RHIC-II Science Workshop, BNL, November 18, 2004

New opportunities in high p_T and small x physics

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BNL

BROOKHAVEN NATIONAL LABORATORY

Outline

- What have we learned so far?
- Why high p_T?
- Why small x?
- Why RHIC II?

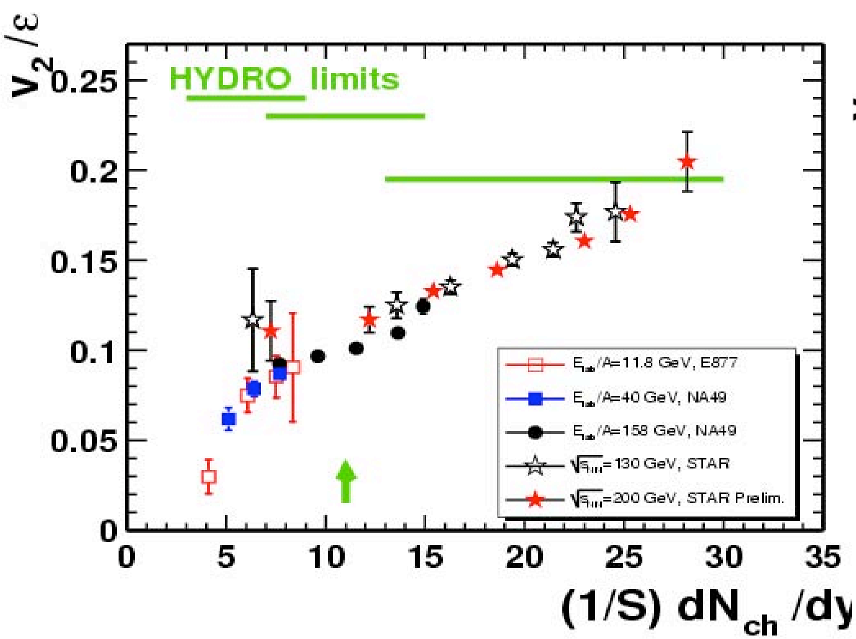
how processes at high p_T and small x
help us to understand:

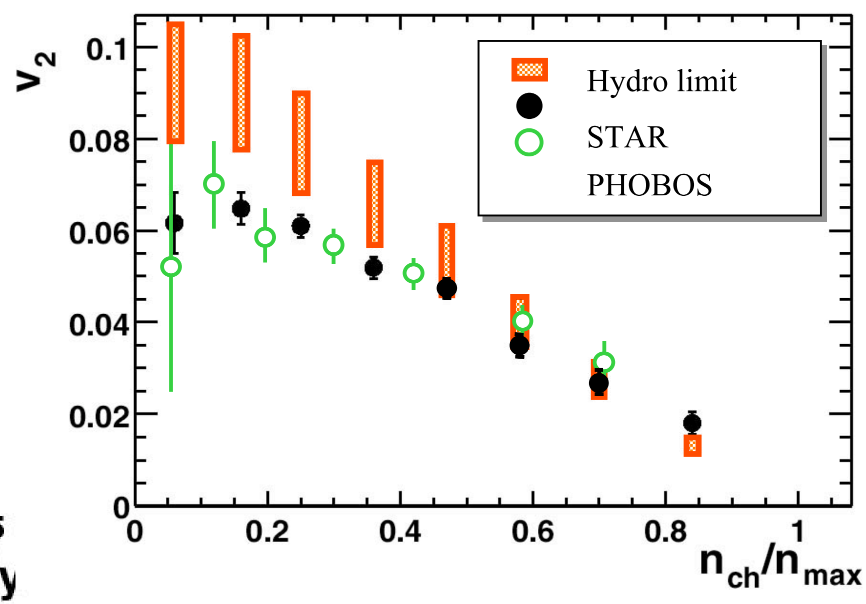
- Color Glass Condensate
- (strongly coupled) Quark-Gluon Plasma

What have we learned from RHIC so far ?

I. Collective flow =>

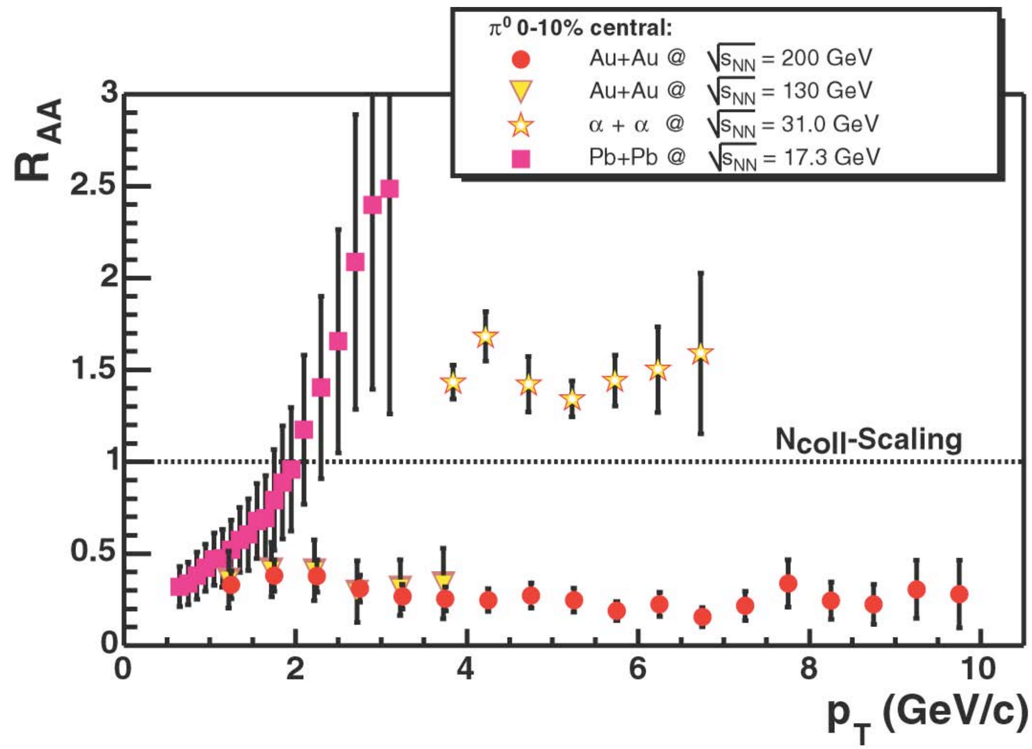
Au-Au collisions at RHIC produce strongly interacting matter





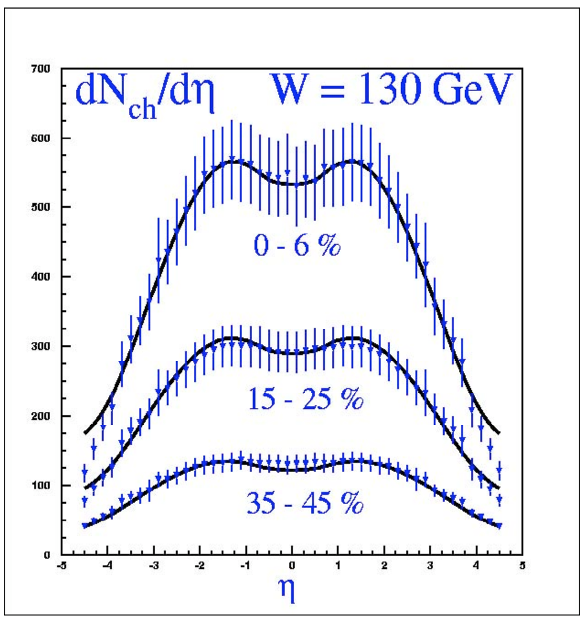
What have we learned from RHIC so far ?

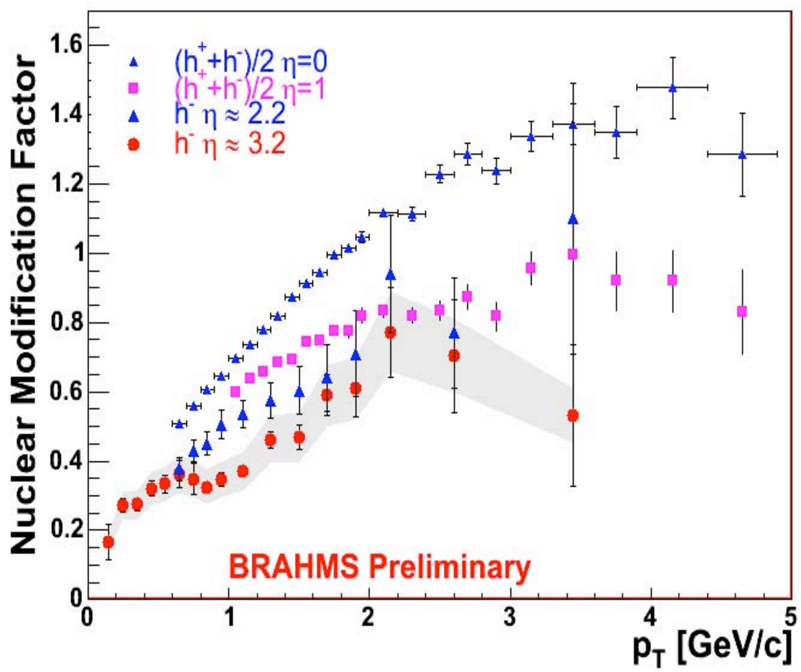
II. Suppression of high p_T particles =>
consistent with the predicted jet energy loss from induced gluon radiation in dense QCD matter



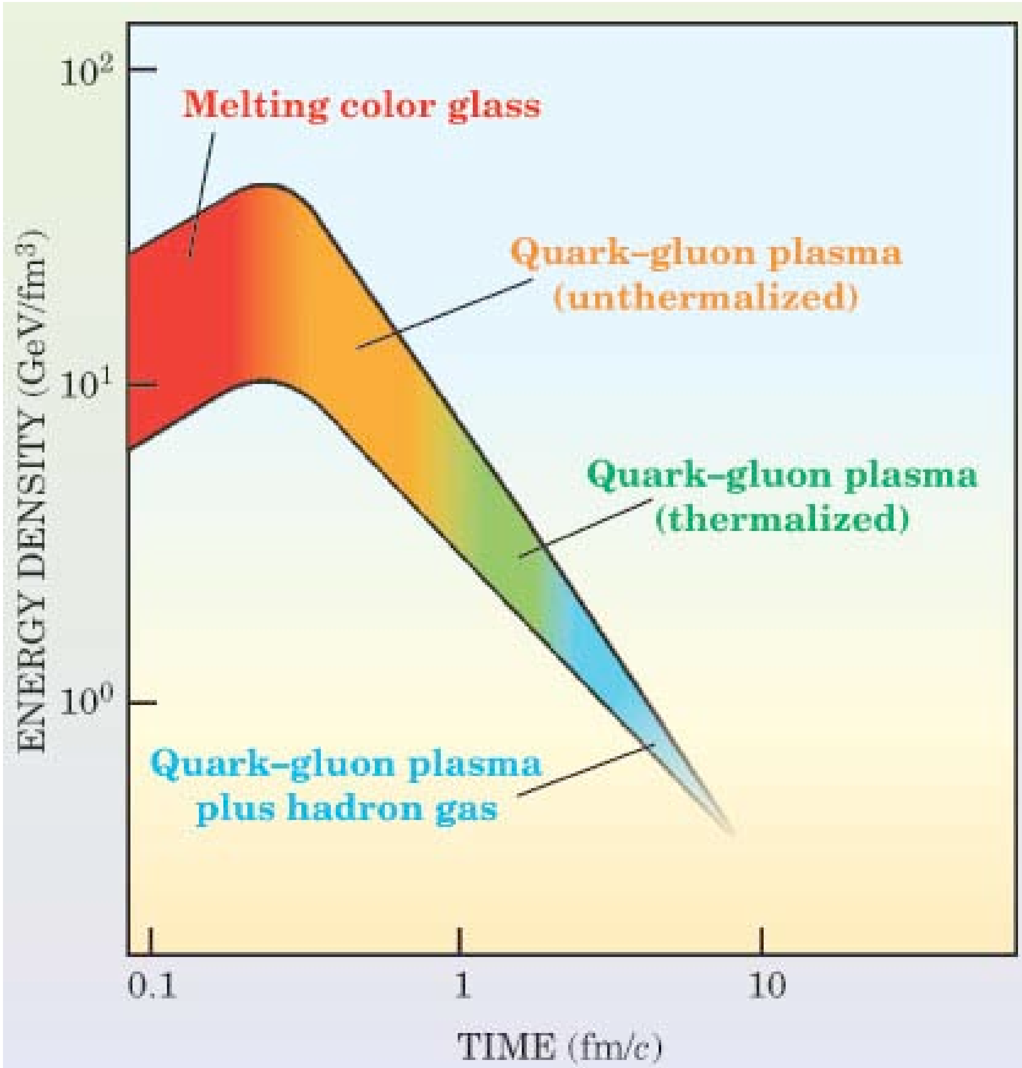
What have we learned from RHIC so far ?

III. "Small" hadron multiplicities +
suppression of high p_T particles at forward rapidities =>
coherent interactions in the initial state, consistent
with the presence of parton saturation/Color Glass Condensate





The emerging picture



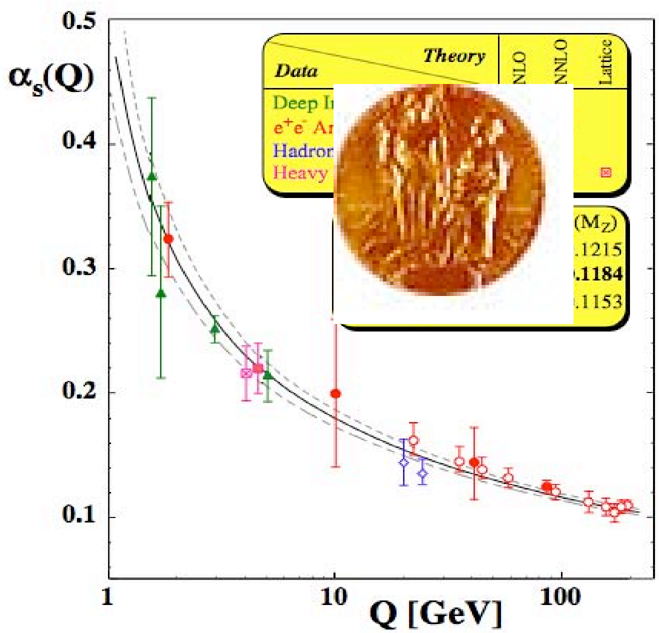
T. Ludlam,
L. McLerran,
Physics Today
October 2003

What we still need to know

- Is the produced matter a thermalized Quark-Gluon Plasma ?
  if yes, what are its properties ?

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

Why high p_T?



At short distances,
the strong force becomes weak -

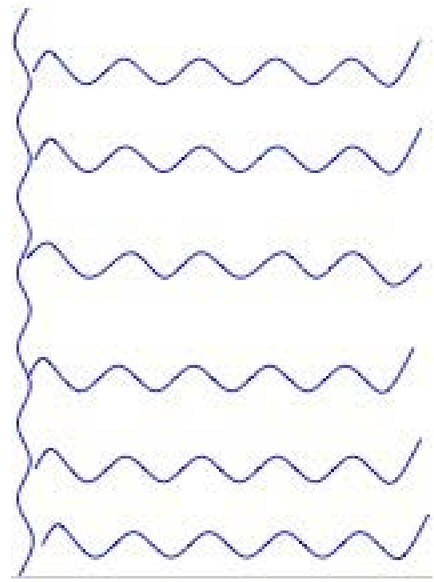
one can access the "asymptotically free" regime in hard processes

But: the harder a parton is hit,
the more intense radiation it emits;
this happens because even though
$\alpha_s << 1$, $\alpha_s \ln (Q^2 / \Lambda^2) \sim 1$
(large phase space)

=> Scaling violations, jet structure

Why small x?

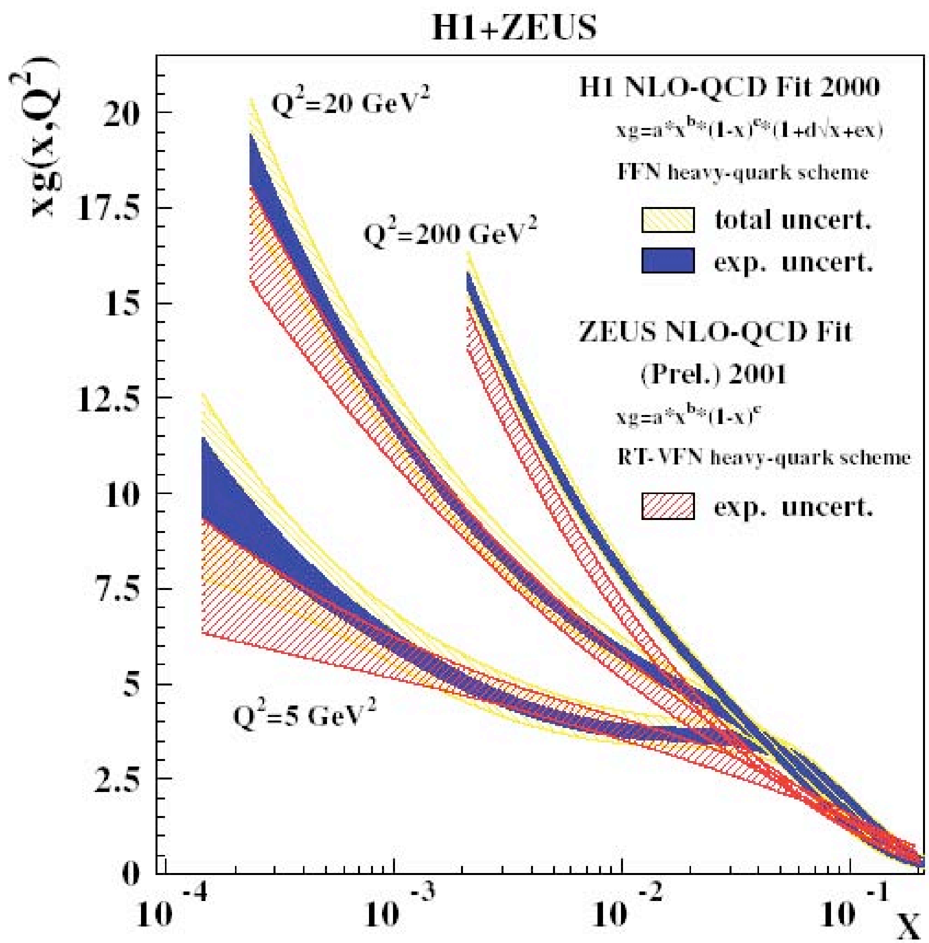
At small x, the gluon propagator is dressed by the quantum evolution:

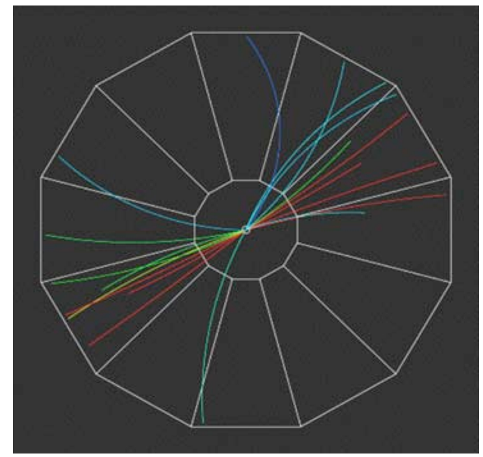


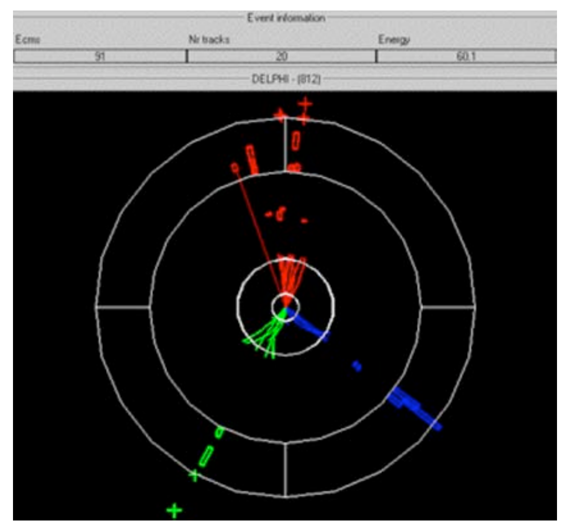
this is because the probability to emit an extra gluon is $\sim \alpha_s \ln(1/x) \sim 1$

As a result, the gluon propagators at small x acquire an anomalous dimension

Resolving the gluon cloud at high Q^2 and small x



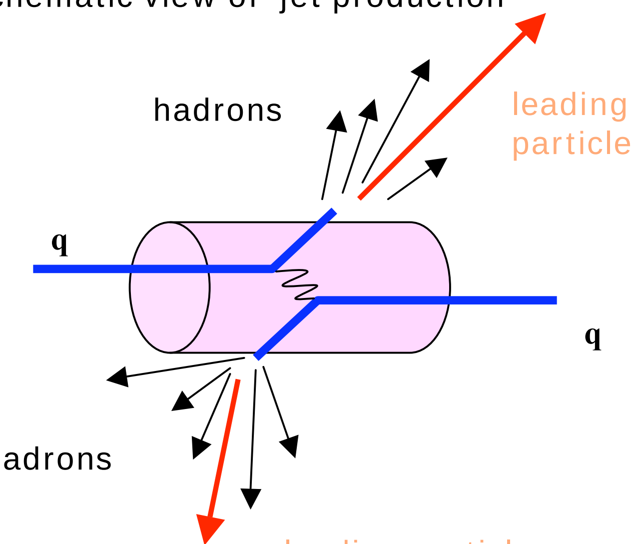




Fast partons as a probe

J.Bjorken,
M.Gyulassy,
X.N.Wang, …

In QCD vacuum, the probability of gluon radiation ~ $\alpha_s \ln (Q^2 / \Lambda^2)$;



in medium, the scale Λ is determined by the properties of matter:

In hot quark-gluon plasma

$\Lambda^2 = \hat{q}_{hot} L$ $\hat{q}_{hot}$ - transport coeff.

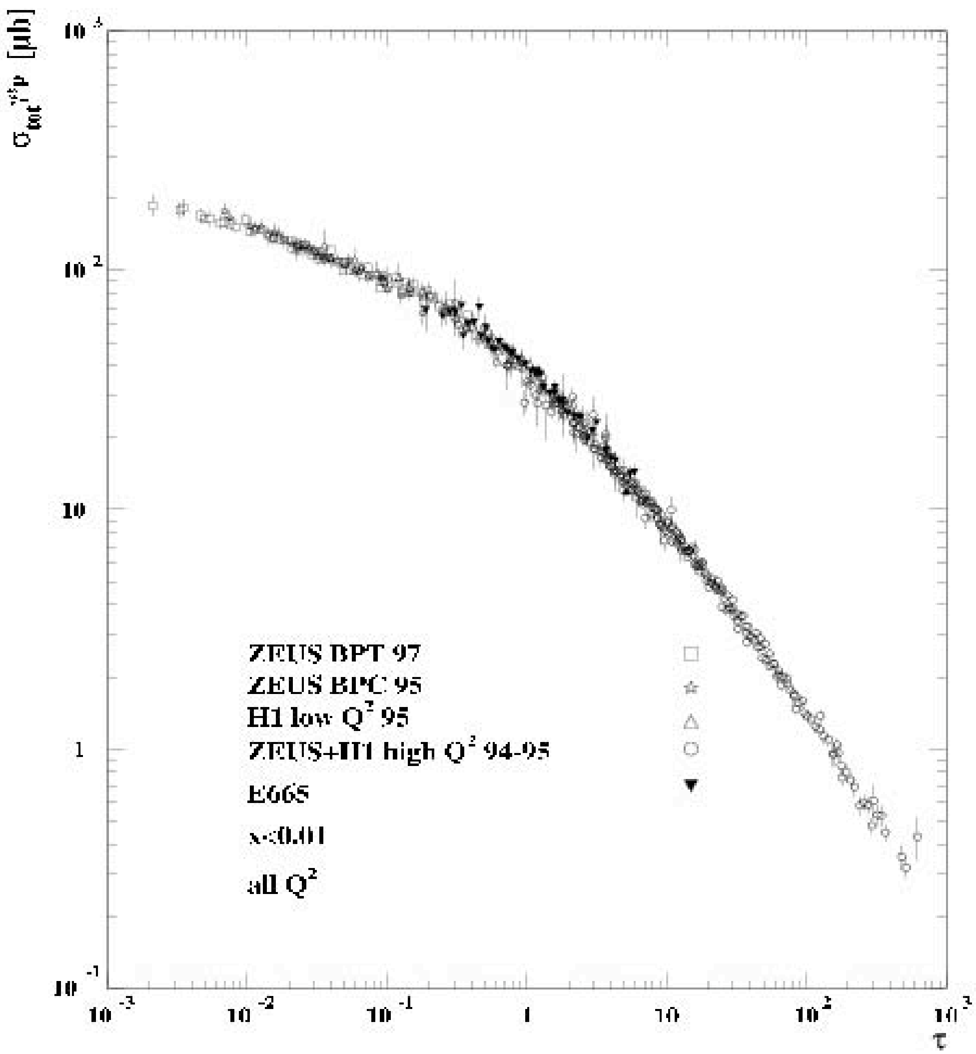
L - size of the system

In cold nucleus at small x

$\Lambda^2 = Q_s^2$ - the saturation scale; $Q_s^2 = \hat{q}_{cold} L$

R.Baier,
Yu.Dokshitzer,
A.Mueller,
S.Peigne,
D. Schiff

Novel physics at small x

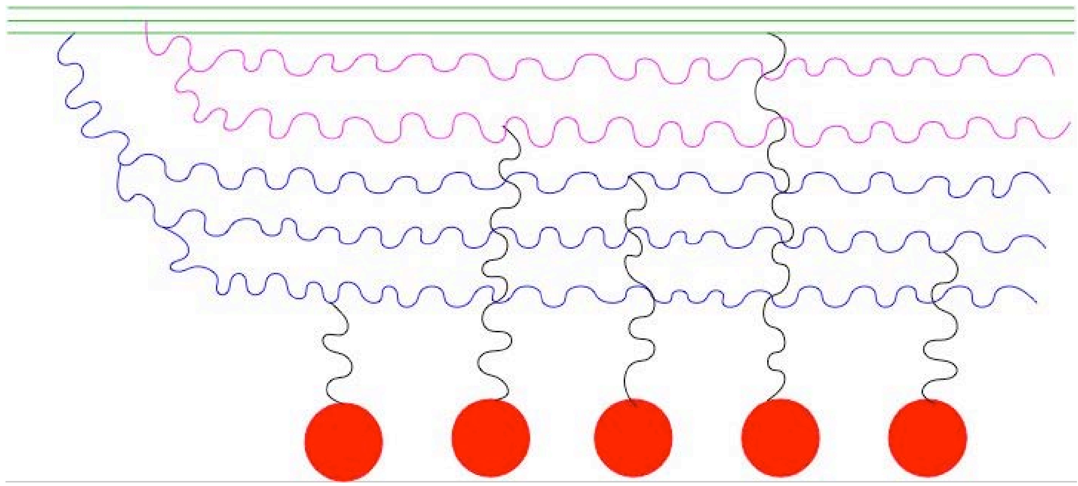


Geometric scaling

A.Stasto, K.Golec-Biernat, J.Kwiecinski

Levin, Tuchin;
Iancu, Itakura, McLerran;
Mueller, Triantafyllopoulos; …

Quantum evolution and hard processes on nuclei



DK, Levin, McLerran hep-ph/0210332;

DK, Kovchegov, Tuchin hep-ph/030737

Albacete et al hep-ph/0307179

1) Small x evolution leads to 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

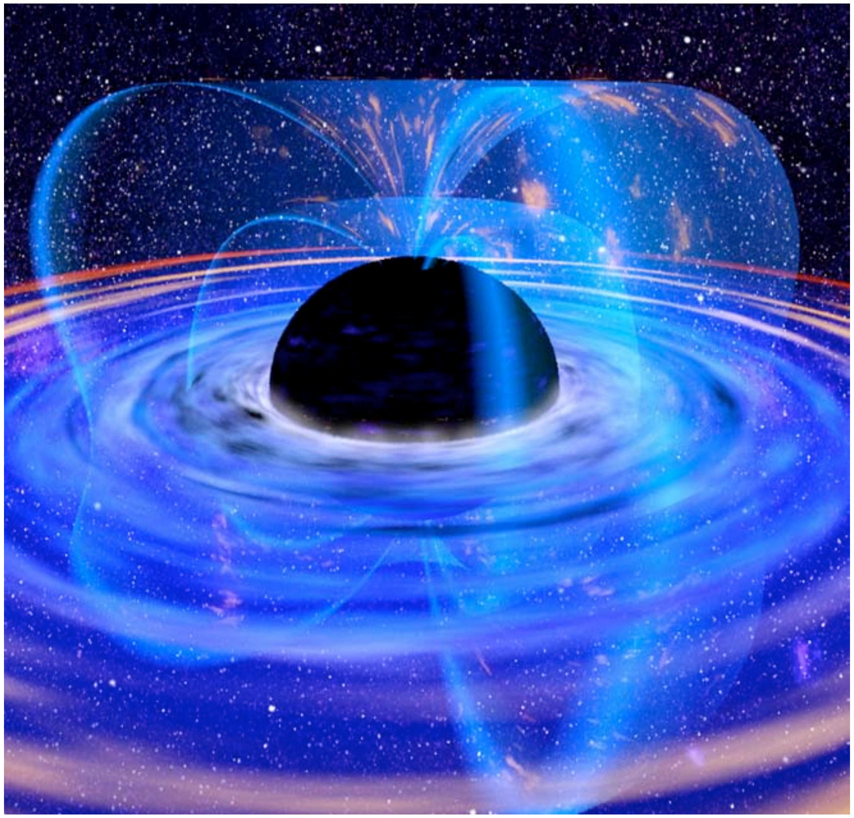
3) Since $Q_s^2 \sim A^{1/3}$ the A-dependence is changed

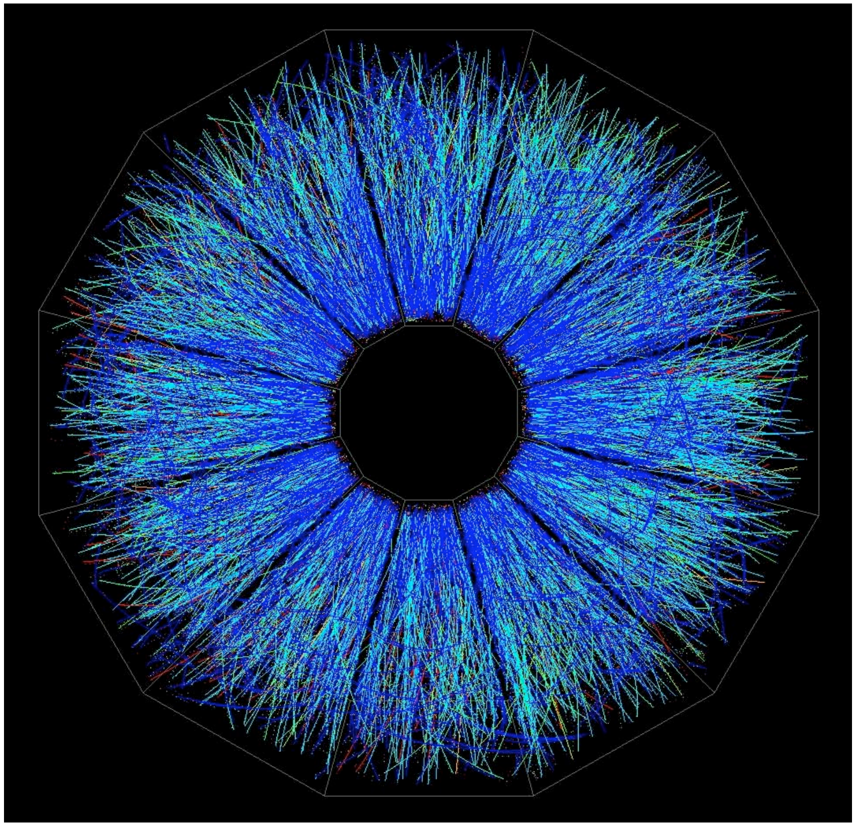
=>

Expect high p_T suppression in dAu at small x

Quantum fluctuations in the presence of classical background: from Hawking radiation to Color Glass Condensate

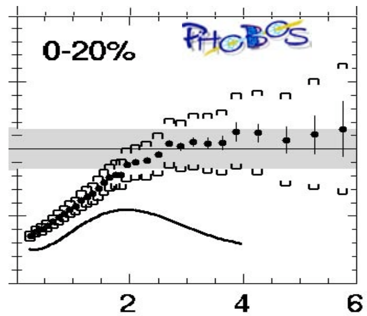
Hawking radiation

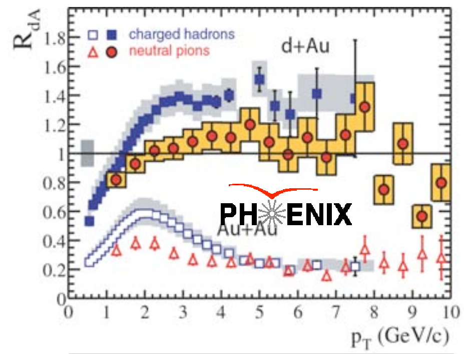


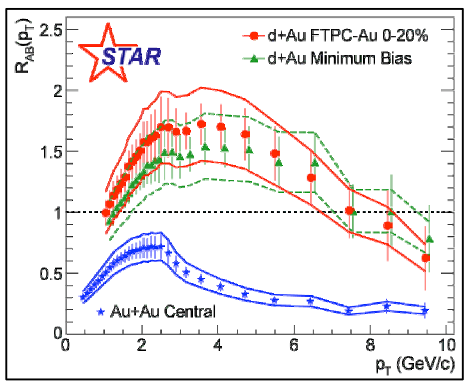


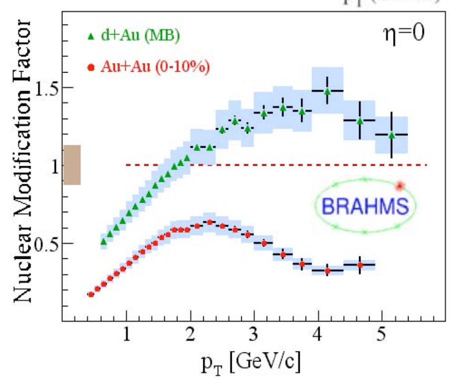
What do we still need to know?

d-Au experiments have shown that at y=0 the suppression of high p_T particles is a final-state effect:









I. can we <u>prove</u> that it is due to the radiative energy loss in sQGP?
several ideas; one of them is to use heavy quarks

Heavy quark colorimetry of QCD matter

Yu.Dokshitzer, DK
hep-ph/0106202

col·or·im·e·try *noun*
col·or·im·e·ter *noun* **:**
an instrument or device for determining and specifying colors; *specifically* **:** one used for chemical analysis by comparison of a liquid's color with standard colors

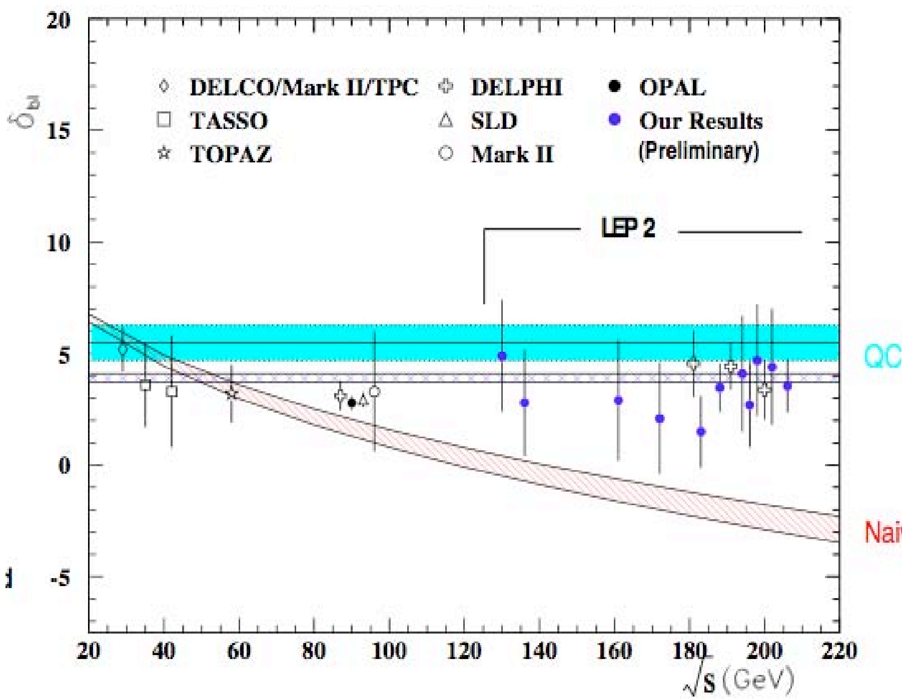
Merriam-Webster Dictionary

The propagation of heavy quarks in QCD matter is strongly affected by the interplay of the "dead cone" and LPM effects at energies up to

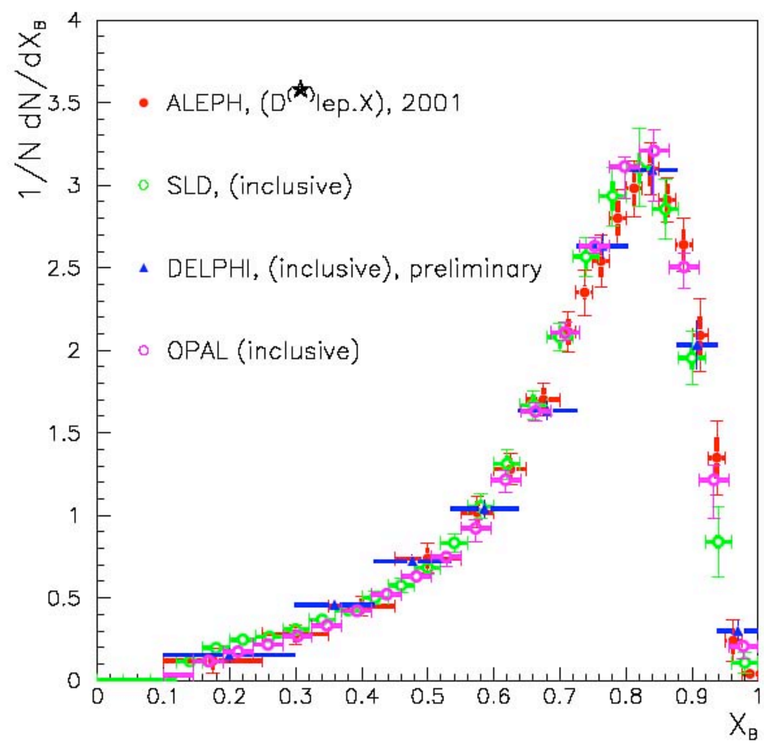
$$E \leq M\sqrt{\hat{q}L^3}$$

(a consequence of quantum mechanics & causality)

Heavy quarks fragment differently



OPAL Collaboration



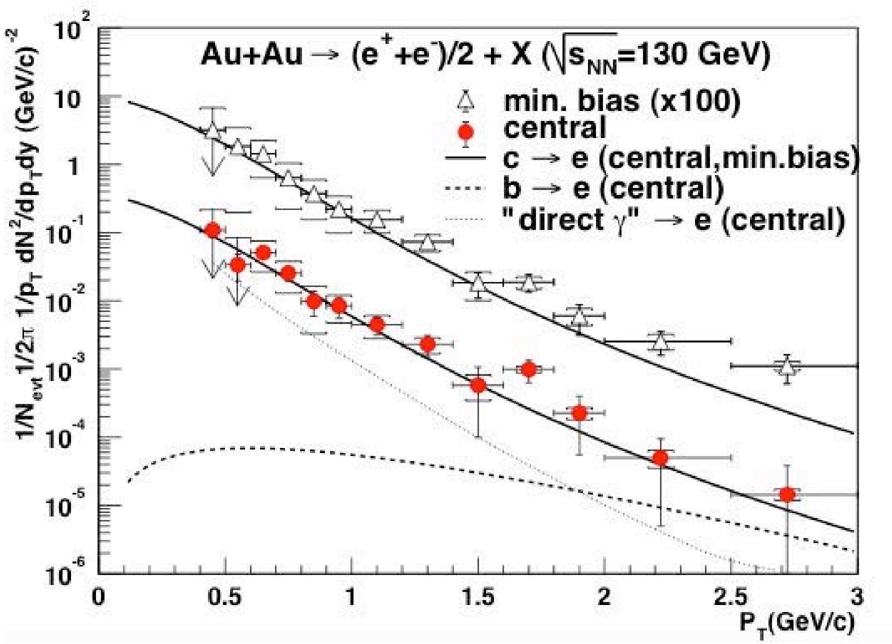
Heavy quarks produce a larger number of particles

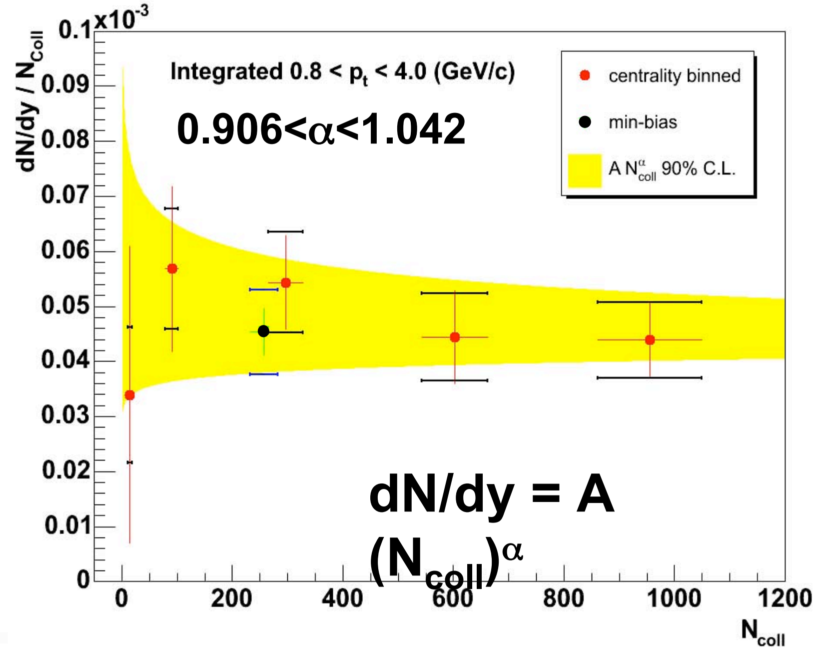
and carry a larger fraction of jet momentum

What do we still need to know?

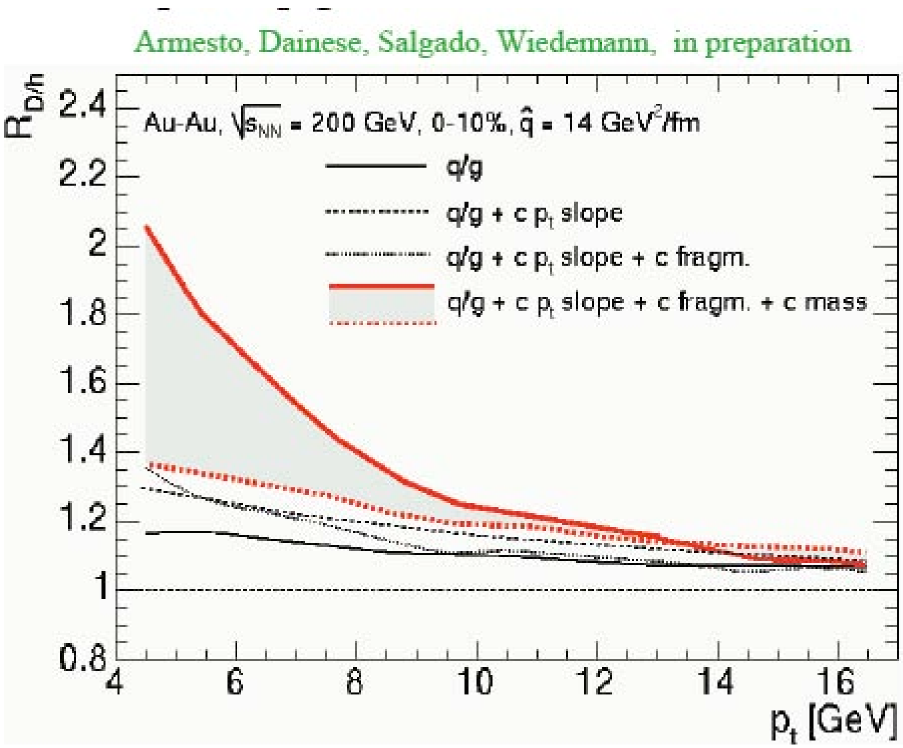
induced radiation should be suppressed for heavy quarks; is it?

Recent work:
M.Djordjevic, M.Gyulassy ‘03
B.Zhang, E.Wang, X.-N. Wang’04
N.Armesto, C.Salgado, U.Wiedemann’04



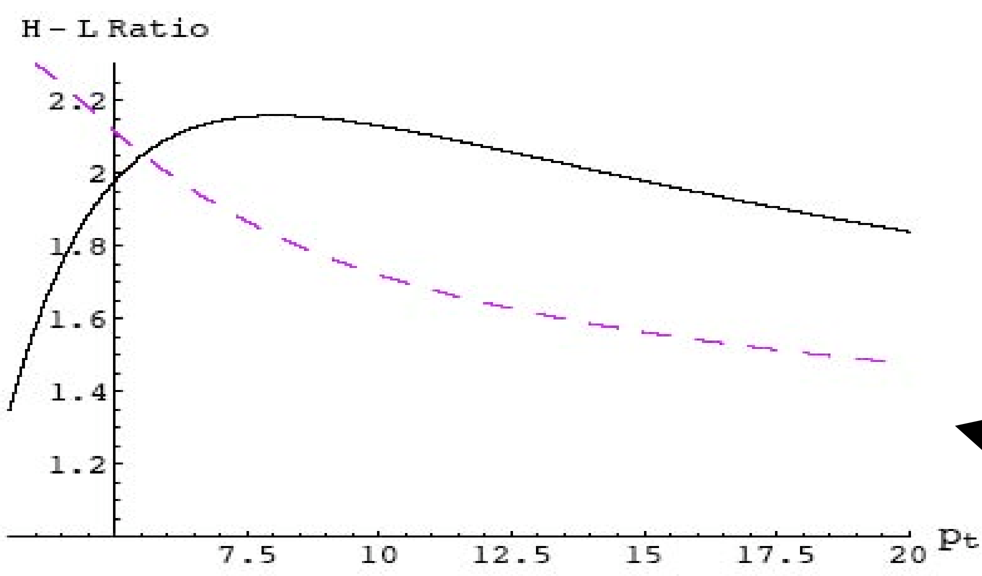


Data from PHENIX



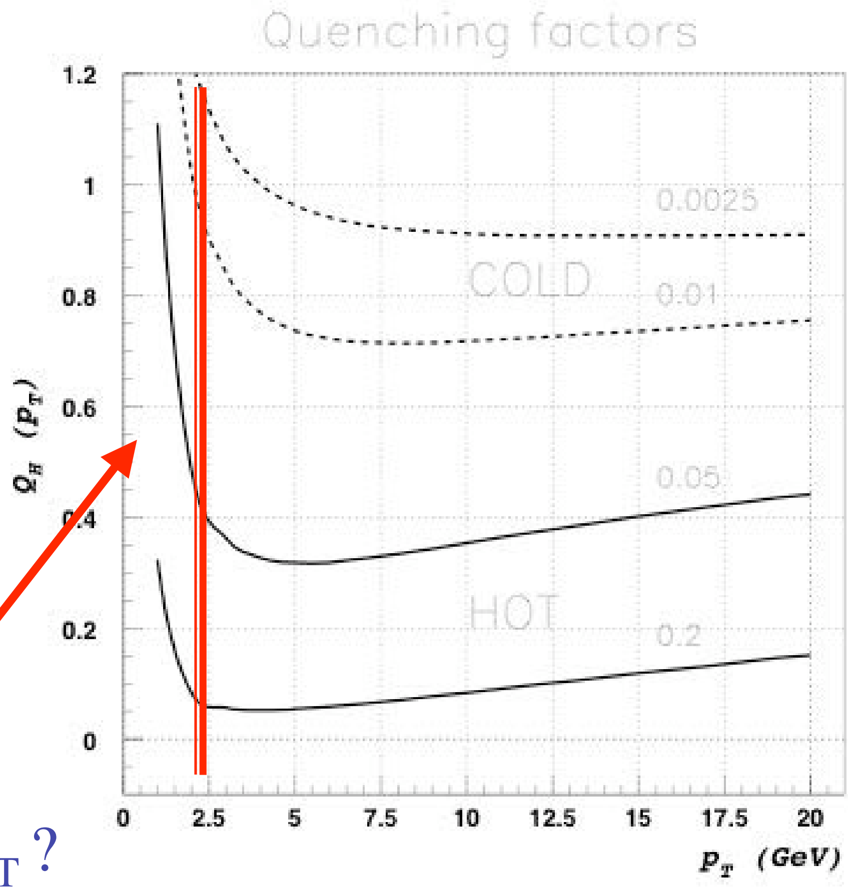
N.Armesto,
M. Djordjevic,
M. Gyulassy,
C.Salgado,
U. Wiedemann,
X.N. Wang, …

Enhancement of
the D/h ratio as
a signature of the radiative
energy loss in the QGP



Yu.L.Dokshitzer and DK,
Phys.Lett.B519 (2001) 199

AuAu collisions: charm quenching



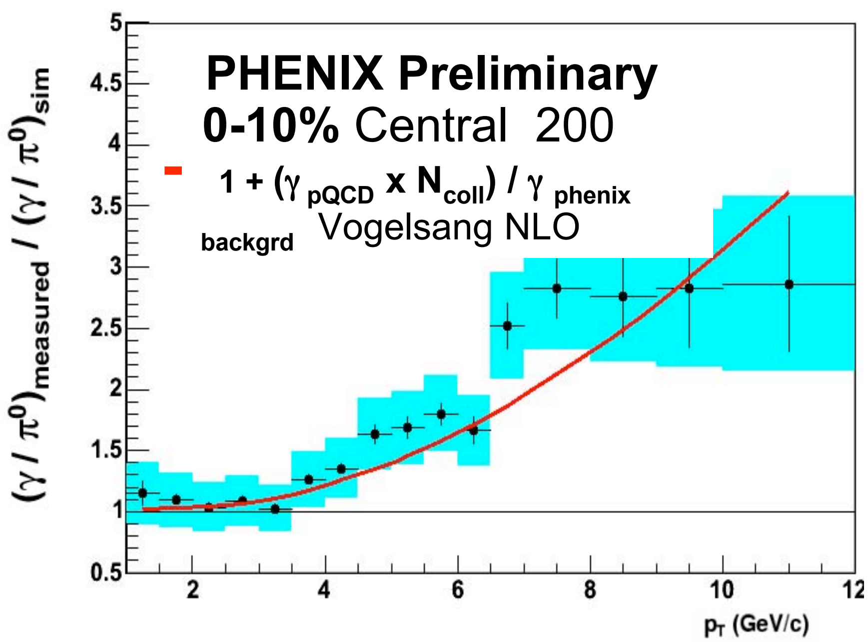
Heavy quark
flow at small p_T ?

DK & K. Tuchin, hep-ph/0310358

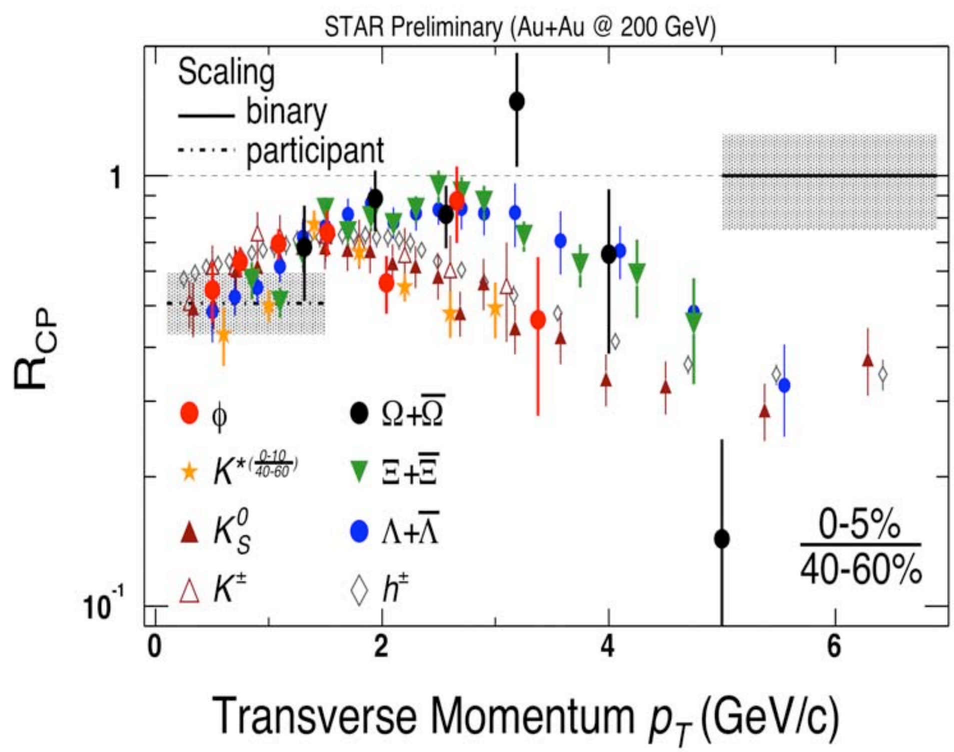
What do we still need to know?

II. can we prove that it is due to the radiative energy loss in sQGP?

Direct photons as a probe

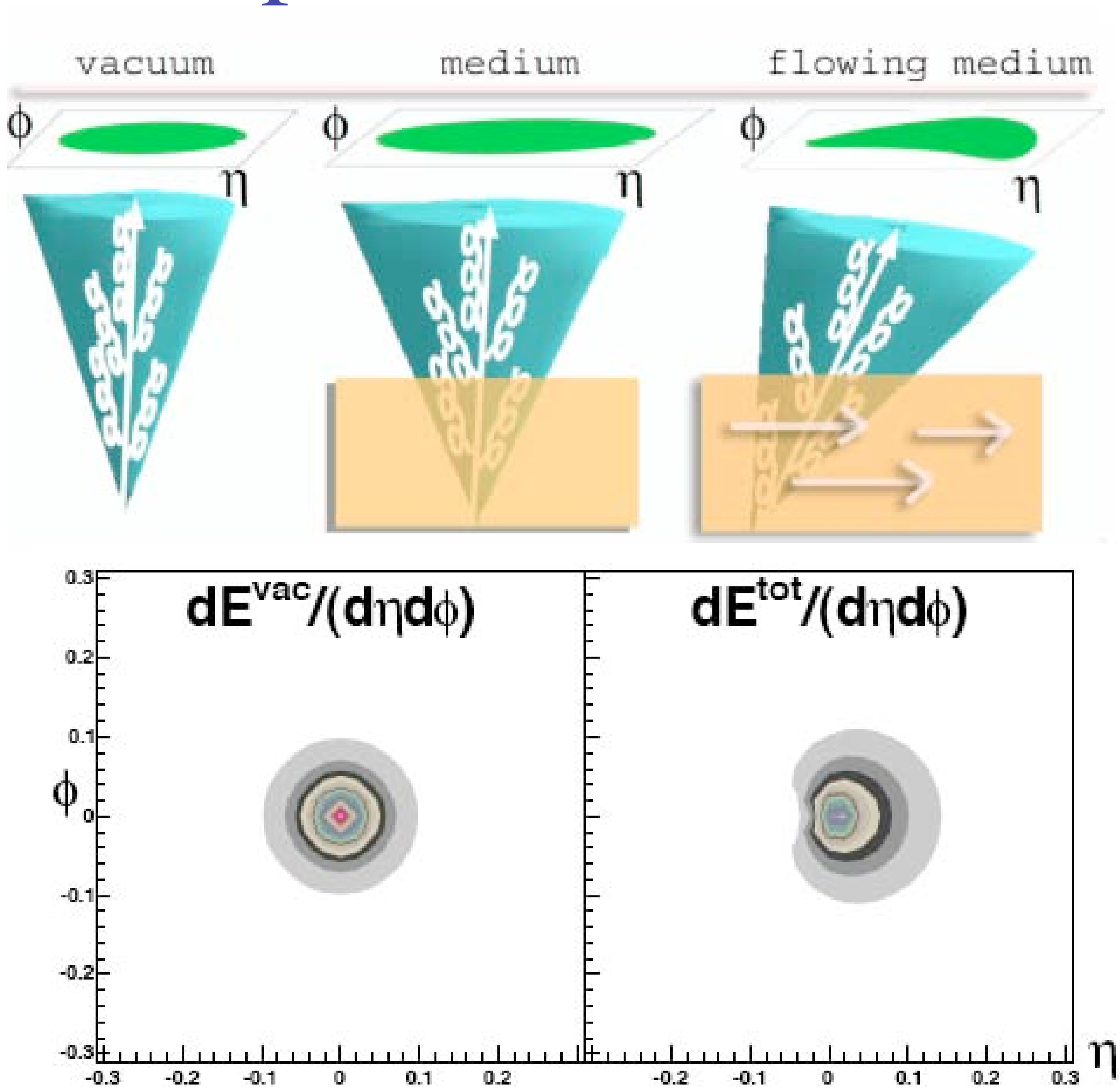


What is the origin of the "B/π puzzle"?



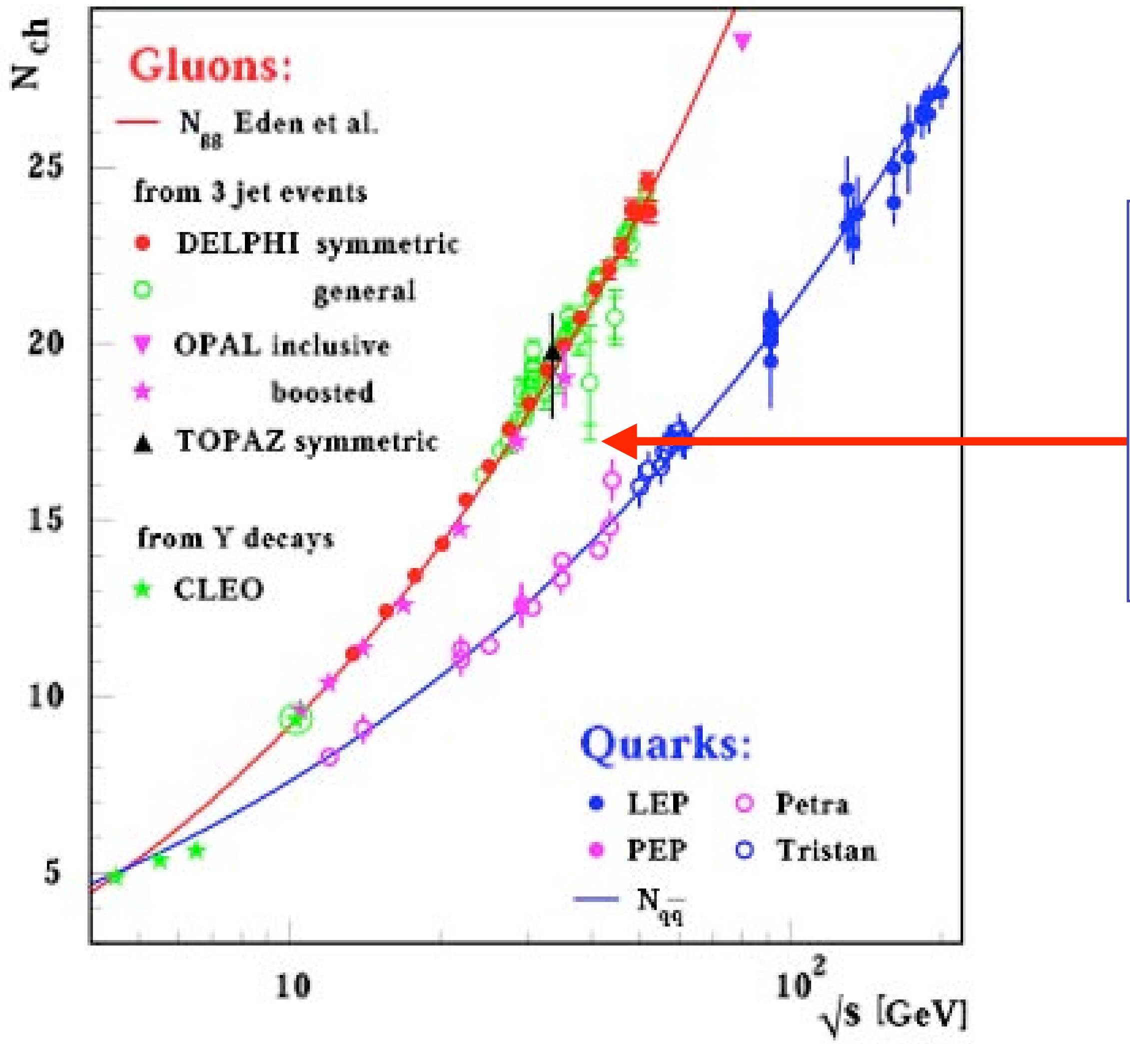
Might become possible with luminosity upgrade:

Jet shapes in Au-Au collisions??



N.Armesto,
U.Wiedemann

Quark and gluon jets are different



The difference in hadron multi-plicities becomes visible at large momenta

Tagging gluon jets e.g. by g->ccbar ?

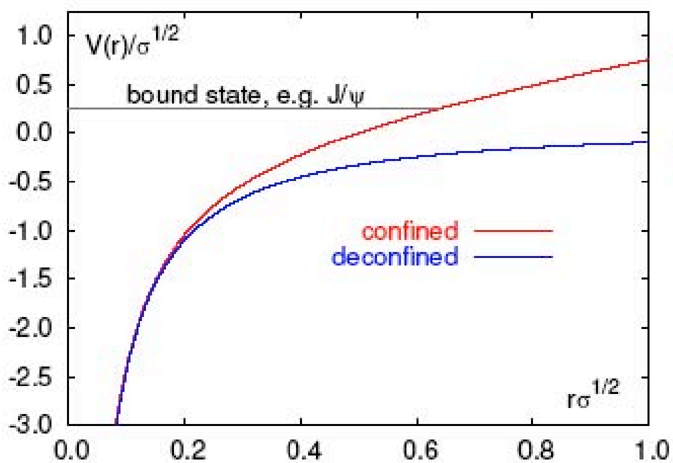
What do we still need to know?

II. Testing QGP with heavy quarkonia

The Matsui-Satz argument:

- deconfinement $\Rightarrow$ screening

  $\Rightarrow$ no heavy quark bound states in a QGP



$V_{\bar{q}q}(r,T) \rightarrow \infty$ confinement

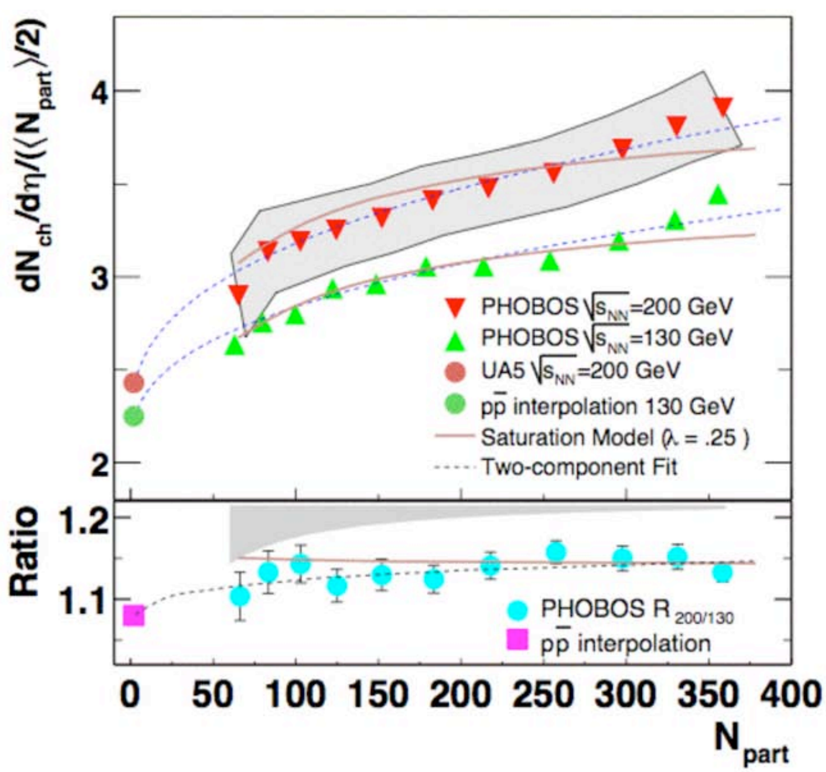
$V_{\bar{q}q}(r,T) < \infty$ deconfinement

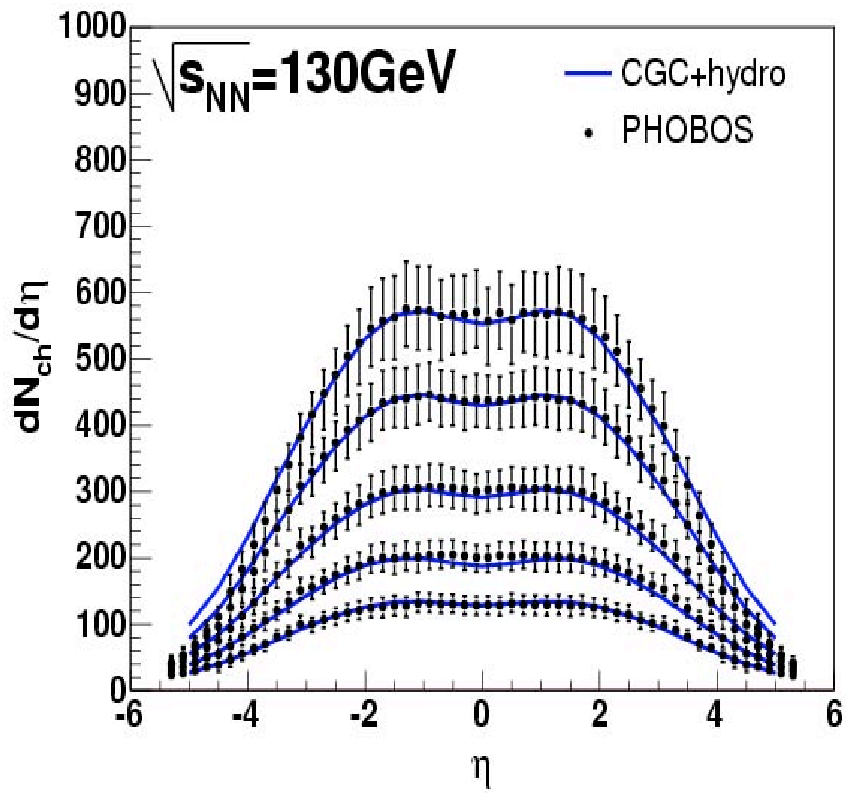
F.Karsch, P.Petreczky,…

the link between the observables and the McLerran-Svetitsky confinement criterion

What do we still need to know?

III. The data on hadron multiplicities in Au-Au and d-Au collisions support the Color Glass Condensate picture:

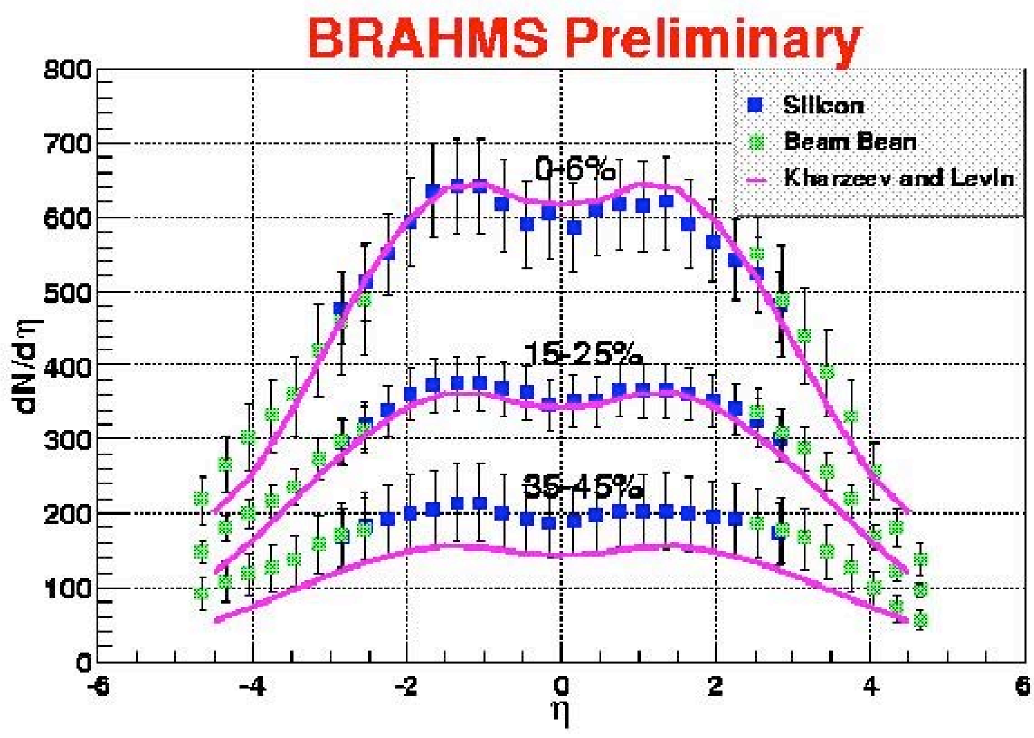


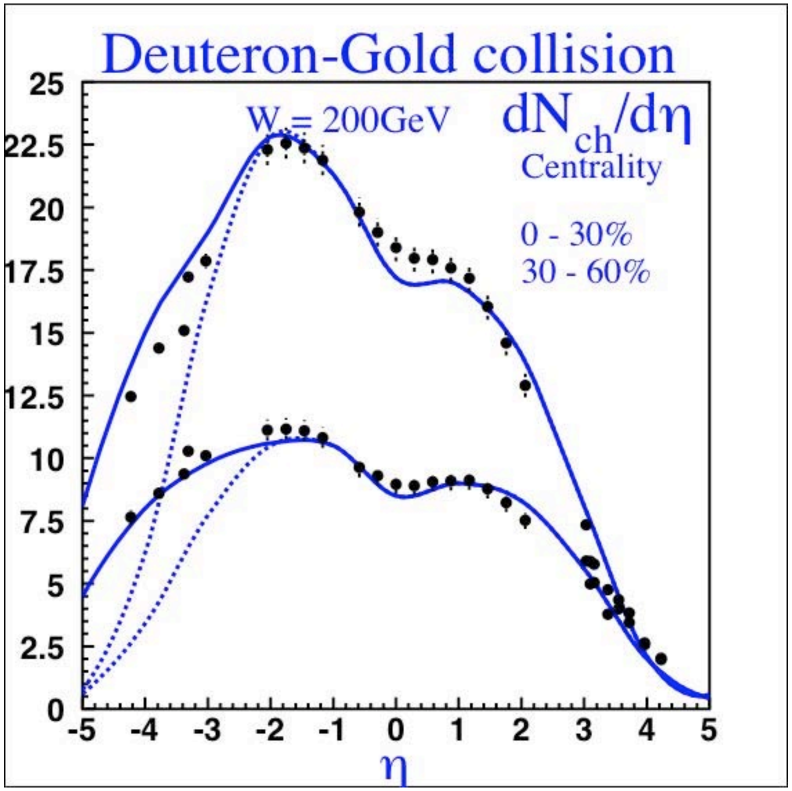


CGC+QGP: Hirano, Nara

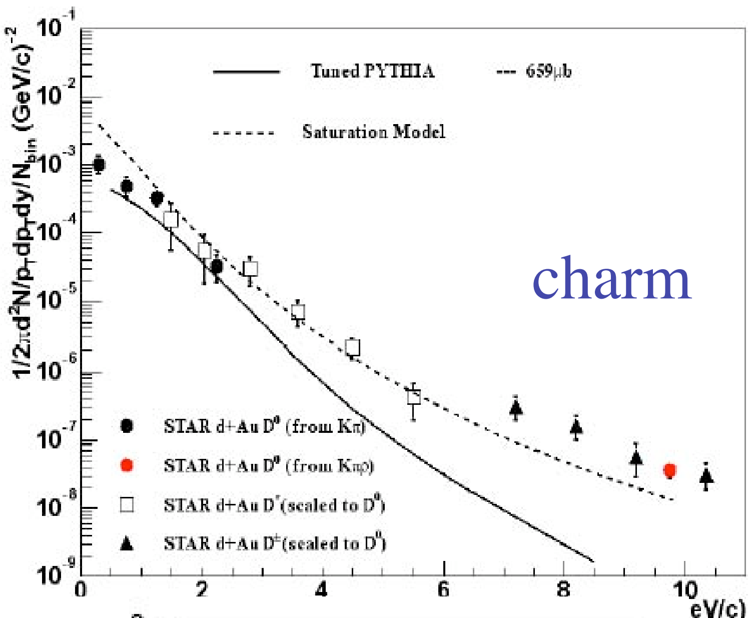
What do we still need to know?

III. The data on hadron multiplicities in Au-Au and d-Au collisions support the Color Glass Condensate picture:

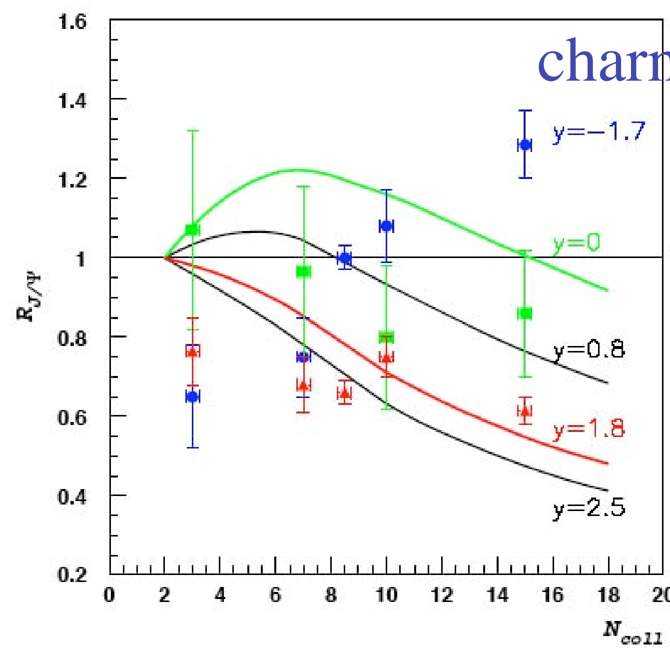




CGC confronts the data

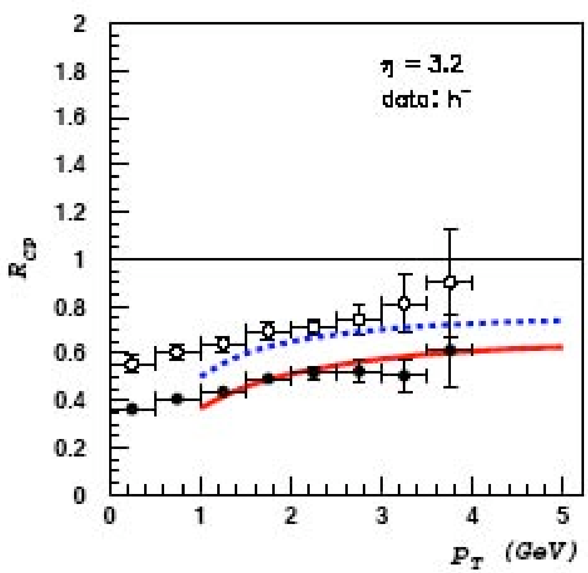


charm

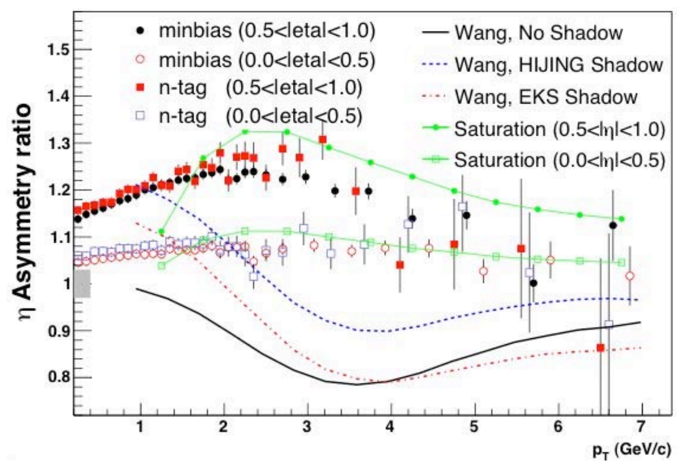


charmonium

K.Tuchin et al



hadrons



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

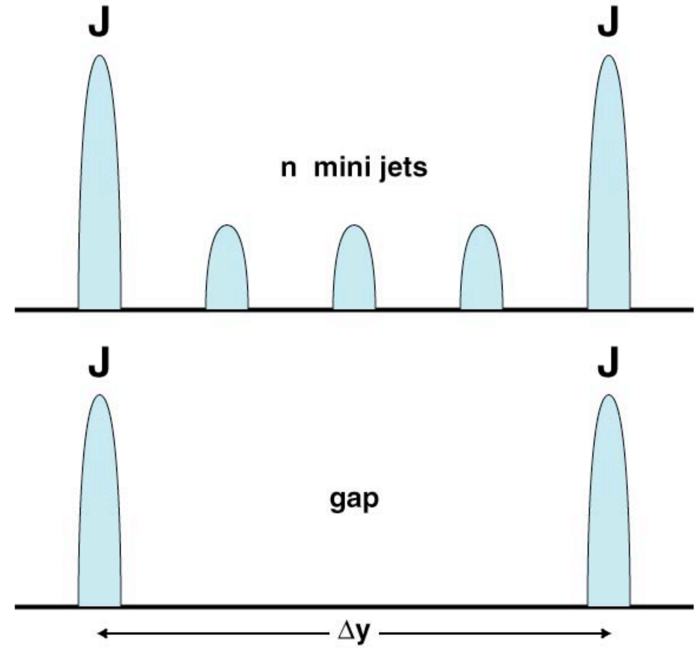
•Back-to-back correlations for jets separated by several units of rapidity are very sensitive to the evolution effects

A.H.Mueller,H.Navelet, '87

and to the presence of CGC

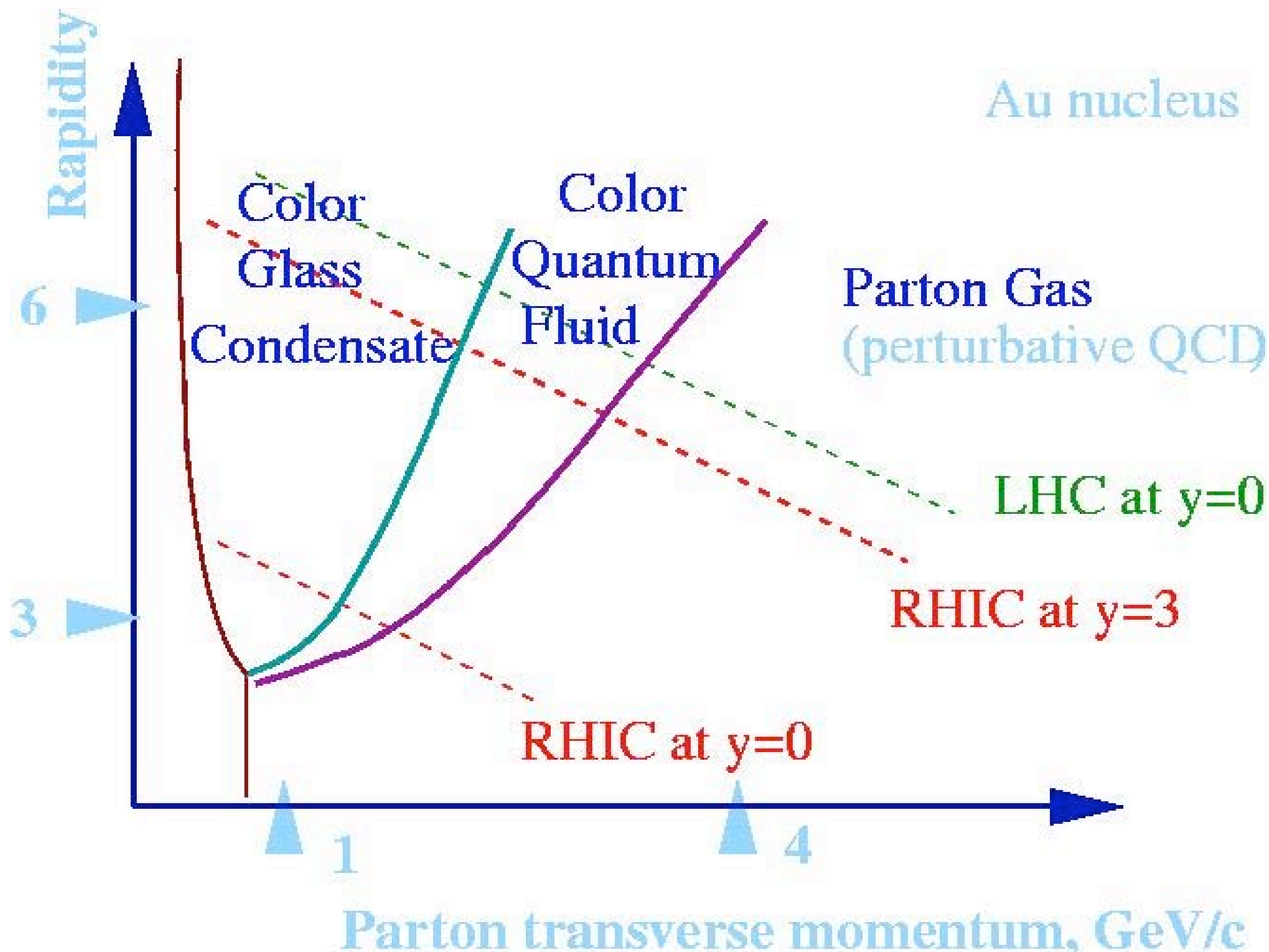
DK, E.Levin,L.McLerran, hep-ph/0403271;

Yu. Kovchegov, K. Tuchin, J. Jalilian-Marian,…

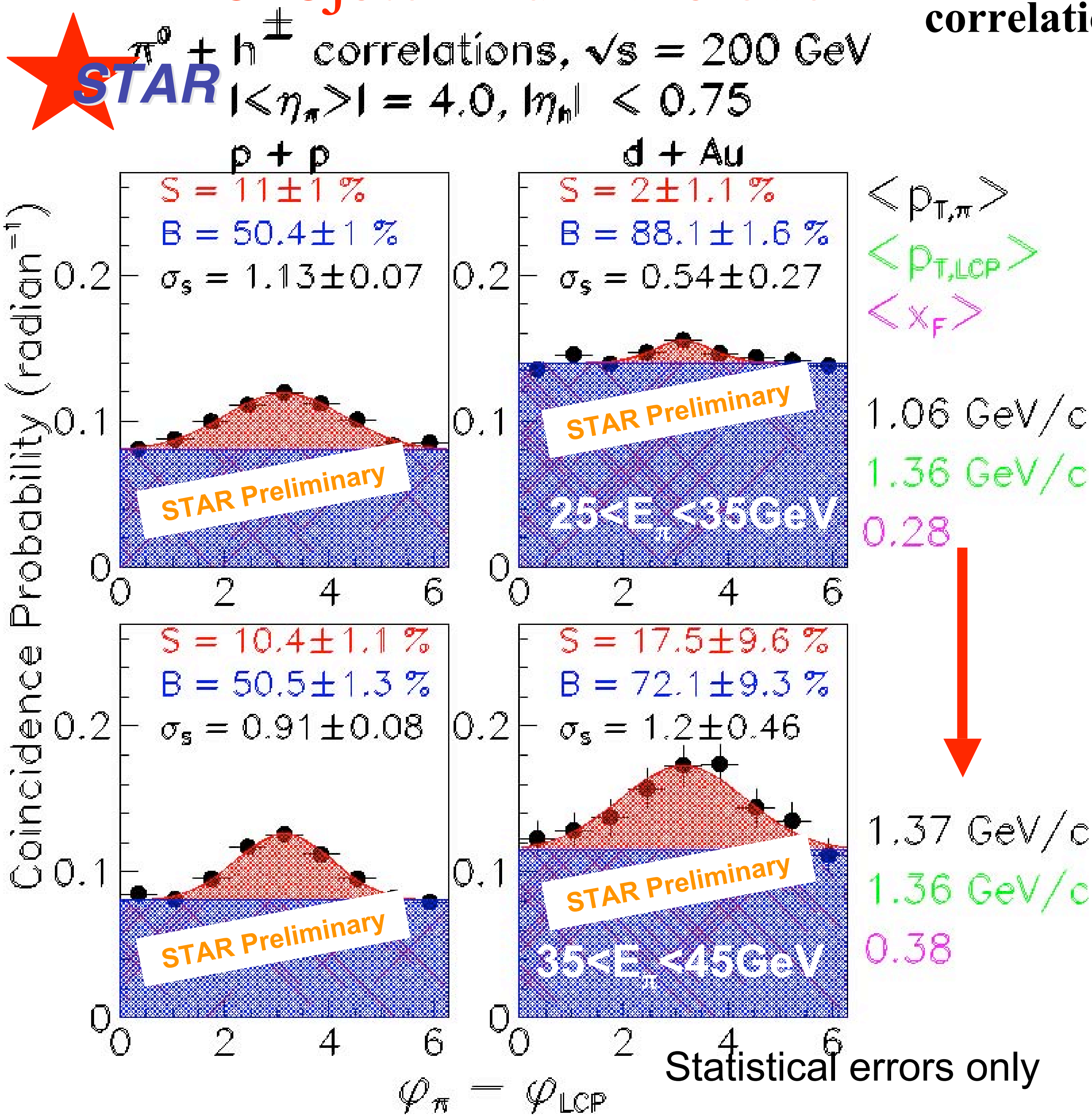


Recent results from STAR: L. Bland, A. Ogawa, G. Rakness, …
Talk at DIS'04

Phase diagram of high energy QCD



Monojets in dA are back

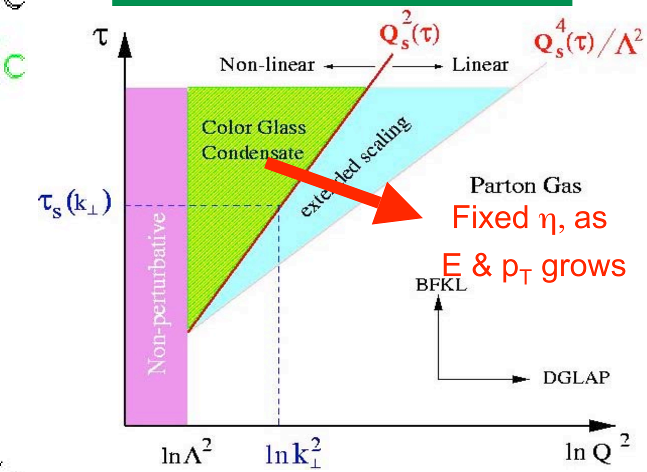


Large rapidity gap π^0+$h^\pm$ correlation data…

- **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) %

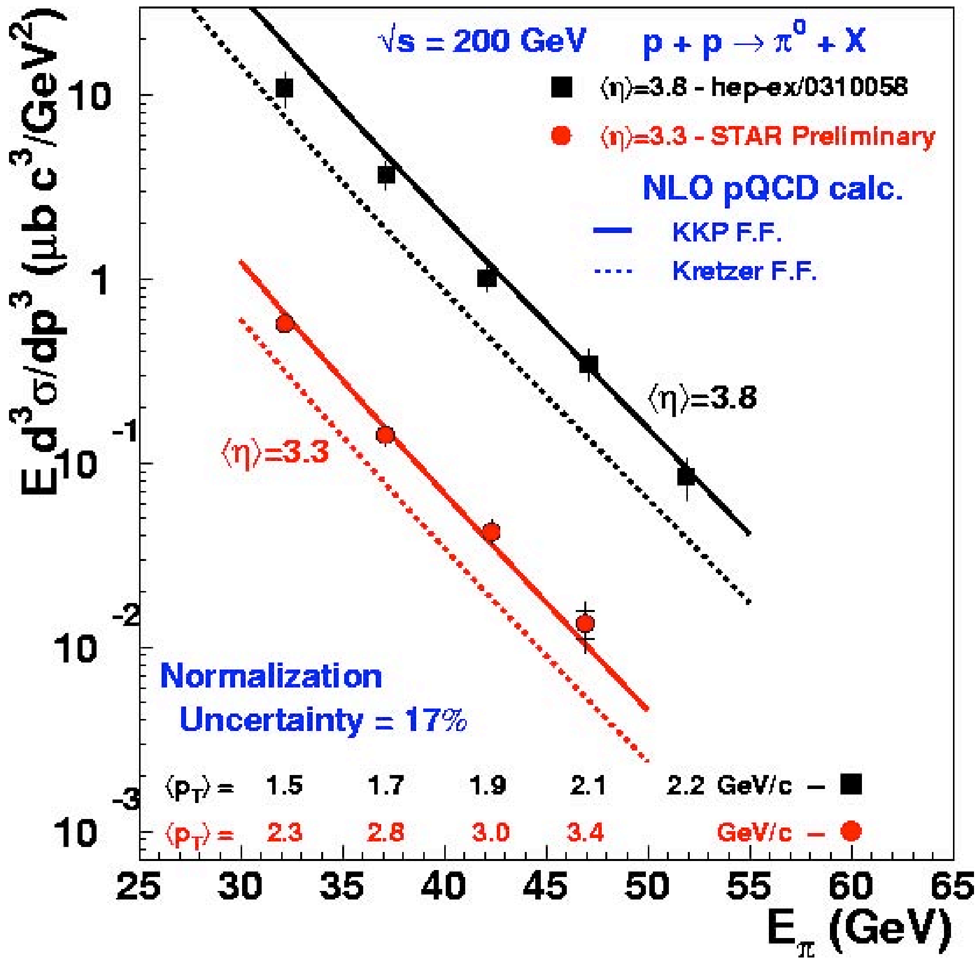
Consistent with CGC picture



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

as expected by HIJING

pQCD works in forward pp



STAR data

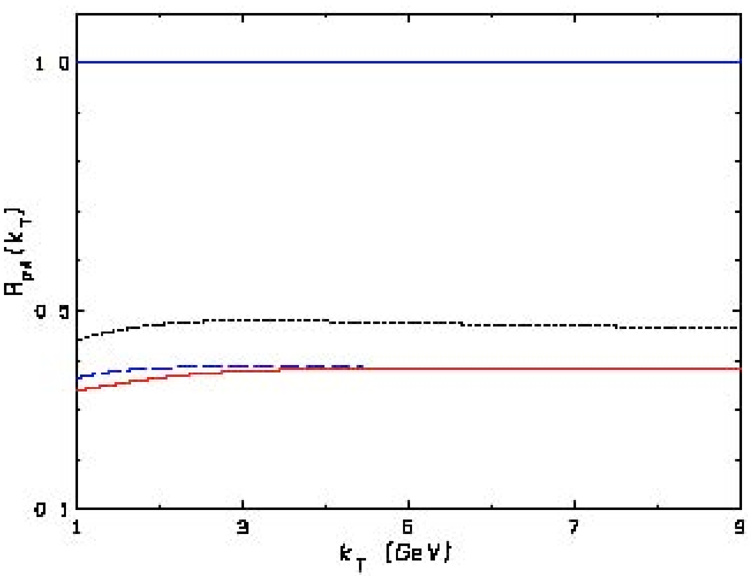
NLO pQCD:
W.Vogelsang

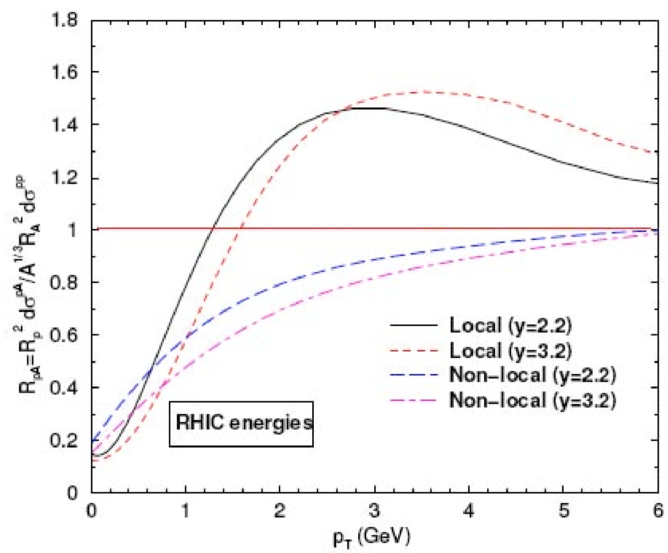
Are the effects observed at forward rapidity due to parton saturation in the CGC?

- Open charm, dileptons, photons in the forward region

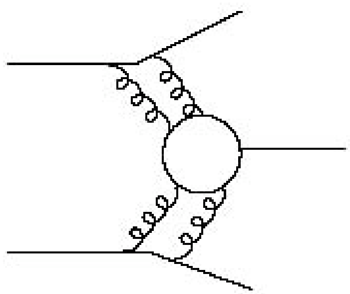
DK, K.Tuchin, hep-ph/0310..

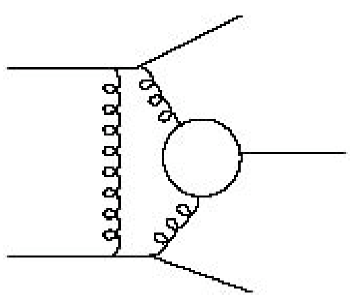
R.Baier,A.H.Mueller,D.Schiff, hep-ph/0403201;
J.Jalilian-Marian, F. Gelis,
R. Venugopalan, B. Gay Ducati,…



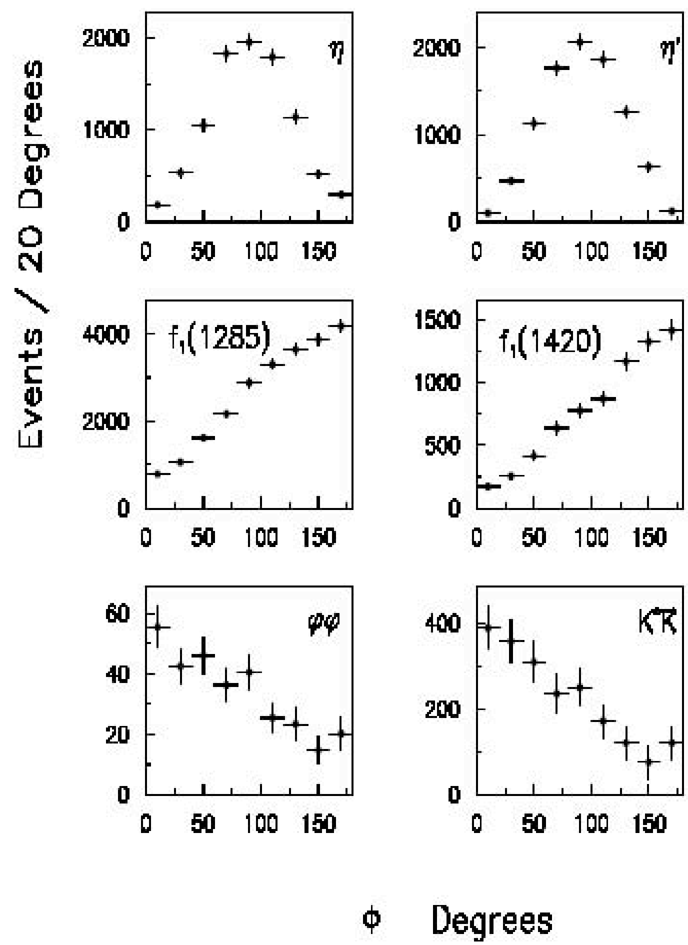


Double diffractive production: probing the gluon clouds at large distances





From J.Ellis, DK hep-ph/9811222



From A.Kirk et al, WA102 Coll, hep-ph/9810221

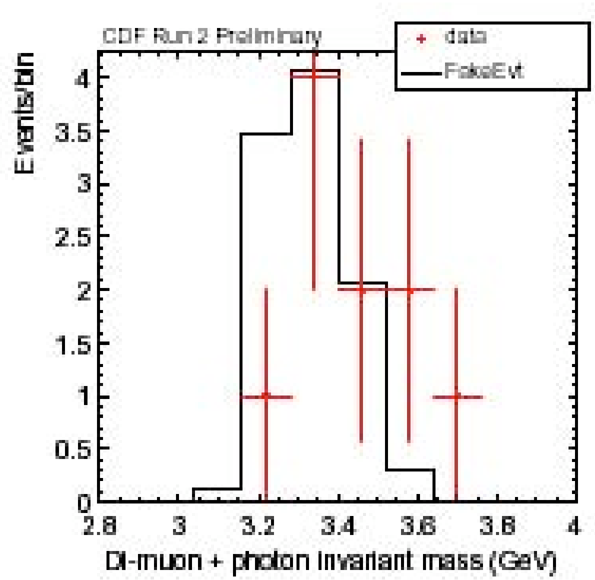
Double diffractive production: probing the gluon clouds at large distances

One example:

pp -> χ_c pp

Experimental bound
at SPS energy;
WA102: $\sigma < 2$ nb
hep-ex/0006005

observed at Tevatron?



M.Albrow

Diffractive studies at RHICII?

theoretical prediction:
600 - 700 nb

Khoze, Martin, Ryskin; Yuan

What has to be done?

To characterize the properties of the Quark Gluon Plasma, and to explore the Color Glass Condensate, we need to

Study hard processes in a wide range of rapidity and transverse momentum, with identified particles

(RHIC, RHIC II, LHC, eRHIC)

heavy quark jets; jet (jet + γ, …) azimuthal correlations at large Δ y; heavy quarkonia; dileptons at high p_T; direct photons and HBT; diffraction; …