Heavy quarks in QCD matter: history and the future

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Heavy quarks do matter in QCD

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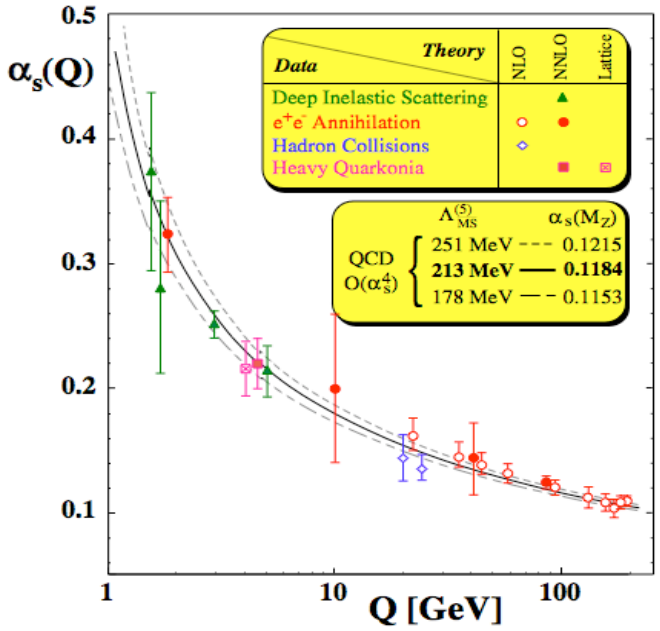
Why heavy quarks?

Heavy quark masses M_H are generated at the electroweak scale, and are external parameters in QCD;

Heavy quarks are "heavy" because their masses are large on the typical QCD scale of Λ_{QCD}:

$$M_H >> \Lambda_{QCD}$$



$$\alpha_s(M_H) \ll 1$$

$$\frac{\langle \alpha_s G^2 \rangle}{M_H^4} \ll 1$$

Production of heavy quarks

The production of heavy quarks is reasonably well described by pQCD methods
(not without problems, though…): reviews by M. Cacciari,
J. Qiu,
W. Vogelsang

The description of quarkonium production is much more difficult

reviews by G. Bodwin,
R. Vogt

Why heavy quarks?

QCD matter is characterized by dimensionful parameters: saturation scale Q_S, density, transport coefficient $\hat{q}$, …

$$M_H \leftrightarrow Q_s,\ Q_s^2/\Lambda_{\rm QCD},\ \rho^{1/3},\ T,\ \sqrt{\hat{q}L},...$$

depending on their values, “heavy” quarks can behave either as heavy or as light !

⇒Use heavy quarks to extract information about the properties of QCD matter

Why heavy quarkonia? (I)

Heavy quarkonia are characterized by the size

$$R \sim \frac{1}{\alpha_s \; M_H}$$

and the binding energy

$$\epsilon \sim \alpha_s^2 \; M_H$$

Even though $M_H >> \Lambda_{QCD}$, the inverse radius and the binding energy are not large enough to justify an entirely perturbative treatment even for bottomonium; Heavy quakonia are thus a valuable source of knowledge about non-perturbative QCD

(… and a source of trouble for the models aimed at describing their production mechanisms …)

Why heavy quarkonia? (II)

Heavy quarkonia are very sensitive to the properties of QCD matter; when Debye length becomes smaller than the size of quarkonium,

$$R_{Debye}(T) \sim 1/(gT) < R_{Quarkonium} \sim 1 / (\alpha_s M_H),$$

quarkonia are screened out of existence T. Matsui & H. Satz '86
this happens when $T \sim g M_H$

(what is the corresponding formula for strong coupling?)

However, even before that, when $T \sim \varepsilon \sim \alpha_s^2 M_H$,
quarkonia will be dissociated due to thermal activation

Why heavy quarkonia? (III)

In cold matter, dissociation rate is relatively small due to the softness of gluon distributions in confined matter, but it is large, O(1 fm^{-1}), in hot QCD matter

DK & H. Satz '94

Dissociation mechanism - gluo-effect

E.Shuryak '78
G.Bhanot, M.Peskin '79

dominates if $\frac{\epsilon}{T} \gg 1$ (strong coupling regime)

Screening dominates if $\frac{\epsilon}{T} \ll 1$ (weak coupling)

Can one use also the survived quarkonia for the diagnostics?

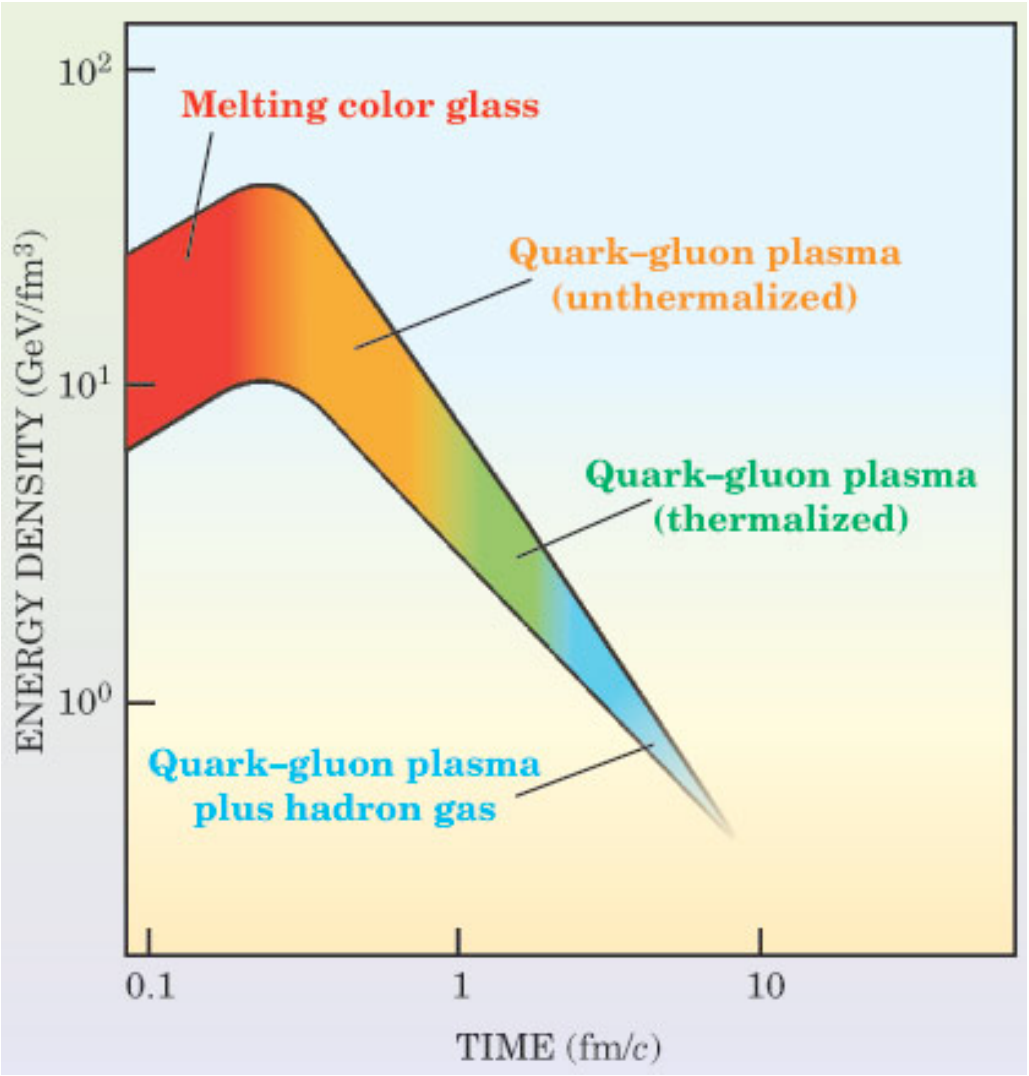
Yes, perhaps - pQCD predicts transverse polarization for J/ψ; Experimentally, it is not true due to non-perturbative, long-distance contributions.

If indeed $R_{Debye}(T) < R_{Quarkonium}$, pQCD predictions may be vindicated:

$W(\theta) \sim 1 + \alpha \cos^2\theta$, $\alpha = 0.3 - 0.4$

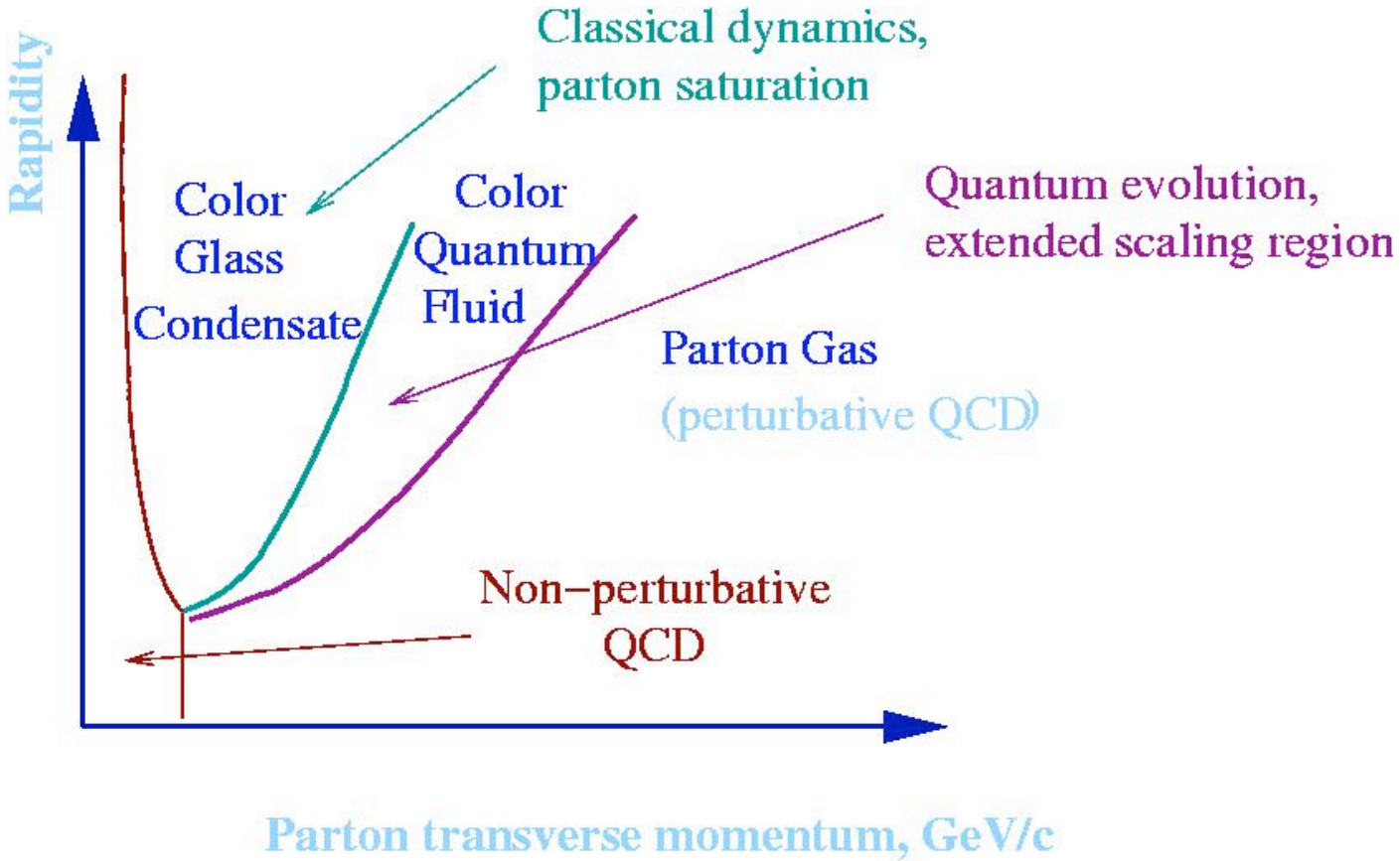
B.L. Ioffe & DK hep-ph/0306176

Time evolution in heavy ion collisions

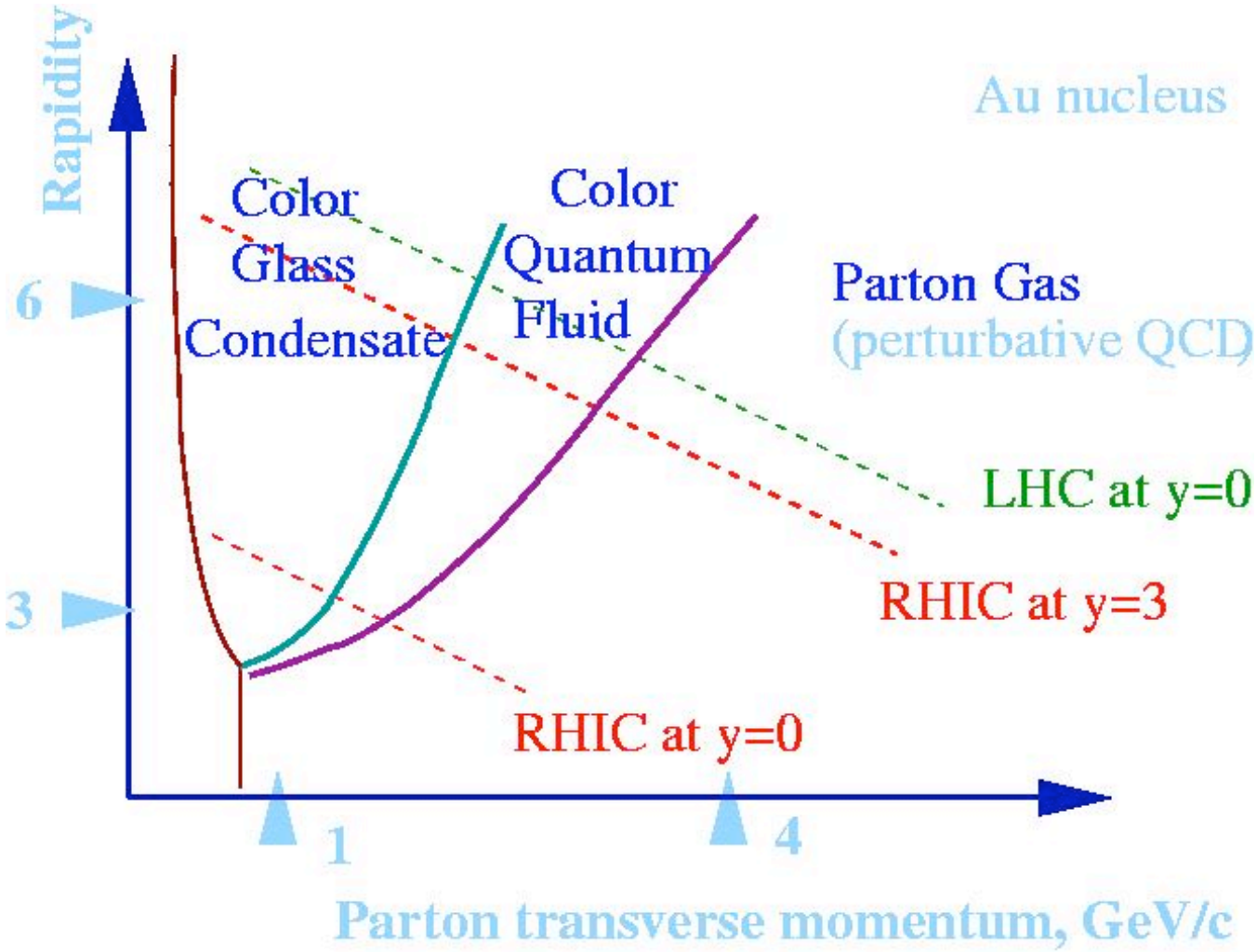


T. Ludlam,
L. McLerran,
Physics Today
October 2003

The phase diagram of high energy QCD



Phase diagram of high energy QCD



Heavy quarks and the Color Glass Condensate

Talk by R.Venugopalan

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

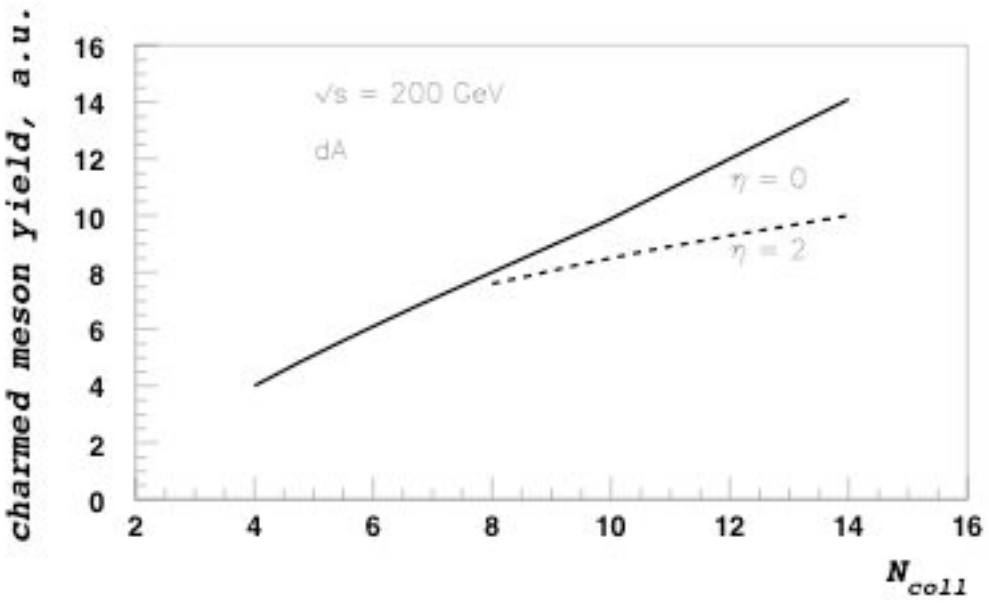
In addition, even when

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

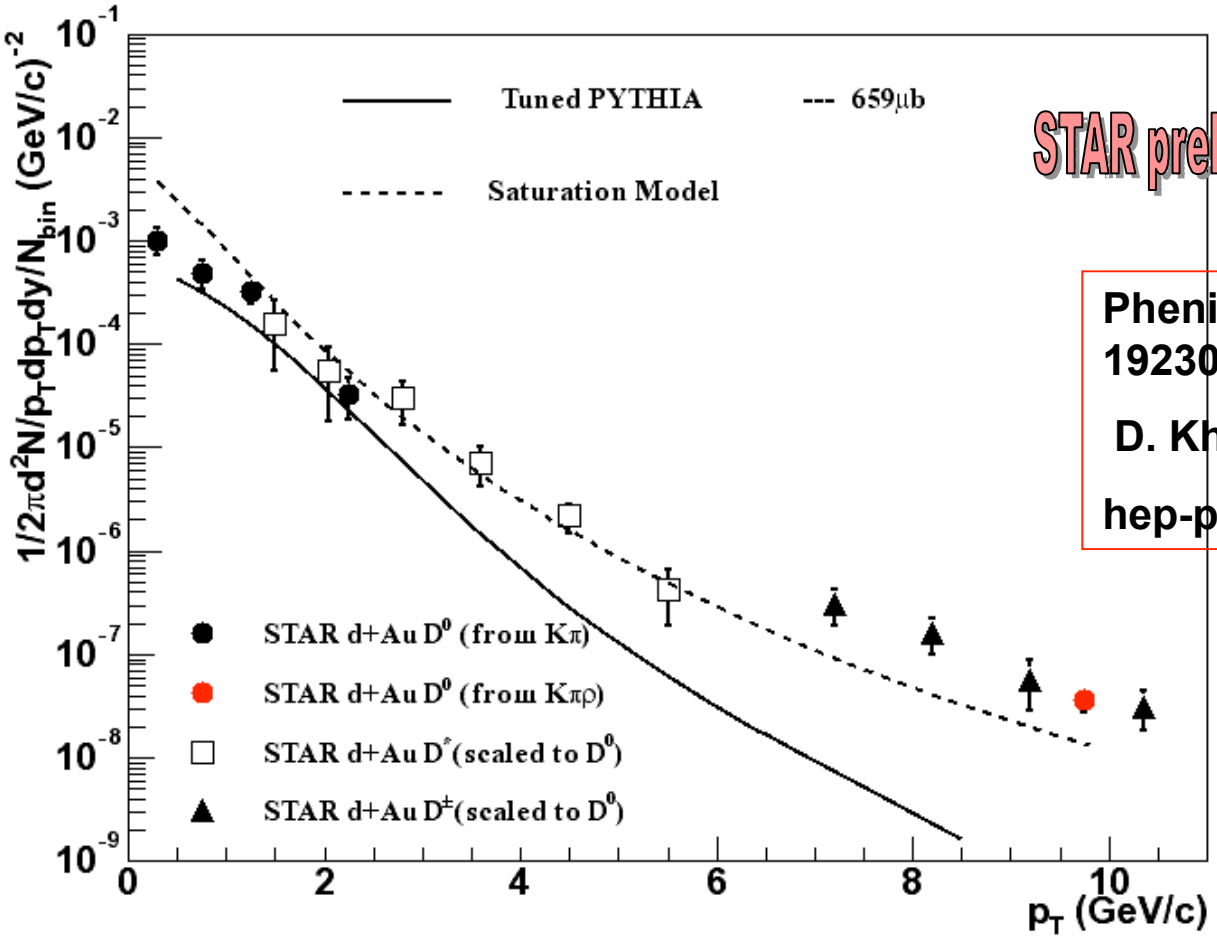
the production of heavy quarks is significantly
affected by the presence of the CGC,
similarly to what happens in the case of high Pt production
at forward rapidities

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

The results: dAu collisions



Open charm spectrum is hard !



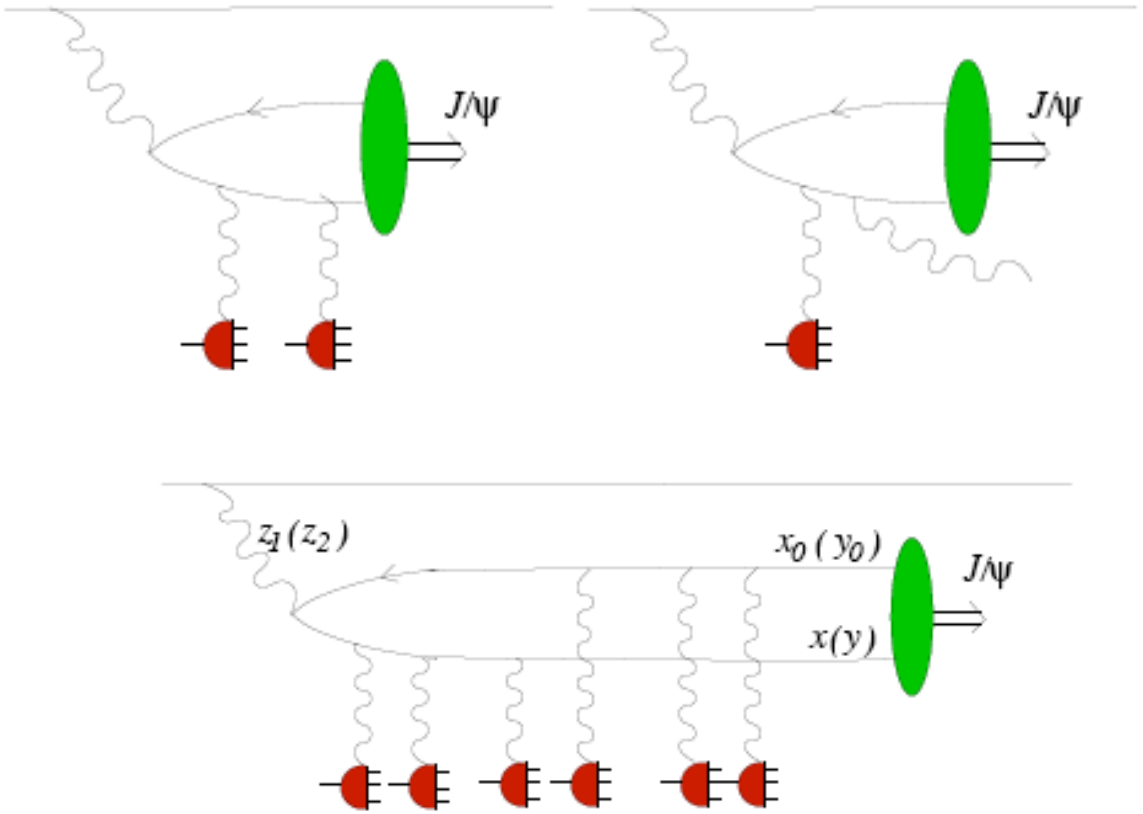
Phenix: Phys. Rev. Lett. 88, 192303(2002)

D. Kharzeev & K. Tuchin,

hep-ph/0310358

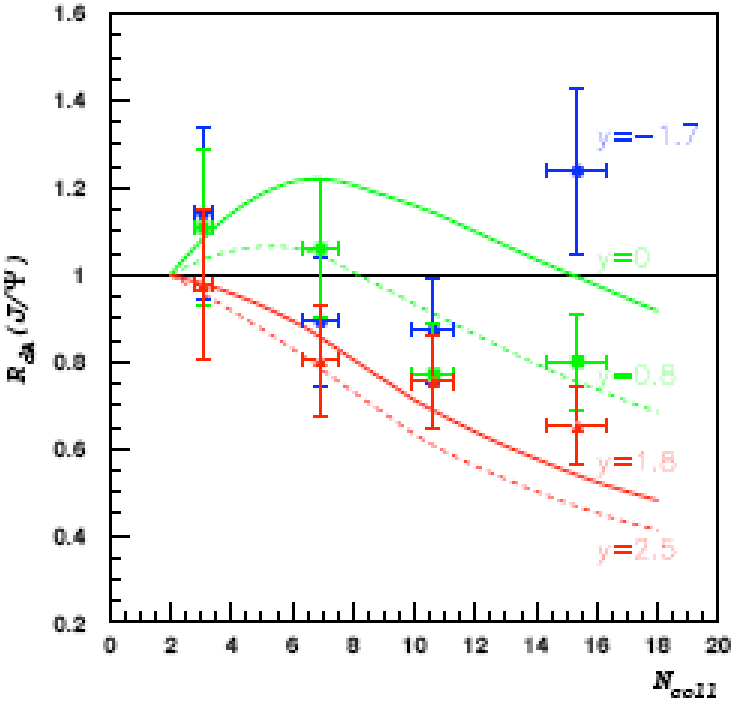
An Tai, STAR, QM'04

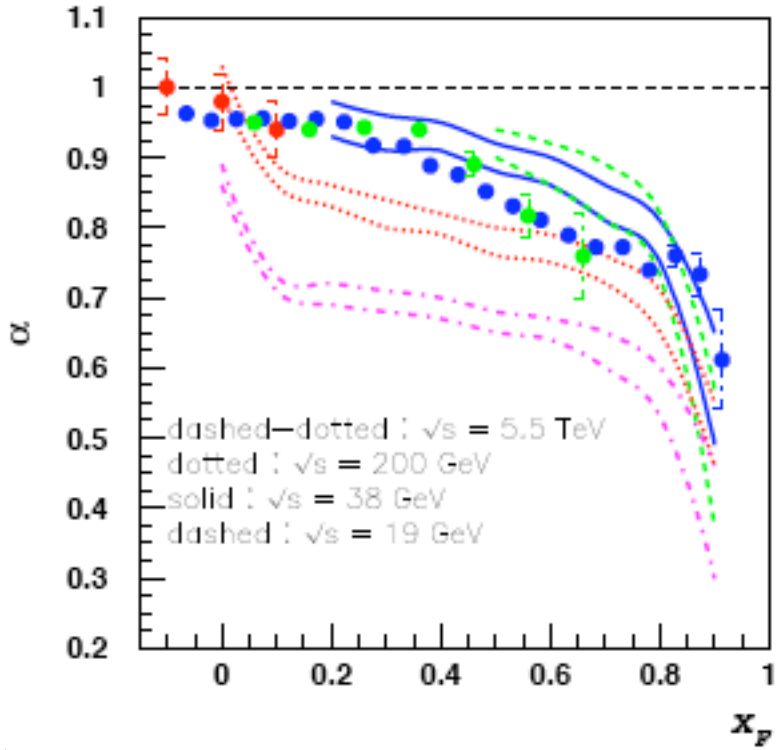
J/Ψ production in the Color Glass Condensate



J/Ψ production in the Color Glass Condensate

"x_F scaling"

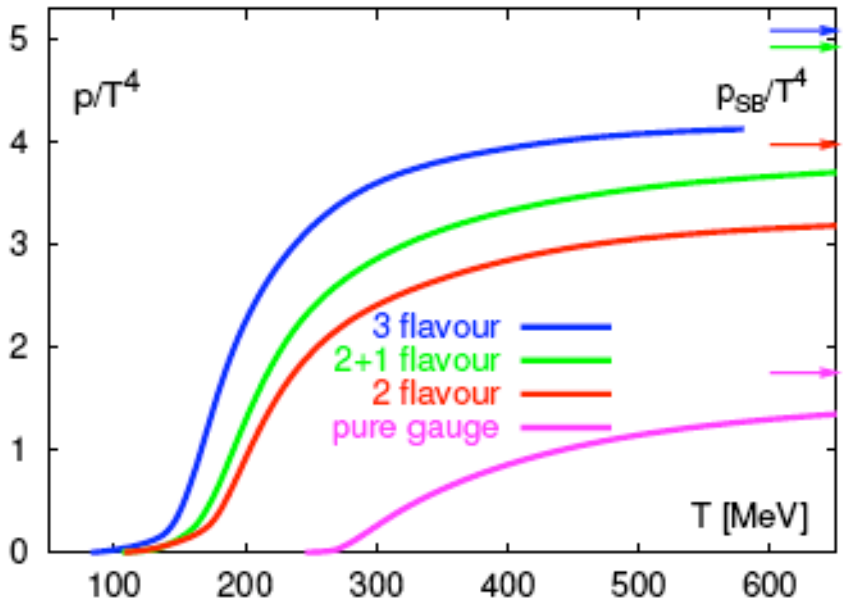




Data: PHENIX Coll., nucl-ex/0507032

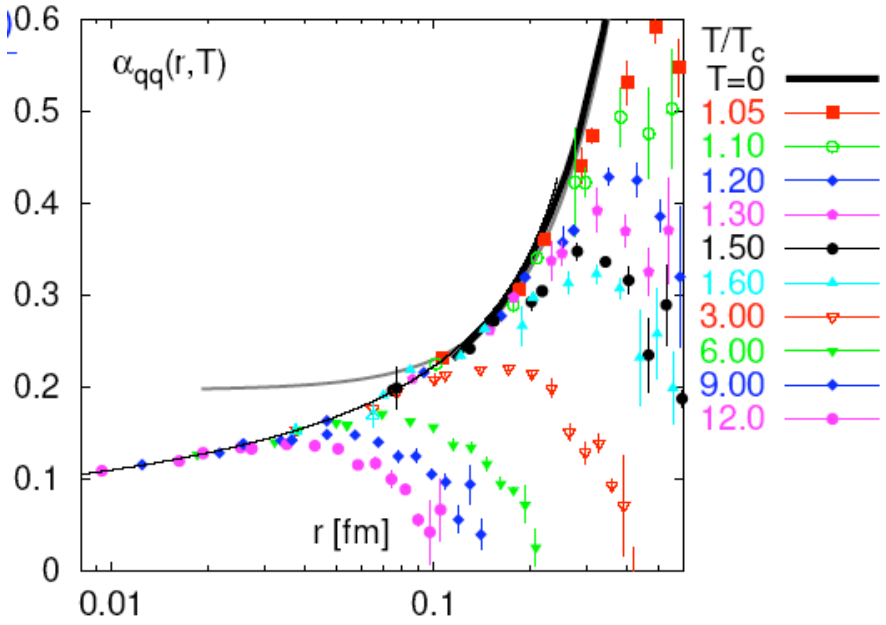
DK, K.Tuchin, hep-ph/0510358

Strongly coupled QGP



F.Karsch et al

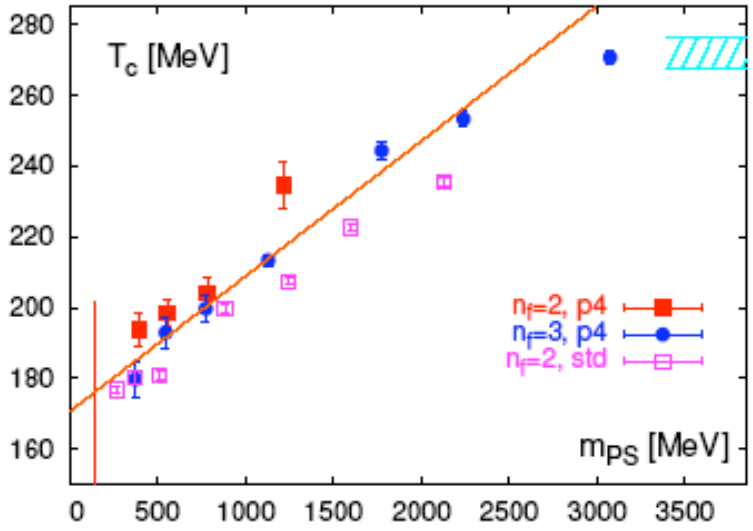
$$\epsilon \neq 3P$$



T-dependence of
the running coupling
develops in the NP-region
at $T < 3\ T_c$

sQGP

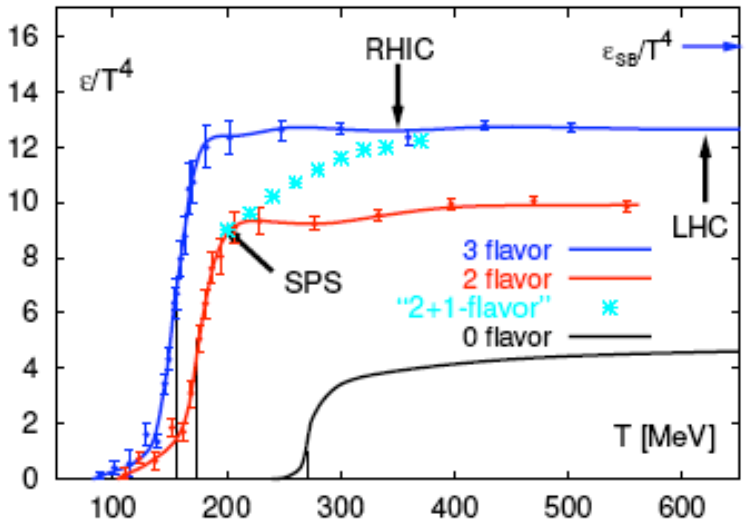
F.Karsch, P.Petreczky, …



$m_{PS} \simeq 140\ MeV: \quad T_c \simeq 175\ MeV$

$m_{GB} \simeq 1.5\ GeV: \quad T_c \simeq 265\ MeV$
$(m_{PS} = \infty)$

lightest masses apparently do not control the transition

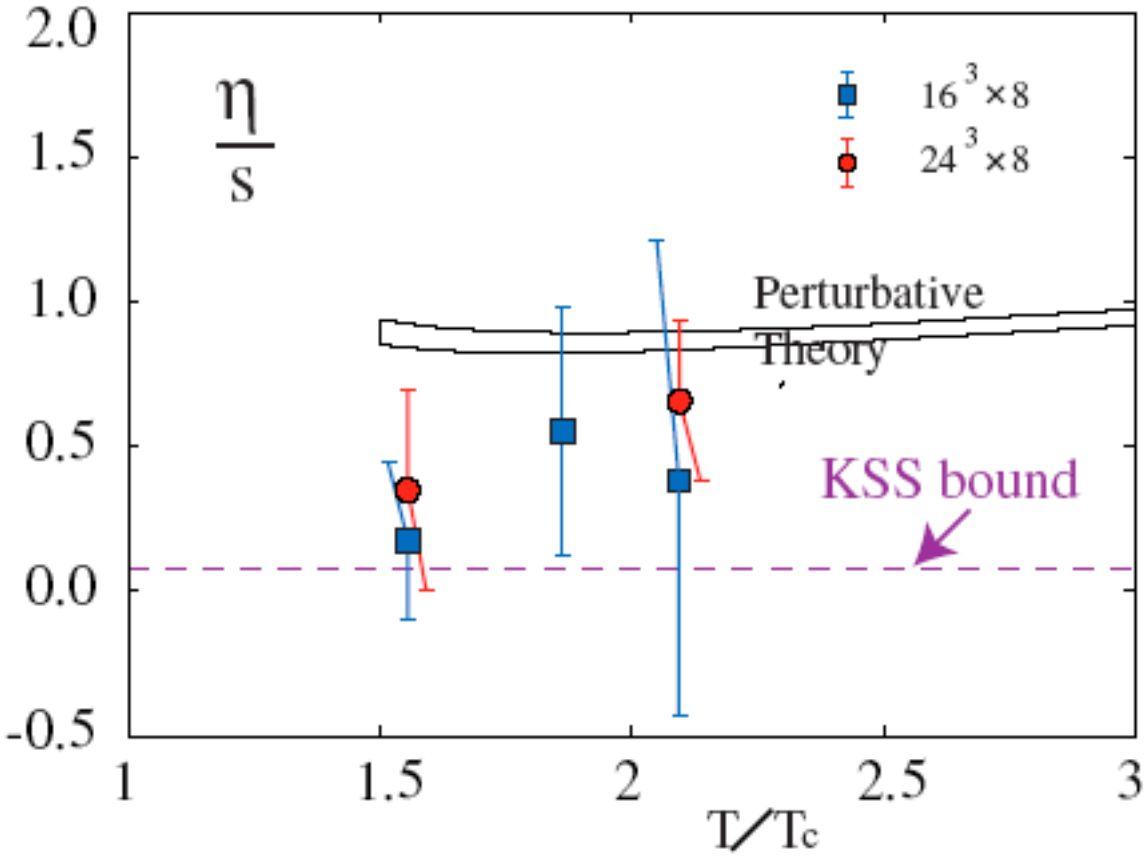


$n_f = 2: \quad \epsilon_c \simeq (6 \pm 2)\ T_c^4$
$\simeq (0.3 - 1.3)\ GeV/fm^3$

$n_f = 0: \quad \epsilon_c \simeq (0.5 - 1)\ T_c^4$
$\simeq (0.3 - 0.7)\ GeV/fm^3$

change in ϵ_c/T_c^4 compensated by shift in T_c
transition sets in at similar energy (or parton) densities $\Rightarrow$ percolation

sQGP: more fluid than water?

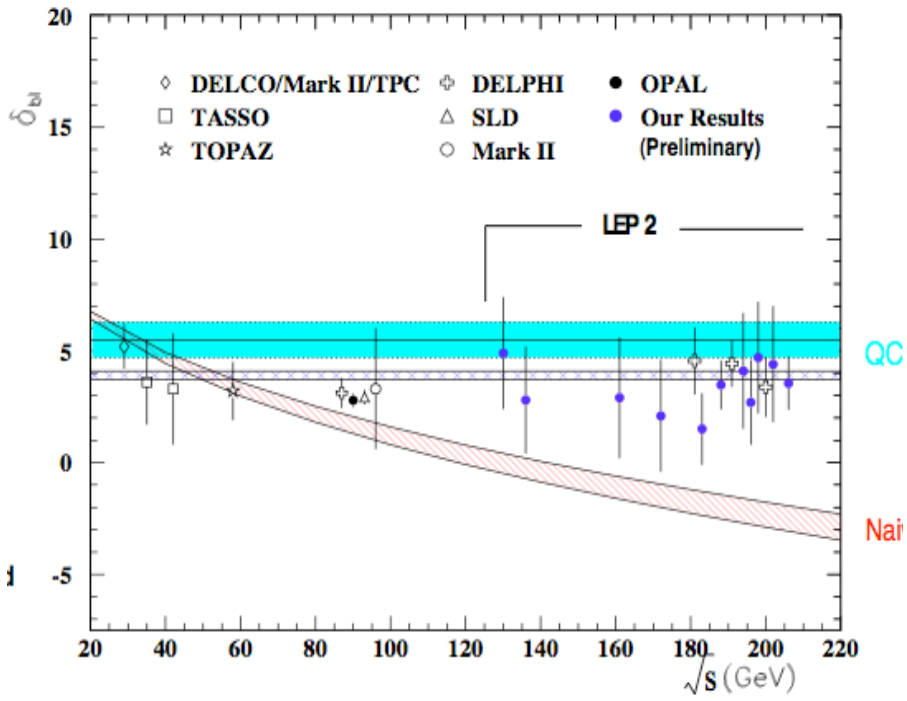


Perfect fluid

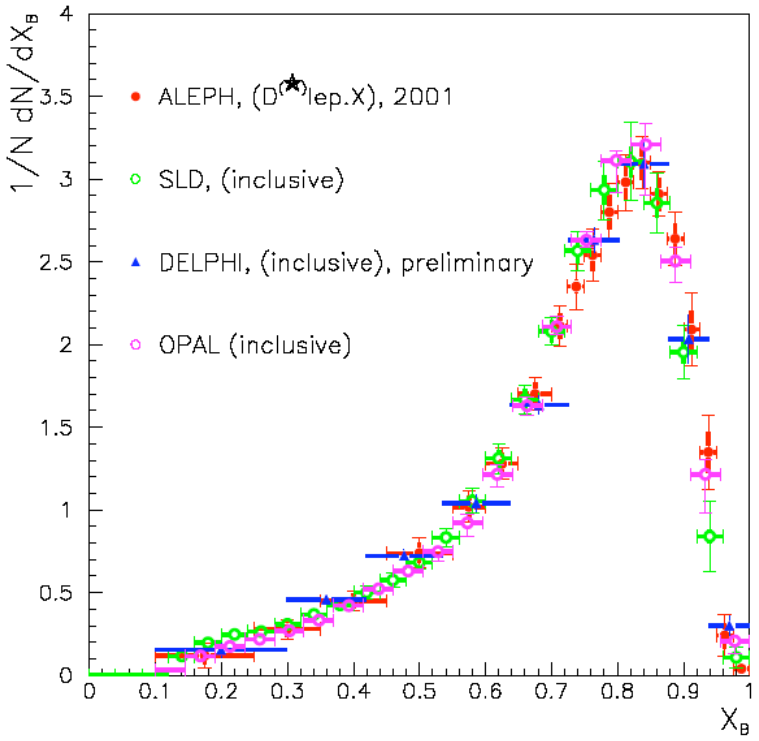
A.Nakamura and S.Sakai,
hep-lat/0406009

KSS bound:
strongly coupled SUSY QCD = classical supergravity

Heavy quarks in QCD vacuum



OPAL Collaboration



Heavy quarks produce a larger number of particles

and carry a larger fraction of jet momentum

Heavy quark colorimetry of QCD matter

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

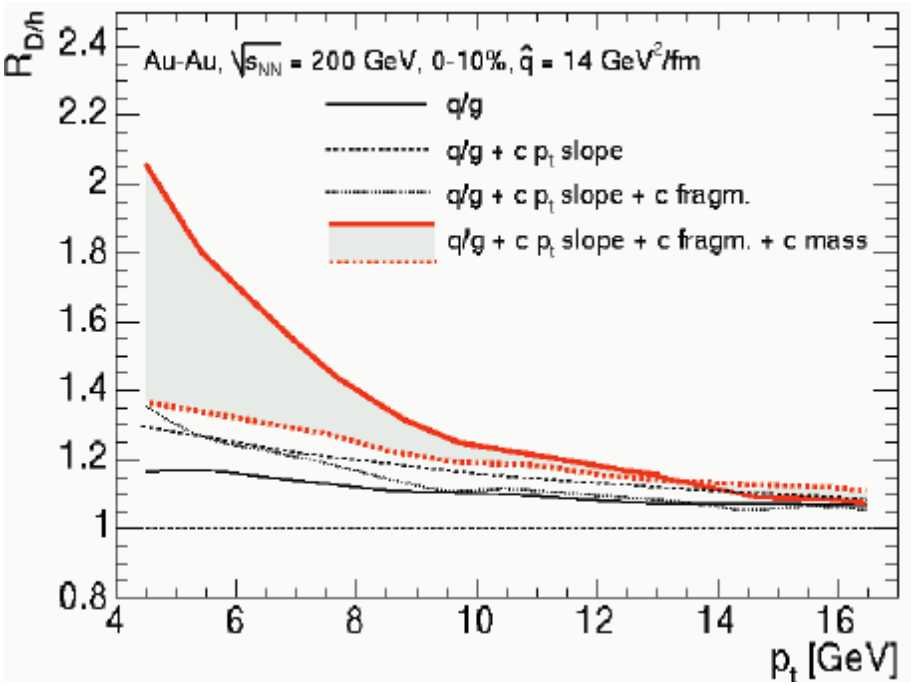
The propagation of heavy quarks in QCD matter is strongly affected by the interplay of the "dead cone" and quantum interference effects (LPM) at energies up to

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

(a consequence of quantum mechanics & causality)

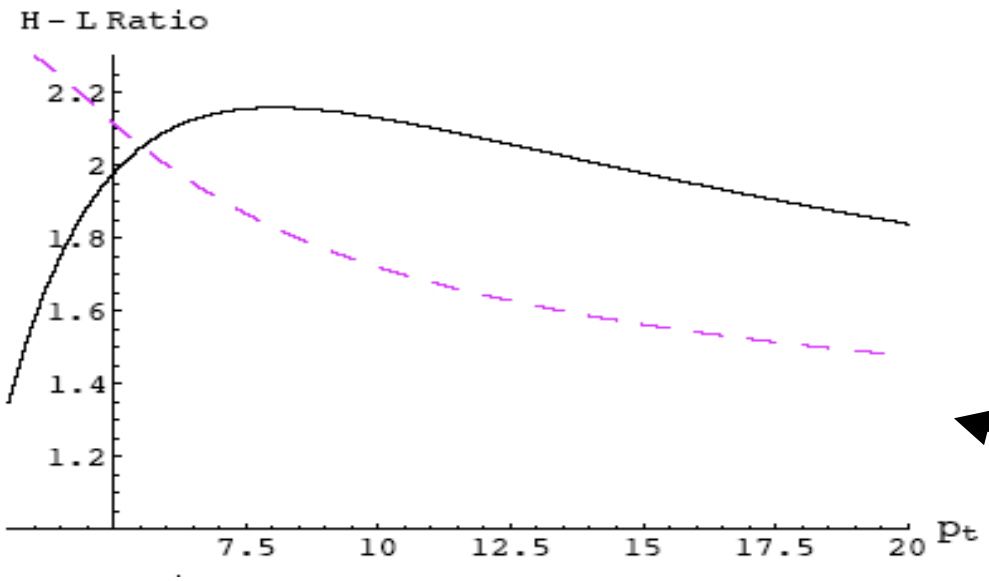
Yu.Dokshitzer, DK
hep-ph/0106202

Armesto, Dainese, Salgado, Wiedemann, in preparation



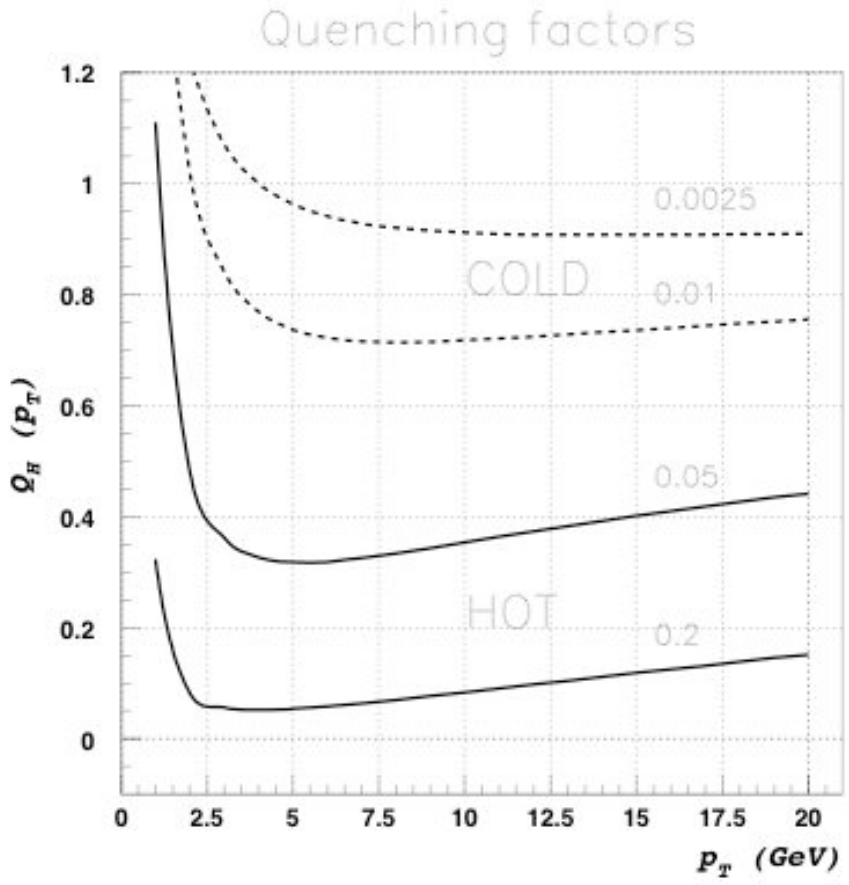
N.Armesto,
M. Djordjevic,
M. Gyulassy,
C.Salgado,
U. Wiedemann,
X.N. Wang, …

Enhancement of
the D/h ratio as
a signature of the radiative
energy loss in the QGP:
Heavy quarks lose less



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

Charm: the magnitude of suppression

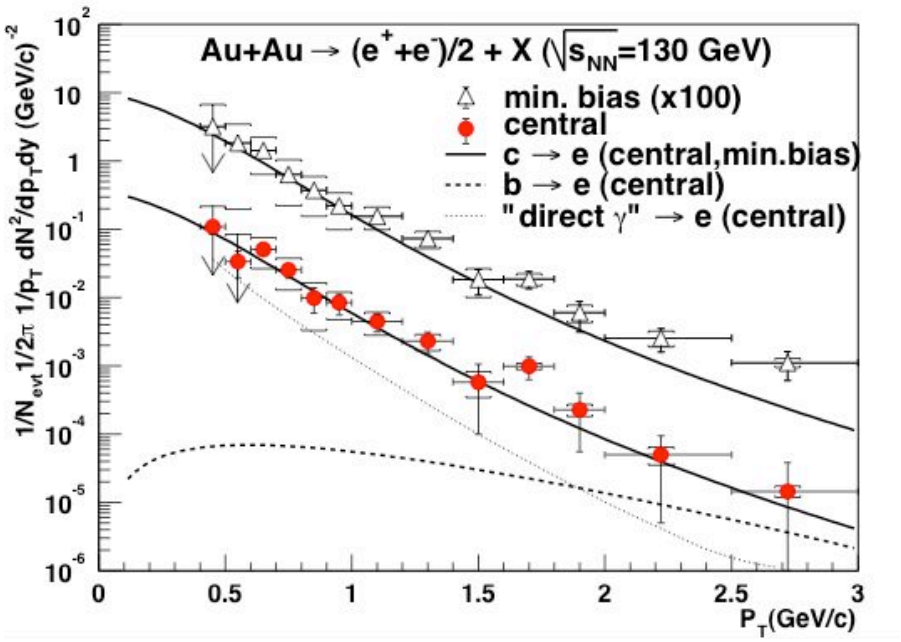


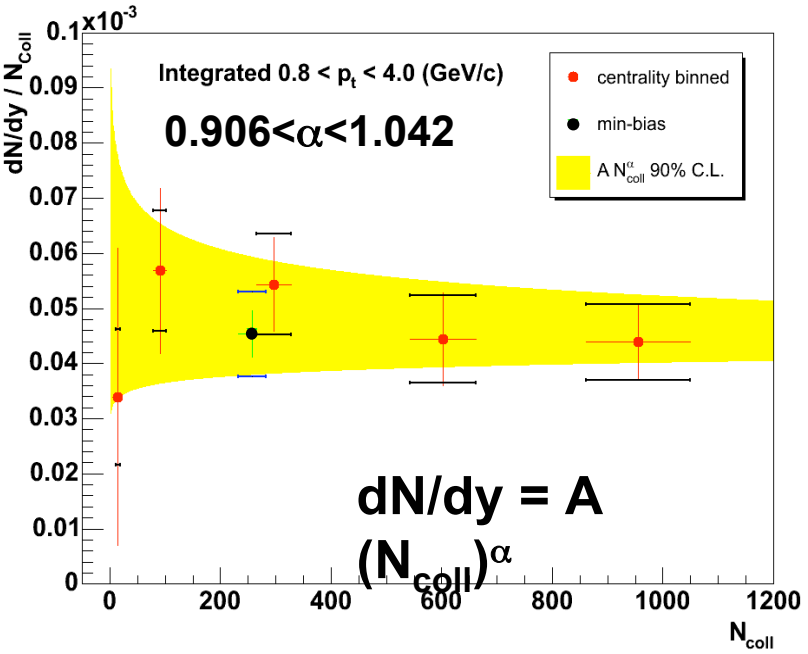
DK & K. Tuchin, hep-ph/0310358

At this Workshop, talks by M.Djordjevic, S.Wicks,…

For heavy quarks the induced gluon radiation should be suppressed; is it?

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

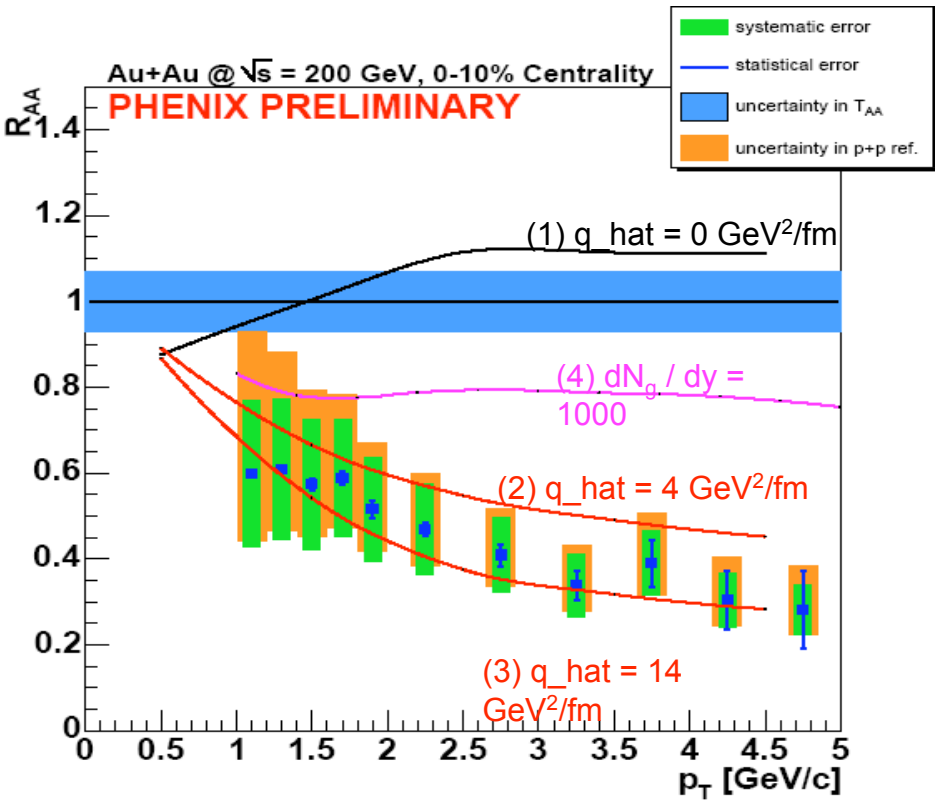


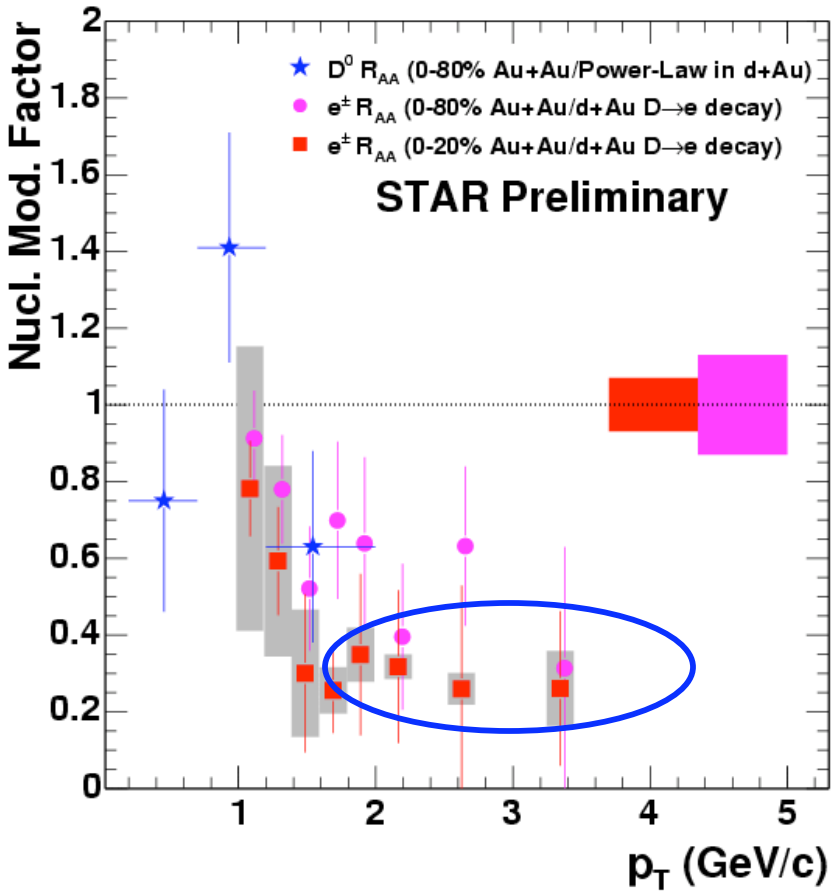


Data from PHENIX

AuAu collisions: charm is quenched!?

a serious problem for the naïve radiative energy loss scenario?





PHENIX Coll., Quark Matter'05

STAR Coll., Quark Matter'05

AuAu collisions: charm is quenched!?

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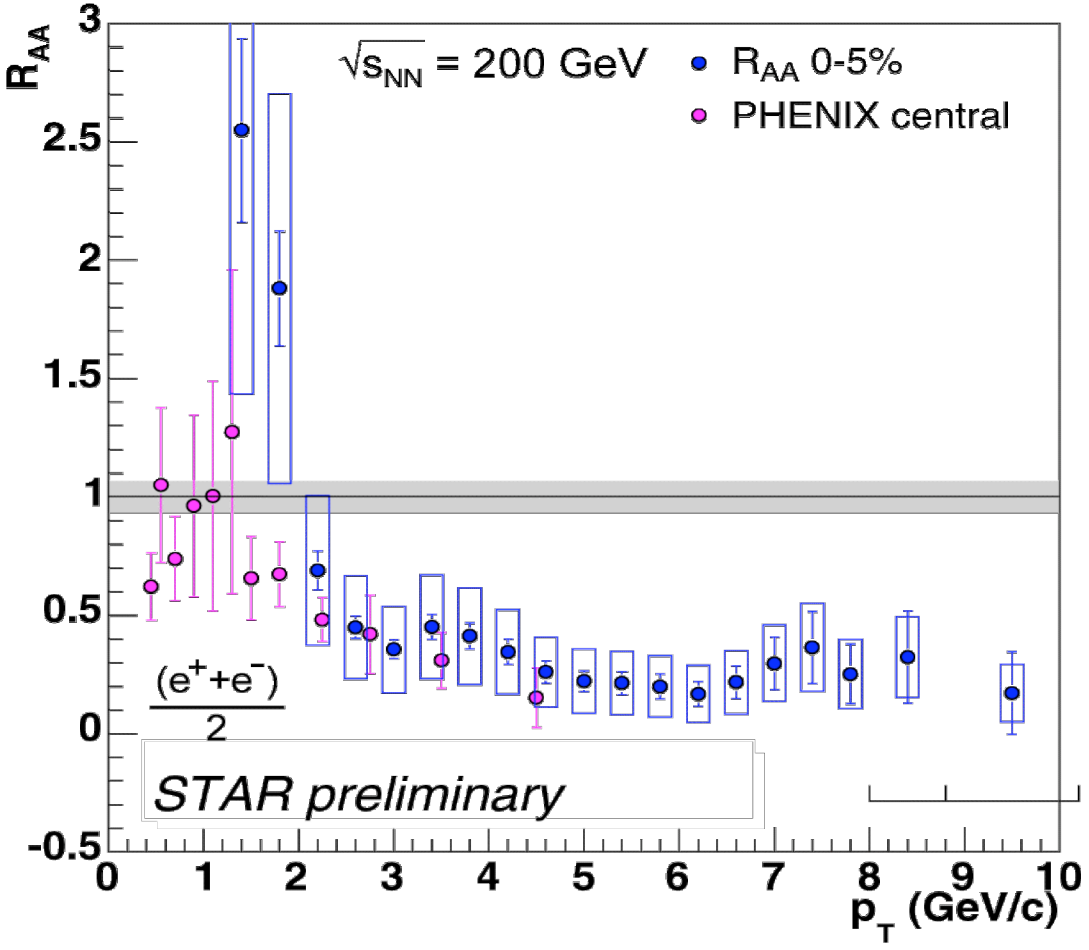
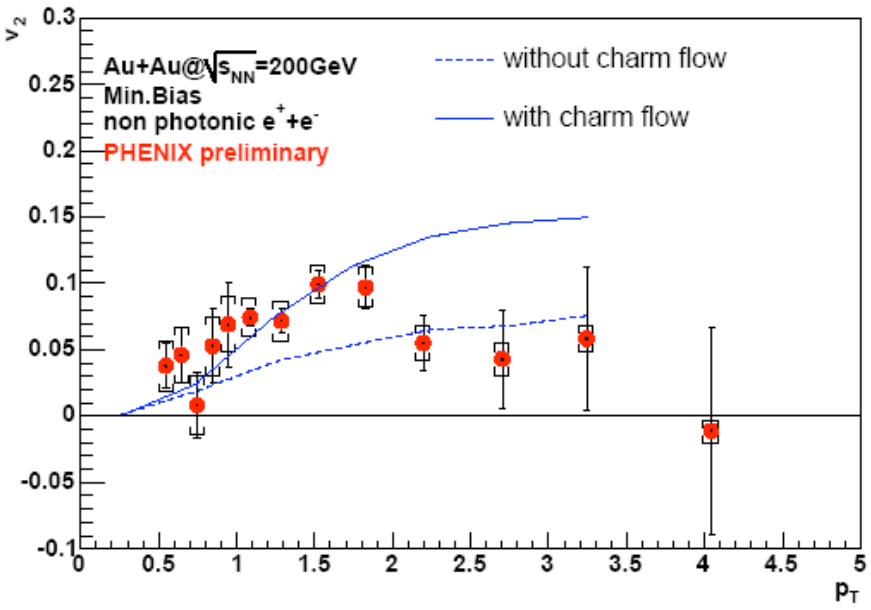


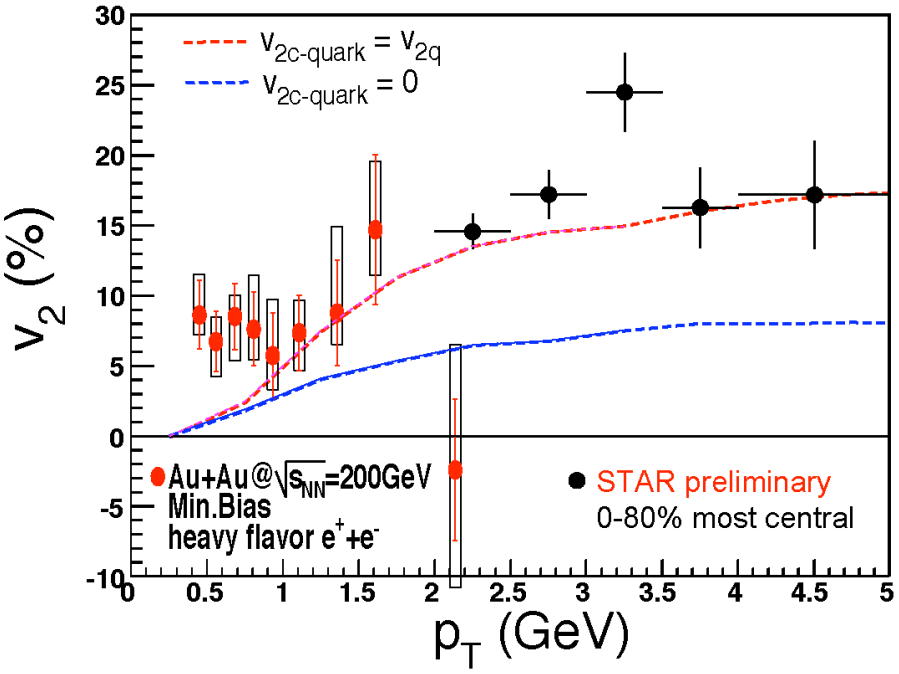
STAR Coll., Quark Matter'05

AuAu collisions: charm flows!

Extract the heavy quark transport coefficients?

P.Petreczky, D.Teaney, hep-ph/0507318





PHENIX Coll., Quark Matter'05

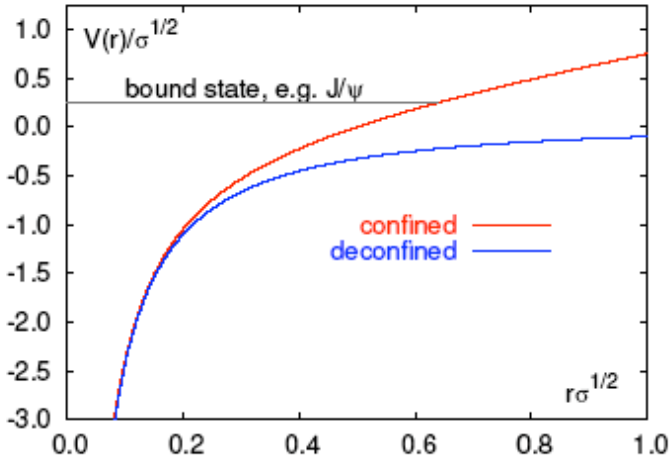
STAR Coll., Quark Matter'05

Heavy quarkonium as a probe

The Matsui-Satz argument:

- deconfinement $\Rightarrow$ screening

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



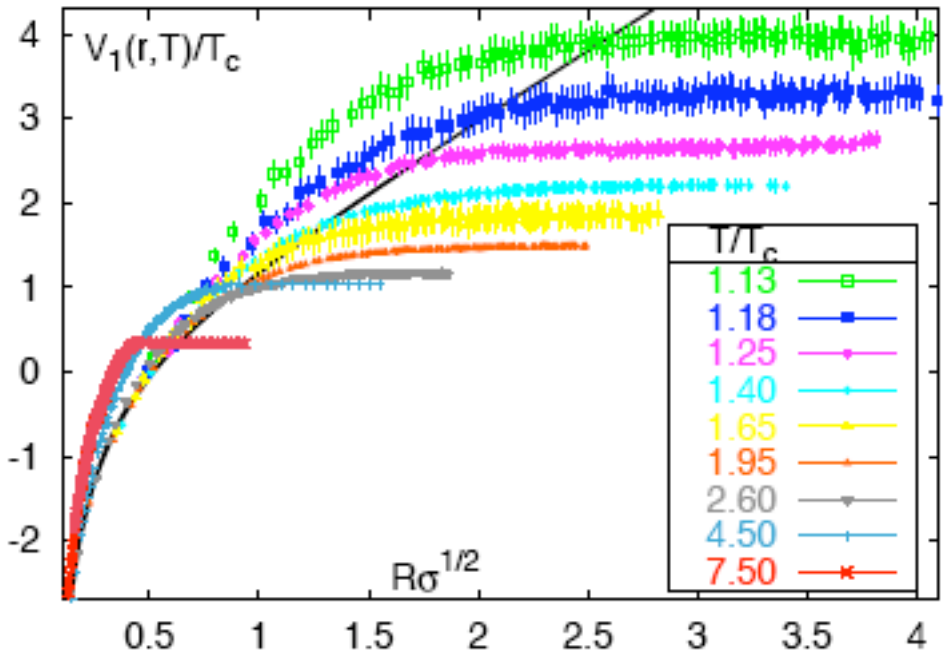
$V_{\bar{q}q}(r,T) \to \infty$ confinement

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

F.Karsch

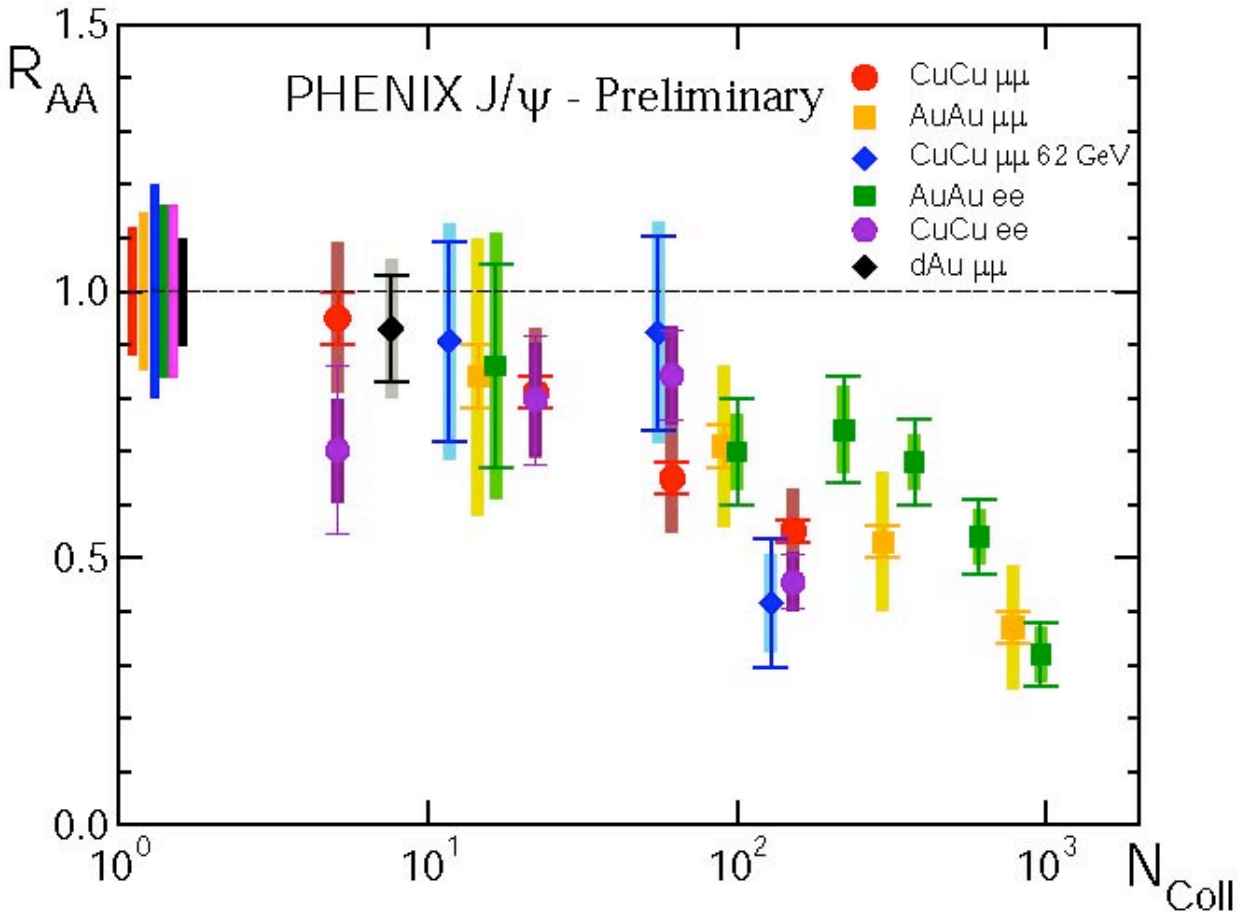
the link between the observables and the McLerran-Svetitsky confinement criterion

Heavy quark internal energy above T



O.Kaczmarek, F. Karsch, P.Petreczky,
F. Zantow, hep-lat/0309121

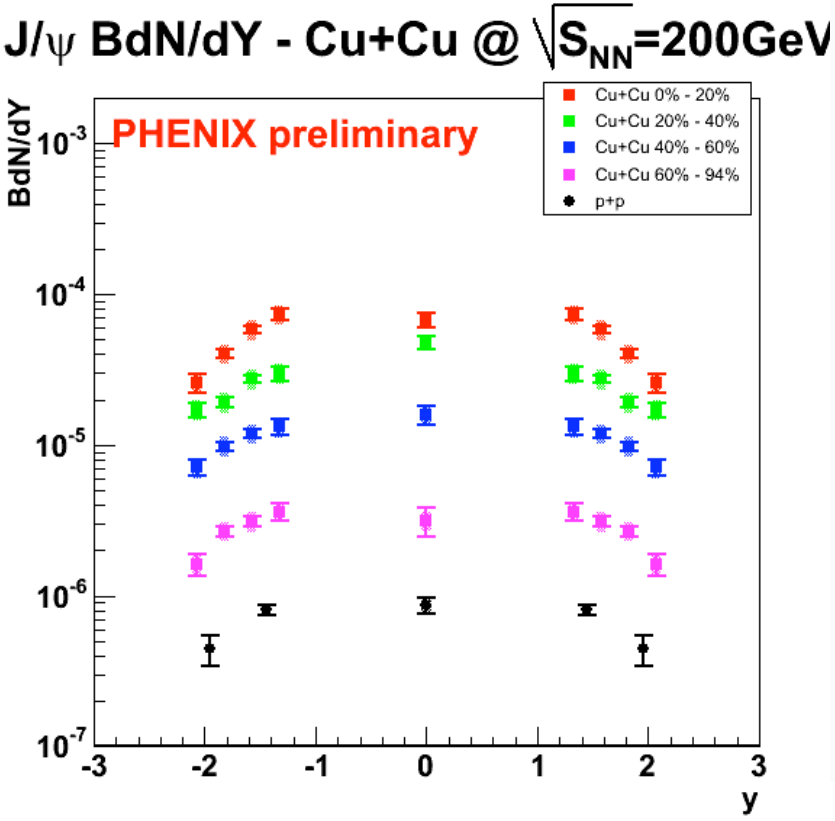
J/ψ suppression at RHIC

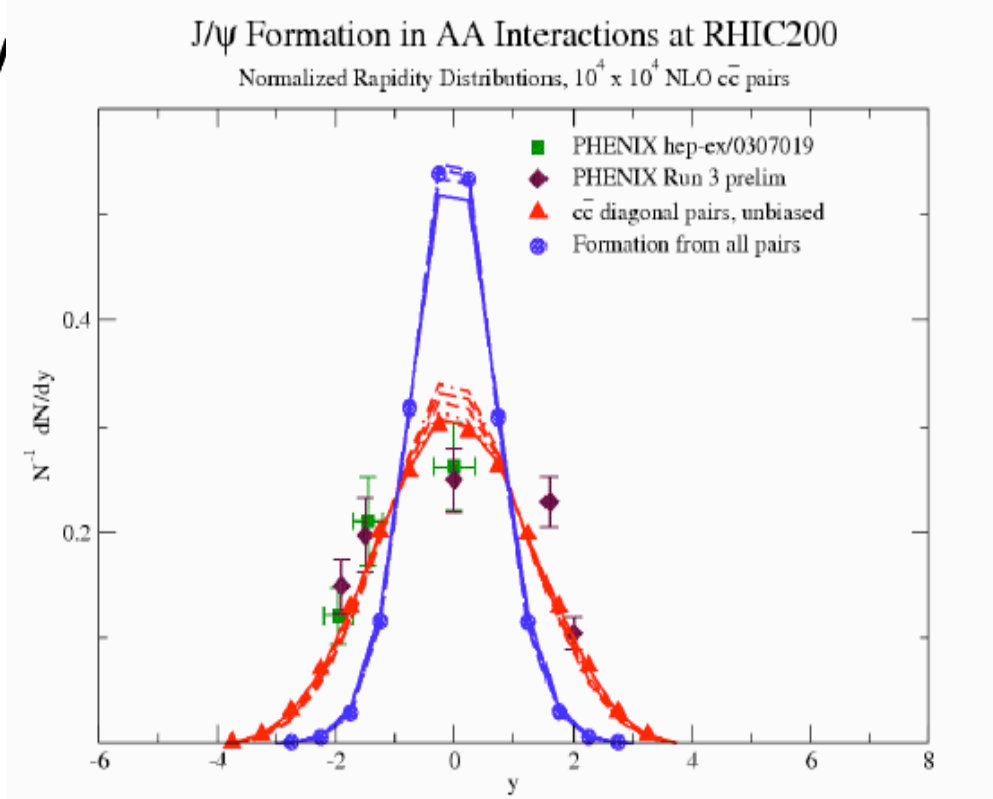


"same as at SPS"?

Recombination of charm quarks?

R.Rapp, J. Rafelski, R.Thews,…



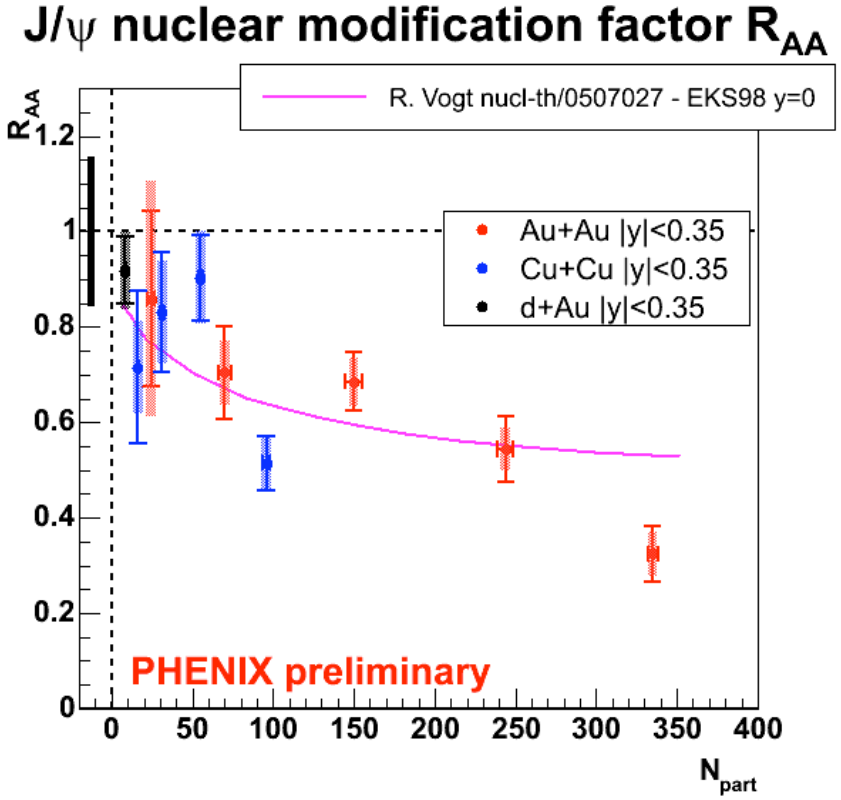


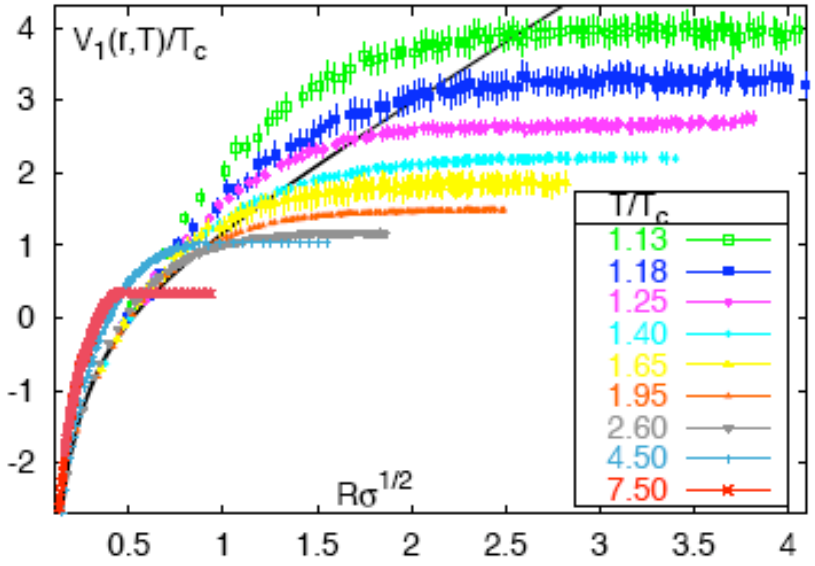
R.Thews

Recombination narrows the rapidity distribution; is this seen?
Are high p_t charmonia suppressed stronger than open charm?

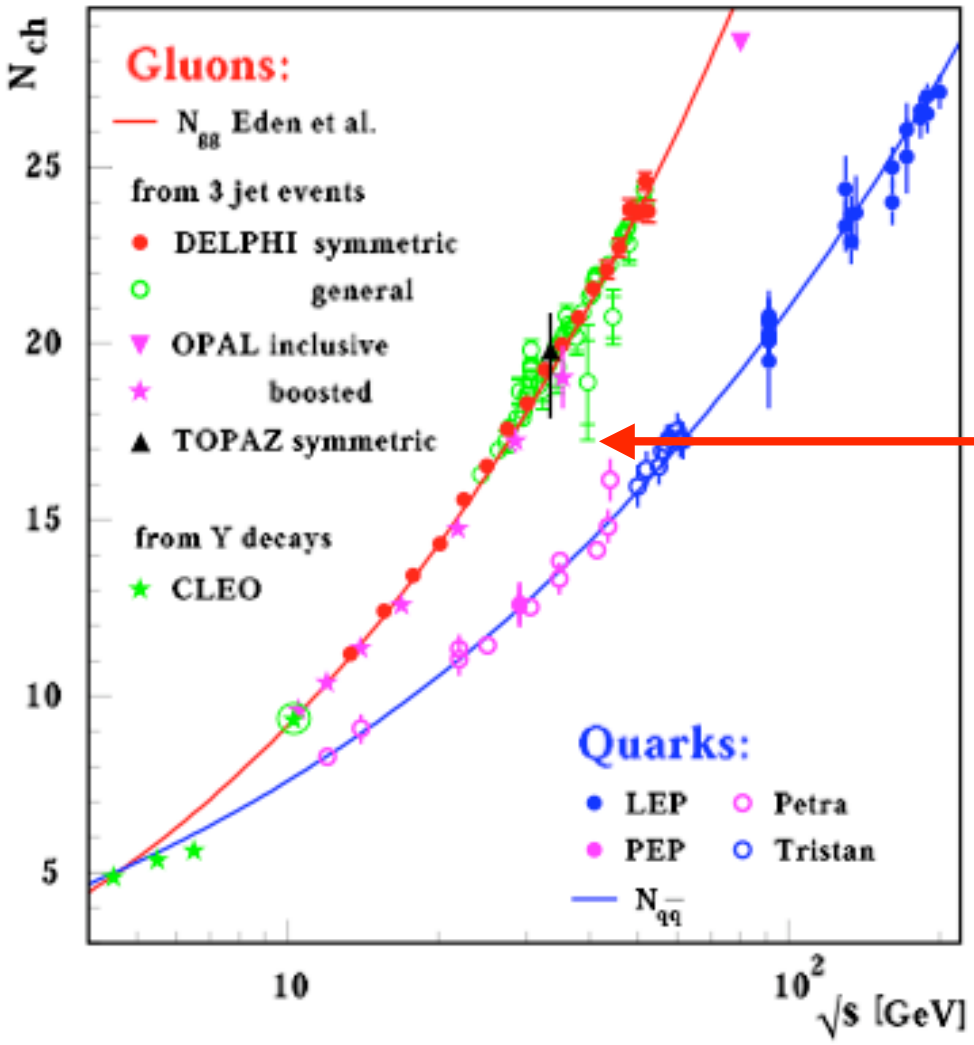
…or the survival of direct J/ψ's in the plasma?

H.Satz





Charm-tagged quark and gluon jets?



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

Tagging gluon jets by g->ccbar and quark jets by leading charmed hadrons?

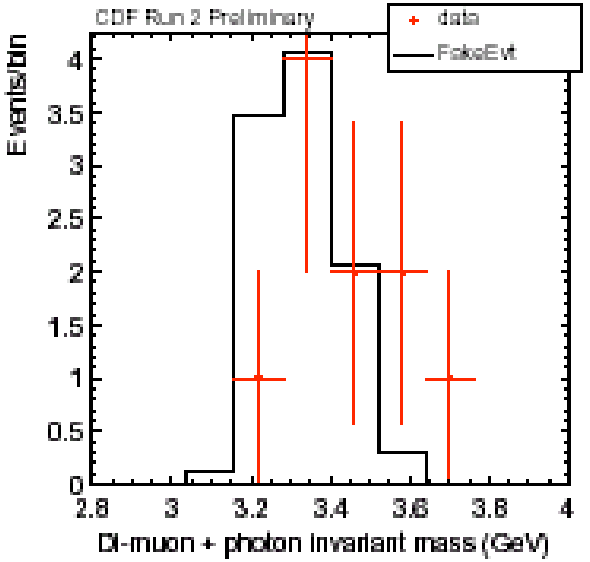
Charm in double diffractive production: probing the gluon clouds at large distances

One example:

$pp \rightarrow \chi_c\, pp$

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

observed at Tevatron?



M.Albrow et al,
CDF Coll.

Diffractive studies at RHICII?

theoretical prediction:
600 - 700 nb
Khoze, Martin, Ryskin; Yuan

Summary

Heavy quarks and quarkonia are valuable tools for the diagnostics of QCD matter -

Both the history and the future of the topic look bright!