

Parton energy loss in color fields at strong coupling

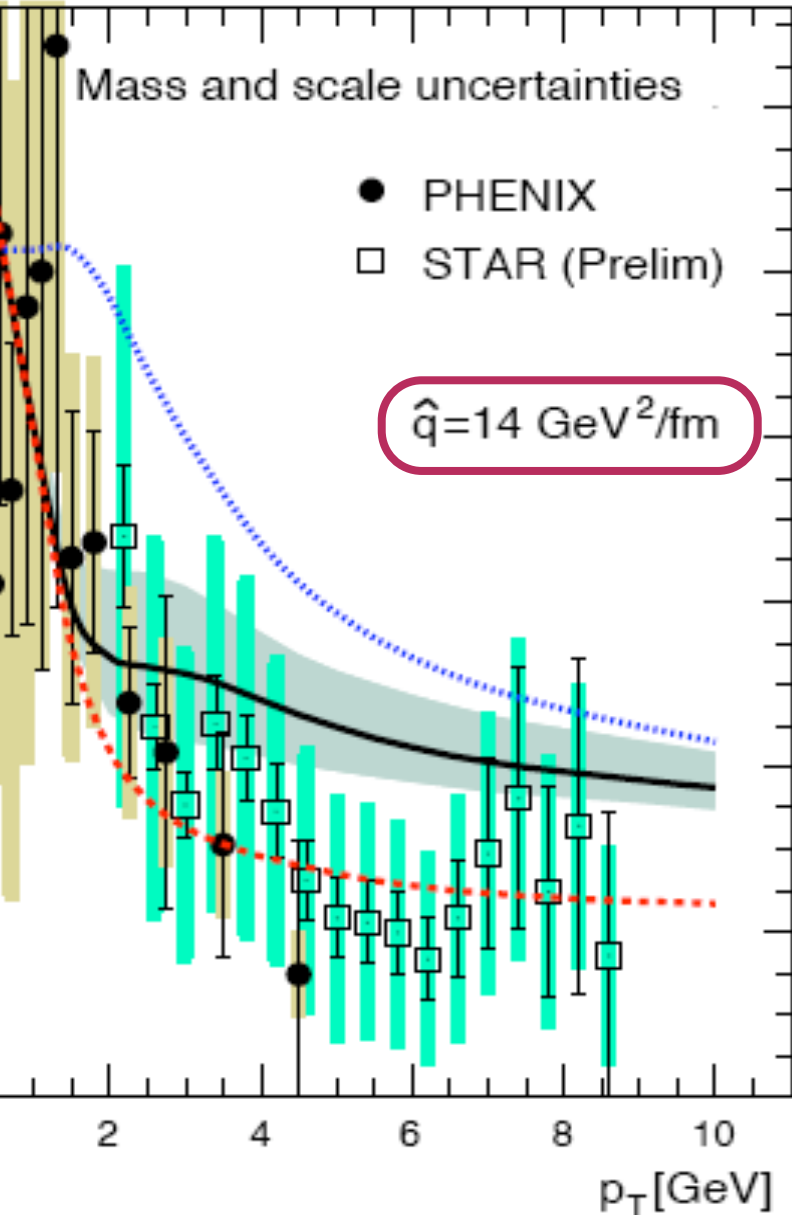
D. Kharzeev

arXiv: 0806.0358

Outline

- The heavy quark suppression puzzle
- Back to the drawing board?
pQCD approach to parton energy loss
- Energy loss at strong coupling: AdS/CFT
prospective
- Universal upper bound on parton energy
- Experimental tests

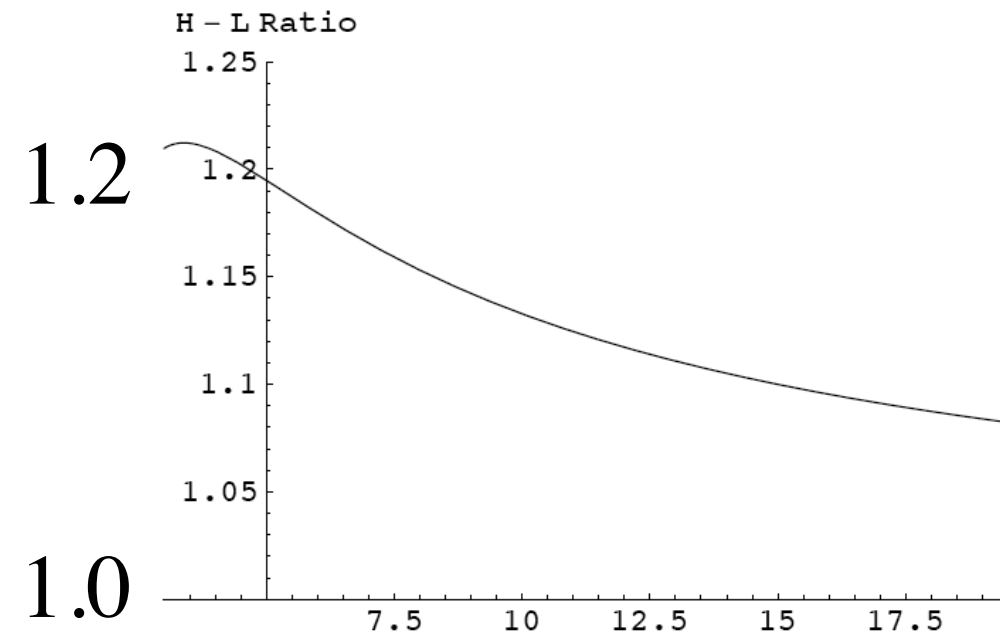
a test of the perturbative radiative energy loss scenario



N.Armento, M.Cacciari, A.Dainese,
C.Salgado,U.Wiedemann,
hep-ph/0511257

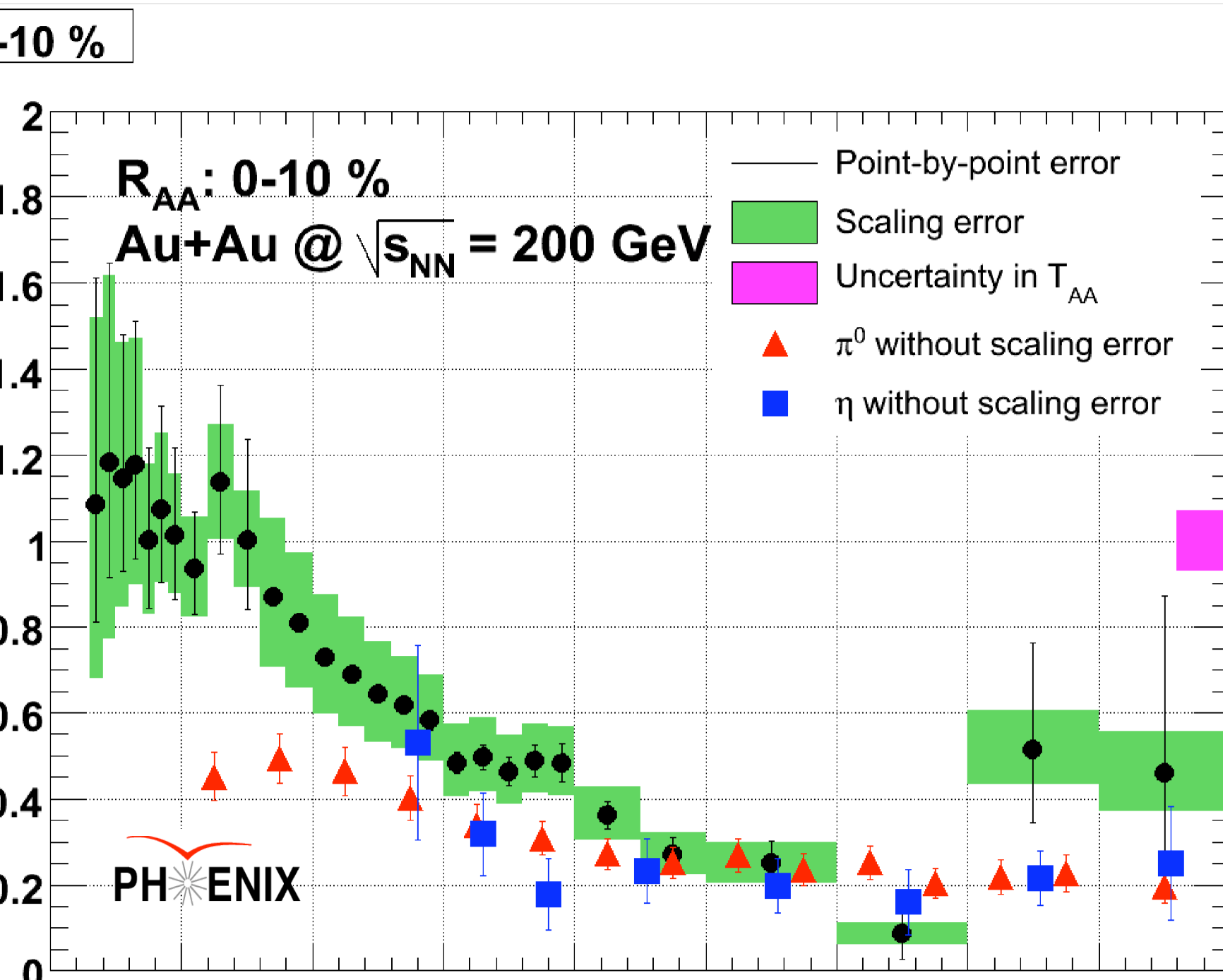
Heavy quarks must lose energy because of the “dead cone” effect

Yu. Dokshitzer, DK, ‘01



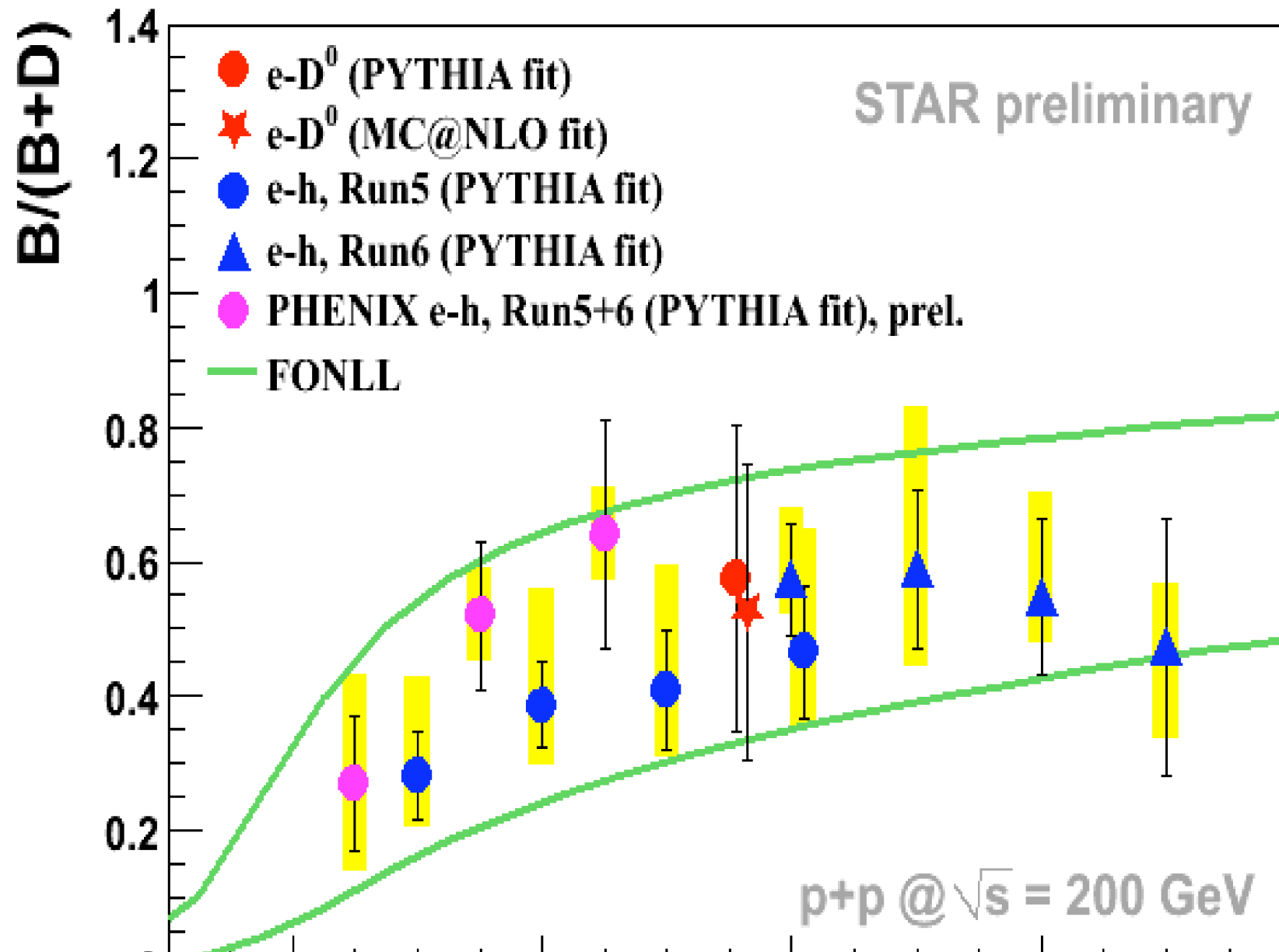
Heavy-to-light ratios
exceed unity:
~ 20% effect for charm,

BUT: Heavy quarks are suppressed...



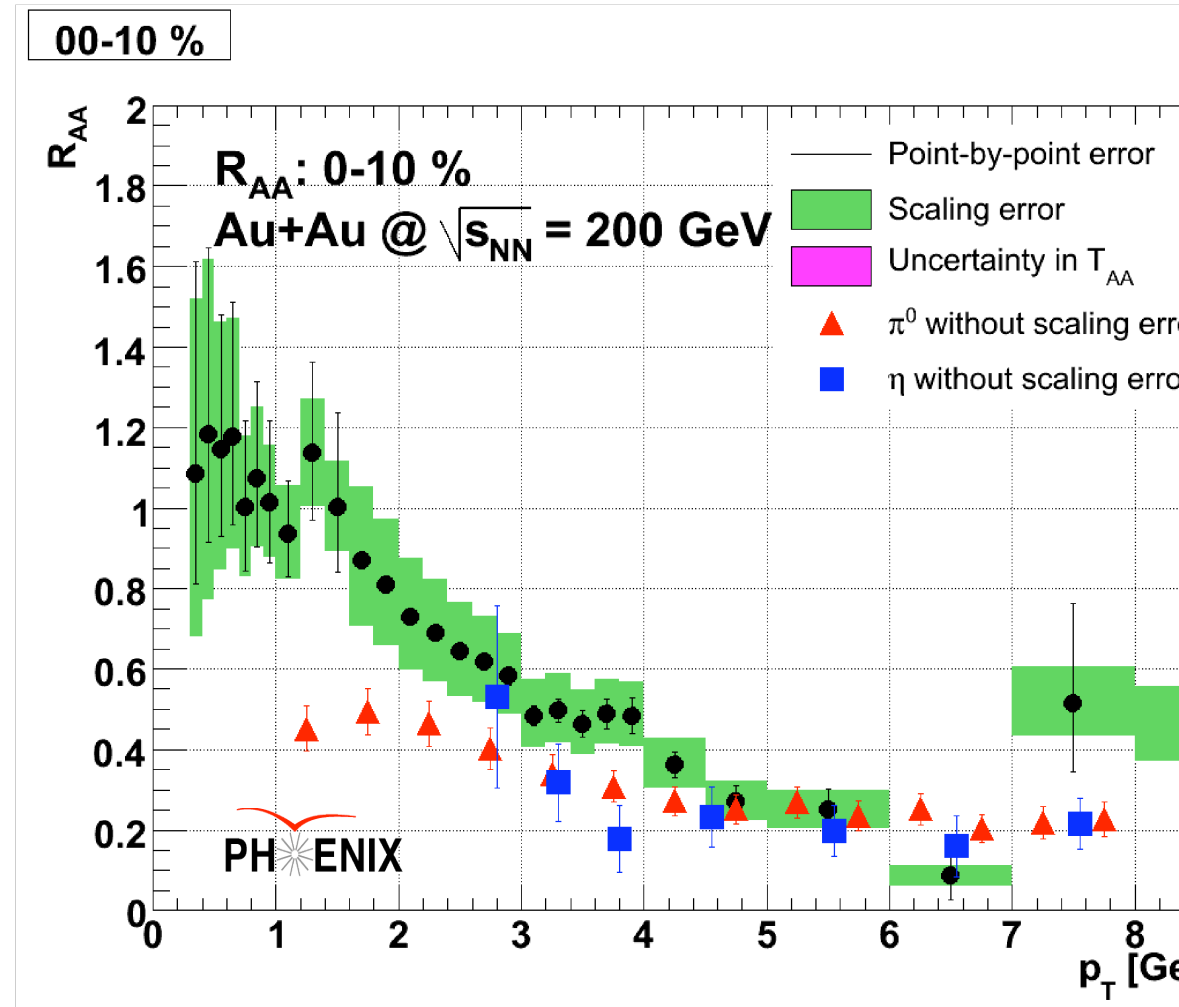
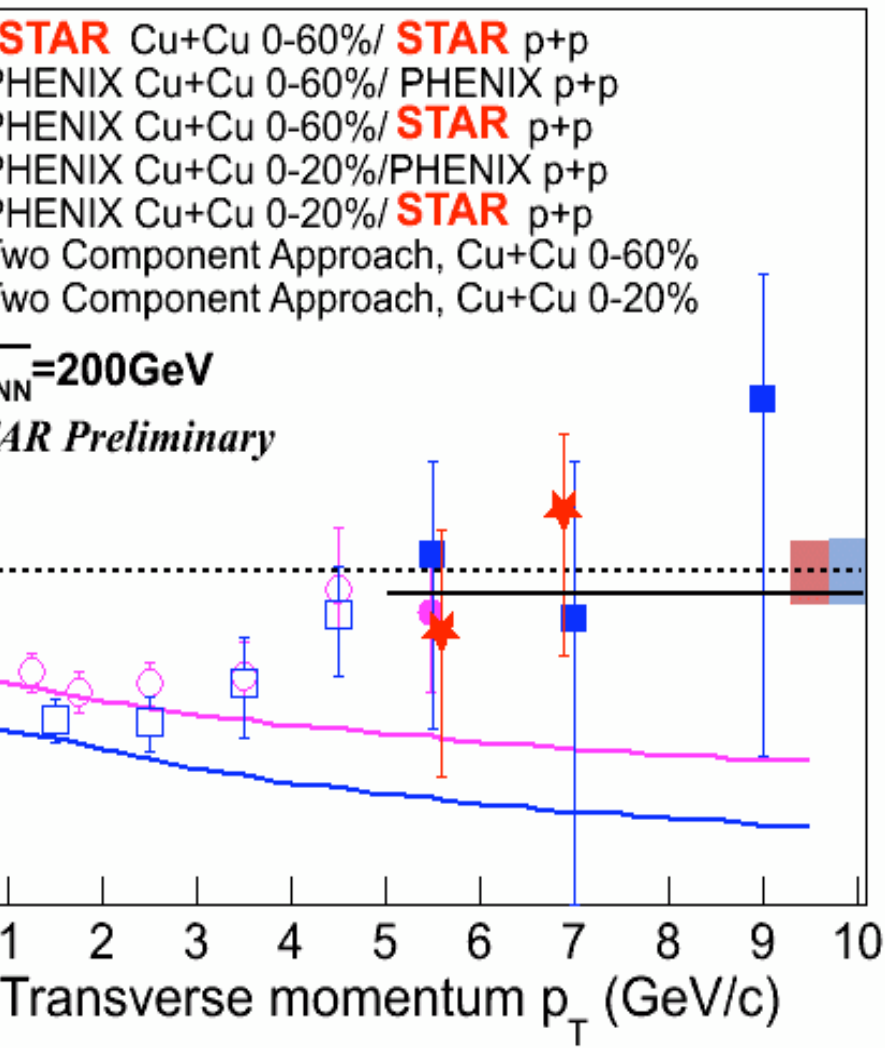
QM'08

Even b-quarks seem to be suppressed...



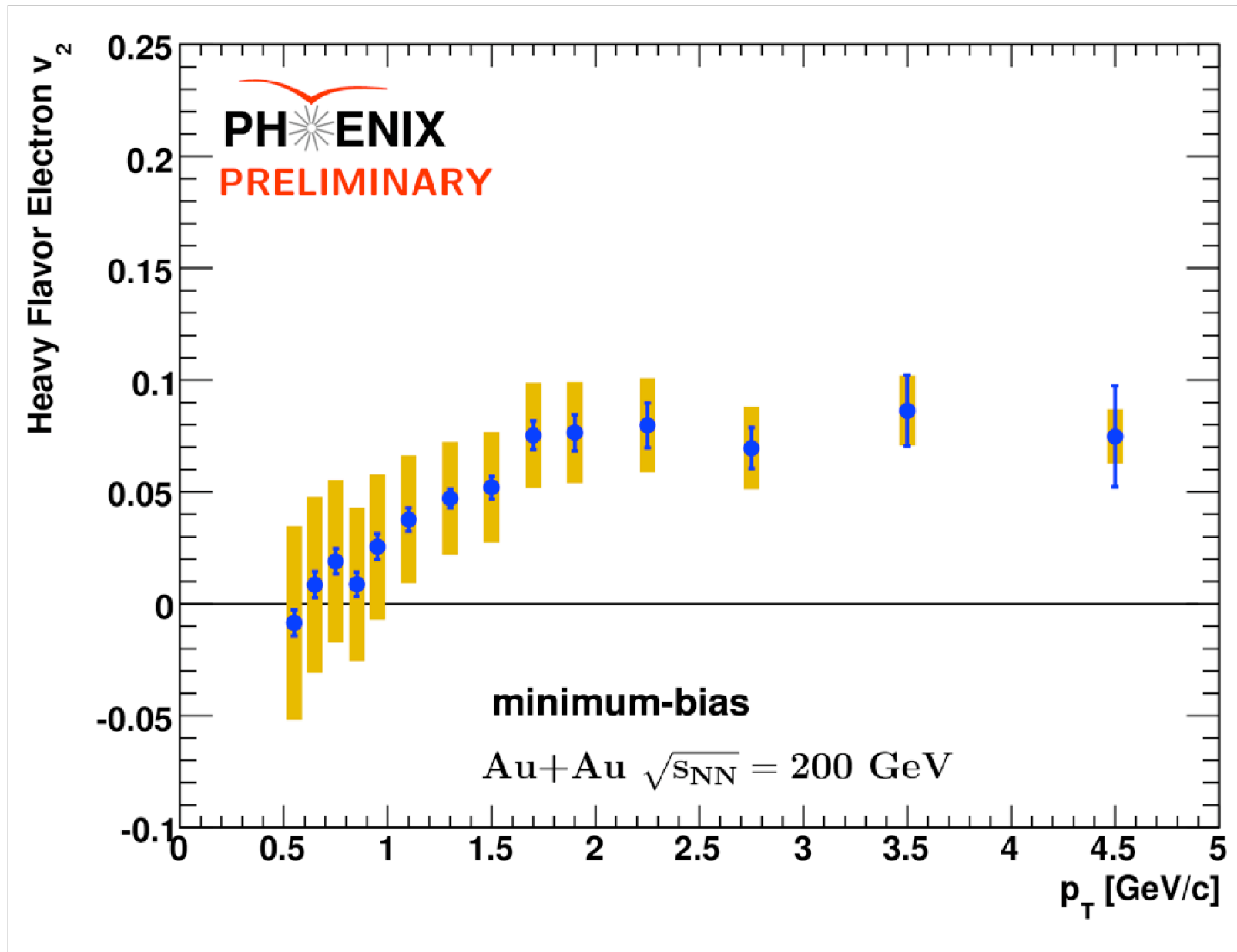
QM '0

Heavy quark suppression is due to color interactions:



Colored heavy quarks are suppressed,
color-neutral quarkonia are not (?)

Moreover, c and b-quarks even seem to flow



QM 'C

Is there a way to understand this?



“Well, back to the old drawing board”

pQCD approach to the energy loss: the basic ingredients

Weak coupling

Multiple scattering with eikonal propagation

Landau-Pomeranchuk-Migdal interference

appropriate scale: $\alpha_s(Q^2 = \hat{q}L)$
cold matter, saturation momentum $Q_s^2 = \hat{q}L$

the condition: $Q^2 = \hat{q}L \gg \Lambda_{\text{QCD}}^2$ $\hat{q} \equiv \rho \int \frac{d\sigma}{dq^2}$

Gyulashvili
Blaizot
Zakharov
Gelis

pQCD approach to the energy loss: the basic assumptions

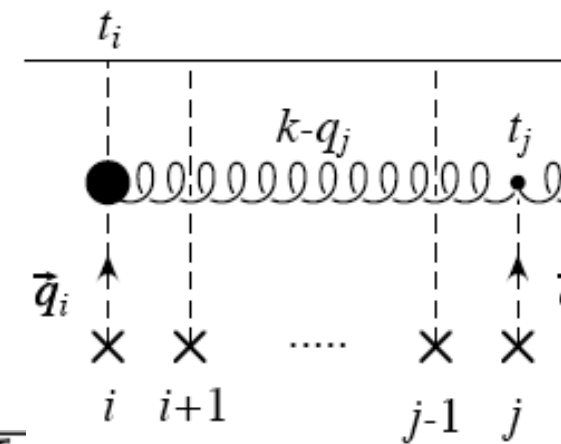
Multiple scattering with eikonal propagation
(static, uncorrelated scattering centers)

independent scatterings $\lambda \gg \mu^{-1}$

large number of them $\lambda \ll L$

soft gluons are emitted $\omega \ll E$

scatter at small angle $\theta_s \sim \frac{k_{\perp}}{\omega} \sim \frac{\sqrt{\hat{q}L}}{\omega}$



Notation

λ mean free

L size of the medium

μ Debye mass

ω energy of the emitted gluon

E energy of the incident particle

the condition: $Q^2 = \hat{q}L \ll z^2 E^2$

Note: independent scatterings $\longleftrightarrow$ large viscosity

pQCD approach to the energy loss: the basic assumptions

What is the reasonable range of values for $\hat{q}$?

so far we have

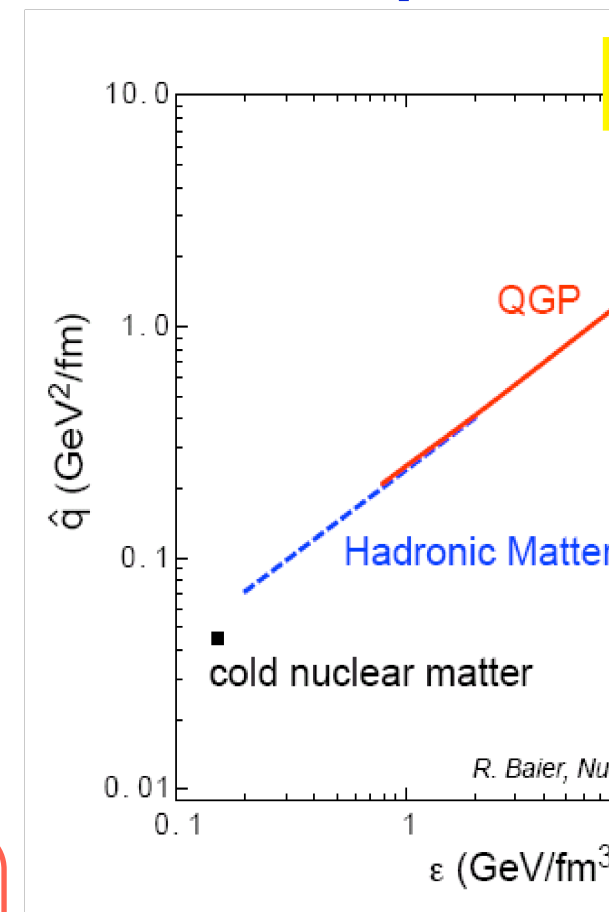
$$\Lambda_{\text{QCD}}^2 \ll \hat{q} L \ll z^2 E^2$$

take $L=5$ fm, $z=0.1$:

$$\ll \hat{q} \text{ [GeV}^2/\text{fm]} \ll 2 \cdot 10^{-3} E(\text{GeV})^2$$

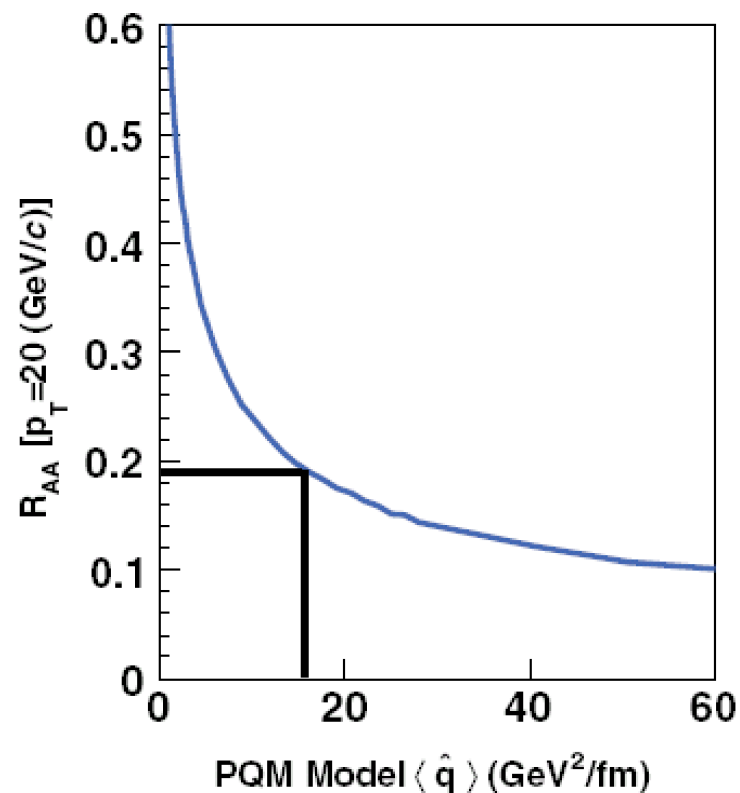
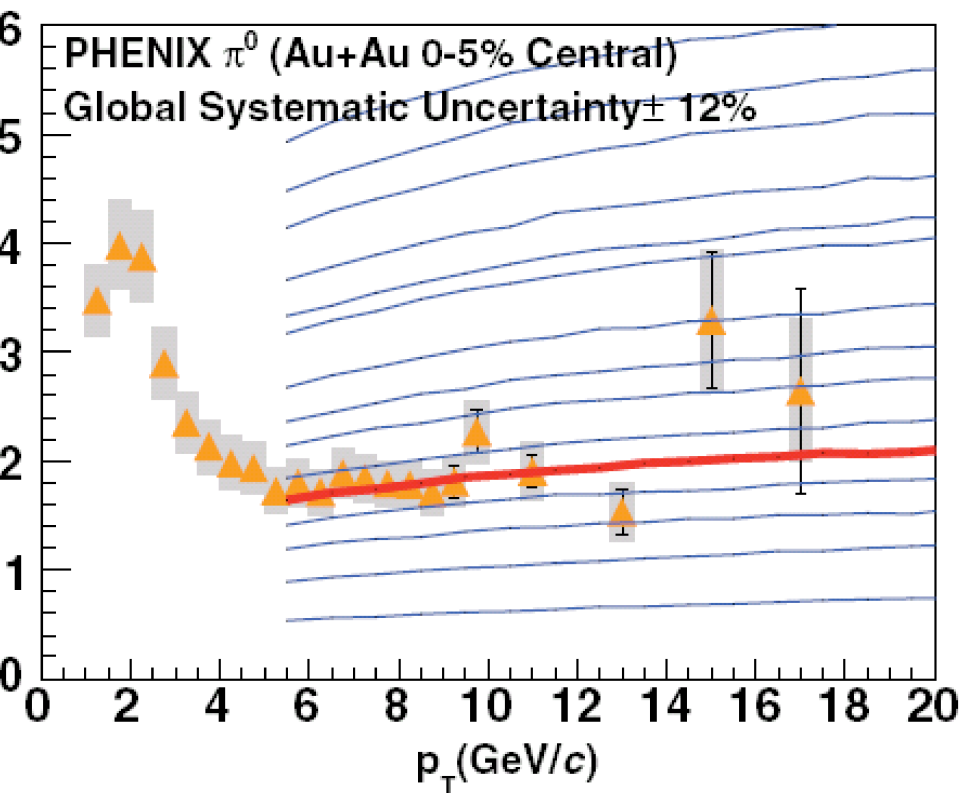
for $E < 50$ GeV,

$$0.01 \ll \hat{q} \ll 5 \text{ [GeV}^2/\text{fm]}$$



BDMPS original values: ≈ 0.1 (cold matter)

data?



Talk
J. Nagle,

$$\langle \hat{q} \rangle = 13.2 \pm_{3.2}^{2.1} \pm_{5.2}^{6.3} \frac{\text{GeV}}{\text{fm}}$$

corresponding energy loss is

$$\Delta E \simeq \frac{\alpha_s}{\pi} N_c \hat{q} L^2 \simeq (L(\text{fm})/5)^2 \cdot 500 \text{ GeV}$$

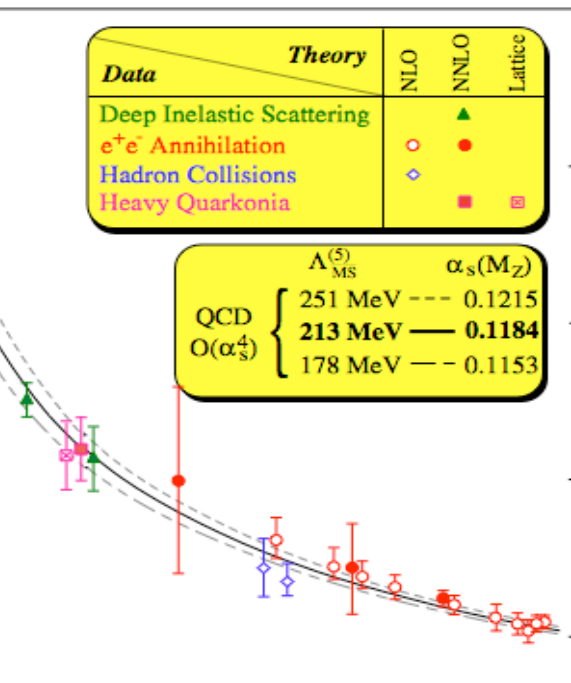
If L is as small as $L = 1 \text{ fm}$, energy loss is about 20

heavy quarks: “power corrections”

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

quarks are “heavy” because their masses are large
typical QCD scale of Λ_{QCD} :

$$M_H \gg \Lambda_{\text{QCD}} \rightarrow \alpha_s(M_H)$$



vacuum fields are weak
on the heavy quark scale:

may be treated as perturbation

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

Classical interpretation:

$$\frac{(\text{Lorentz force})^2}{\dots} \ll 1$$

What if the
and the force

perturbative methods
work when the coupling
is small

Strong coupling methods
work when the coupling
is large

Consider $\alpha_s = 0.3$

“Reasonably” weak,

$$\alpha_s \ll 1$$

“Reasonably” strong,

$$\lambda = g^2 N_c = 4\pi\alpha_s N_c \simeq$$

The domain of physical interest (few GeV) is claimed
to be simultaneously weakly and strongly coupled
with “reasonable” justifications on both sides

strong coupling methods provide an insight

Need a real-time, strong coupling method

At present, limited to N=4 SUSY Yang-Mills:
a theory very different from QCD!

(conformal: no confinement, no asymptotic freedom;
in plasma, no bulk viscosity)

but anyway, what happens to heavy (and light) quarks
at high momentum?

Energy loss in AdS/CFT: some references

Langevin dynamics of heavy quarks, finite T:

C. Herzog, A. Karch, P. Kovtun, C. Kozcaz,
L. Yaffe, hep-th/0605158;
S. Gubser, hep-th/0605182;
J. Casalderrey-Solana, D. Teaney, hep-ph/06

Radiative energy loss at finite T:

S. Sin and I. Zahed, hep-th/0407215;
N. Chernicoff and A. Guijosa, arXiv:0803.3

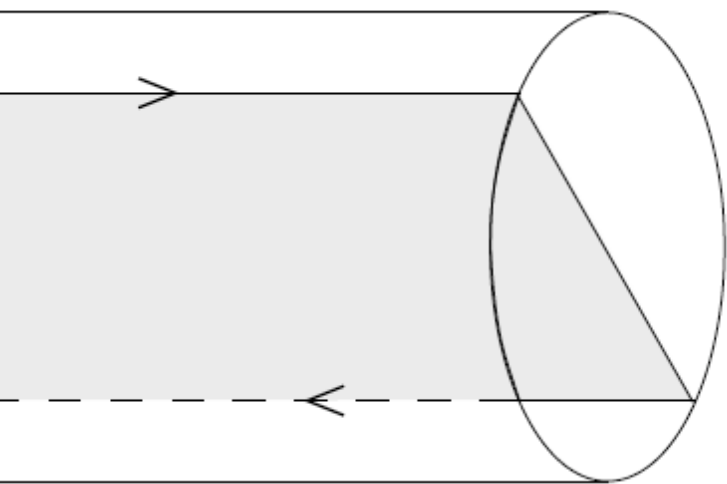
Computing q -hat:

H. Liu, K. Rajagopal, U. Wiedemann, hep-p
N. Chernicoff, J. Garcia, A. Guijosa, arXiv:
P. Argyres, M. Edalati, J. Vazquez-Poritz, he

Matching pQCD approach to energy loss:

F. Dominguez, C. Marquet, A. Mueller, B. W
arXiv:0803:3234;
Y.Hatta, E. Iancu, A. Mueller, arXiv:0803:24
A. Mueller, arXiv: 0805.3140

Talk by W. Horowitz



$$E_{rad}(T) = \frac{\sqrt{\lambda}}{2\pi} \int_{-\infty}^T dt \frac{\vec{a}^2 - (\vec{v} \times \vec{a})^2}{(1 - \vec{v}^2)^3}$$

A.M
hep-th

with the substitution $\frac{\sqrt{\lambda}}{2\pi} \leftrightarrow \frac{2e^2}{3}$

Lienard formula (1898) from classical electrodynamics

note: **non-Abelian, strongly coupled** theory;

linear dependence on the path length -

a consequence of integrability at large N;

once it has been established, the formula

fixed by Lorentz invariance and dimensional analysis (La

$$P^\mu = \frac{\sqrt{\lambda}}{2\pi} \int \frac{d^2 x_\rho}{d\tau^2} \frac{d^2 x^\rho}{d\tau^2} dx^\mu$$

clairage Électrique

VUE HEBDOMADAIRE D'ÉLECTRICITÉ

DIRECTION SCIENTIFIQUE

r à l'École Polytechnique, Membre de l'Institut. — A. D'ARSONVAL, Professeur au Collège
ore de l'Institut. — G. LIPPMANN, Professeur à la Sorbonne, Membre de l'Institut. —
fesseur à l'École centrale des Arts et Manufactures. — H. POINCARÉ, Professeur à la
e de l'Institut. — A. POTIER, Professeur à l'École des Mines, Membre de l'Institut. —
sieur agrégé de l'Université.

CHAMP ÉLECTRIQUE ET MAGNÉTIQUE

R UNE CHARGE ÉLECTRIQUE CONCENTRÉE EN UN POINT ET ANIMÉE
D'UN MOUVEMENT QUELCONQUE

'une masse électrique en
ensité ρ et de vitesse u en
duit le même champ qu'un
ction d'intensité $u\rho$. En con-
ons d'un précédent article (1)
pour déterminer le champ,

$$-\frac{d^3}{d\tau^3}) = \rho u_x + \frac{df}{dt} \quad (1)$$

$$-\frac{dg}{d\tau}) = -\frac{1}{4\pi} \frac{dx}{dt} \quad (2)$$

es déduites par permutation
utre les suivantes

$$\left(\frac{df}{dx} + \frac{dg}{dy} + \frac{dh}{dz} \right) \quad (3)$$

$$+ \frac{d^3}{dy} + \frac{d^2}{d\tau} = 0. \quad (4)$$

d'équations on déduit faci-
ns

$$f = V^2 \frac{d\rho}{dx} + \frac{d}{dt} (\rho u_x) \quad (5)$$

Soient maintenant quatre fonctions ψ , F ,
 G , H définies par les conditions

$$\left(V^2 \Delta - \frac{d^2}{dt^2} \right) \psi = -4\pi V^2 \rho. \quad (7)$$

$$\left(V^2 \Delta - \frac{d^2}{dt^2} \right) F = -4\pi V^2 \rho u_x$$

$$\left(V^2 \Delta - \frac{d^2}{dt^2} \right) G = -4\pi \rho u_y$$

$$\left(V^2 \Delta - \frac{d^2}{dt^2} \right) H = -4\pi V^2 \rho u_z \quad (8)$$

On satisfera aux conditions (5) et (6) en pre-
nant

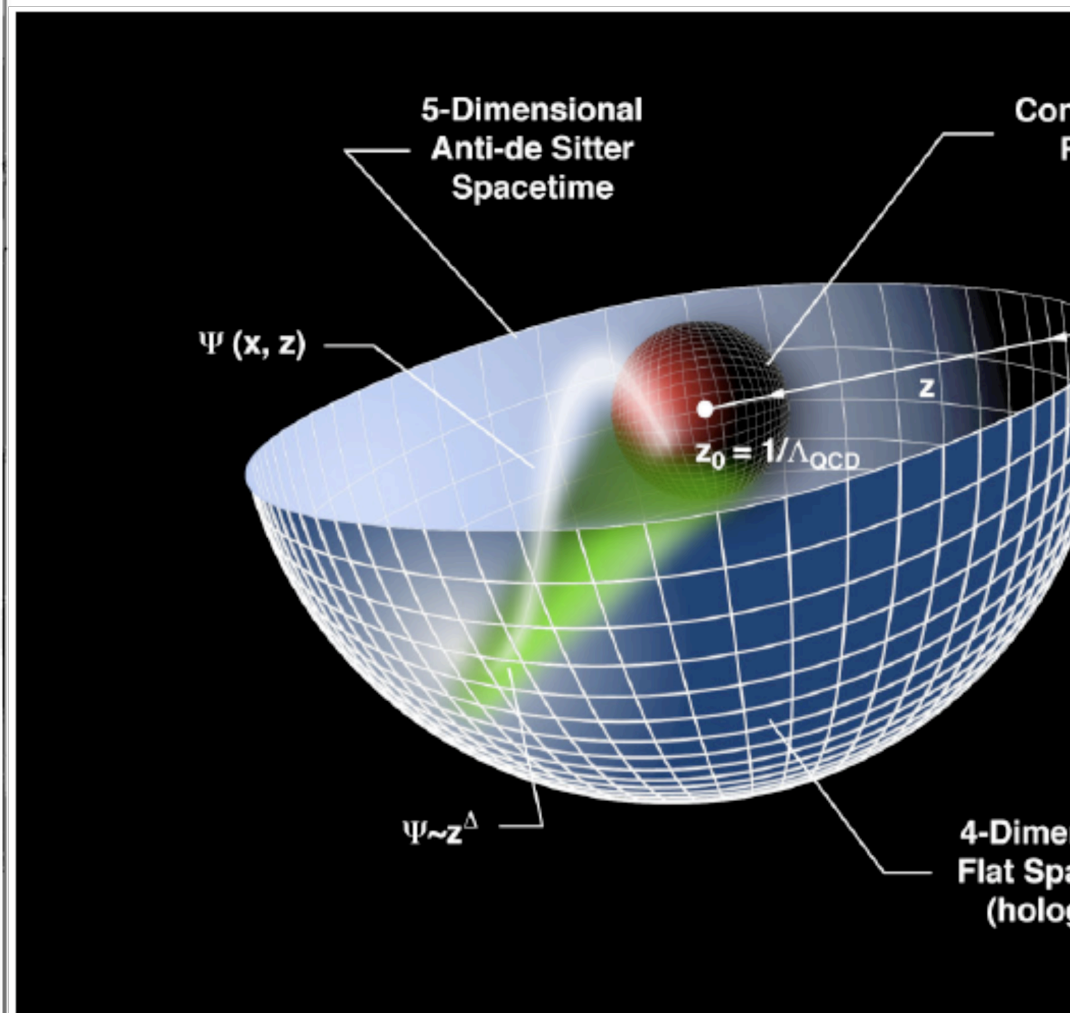
$$4\pi f = -\frac{d^2 \psi}{dx^2} - \frac{1}{V^2} \frac{dF}{dt} \quad (9)$$

$$a = \frac{dH}{dy} - \frac{dG}{d\tau}. \quad (10)$$

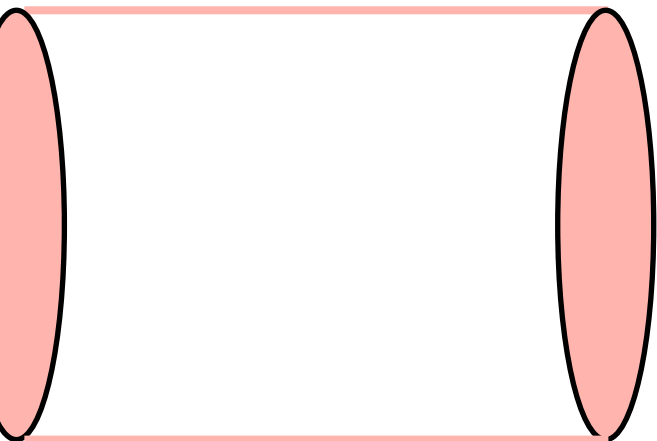
Quant aux équations (1) à (4), pour qu'elles
soient satisfaites, il faudra que, en plus de (7)
et (8), on ait la condition

$$\frac{d^2 \psi}{dt^2} + \frac{dF}{dx} + \frac{dG}{dy} + \frac{dH}{dz} = 0. \quad (11)$$

Occupons-nous d'abord de l'équation (7).



in heavy ion collisions



strings;
color flux tubes;
longitudinal color fields;
“glasma” fields;
sphalerons, ...

Some references:

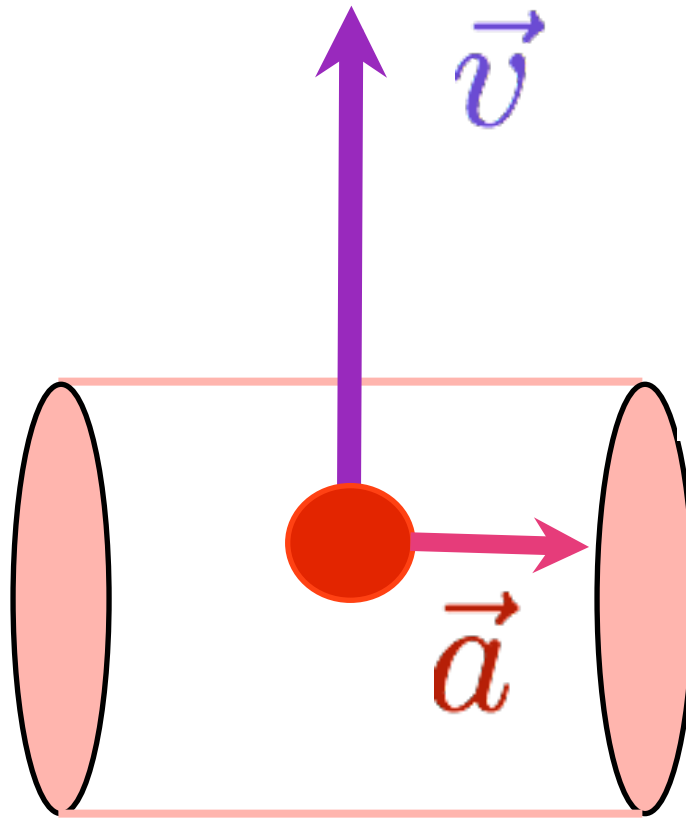
- DK, Yu.Kovchegov, E.Levin, hep-ph/0007182; hep-ph/0106248;
E. Shuryak, hep-ph/0101269;
DK, A. Krasnitz, R.Venugopalan, hep-ph/0109253;
R. Janik, E. Shuryak, I. Zahed, hep-ph/0206005;
DK, E.Levin, K.Tuchin, hep-ph/0602063;
T. Lappi and L. McLerran, hep-ph/0602189;
A.Iwazaki, arXiv:0712.1405;
H.Fujii and K. Itakura, arXiv:0803.1410;
A.Dumitru, F.Gelis, L. McLerran, R.Venugopalan, arXiv:0804.3858,

Ins
sph

the dependence on parton energy

$$\frac{dE_{rad}}{dt} = \frac{\sqrt{\lambda}}{2\pi} \frac{1}{m^2} \vec{F}^2$$

energy loss
constant



color flux tube

$$\frac{dE_{rad}}{dt} = \frac{\sqrt{\lambda}}{2\pi} \frac{1}{m^2} \gamma$$

energy loss
grows $\sim E^2$

Note: $T=0$ is appropriate
at early times prior
to thermalization

energy of the parton obeys
simple differential equation:

$$-\frac{dE}{dx} = \frac{\sqrt{\lambda}}{2\pi} \frac{\vec{F}^2(x)}{m^4} E^2$$

us solve it; note that

$$\frac{dE}{E^2} = -d\left(\frac{1}{E}\right)$$

therefore we get

$$\frac{1}{E_f} = \frac{1}{E_0} + \frac{\sqrt{\lambda}}{2\pi} \int_0^L dx \frac{\vec{F}^2(x)}{m^4}$$

As the initial energy of the parton E_0 goes to infinity
the final energy E_f stays constant!

$$E_{bound} = \frac{2\pi}{\sqrt{\lambda}} \frac{m^4}{F^2} \frac{1}{L}$$

DK, arXiv:0806.

parton dispersion relation has a singularity at

$$F_{crit} = \frac{2\pi m^2}{\sqrt{\lambda}}$$

m is the constituent mass

interpretation: the force of that strength
can produce quark-antiquark pairs

N.Chernicoff and
arXiv: 0803

(Born-Infeld action)

induce confinement as an external force; is it critical?

$$m = 300 \text{ MeV} \text{ and } \alpha_s = 0.3 \quad \rightarrow \quad \sigma \simeq 0.85 \text{ GeV}$$

size of constituent quark $z_m = \sqrt{\lambda}/2\pi m \simeq 0.35 \text{ fm}$

confinement as vacuum polarization by super-critical color charge

Domain of applicability:

in the rest frame of the charge,
the field strength should obey

$$G_{rest} \ll \frac{m^2}{e^3}$$

in the frame where the
charge is moving,

$$G = G_{rest}/\gamma,$$

the Lorentz force is

$$F = eG$$

therefore we get a condition on the external force

$$F \ll \frac{m^2}{e^2}$$

ratio of the “radiation drag” and the Lorentz forces

$\frac{F_{drag}}{F}$ will however always grow large at large energies



I.Ya. Pomeranchuk

What does it mean?

light constituent partons
even simpler formula:
("critical" force)

$$E_{bound} = \frac{\sqrt{\lambda_c}}{2\pi} \frac{1}{L}$$

numerically,

$$E_{bound}^{light, charm} \leq \frac{1}{L(\text{fm})} \text{ GeV}$$

or b-quarks

$$E_{bound}^{bottom} \leq \frac{14}{L(\text{fm})} \text{ GeV}$$

Only surface emission!

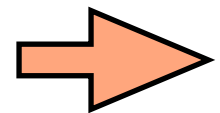
(except for b-quarks in semi-peripheral collisions)

Rough estimates; depend crucially on the strength of the produced field;
b-quarks are very sensitive to it, lighter partons are not

UBM (Universal Bound Model):

above $p_t \sim 5$ GeV, constant R_{AA} of magnitude given by the
surface-to-volume ratio: **all hadrons, all γ , all p_t**
down to semi-peripheral collisions

(except for b-quarks in semi-peripheral collisions)



$$R_{AA} = c \times \frac{(N_{part}/2)}{N_{coll}}$$

$c \sim 1$ is the only unknown constant
(determined by the thickness of the “corona”)

Data from:
A. Adare et al [PHE
arXiv:0801.402

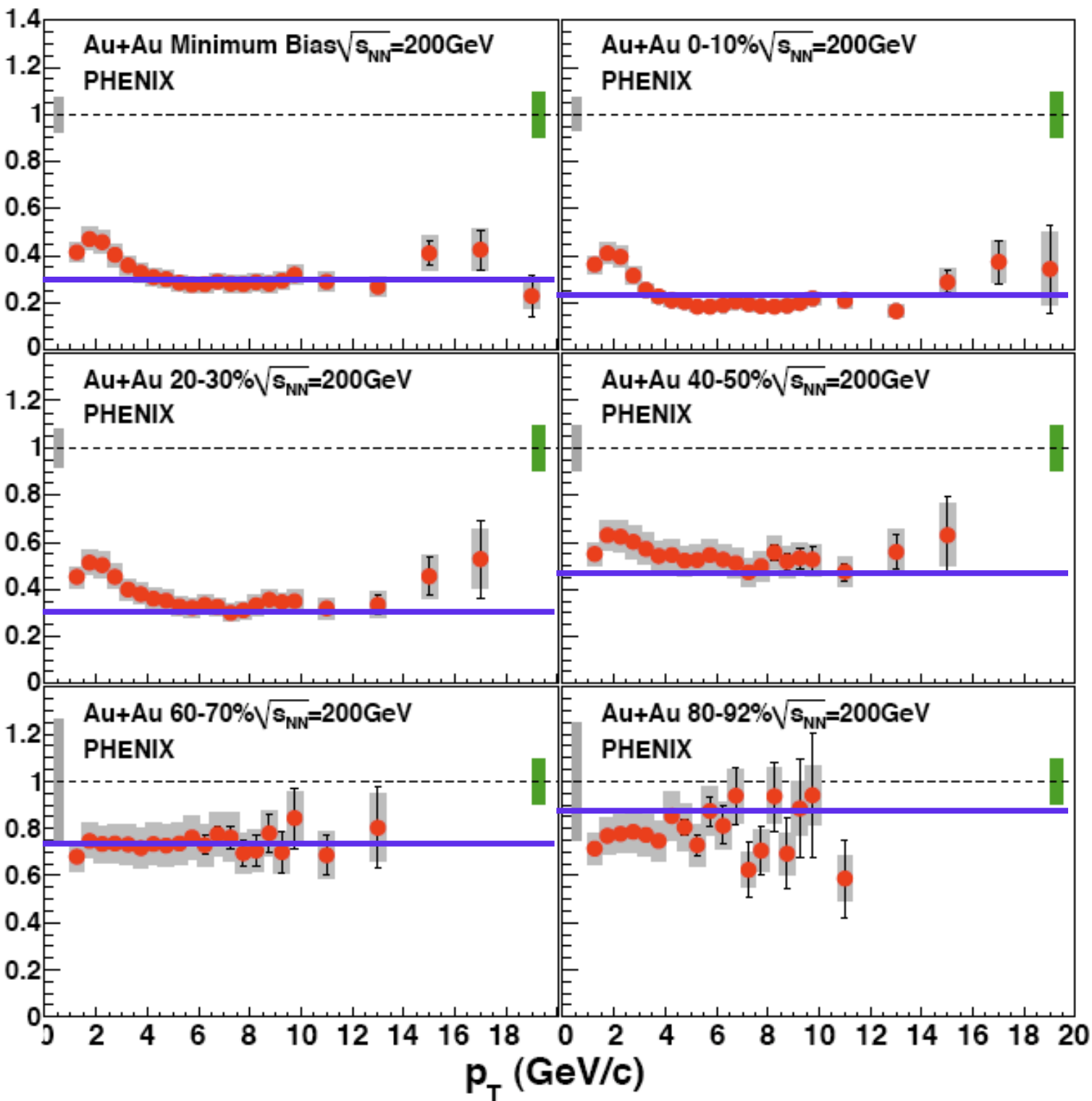
$N_{\text{part}}, N_{\text{coll}}$ from
DK, M. Nardi
nucl-th/001202

UBM:

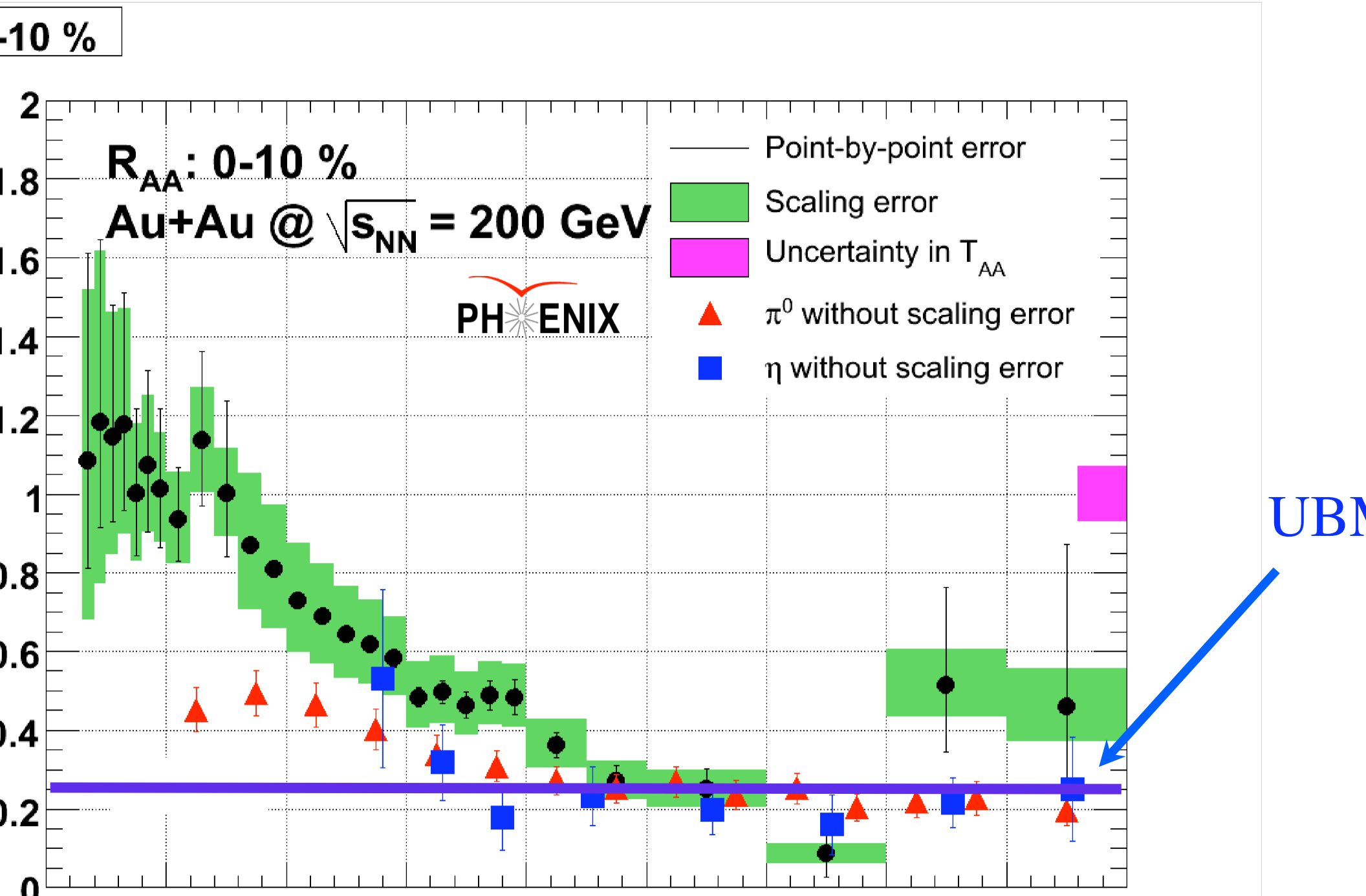
$$R_{AA} = c \times \frac{(\Lambda)}$$

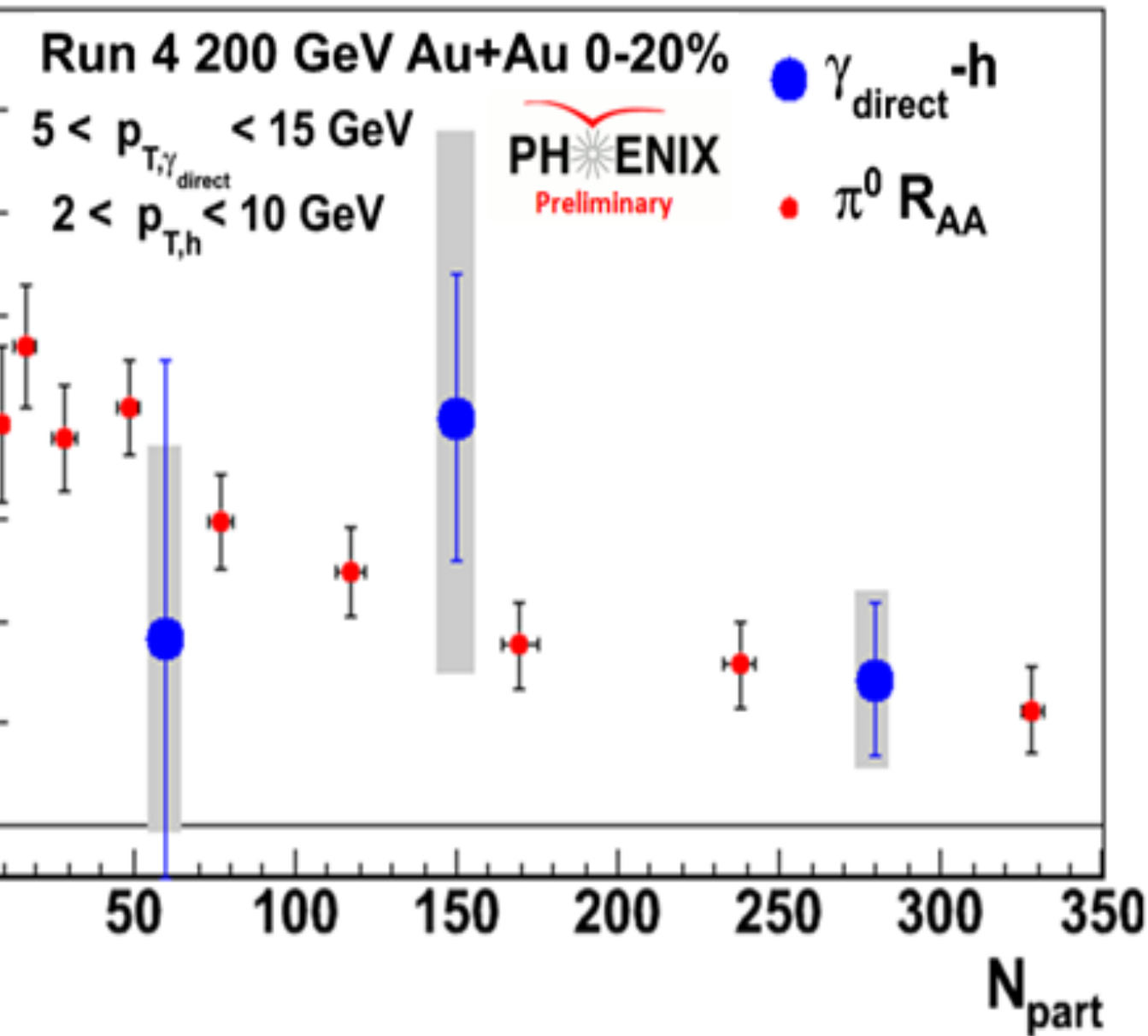
One parameter
Not a real

$$c = 1.5 \pm$$



Heavy quarks and UBM:

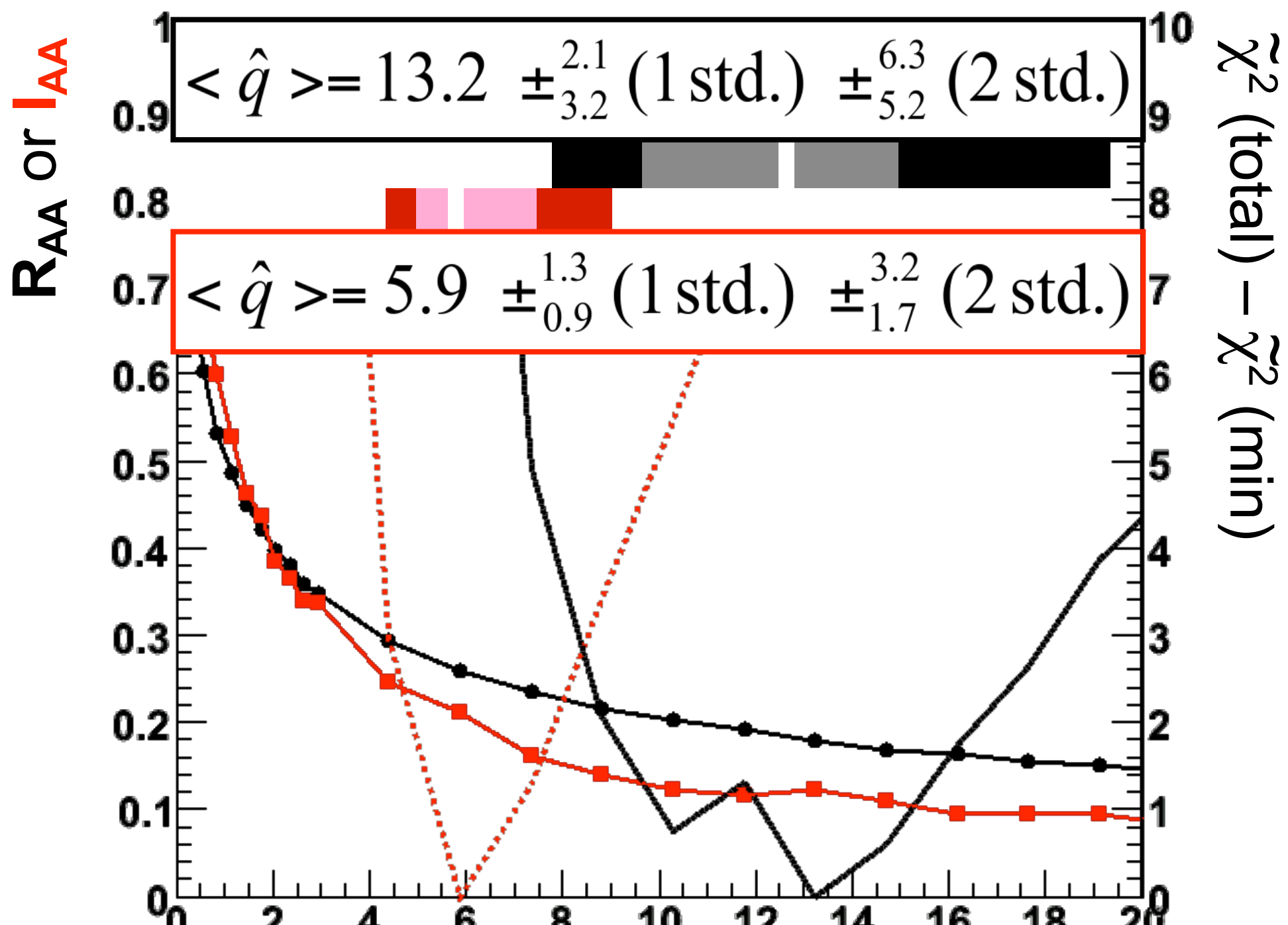




J. Frantz [PHENIX]
Hard Probes'08

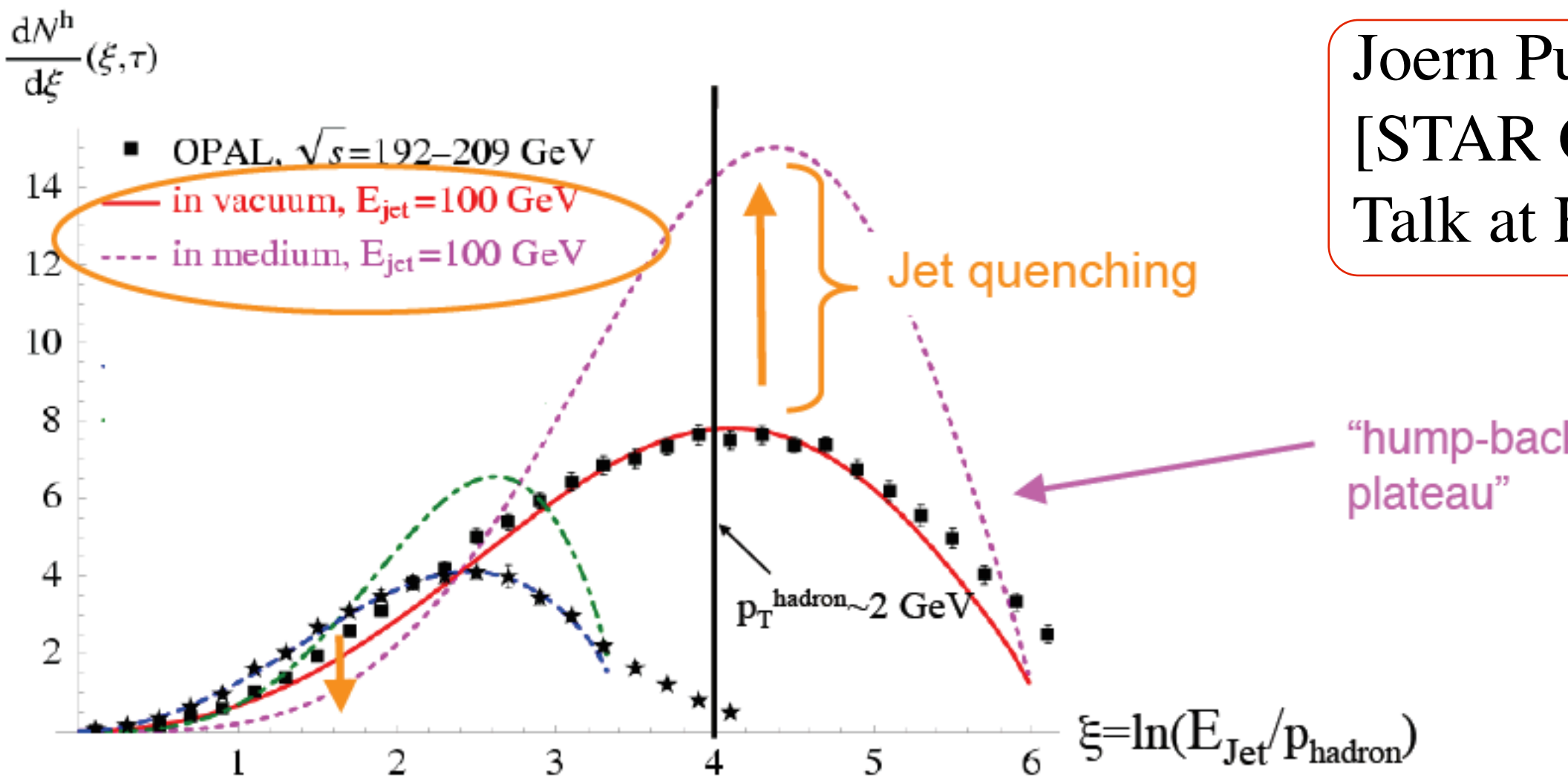
$R_{AA} \sim R_{AA} \rightarrow$ surface bias paradigm (still with large uncertainties)

first look @ Run7 statistical improvements look



MLLA: good description of vacuum fragmentation (basis of PYTHIA)

Introduce medium effects at parton splitting *Borghini and Wiedemann, hep-ph/0506218*



Joern Pu
[STAR C
Talk at I

quenching $\Rightarrow$ fragmentation should be strongly modified at $p_T^{hadron} \sim 1-5$ GeV

Can we measure this at RHIC @ 200 GeV?

Au+Au HT $E_t > 7.5$ GeV; p+p HT $E_t > 5.4$ GeV

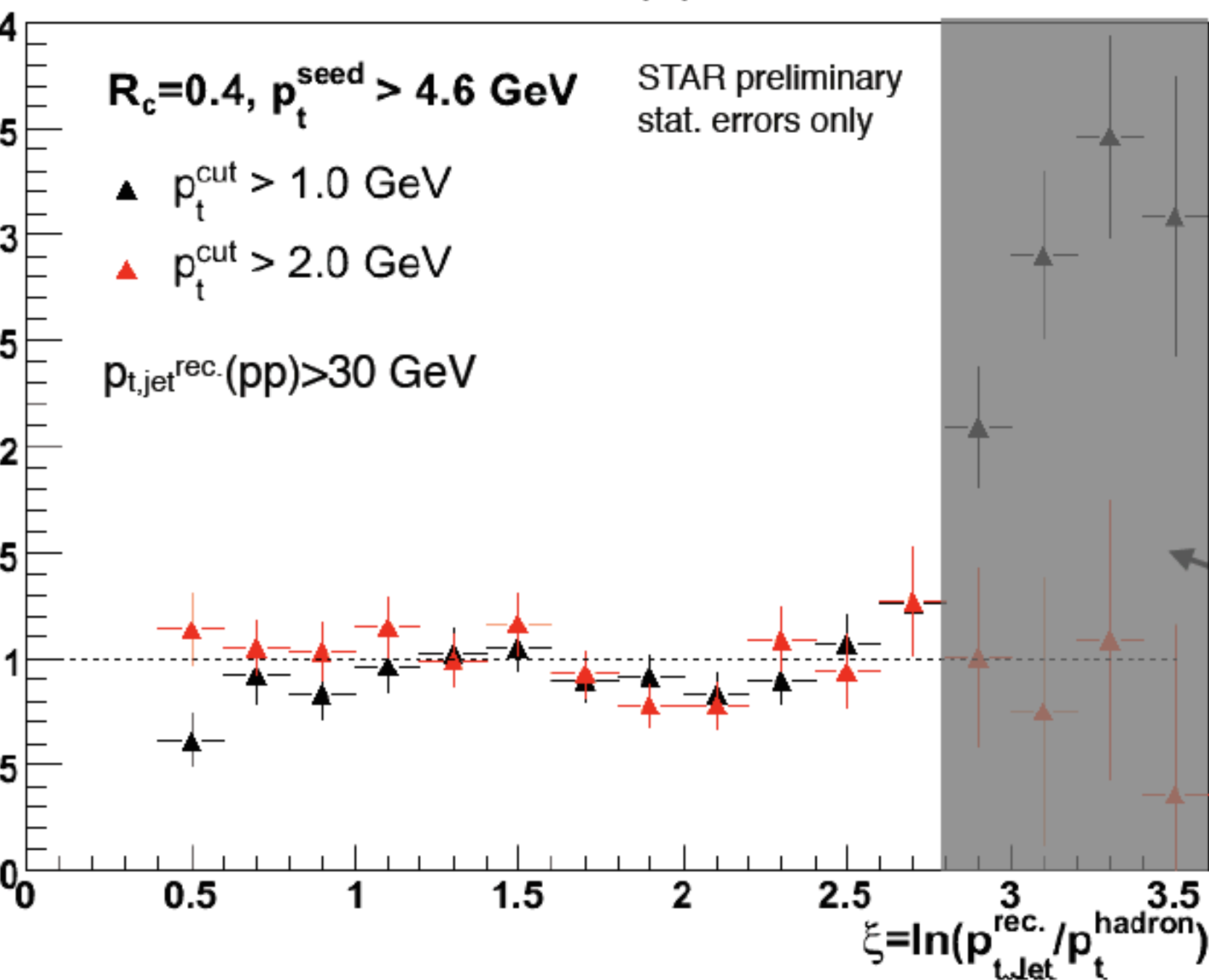
$R_c = 0.4$, $p_t^{\text{seed}} > 4.6$ GeV

STAR preliminary
stat. errors only

▲ $p_t^{\text{cut}} > 1.0$ GeV

▲ $p_t^{\text{cut}} > 2.0$ GeV

$p_{t,\text{jet}}^{\text{rec.}}(\text{pp}) > 30$ GeV



To select correct
p+p jet-population
0-20% Au+Au
Pythia simulation

$p_{t,\text{jet}}^{\text{rec.}}(\text{Au+Au})$
for $p_t^{\text{cut}} > 2$ GeV

$p_{t,\text{jet}}^{\text{rec.}}(\text{Au+Au})$
for $p_t^{\text{cut}} > 1$ GeV

dominated by
uncertainty
due to background
subtraction
 $p_t^{\text{hadron}} < 2$ GeV

apparent modification in the fragmentation function with respect to p+p

TAR preliminary; stat. errors only
T not trigger bias corrected!

LOCone

$R_c=0.4$, $p_t^{\text{Seed}} > 4.6$ GeV
 $p_t^{\text{cut}} > 2$ GeV

Au+Au HT 0-10%
Au+Au MB 0-10%
p scaled by N_{bin}

10 20 30 40 50
 E_T [GeV]

- With $p_t^{\text{cut}} > 2$ GeV:
jet yields suppressed

- p_t^{cut} biases jet select

(More details/systematics see talk)

$p_{t,\text{jet}} > 30$ GeV: range
for fragmentation fun
measurements

Caveat: Additional bias due to
triggered events.

Study trigger bias with minbias
events (on tape)

pts: p+p mid-cone corrected to particle level (scaled by N_{bin})

points: Au+Au minbias corrected for p_t^{cut} and eff. using Pythia

points: Au+Au HT trigger not corrected for p_t^{cut} and eff. using Pythia

scenarios:

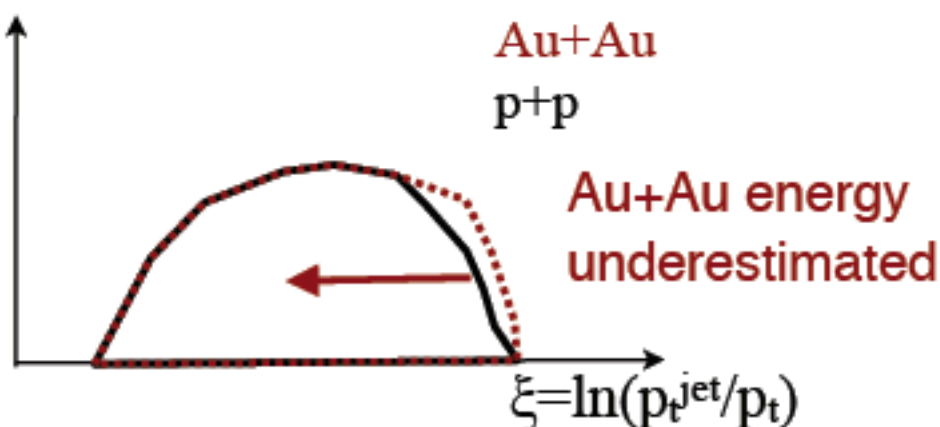
-energy bias due to energy loss and p_t^{cut} :

-based correction underestimates jet energy carried by low p_t particles

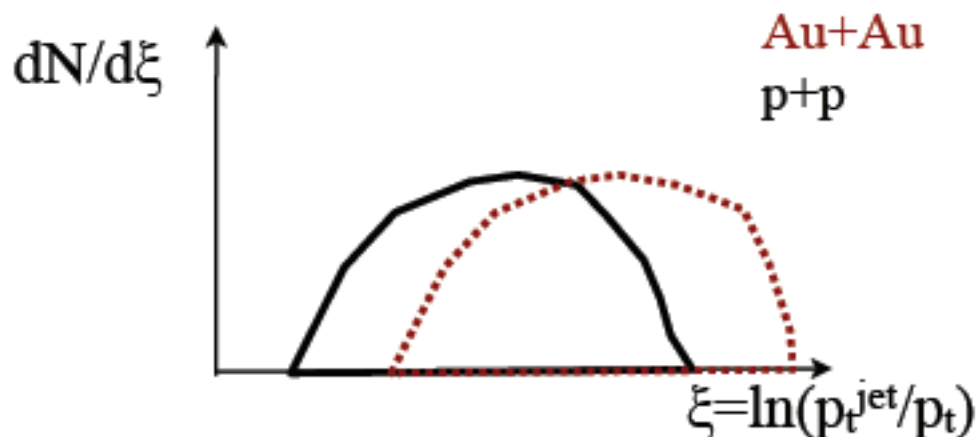
+Au jet energy is underestimated

Large Au+Au quenching:

observed distributions



true distributions



"black-and-white":

fraction of jets quenched so much that they are lost; surviving jets are unmodified

have all the tools and data needed to address and distinguish between these two scenarios, but MC quenching model needed !

even ~ 50 GeV jets are quenched;
evidently their fragmentation is not
modified by the medium (?)

talks by J. Putschke, S.
M. Heinz at Hard Probe

A speculation:

only jets from the surface escape,
no jets from the bulk (the bound)

Lienard formula predicts not only the magnitude of
energy loss, but the entire momentum and angular
distribution of the induced “radiation”:
quantitative comparison is possible

Summary

If the AdS/CFT correspondence provides a qualitatively correct guidance to what happens at strong coupling and strong fields, there should exist a universal upper bound on the energy of partons escaping from the interaction region

The existence of the bound, and the corresponding angular and energy dependencies of the medium-induced radiation can (and should be) tested in experiment