"The QCD phase diagram", Skopelos, 29 May - 2 June, 2004

Color Glass Condensate at RHIC and LHC

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Outline

- What is Color Glass Condensate?
- CGC and Quark-Gluon Plasma
- Manifestations of CGC at RHIC:
  - hadron multiplicities
  - high p_T suppression at forward rapidity
  - back-to-back correlations
- Future tests at RHIC and LHC
  - correlations, heavy quarks, dileptons, direct photons

    …

QCD and the classical limit

QCD = Quark Model + Gauge Invariance

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

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

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

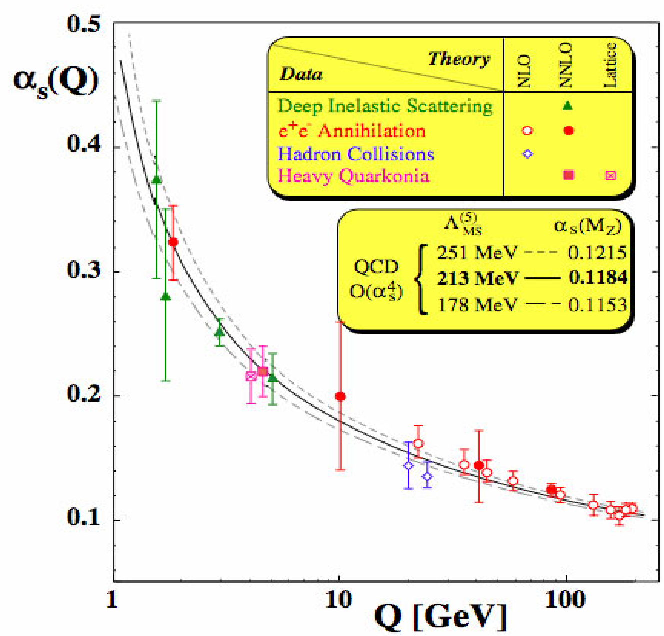
$$L_{\mathrm{QCD}} = \sum_q \bar{q}(x)\left(i\gamma_\mu D^\mu - m_q\right) q(x) - \frac{1}{4g^2} \mathrm{tr}\, G^{\mu\nu}(x) G_{\mu\nu}(x);$$

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

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

=> Need weak coupling and strong fields

Asymptotic freedom and the classical limit of QCD

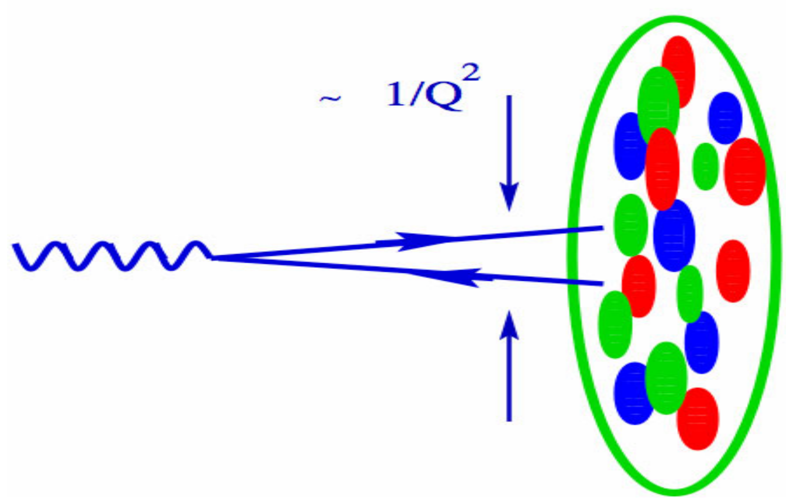


Classical limit S>>1 requires weak coupling and strong fields;
Large distances: non-perturbative fields, large coupling…

Is there a place for classical methods?

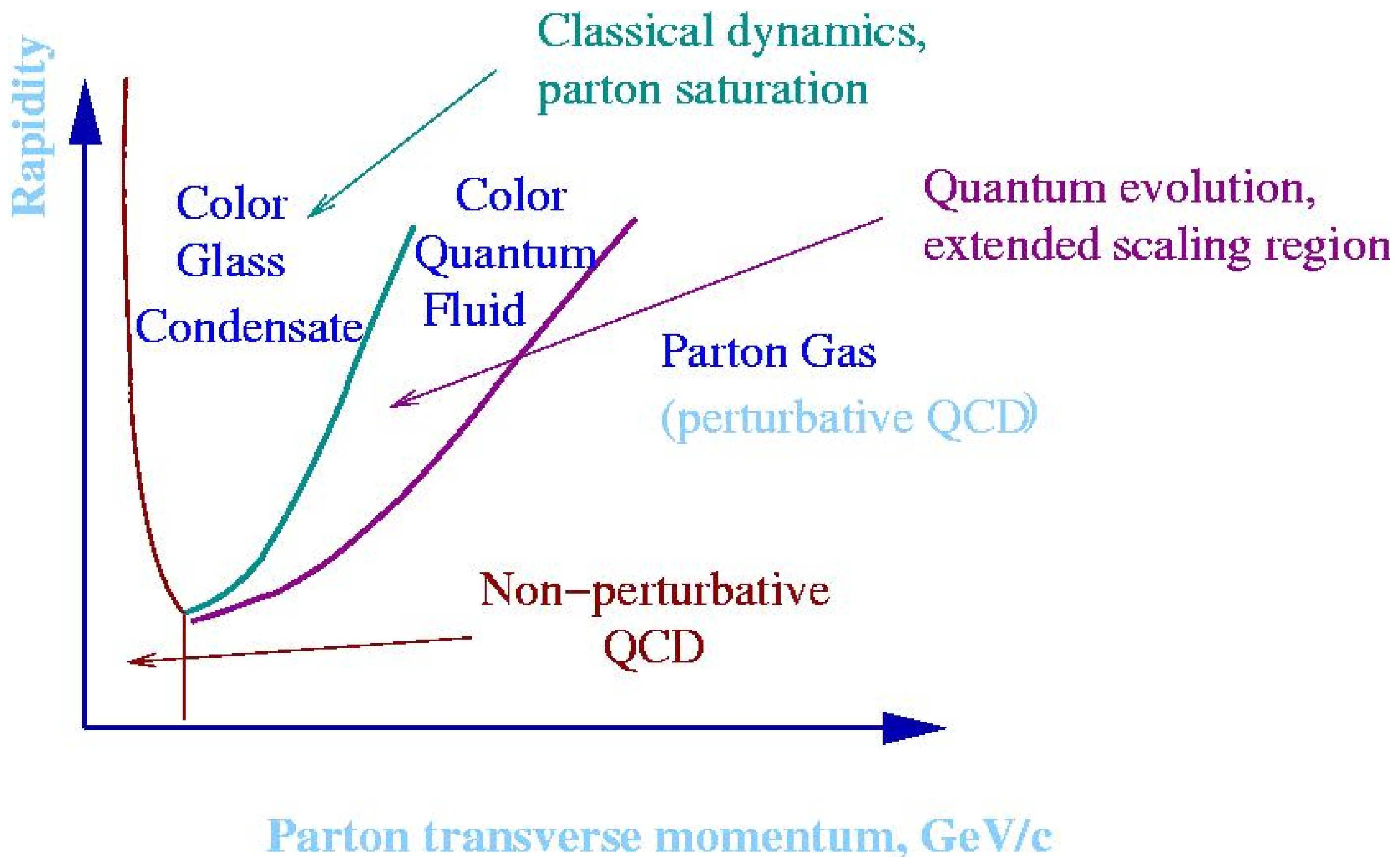
Parton saturation and the classical limit of QCD

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

CGC and total multiplicities in Au-Au

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

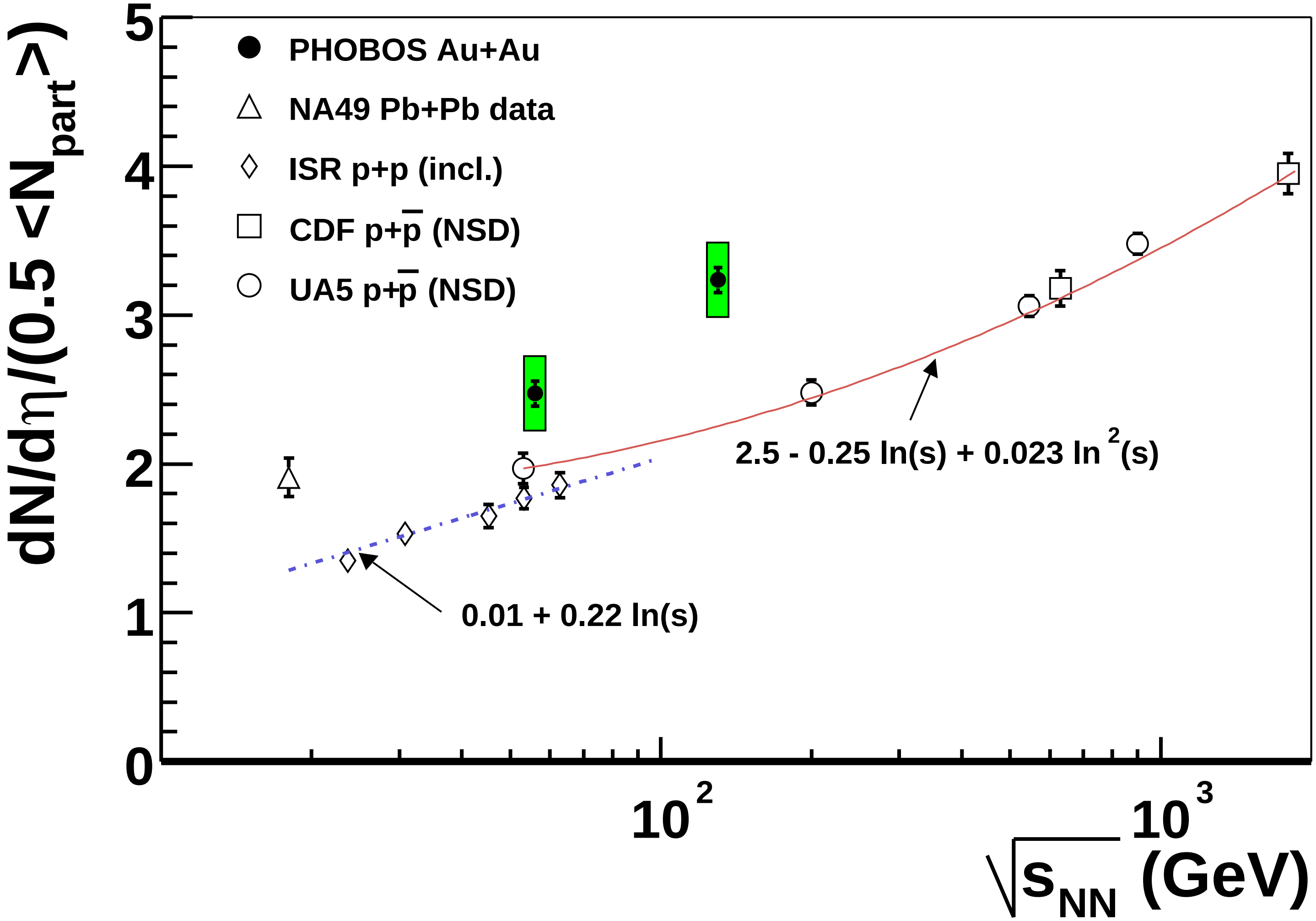
$$n \sim \frac{S_A Q_s^2}{\alpha_s(Q_s^2)} \sim N_{part} \ \ln N_{part}$$

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

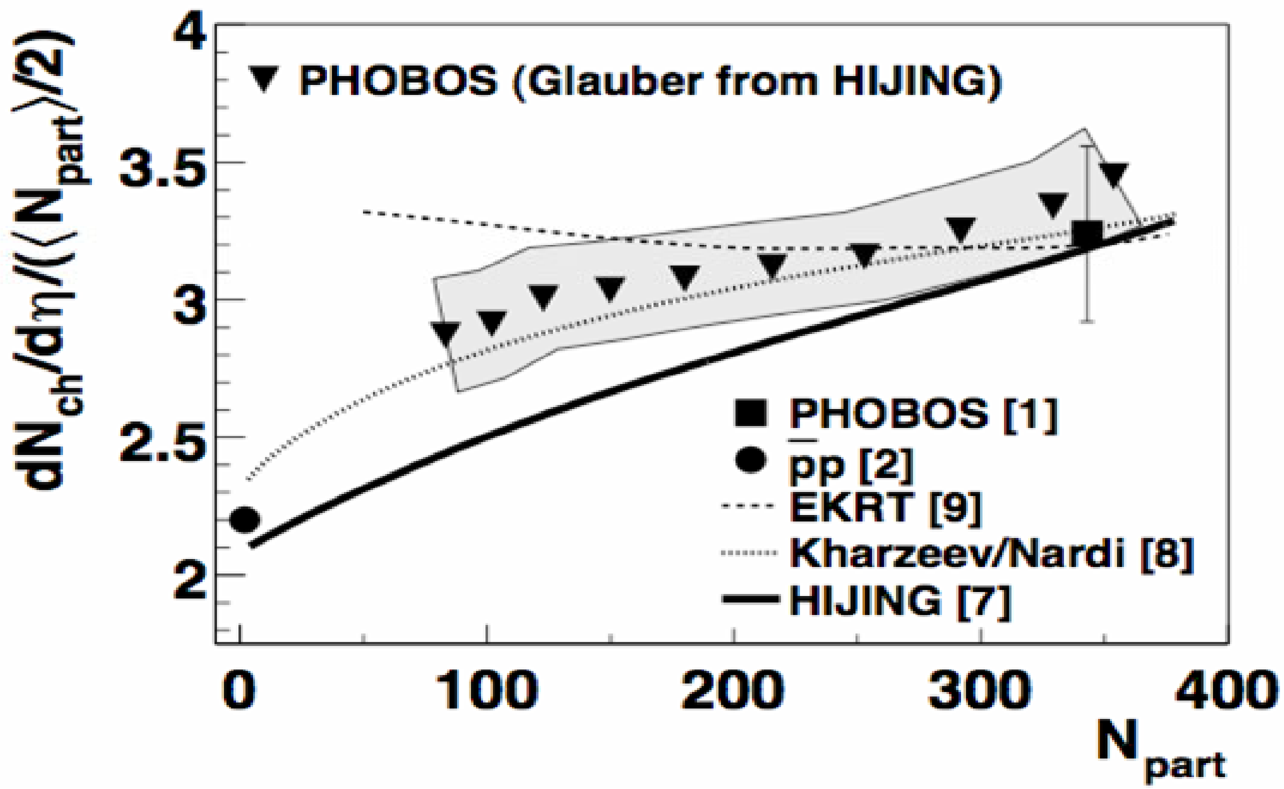
Parton interactions at RHIC are coherent !

$$N_{coll} \sim N_{part}^{4/3}$$

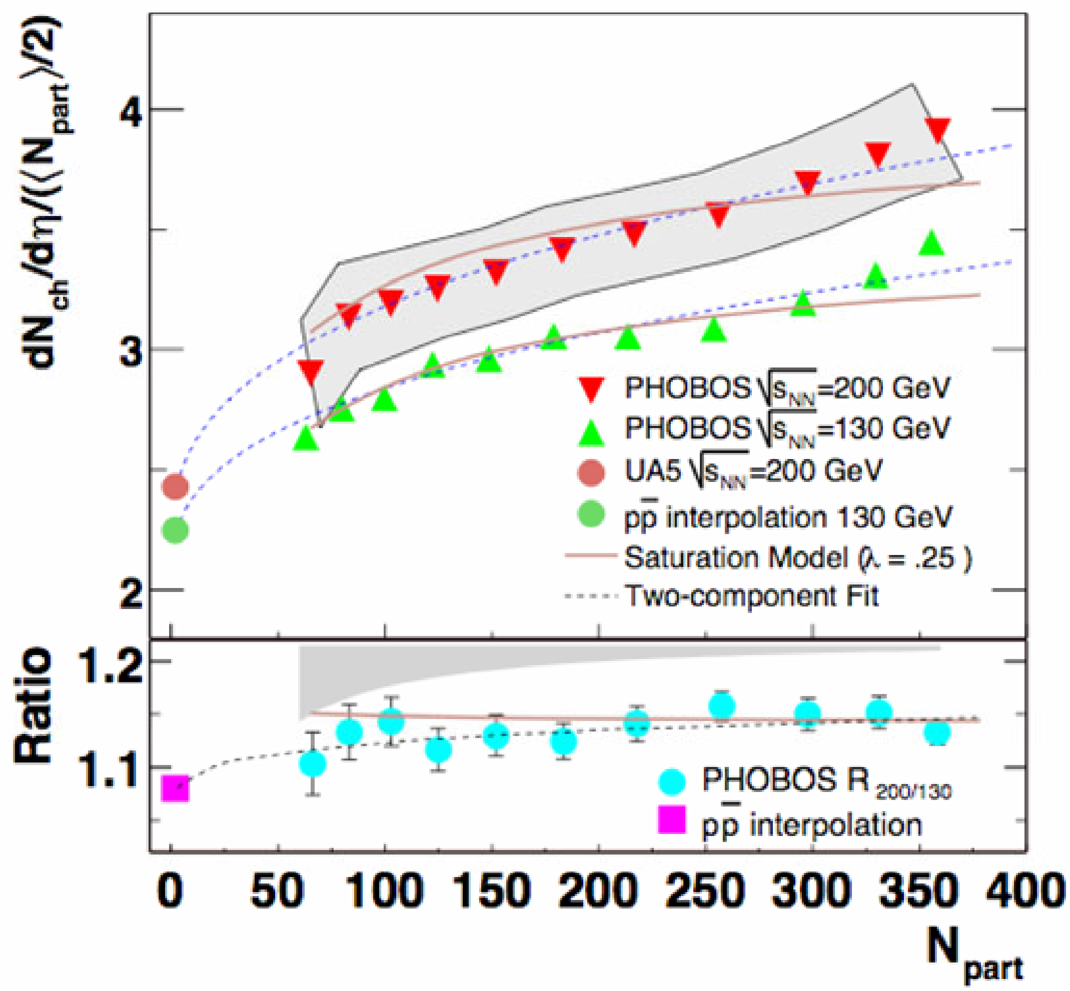
$dN_{ch}/d\eta$ @ η=0 vs Energy



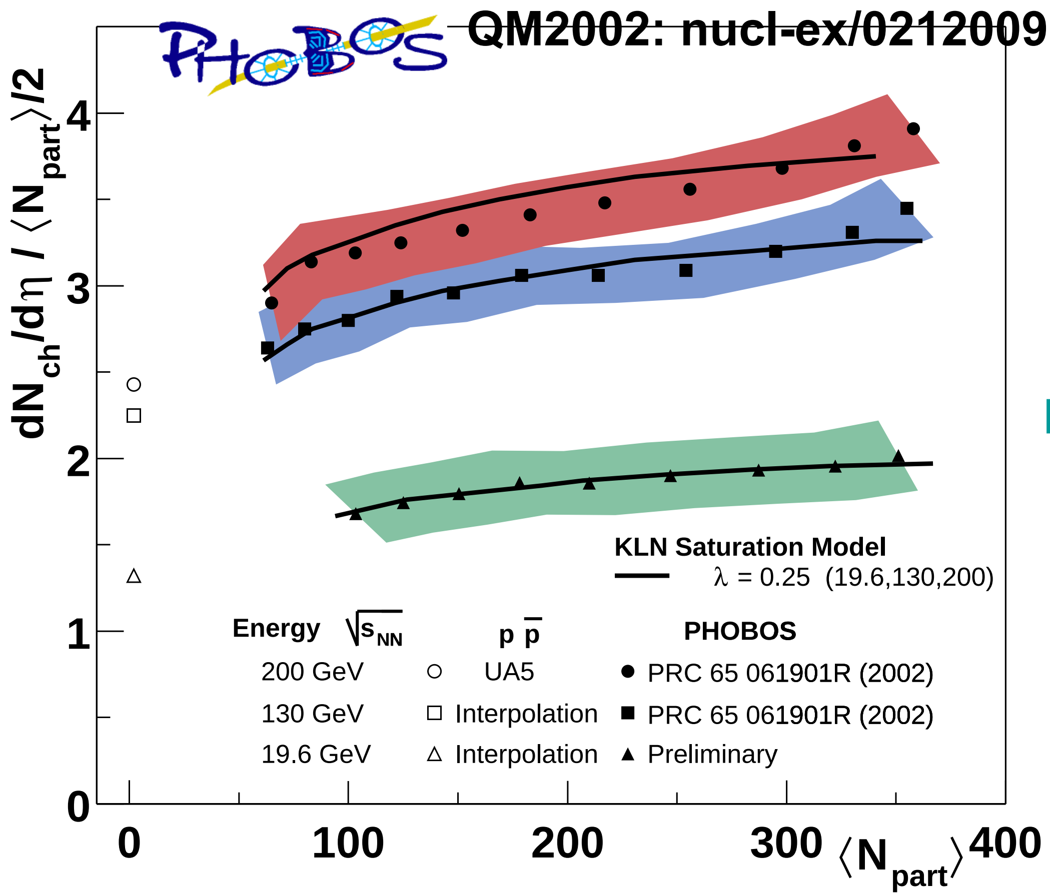
Centrality dependence of hadron multiplicity



Centrality dependence at different energies



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:

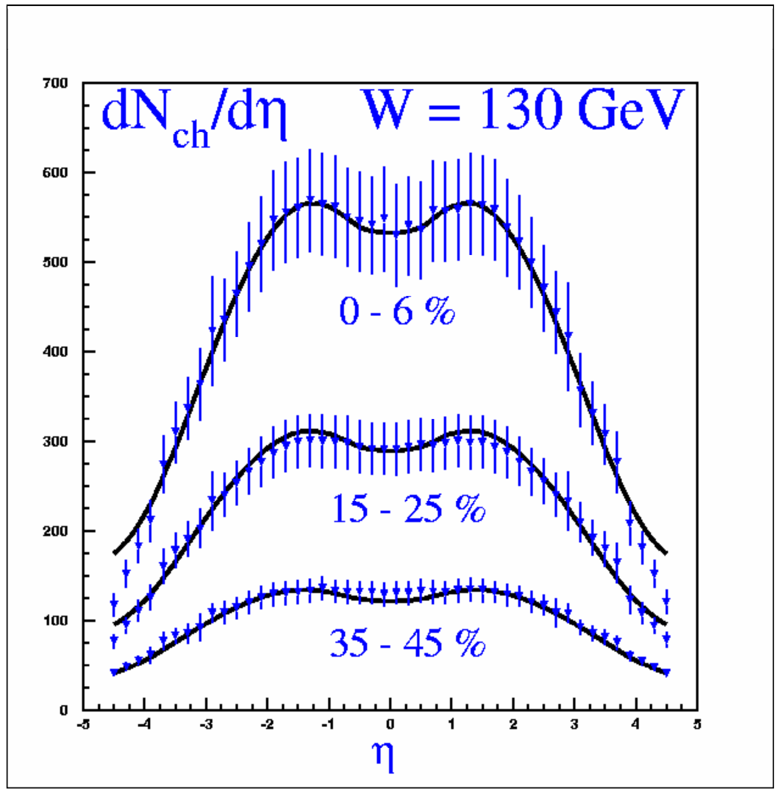
$xG(x) \sim x^{-\lambda}$

Describes energy dependence correctly!

Color Glass Condensate describes the Au-Au data

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

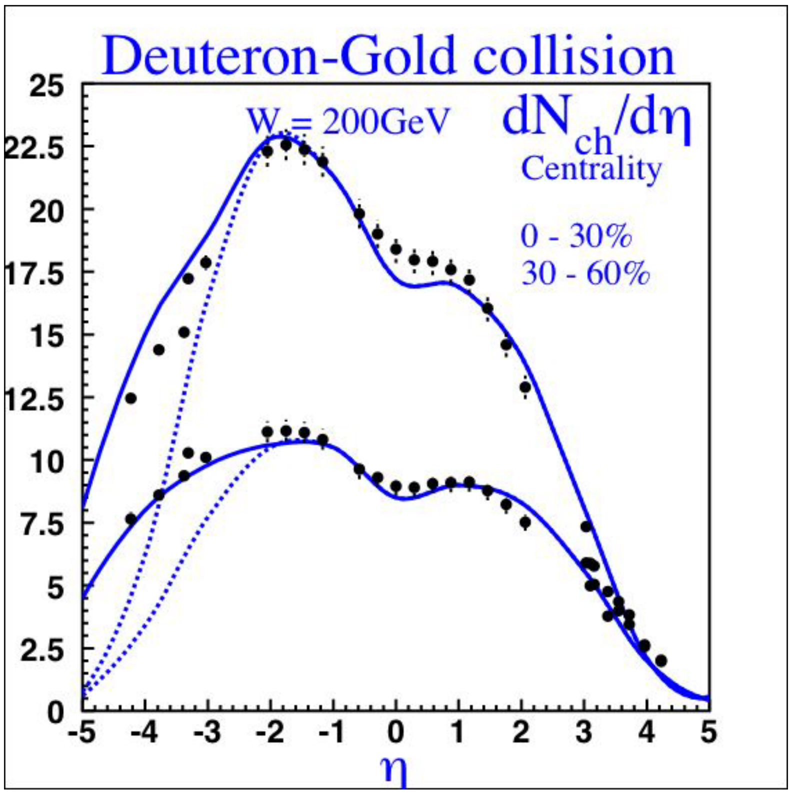
Au + Au at 130 GeV

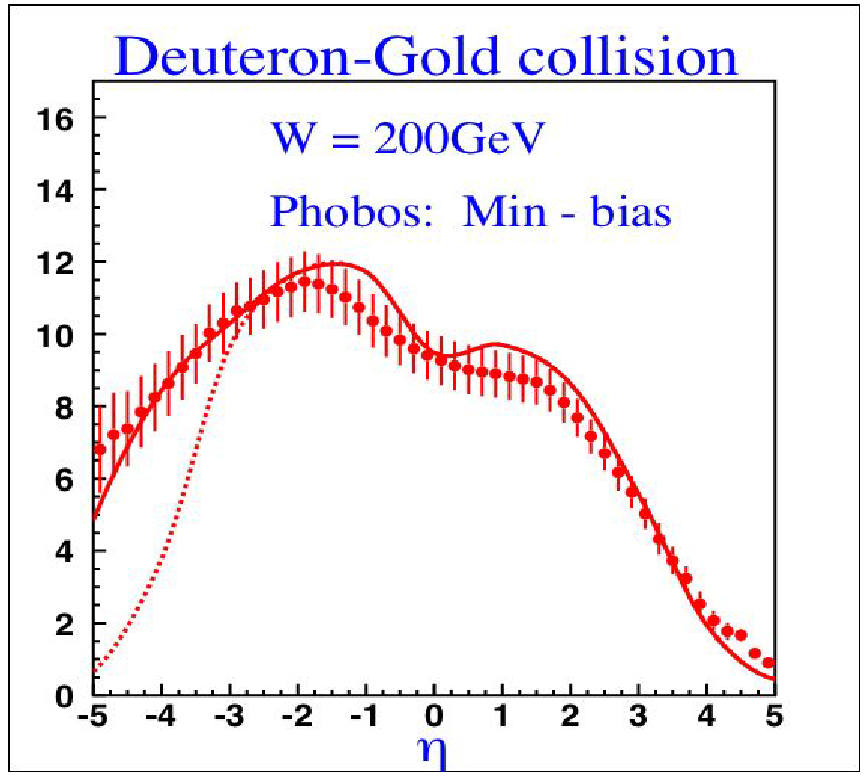


BRAHMS and PHOBOS Colls: Rapidity dependence of hadron production at 130, 200 GeV is described well by the CGC approach

63 GeV data?

d-Au multiplicities

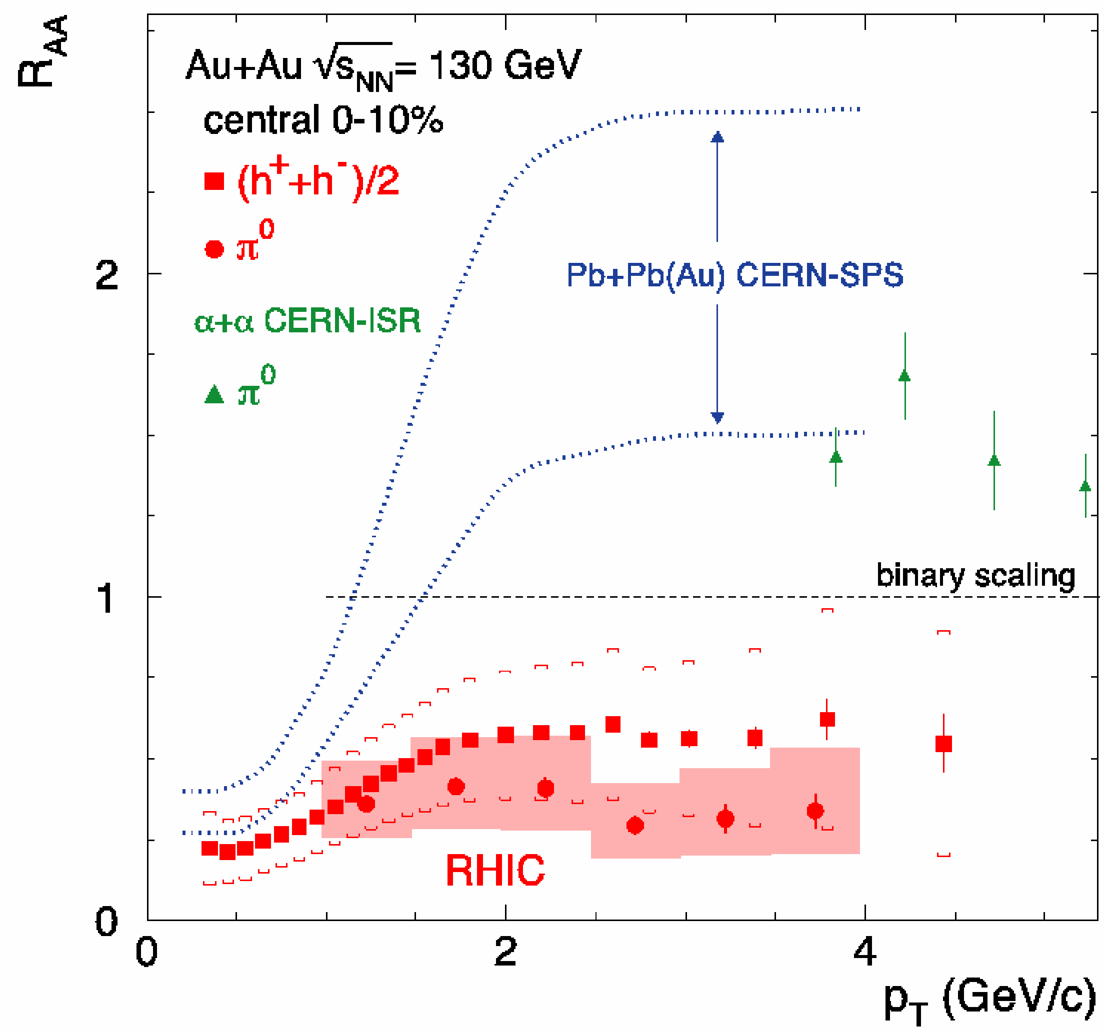




Data from BRAHMS and PHOBOS Collaborations

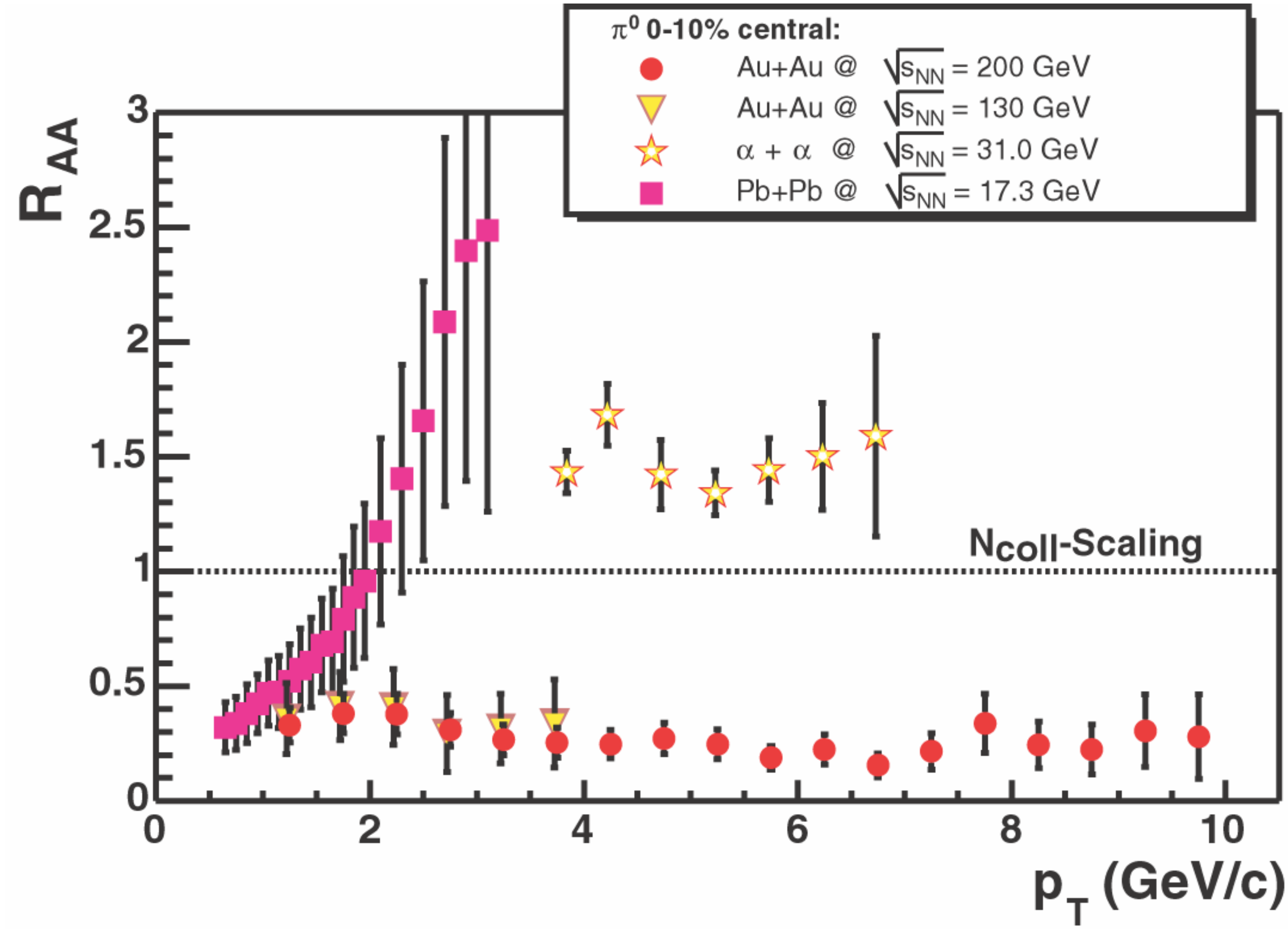
DK, E.Levin and M.Nardi, Nucl.Phys.A730(2004)448,
+ erratum, hep-ph/0212316

The discovery of high p_T suppression at RHIC



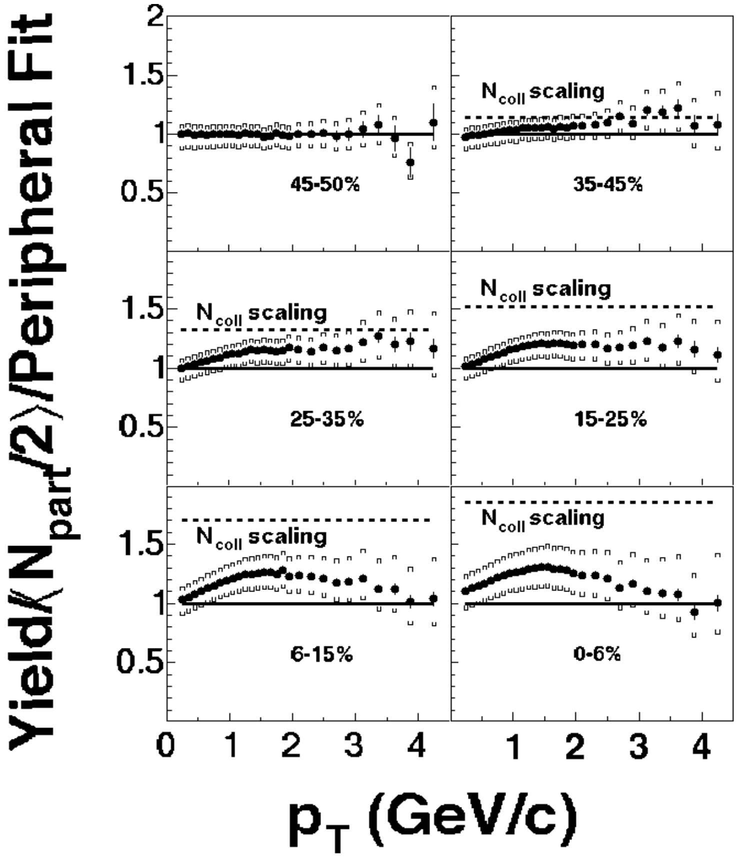
What happens at higher transverse momenta?

PHENIX and STAR extend measurements to ~ 10 GeV

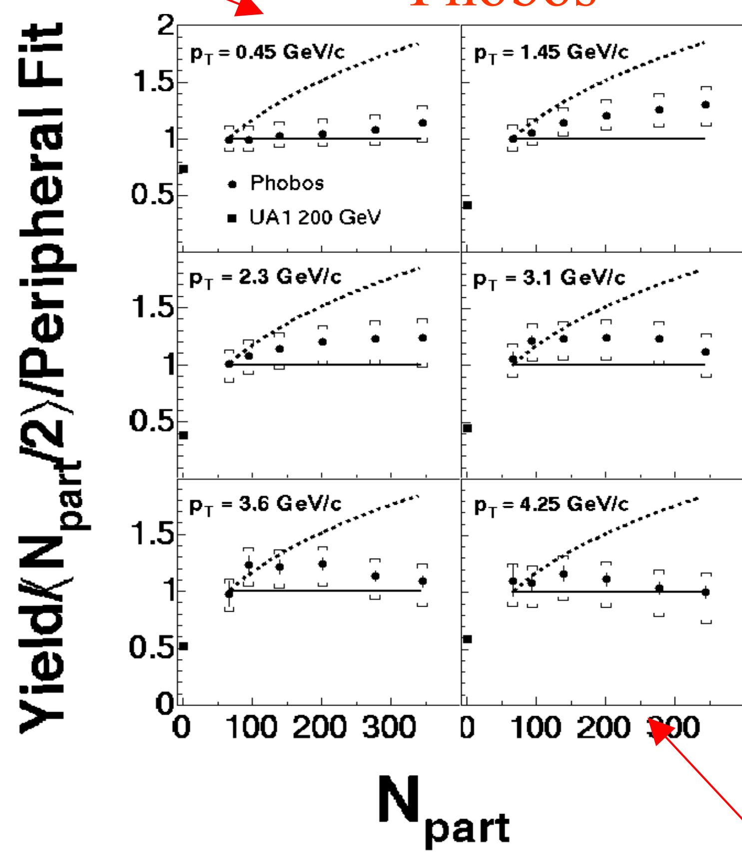


Centrality Dependence vs p_T

Phobos



Phobos



Is this the jet quenching in QGP?

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

DK, Levin, McLerran hep-ph/0210332

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

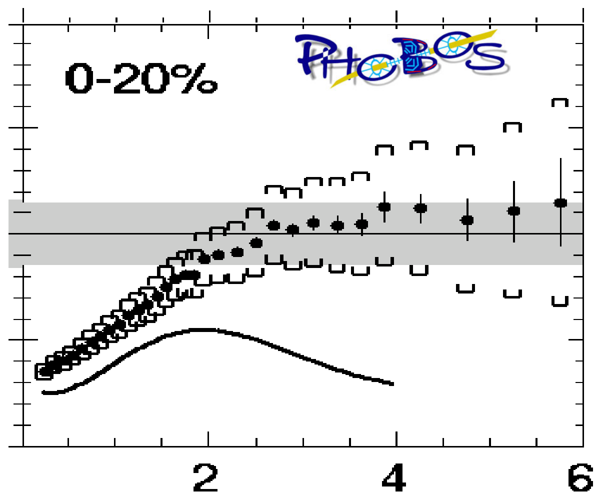
Yes, possibly:

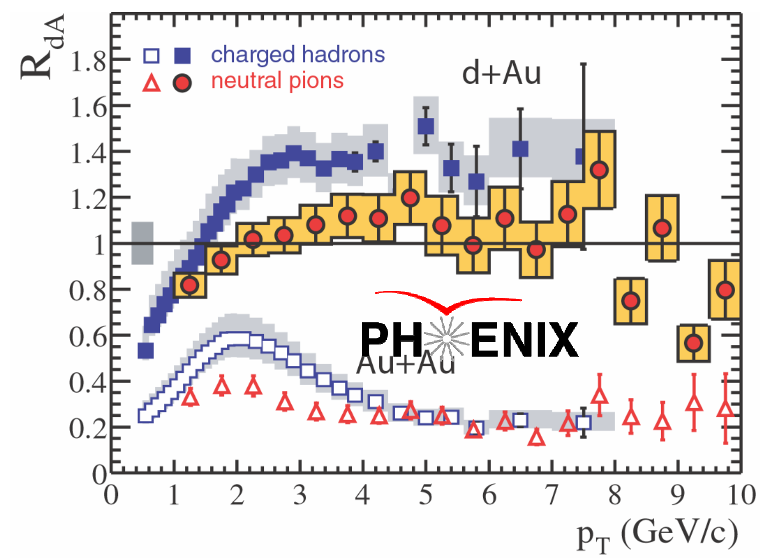
1) Small x evolution leads to the modification of gluon propagators - "anomalous dimension": $\frac{1}{Q^2} \to \left(\frac{1}{Q^2}\right)^\gamma$ $\gamma \simeq 1/2$

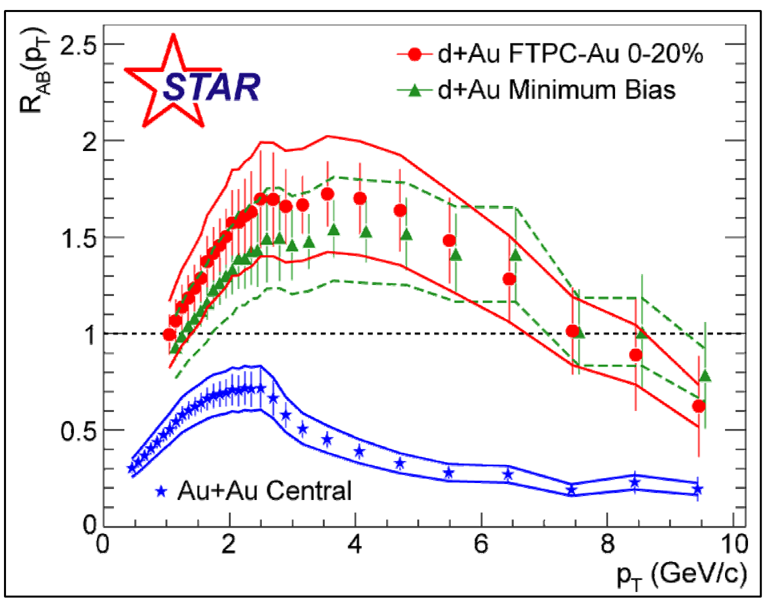
2) Q_s is the only relevant dimensionful parameter in the CGC; thus everything scales in the ratio Q_s^2/Q^2

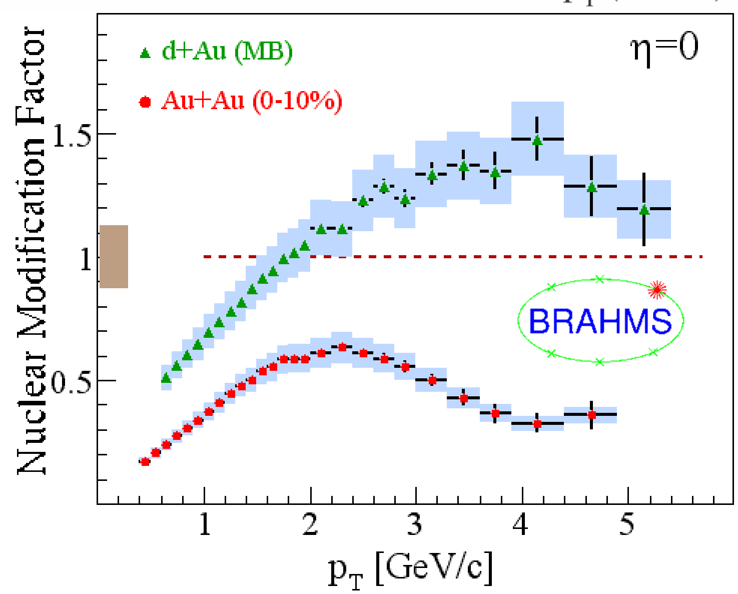
3) Since $Q_s^2 \sim A^{1/3}$ the A-dependence is changed
=> N_{part} scaling!
Leads to suppression in dAu at small x

D-Au collisions: suppression or enhancement?

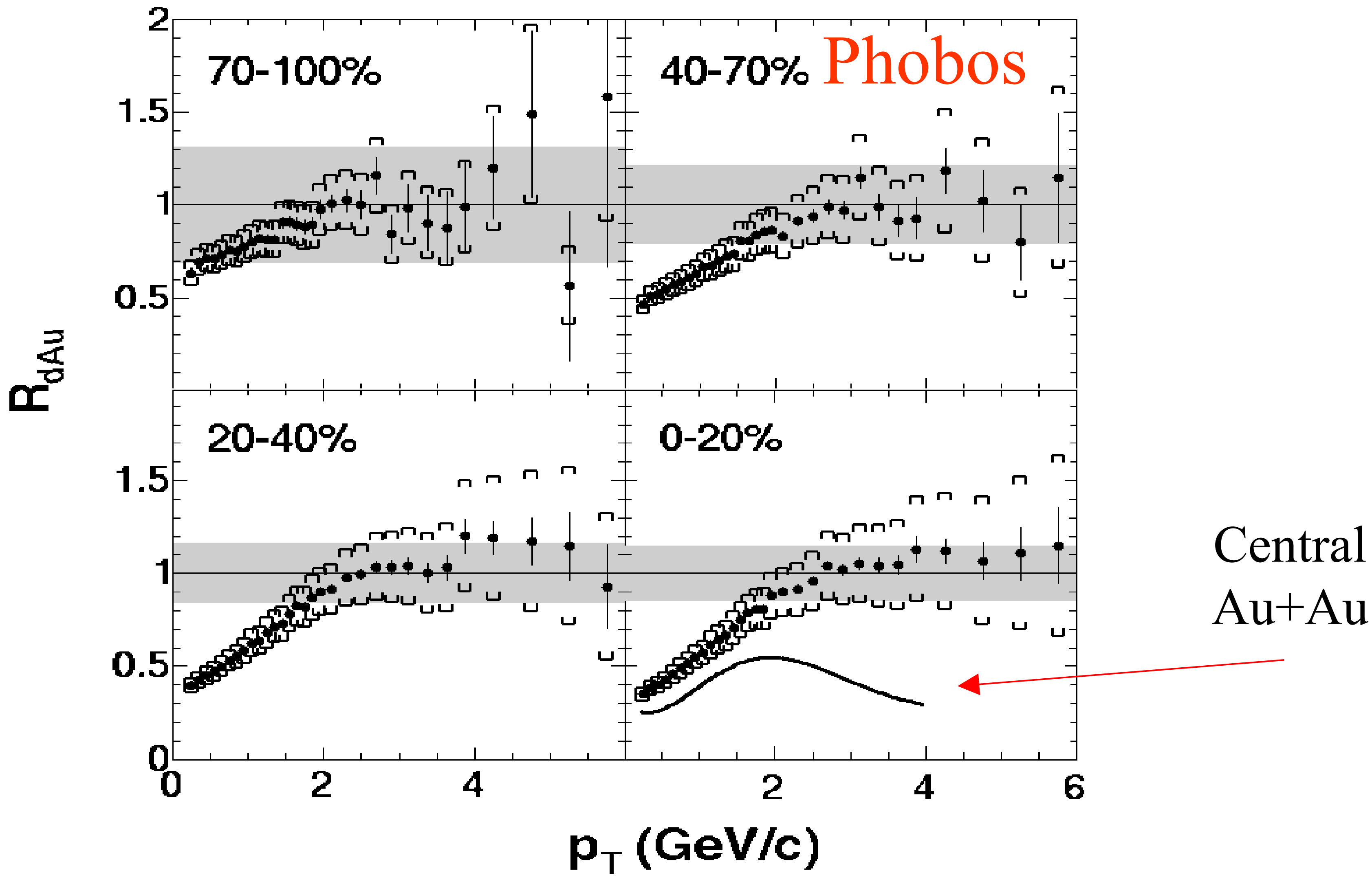






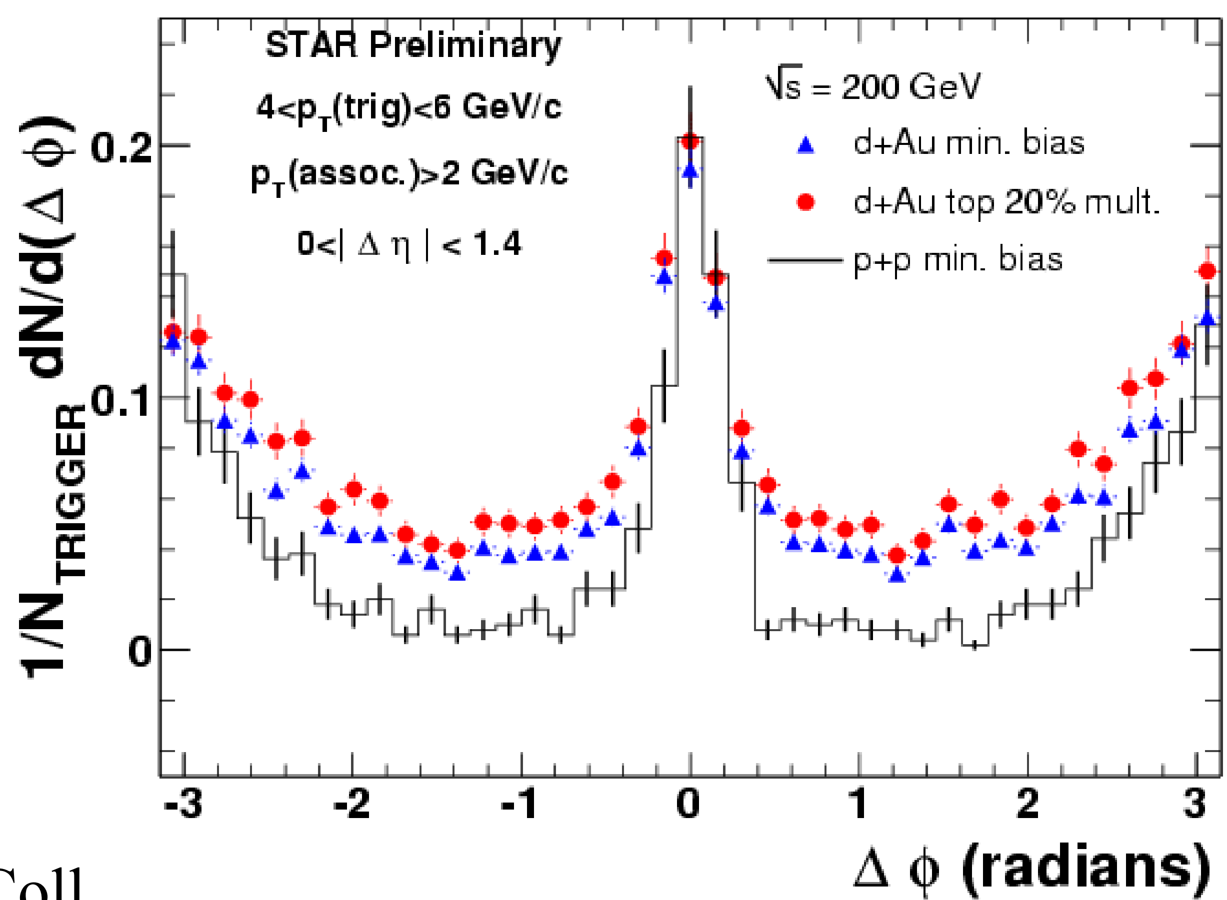


R_{dAu} vs p_T


70-100%
40-70%
Phobos
20-40%
0-20%
R_{dAu}
p_T (GeV/c)
0
0.5
1
1.5
2
4
6
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:

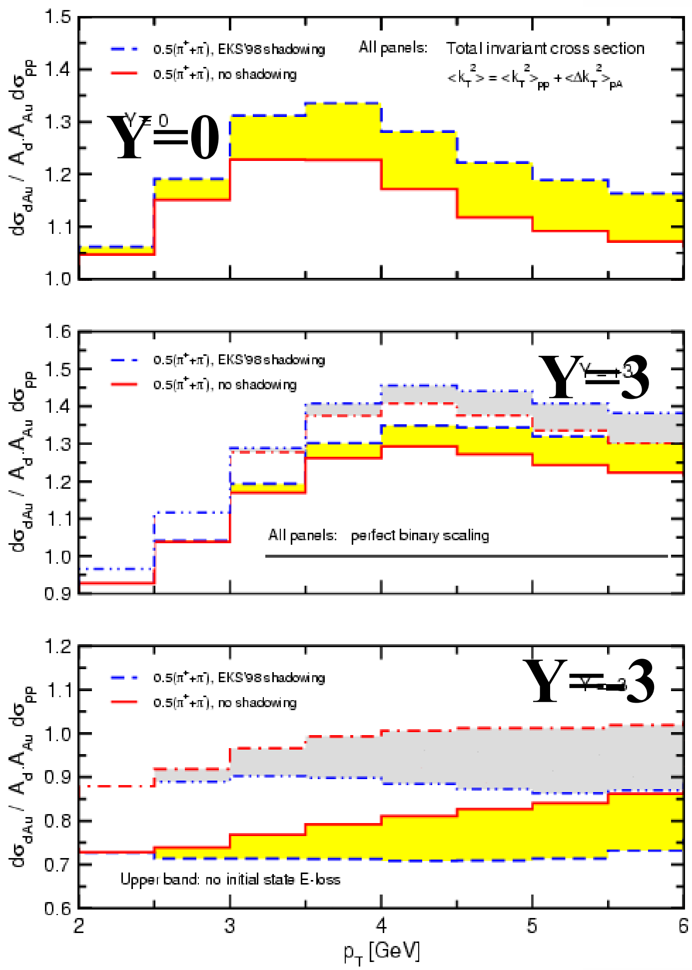
DK, E. Levin and L. McLerran, hep-ph/0210332;
DK, Yu.Kovchegov and K. Tuchin, hep-ph/0307037 v2
R. Baier, A. Kovner, U. Wiedemann, hep-ph/0305265 v2
J. Albacete, N. Armesto, A. Kovner, C. Salgado,
U. Wiedemann, hep-ph/0307179;

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;…

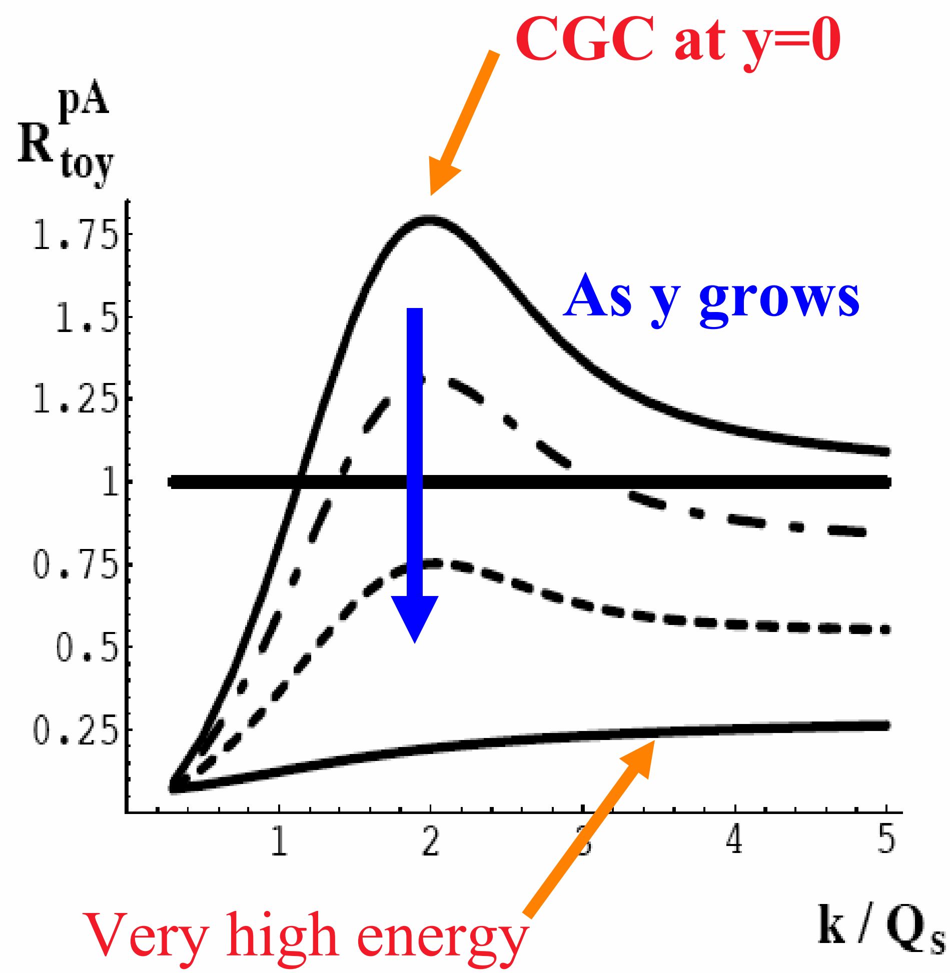
Model predictions

I. Vitev nucl-th/0302002 v2



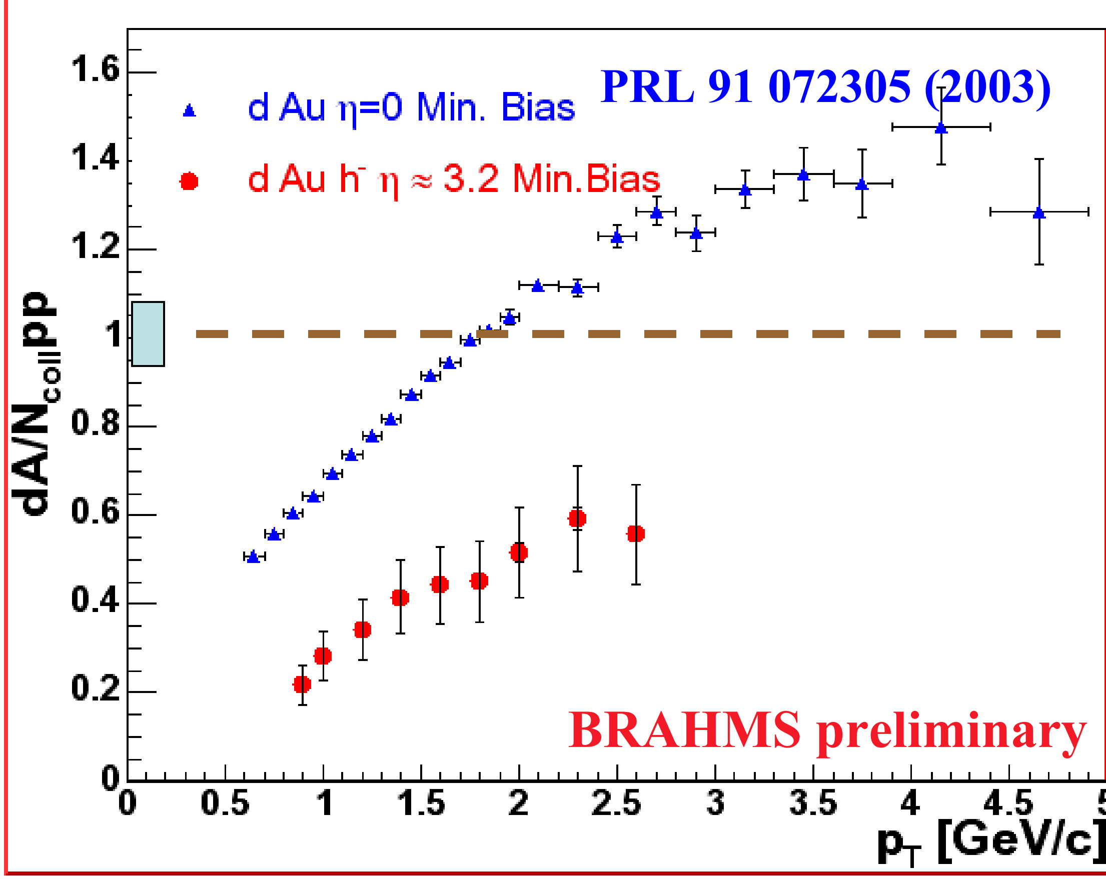
D. Kharzeev, Yu. Kovchegov and

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



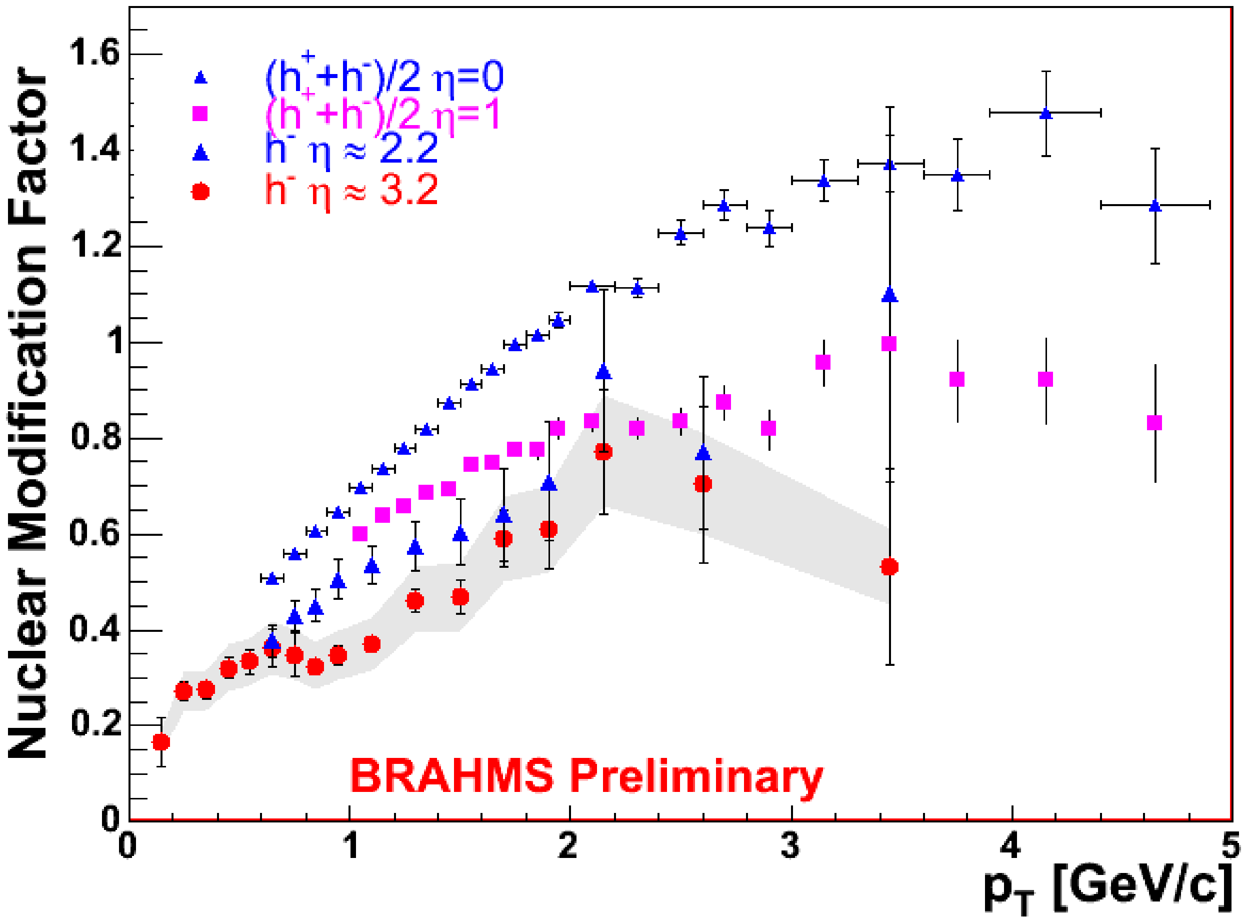
R. Debbe, BRAHMS Collaboration, Talk at the DNP Meeting, Tucson, November 2003

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:

$N_{coll} = 7.2 \pm 0.3$

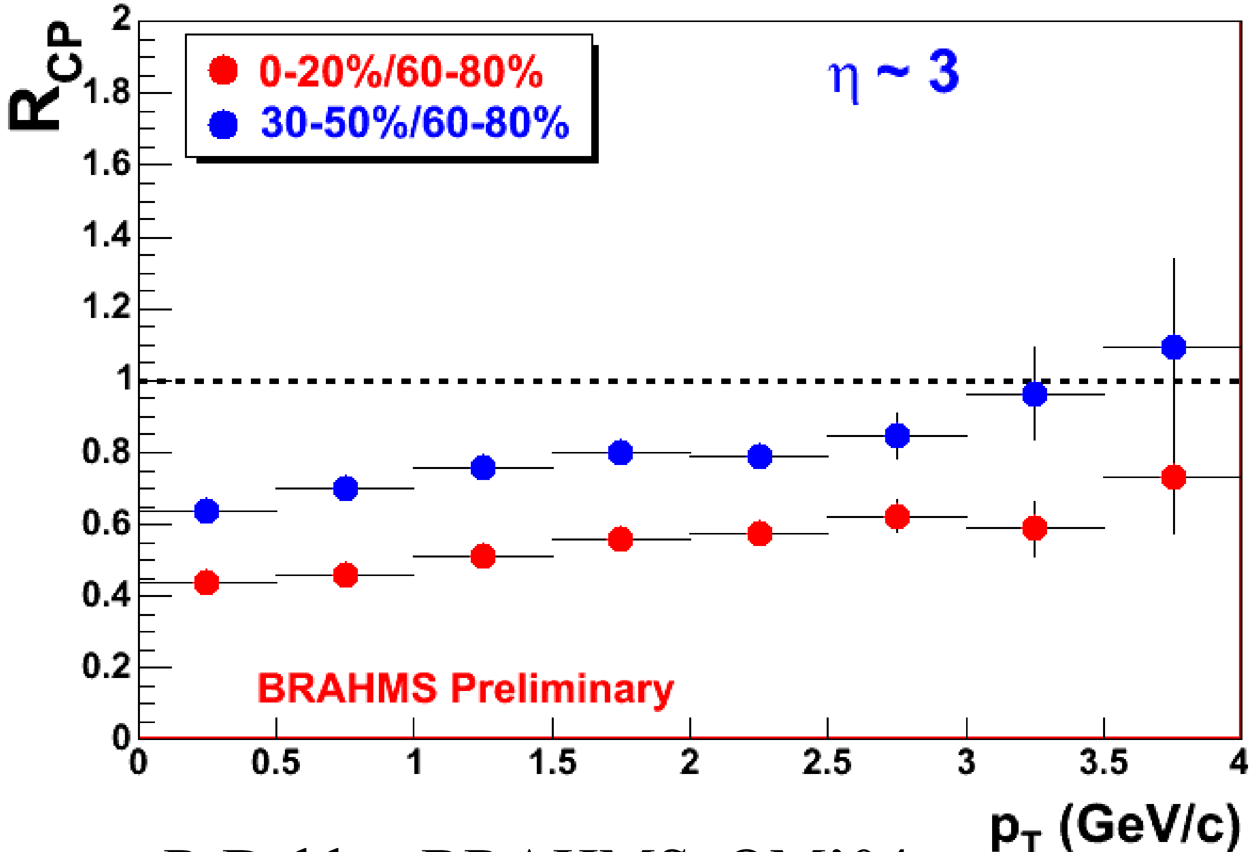
Statistical errors dominant over the systematic ones at η=2 and 3

Systematic error (not shown) ~15%

The values for η=0 were published in:

PRL 91 072305 (2003)

Centrality dependence



R.Debbe, BRAHMS, QM'04

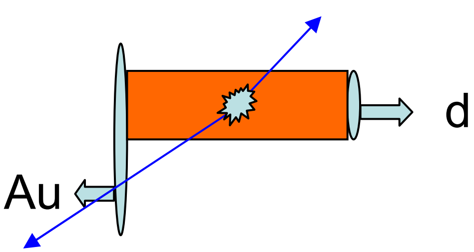
All numerators and denominator are scaled by the appropriate estimated number of binary collisions (HIJING + BRAHMS GEANT)

The ratios are corrected for trigger inefficiency.

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

Centrality Dependence of Particle Production @Fwd/Bwd Directions

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

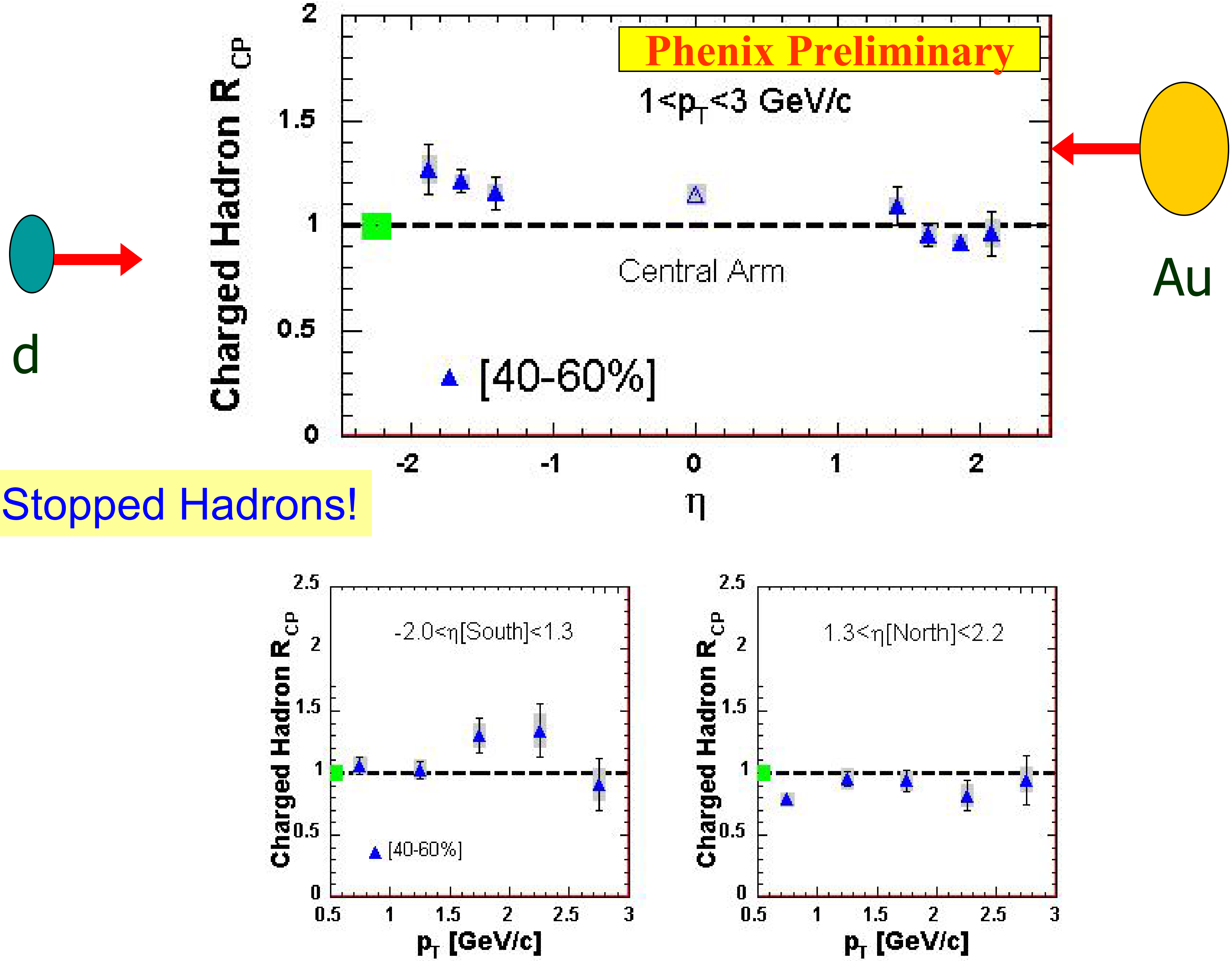


$$R_{CP}^{dAu}(P_T, y) \propto \frac{\dfrac{\Delta N^{cent-XX}}{<N_{coll}>}}{\dfrac{\Delta N^{60-88\%}}{<N_{coll}>}};$$

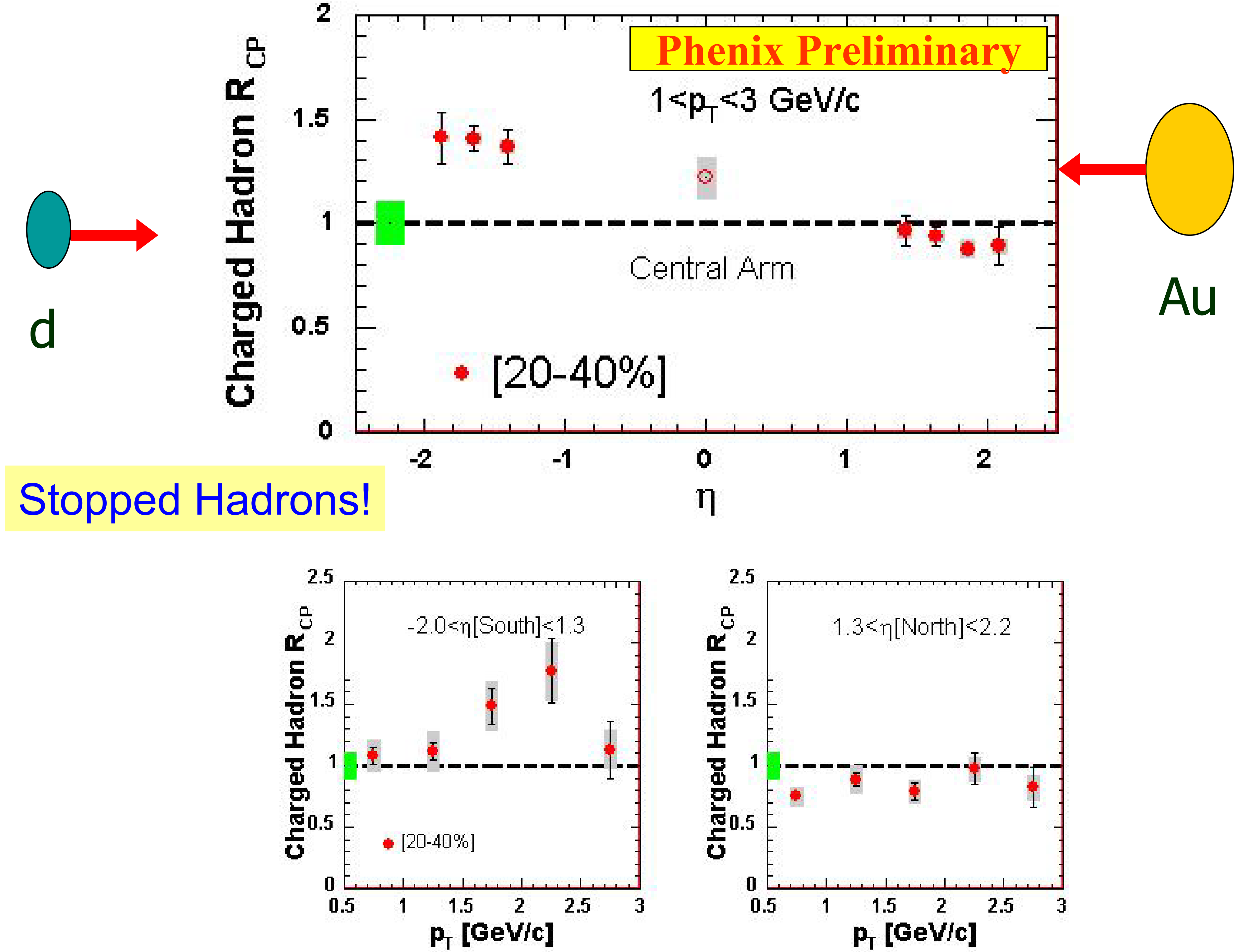
$$cent-XX = 0-20\%, 20-40\%, 40-60\%$$

Ming Liu, PHENIX, QM'04

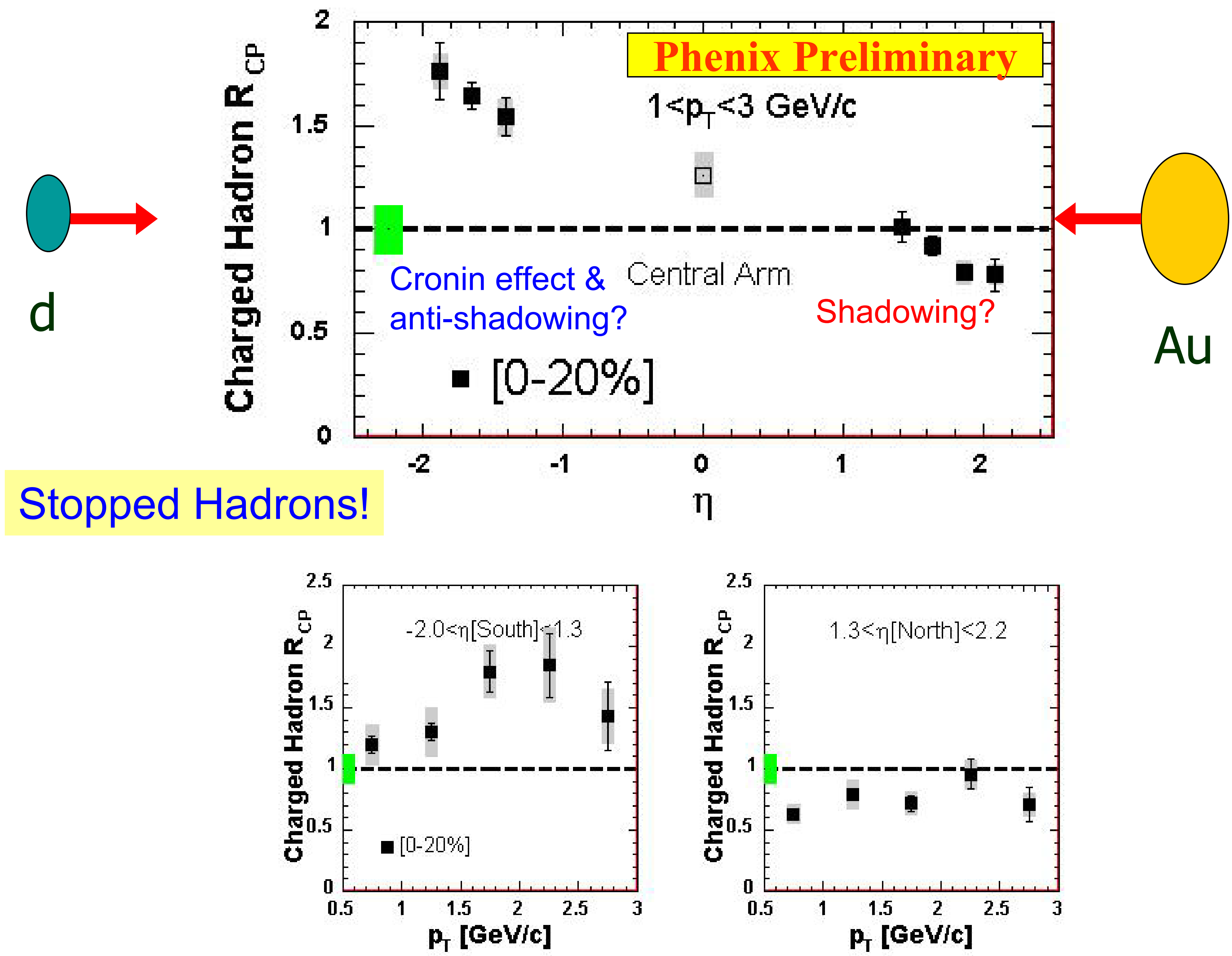
=> Talk by M. Liu



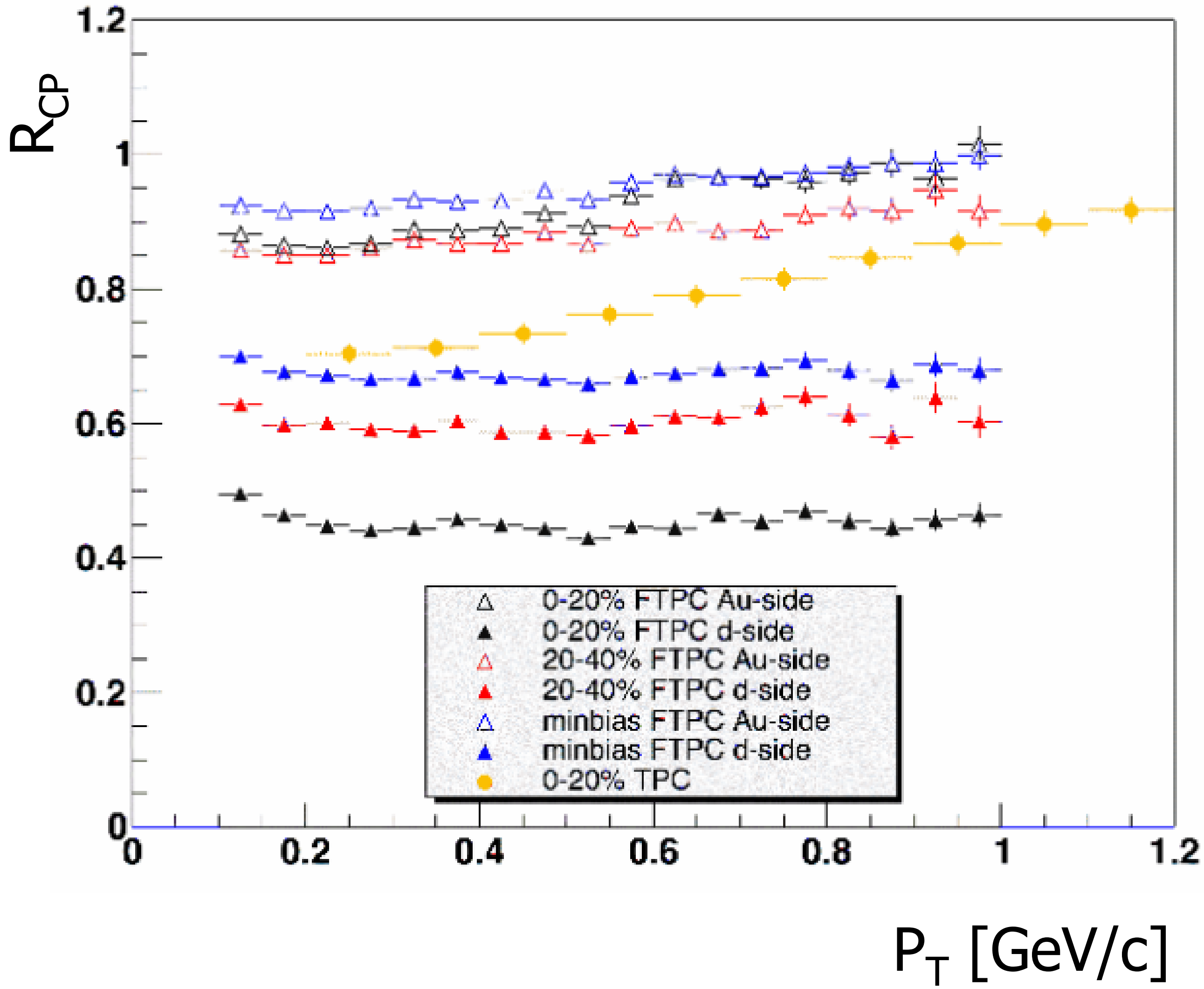
Stopped Hadrons!



d
Au
Phenix Preliminary
1<p_T<3 GeV/c
Central Arm
[20-40%]
Charged Hadron R_CP
η
Stopped Hadrons!
-2.0<η[South]<1.3
[20-40%]
1.3<η[North]<2.2
p_T [GeV/c]


d
Au
Phenix Preliminary
1<p_T<3 GeV/c
Charged Hadron R_CP
Cronin effect &
anti-shadowing?
Central Arm
Shadowing?
[0-20%]
η
Stopped Hadrons!
-2.0<η[South]<-1.3
1.3<η[North]<2.2
p_T [GeV/c]

d+Au R_{CP} at forward rapidities

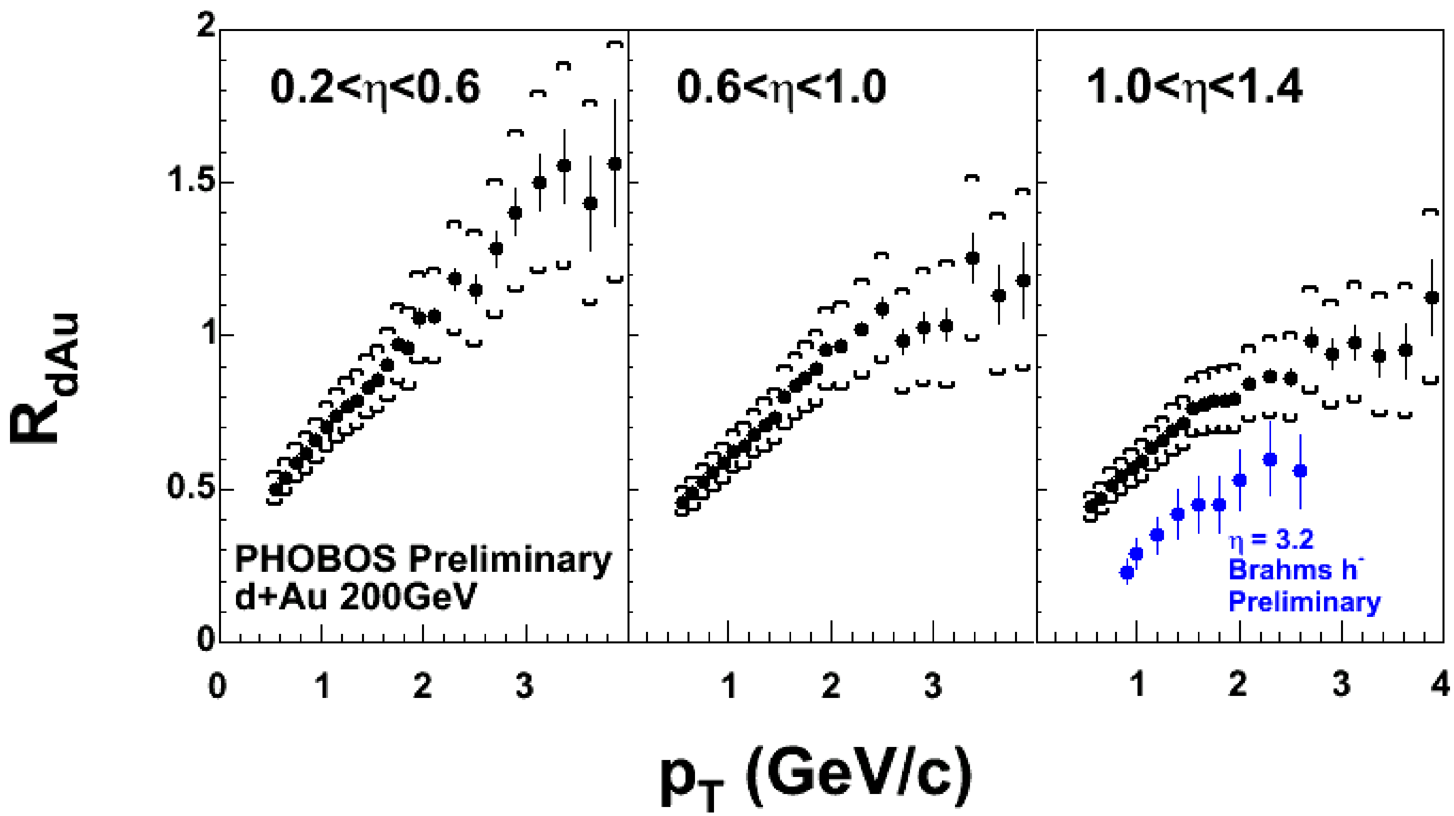


- Au-Side R_{CP} shows almost no variation with centrality

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

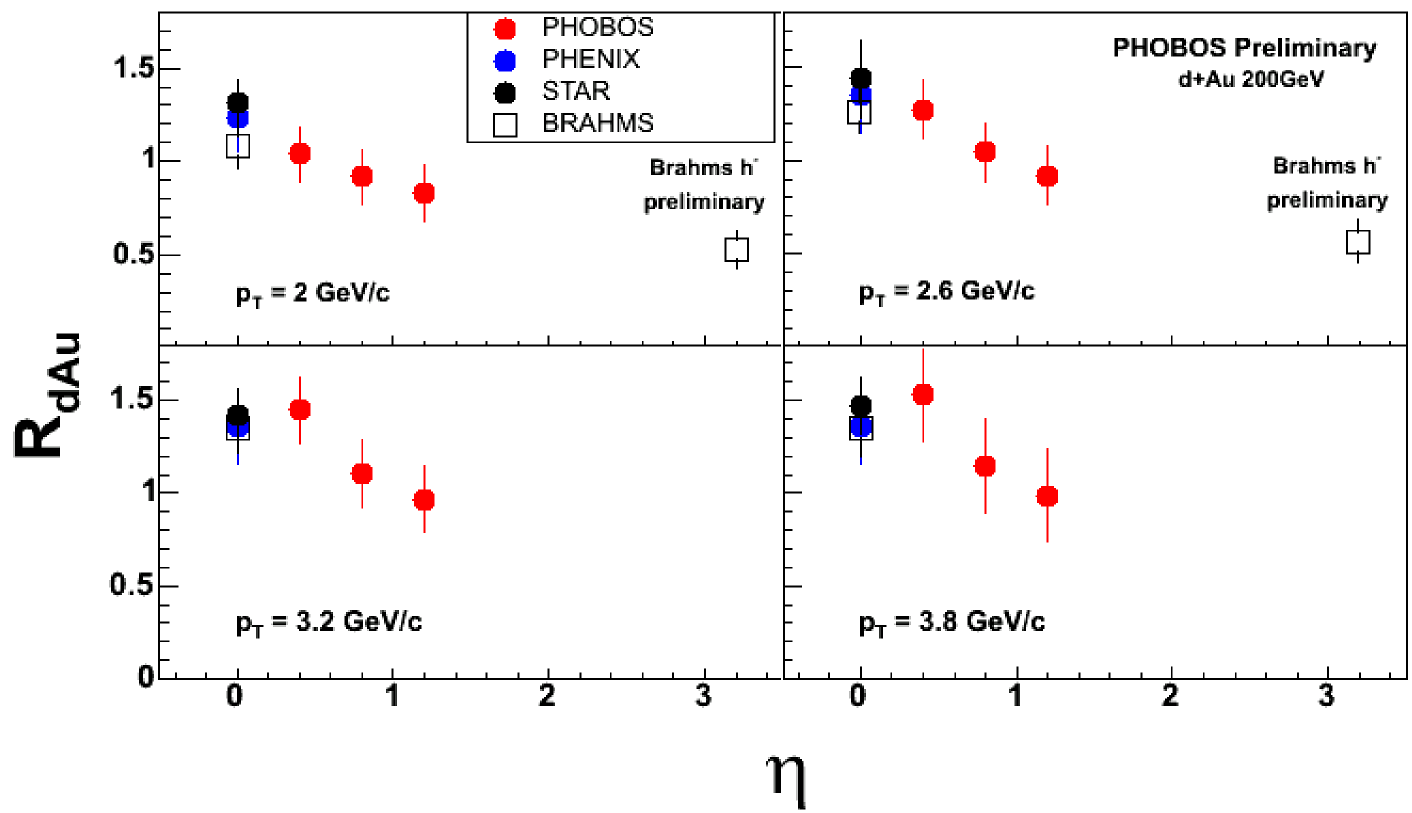
L.Barnby, STAR, QM'04

d Au spectra at (not so) forward rapidity

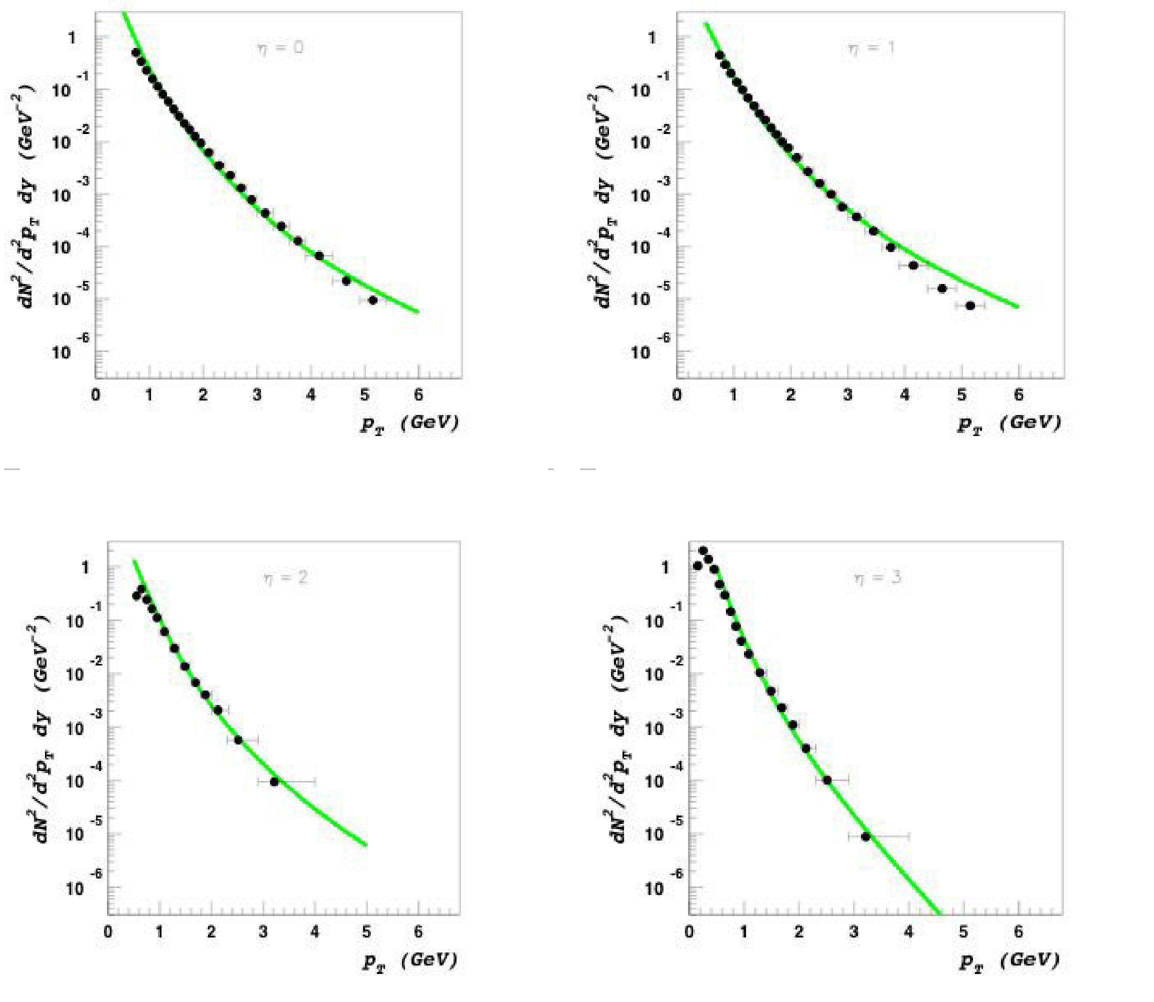


P. Steinberg, PHOBOS, QM’04

Rapidity dependence of R_{dAu}



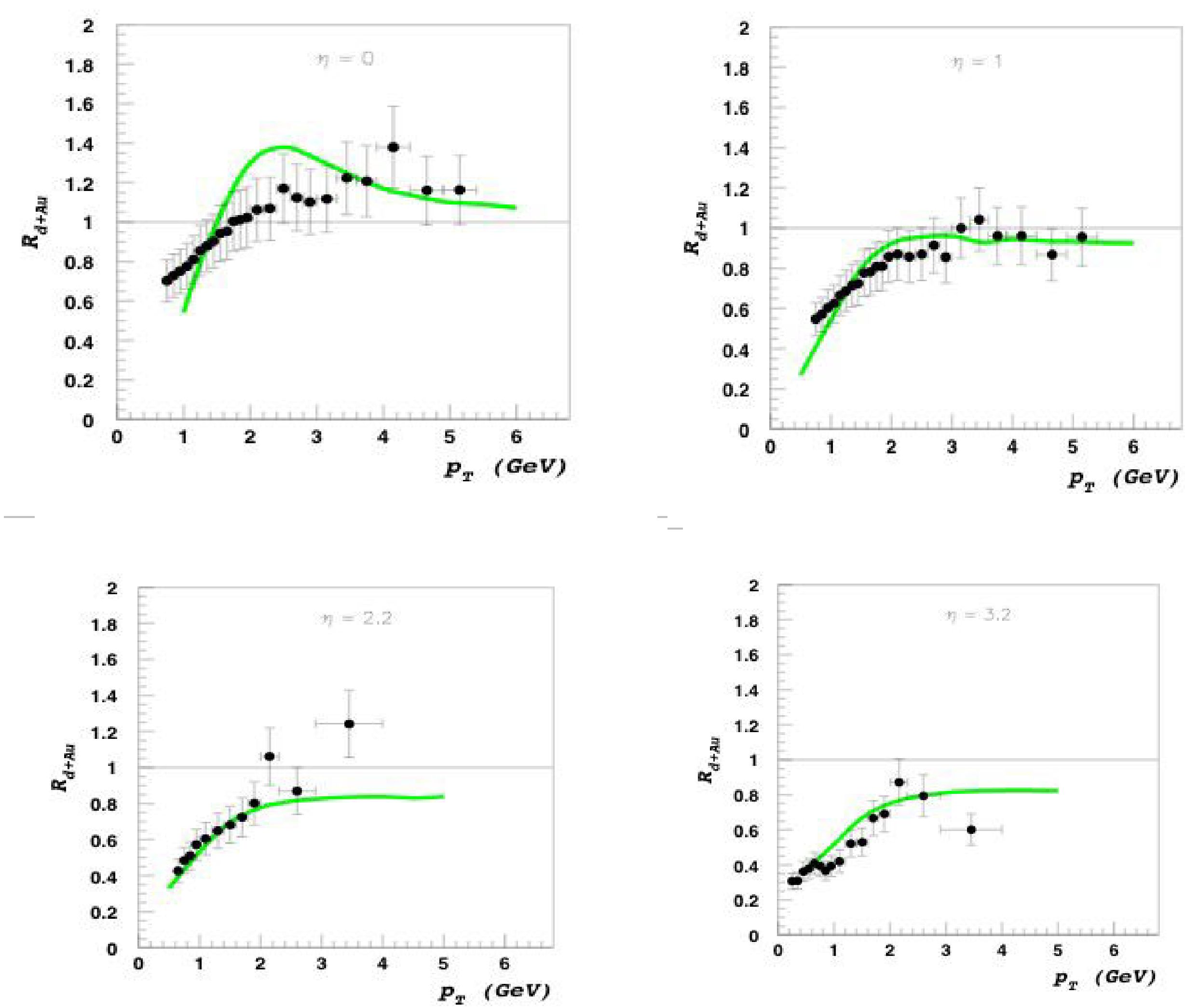
Color Glass Condensate: confronting the data I



BRAHMS data,
$\eta = 0,\ 1,\ 2.2,\ 3.2$

DK, Yu. Kovchegov, K. Tuchin, hep-ph/0405045

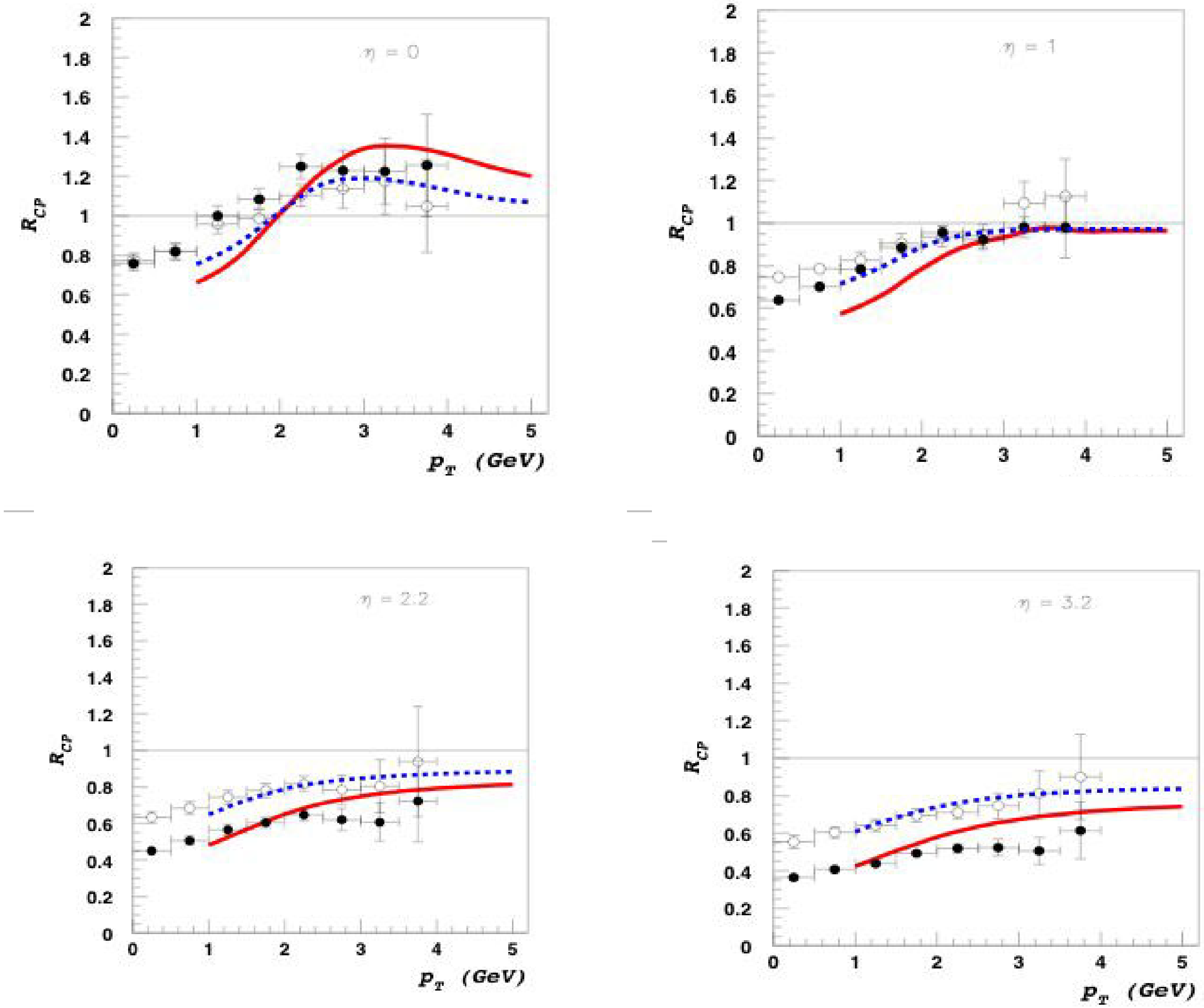
Color Glass Condensate: confronting the data II



BRAHMS data,
$\eta = 0, \quad 1,$
$\quad 2.2, 3.2$

DK, Yu. Kovchegov, K. Tuchin, hep-ph/0405045

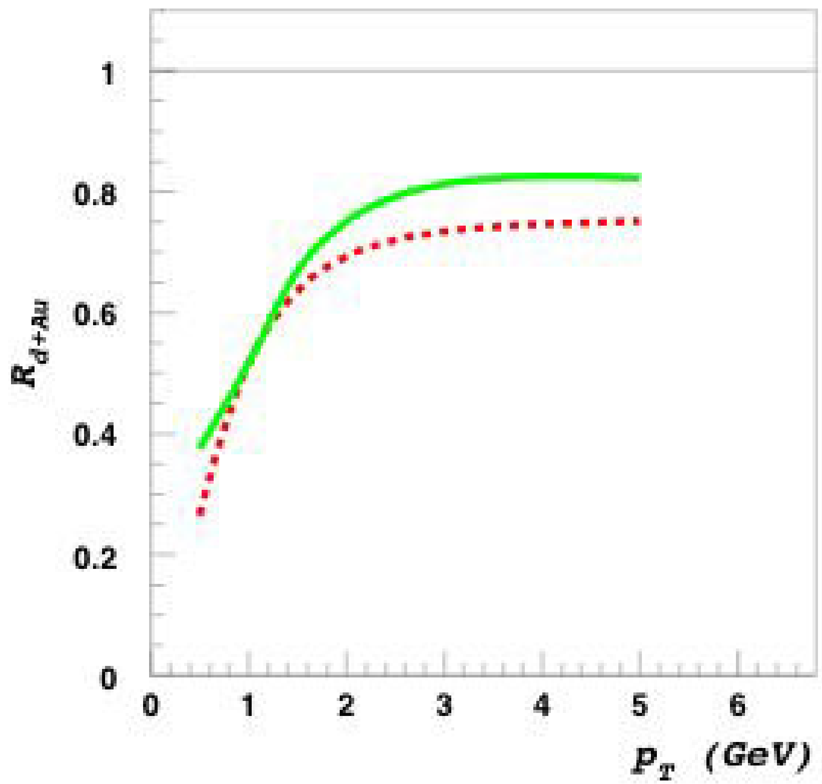
Color Glass Condensate: confronting the data III



BRAHMS data, R_{CP}
$\eta = 0,\ 1,\ 2.2,\ 3.2$

DK, Yu. Kovchegov, K. Tuchin, hep-ph/0405045

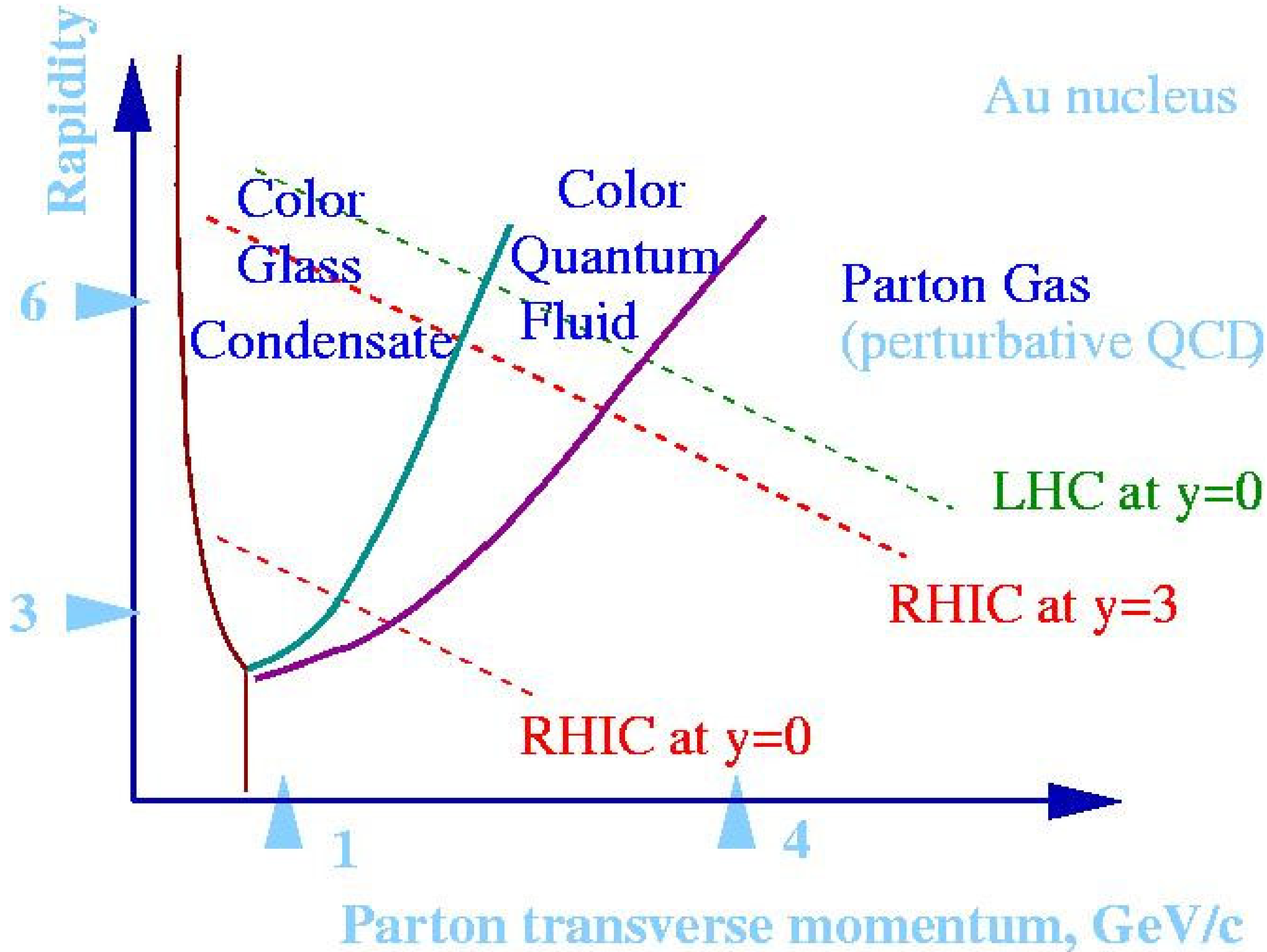
Color Glass Condensate at the LHC



At the LHC (red line),
even the mid-rapidity,
high p_T production
will be dominated
by the CGC

DK, Yu. Kovchegov, K. Tuchin, hep-ph/0405045

Phase diagram of high energy QCD



Are the effects observed at forward rapidity due to parton saturation in the CGC?

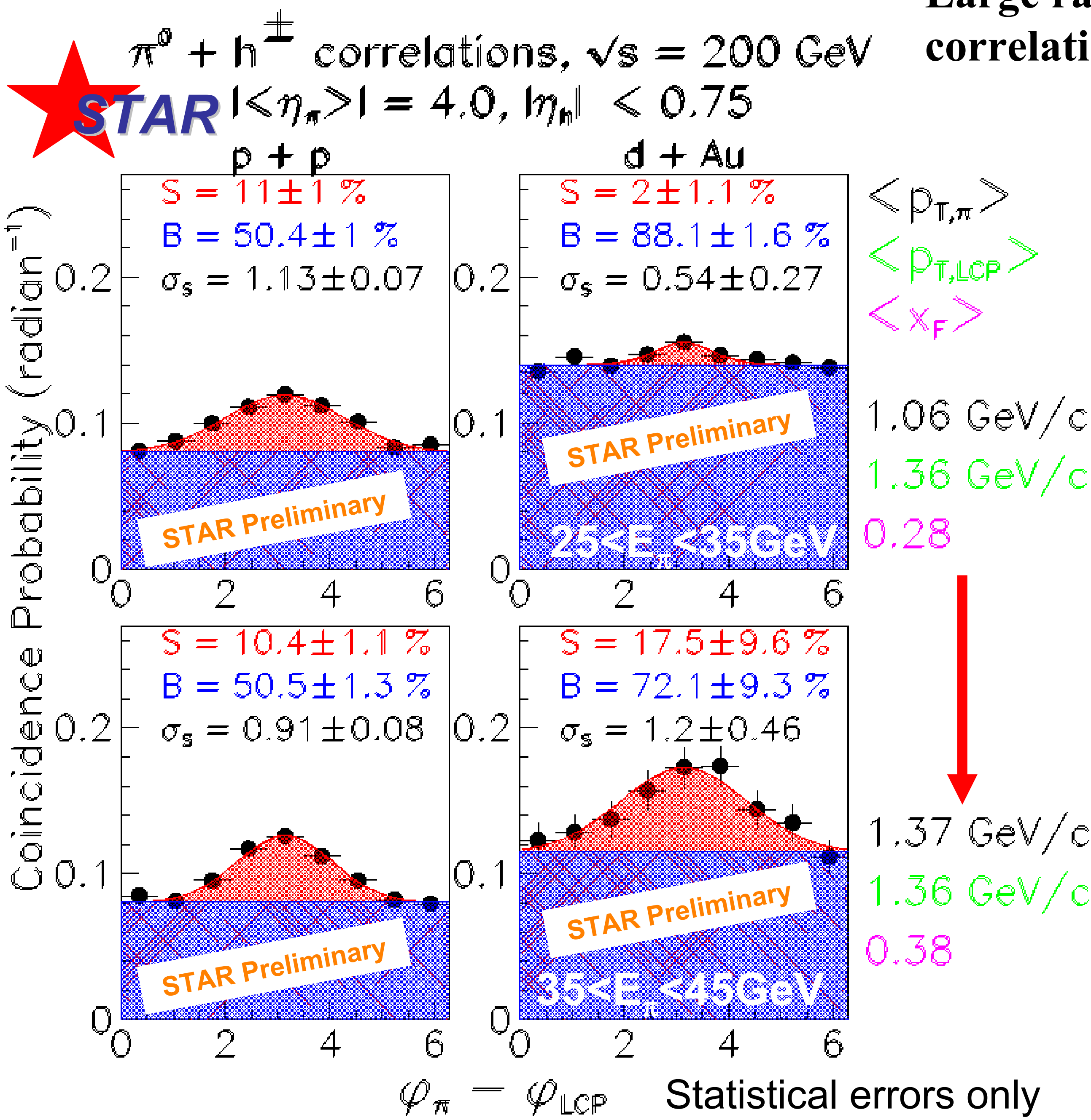
- Back-to-back correlations for jets separated by several units of rapidity are very sensitive to the evolution effects A.H.Mueller,H.Navelet, ‘87 and to the presence of CGC DK, E.Levin,L.McLerran, hep-ph/0403271

Recent results from STAR: A. Ogawa, Talk at DIS’04

- Open charm, dileptons, photons in the forward region DK, K.Tuchin, hep-ph/0310..

R.Baier,A.H.Mueller,D.Schiff, hep-ph/0403201;
J.Jalilian-Marian, F. Gelis, R. Venugopalan

Large rapidity gap π^0+$h^\pm$ correlation data…

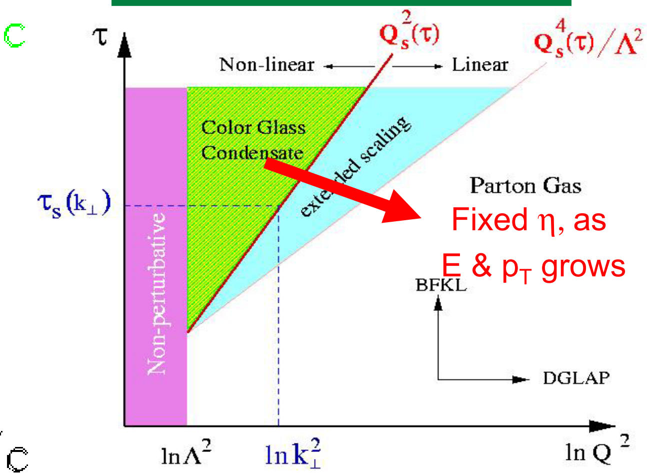


Statistical errors only

- are suppressed in d+Au relative to p+p at small $\langle x_F\rangle$ and $\langle p_{T,\pi}\rangle$

$S_{pp}-S_{dAu}$ = (9.0 ± 1.5) %

Consistent with CGC picture



- are consistent in d+Au and p+p at larger $\langle x_F\rangle$ and $\langle p_{T,\pi}\rangle$

as expected by HIJING

Heavy quarks and the Color Glass Condensate

In CGC, heavy quarks can behave either as “light” or “heavy”

Naïve consideration:

DK & K. Tuchin, hep-ph/0310358

CGC is characterized by the chromo-electric field

$$E \sim \frac{Q_s^2}{g}$$

when the strength of the field is

$$gE \sim \frac{M}{1/M} = M^2$$

or

$$Q_s^2 \geq M^2$$

heavy quarks no longer decouple => they are not really “heavy”

Heavy quarks and the Color Glass Condensate

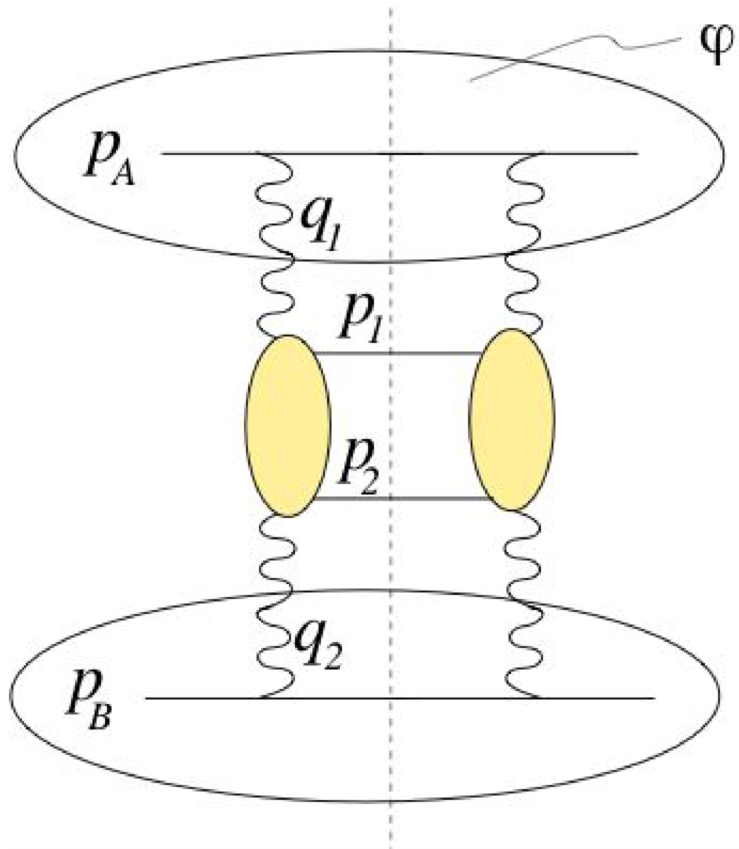
In addition, even when

$$Q_s \leq M \leq \frac{Q_s^2}{\Lambda}$$

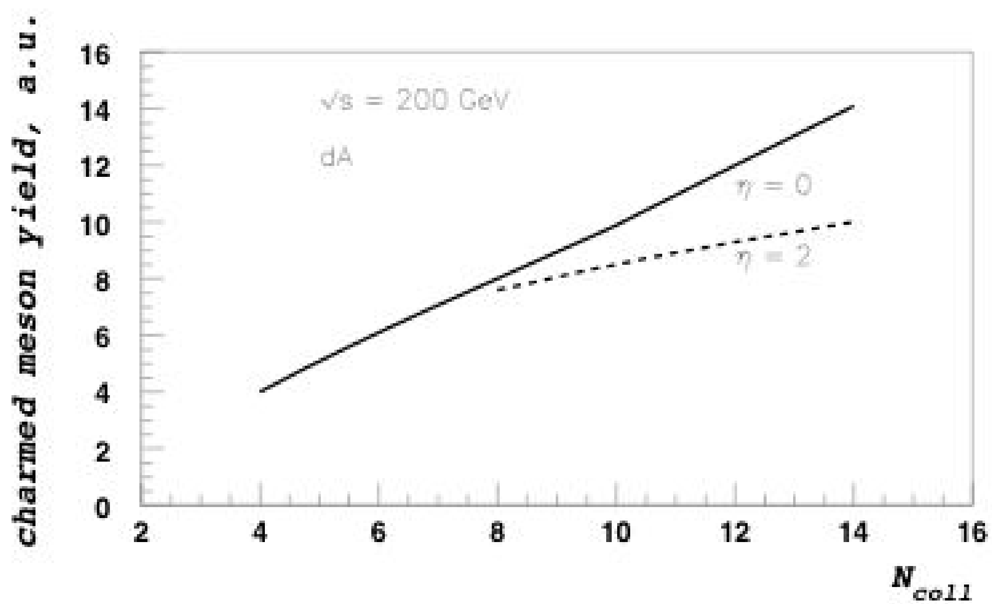
the production of heavy quarks is significantly
affected by the presence of the CGC,
similarly to what happens in the case of high Pt production
at forward rapidities

DK, E.Levin, L.McLerran;
DK, Yu. Kovchegov, K. Tuchin;
R. Baier, A.Kovner, U.Wiedemann;
J. Albacete et al

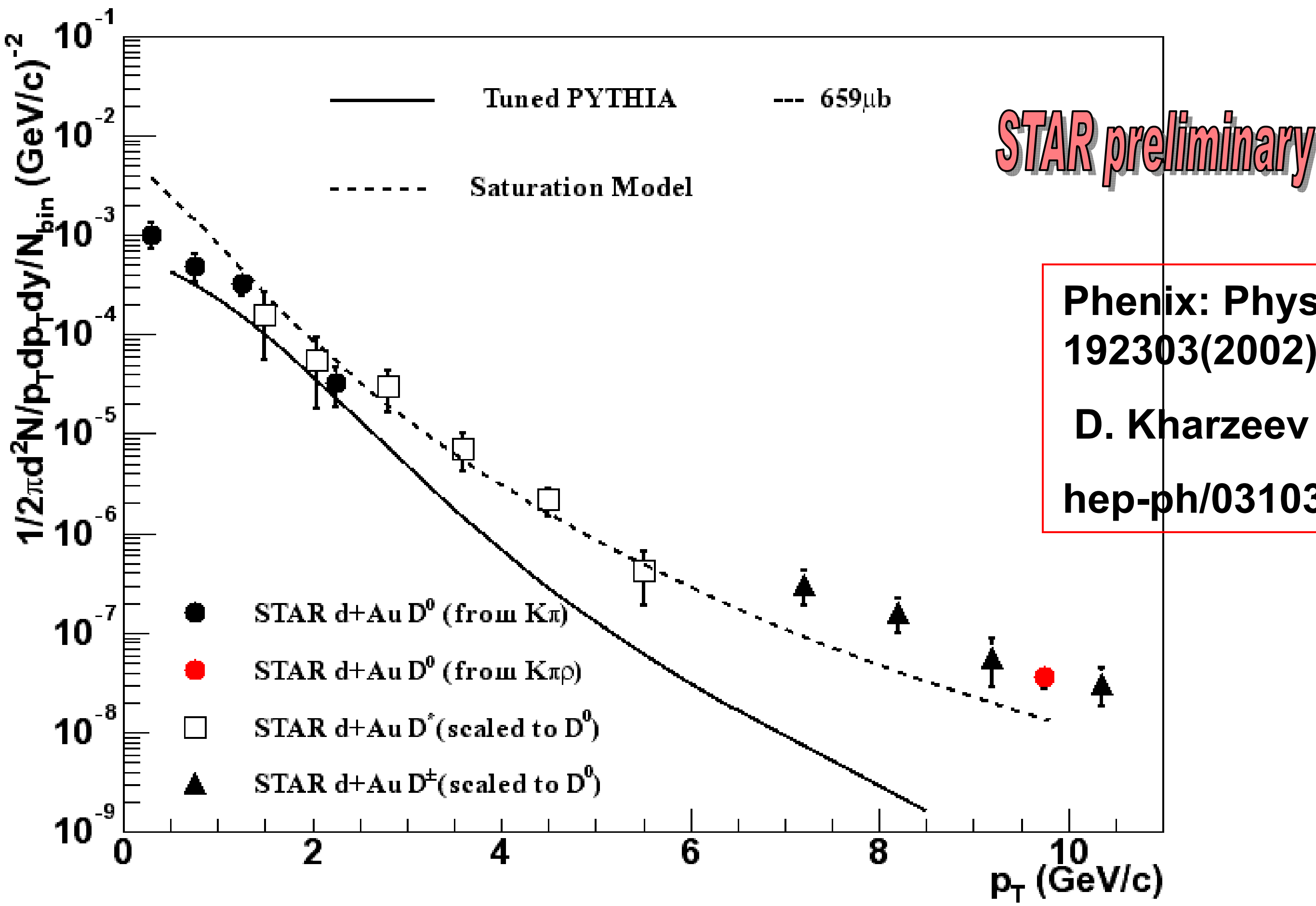
The formalism: K_T factorization



The results: dAu collisions



Open charm spectrum is hard !



Phenix: Phys. Rev. Lett. 88, 192303(2002)

D. Kharzeev & K. Tuchin, hep-ph/0310358

An Tai, STAR, QM'04

From CGC to Quark Gluon Plasma: approach to thermalization

The data on azimuthal anisotropy of hadron production indicate strong final state interactions at short time scales

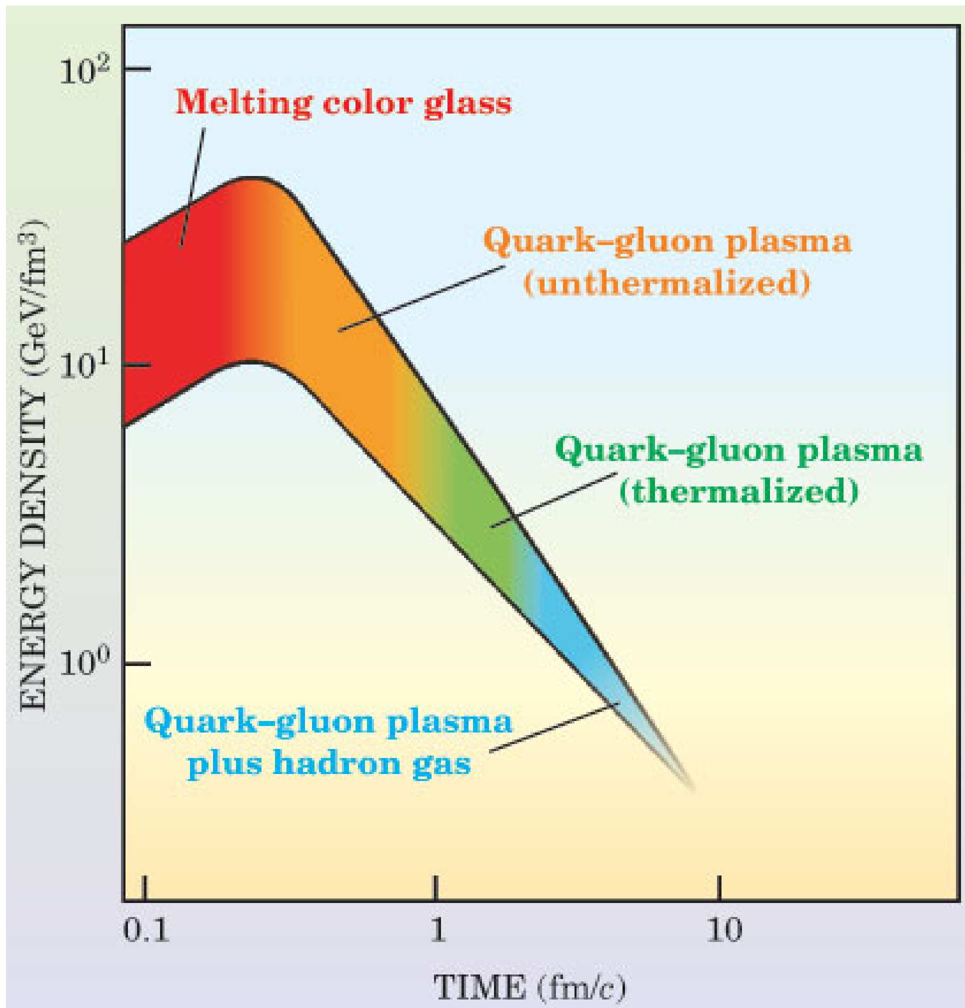
$$\tau_{eq} \simeq 0.6\ fm$$

U.Heinz,
E.Shuryak

Problem: if interactions are perturbative, interaction probabilities are small - suppressed by powers of α_s
if interactions are non-perturbative, characteristic re-interaction time is about 1 fm
Possible solution: CGC sets a fast time scale $\tau \sim 1/Q_s$ (~ 0.2 fm) and classical fields $A \sim 1/g$ re-interact with ~ O(1) probability
(almost) isentropic evolution => ideal hydrodynamics is reasonable

R.Baier, A.H.Mueller, D. Schiff, D.T. Son, PLB502(2001)51; 539(2002)46; …

From CGC to Quark Gluon Plasma



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

Summary

Relativistic heavy ion collisions allow to study
QCD of strong color fields

Growing evidence of Color Glass Condensate
at RHIC

A dedicated forward physics program at RHIC
and LHC is needed

Back-up slides

Is this "just shadowing"?

Yes, it is - shadowing is the deviation of nuclear parton distributions from the nucleon's ones.
CGC is a theory of shadowing

Conventional parameterizations of shadowing have so far failed in describing the rapidity and centrality dependence of the data (EKS, de Florian, Accardi-Gyulassy,…

Some approaches (e.g. HIJING shadowing) describe suppression at y=3, but also predict it at y=0.

NB:approaches relating shadowing to diffraction should work

Are “alternative explanations” possible?

Yes!

In QCD, the physical picture depends on the Lorentz frame and on the gauge
(e.g., parton model is formulated in the infinite momentum frame)

CGC with quantum evolution corresponds, in the target rest frame, to a combination of different effects:
multiple scattering + shadowing + radiative energy loss.

It provides a unified theoretical framework

What has to be done

- Study hard processes in a wide range of rapidity, with identified high p_T particles

  1) jet (jet + γ, …) azimuthal correlations
     at large Δ y

  2) heavy quark jets

  3) heavy quarkonia

  4) dileptons at high p_T

  ….