QCD and Heavy Ions

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Outline

- QCD of strong color fields:

  parton saturation and Color Glass Condensate
- CGC and Quark-Gluon Plasma
- Manifestations of CGC at RHIC:
  - hadron multiplicities
  - high p_T suppression at forward rapidity
- Future tests: RHIC, LHC, eRHIC

QCD and the classical limit

QCD = Quark Model + Gauge Invariance

$$q(x) \to \exp\left(i\omega_a(x)T^a\right)\ q(x),$$

$$\left[T^a, T^b\right] = if^{abc}T_c$$

For $\tilde{A}_\mu = \frac{1}{g}A_\mu$,

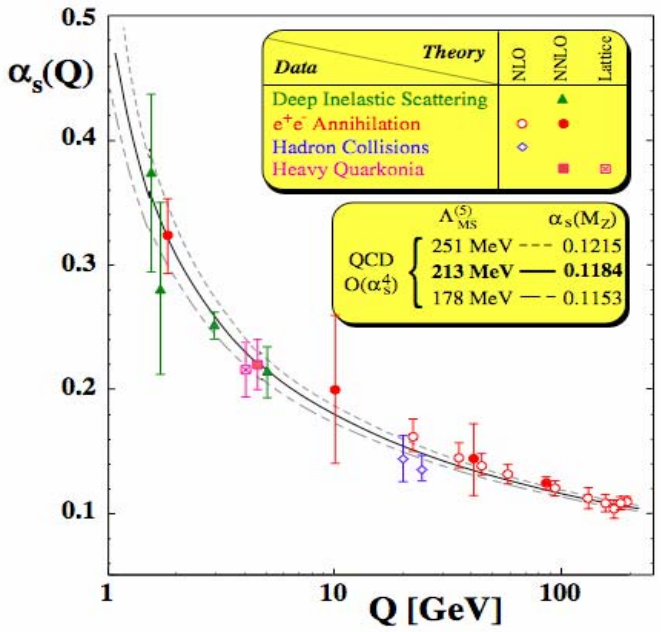
$$L_{\mathrm{QCD}} = \sum_q \bar{q}(x)\left(i\gamma_\mu D^\mu - m_q\right)q(x) - \frac{1}{4g^2}\mathrm{tr}\ G^{\mu\nu}(x)G_{\mu\nu}(x);$$

Classical dynamics applies when the action is large: $(\hbar \to 0)$

$$\frac{S_{QCD}}{\hbar} \sim \frac{1}{g^2\hbar}\int d^4x\ \mathrm{tr}\ G^{\mu\nu}(x)G_{\mu\nu}(x) \gg 1$$

=> Need weak coupling and strong fields

Asymptotic freedom and the classical limit of QCD

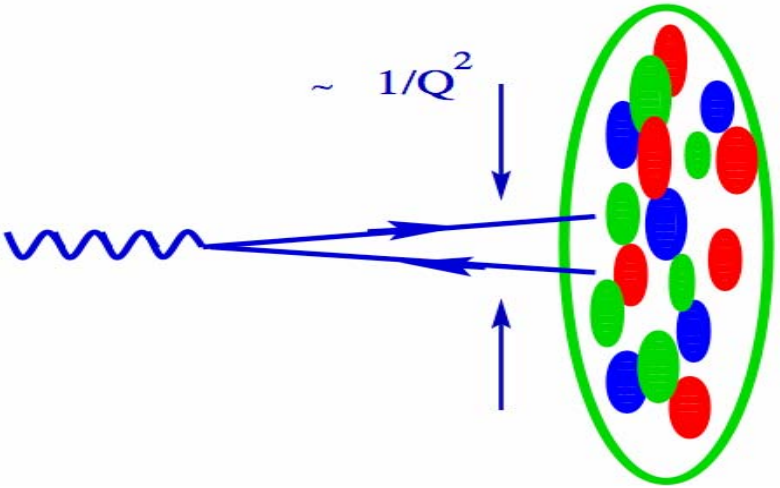


Classical limit S>>1 requires weak coupling and strong fields;
Large distances: strong fields but large coupling…

Is there a place for classical methods?

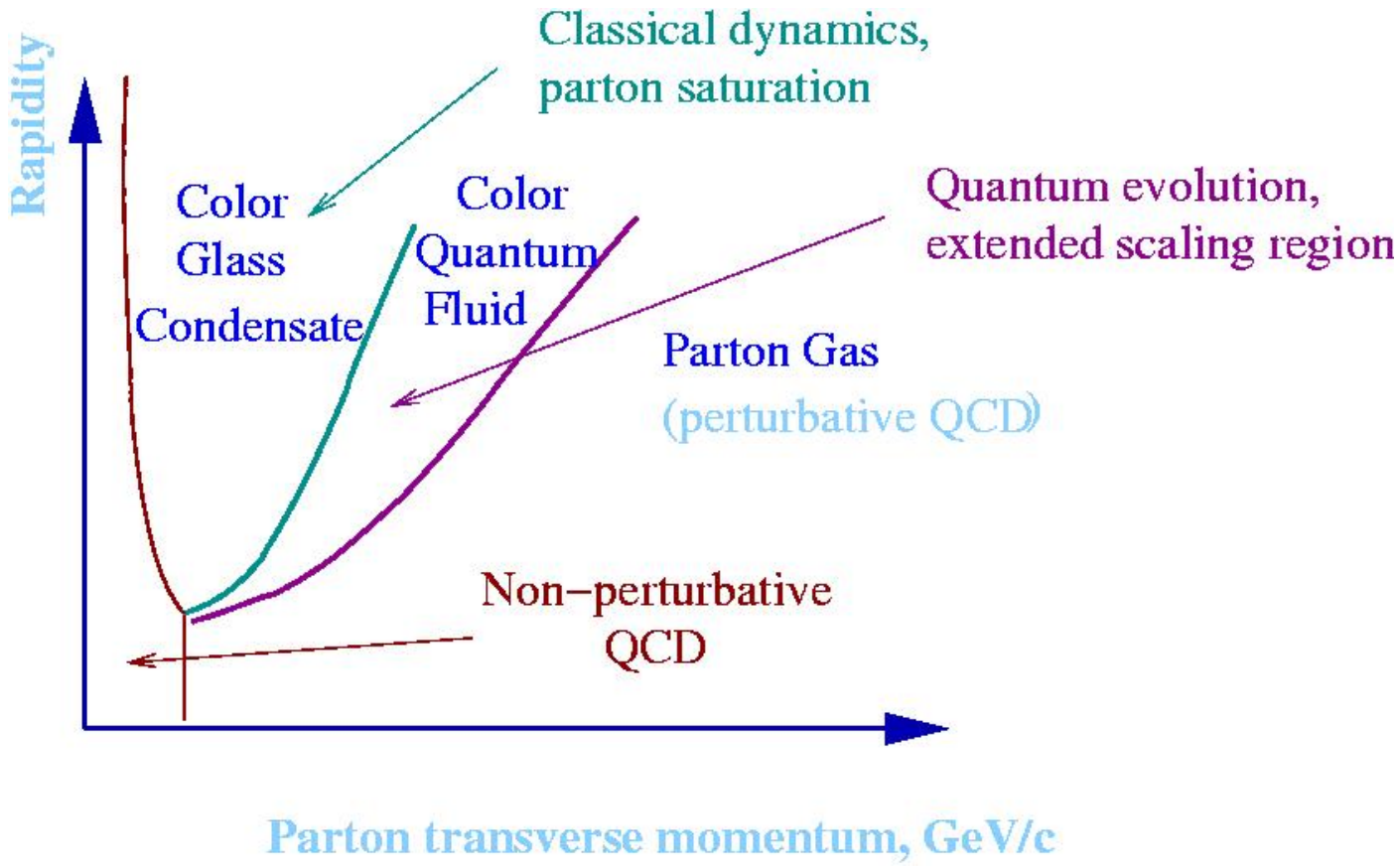
Parton saturation and the classical limit of QCD

At small Bjorken x, hard processes develop over large longitudinal distances $l_c \sim \frac{2\nu}{Q^2} = \frac{1}{mx}$



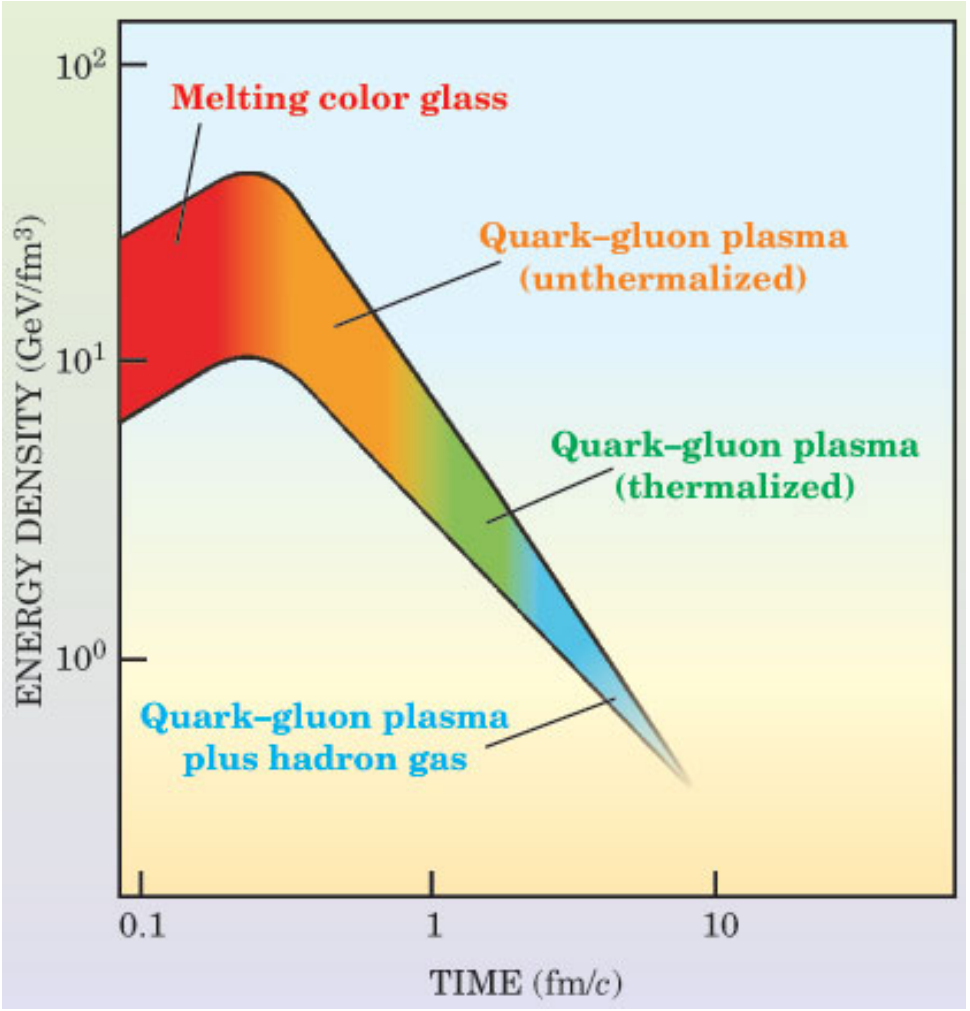
All partons contribute coherently => at sufficiently small x and/or large A strong fields, weak coupling!

The phase diagram of high energy QCD



… no numbers yet, but they will follow

From CGC to Quark Gluon Plasma



L. McLerran,
T. Ludlam,
Physics Today,
October 2003

CGC and total multiplicities in Au-Au

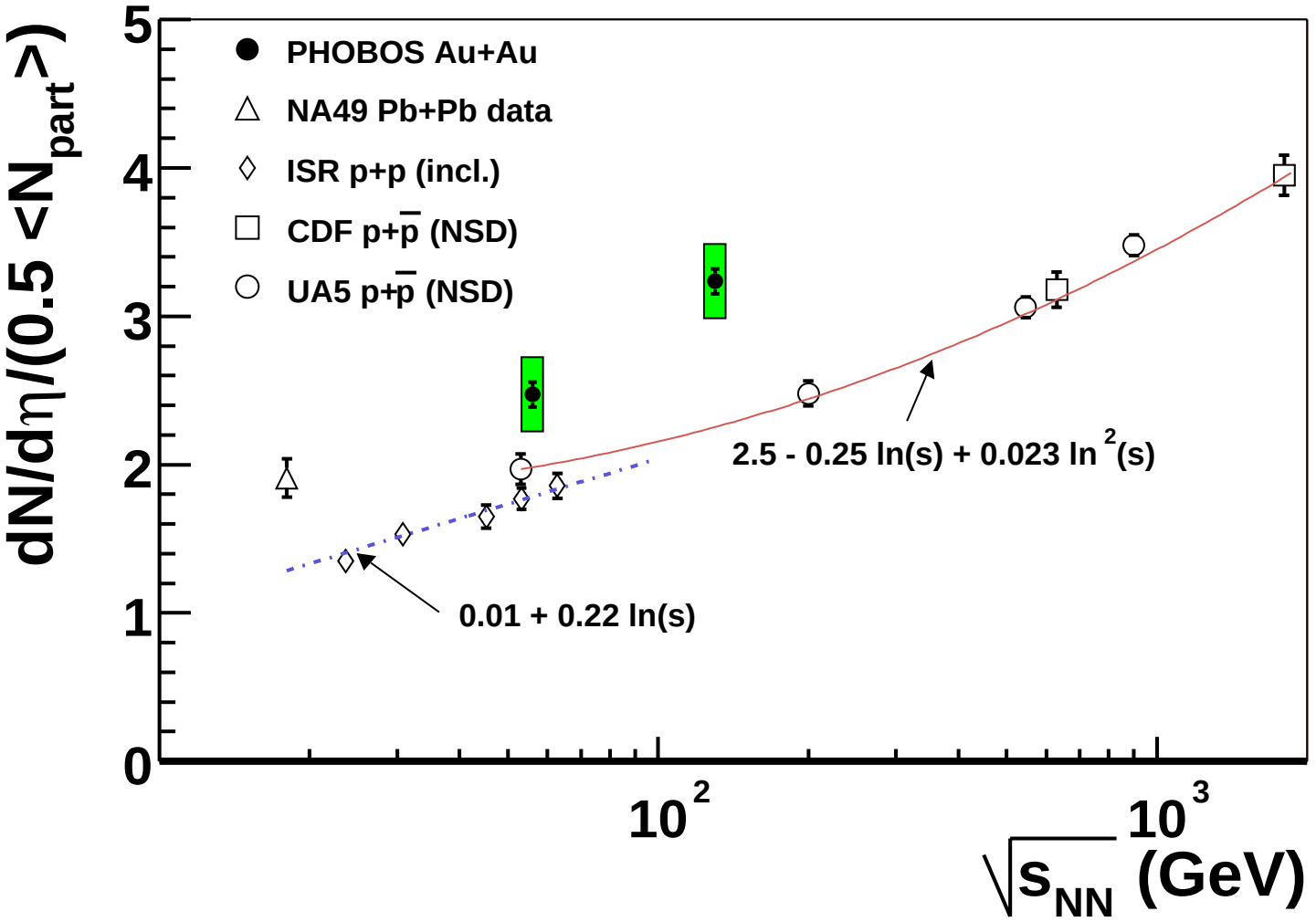
CGC predicts very simple dependence of multiplicity on atomic number A / N_{part}:

$$n \sim \frac{S_A Q_s^2}{\alpha_s(Q_s^2)} \sim N_{part} \ \ln N_{part}$$

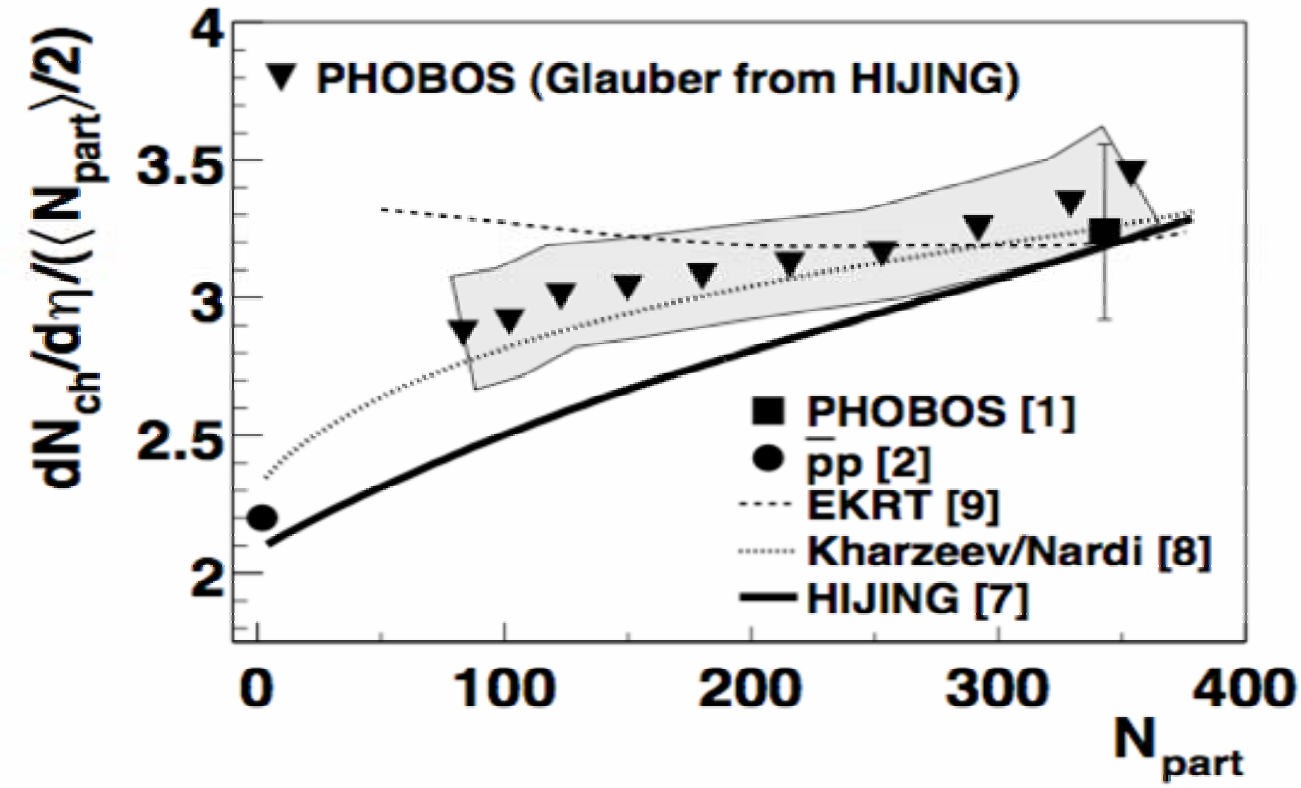
Almost like in “wounded nucleon” and string-based models;
Agrees unexpectedly well with “soft + hard” parameterizations

Parton interactions at RHIC are coherent ! $N_{coll} \sim N_{part}^{4/3}$

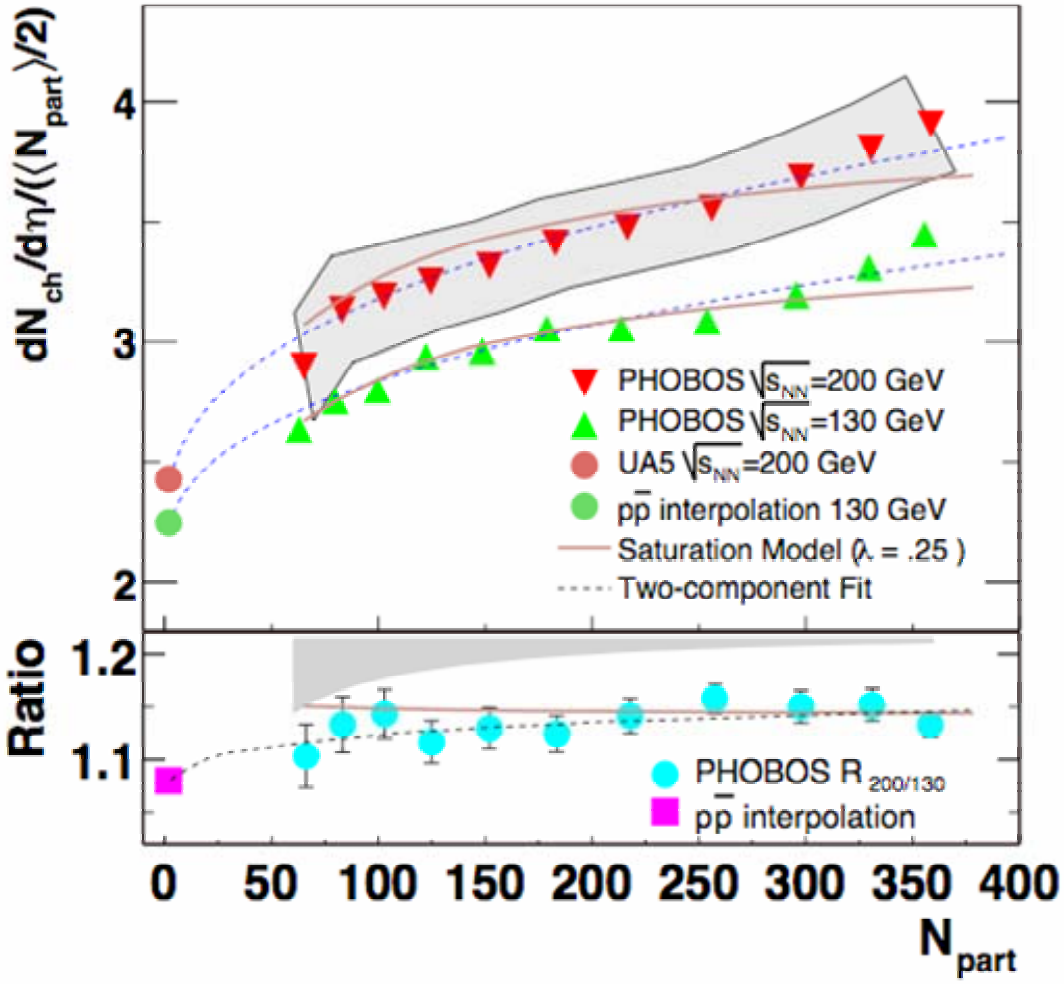
$dN_{ch}/d\eta$ @ η=0 vs Energy



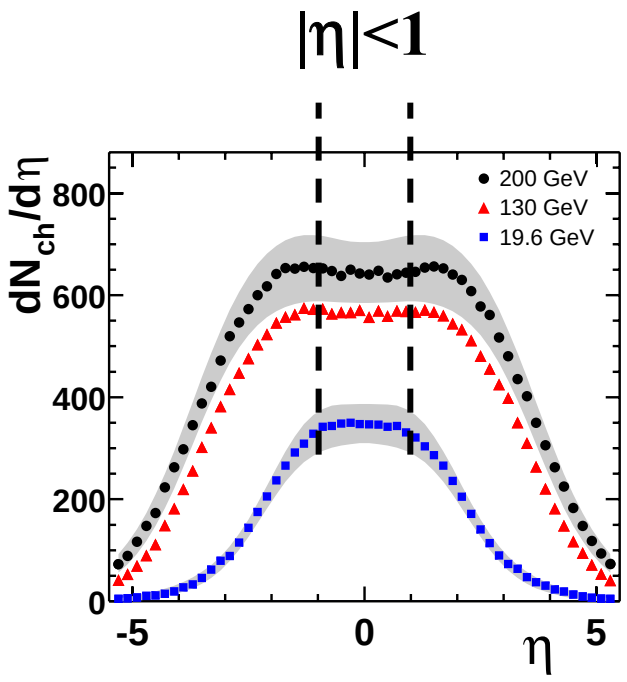
Centrality dependence of hadron multiplicity

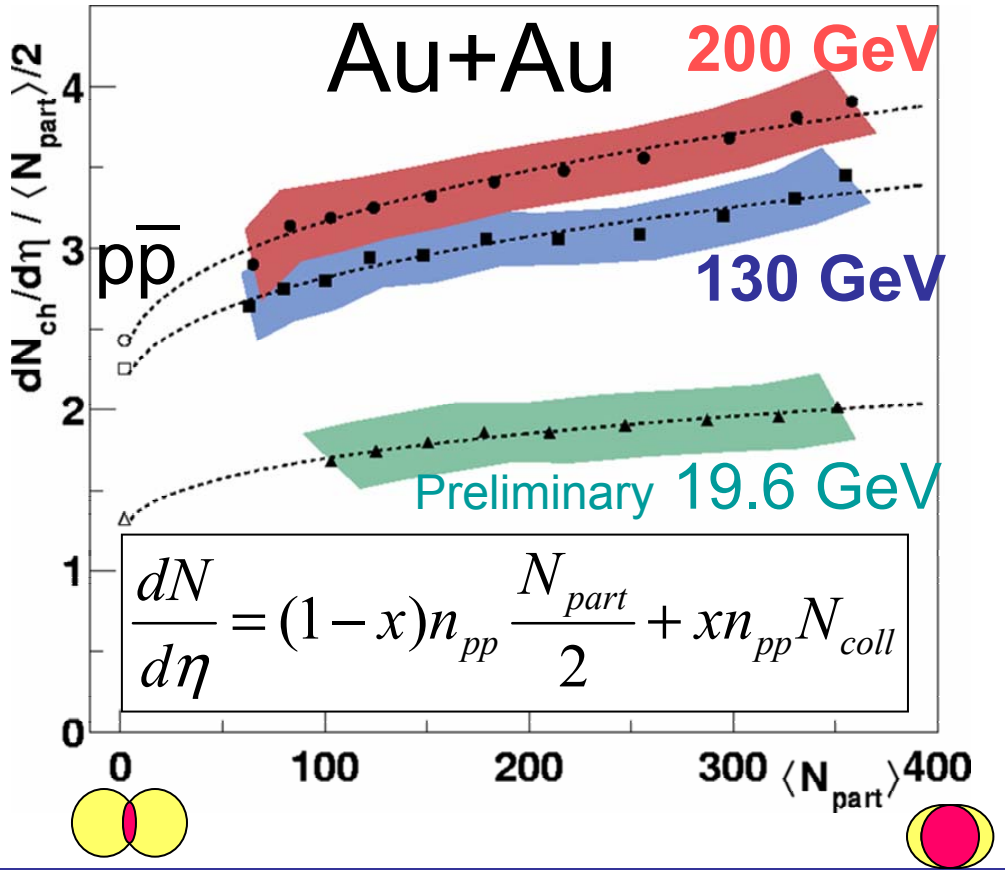


Centrality dependence at different energies



Midrapidity charged particle production

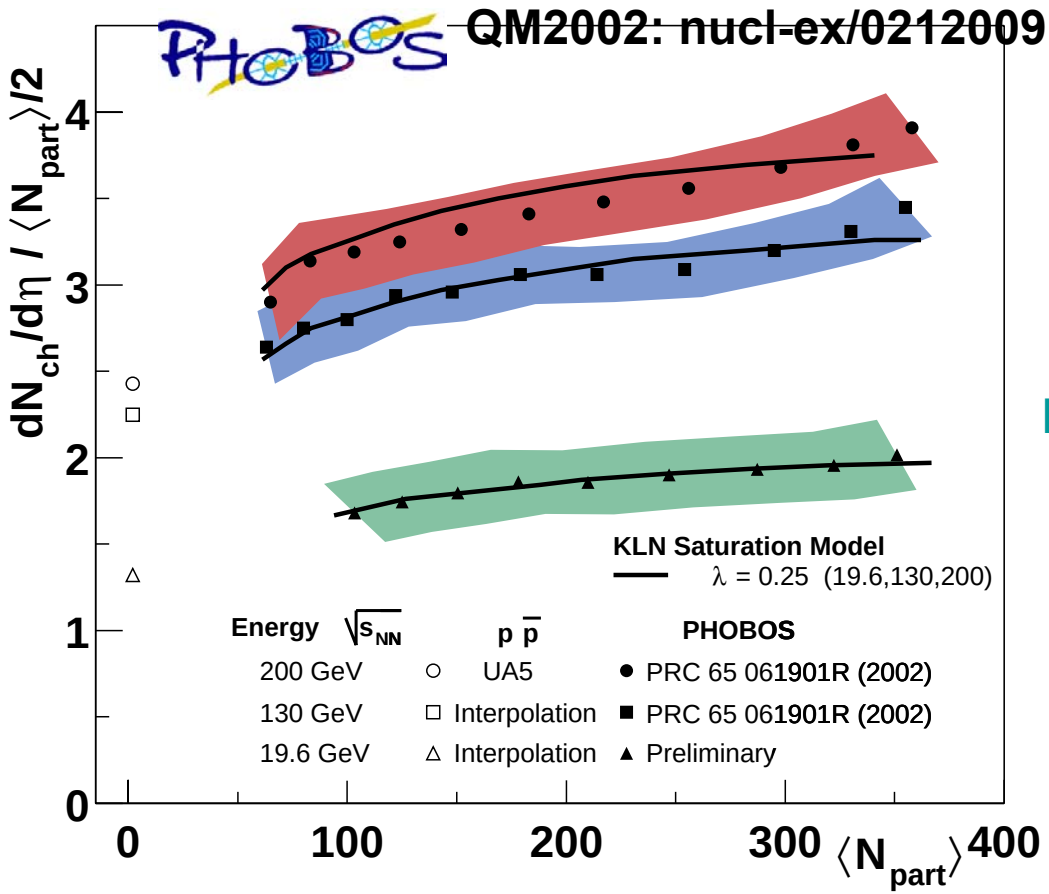




Collision scaling does NOT disappear at low energy.
Problem for naïve “minijet” based models.

M. Baker, PHOBOS

Initial state parton saturation?



200 GeV

130 GeV

Preliminary 19.6 GeV

$$\frac{dN}{d\eta} \propto \frac{1}{\alpha_s} \sim \ln\left(Q_s^2 / \Lambda_{QCD}^2\right)$$

Kharzeev, Levin, Nardi, hep-ph/0111315

λ~0.25 from fits to HERA data:

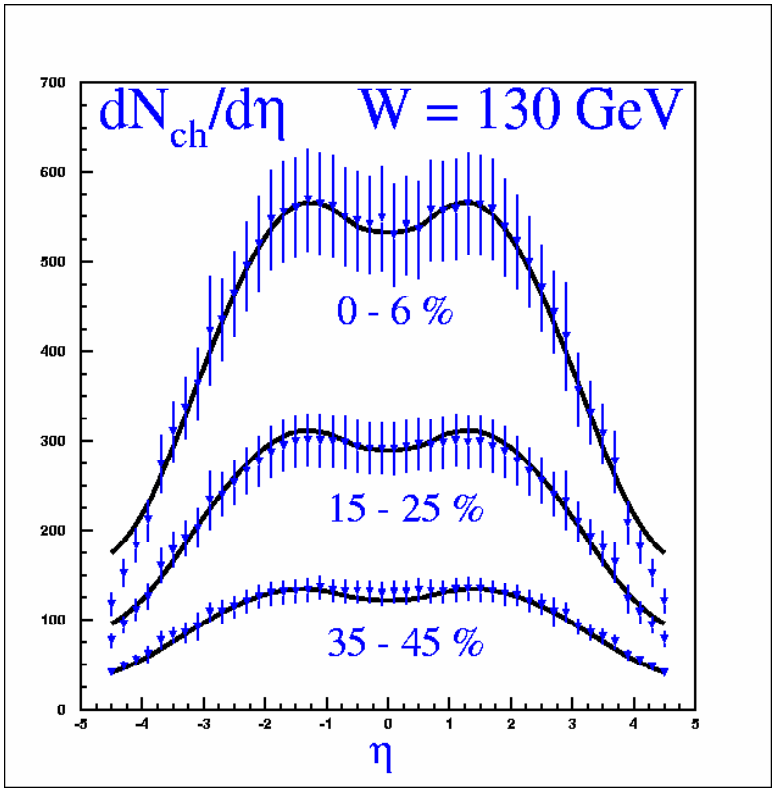
$xG(x) \sim x^{-\lambda}$

Describes energy dependence correctly!

Color Glass Condensate describes the Au-Au data

Kharzeev & Levin, Phys. Lett. B523 (2001) 79

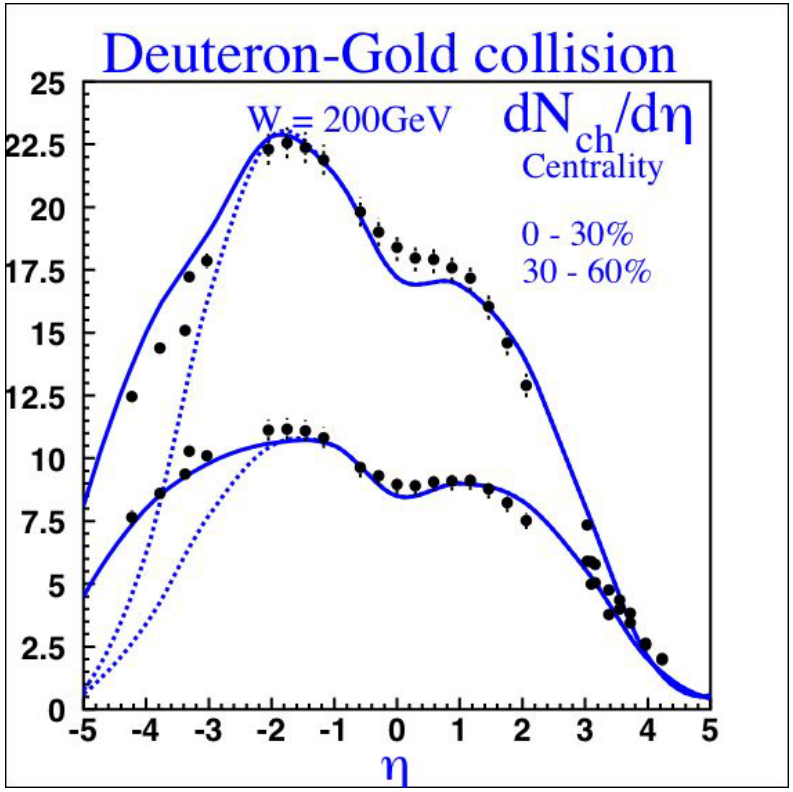
Au + Au at 130 GeV



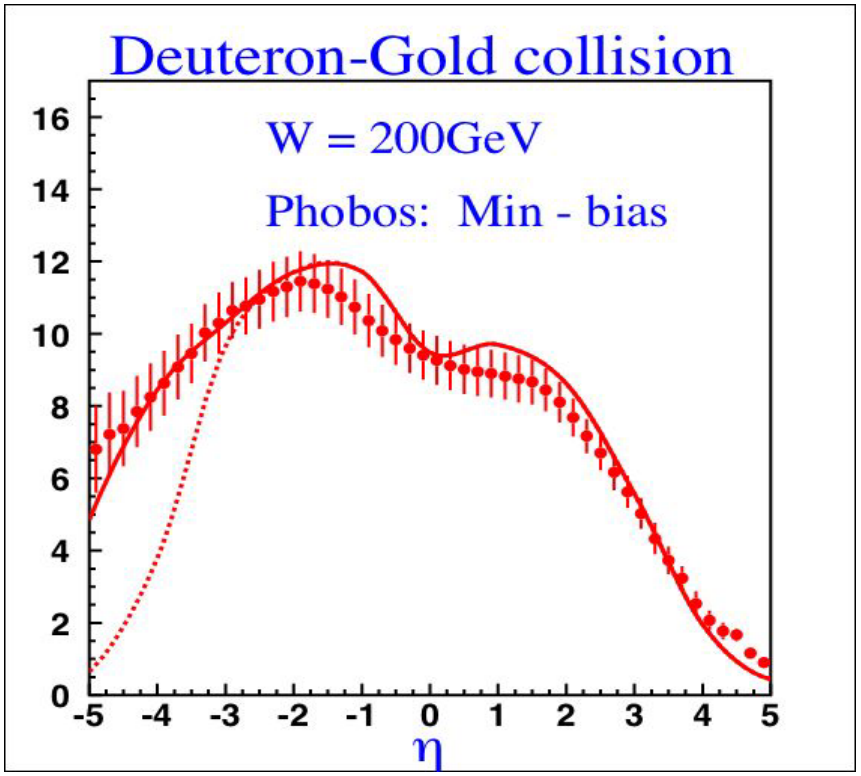
PHOBOS Coll., R. Noucier

- We need a simpler system such as d + Au in order to understand a complex system Au + Au
- The results of d+Au are crucial for testing the saturation approach

D-Au multiplicities

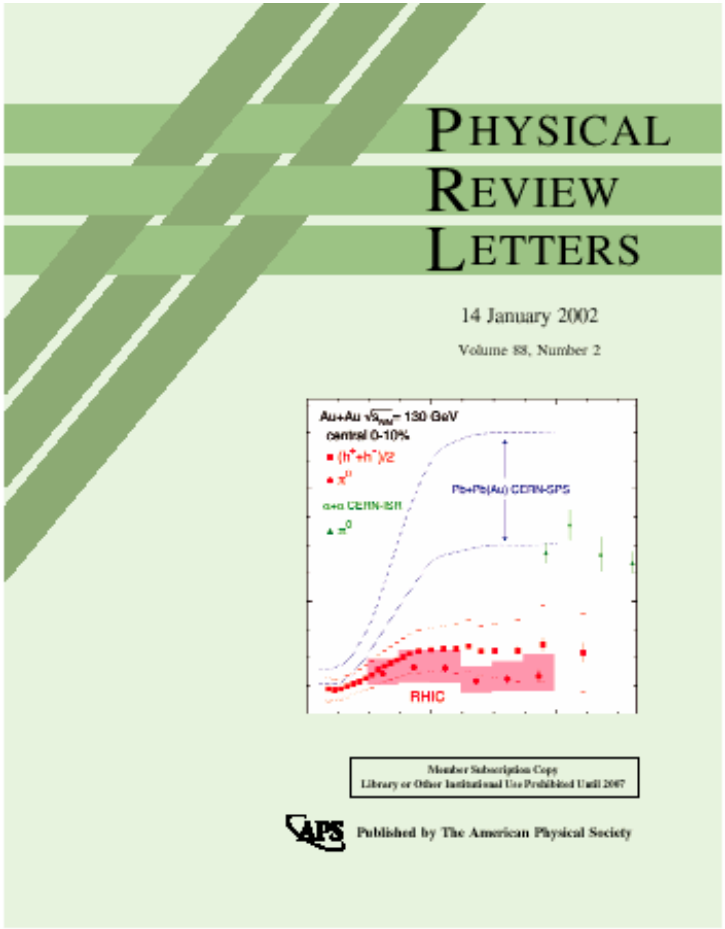


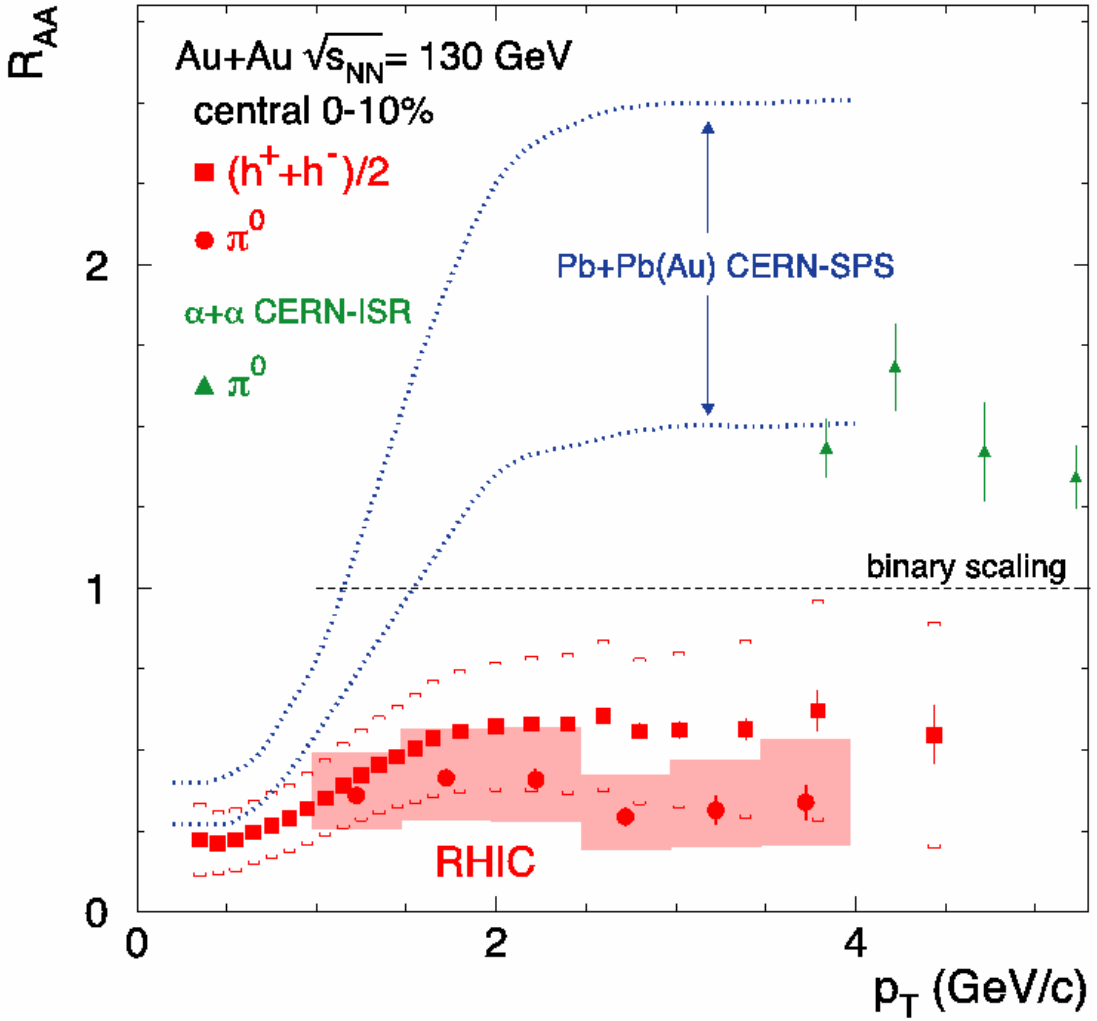
Data from BRAHMS



and PHOBOS Collaborations

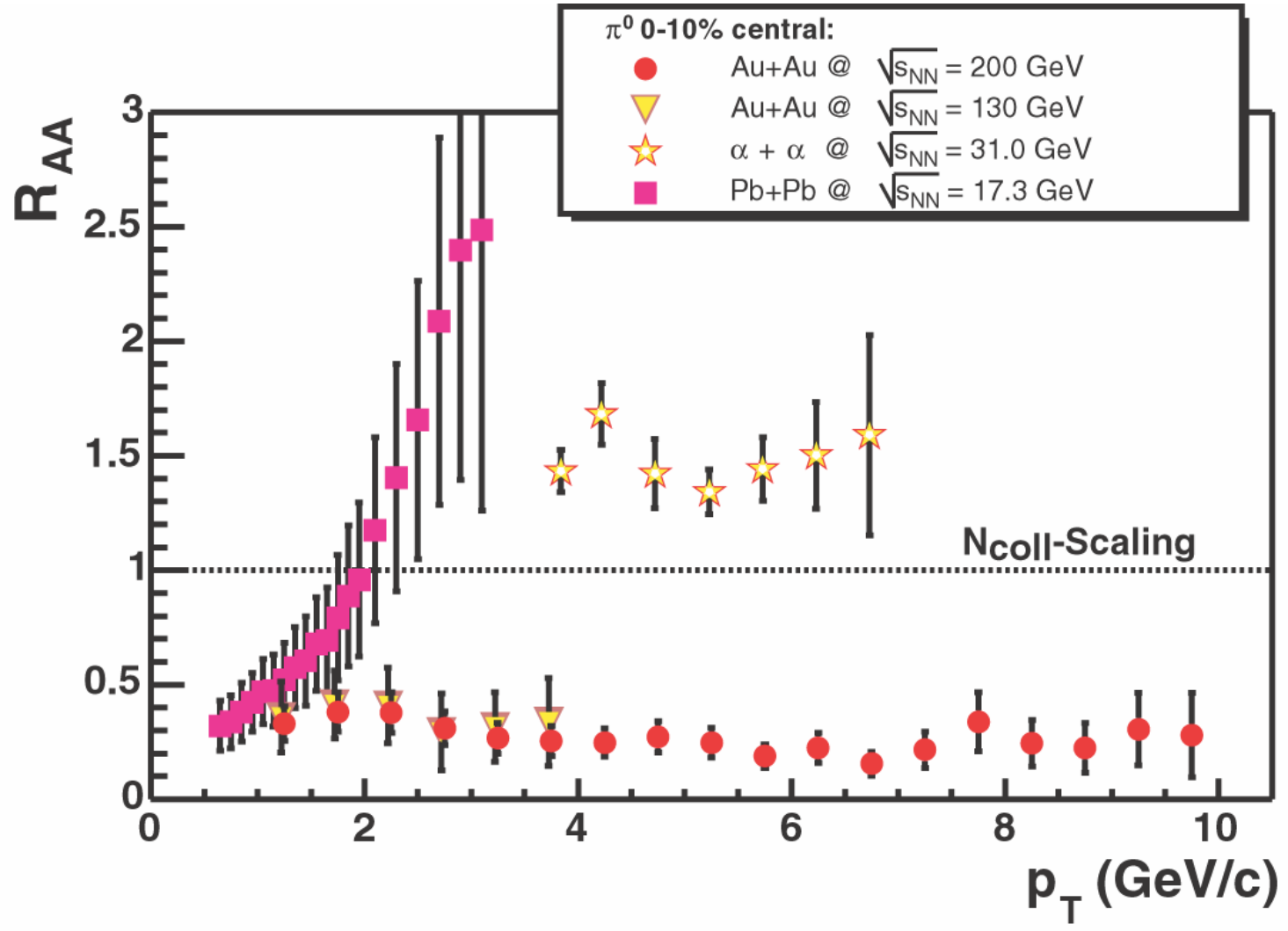
The discovery of high p_T suppression at RHIC





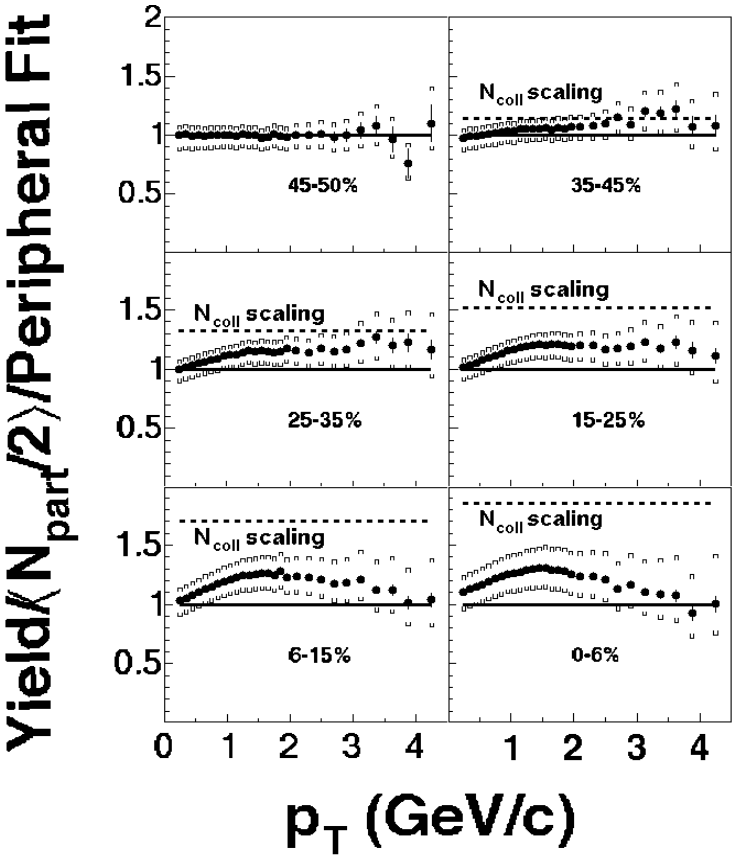
What happens at higher transverse momenta?

PHENIX and STAR extend measurements to ~ 10 GeV

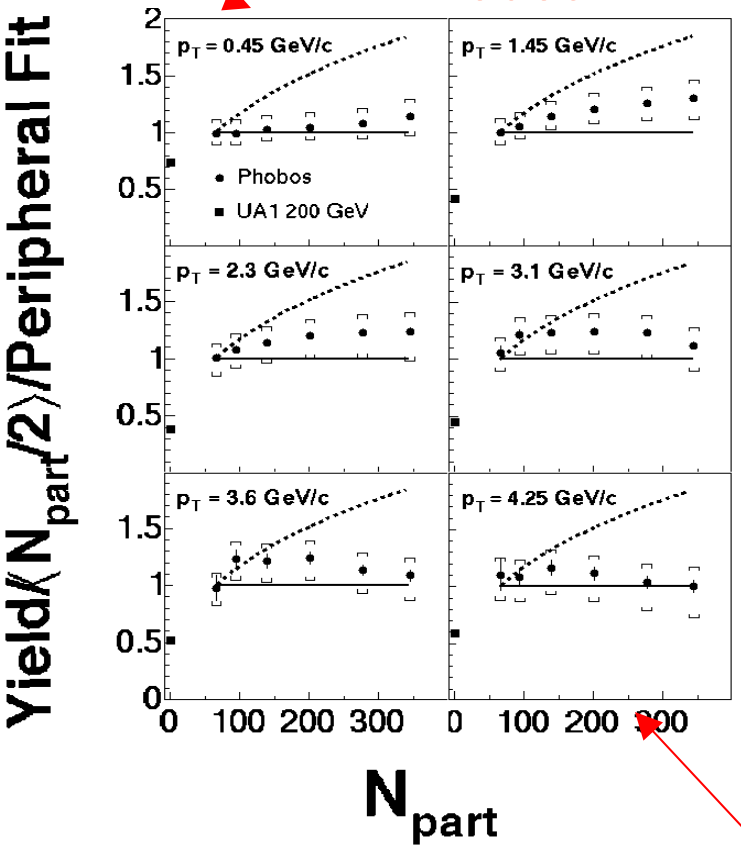


Centrality Dependence vs p_T

Phobos



Phobos



Is this the jet quenching in QGP?

Very likely;
but could there be
alternative explanations? (2002)

Bjorken;
Gyulassy, Wang;
Baier, Dokshitzer,
Mueller, Peigne, Schiff;
Wiedemann, Salgado;
Vitev, Levai, …

DK, Levin, McLerran hep-ph/0210332

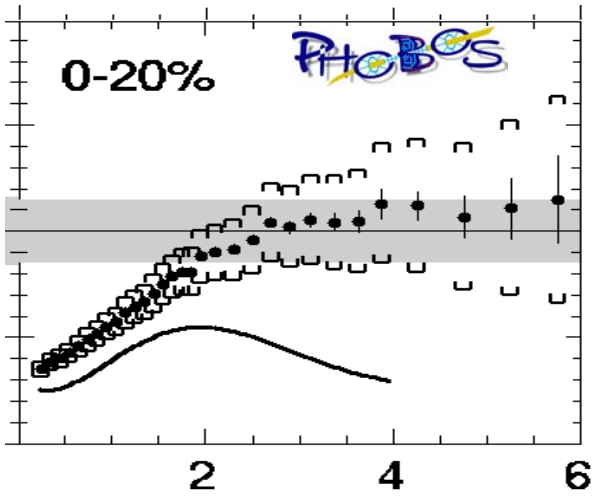
Yes, possibly:

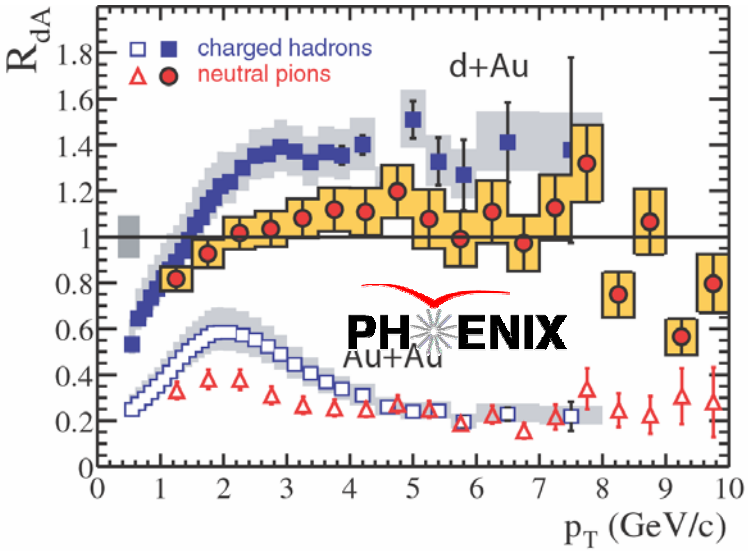
1) Small x evolution leads to
the modification of gluon propagators -
"anomalous dimension": $\frac{1}{Q^2} \to \left(\frac{1}{Q^2}\right)^{\gamma} \qquad \gamma \simeq 1/2$

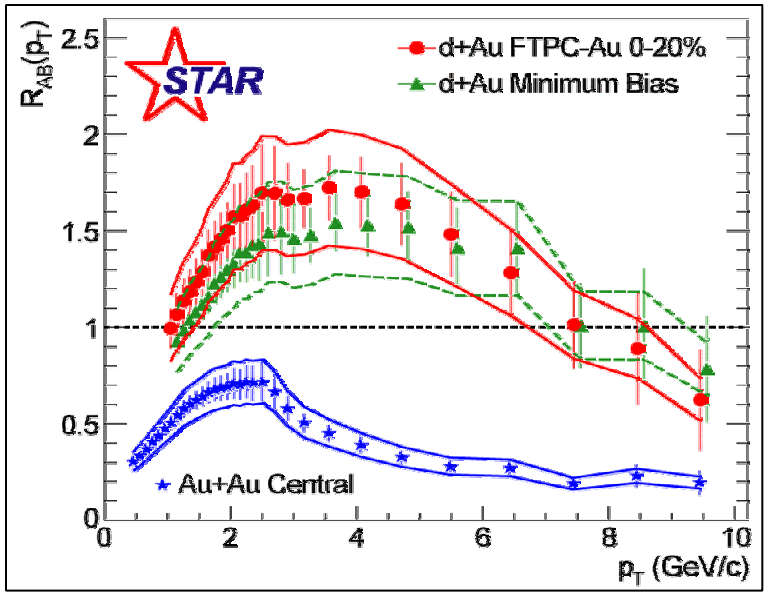
2) Q_s is the only relevant dimensionful parameter in the CGC;
thus everything scales in the ratio Q_s^2/Q^2

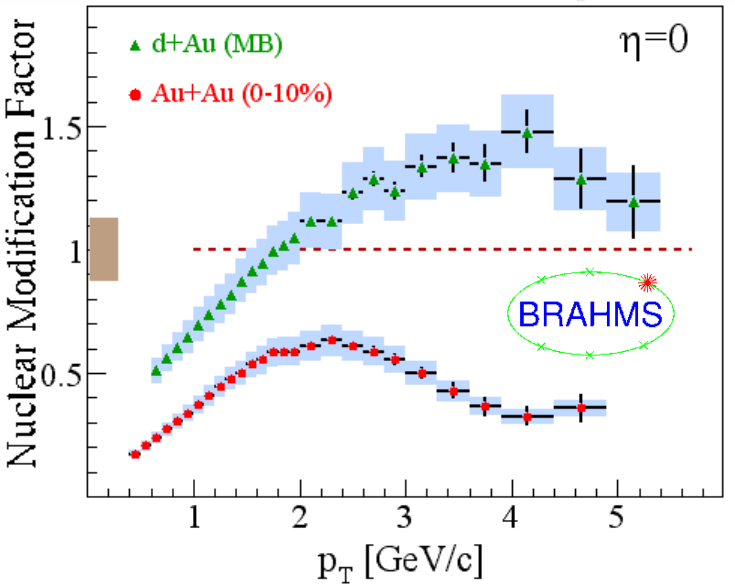
3) Since $Q_s^2 \sim A^{1/3}$ the A-dependence is changed
=> N_{part} scaling!

D-Au collisions: suppression or enhancement?

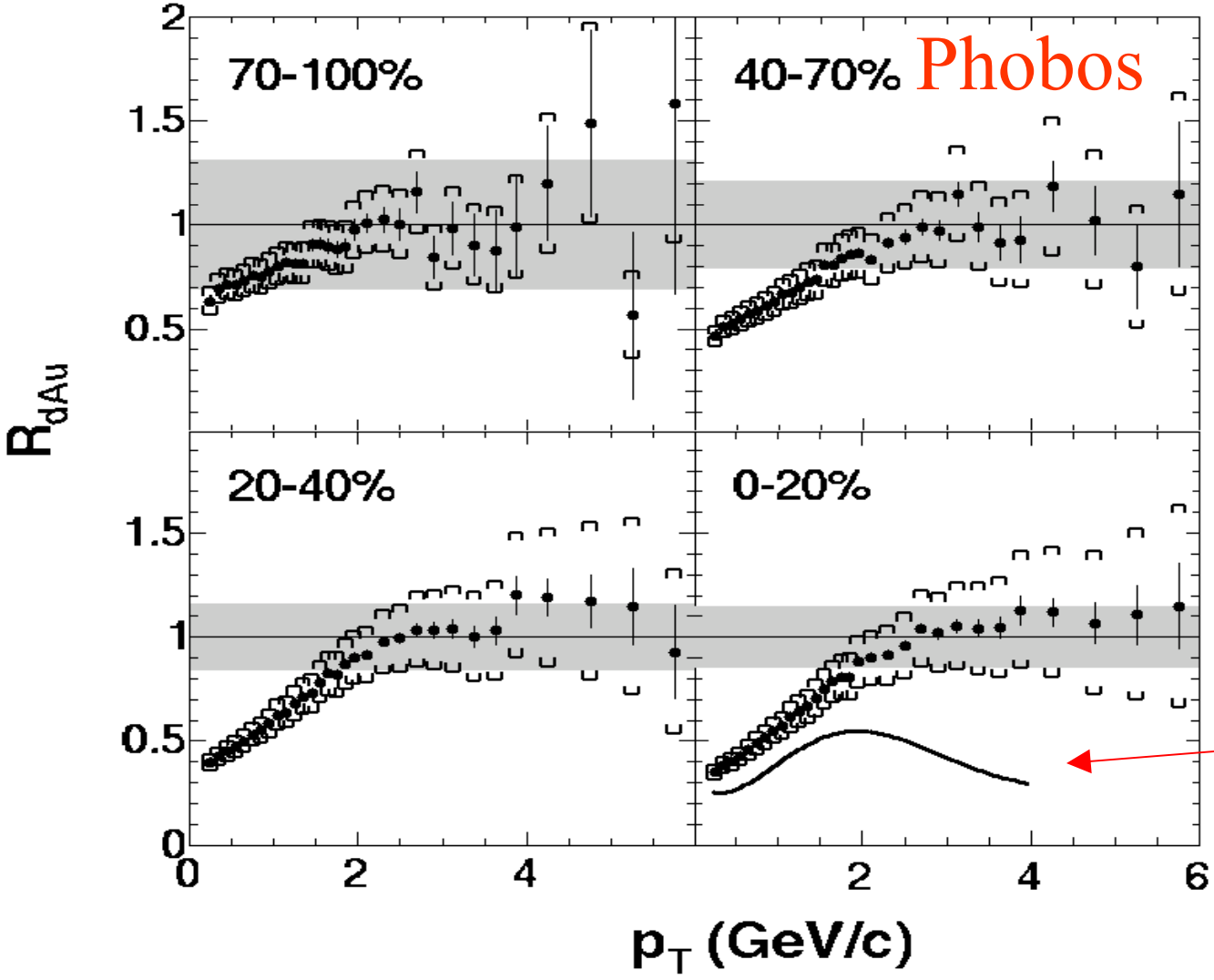








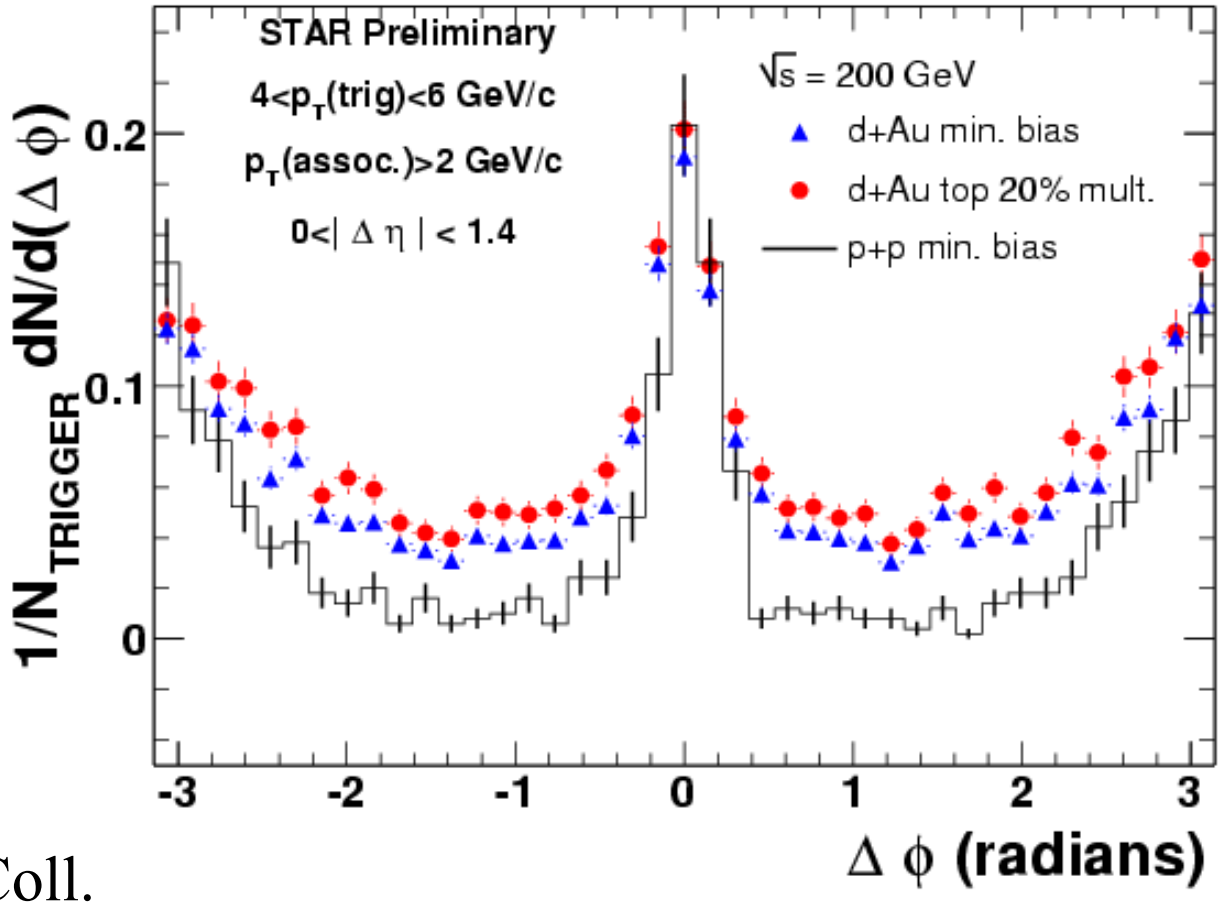
R_{dAu} vs p_T



Central
Au+Au

p+p vs. d+Au

No "data manipulation"



D. Hardtke, STAR Coll.

- Azimuthal correlations are *qualitatively* consistent
- Quantitative evaluation will constrain
  - o Nuclear k_T from initial state multiple scattering
  - o Shadowing
- Models that predict "monojets" due to initial state effects ruled out

Conclusion:
high p_T suppression is a final-state effect

Can one prove that it is due to a radiative jet energy loss
In the Quark-Gluon Plasma?

Quite likely: one possibility is to use the heavy quarks

Yu.Dokshitzer, DK '01

Radiation off heavy quarks is suppressed ("dead cone")
=> less quenching

On the other hand, D mesons have about the same size as pions and kaons, and so in the hadron absorption scenario the suppression should be the same

However, the arguments for the CGC-caused suppression should hold for sufficiently small x;

Does this happen at RHIC?

Study the forward rapidity region:

$$Q_s^2(s;y) = Q_s^2(s;0)\ \exp(\lambda y);$$

Moving to y=+4 from y=0 increases the saturation scale by factor of three

Expectations for R_{dAu} at large rapidity

Agreement on the presence of suppression due to the quantum Small x evolution in the CGC picture:

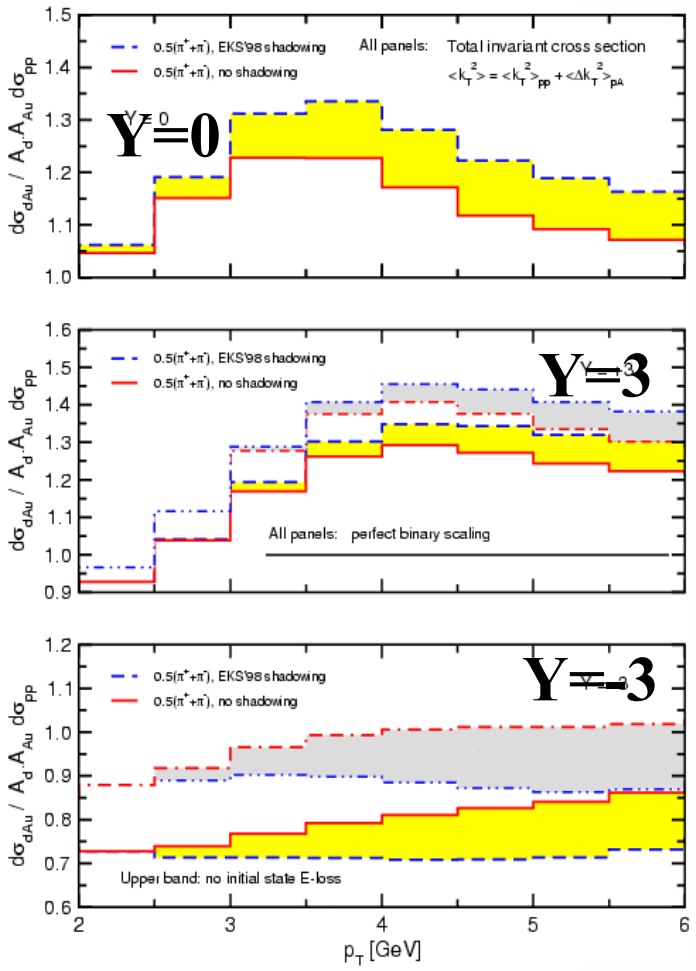
DK, E. Levin and L. McLerran, hep-ph/0210332;
R. Baier, A. Kovner, U. Wiedemann, hep-ph/0305265 v2
DK, Yu.Kovchegov and K. Tuchin, hep-ph/0307037 v2
J. Albacete, N. Armesto, A. Kovner, C. Salgado,
U. Wiedemann, hep-ph/0307179;

Agreement on the presence of Cronin effect in the classical approach and in the multiple scattering picture:

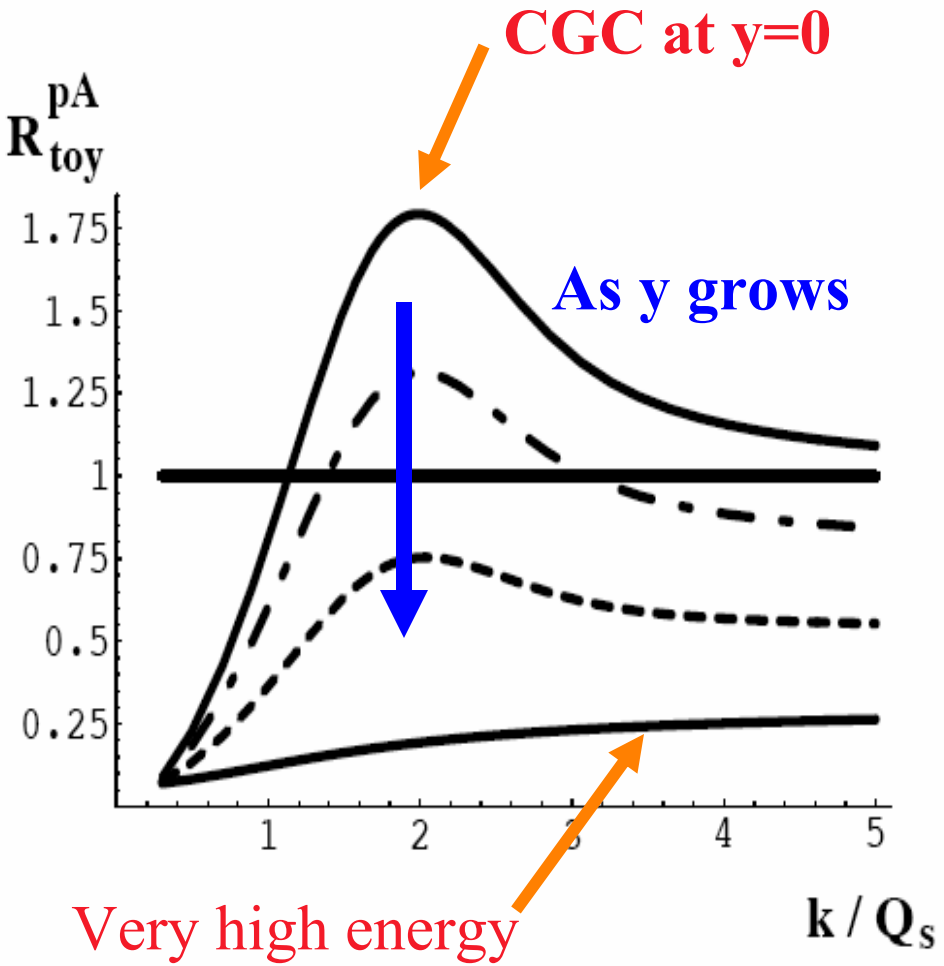
L.McLerran and R.Venugopalan; Yu.Kovchegov and A.H.Mueller;
J. Jalilian-Marian; A. Dumitru; F. Gelis;…
X.N.Wang; M. Gyulassy; I. Vitev;…

Model predictions

I. Vitev nucl-th/0302002 v2

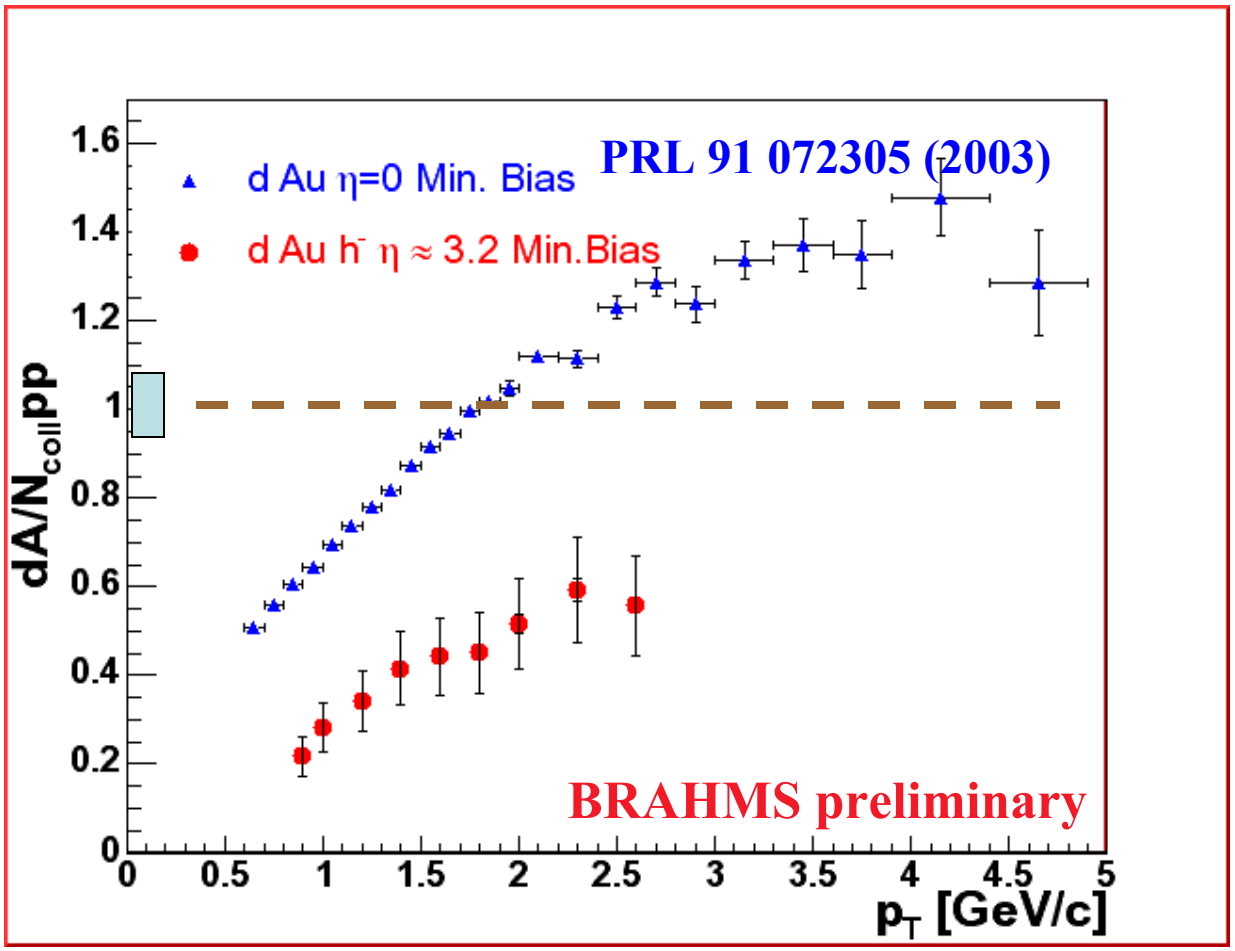


D. Kharzeev, Yu. Kovchegov and K. Tuchin, hep-ph/0307037



R. Debbe, BRAHMS Coll., Talk at DNP Meeting, Tucson, November 2003

d-Au Nuclear Modification factor at η ~3.2



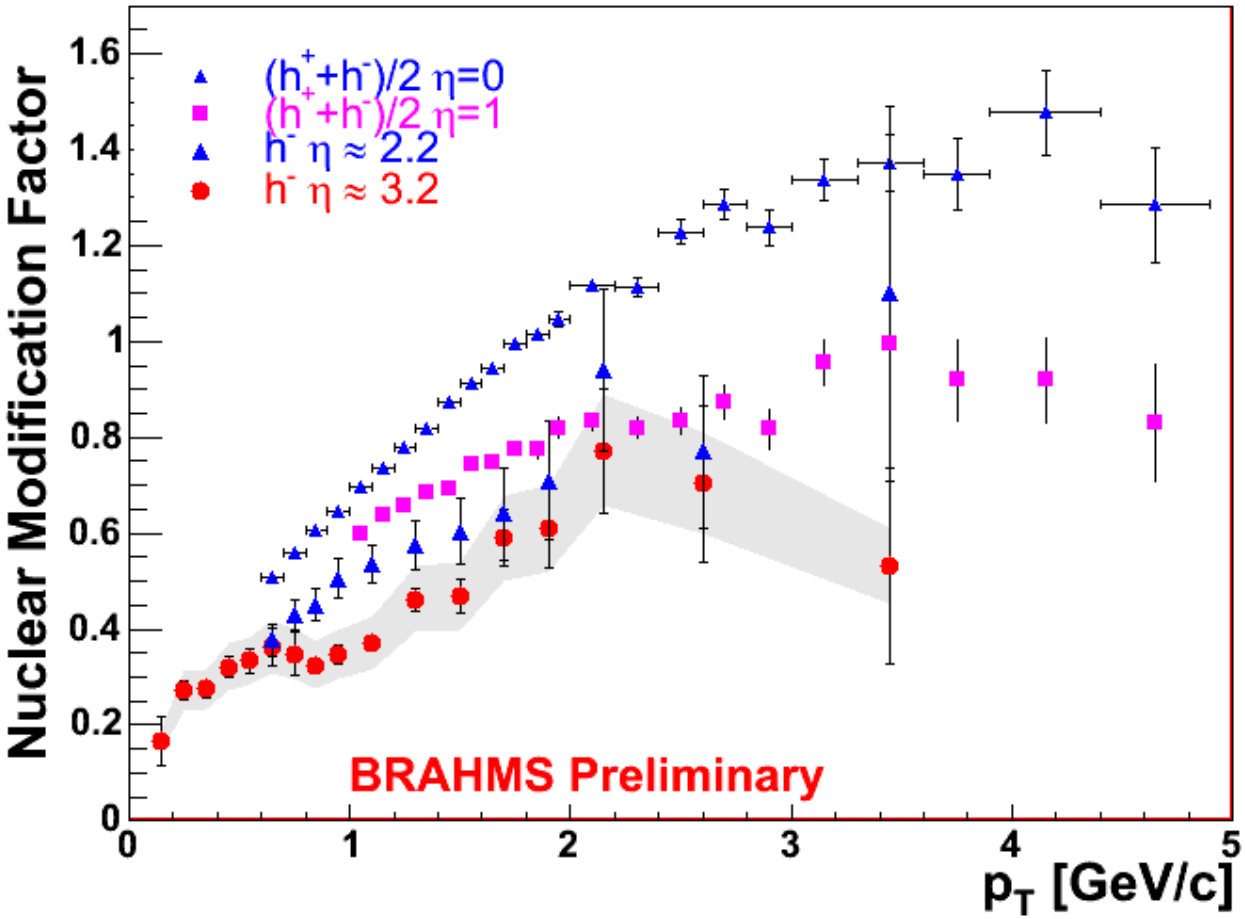
R. Debbe, BRAHMS Collaboration, Talk at the DNP Meeting, Tucson, November 2003

RdAu compares the yield of **negative particles** produced in dAu to the scaled number of particles with same sign in p-p

The scale is the number of binary collisions:

N_{coll}=7.2
(minimum biased)

R_{dAu} at different rapidities



All ratios extracted from minimum biased data samples

R.Debbe, BRAHMS, QM'04

Number of binary collisions in minimum biased events is estimated:

$N_{coll} = 7.2 \pm 0.3$

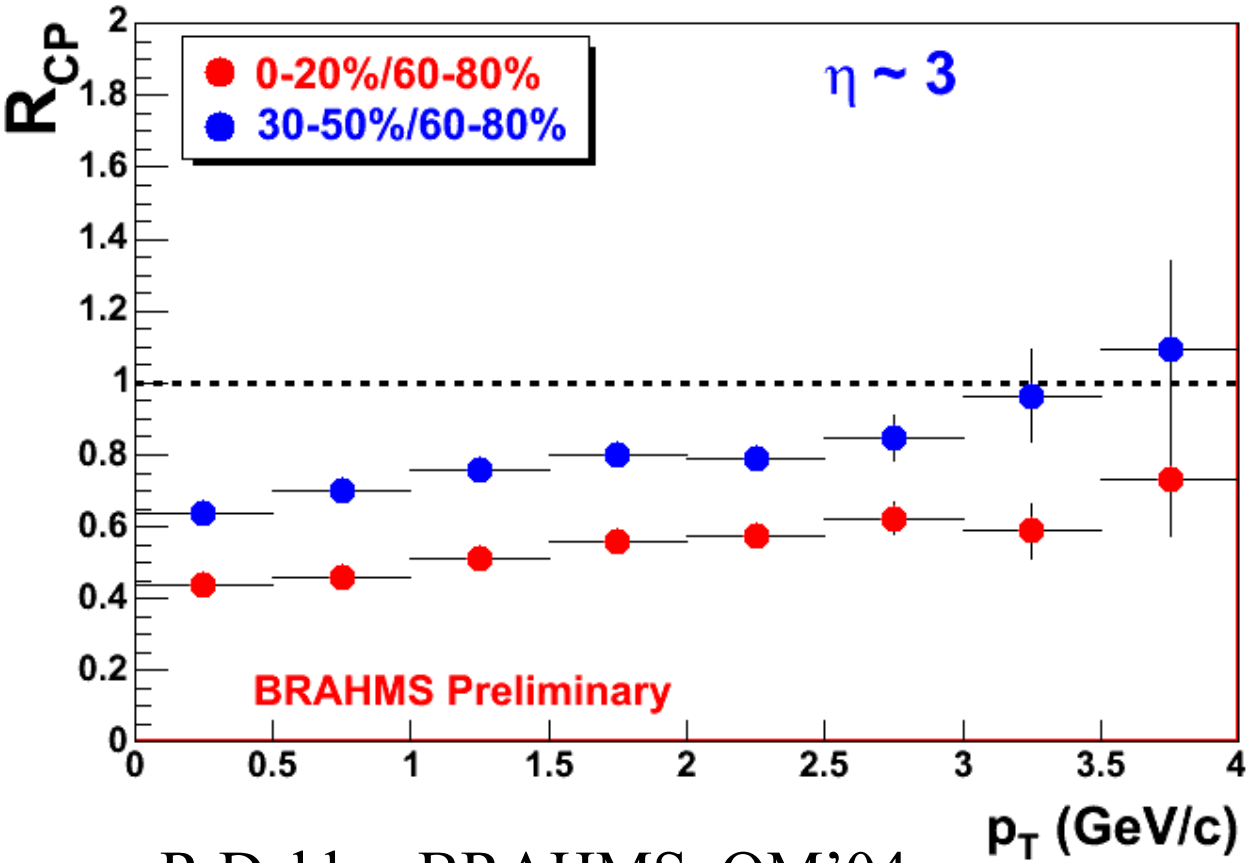
Statistical errors dominant over the systematic ones at η=2 and 3

Systematic error (not shown) ~15%

The values for η=0 were published in:

PRL 91 072305 (2003)

Centrality dependence



R.Debbe, BRAHMS, QM'04

All numerators and denominator are scaled by the appropriate estimated number of binary collisions (HIJING + BRAHMS GEANT)

The ratios are corrected for trigger inefficiency.

All other corrections (acceptance, tracking efficiency..) cancel out.

Discussion

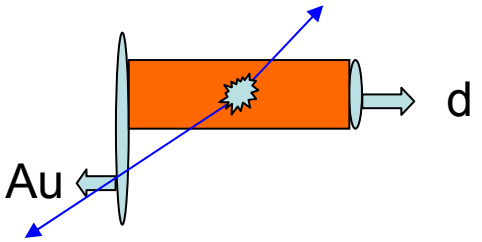
BRAHMS has measured a clear modification of the Cronin peak as we detect charged particles at pseudo-rapidities ranging from 0 to 3.

We also found that particle yields at all values of p_T are more suppressed in central events at high rapidity.

Both results are consistent with a description of the Au wave function **evolving in ln(1/x)** (rapidity) into a saturated non-linear medium.

Centrality Dependence of Particle Production @Fwd/Bwd Directions

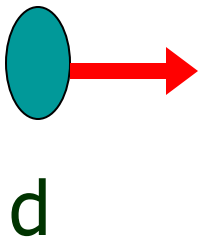
1. Stopped hadrons
   - Mesons + Baryons
2. Light mesons
   - Pions + Kaons
3. Heavy flavors
   - Charm + Beauty



$$R_{CP}^{dAu}(P_T, y) \propto \frac{\dfrac{\Delta N^{cent-XX}}{< N_{coll} >}}{\dfrac{\Delta N^{60-88\%}}{< N_{coll} >}};$$

$$cent-XX = 0-20\%, 20-40\%, 40-60\%$$

Ming Liu, PHENIX, QM'04



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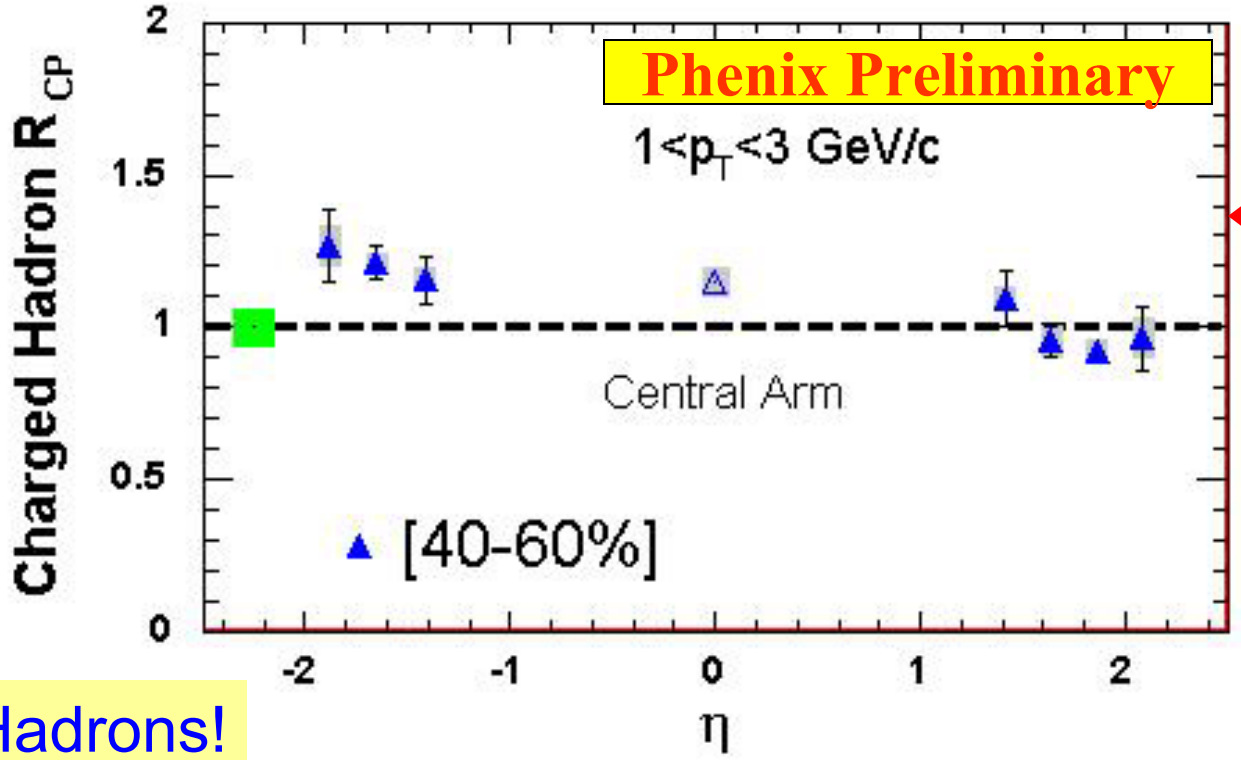
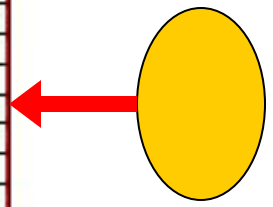
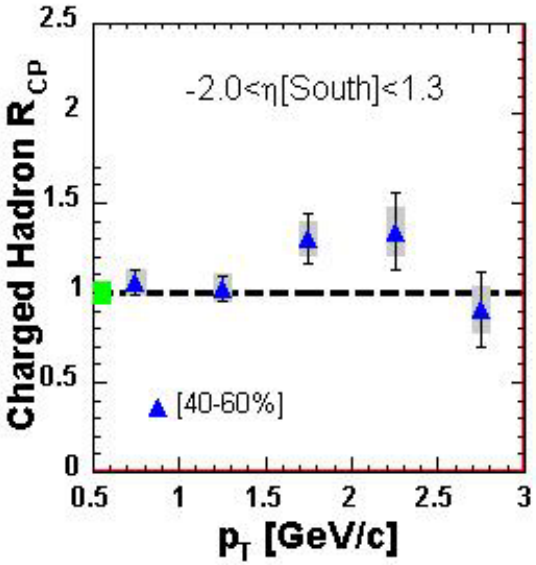
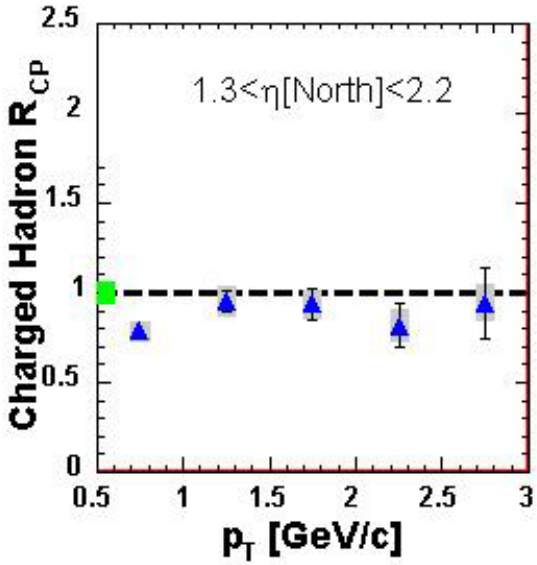


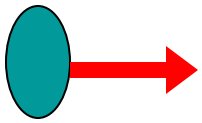


Au

Stopped Hadrons!







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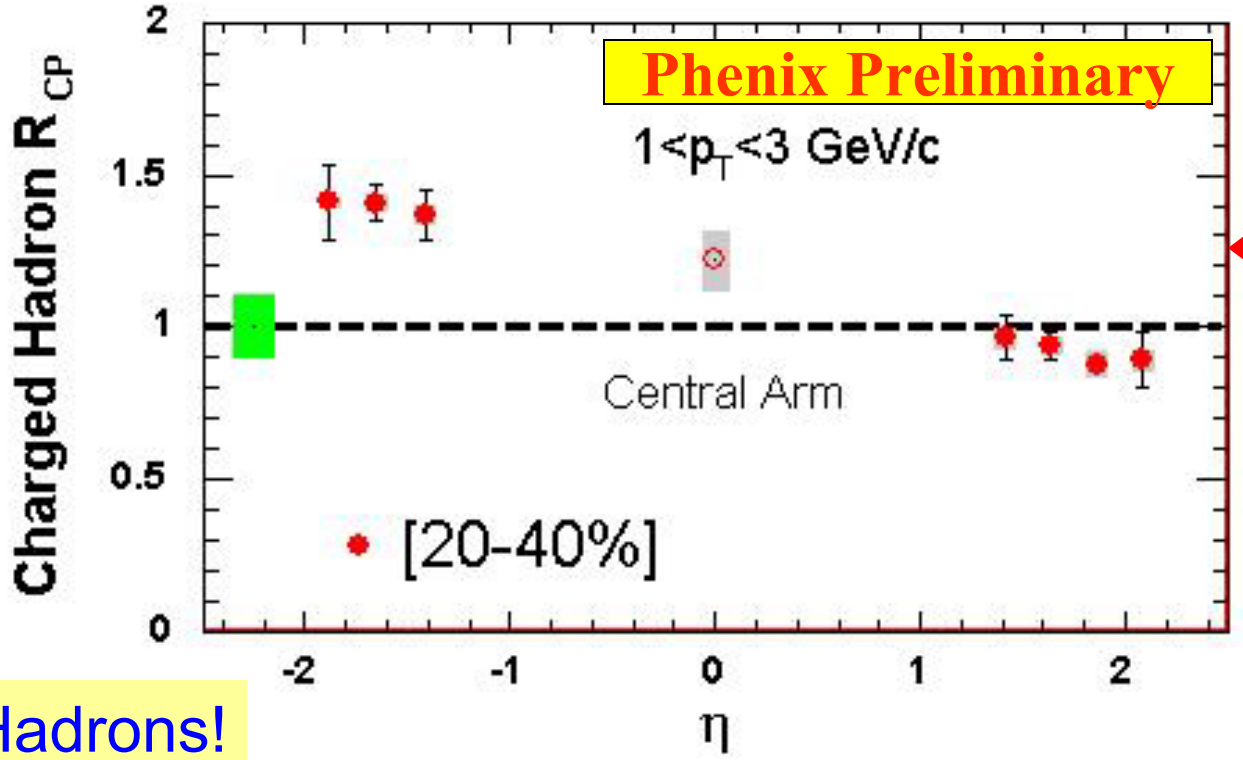
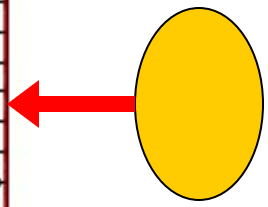
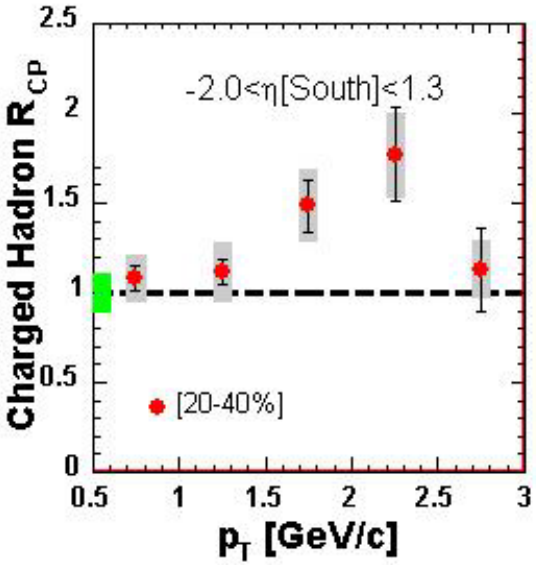
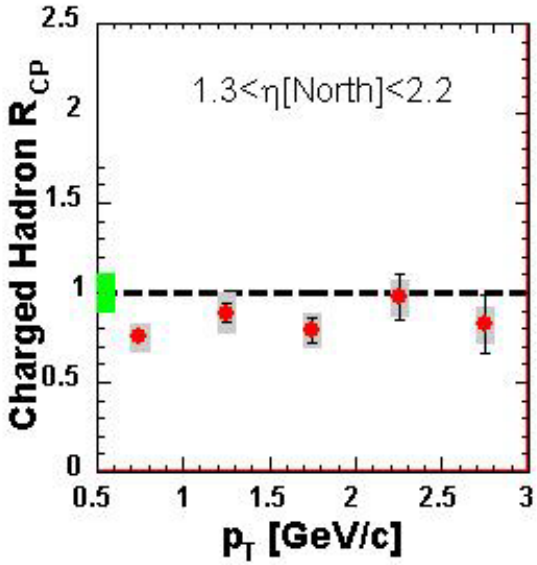


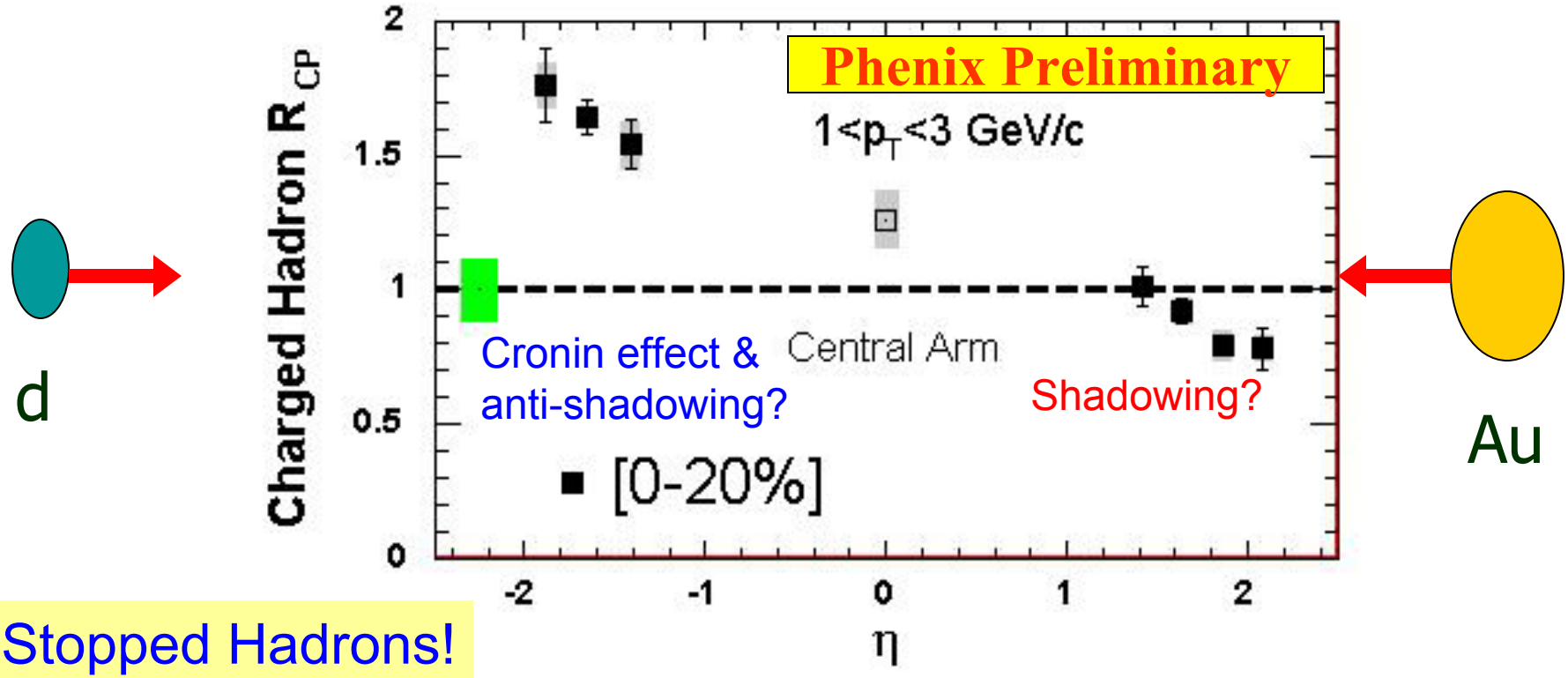


Au

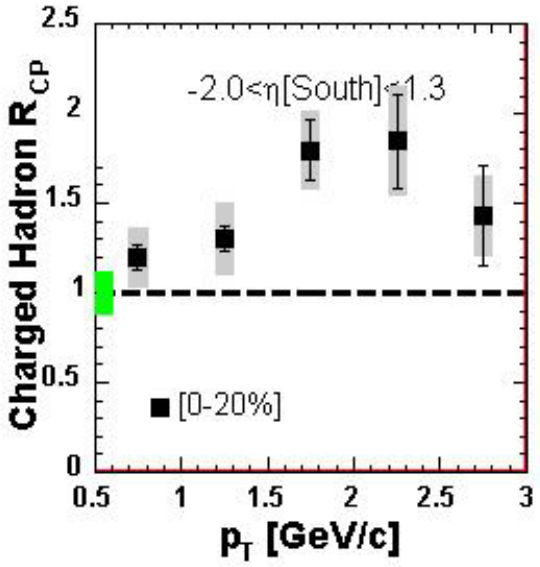
Stopped Hadrons!

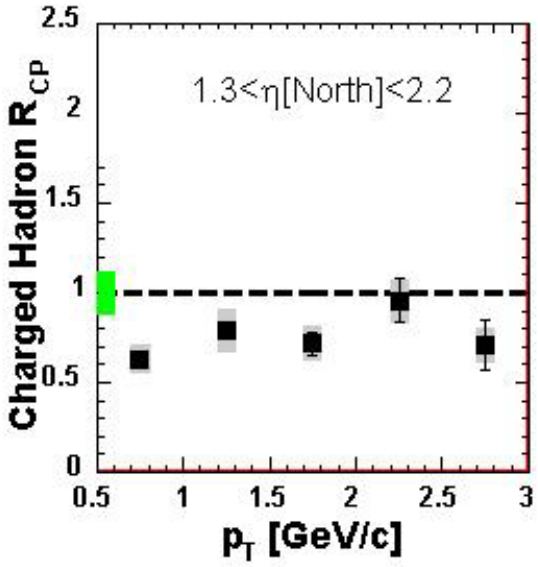






Stopped Hadrons!





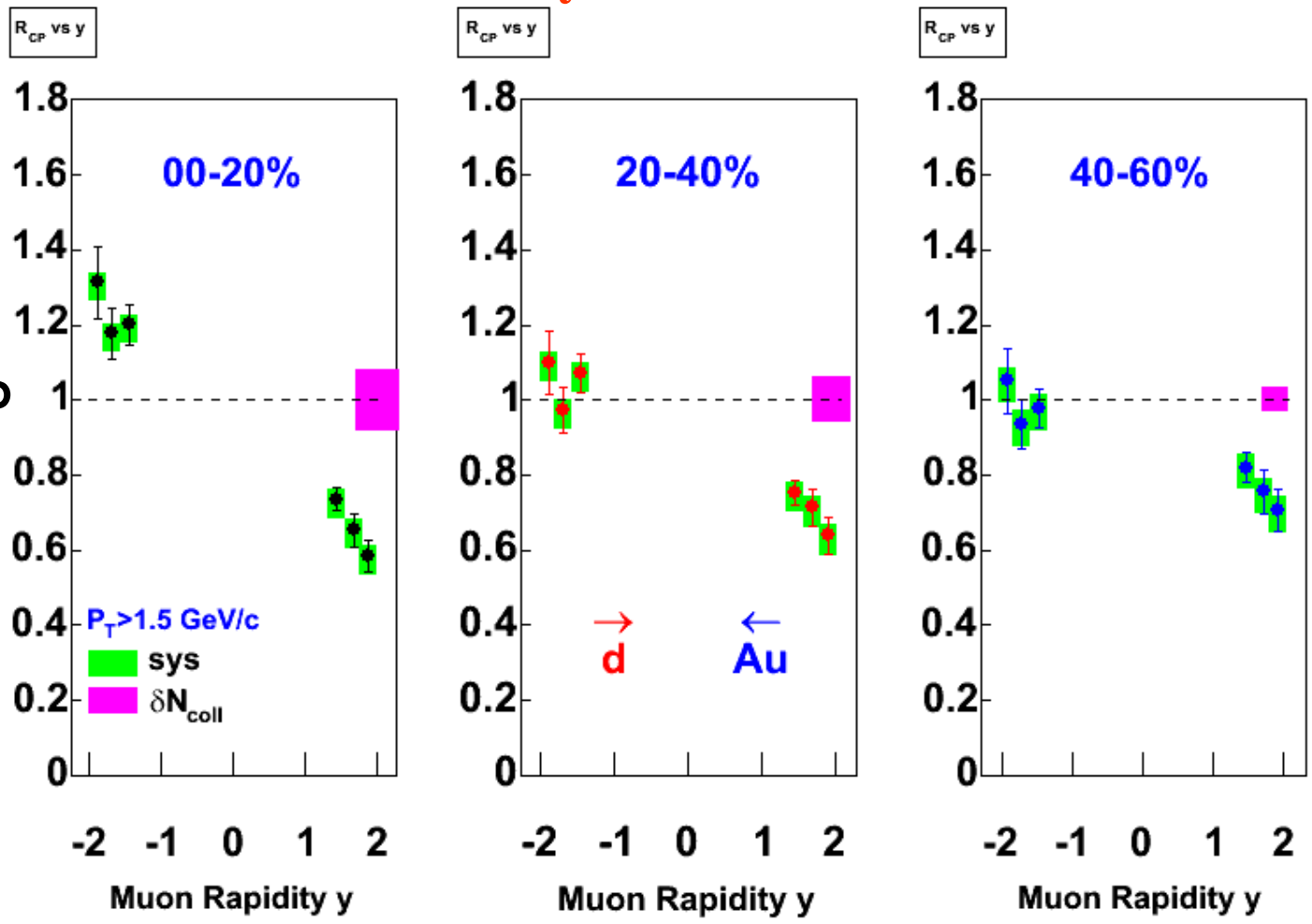
$R_{CP}(y)$: Muons from Light Meson Decays

Phenix Preliminary

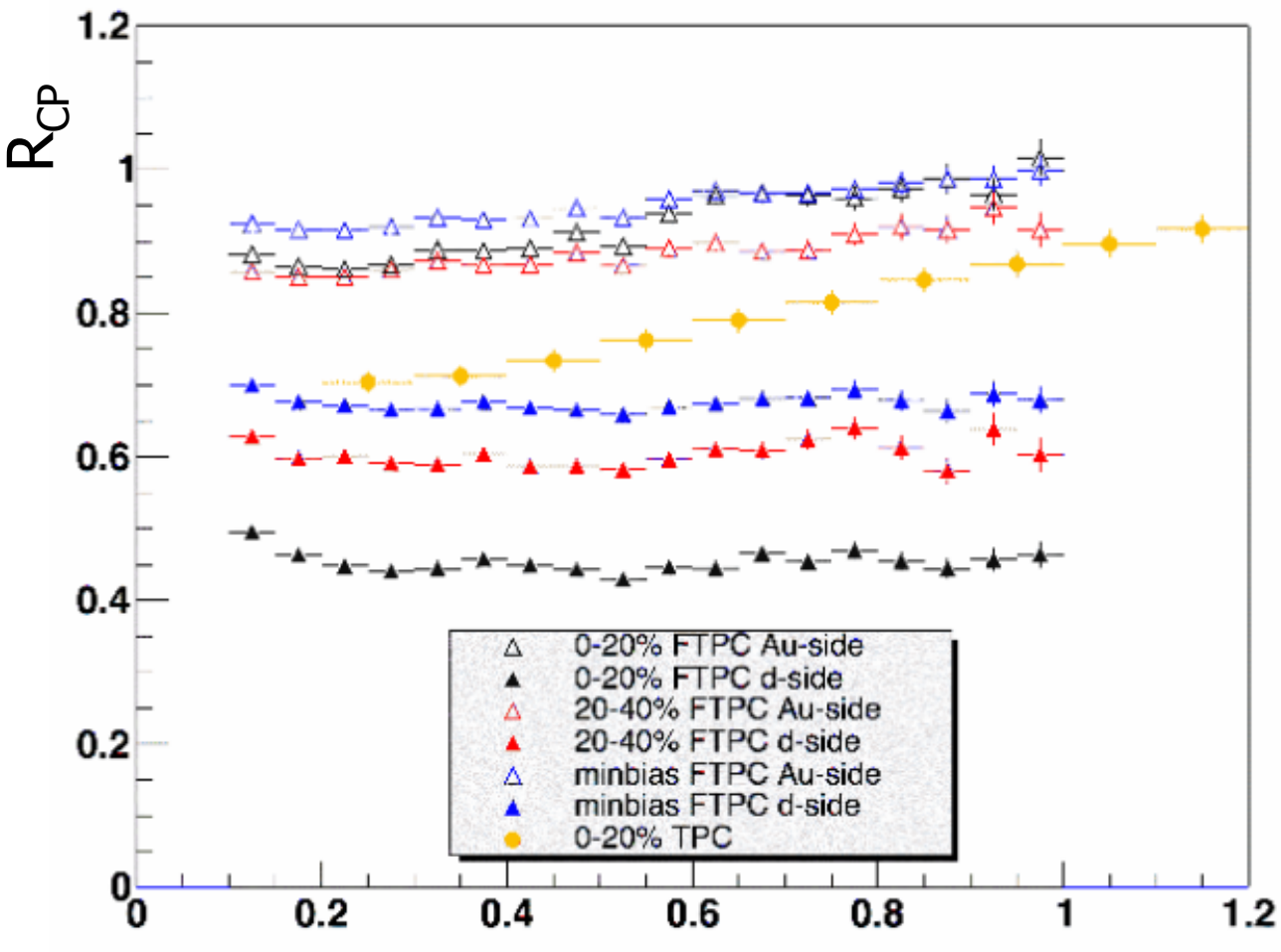
R_{CP}

$\pi^{\pm} \rightarrow \mu^{\pm} + \nu$

$K^{\pm} \rightarrow \mu^{\pm} + \nu$



d+Au R_{CP} at forward rapidities

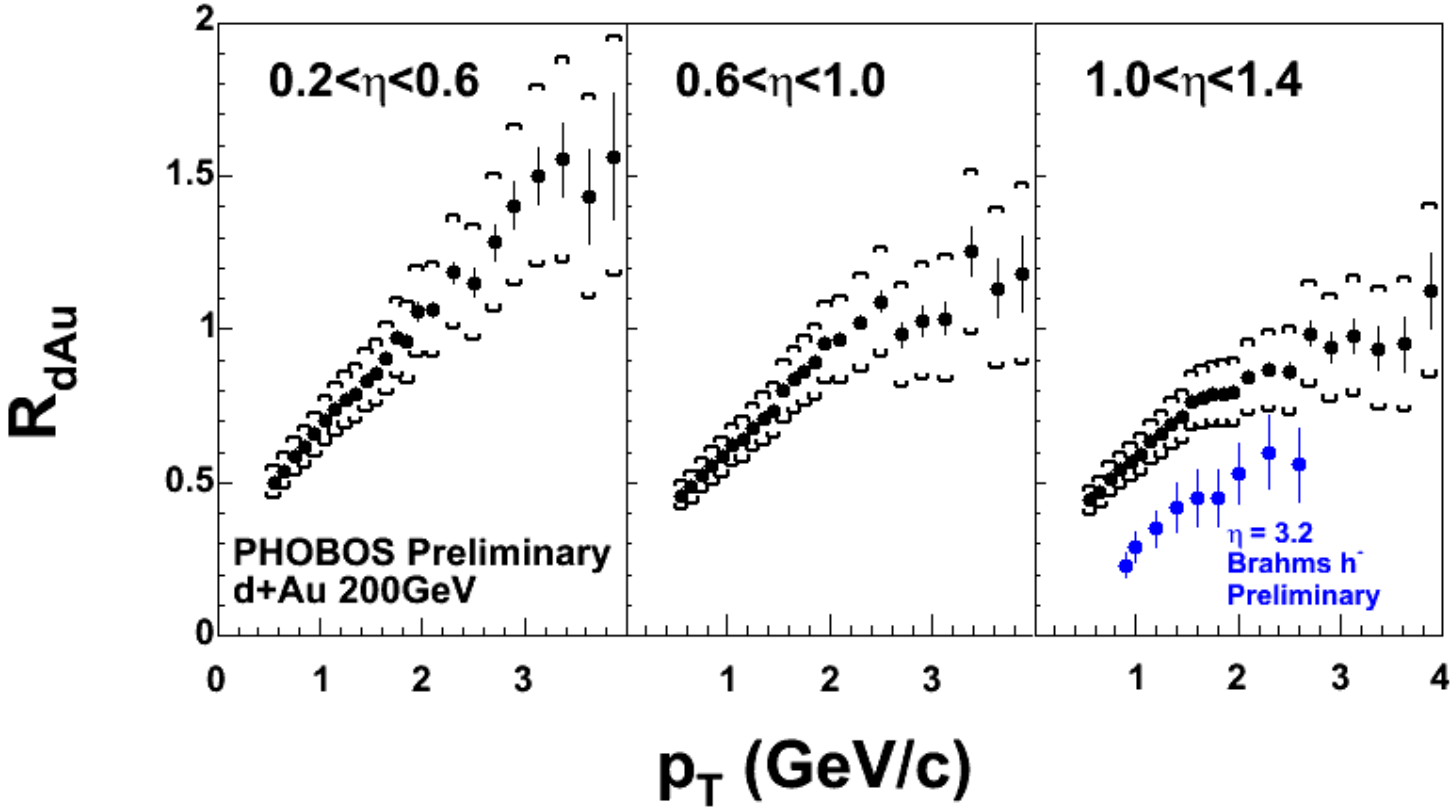


- Au-Side R_{CP} shows almost no variation with centrality

- d-side is interesting: more central is more suppressed

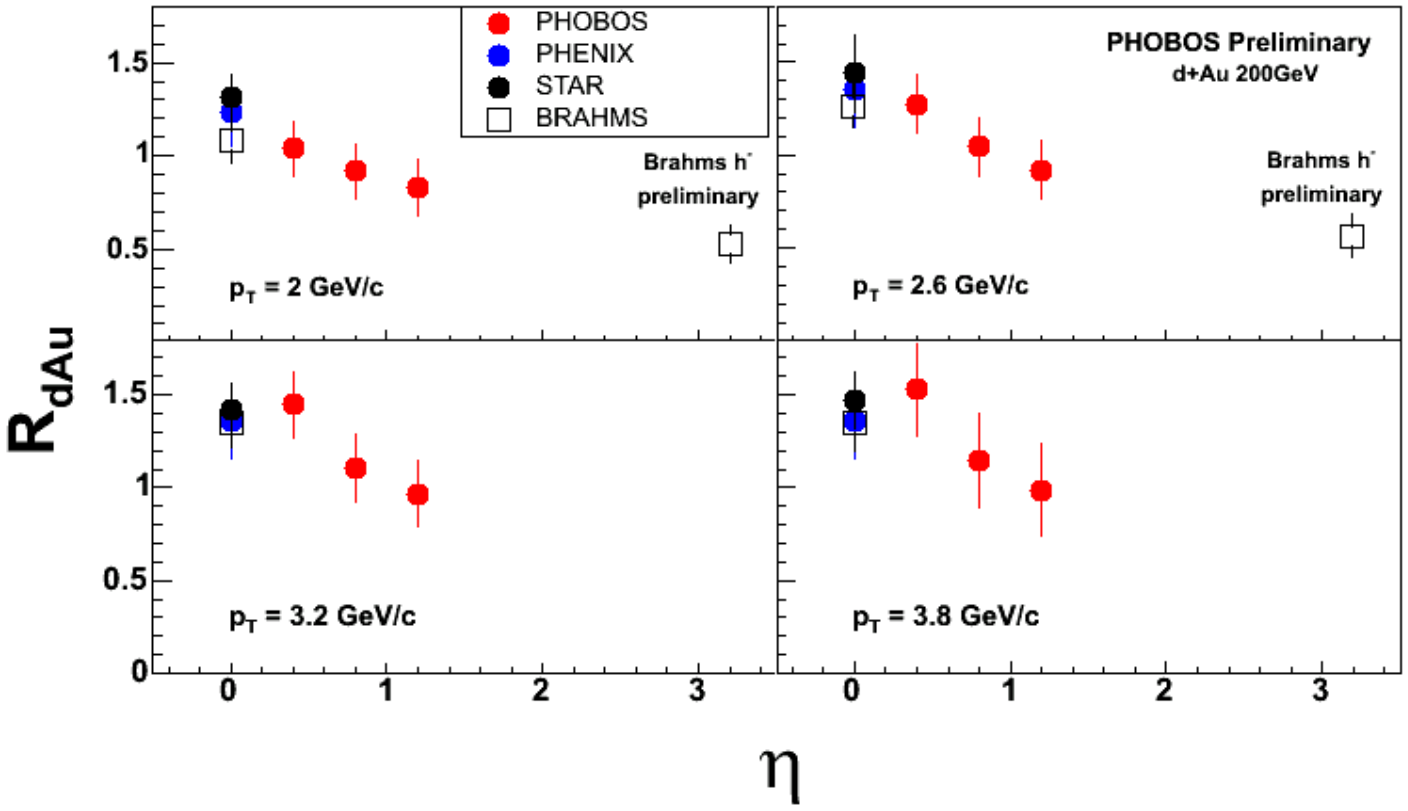
L.Barnby, STAR, QM'04

d Au spectra at (not so) forward rapidity

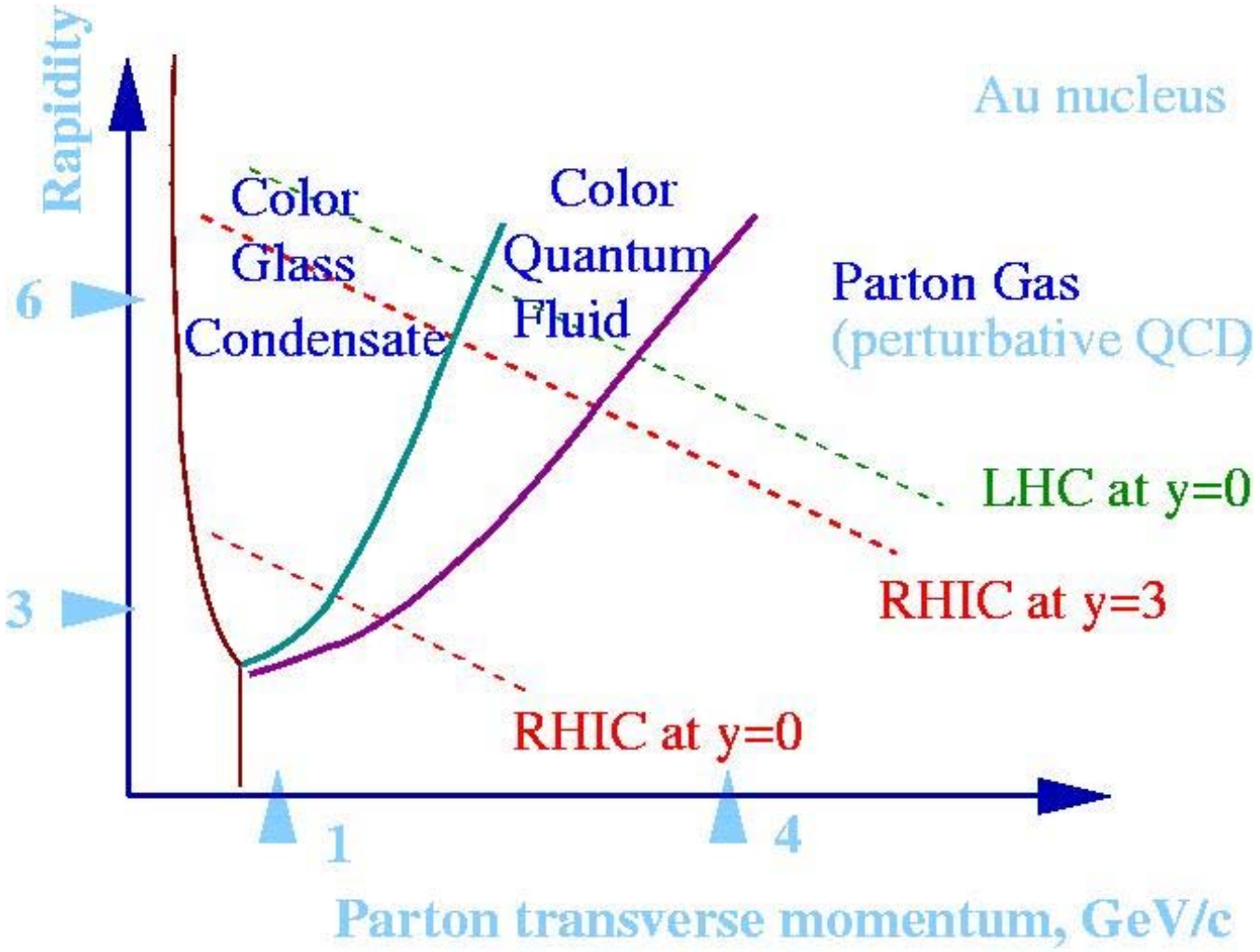


P. Steinberg, PHOBOS, QM'04

Rapidity dependence of R_{dAu}



Phase diagram of high energy QCD



Summary

Recent results from RHIC indicate strong non-linear effects at small x

Combined with observations at HERA, and supplemented by further tests, these results can lead to the discovery of parton saturation in the Color Glass Condensate

Major implications for future programs at RHIC, the LHC, and eRHIC