Color Glass Condensate at RHIC

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Outline

- What is Color Glass Condensate?
- CGC and Quark-Gluon Plasma
- Manifestations of CGC at RHIC:
    - o hadron multiplicities
    - o high p_T suppression at forward rapidity: BRAHMS discovery
- Future tests
    - o back-to-back correlations and monojets
    - o open charm => talk by K. Tuchin

QCD and the classical limit

QCD = Quark Model + Gauge Invariance

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

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

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

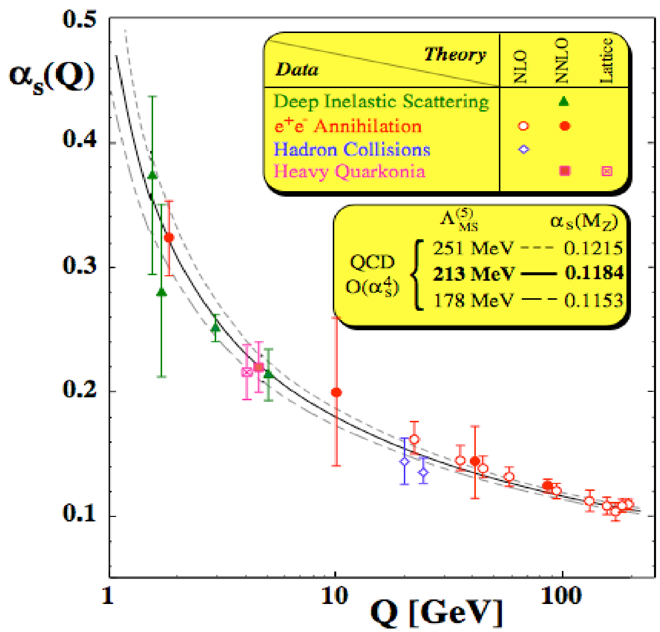
$$L_{\rm QCD} = \sum_q \bar{q}(x)\left(i\gamma_\mu D^\mu - m_q\right) q(x) - \frac{1}{4g^2} {\rm tr}\, G^{\mu\nu}(x) G_{\mu\nu}(x);$$

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

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

=> 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…

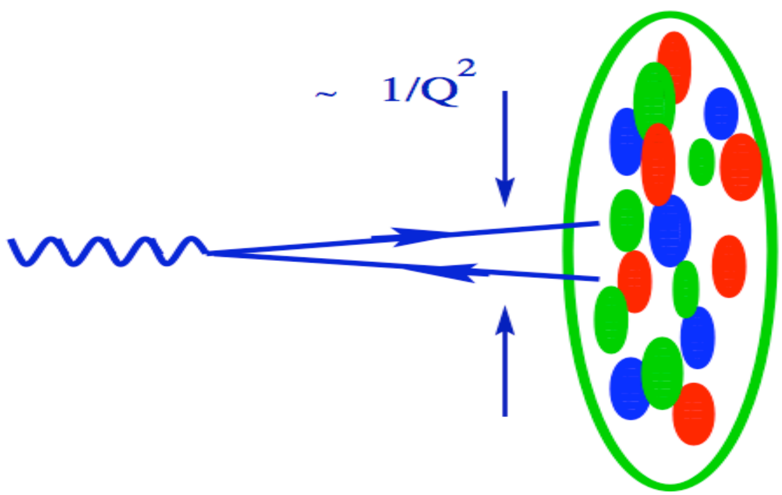
Is there a place for classical methods?

Gribov-Levin-Ryskin; Mueller, Qiu,..

McLerran-Venugopalan; Kovchegov, Jalilian-Marian, Kovner, Weigert, Iancu,…

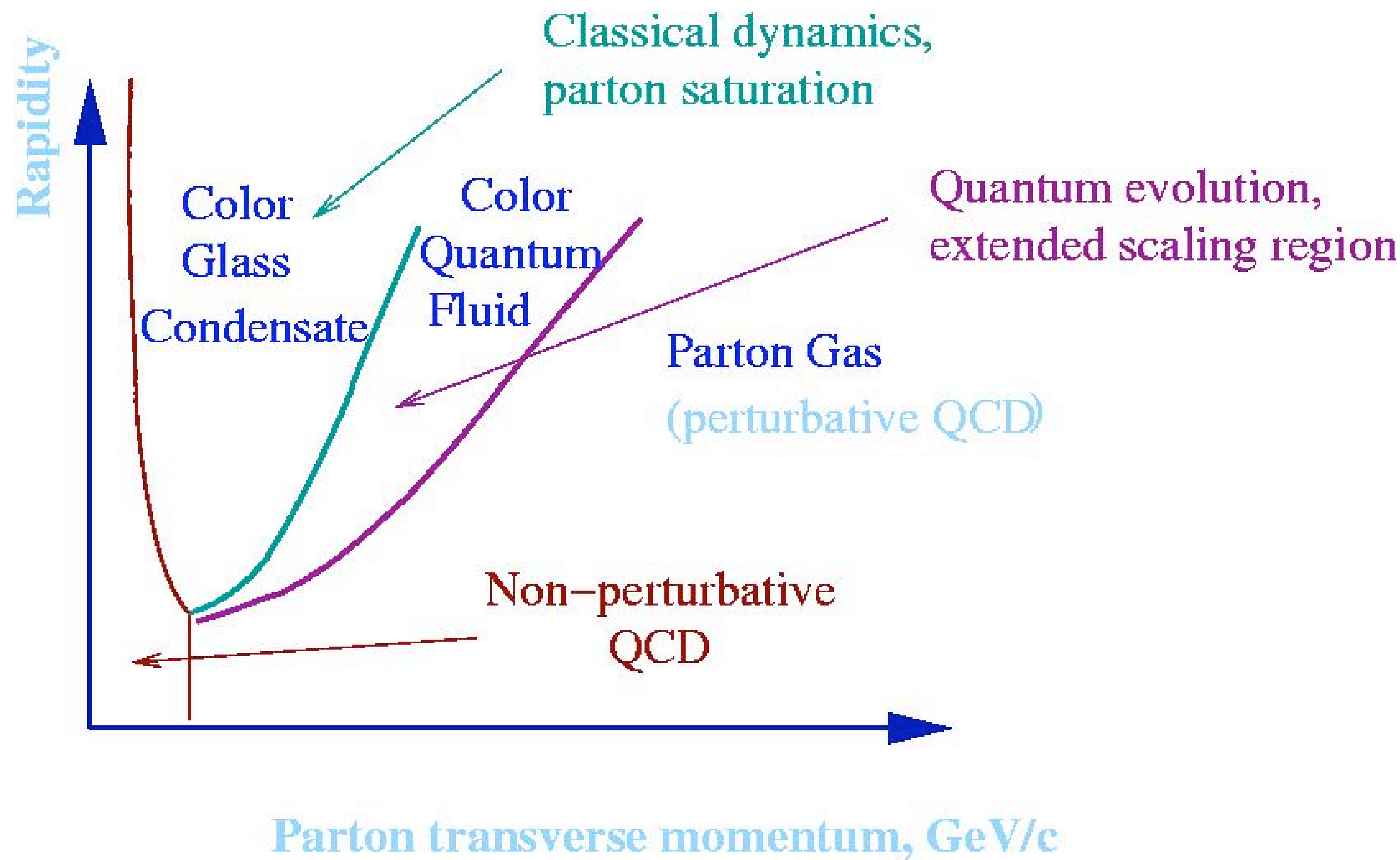
Parton saturation and the classical limit of QCD

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

CGC and total multiplicities in Au-Au

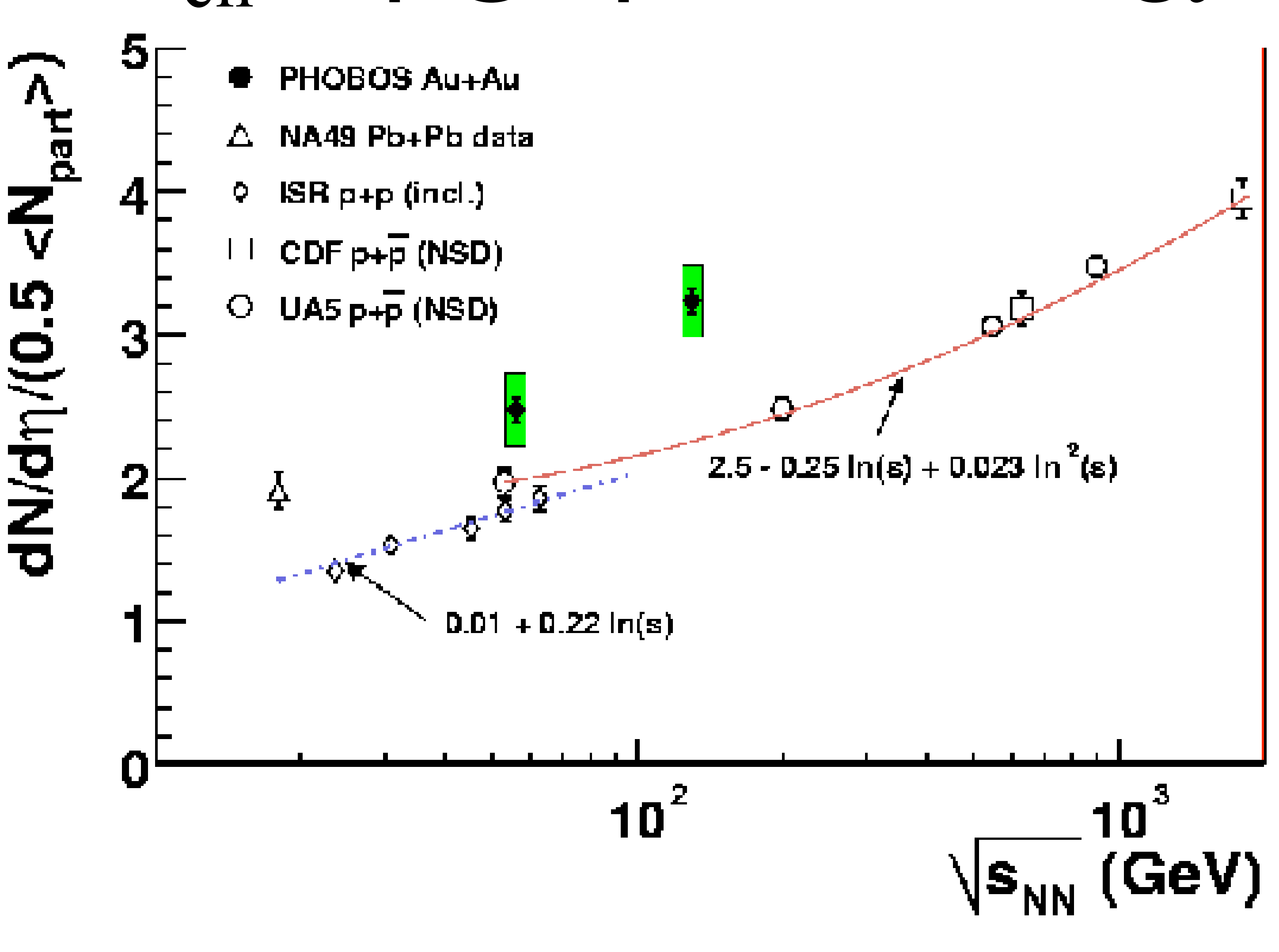
CGC predicts very simple dependence of multiplicity on atomic number A / N_{part}:

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

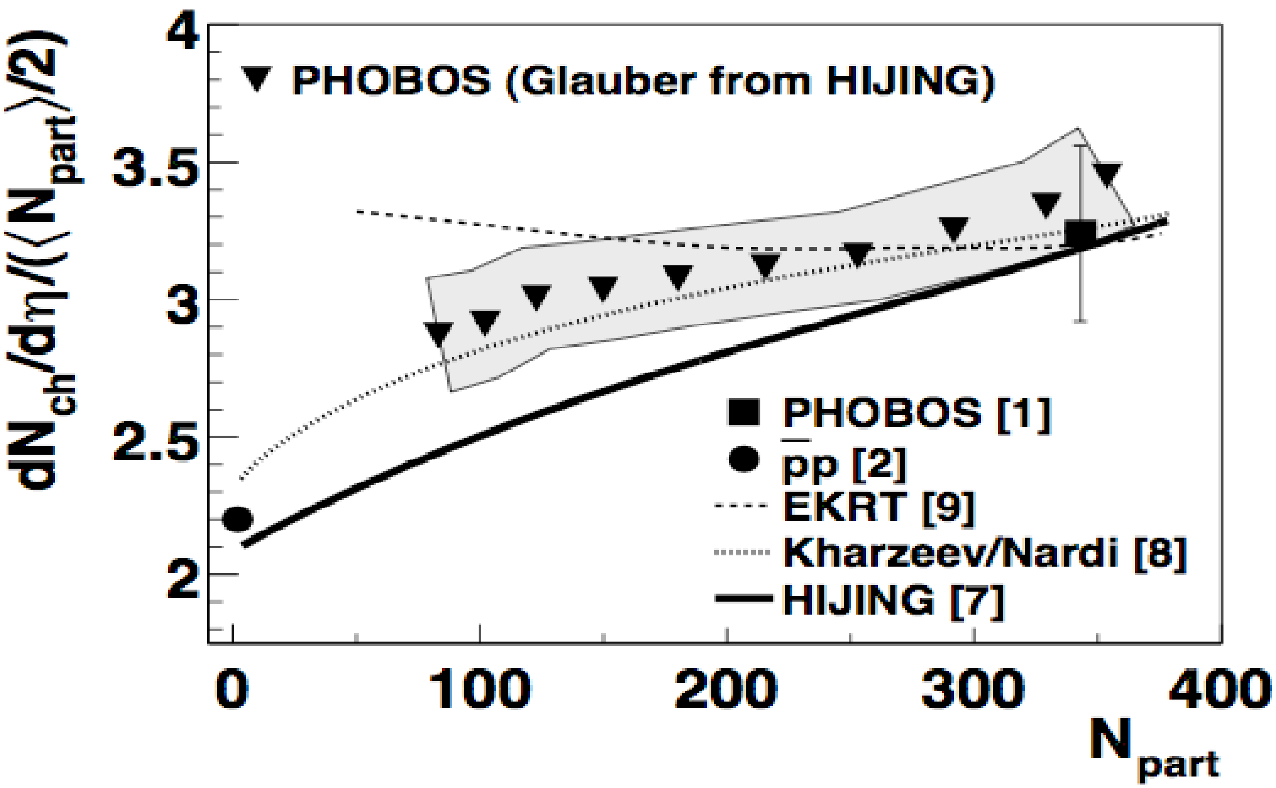
Almost like in "wounded nucleon" and string-based models;
Agrees unexpectedly well with "soft + hard" parameterizations

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

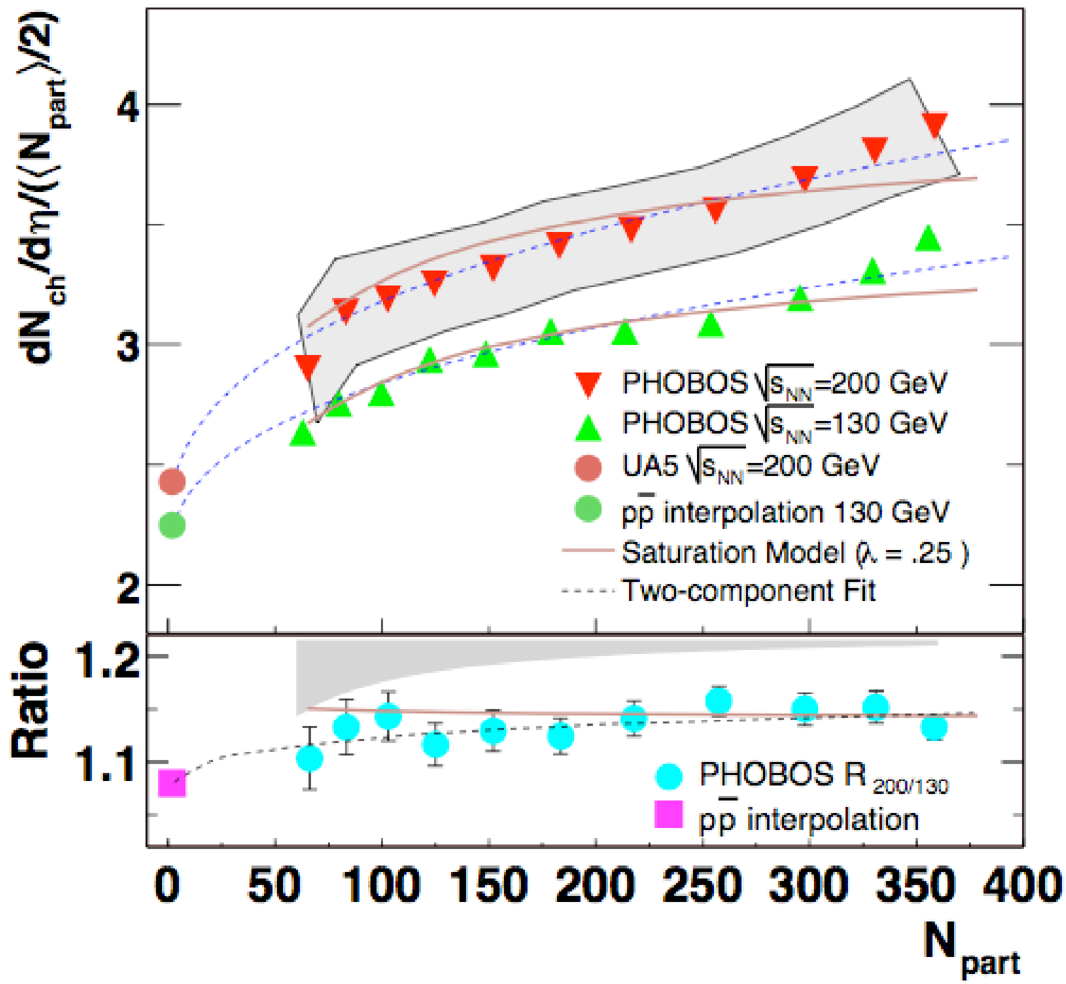
$dN_{ch}/d\eta$ @ η=0 vs Energy



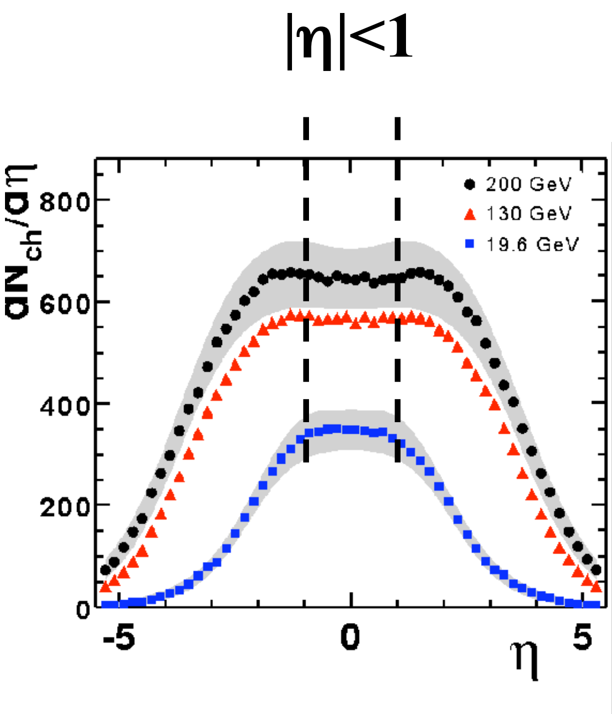
Centrality dependence of hadron multiplicity

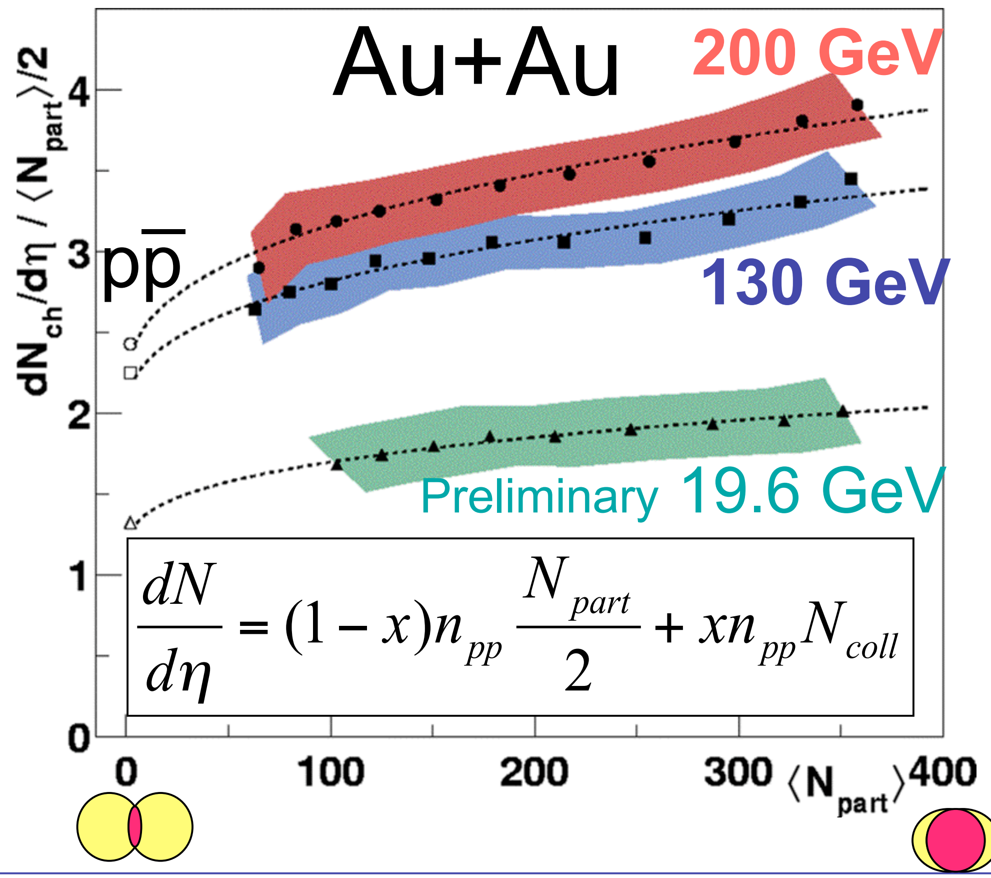


Centrality dependence at different energies



Midrapidity charged particle production

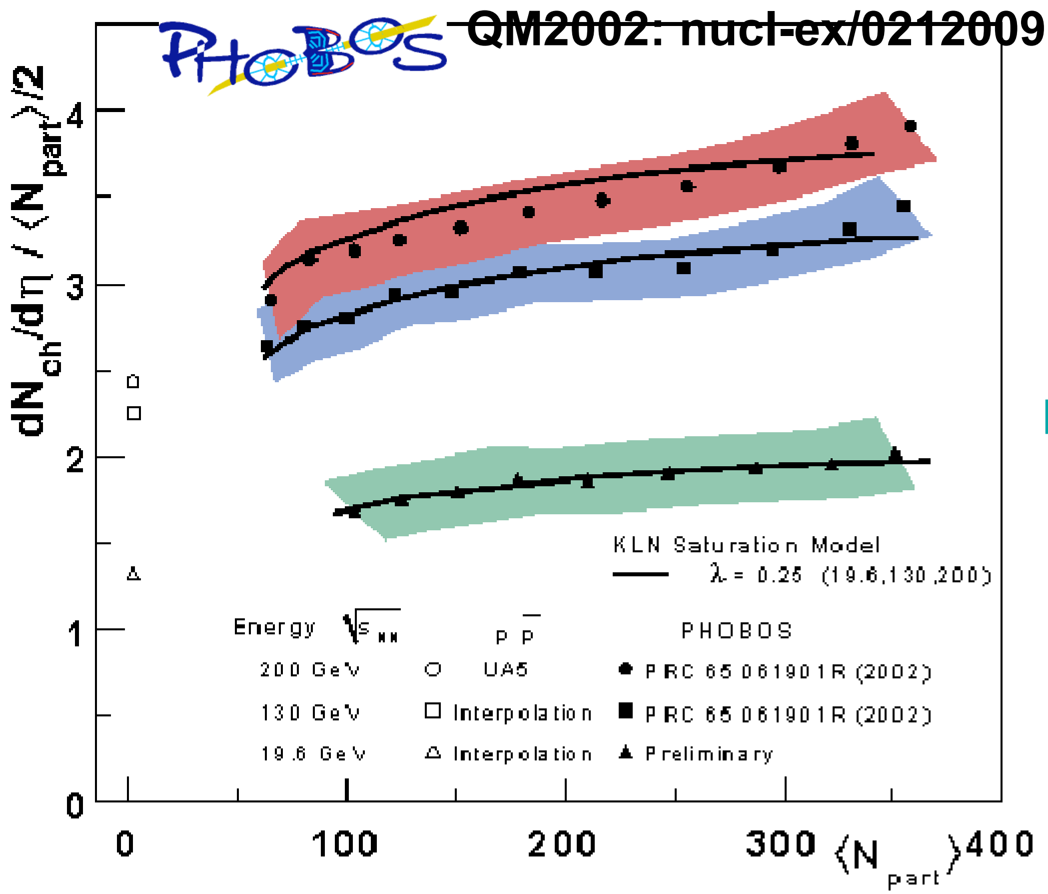




Collision scaling does NOT disappear at low energy.
Problem for naïve “minijet” based models.

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:

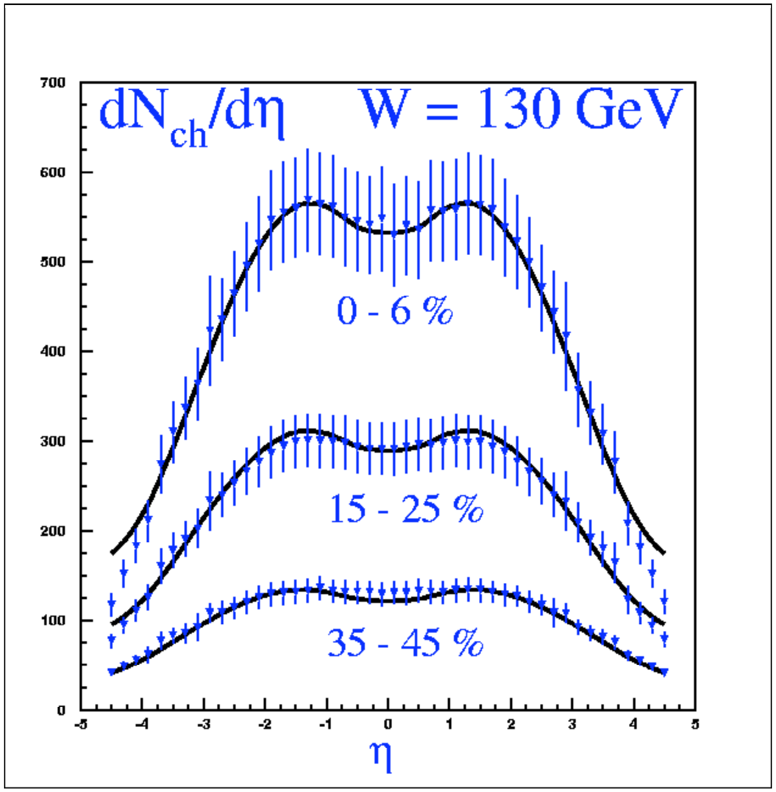
$xG(x) \sim x^{-\lambda}$

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

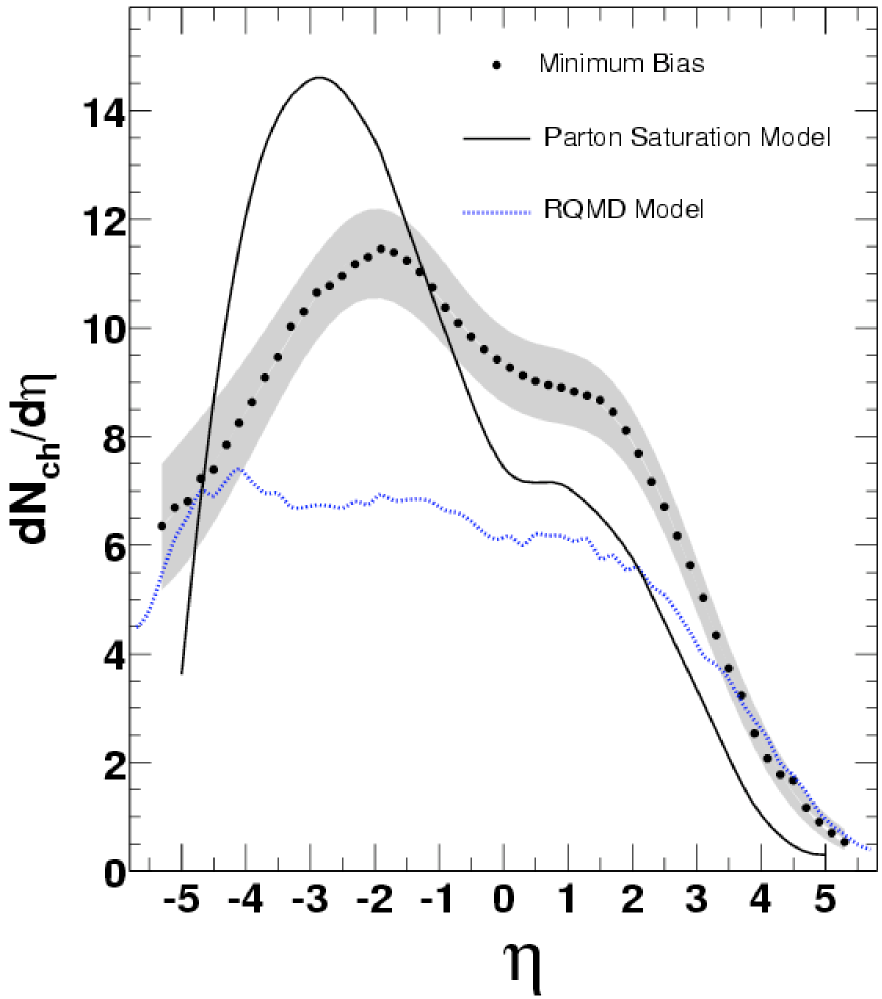
Multiplicity distribution in d-Au collisions

- Parton saturation (KLN) and RQMD models are inconsistent with the data

- KLN model overestimates the height of the gold side peak, underestimates its width, and predicts the peak at $\eta \sim -3$ rather than $\eta = -1.9$ as in data.

Parton saturation model predictions for d + Au:
D. Kharzeev et al., arXiv:hep-ph/0212316

nucl-ex/0311009 and Submitted to PRL



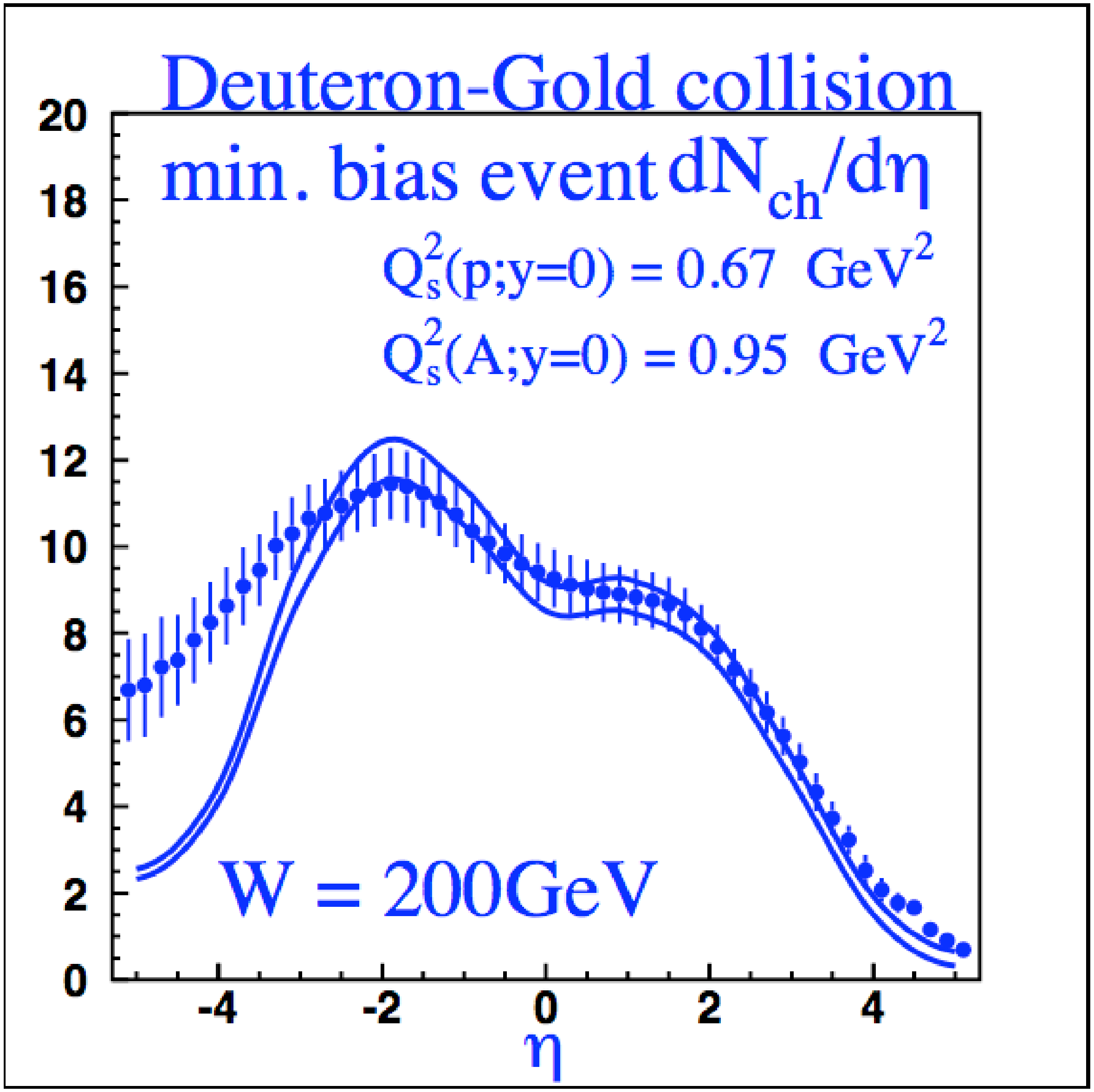
Disagreement with the data is pronounced especially in the Au fragmentation region (large x in the nucleus)

Note: the calculations assume no additional parton multiplication in Au-Au !

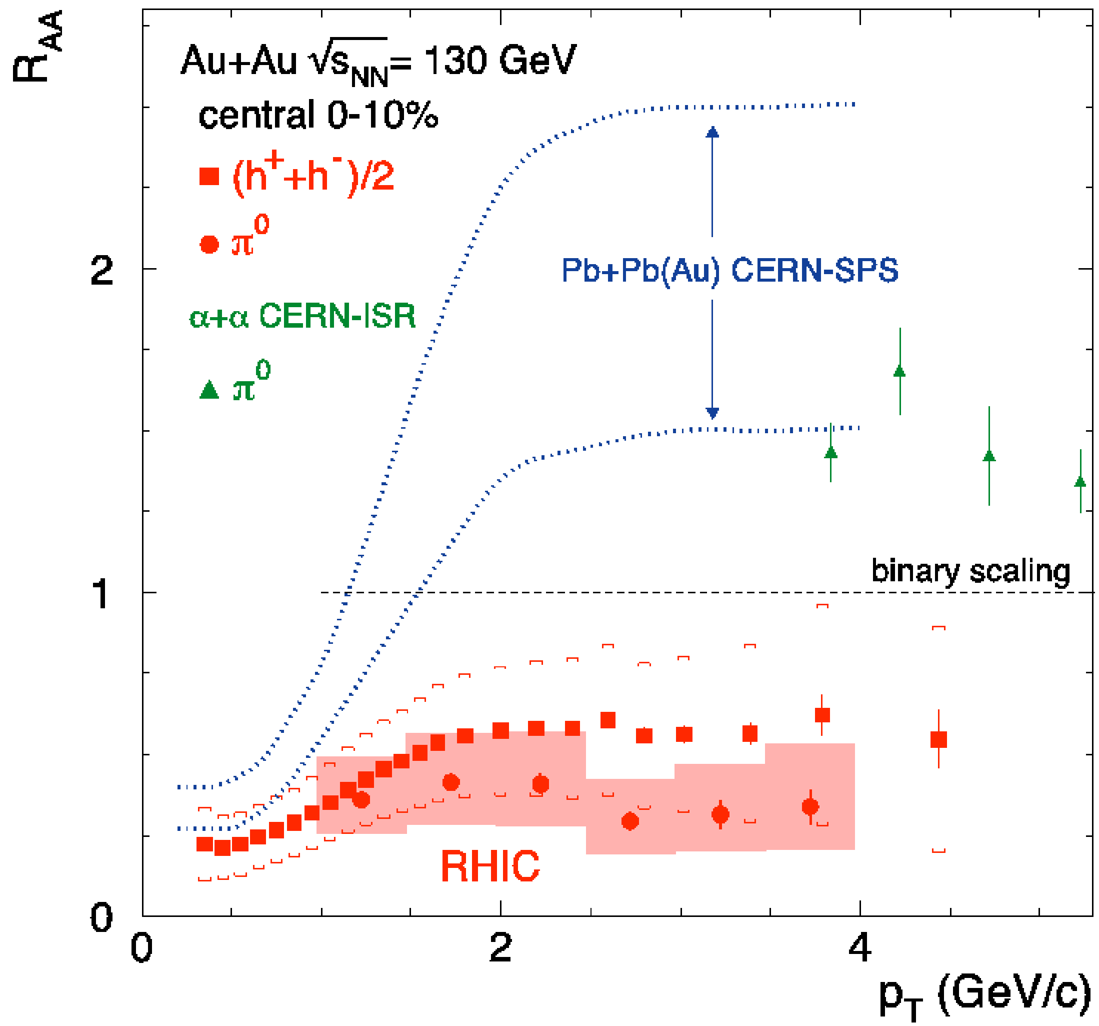
The prediction was made in terms of an analytical formula; However comparison to the data requires determination of the number of participants

…our calculation of N_{part} was based on the optical approximation -holds for large A (Au) but not for d => a half of the inclusive cross section has $N_{part}^{d} < 1$
In the experiment, and in Monte Carlo, $N_{part}^{d} >= 1$…

Most of the discrepancy disappears; Au fragmentation still a problem

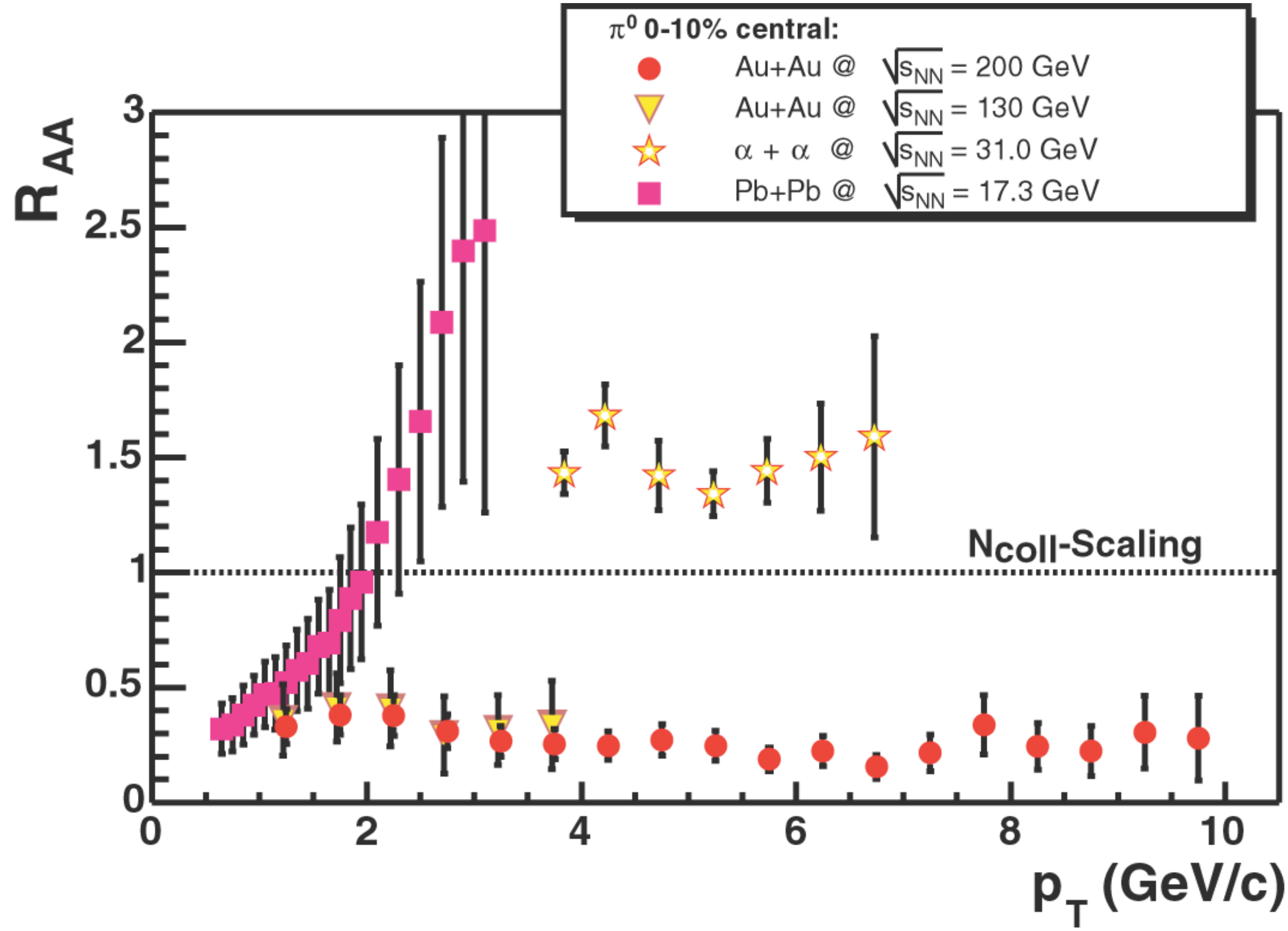


The discovery of high p_T suppression at RHIC

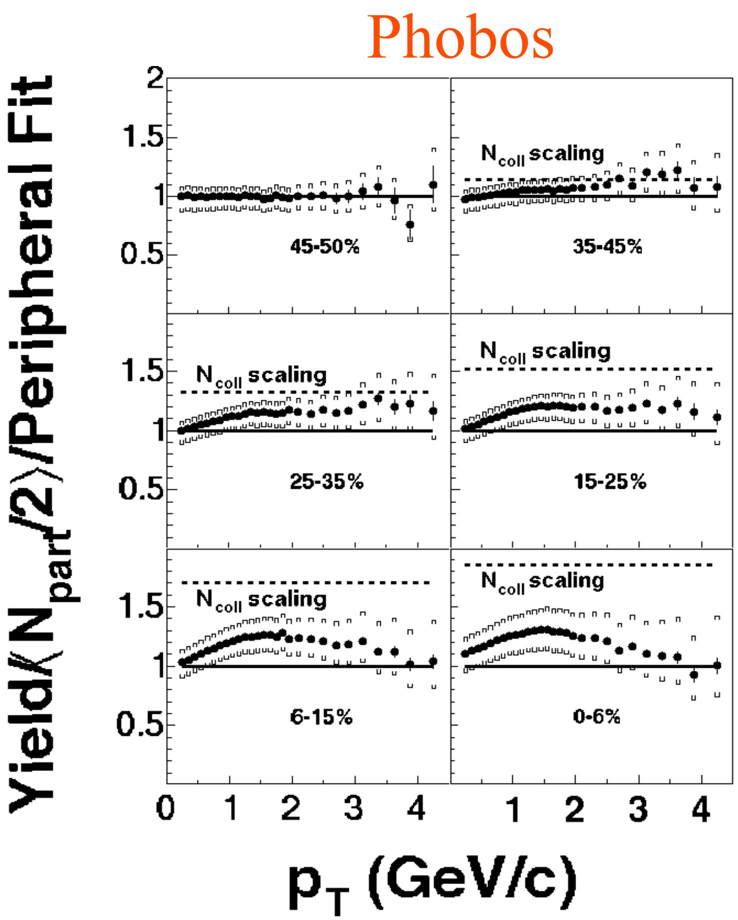


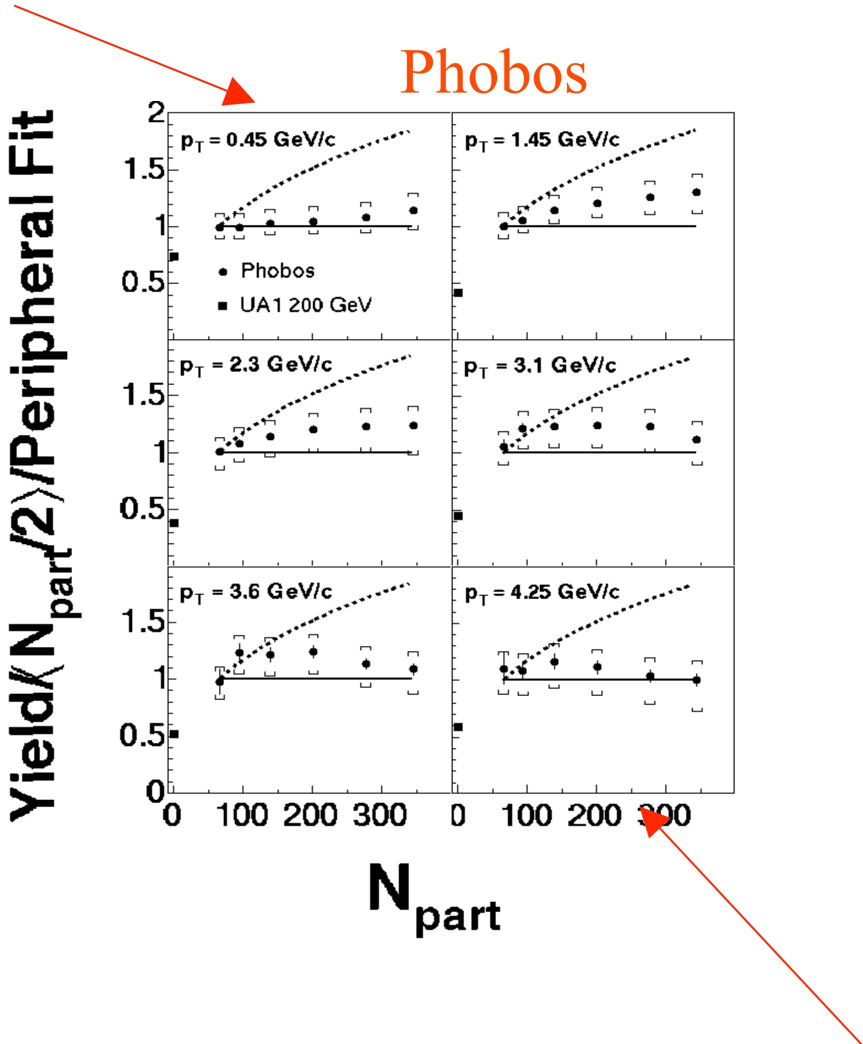
What happens at higher transverse momenta?

PHENIX and STAR extend measurements to ~ 10 GeV



Centrality Dependence vs p_T





Is this the jet quenching in QGP?

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

DK, Levin, McLerran hep-ph/0210332

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

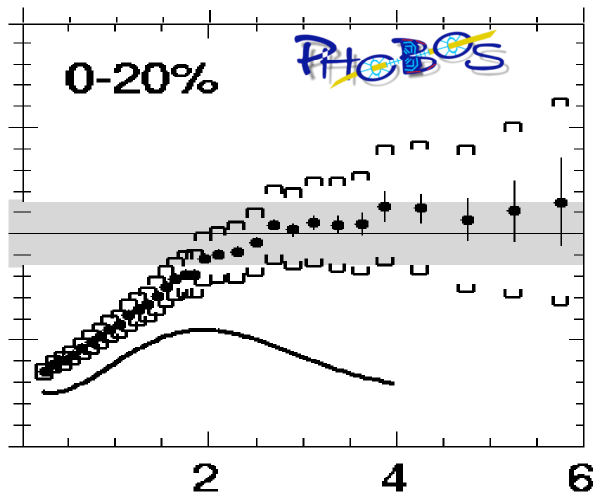
Yes, possibly:

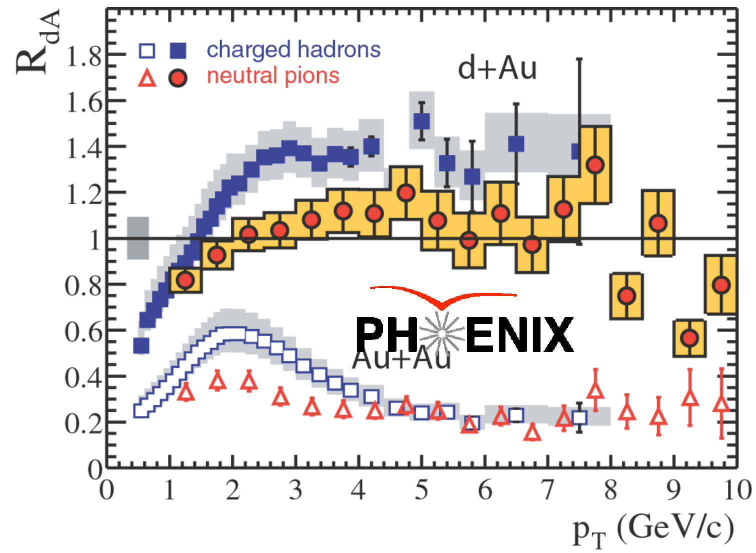
1) Small x evolution leads to the modification of gluon propagators - "anomalous dimension": $\frac{1}{Q^2} \to \left(\frac{1}{Q^2}\right)^\gamma$ $\gamma \simeq 1/2$

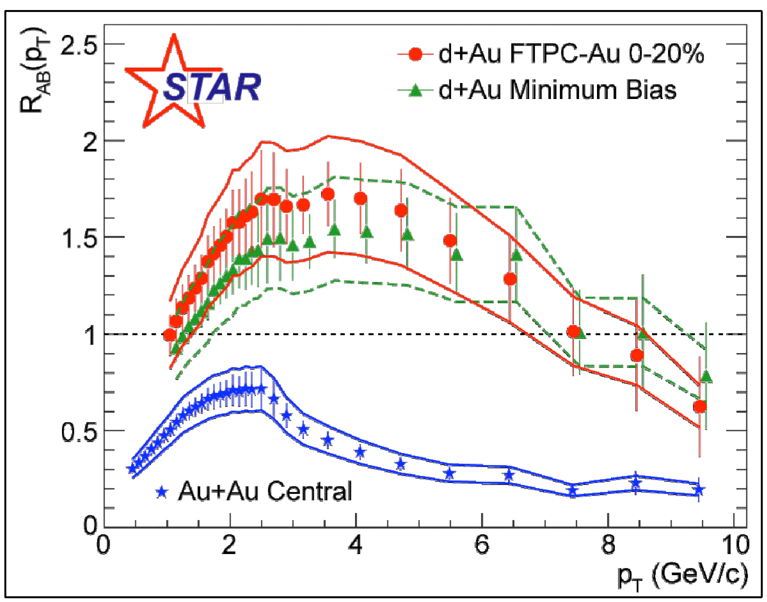
2) Q_s is the only relevant dimensionful parameter in the CGC; thus everything scales in the ratio Q_s^2/Q^2

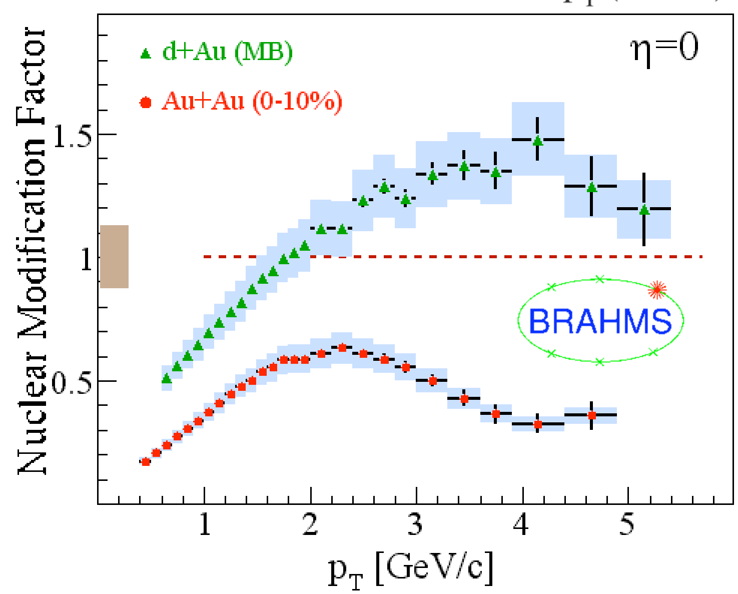
3) Since $Q_s^2 \sim A^{1/3}$ the A-dependence is changed => N_{part} scaling!

D-Au collisions: suppression or enhancement?

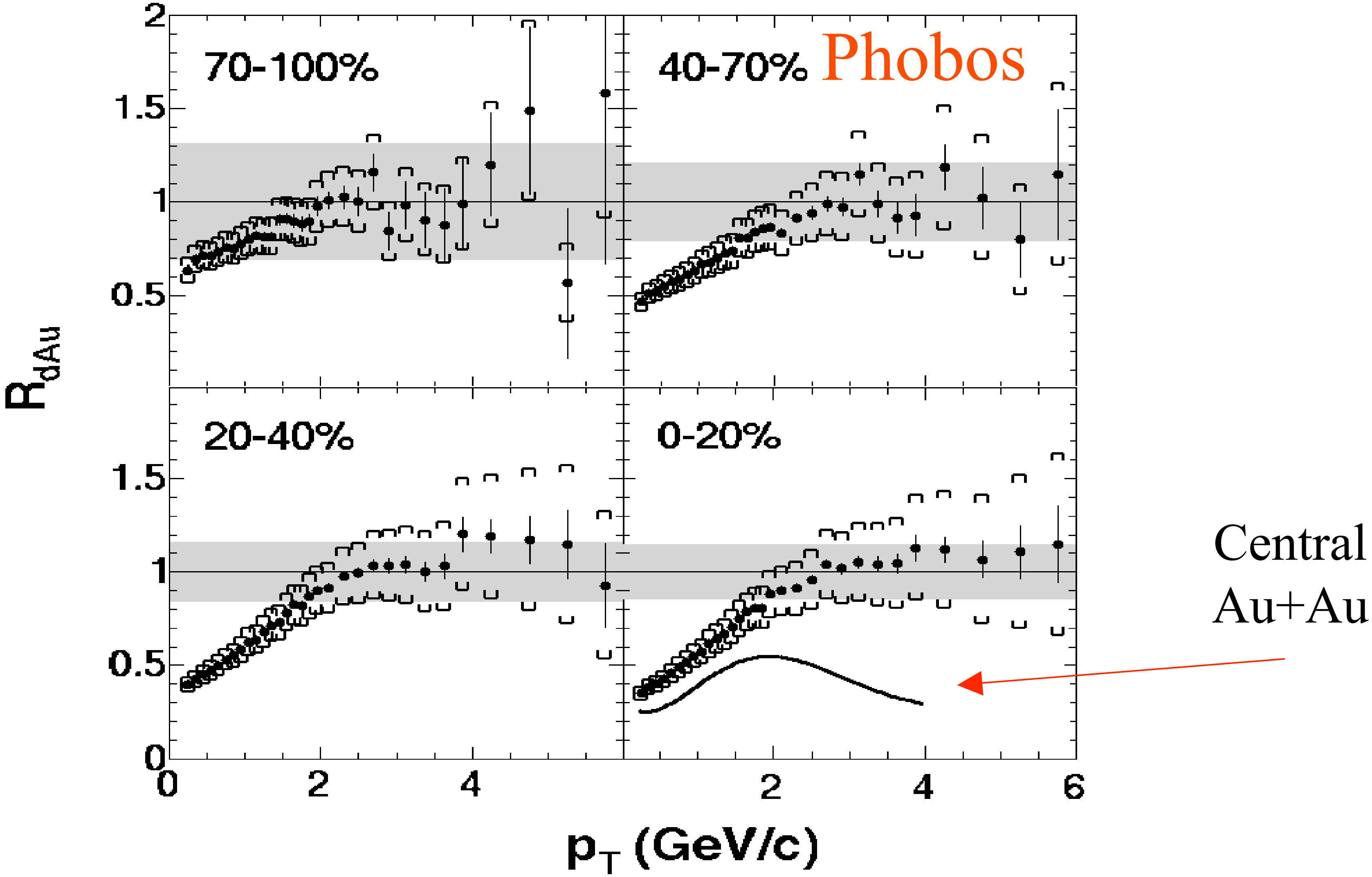






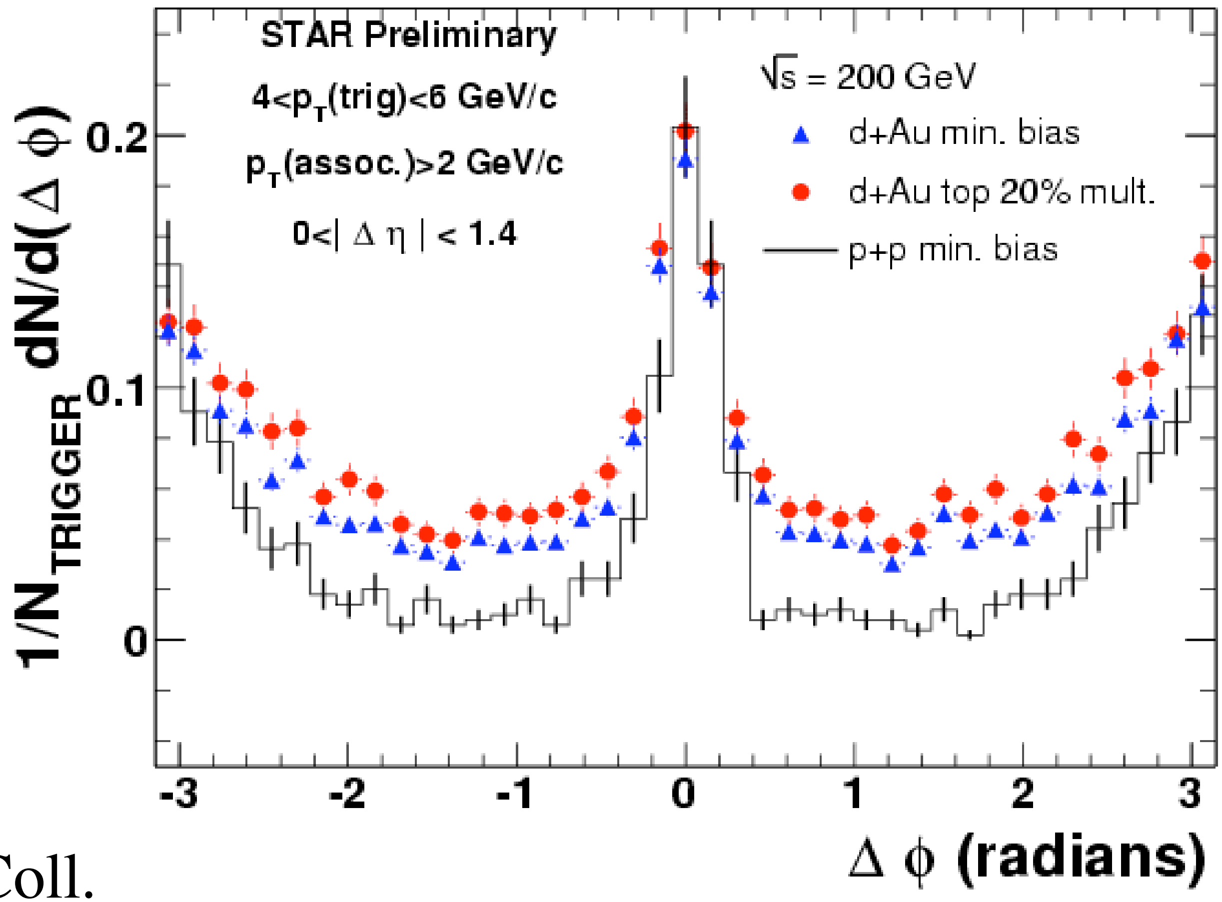


R_{dAu} vs p_T



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

DK, Yu.Dokshitzer '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:

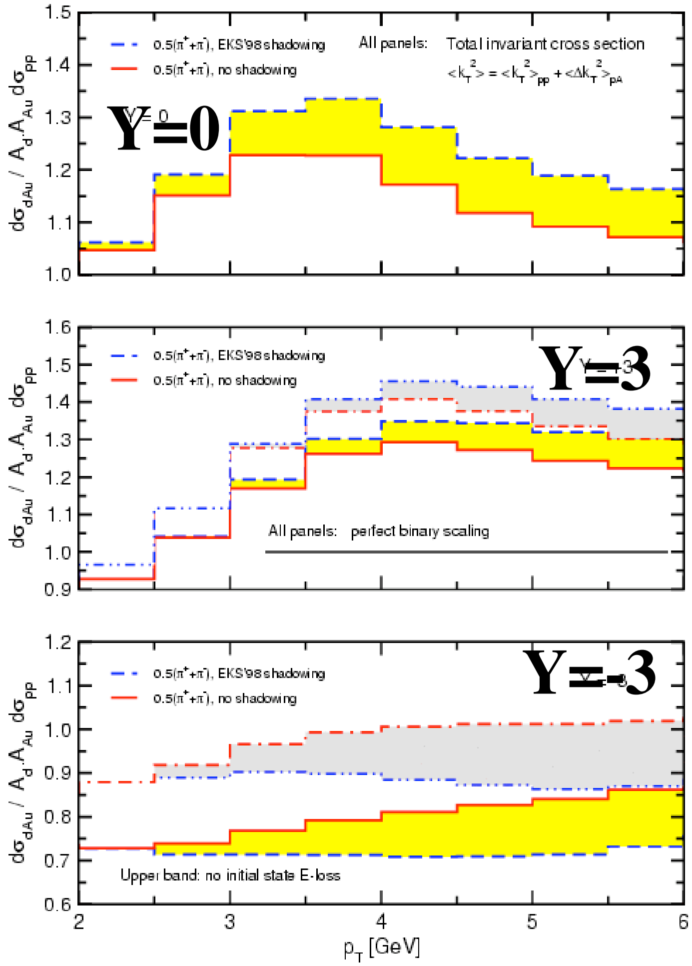
DK, E. Levin and L. McLerran, hep-ph/0210332;
R. Baier, A. Kovner, U. Wiedemann, hep-ph/0305265 v2
DK, Yu.Kovchegov and K. Tuchin, hep-ph/0307037 v2
J. Albacete, N. Armesto, A. Kovner, C. Salgado,
U. Wiedemann, hep-ph/0307179;

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;…

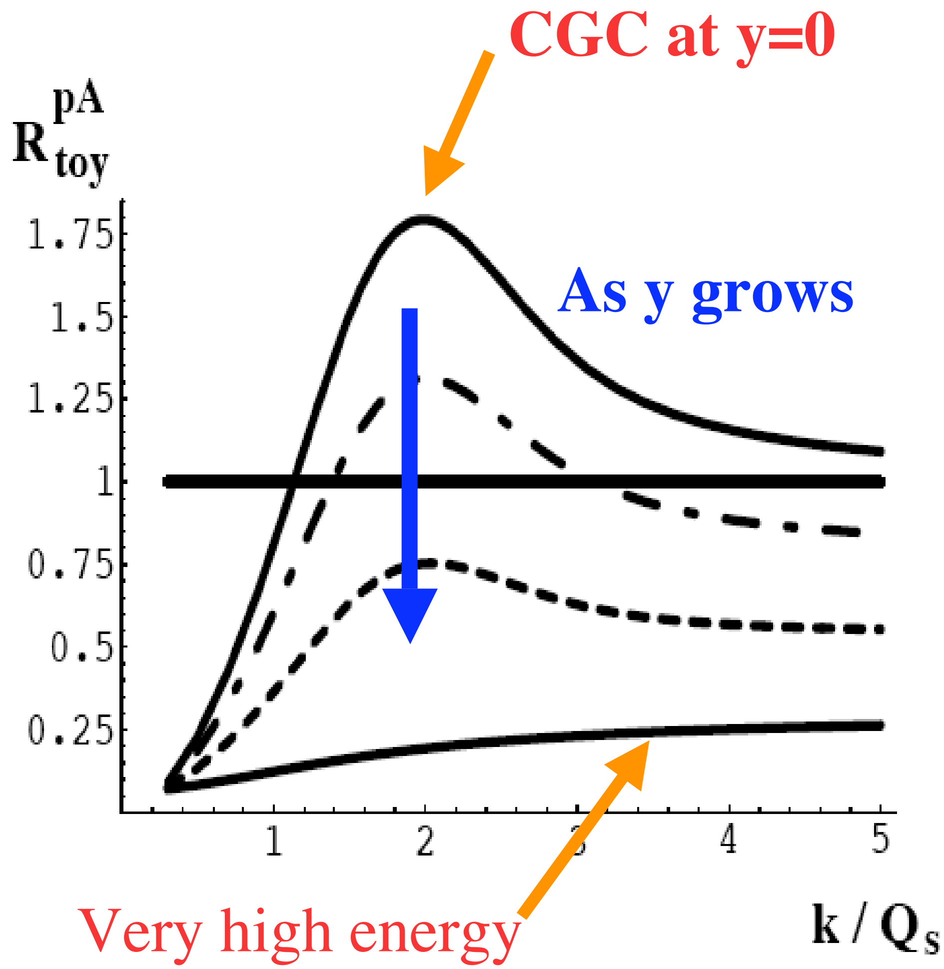
Model predictions

I. Vitev nucl-th/0302002 v2



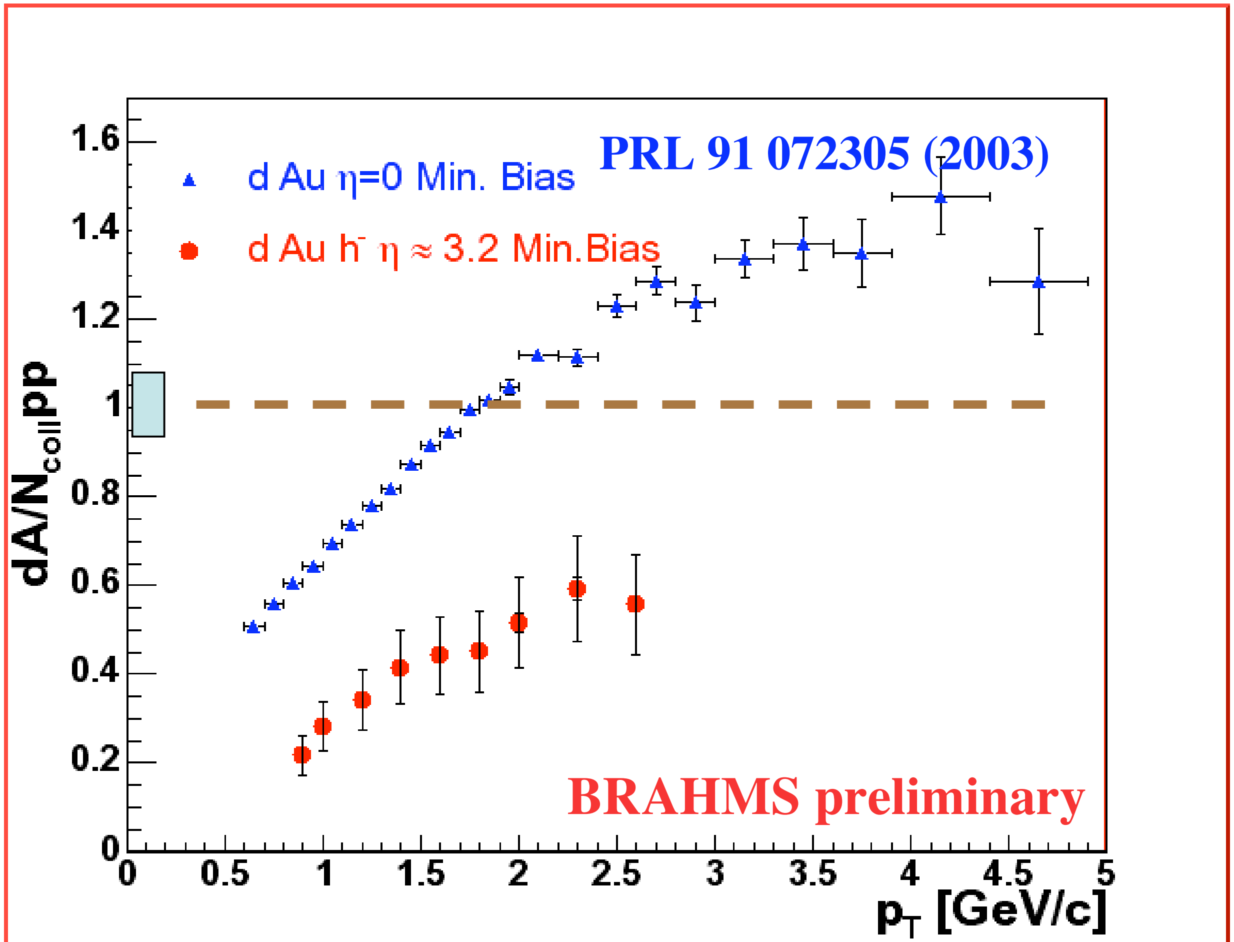
D. Kharzeev, Yu. Kovchegov and

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

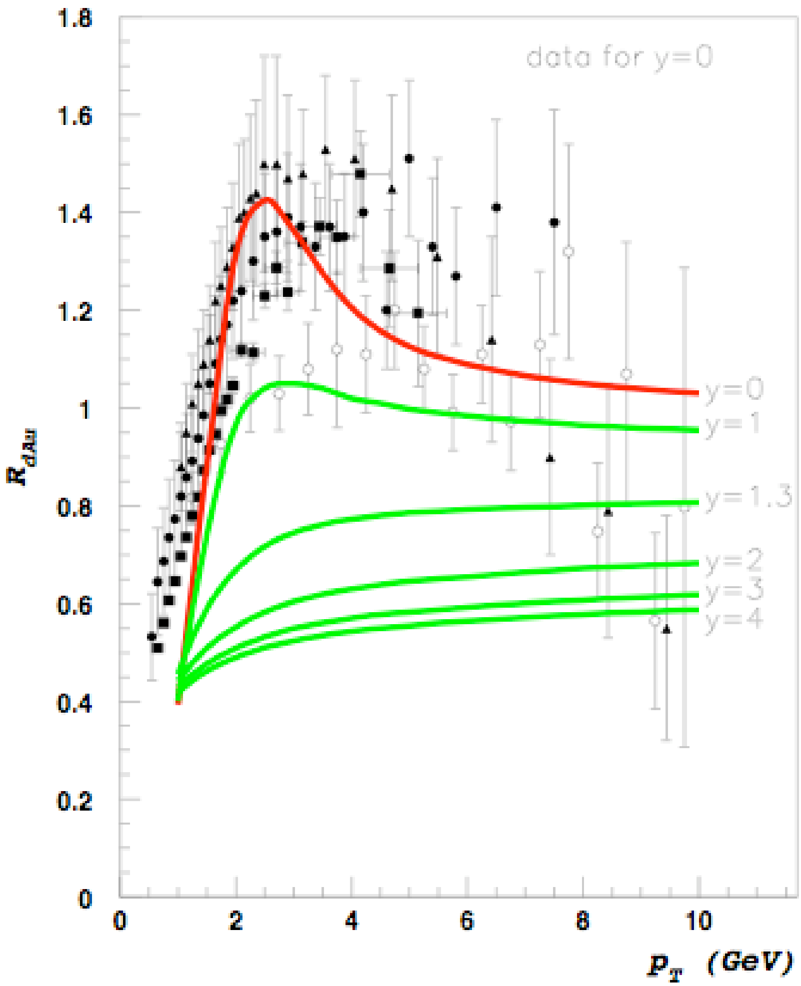
RdAu compares the yield of **negative particles** produced in dAu to the scaled number of particles with same sign in p-p

The scale is the number of binary collisions:

N_{coll}=7.2

(minimum biased)

Color Glass Condensate: confronting the data



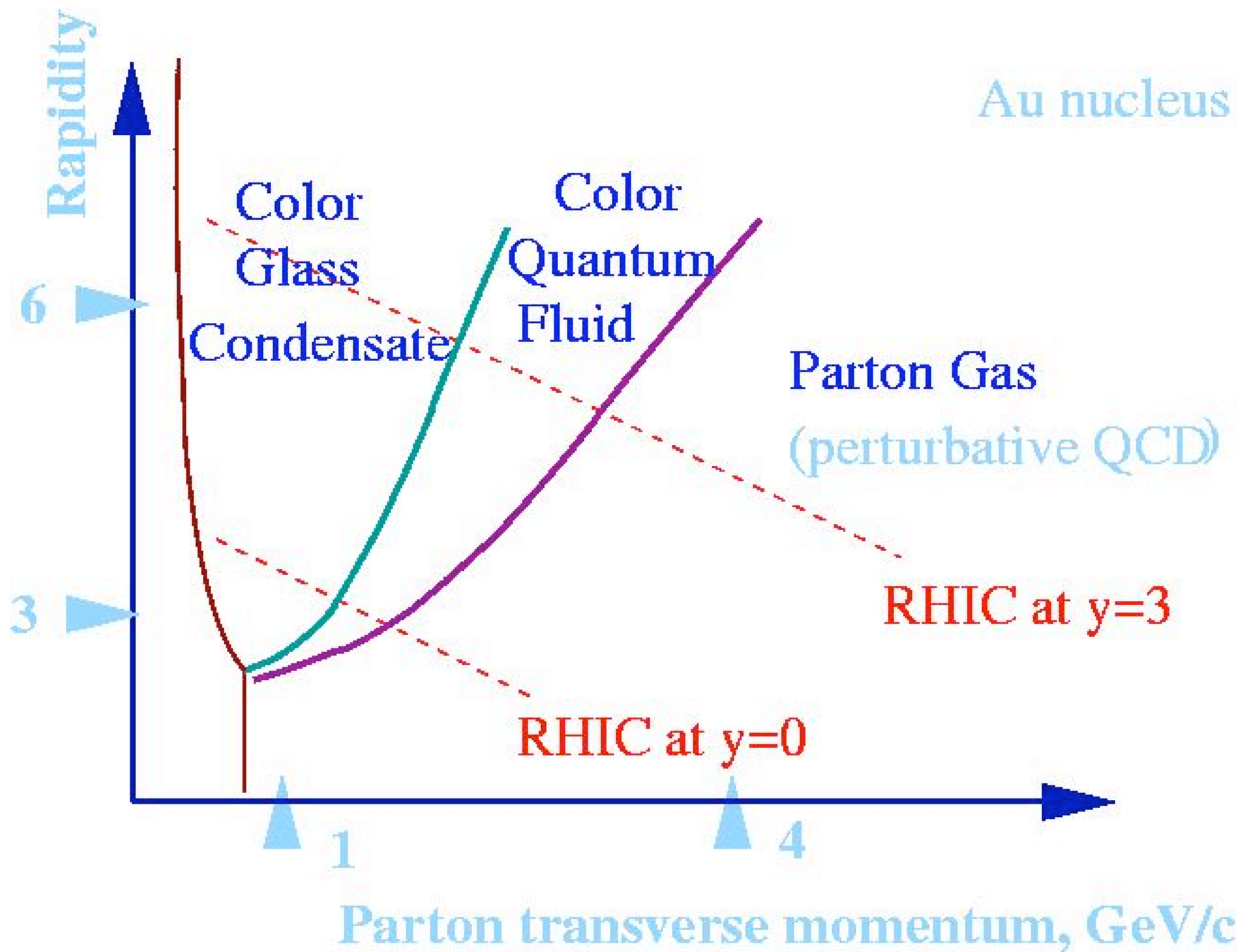
The effects of quantum Evolution in the CGC set in very rapidly

RHIC energy is ideal

talk by K. Tuchin/Yu.Kovchegov

DK, Yu. Kovchegov, K. Tuchin,
To appear

Phase diagram of high energy QCD and RHIC



Summary

If confirmed, BRAHMS result represents
<u>a major discovery</u>

To interpret it in an unambiguous way,
one needs to study:
Centrality dependence
<u>Back-to-back correlations</u>