Hadron Production at Forward Rapidity in Nuclear Collisions at RHIC

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For BRAHMS Collaboration

BRAHMS

From Collider to Cosmic Ray, 2005

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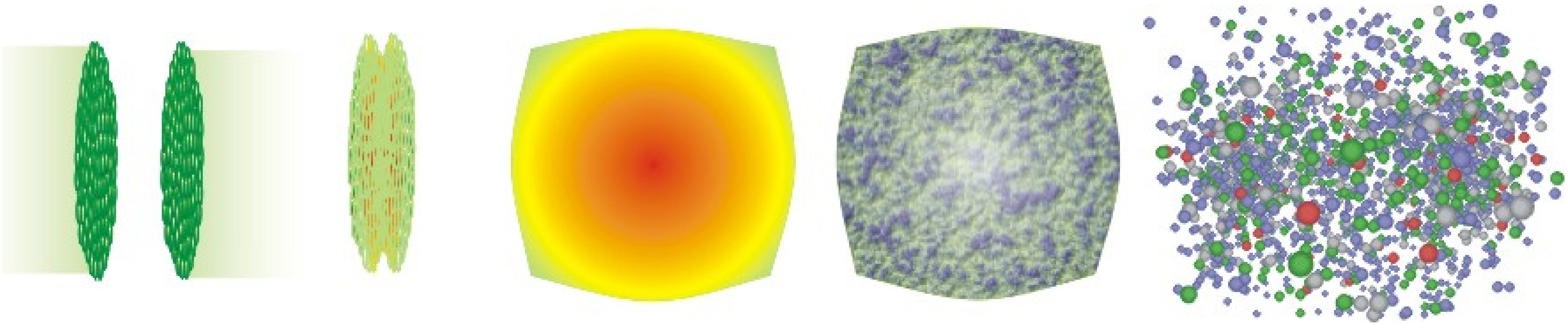
Outline

- Introduction
  1. RHIC
  2. BRAHMS experiment
- Probes measured by BRAHMS
  1. Nuclear stopping
  2. Particle production
  3. Nuclear Modification Factor
- Summary

Heavy Ion Collision Scenario



Initial condition:
high-Q^2 interactions
medium formation

Initial state:
(1) Color Glass Condensate
(2) Shadowing effect
(3) Initial multiple scattering
Cronin effect

hot, dense medium
expansion
hadronization

elliptic flow:
(1) Hydrodynamics
(2) EOS

hadrons
hadronic scatterings
freeze-out

ratios, spectra
(1) Jet quenching
(2) Parton recombination

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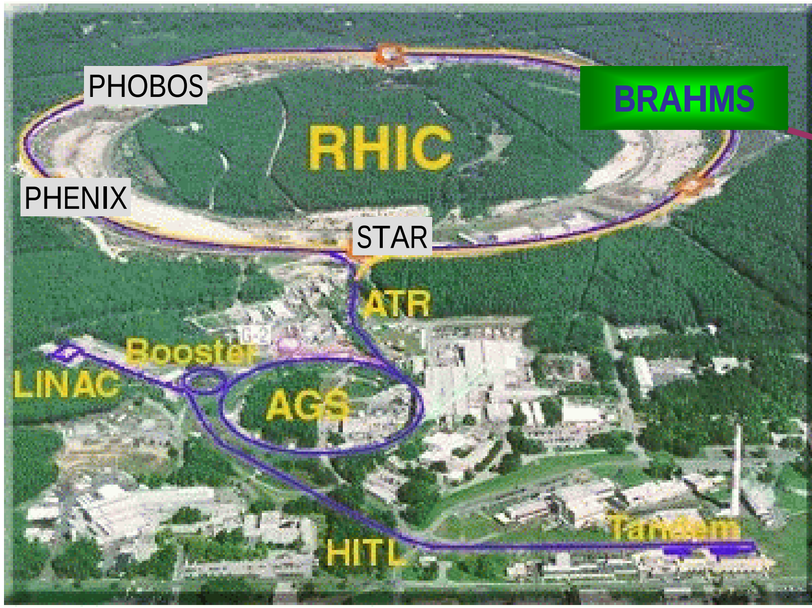
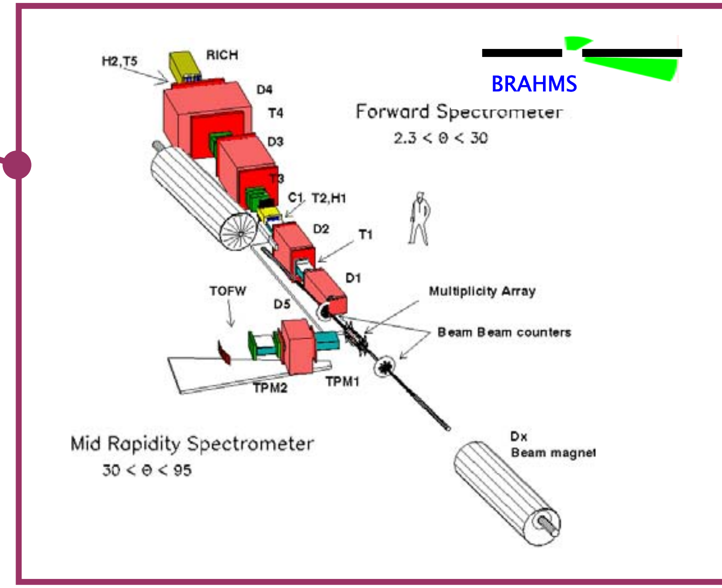
The Relativistic Heavy Ion Collider (RHIC)





energies:

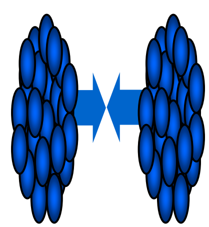
$\sqrt{s_{NN}} = 200GeV$

$\sqrt{s_{NN}} = 130GeV$

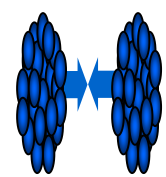
$\sqrt{s_{NN}} = 62.4GeV$

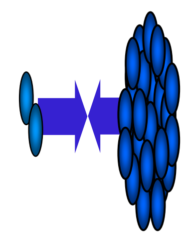
$\sqrt{s_{NN}} = 20GeV$

Au+Au



Cu+Cu





d+Au

p+p

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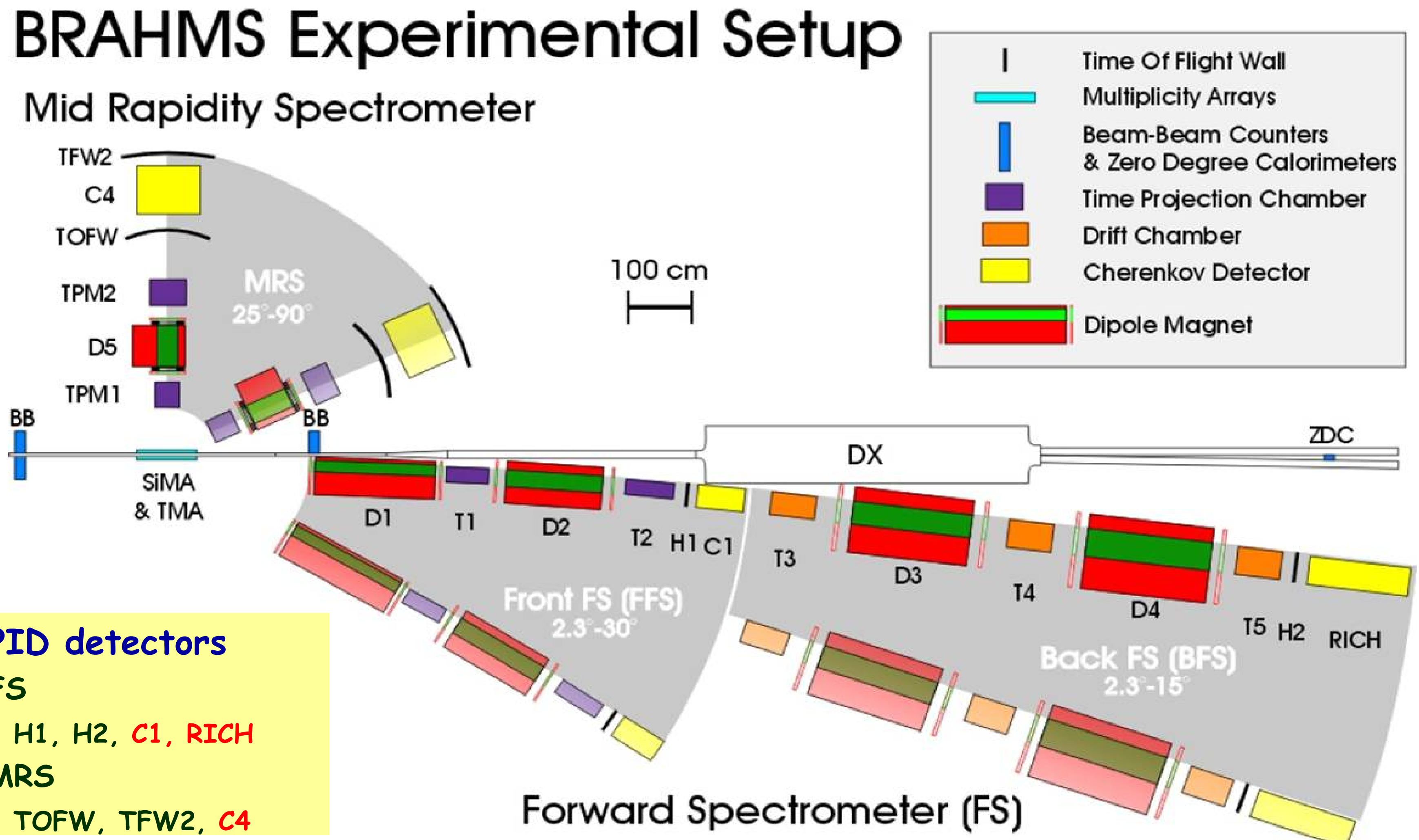
Broad Range Hadron Magnetic Spectrometers



PID detectors

FS

H1, H2, C1, RICH

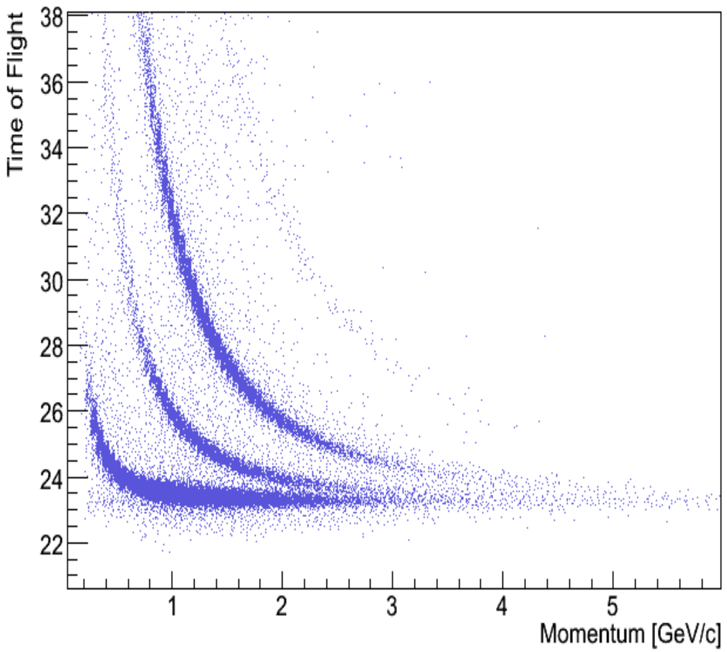
MRS

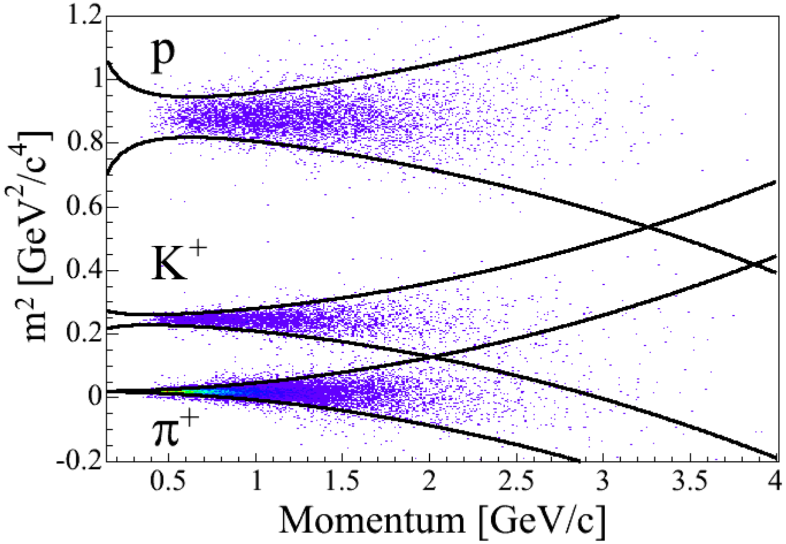
TOFW, TFW2, C4

BRAHMS experiment

➢PID detectors - TOF

Time Of Flight





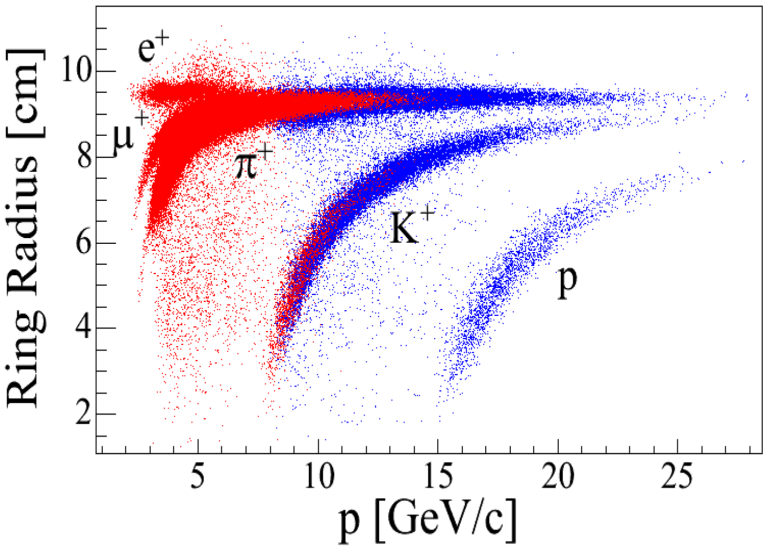
2σ cut	MRS TOFW	MRS TFW2	FS TOF1	FS TOF2
π / K	2.0 GeV/c	2.5 GeV/c	3.0 GeV/c	4.5 GeV/c
K / p	3.5 GeV/c	4.0 GeV/c	5.5 GeV/c	7.5 GeV/c

BRAHMS experiment

➢PID detectors

RICH

CHERENKOV



RICH: Cherenkov light focused on spherical mirror → ring on image plane

In Forward-Rapidity arm

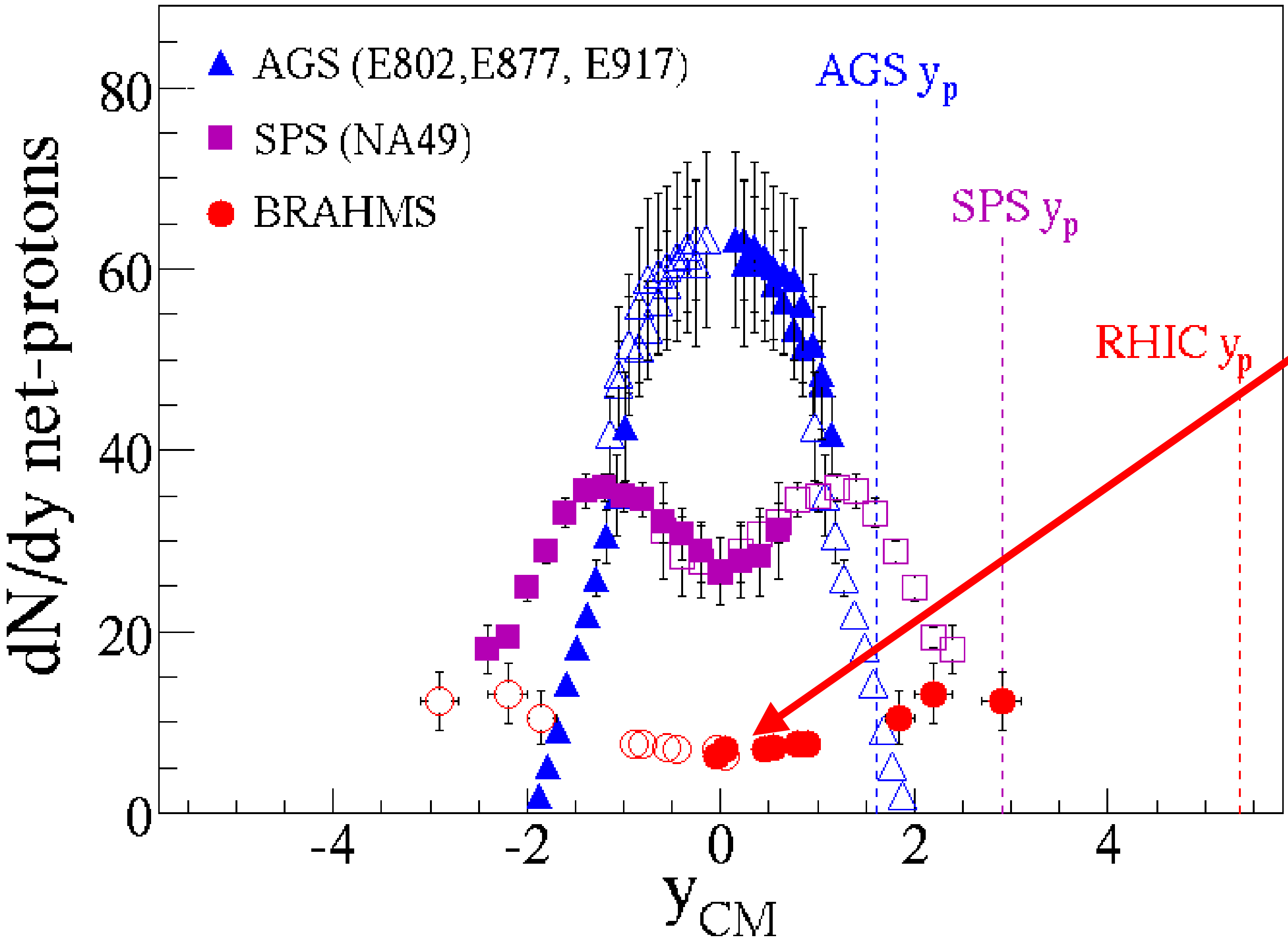
Ring radius vs momentum gives PID
π / K separation 25 GeV/c
Proton ID up to 35 GeV/c

In Middle-Rapidity arm

C4 Threshold:
π / K separation 9 GeV/c

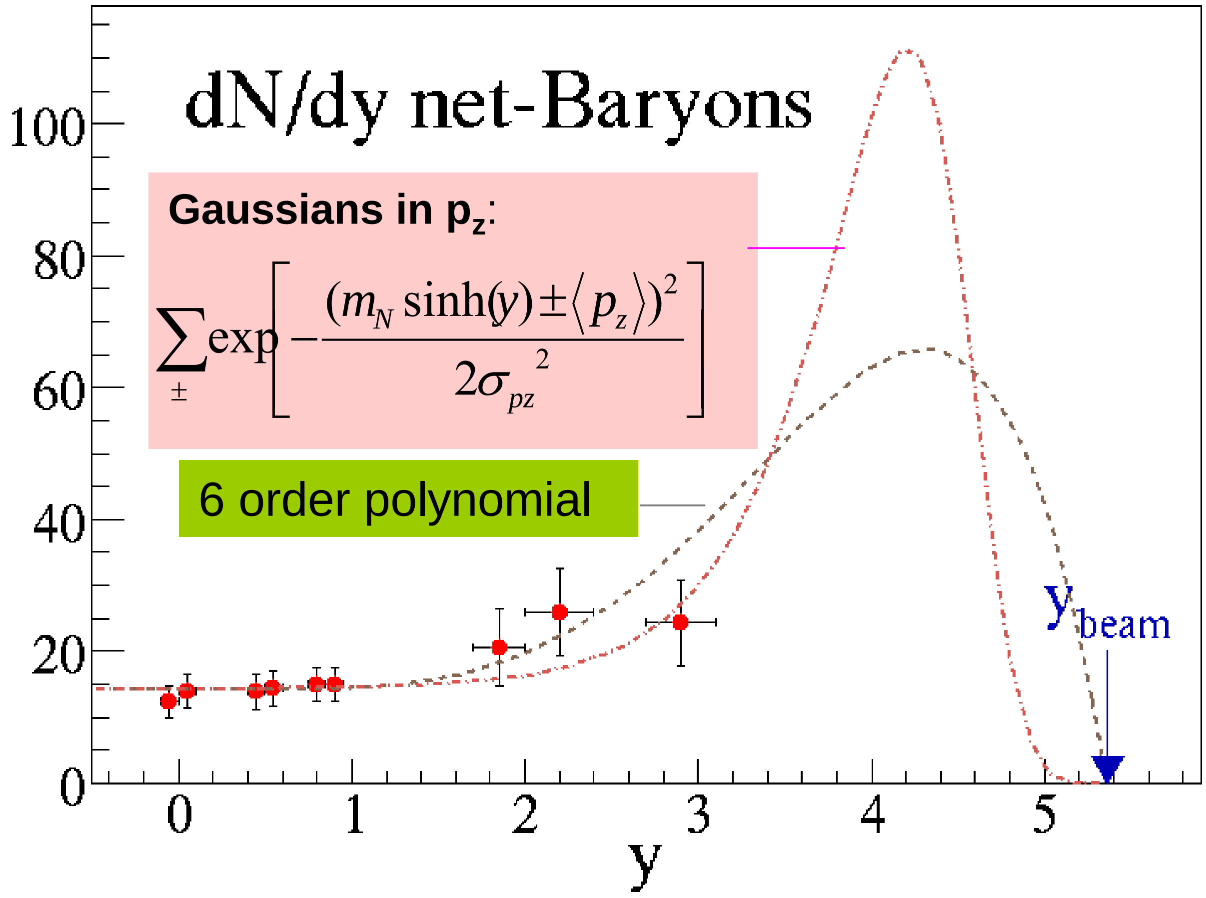
Stopping (1)

Energy dependence



At RHIC the mid-rapidity region is almost net-proton free.

Stopping (2)



Net-baryon obtianed after feed-down & neutron corrections

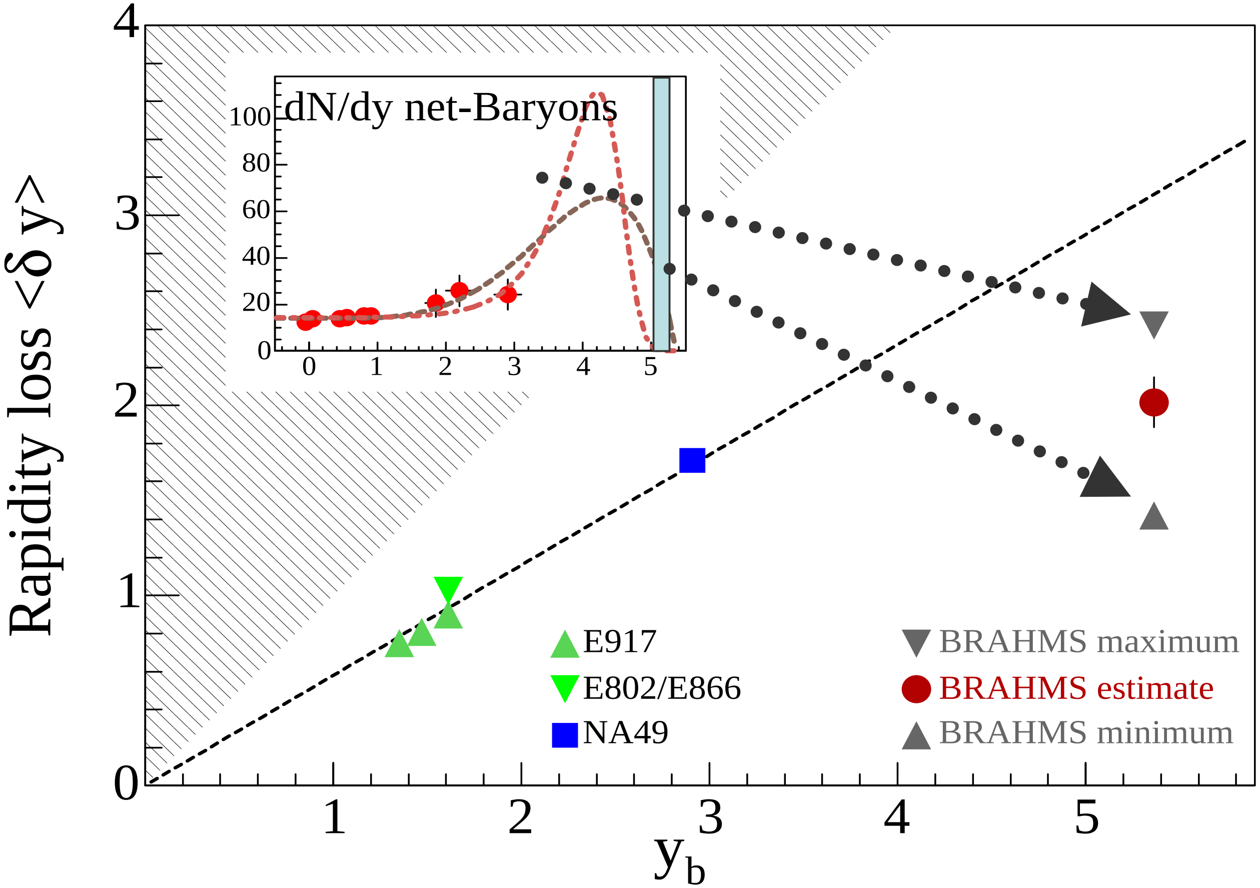
$\langle \delta y \rangle = 2.03 \pm 0.16$

$\langle \delta y \rangle = 2.00 \pm 0.10$

Rapidity loss: (N$_{part}$= 357 ± 10)

$$\langle \delta y \rangle = y_p - \langle y \rangle = y_p - \frac{2}{N_{part}} \int_0^{y_p} y \frac{dN_{(B-\overline{B})}}{dy} dy$$

Rapidity loss and Energy loss



- Upper limit to rapidity loss?
- Energy loss:

$$\int_{-y_p}^{y_p} \langle m_T \rangle_y \frac{dN_{(B-\bar{B})}}{dy} \cosh y \, dy$$

ΔE = 25.7 ± 2.1 TeV

ΔE/nucleon = 72 ± 6 GeV

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Stopping summary

- Net-baryon poor midrapidity region
  - dN(net-protons)/dy = 7
- Largest observed rapidity loss
  - $\langle \delta y \rangle = 2$
- Stopping power at RHIC
  - central Au+Au at RHIC: 72%
  - central Pb+Pb at SPS : 68%
  - central S+S at SPS: 58%
  - p+p collisions: $\approx$ 50%

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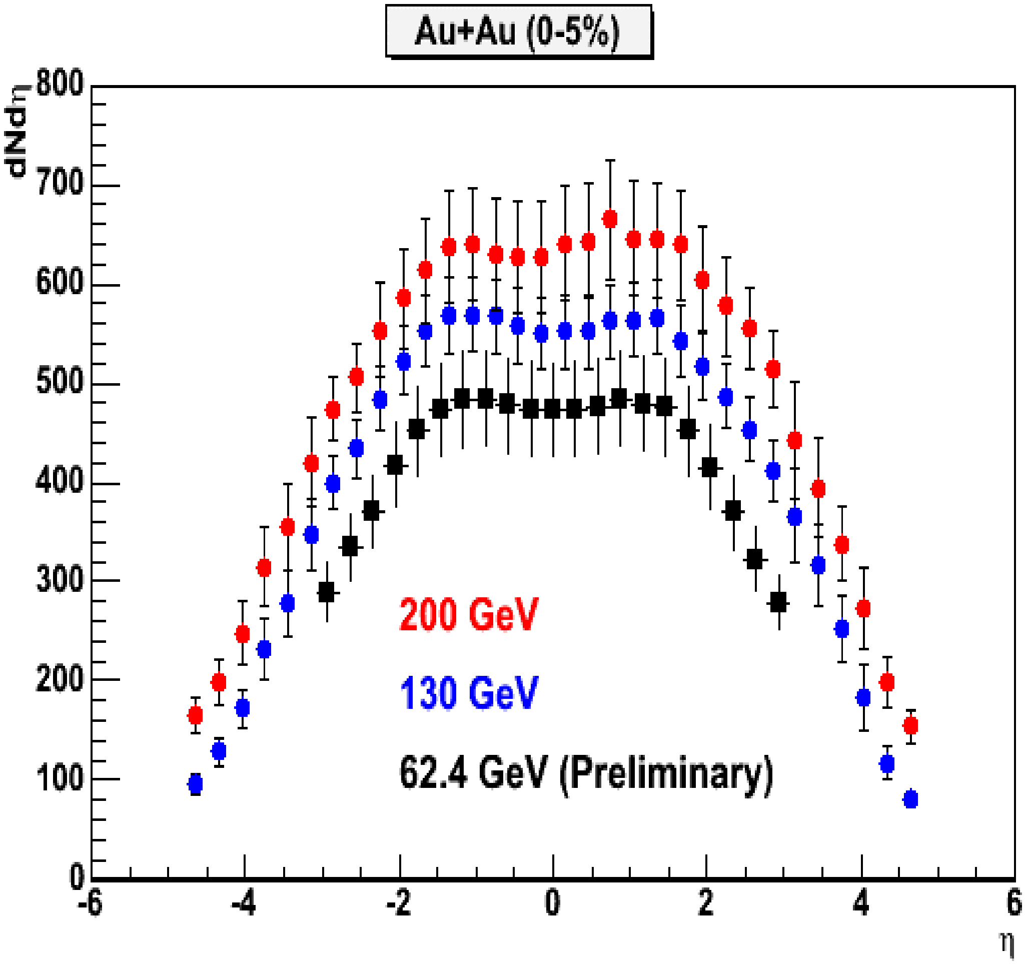
Particle Production

Energy dependence



Energy density: Bjorken 1983

$e_{BJ} = 3/2 \times (\langle E_t \rangle / \pi R^2 \tau_0)\, dN_{ch}/d\eta$

assuming formation time t_0=1fm/c:

>5.0 GeV/fm^3 for AuAu @ 200 GeV

>4.4 GeV/fm^3 for AuAu @ 130 GeV

>3.7 GeV/fm^3 for AuAu @ 62.4 GeV

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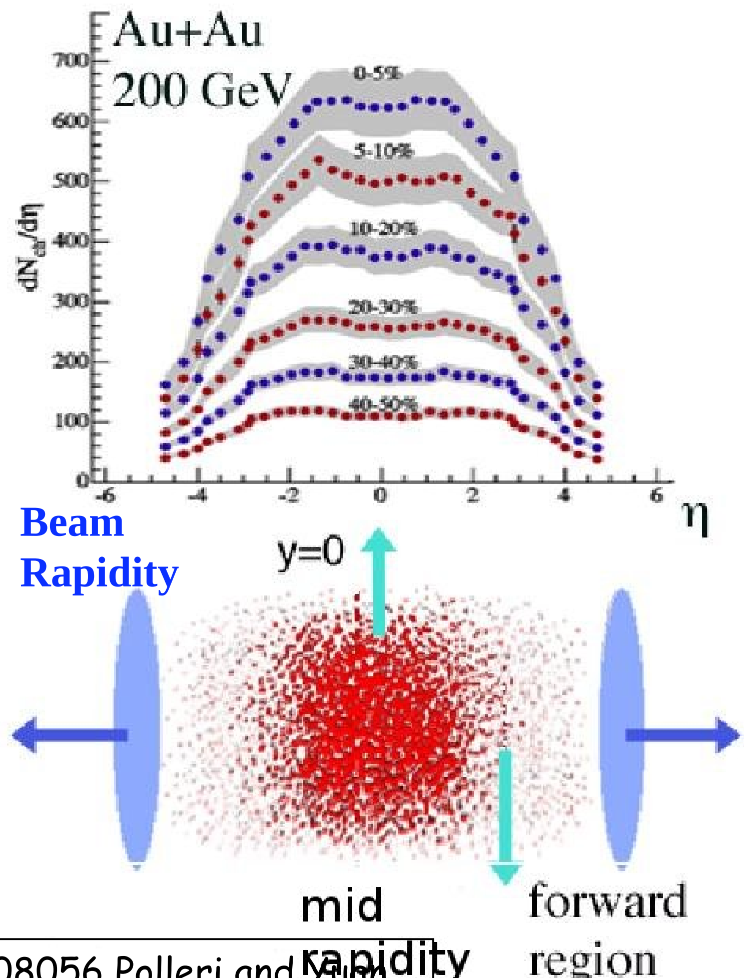
Particle Production

Centrality dependence of charged particles



Nucl-th/0108056 Polleri and Yuan

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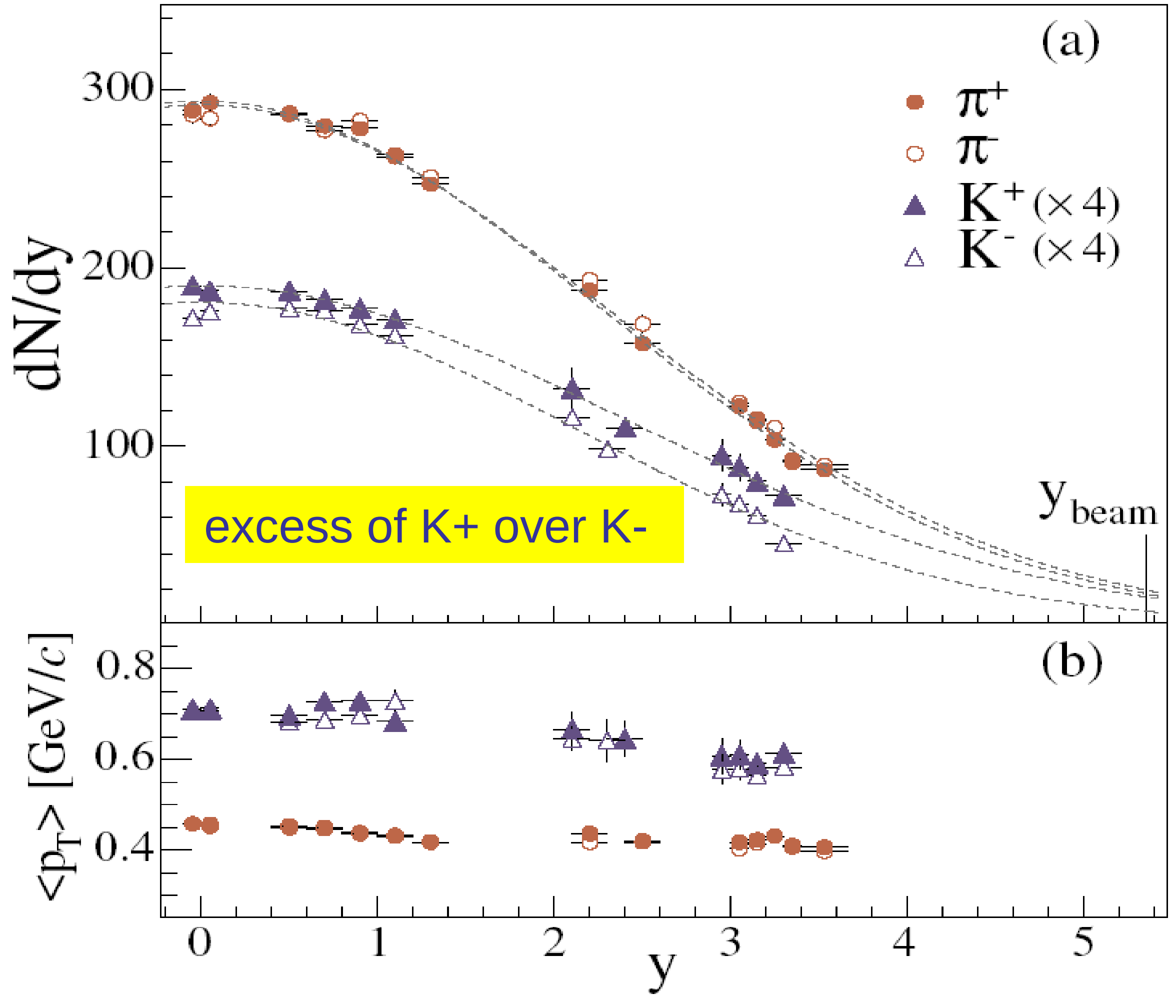
Particle Production



(a) Pion and kaon rapidity densities dN/dy as a function of rapidity

(b) mean transverse momentum $\langle p_T \rangle$ as a function of rapidity.

Errors are statistical.

PRL **94,** 162301 (2005)

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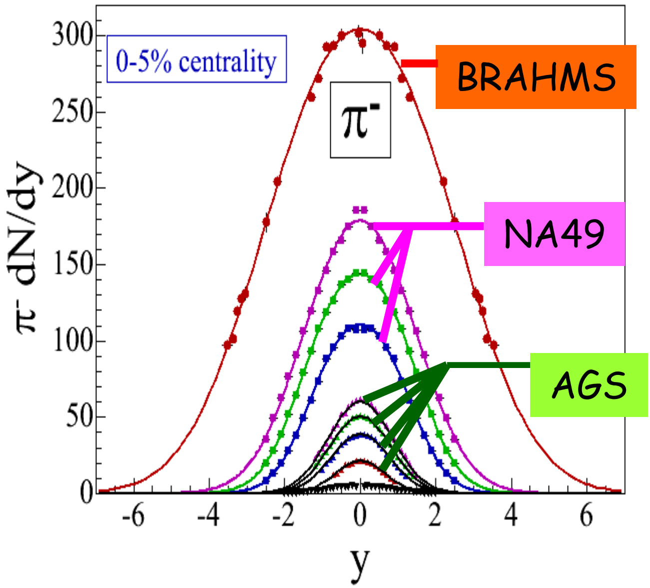
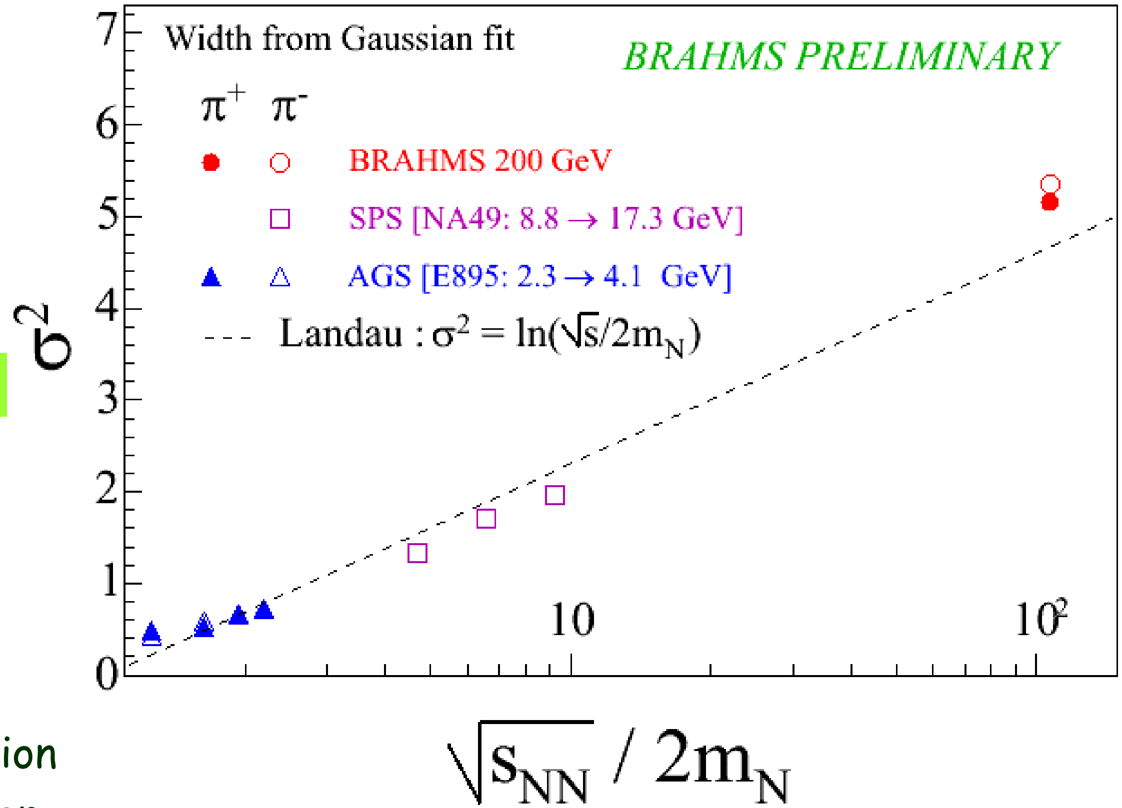




- Landau hydrodynamics
  - Gaussian rapidity distribution
  - Observed in hadron - hadron collisions
  - Width σ depends only on c.m. energy:

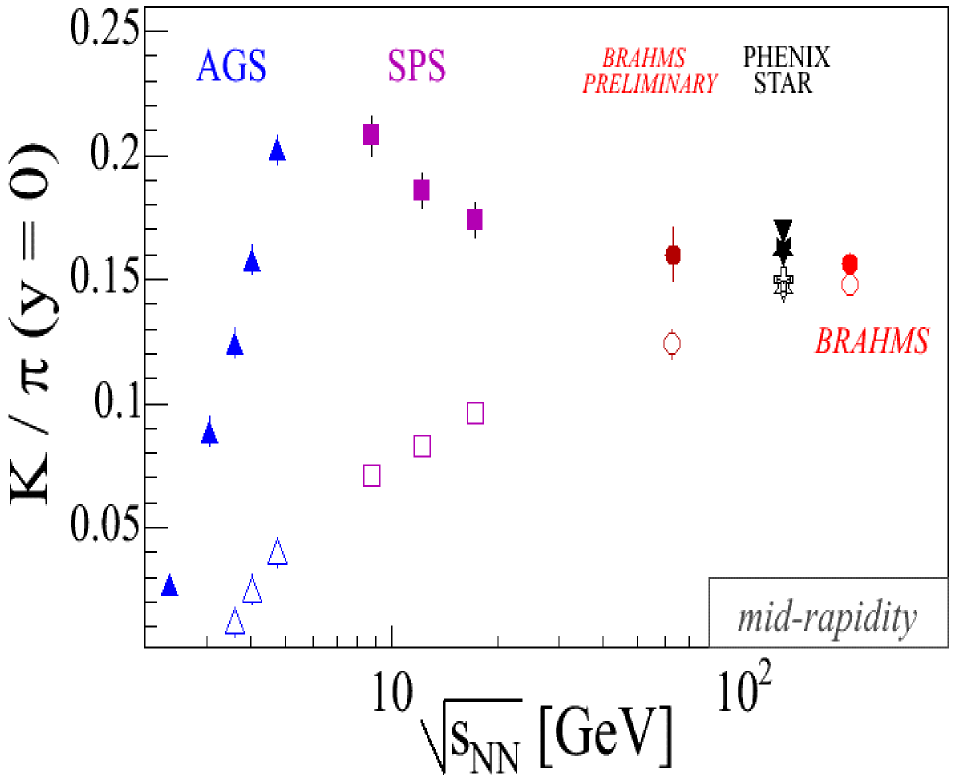
$$\sigma^2 = \ln\left(\frac{\sqrt{s}}{2m_N}\right)$$

- Finite boost-invariant region for thermodynamic variables
  - Boost-invariant region η < 2
  - Gaussian rapidity distribution

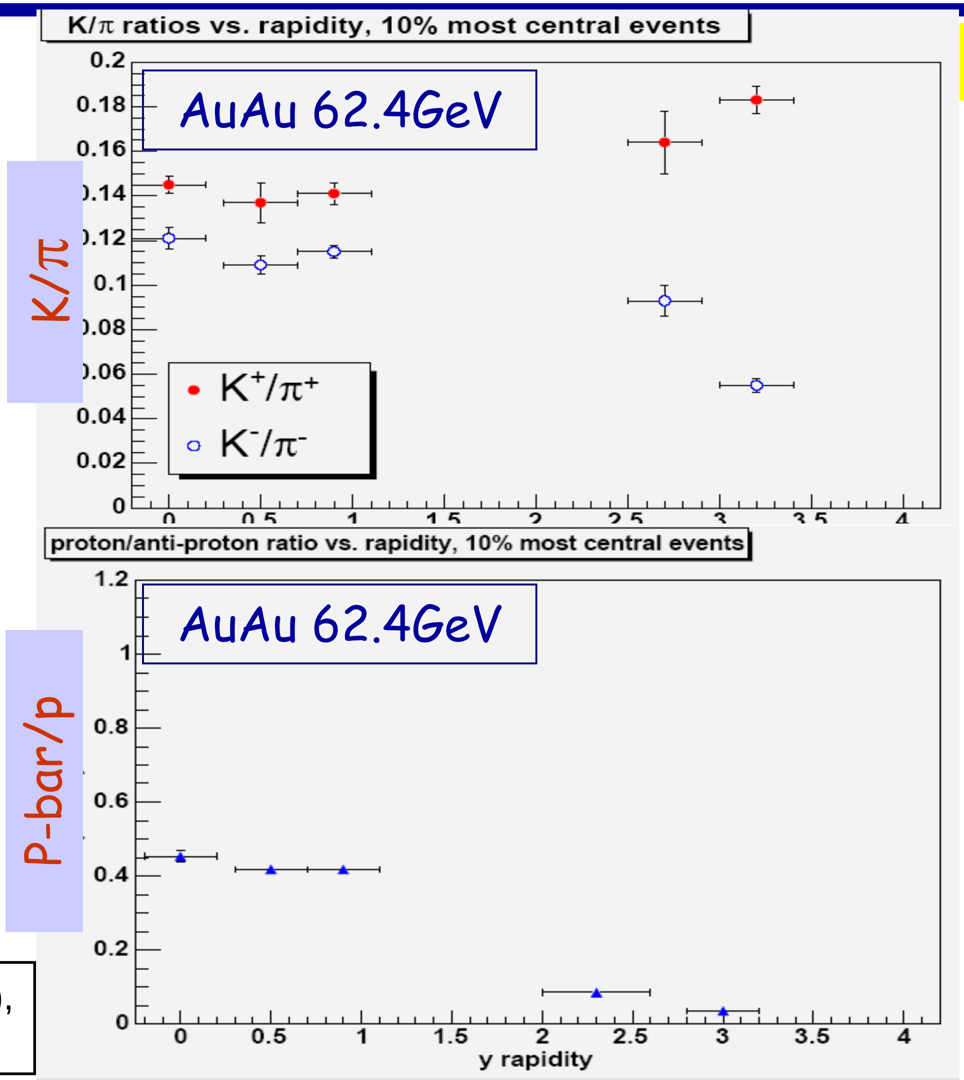
L.D. Landau, Izv. Akad. Nauk SSSR 17 (1953) 52
P.Carruthers, M.Duong-van, PRD 8 (1973) 859

T. Hirano, Y. Nara, nucl-th/0404039

K/π energy dependence, AuAu



K/π Ratios



Rapidity dependence

I. Arsene (BRAHMS), QM2005, poster 126

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Particle Production Summary

- Particle production increase with the energy and the centrality
- The Gaussian distribution of the produced particles
- Excess of K^+ over K^- and SPS-like hadron chemistry in AuAu central collisions at forward rapidity are observed at RHIC

High p_t Suppression & Jet Quenching

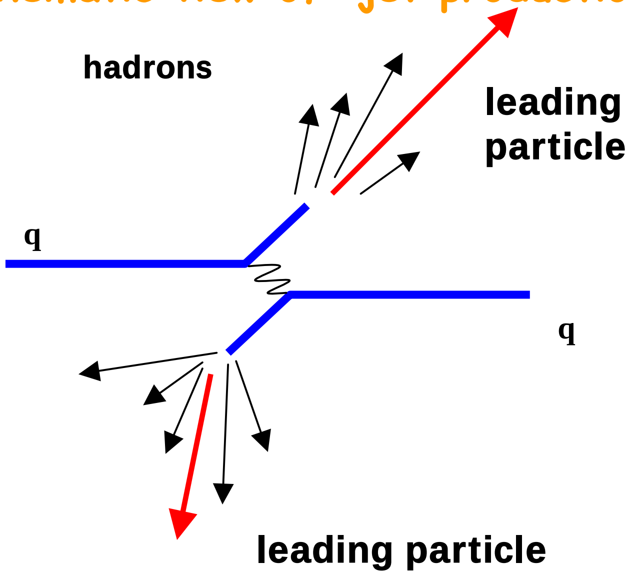
- Particles with high p_t's (above ~2GeV/c) are primarily produced in hard scattering processes early in the collision

- p+p experiments → hard scattered partons fragment into jets of hadrons

- In A-A, partons traverse the medium → Probe of the dense and hot stage

  If QGP → partons will lose a large part of their energy (induced gluon radiation)
  → suppression of jet production
  ↔ Jet Quenching

Schematic view of jet production



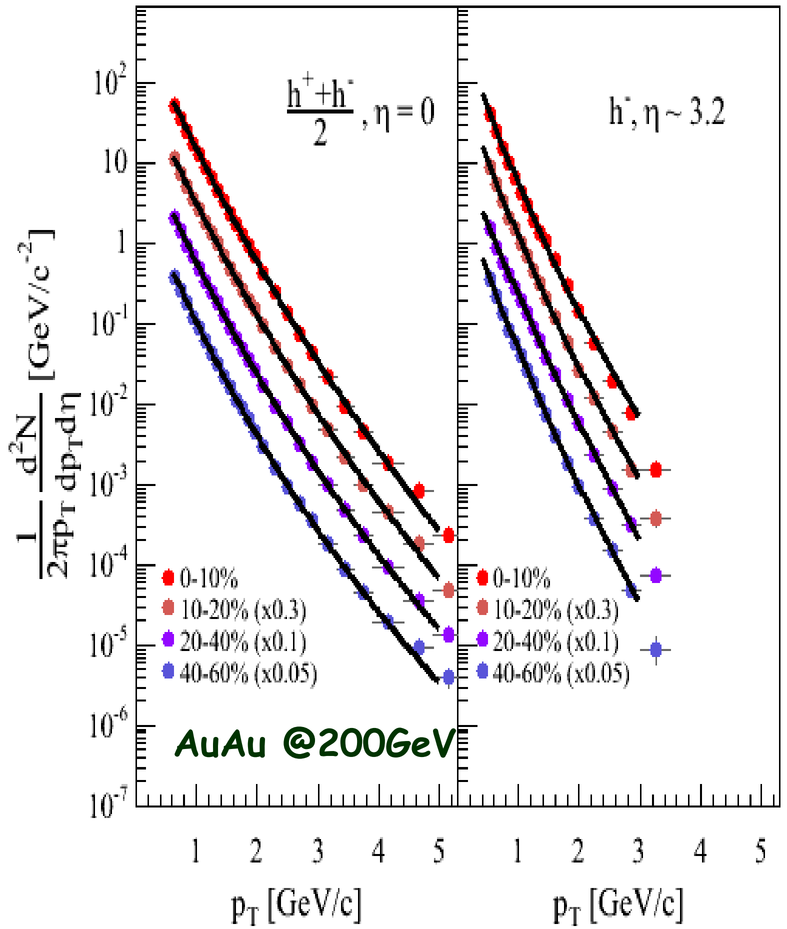
Experimentally → depletion of the high p_t region in hadron spectra

Nuclear Modification Factor

$$R_{AB} = \frac{Yield(AB)}{N_{COLL}(AB) \times Yield(NN)}$$

Scaled by N+N reference

$R_{AB} < 1 \leftrightarrow$ Suppression relative to scaled NN reference



SPS:

1. Data do not show suppression
2. Enhancement ($R_{AB}>1$) due to initial state multiple scattering (Cronin Effect)

$$R_{CP} = \frac{Yield(central)/N_{COLL}(central)}{Yield(peripheral)/N_{COLL}(peripheral)}$$

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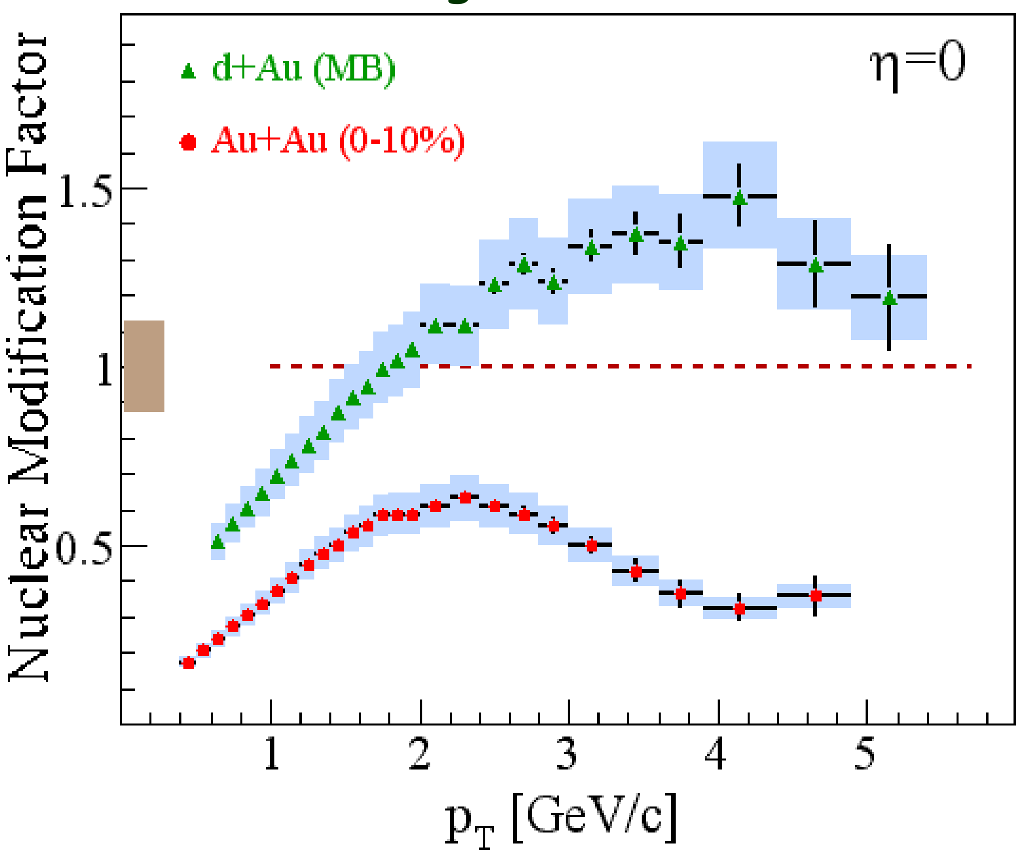
Nuclear Modification Factor

charged hadrons



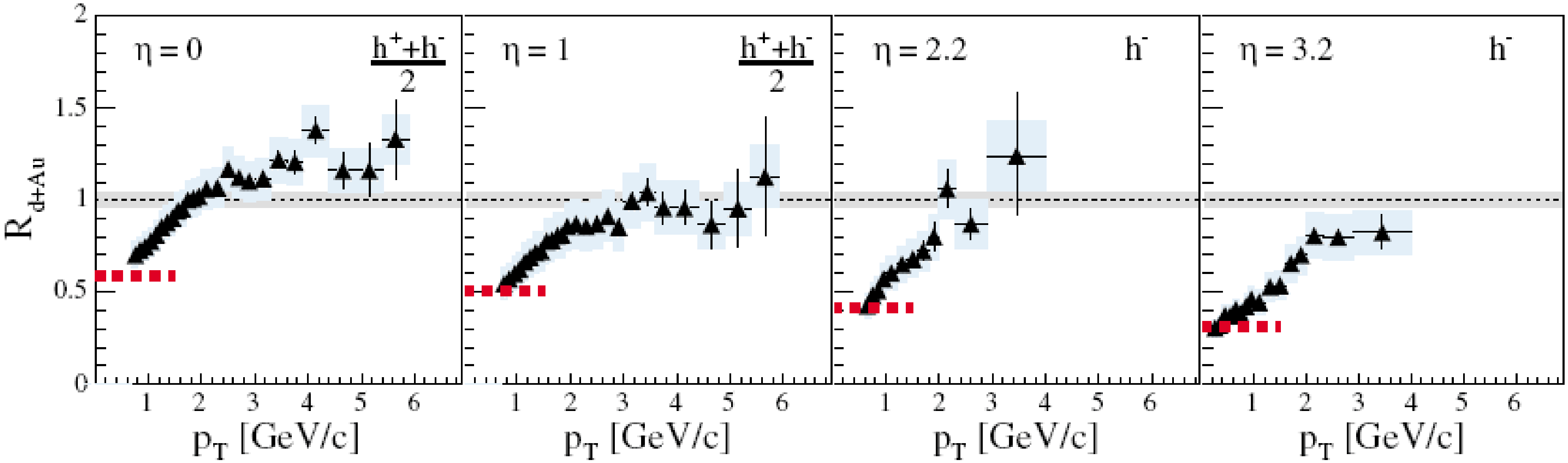
- High p_T enhancement in d+Au collisions at $\sqrt{s_{NN}}$=200 GeV
- Comparing Au+Au to d+Au at midrapidity

⇒ Strong effect of dense medium

⇒ Partonic energy loss

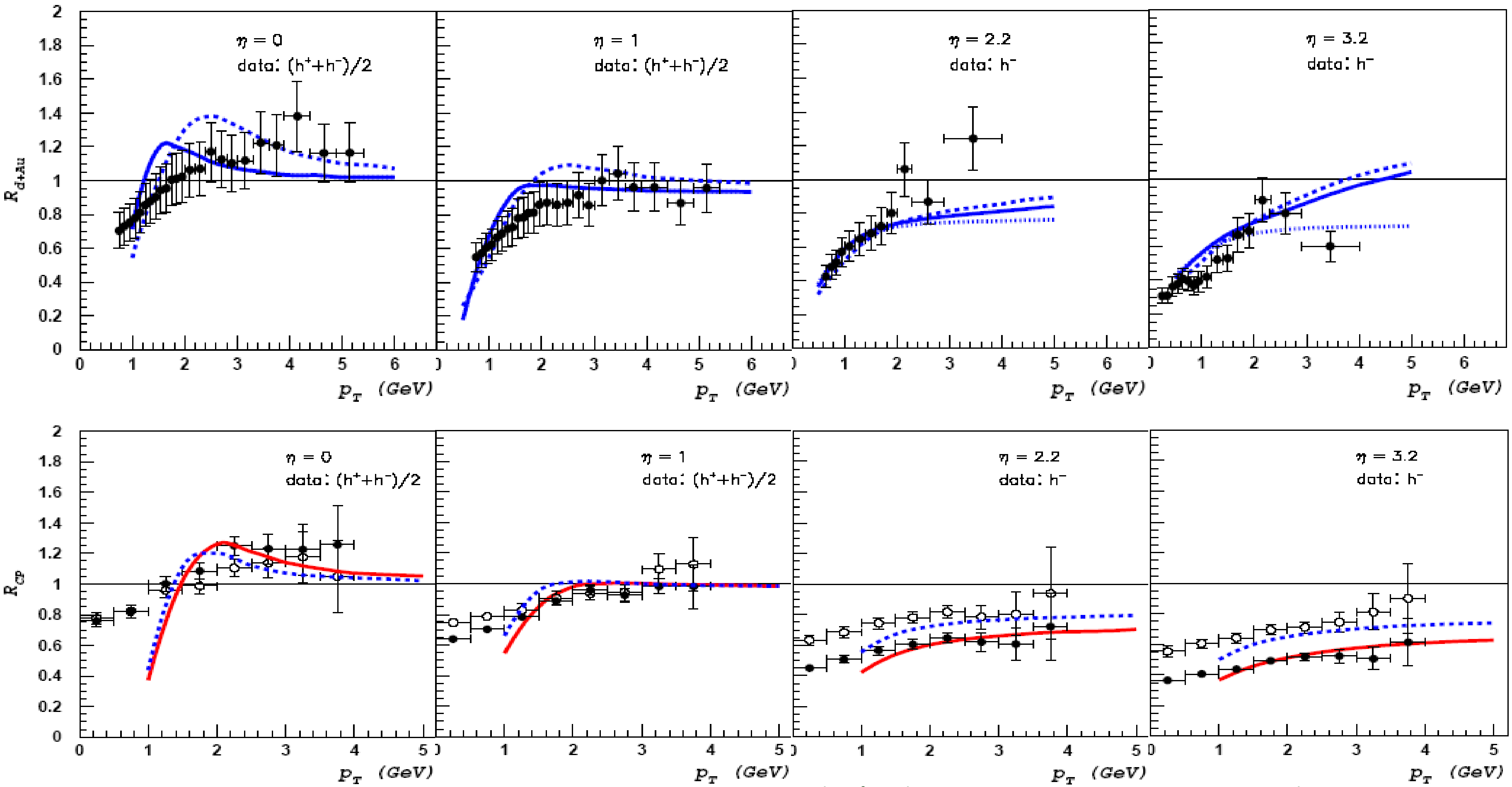
R_{dAu}: Charged hadrons

BRAHMS: PRL 93, 242303 (2004)



- Cronin-like enhancement at η=0
- Clear suppression as η changes from 0 to 3.2

CGC saturation model



CGC model describes R_{dAu} and R_{CP}

D. Kharzeev, Y.V. Kovchegov,
K. Tuchin, hep-ph/0405054 (2004)

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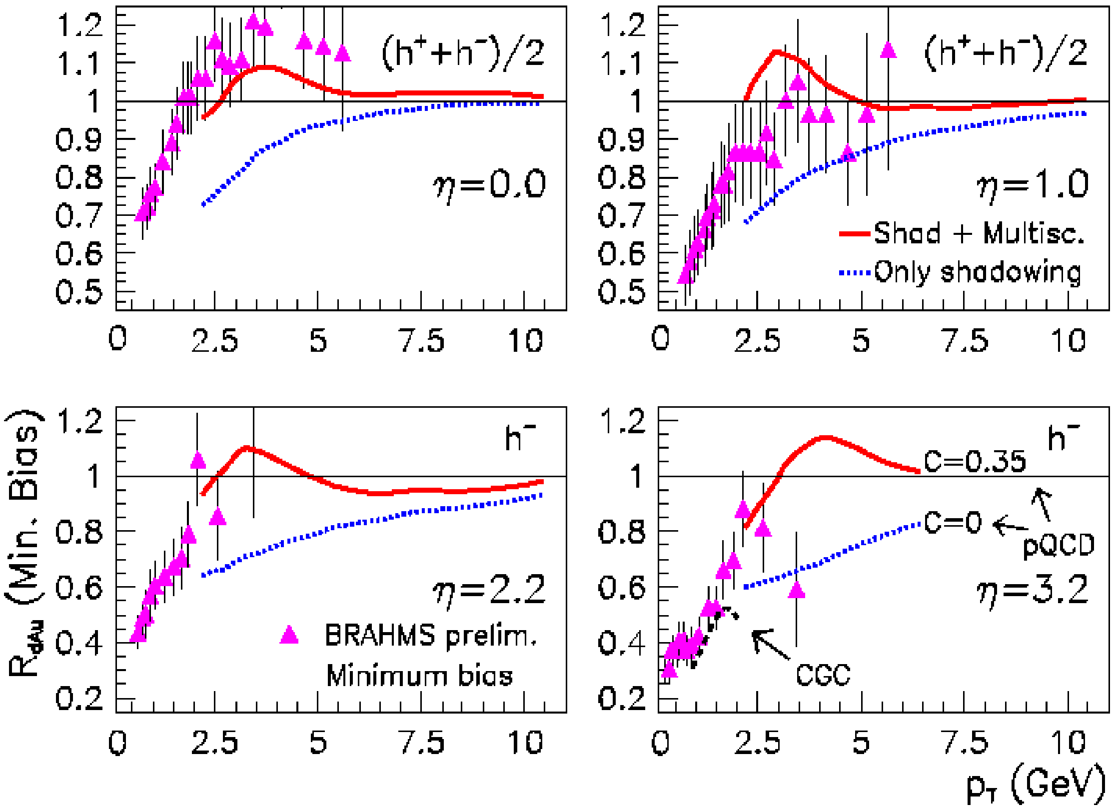
pQCD models

- pQCD-improved parton model
  - Glauber-type collision geometry
  - Nuclear shadowing
  - Initial state incoherent multiple scattering

G.G. Barnafoldi, G. Papp, P. Levai, G. Fai, nucl-th/0404012 (2004)

see also A. Arcadi, M. Gyulasy, nucl-th/0402101 (2004)



- Increasing strength of standard nuclear shadowing with increasing η

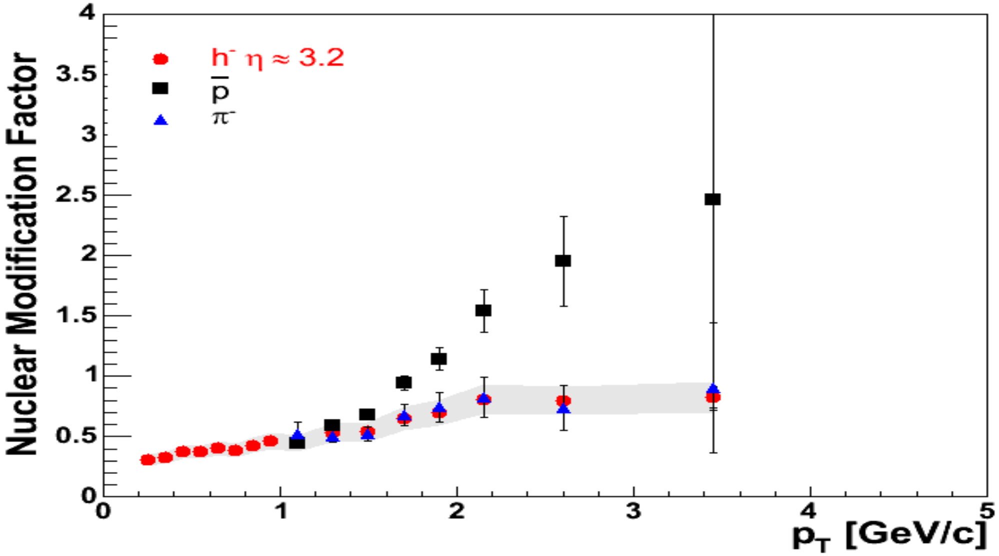
$\Rightarrow$ reasonable agreement between R_{dAu} and pQCD

- but underestimation of centrality dependence of R_{CP}

see R. Vogt, hep-ph/0405060 (2004), Phys. Rev. C70 (2004) 064902

R_{dAu}: identified hadrons

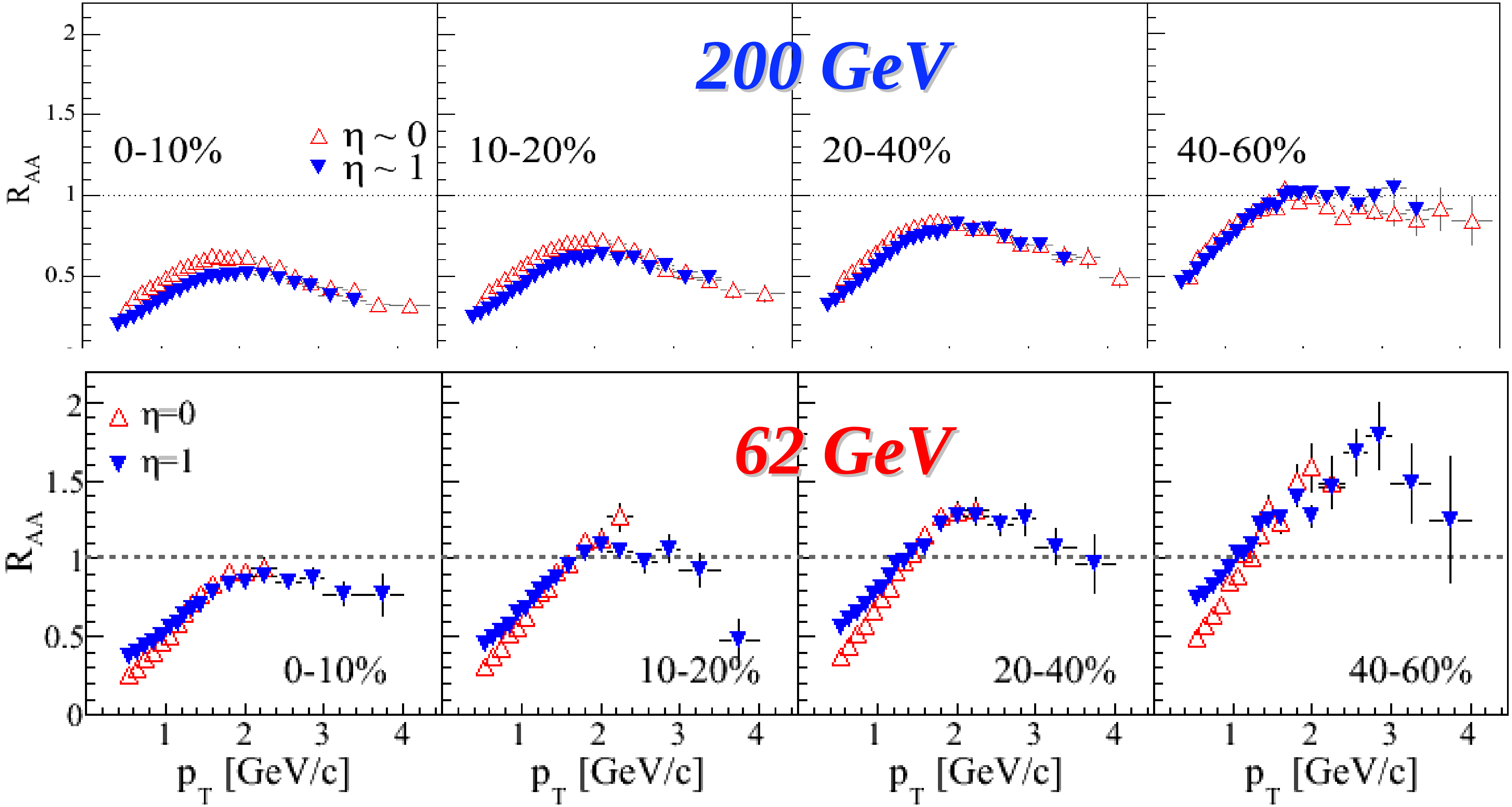
F. Videbaek (BRAHMS), DIS2005



R_{dAu}

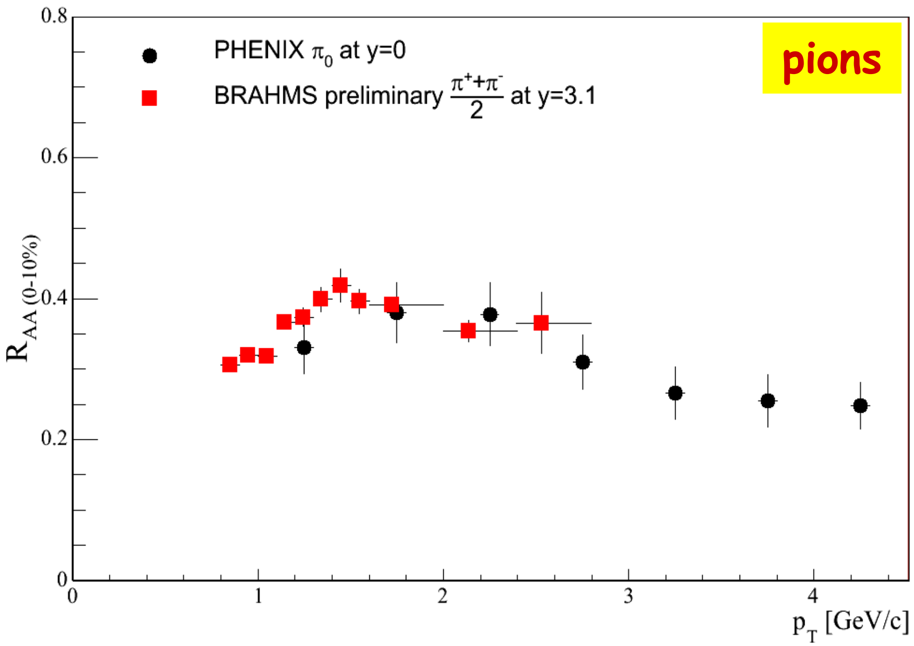
- Strong suppression for π^-
- Enhancement for antiprotons

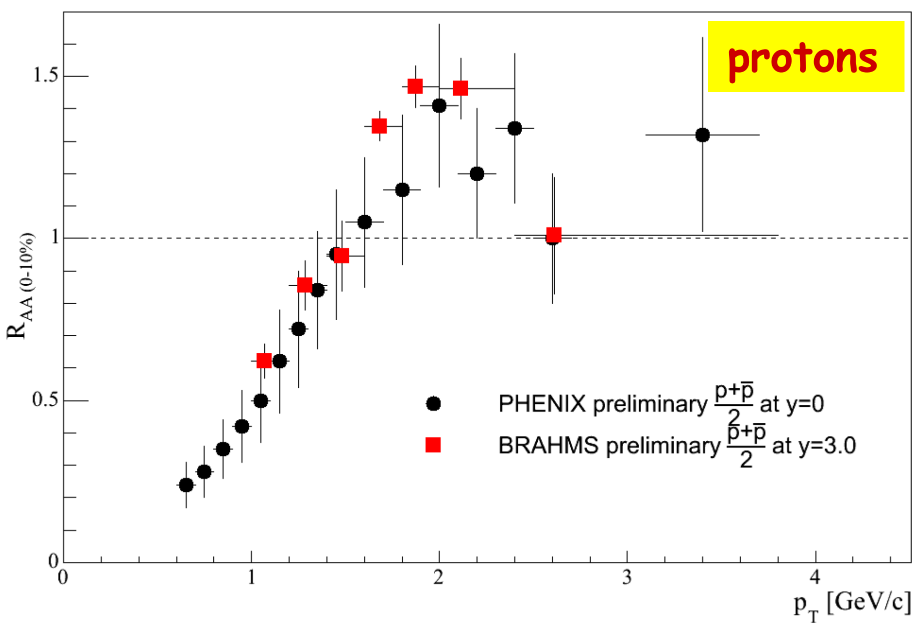
R_{AuAu} energy dependence



R_{AuAu}: identified hadrons

Central Au+Au at 200 GeV





NO change of R_{AuAu} with rapidity

R. Karabowicz (BRAHMS), QM2005

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Nuclear Modification Factor Summary

- Color Glass Condensate model results agree well with the R_{CP} and R_{dAu} measured in BRAHMS; the estimation of R_{dAu} by pQCD with shadowing effect considered also described the data well
- In AuAu collisions, suppression increases with energy for given centrality bin; the suppression increase with the colliding system for given incident energy and centrality bin – that means there is more medium effect in larger colliding system and at higher energy
- R_{AuAu} has no centrality dependence, in contrast to R_{dAu}

Summary

- Strong stopping power was seen at RHIC
- For heavier incident nucleus, in more central and higher energy collisions, the final state jet-quenching effect becomes more important
- Suppression effects in dAu collisions at forward rapidities:

Gluon saturation effect?

BRAHMS Collaboration

I.Arsene[11], I.G. Bearden[6], D. Beavis[1], S. Bekele[6] , C. Besliu[9], B. Budick[5], H. Bøggild[6] , C. Chasman[1], C. H. Christensen[6], P. Christiansen[6], R. Clarke[9], R.Debbe[1], J. J. Gaardhøje[6], K. Hagel[7], H. Ito[10], A. Jipa[9], J. I. Jørdre[8], F. Jundt[2], E.B. Johnson[10], C.E.Jørgensen[6], R. Karabowicz[3], E. J. Kim[4], T.M.Larsen[11], J. H. Lee[1], Y. K. Lee[4], S.Lindal[11], G. Løvhøjden[11], Z. Majka[3], M. Murray[10], J. Natowitz[7], B.S.Nielsen[6], D. Ouerdane[6], R.Planeta[3], F. Rami[2], C. Ristea[6], O. Ristea[9], D. Röhrich[8], B. H. Samset[11], D. Sandberg[6], S. J. Sanders[10], R.A.Sheetz[1], P. Staszel[3], T.S. Tveter[11], F.Videbæk[1], R. Wada[7], H. Yang[8], Z. Yin[8], and I. S. Zgura[9]

[1]Brookhaven National Laboratory, USA, [2]IReS and Université Louis Pasteur, Strasbourg, France
[3]Jagiellonian University, Cracow, Poland,
[4]Johns Hopkins University, Baltimore, USA, [5]New York University, USA
[6]Niels Bohr Institute, University of Copenhagen, Denmark
[7]Texas A&M University, College Station. USA, [8]University of Bergen, Norway
[9]University of Bucharest, Romania, [10]University of Kansas, Lawrence,USA
[11] University of Oslo, Norway

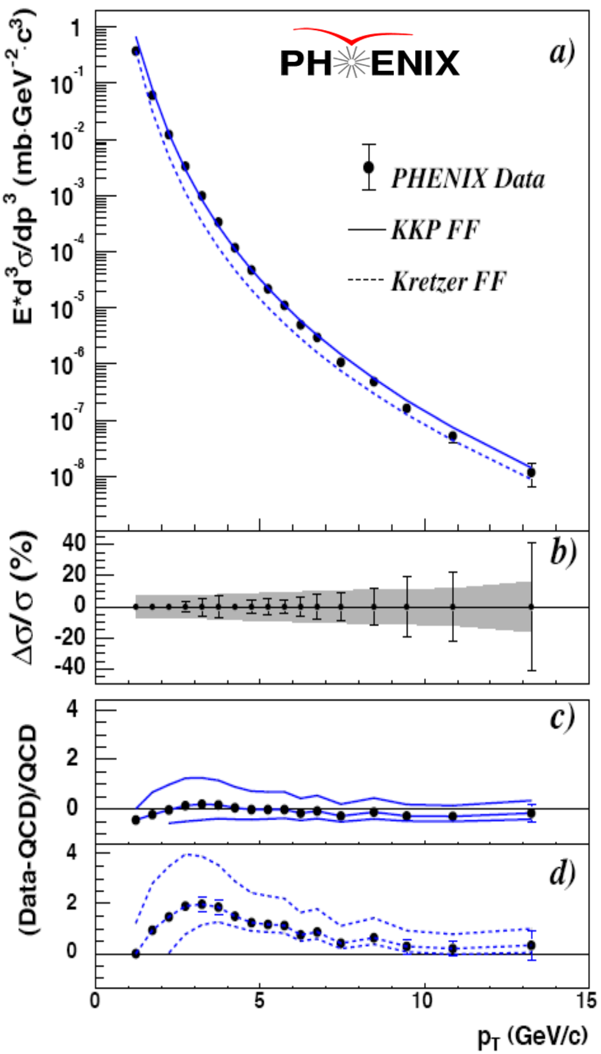
48 physicists from 11 institutions

Thank you!

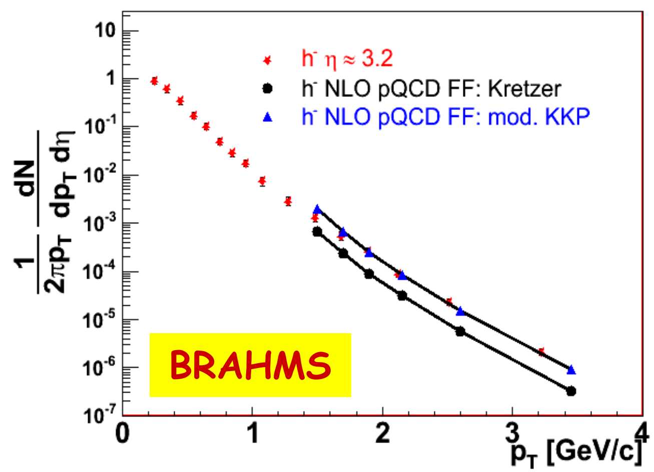
Backup slides

Reference: pp

midrapidity



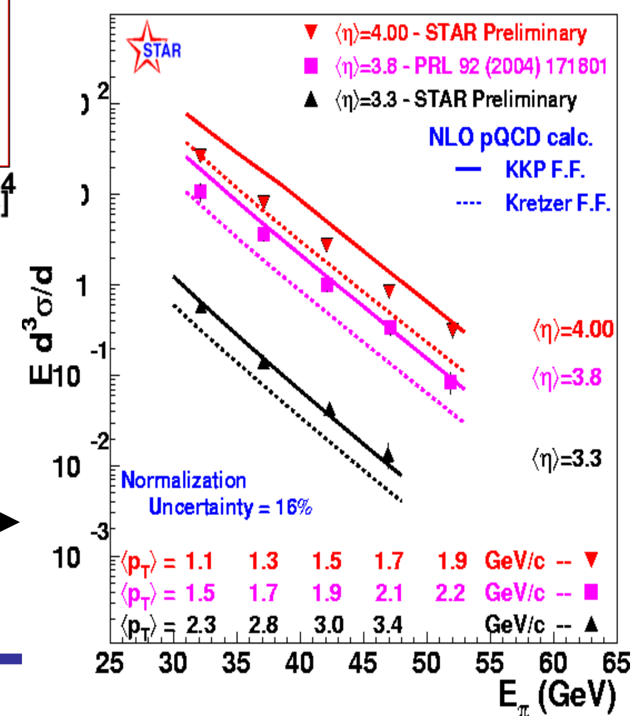
forward rapidities



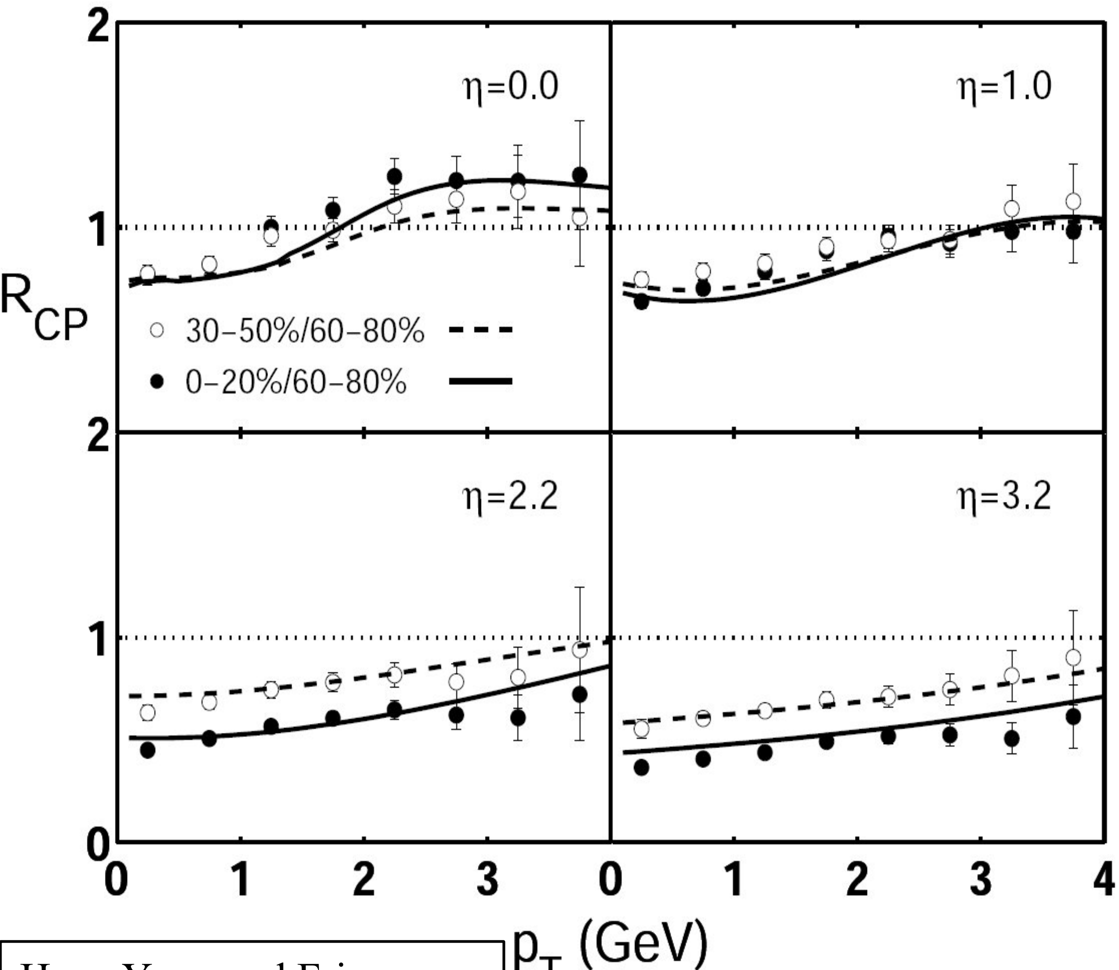
h^-

$$pp \rightarrow \pi^0 X$$

NLO pQCD calc.
(W. Vogelsang)



Recombination model



Hwa, Yang and Fries
Phys.Rev.C71:024902,2005

Important contributions from thermal/shower partons recombination (up to moderate p_T)

Variety of processes can result in suppression

Quality of data is insufficient for ruling out models

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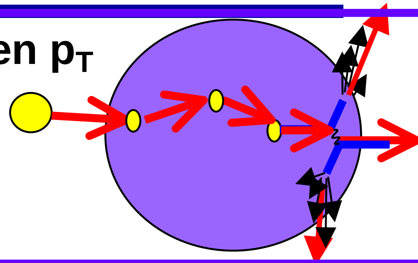
Initial and final effects - dAu

- **Initial effects**
  - Wang, Levai, Kopeliovich, Accardi
- **Especially at forward rapidities:**
  - Eskola, Kolhinen, Vogt, Nucl Phys. A696 (2001) 729-746
  - HIJING
  - D.Kharzeev et al., PLB 561 (2003) 93
- **Others**
  - B. Kopeliovich *et al.*, hep-ph/0501260
  - J. Qiu, I, Vitev, hep-ph/0405068
  - R. Hwa et al., nucl-th/0410111
  - D.E. Kahana, S. Kahana, nucl-th/0406074

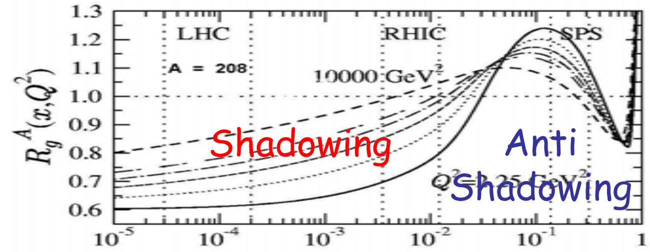
"Cronin effect"

Initial state elastic multiple scattering leading to **Cronin** enhancement (R_{AA}>1)



Nuclear shadowing

depletion of low-x partons

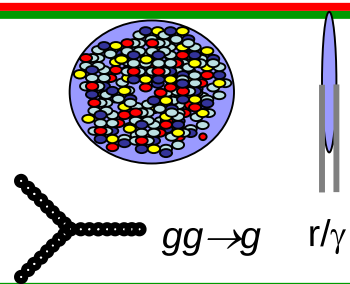


Gluon saturation

depletion of low-x gluons

due to gluon fusion

"Color Glass Condensate (CGC)"



Suppression due to

dominance of projectile valence quarks, energy loss, coherent multiple scattering, energy conservation, parton recombination, ...

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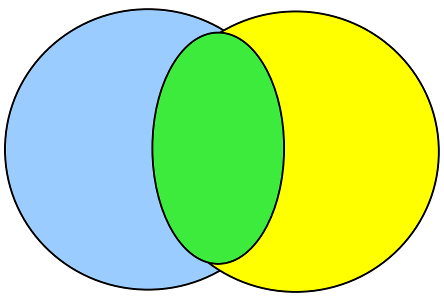
Elliptic Flow

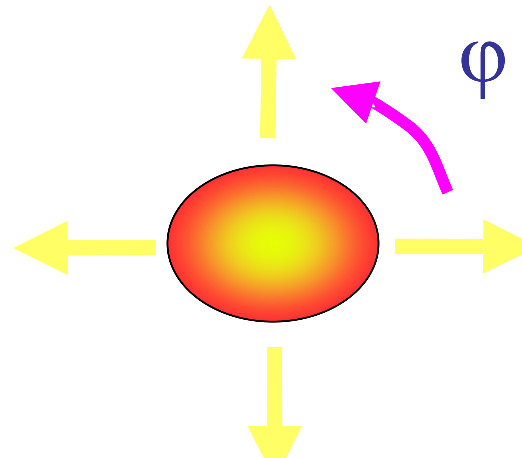
Initial spatial anisotropy…

In peripheral collisions:



…after rescattering leads to …

…final momentum anisotropy



$$E\frac{d^3N}{dp^3}=\frac{1}{2\pi}\frac{d^2N}{p_T\,dp_T\,dy}\left(1+\sum_{n=1}^{\infty}2v_n\cos\left(n\left(\phi-\Psi\right)\right)\right)$$

Elliptic Flow: n = 2

Method

Nth order event plane

$$\Psi_n = \frac{1}{n}\arctan\left(\frac{\sum_{i=1}^{N} w_i n_i^{ch}\sin(n\phi_i)}{\sum_{i=1}^{N} w_i n_i^{ch}\cos(n\phi_i)}\right)$$

Methods describe by
A. M. Poskanzer and S. A. Voloshin
Phys. Rev. C58 (1998) 1671

a,b and c are the Scintillator Tile, the Silicon Strip and the Beam-Beam counters

Observed v_2

$$v_n^{observed} = \langle \cos(n(\phi - \Psi_n)) \rangle$$

Event plane resolution correction

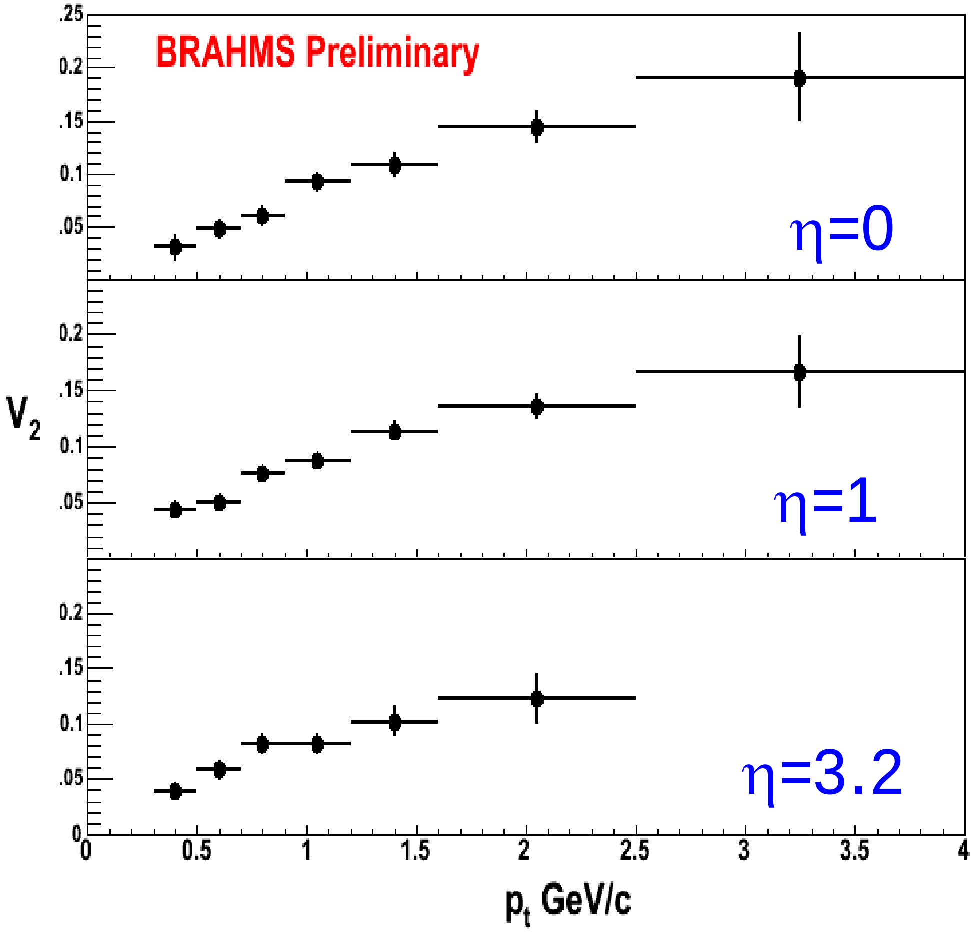
$$\langle \cos 2(\Psi_a - \Psi_R) \rangle = \sqrt{\frac{\langle \cos 2(\Psi_a - \Psi_b) \rangle \langle \cos 2(\Psi_a - \Psi_c) \rangle}{\langle \cos 2(\Psi_b - \Psi_c) \rangle}}$$

Real v_2

$$v_2^R = \frac{v_2^{observed}}{\langle \cos 2(\Psi_a - \Psi_R) \rangle}$$

Elliptic flow (v2) AuAu @200GeV

$$\frac{dN}{d\eta dp_t d\varphi} = \frac{dN}{d\eta dp_t}\frac{1}{2\pi}(1 + 2v_1\cos\varphi + 2v_2(\eta,p_t)\cos2\varphi)$$



No $v_2(p_T)$ rapidity dependence

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