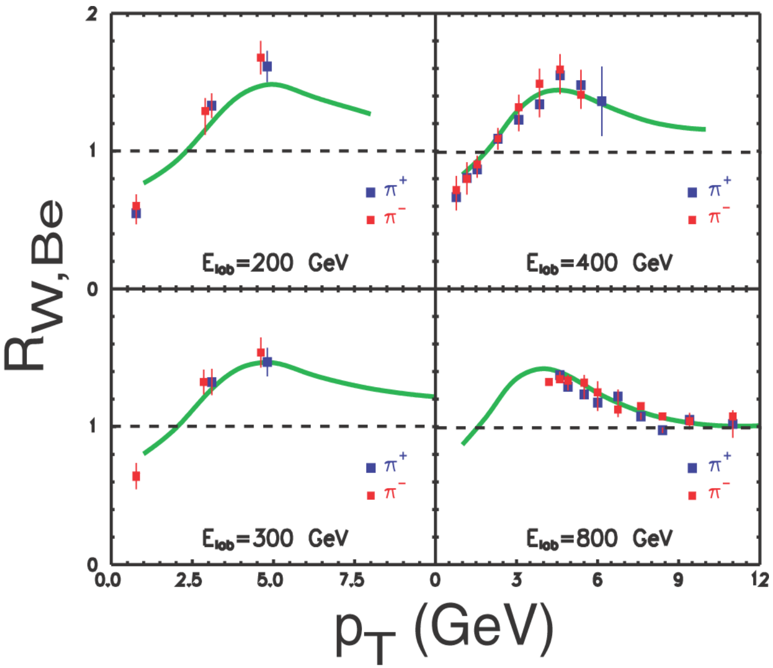
- Pion-suppression reproduced by models with parton energy loss
- p_T-dependence not well described

Initial State Effects

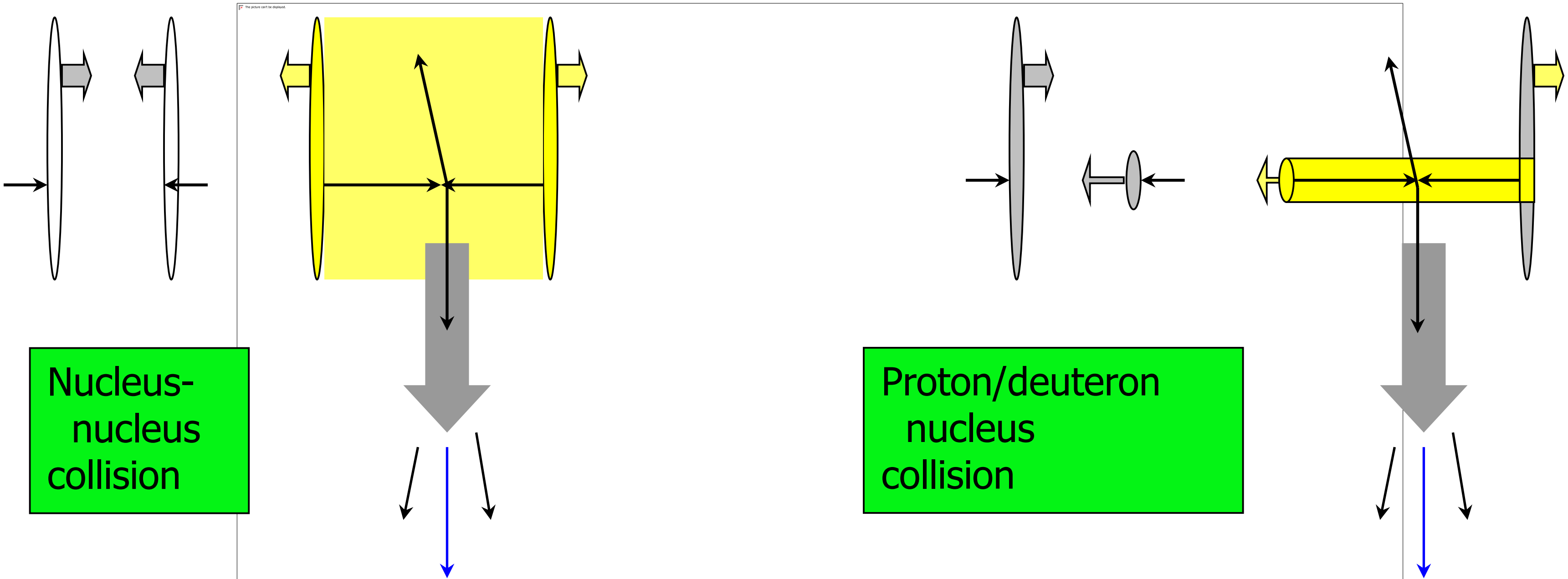
- Initial State Effects:
  Effects which lead to $R_{AA} \neq 1$ at high p_T but which are not related to properties of the hot and dense nuclear matter

- Candidates:
  Initial state multiple soft scatterings (Cronin Effect): increases R_{AA}
  Modification of the nucleon structure functions in nuclei (Shadowing): decreases R_{AA}
  Gluon saturation (Color Glass Condensate): decreases R_{AA} (?)

Cronin-Effect observed in p+A experiments:



p+A (or d+A): The control experiment



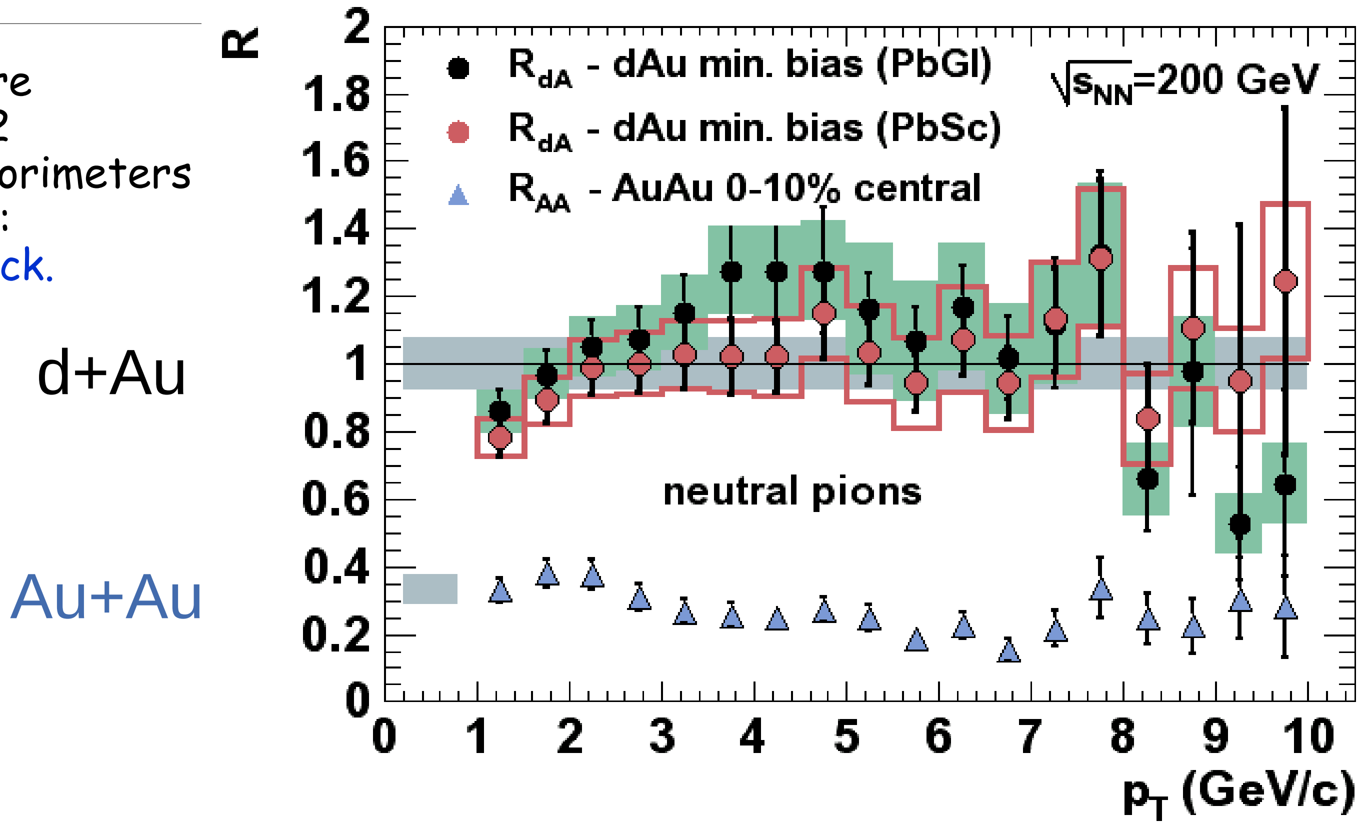
• **Jet Quenching** **interpretation; interaction with medium produced in** **final state** **suppresses jet.**

• **Gluon Saturation** **interpretation, gluons are suppressed in** **initial state** **resulting in suppression of initial jet production rate.**

• **If these initial state effects are causing the suppression of high-P_T hadrons in Au+Au collisions, we should see suppression of high-P_T hadrons in d+Au collisions.**

R_{AA} vs. R_{dA} for Identified π^0

Neutral pions are measured with 2 independent Calorimeters – PbSc and PbGl: Consistency check.

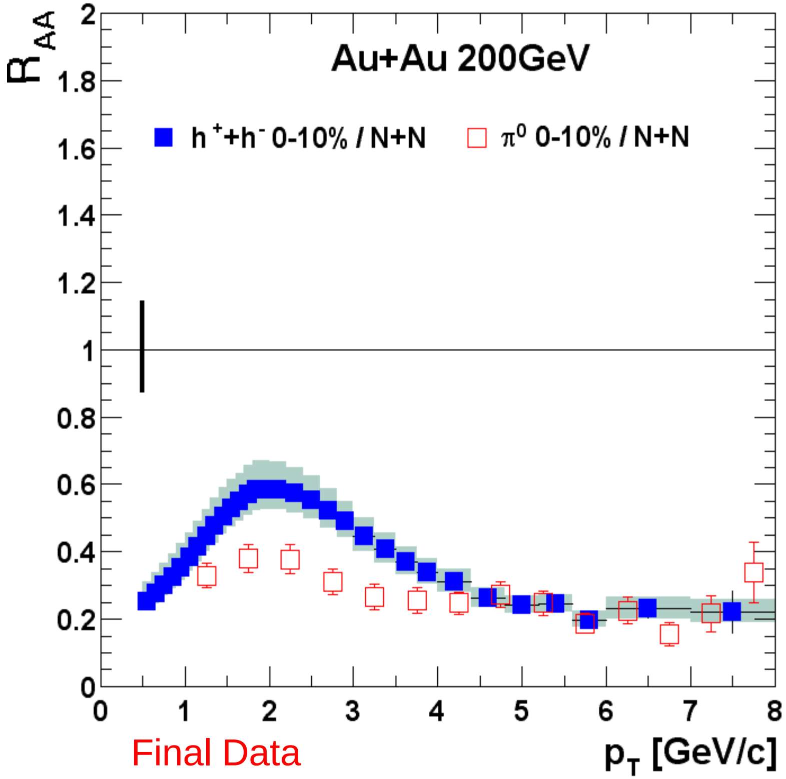


The dAu results (initial state effects only) suggest that the <u>created</u> medium is responsible for high p_T suppression in Au+Au.

PHENIX, PRL91 (2003) 072303.

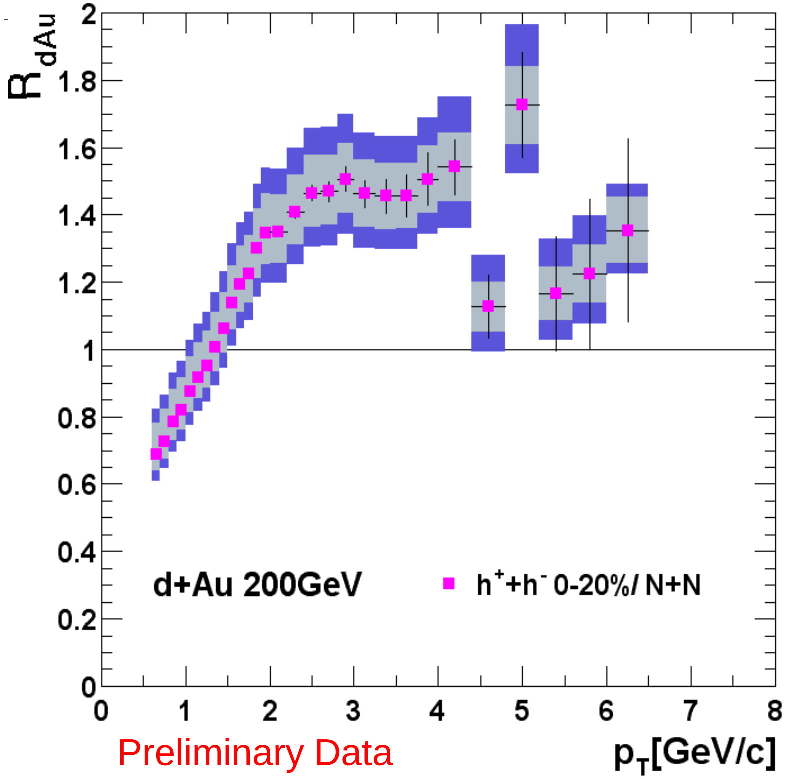
Centrality Dependence

Au + Au



Final Data

d + Au Control

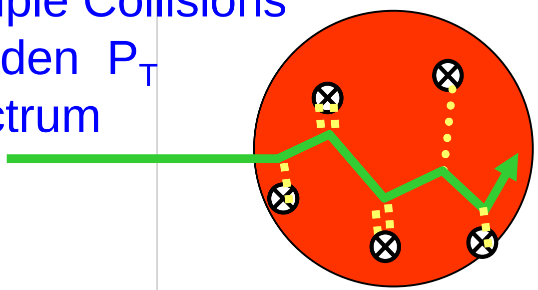


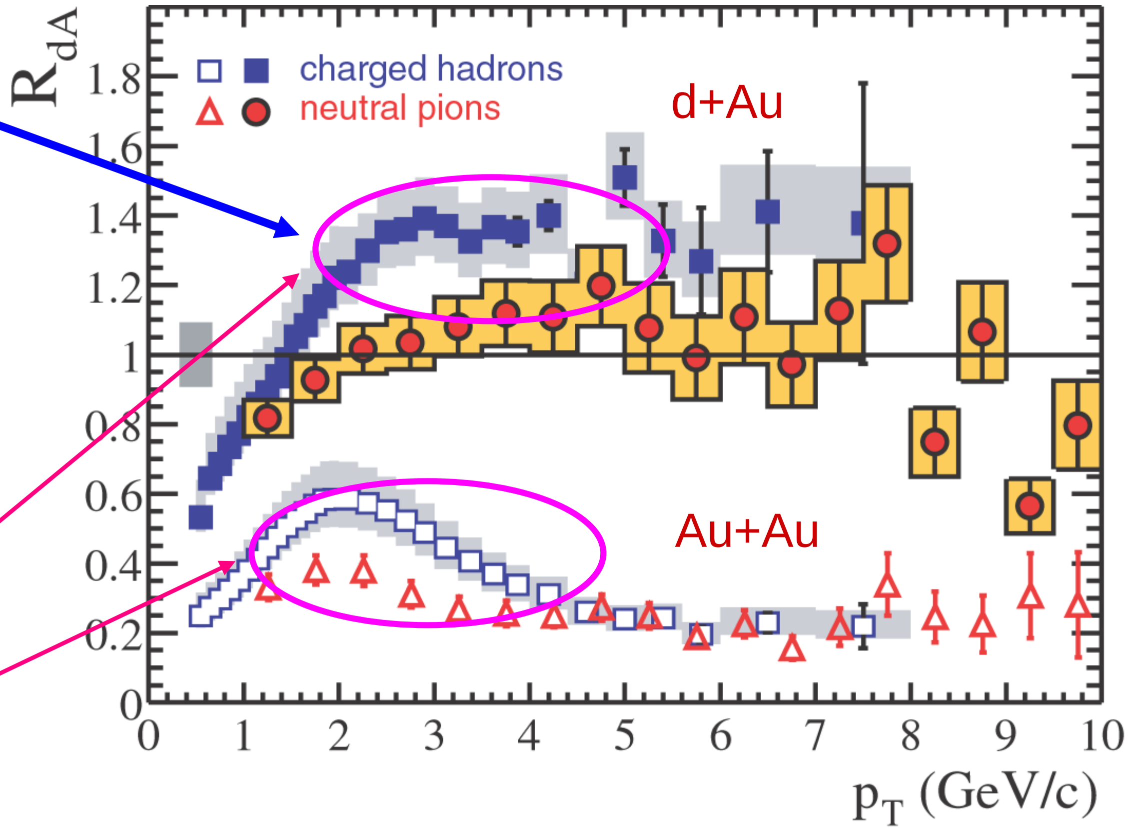
Preliminary Data

- Opposite centrality evolution of Au+Au compared to d+Au control.
- **Initial state enhancement ("Cronin effect") in d+Au is suppressed by final state effect in Au+Au.**
- **Notice difference between π^0 and $h^{+}+h^{-}$ (more later).**

Cronin Effect (R_{AA}>1) : h_ch vs. π^0

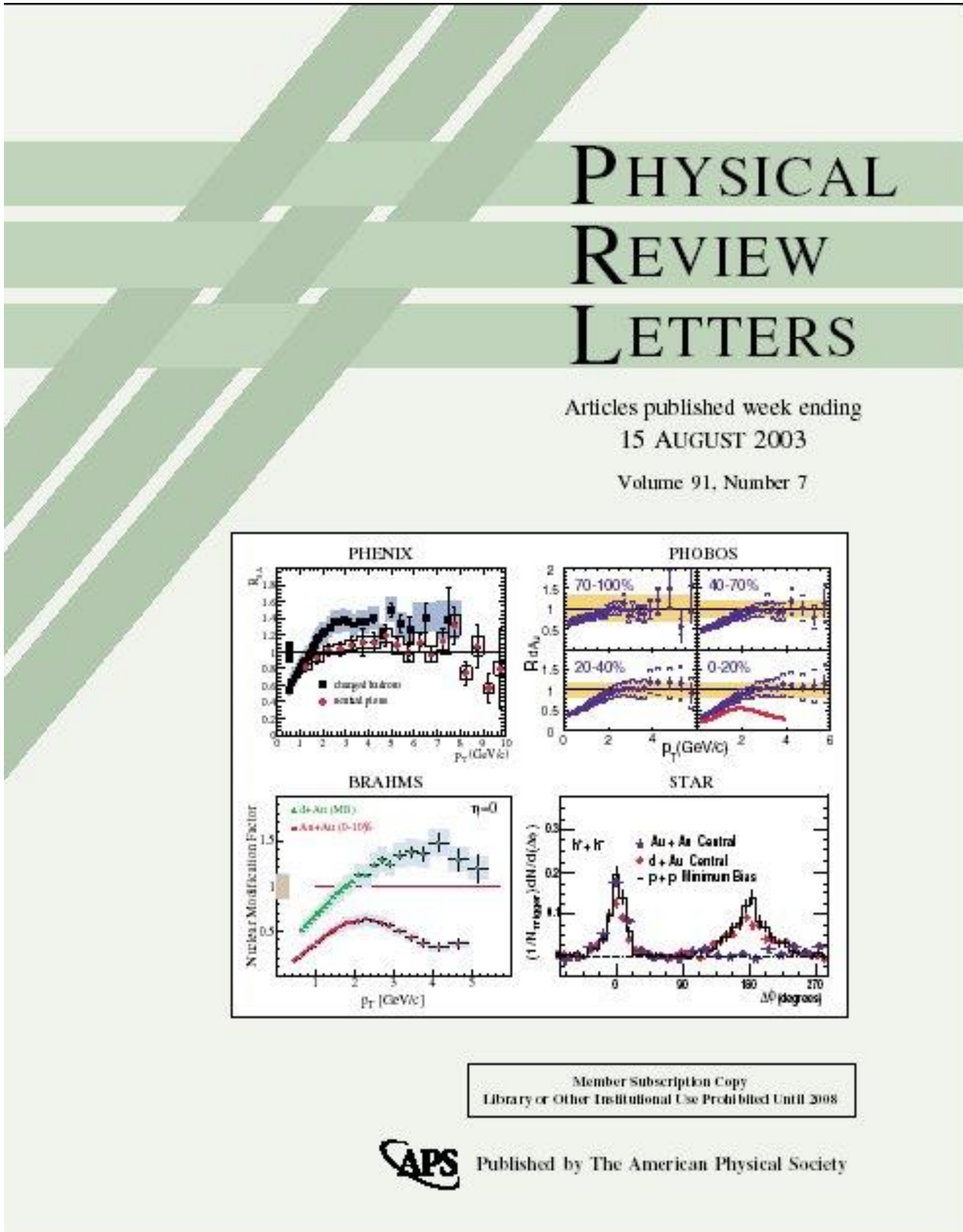
d+Au: Cronin Effect (R_{dA}>1): Initial Multiple Collisions broaden P_T spectrum





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

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



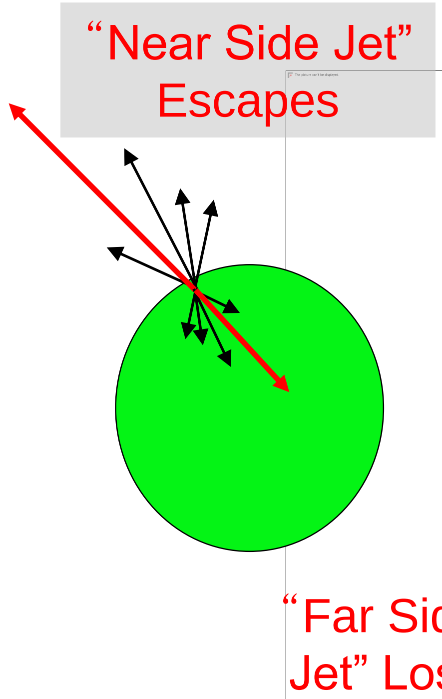
RHIC headline news… August 2003

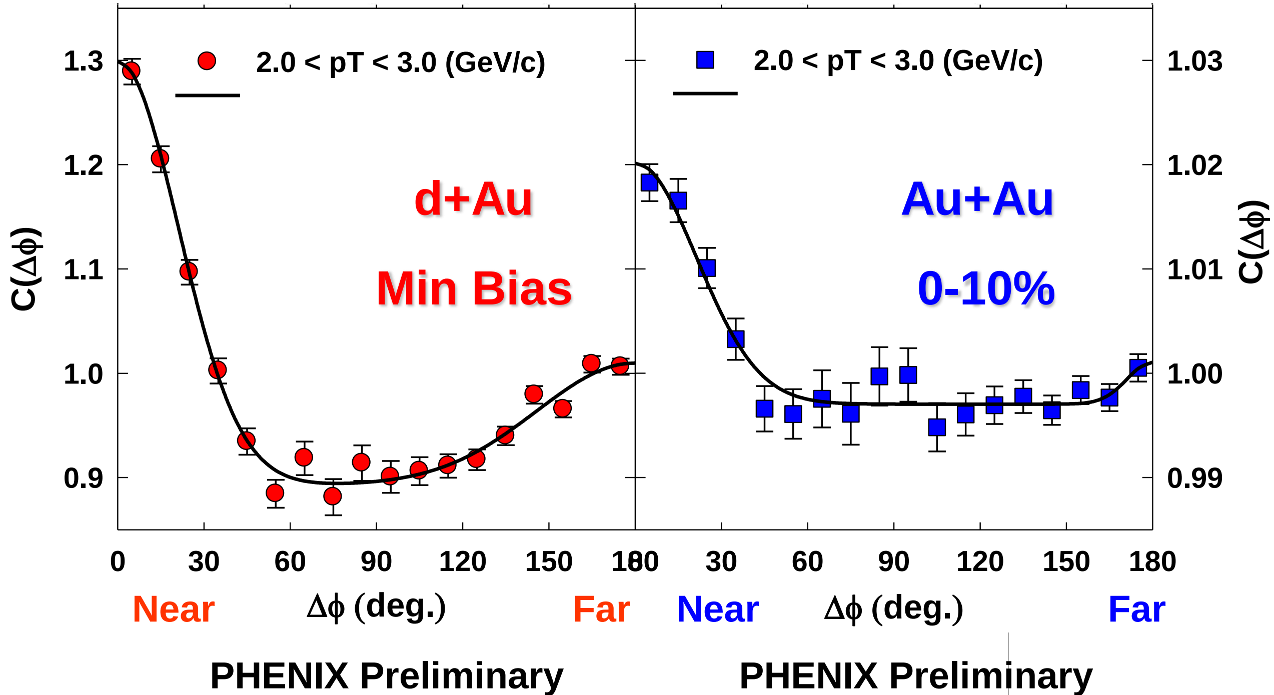
BNL Press Release, June 2003:

Lack of high p_T hadron suppression in d+Au strongly suggests that the large suppression in Au+Au is a final state effect of the produced matter (QGP?!)

PHENIX

Jet Correlations: 2-Particle Correlations



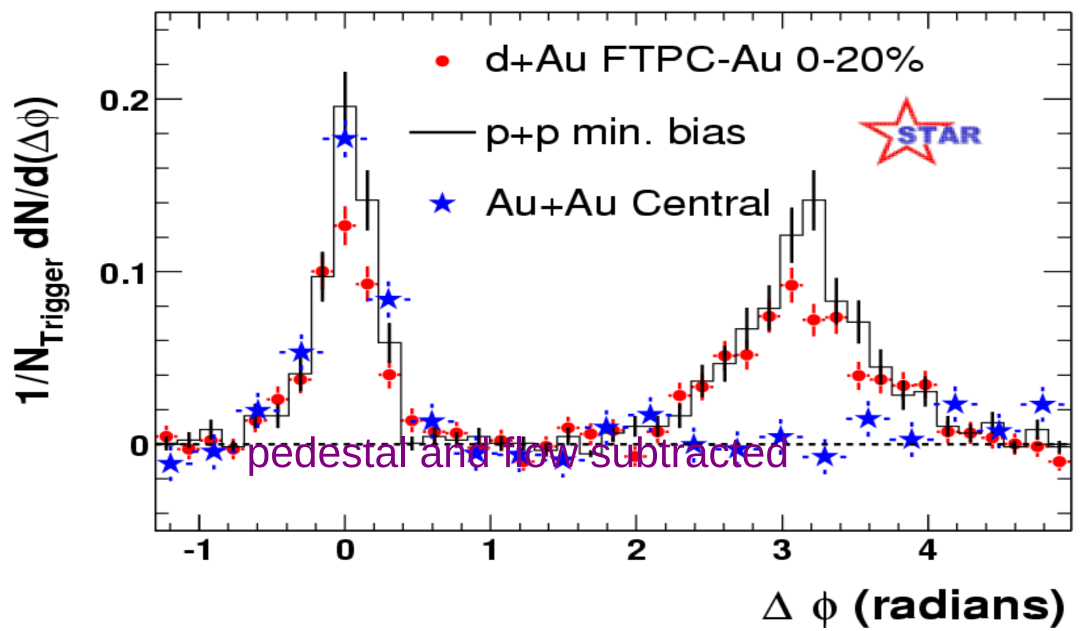


Parton exiting on the periphery of the collision zone should survive while partner parton propagating through the collision zone is more likely to be absorbed if Jet-Quenching is the correct theory.

Far-side Jet is suppressed in Central Au+Au : Further indication of suppression by produced medium.

Two Particle Azimuthal Distribution

The previous PHENIX result is consistent with published STAR result (PRL 91, 072304, 2003)



- Azimuthal distribution similar in p+p and d+Au
- Strong suppression of the far-side jet in central Au+Au

Summary of high-pt Suppression

- There is a massive suppression of high-pt hadron yield in Central AuAu collisions.

- No high-pt suppression in dAu collisions is observed and the initial state effect such as gluon condensation (CGC) can not explain the above suppression.

- The high-pt suppression in Central AuAu is consistent with the final state effect; partonic energy-loss (Jet Quenching) in produced matter (QGP?).

- Far-side Jet is suppressed in Central AuAu : Further indication of suppression by produced medium.