BROOKHAVEN
NATIONAL LABORATORY

Hard Probe Cafe

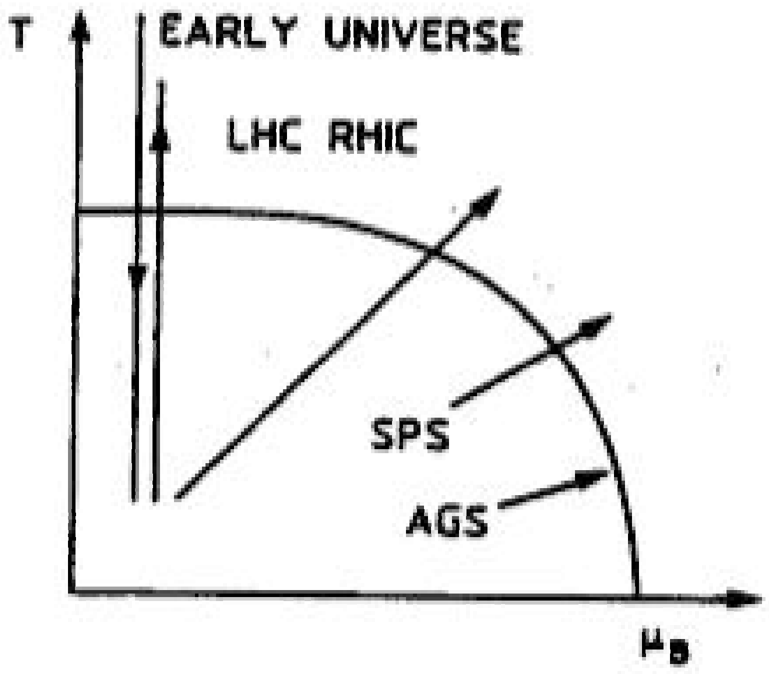
CERN, Geneva 1994
LBL, Berkeley 1994
ECT*, Trento 1995
INT, Seattle 1996
CFIF, Lisbon 1997
INT, Seattle 1998
JYFL, Jyväskylä 1999
BNL, New York 2000
NBI, Copenhagen 2001

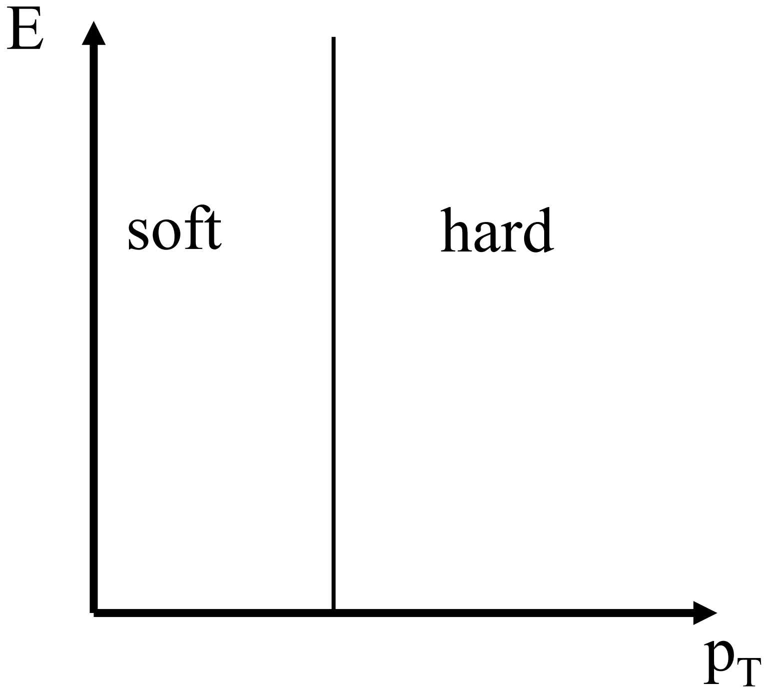
Opening talk
by H. Satz

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Ericeira 2004

QCD maps, ca 1994





The Treaty of Tordesillas: Portugal - Spain, 1494

Dividing
the unknown…

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

The lessons?

1. The less we know, the sharper are the boundaries

2. Sharp boundaries do not last long -

3. They disappear with the advance of knowledge

Why focus on hard probes?

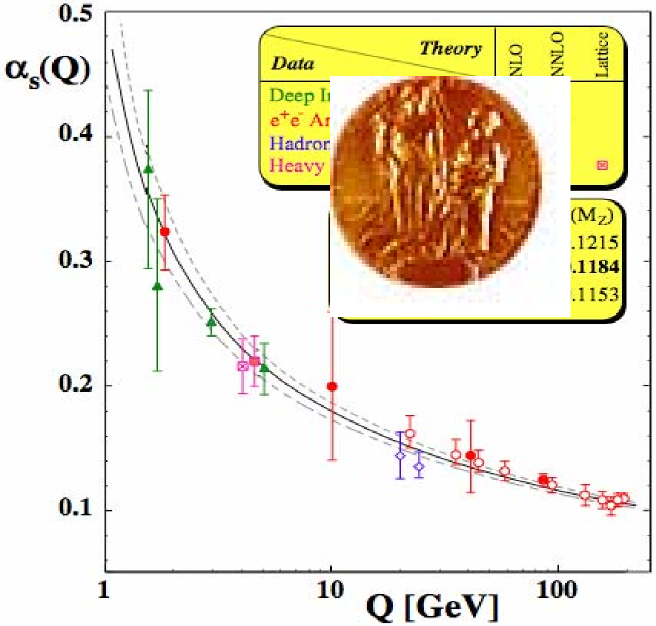
One reason:

I would rather discover a single fact, even a small one, than debate the great issues at length without discovering anything new at all.

-Galileo Galilei

But we have even better ones…

Asymptotic freedom and hard probes



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)

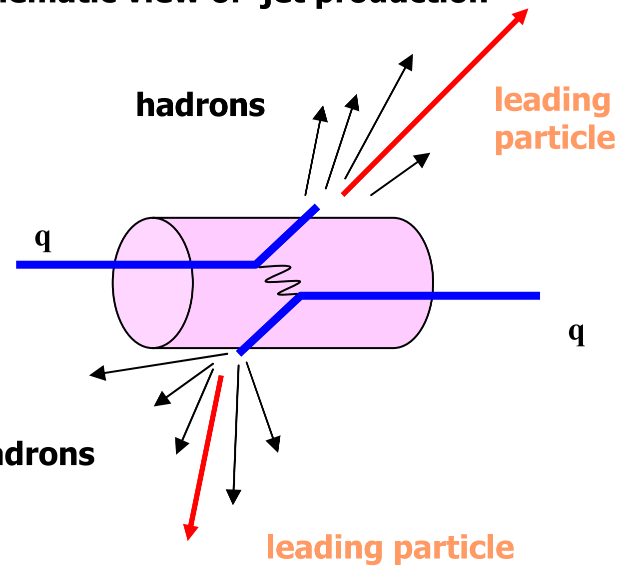
=> Scaling violations, jet structure

Fast partons as a probe

QGP: A.Accardi,
N.Armesto,A.Majumder,
B.Muller,X.N.Wang,
U.Wiedemann

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

schematic view of jet production



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

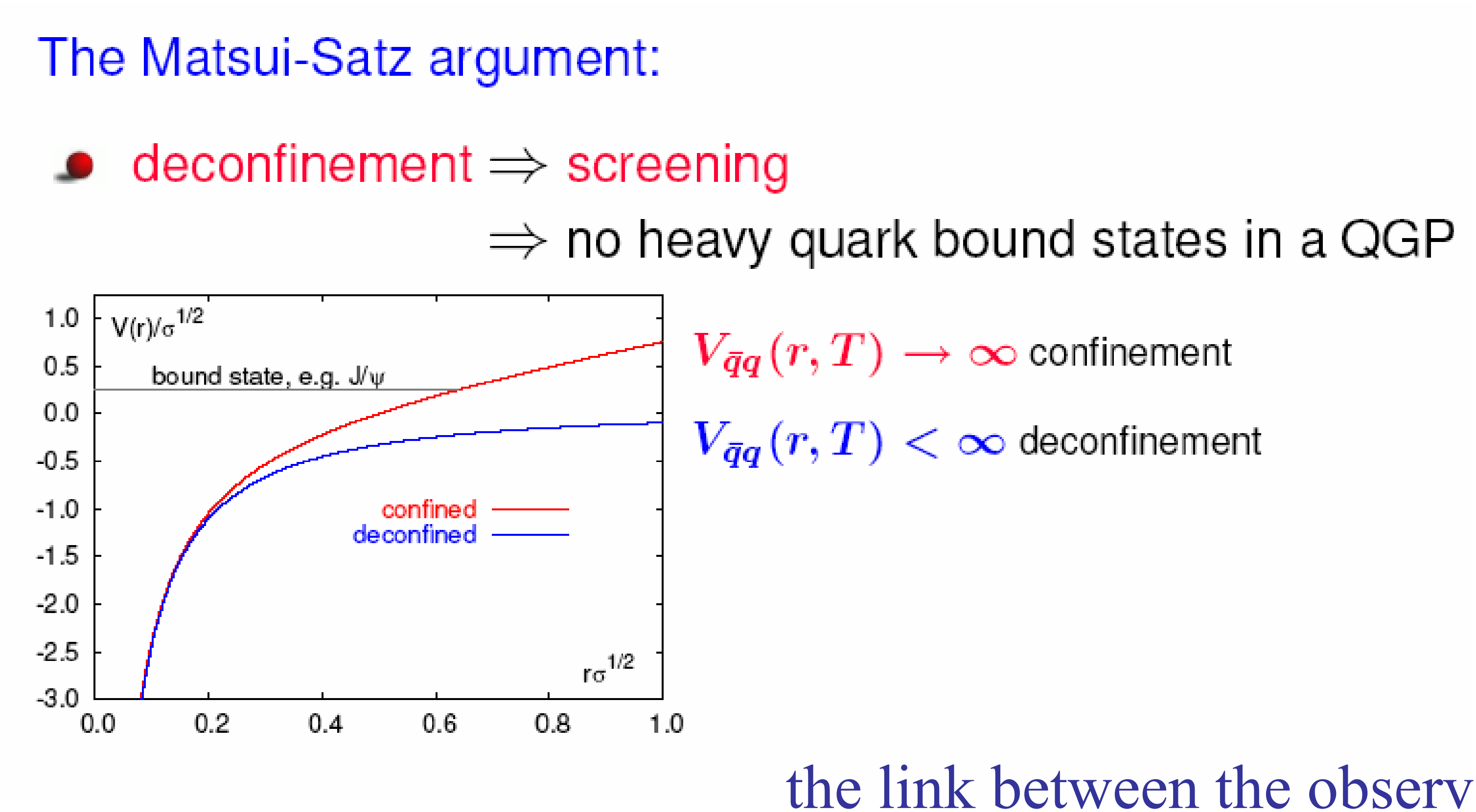
In cold nucleus at small x

$\Lambda^2 = Q_s^2$ - the saturation scale;

$$Q_s^2 = \hat{q}_{cold} L$$

CGC: R.Baier, F.Gelis,
J.Jalilian-Marian, E.Iancu,
L.McLerran, A.Mueller,
D.Triantafyllopoulos,
K.Tuchin, R.Venugopalan

Heavy quarkonium as a probe



The Matsui-Satz argument:

- deconfinement ⇒ screening

  ⇒ 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

Talk by F. Karsch

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

What do we probe?

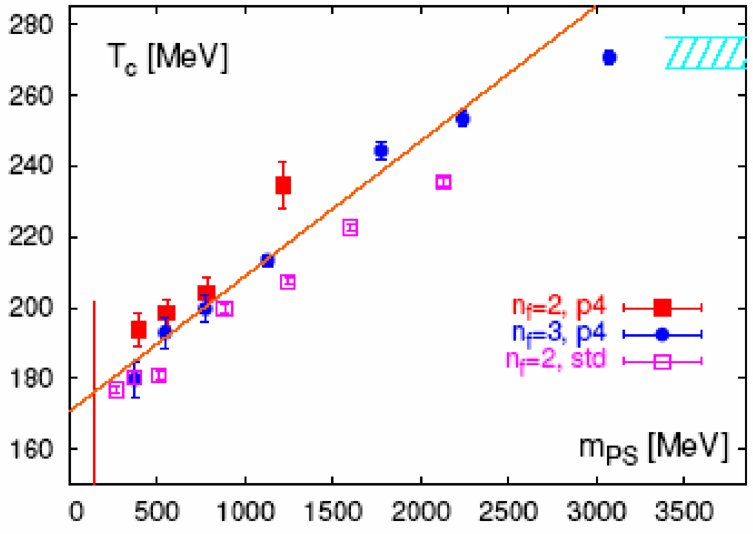
1. Strongly coupled Quark-Guon Plasma

2. Color Glass Condensate

sQGP

J.-P.Blaizot,
R.Gavai,
F.Karsch,
K.Rajagopal,
E.Shuryak

Talk by F.Karsch:

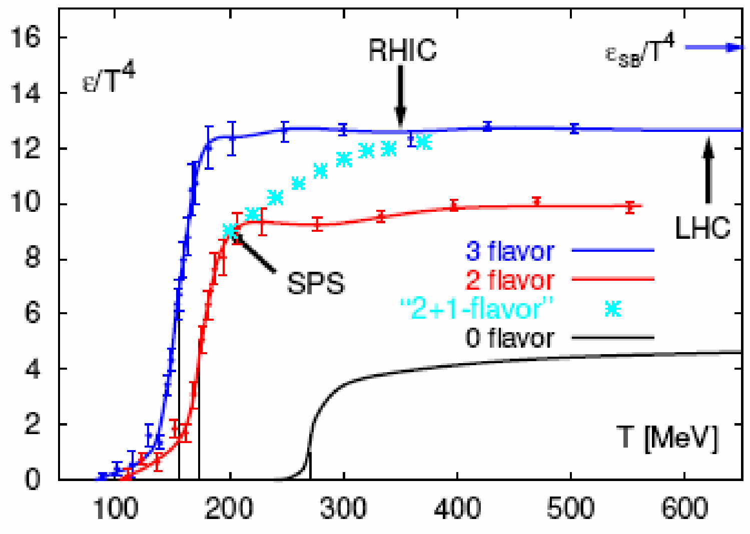


$$m_{PS} \simeq 140\ MeV\ :\ \ T_c \simeq 175\ MeV$$

$$m_{GB} \simeq 1.5\ GeV\ :\ \ T_c \simeq 265\ MeV$$

$$(m_{PS} = \infty)$$

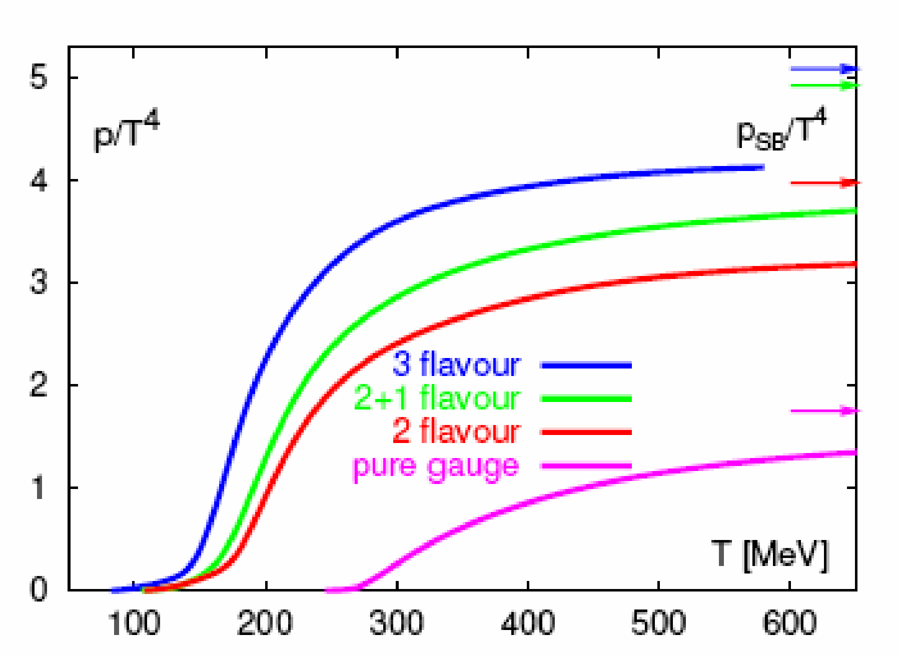
lightest masses apparently do not control the transition

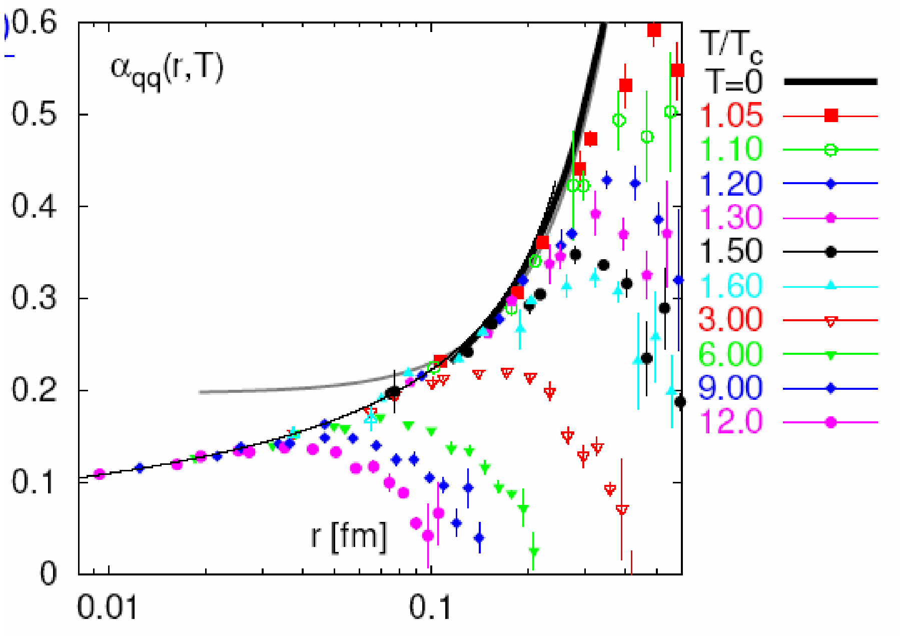


$$n_f = 2:\ \ \epsilon_c \simeq (6 \pm 2)\, T_c^4$$
$$\simeq (0.3 - 1.3)\, GeV/fm^3$$
$$n_f = 0:\ \ \epsilon_c \simeq (0.5 - 1)\, T_c^4$$
$$\simeq (0.3 - 0.7)\, GeV/fm^3$$

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

Strongly coupled QGP



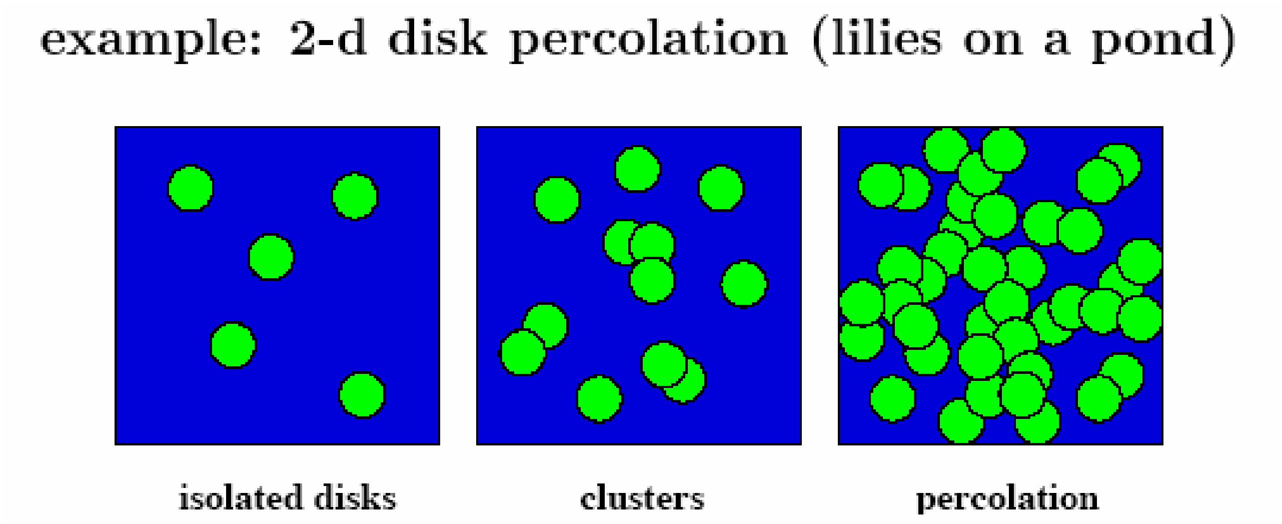


F.Karsch

$\epsilon \neq 3P$

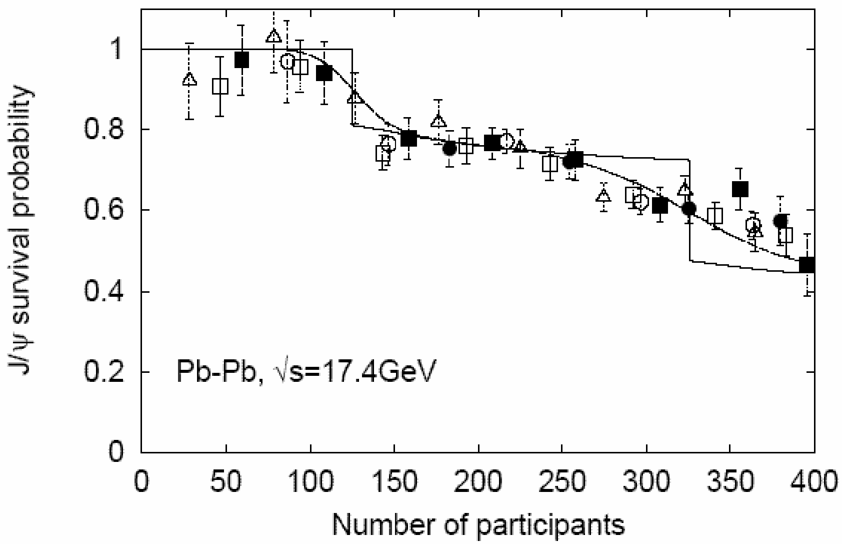
T-dependence of
the running coupling
develops in the NP-region
at $T < 3\ T_c$

Percolation ↔ deconfinement, CGC ?



H.Satz

T.Hatsuda

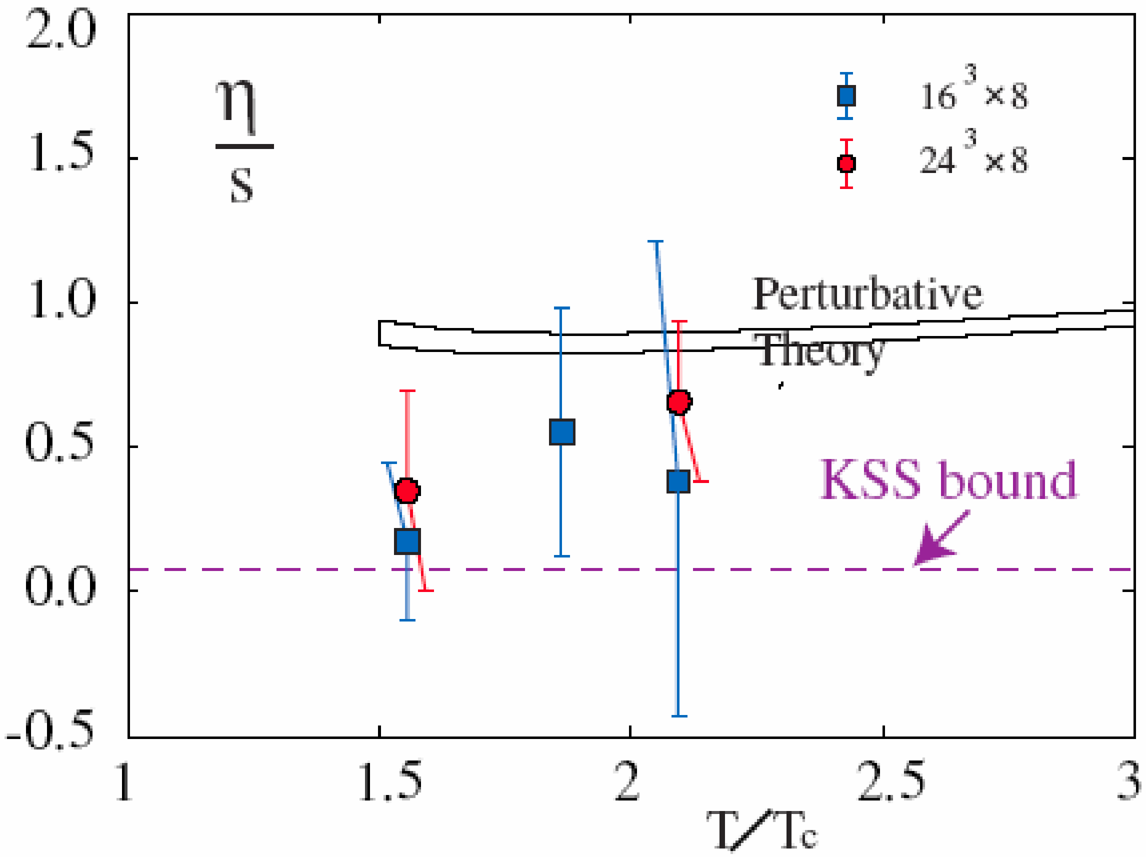


M. Nardi

J. Dias de Deus,
C. Pajares

sQGP: more fluid than water?

J.P.Blaizot,
R.Gavai,
T.Hatsuda,
K.Rajagopal,
E.Shuryak



Perfect fluid

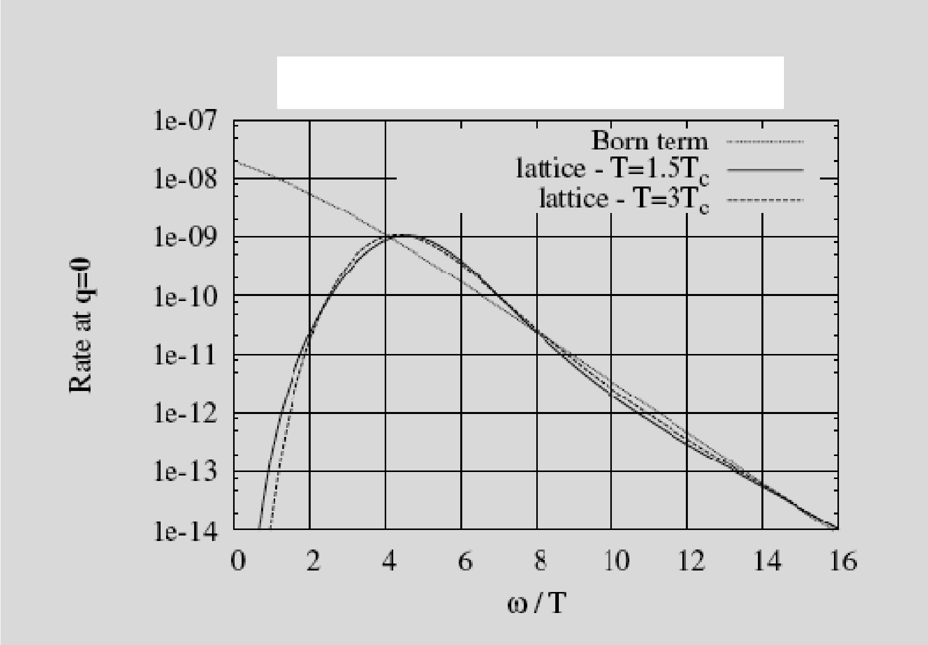
Talk by T. Hatsuda

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

KSS bound:
strongly coupled SUSY QCD = classical supergravity

sQGP and the quasi-particle picture

J.-P.Blaizot, K.Rajagopal



Karsch et al, hep-lat/0110208

Plot from F. Gelis, hep-ph/0209072

Damping is anomalously large

Effect of collisions

Width of quasiparticles

$$\gamma = n\sigma \qquad n \sim T^3$$

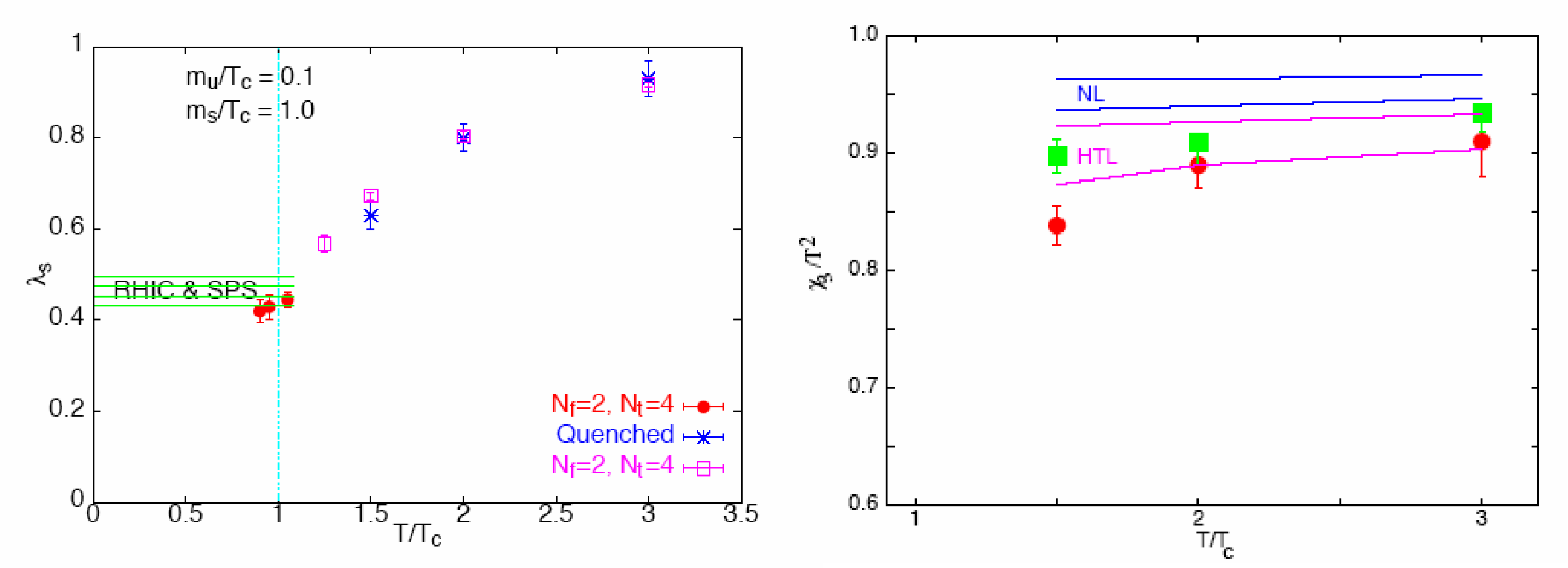
$$\sigma = \int \mathrm{d}q^2 (\mathrm{d}\sigma/\mathrm{d}q^2)$$

$$\mathrm{d}\sigma/\mathrm{d}q^2 \sim g^4/q^4$$

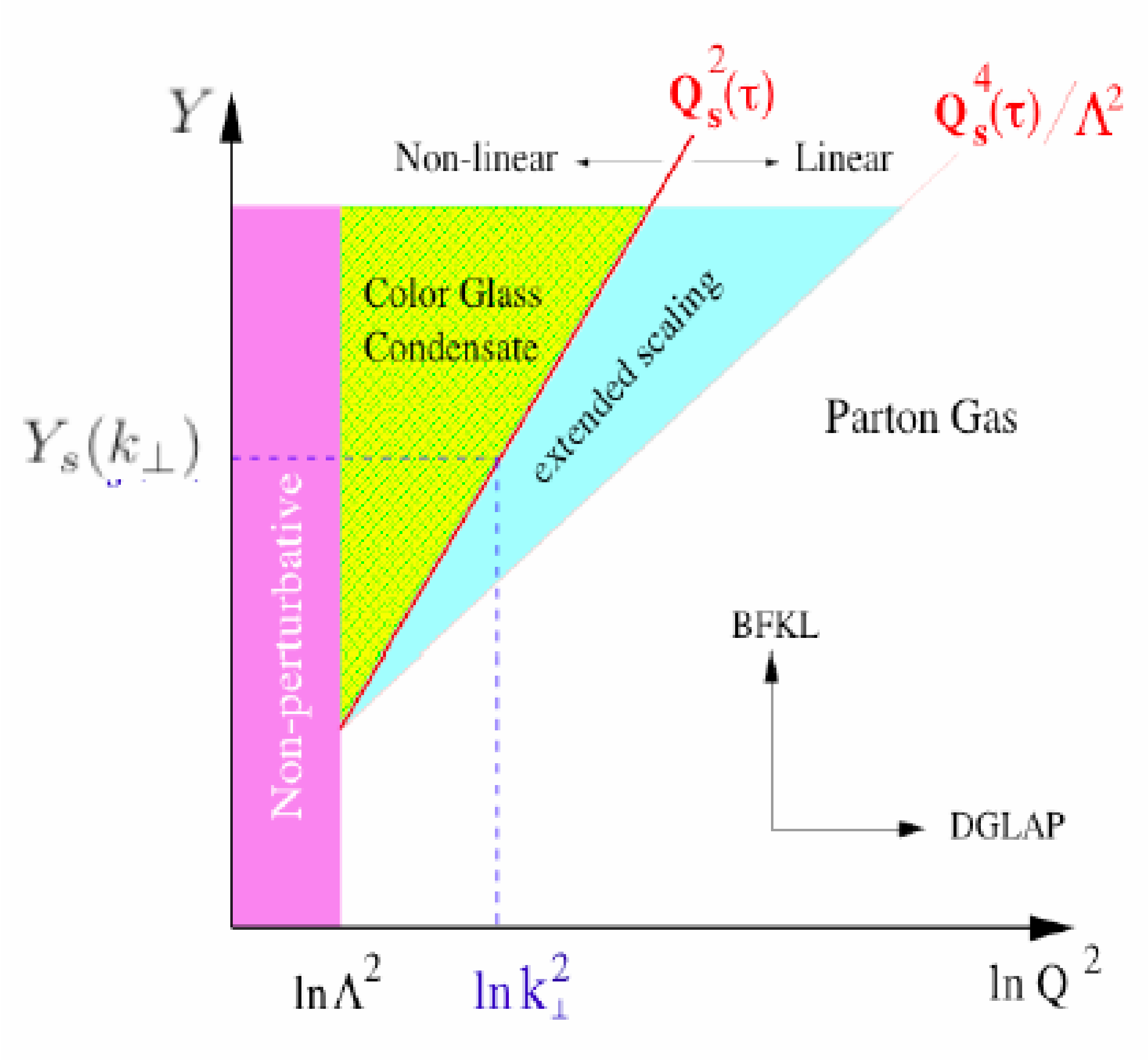
$$\gamma \sim g^4 T^3 \frac{1}{m_D^2} \sim g^2 T$$

Quark number fluctuations in sQGP

R. Gavai

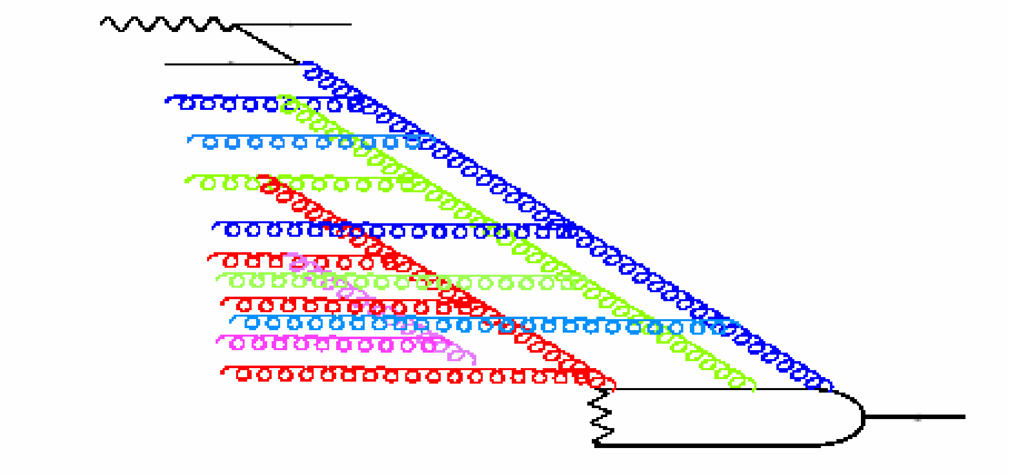


Color Glass Condensate



Overviews:
J. Bartels,
E. Iancu,
L. McLerran,
A. Mueller
R. Venugopalan

In search of the ultimate non-linear evolution equation



GLR, MQ
JIMWLK
BK
BLV, …

Long-standing problem:

Recent advances:
the role of fluctuations
(talk by E. Iancu)

BK-equation (perturbation theory!) predicts
power-law fall-off at large b,
nonperturbative strong interactions needs
exponential fall-off:
need to modify the evolution equation!

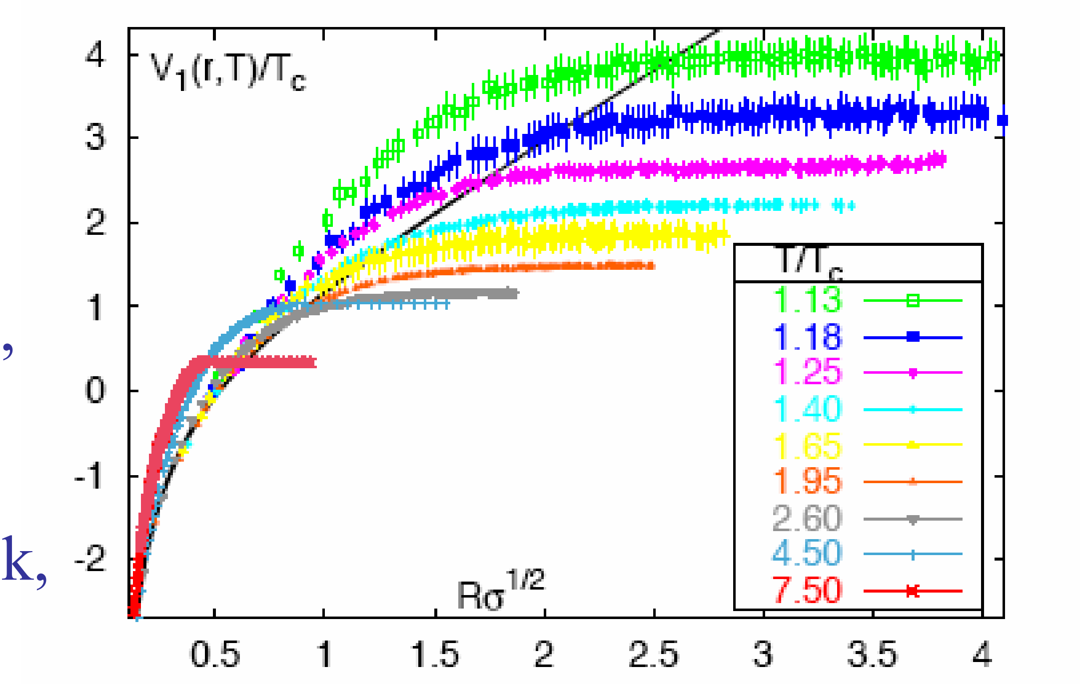
(talk by J. Bartels)

The Probes

1. Heavy Quarkonium
2. Jets
3. Heavy Quarks
4. Dileptons

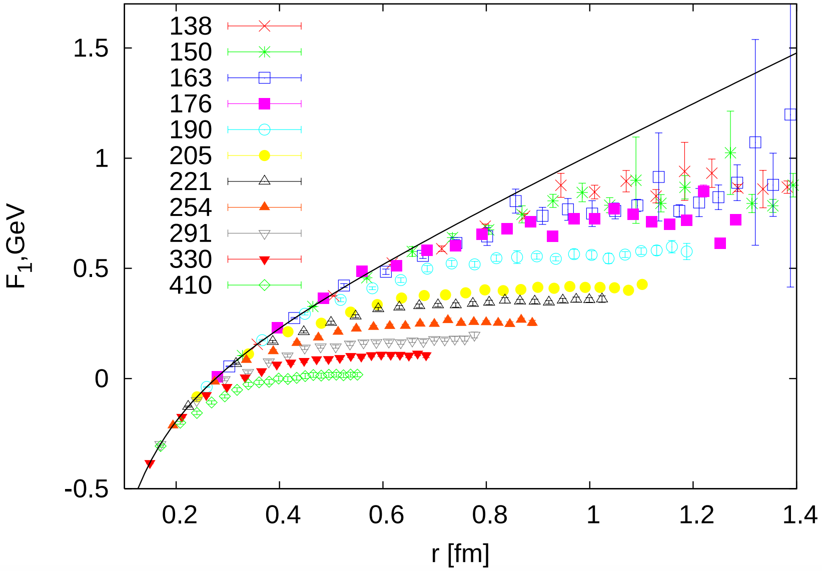
Heavy quark internal energy above T

Talks by
F.Karsch,
P. Petreczky,
K. Petrov,
F. Zantow,
O.Kaczmarek,
S. Digal

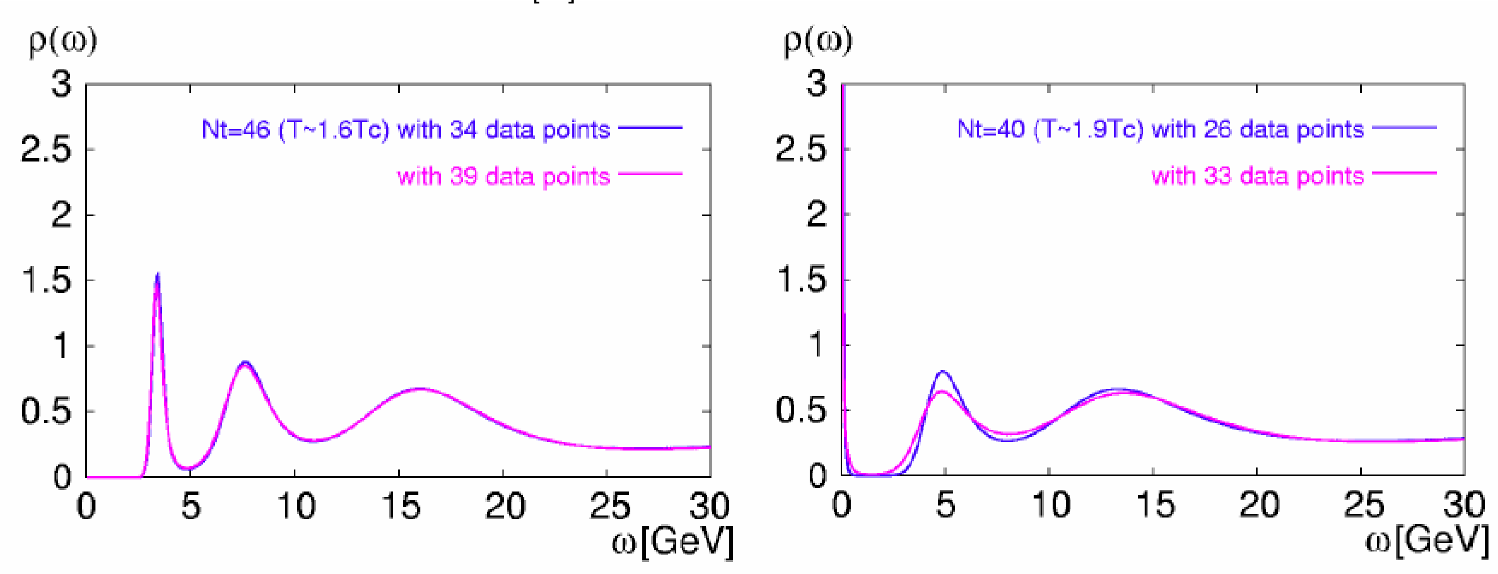


O.Kaczmarek, F. Karsch, P.Petreczky,
F. Zantow, hep-lat/0309121

Heavy quarkonia above T_c



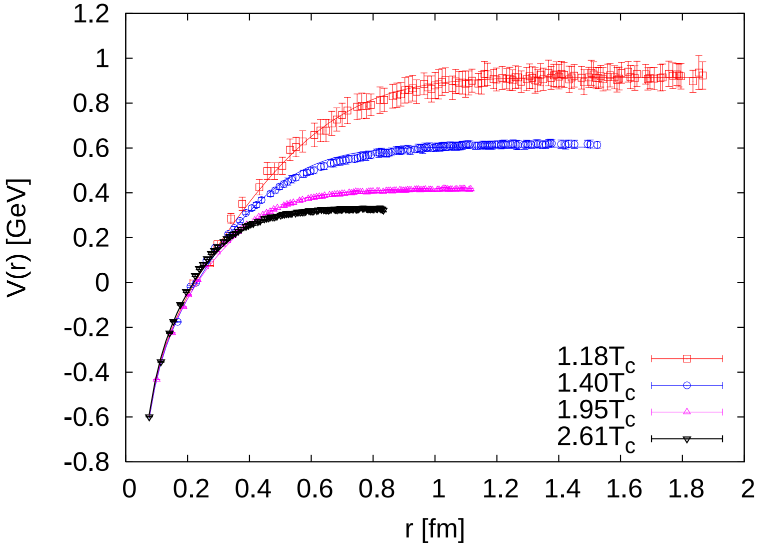
Talks by P.Petreczky,
K.Petrov,
S.Digal,
F.Zantow,
O.Kaczmarek



T.Hatsuda

Heavy quarkonia above T_c: lattice QCD meets potential models

Imaginary time quarkonium correlators $G_{lat}(\tau, T)$ can be reliably calculated on lattice



Talks by
A. Mocsy,
P.Petreczky

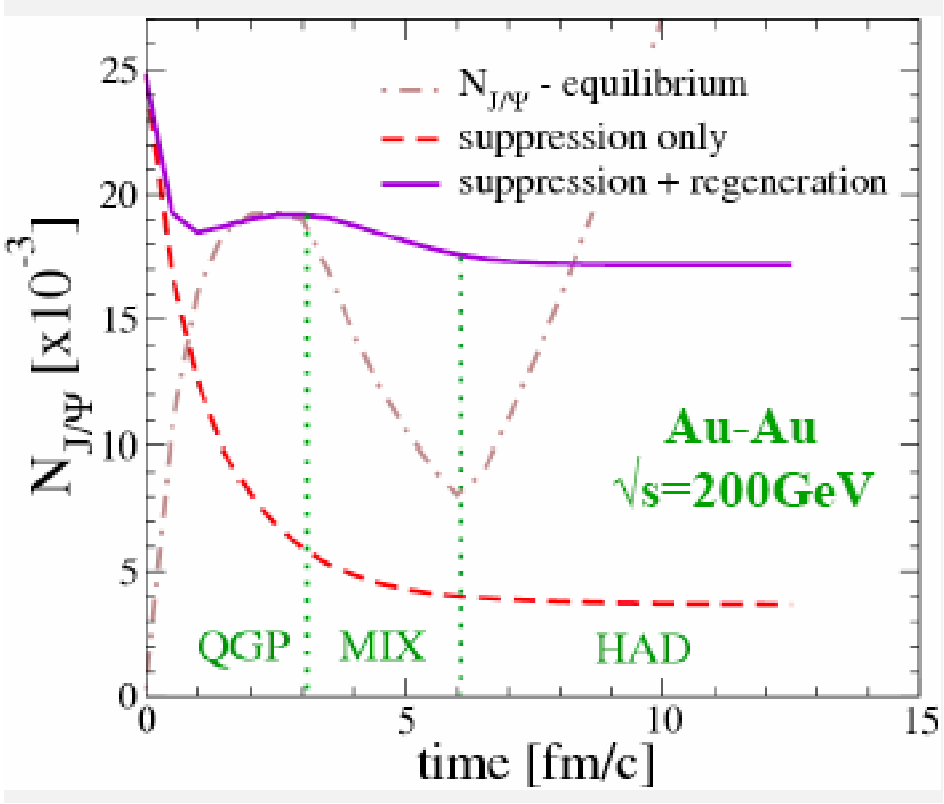
Try to understand them in a potential model;

note: OPE $\neq$ potential model

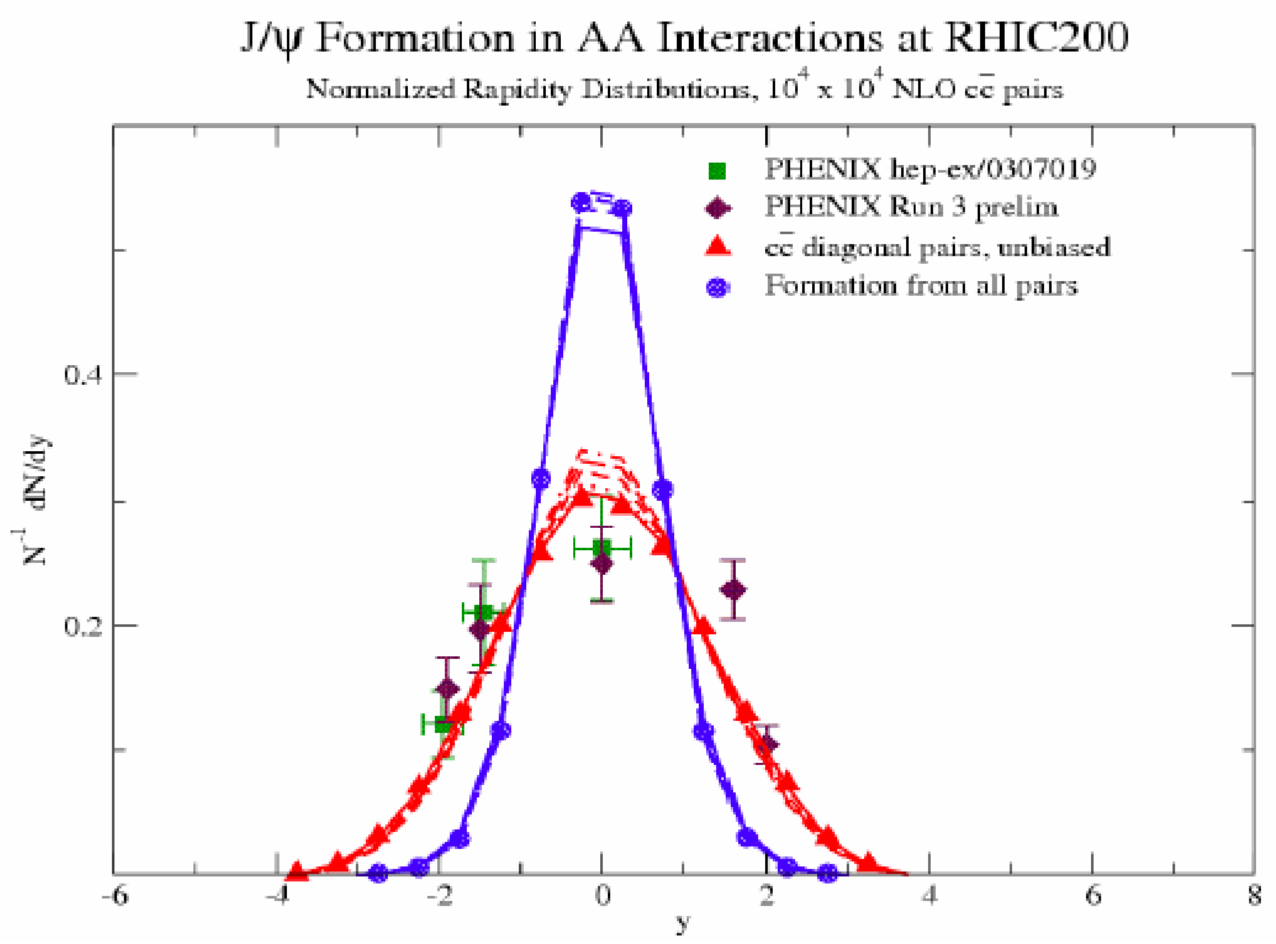
$$\sigma(\omega, T) = 2M_iF_i(T)\delta(\omega^2 - M_i^2(T)) + \theta(\omega - s_0(T))\omega^2, \;\; F_i \sim |R(0)|^2$$

Heavy quarkonia above T_c: screening vs ionization

D. Blaschke,
M. Nardi,
R. Rapp
R. Thews



J/ψ formation from recombined charm pairs

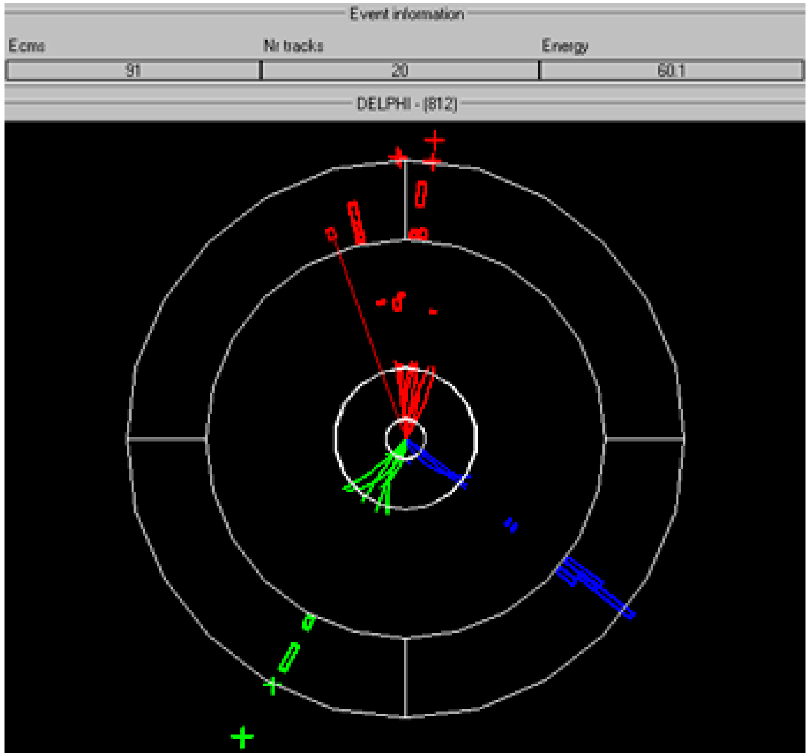


R. Thews
R. Rapp

Recombination
narrows
the rapidity
distribution

Jets

Jet d’Eau
Geneva



Event information

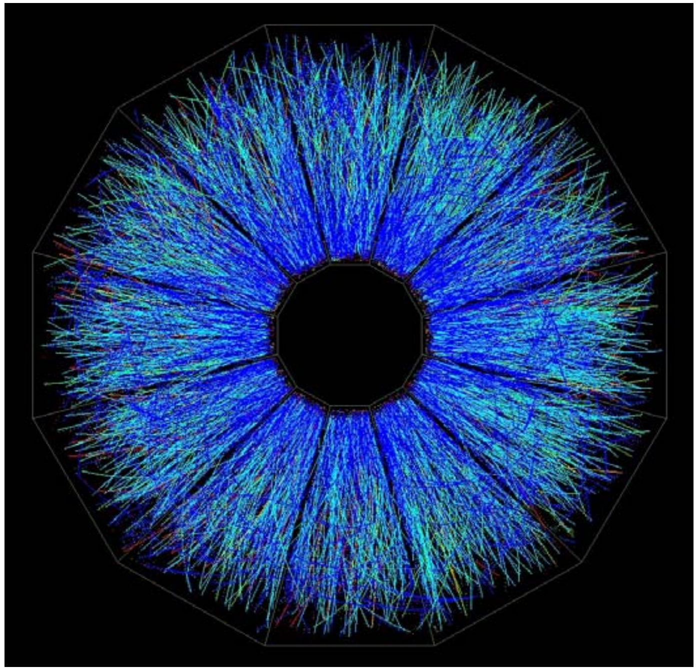
Ecms: 91
Nr tracks: 20
Energy: 60.1

3-jet event at LEP,
CERN, Geneva

Jets - II

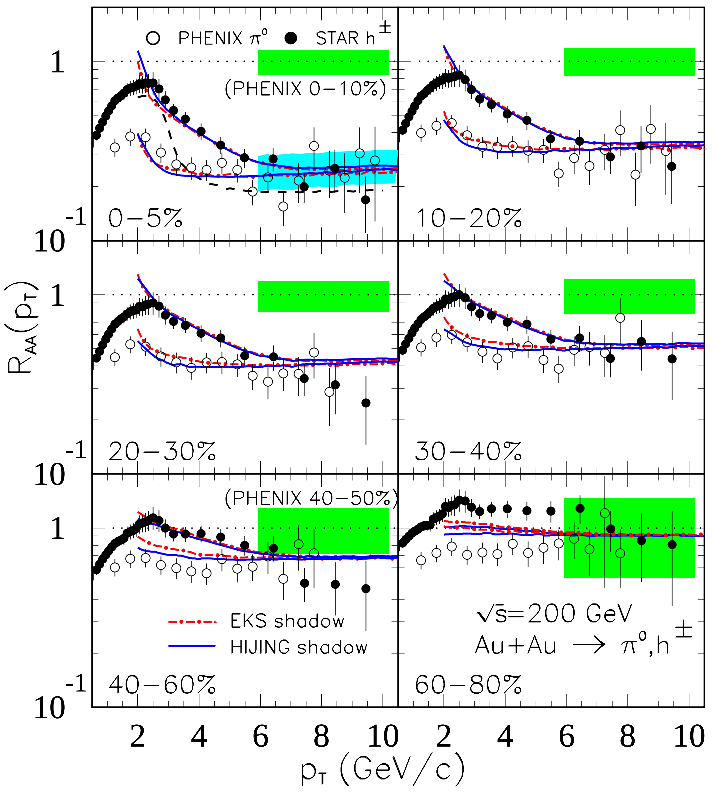
QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

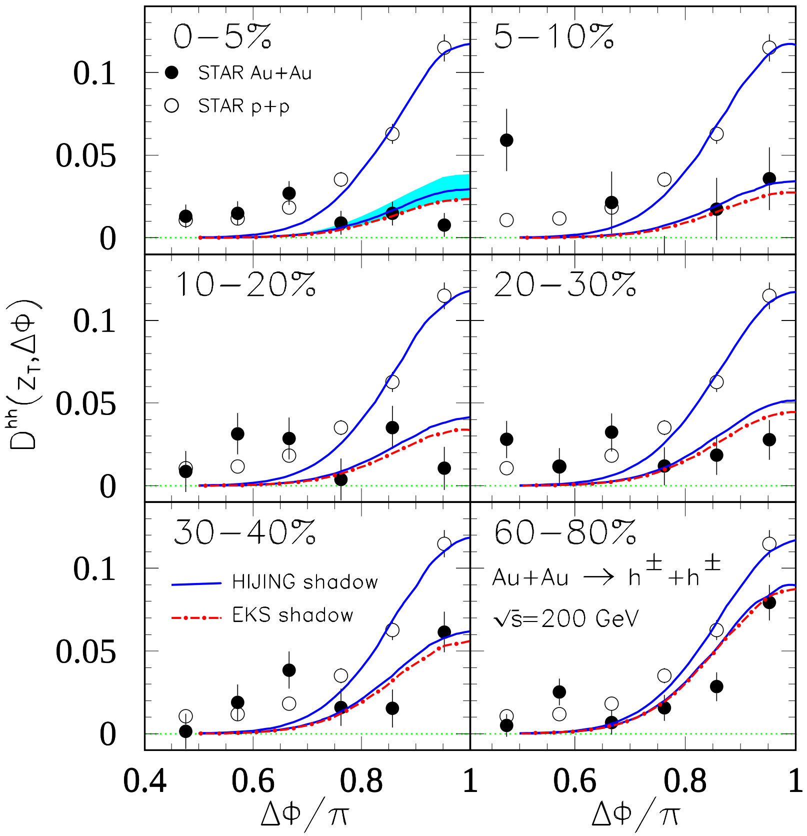
Atlantic ocean,
Coast of Portugal



Au-Au collision event, RHIC
Long Island, New York

Jet suppression



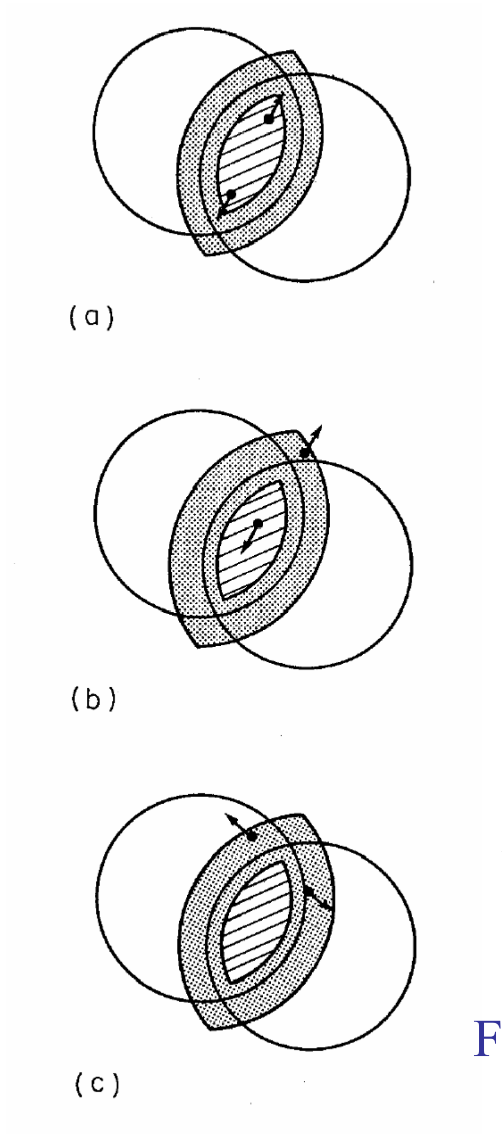


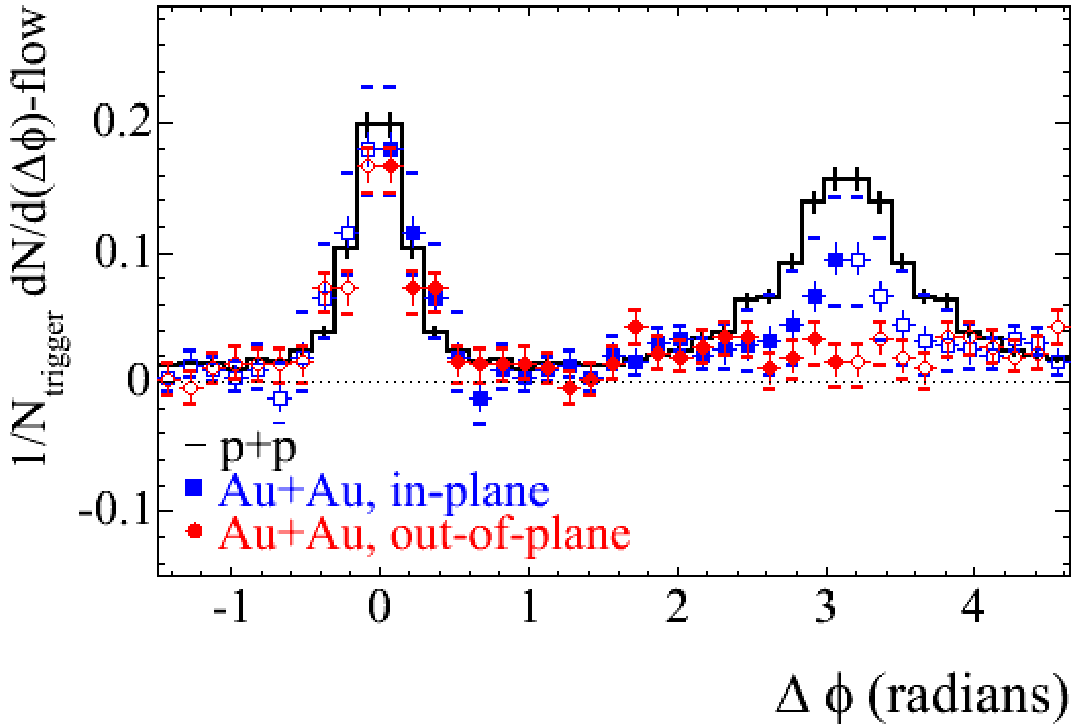
X.-N.Wang

A.Accardi, A.Majumder, U.Wiedemann

Geometry of jet suppression

Talks/lectures by N.Armesto, R.Baier, B.Muller, X.N.Wang, U.Wiedemann

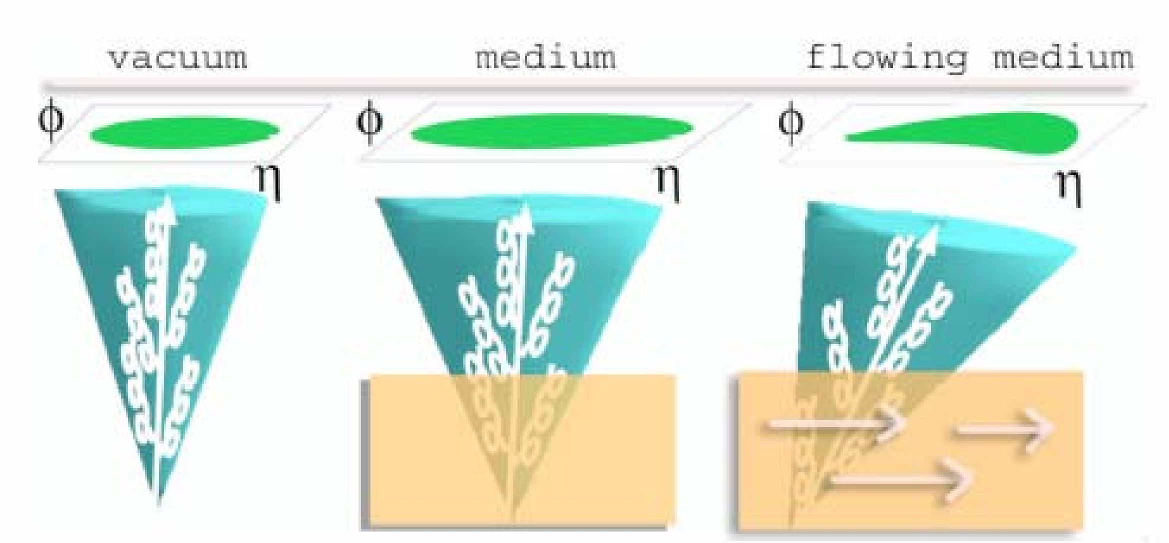


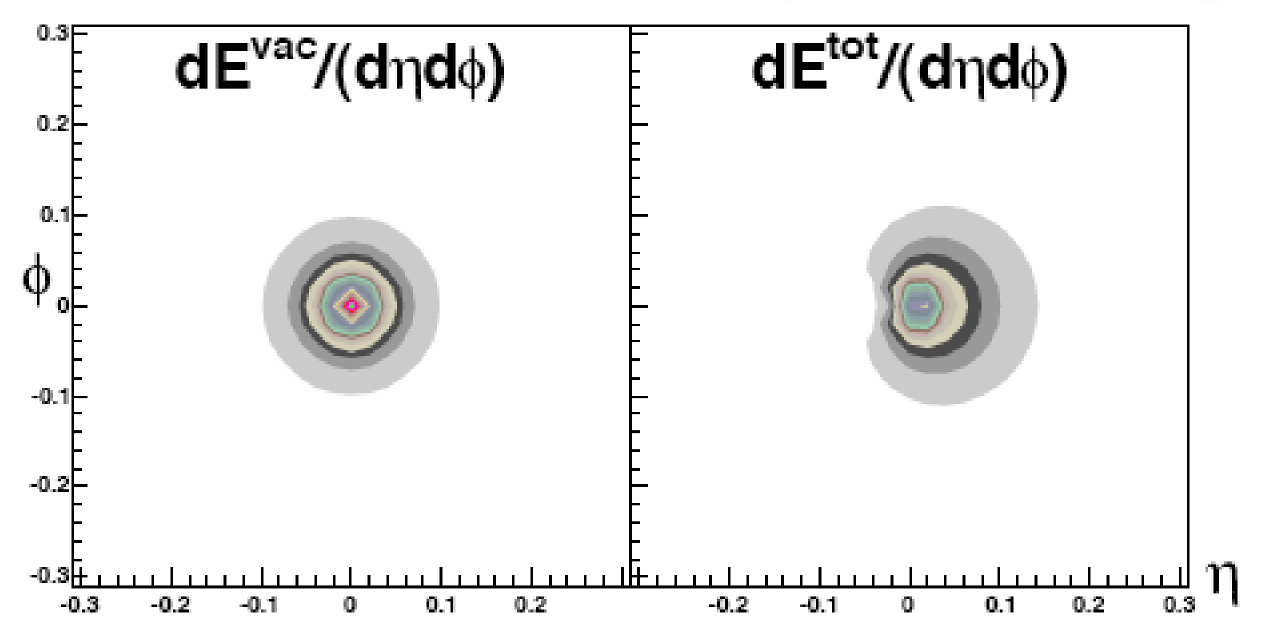


STAR Collaboration

Figure from J.Bjorken, FERMILAB-PUB-82-059-T

Jets and the flow





N.Armesto
U.Wiedemann

Sonic boom in sQGP?

E.Shuryak

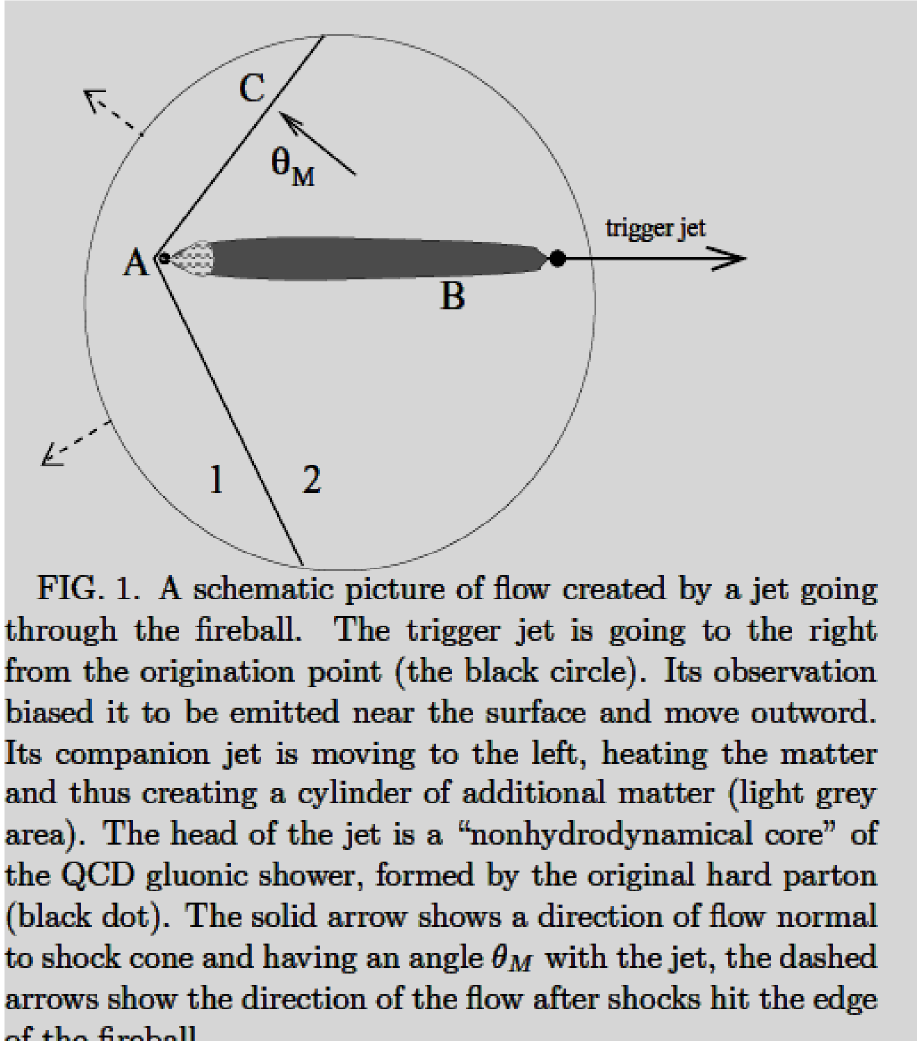


FIG. 1. A schematic picture of flow created by a jet going through the fireball. The trigger jet is going to the right from the origination point (the black circle). Its observation biased it to be emitted near the surface and move outword. Its companion jet is moving to the left, heating the matter and thus creating a cylinder of additional matter (light grey area). The head of the jet is a "nonhydrodynamical core" of the QCD gluonic shower, formed by the original hard parton (black dot). The solid arrow shows a direction of flow normal to shock cone and having an angle θ_M with the jet, the dashed arrows show the direction of the flow after shocks hit the edge of the fireball

Heavy quark energy loss: U. Wiedemann, M. Djordjevic, X.-N.Wang

Testing the Mechanism: E-Loss of Heavy Quarks

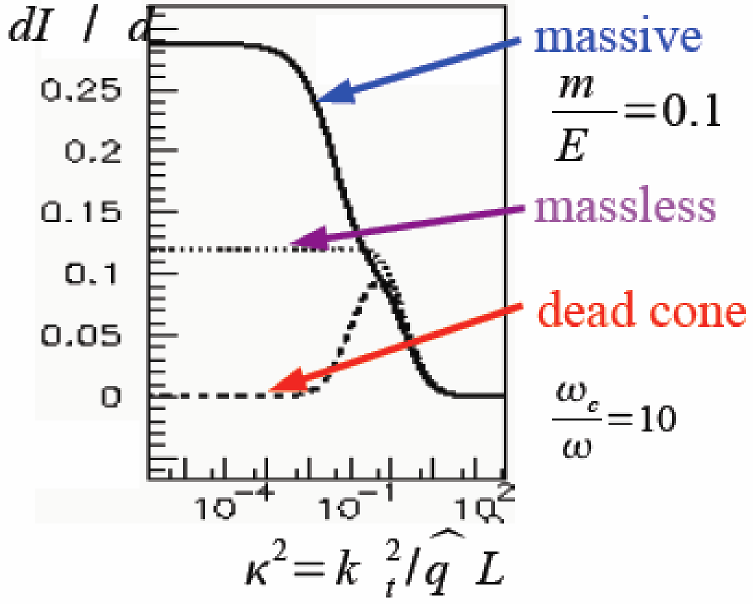
- vacuum radiation suppressed in the dead-cone $\theta < m/E$

Dokshitzer, Kharzeev, PLB 519 (2001) 199

$$\frac{1}{k_t^2} \Rightarrow \frac{k_t^2}{\left(k_t^2 + \omega^2 m^2/E^2\right)^2}$$

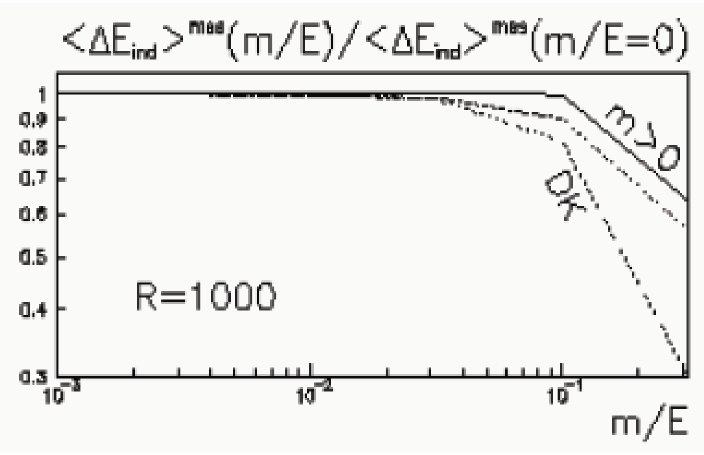
- medium-induced radiation fills the dead-cone

Armesto, Salgado, Wiedemann, PRD69 (2004) 114003



- total energy loss comparable but smaller than in the massless case

Armesto, Salgado, Wiedemann, PRD69 (2004) 114003
B.W. Zhang, E. Wang, X.N. Wang, PRL93 (2004) 072301
Djordjevic, Gyulassy, NPA733 (2004) 265

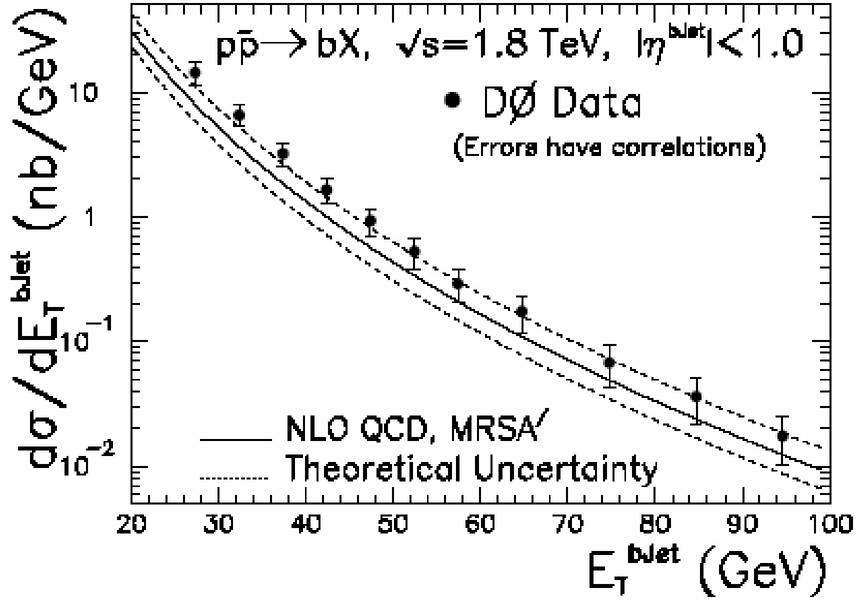


Caveat: mass effect significant if quark is slow

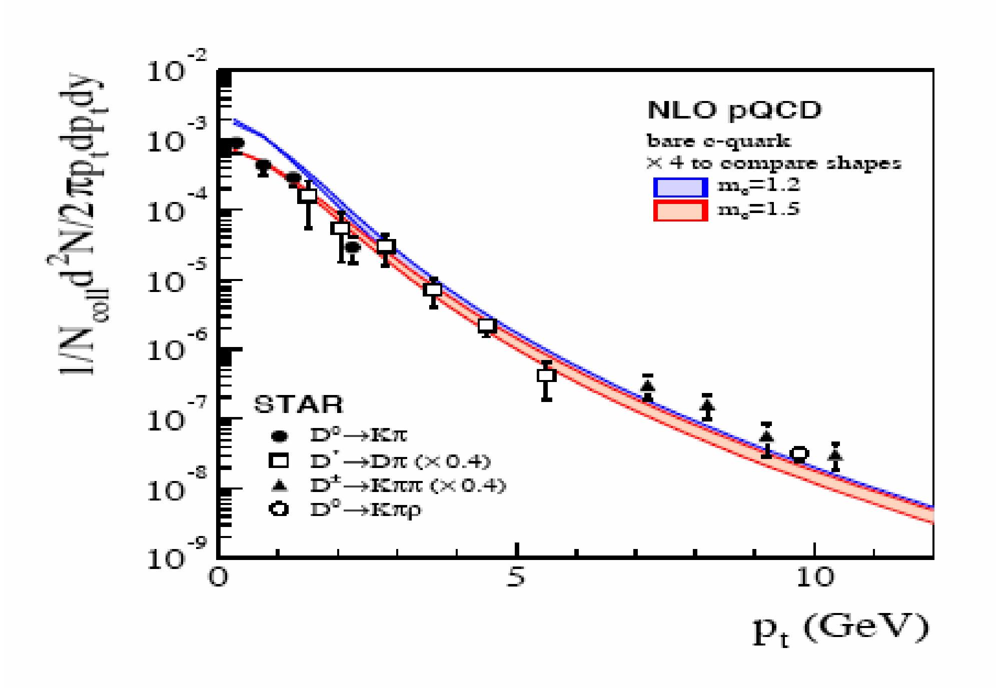
→ hadronization inside medium for pt > 7 GeV

→ significant uncertainties

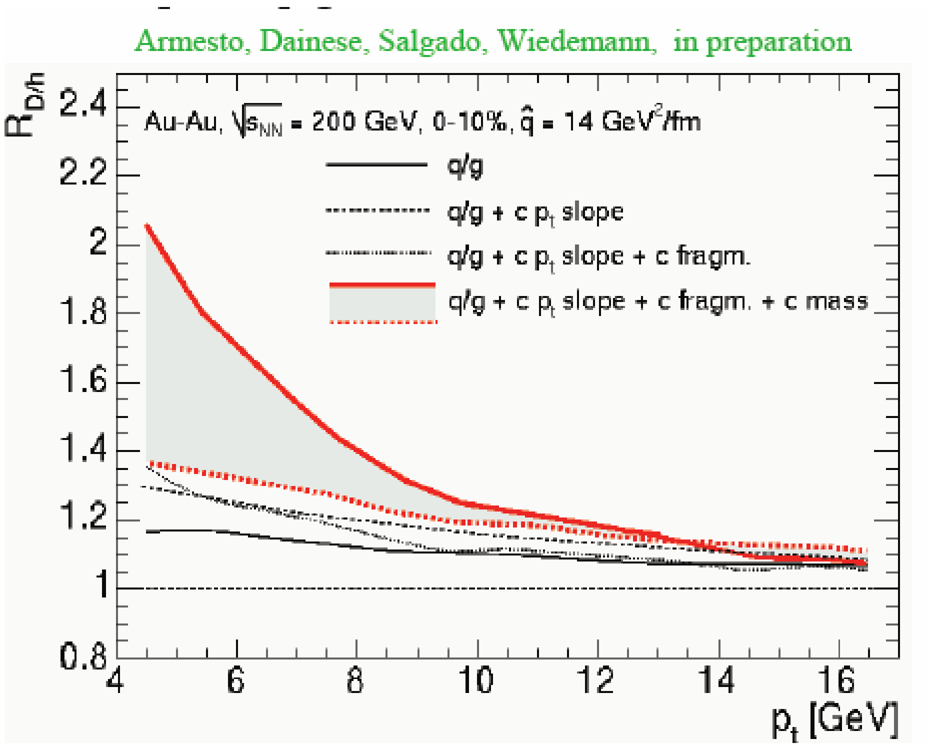
Heavy Quarks



S. Frixione:
Heavy quarks and resummations



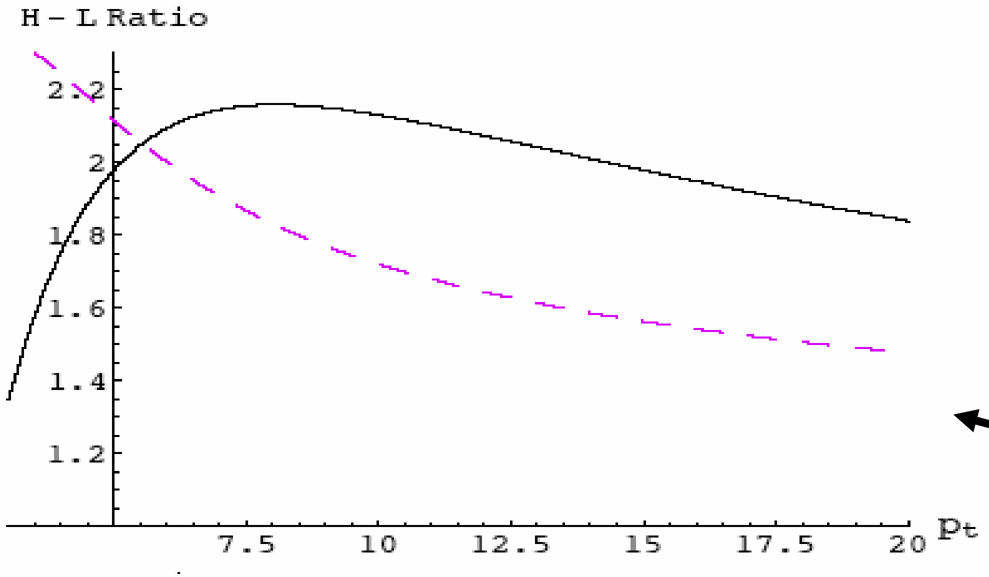
R. Vogt:
the influence
of fragmentation
functions



Armesto, Dainese, Salgado, Wiedemann, in preparation

M. Djordjevic,
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

Dileptons from the QGP

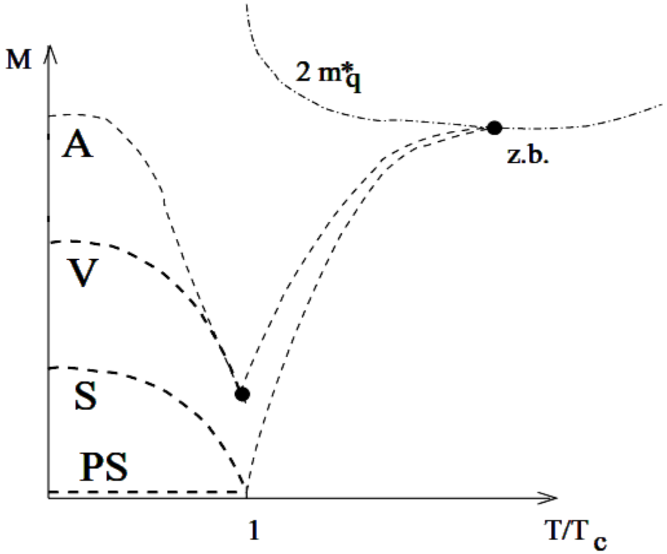
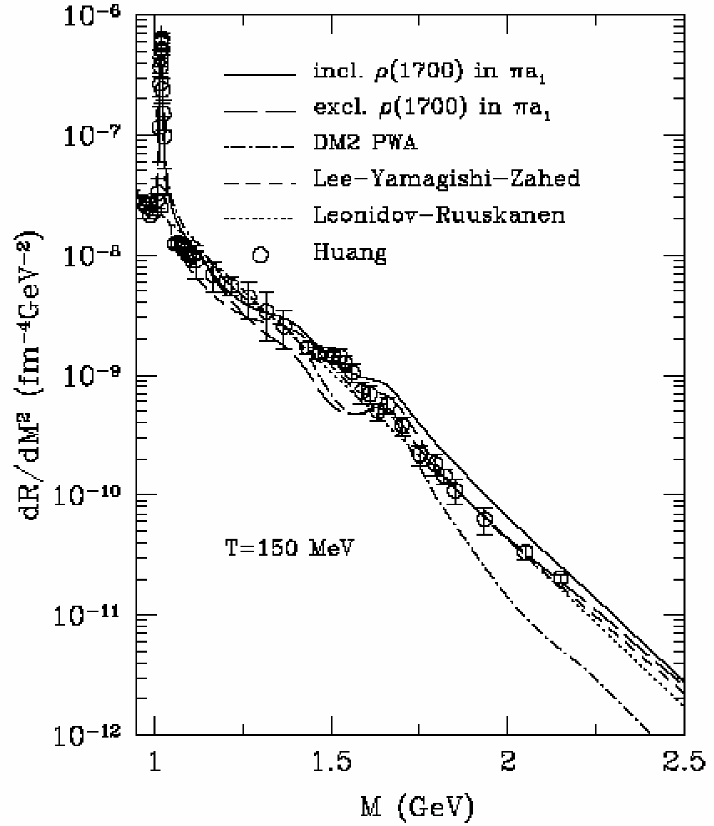


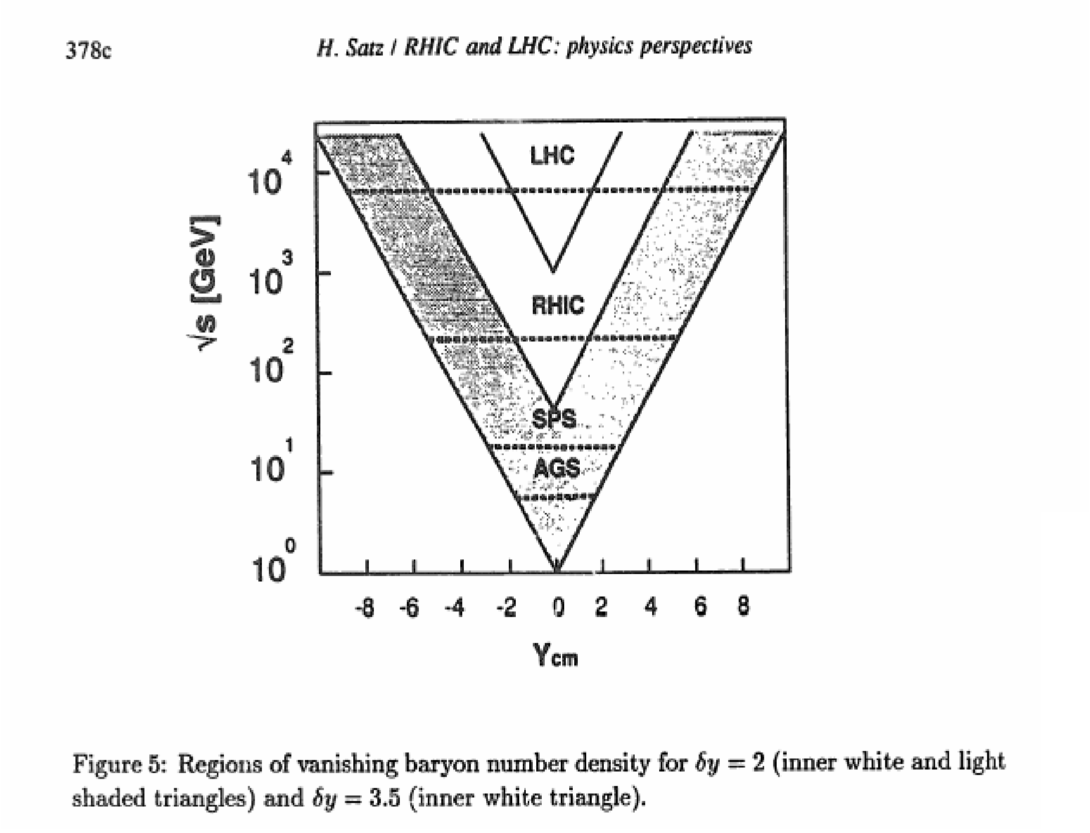
FIG. 1. Schematic T-dependence of the masses of $\bar{q}q$ st
A, V, S and PS stand for axial, vector, scalar and pseudosc
states. The dash-dotted line shows a behavior of twice
quasiparticle mass. Two black dots indicate places wher
hope the dilepton signal may be observable.



E.Shuryak: dileptons from sQGP

C.Gale: dileptons and Spectral functions

Baryon dynamics


378c

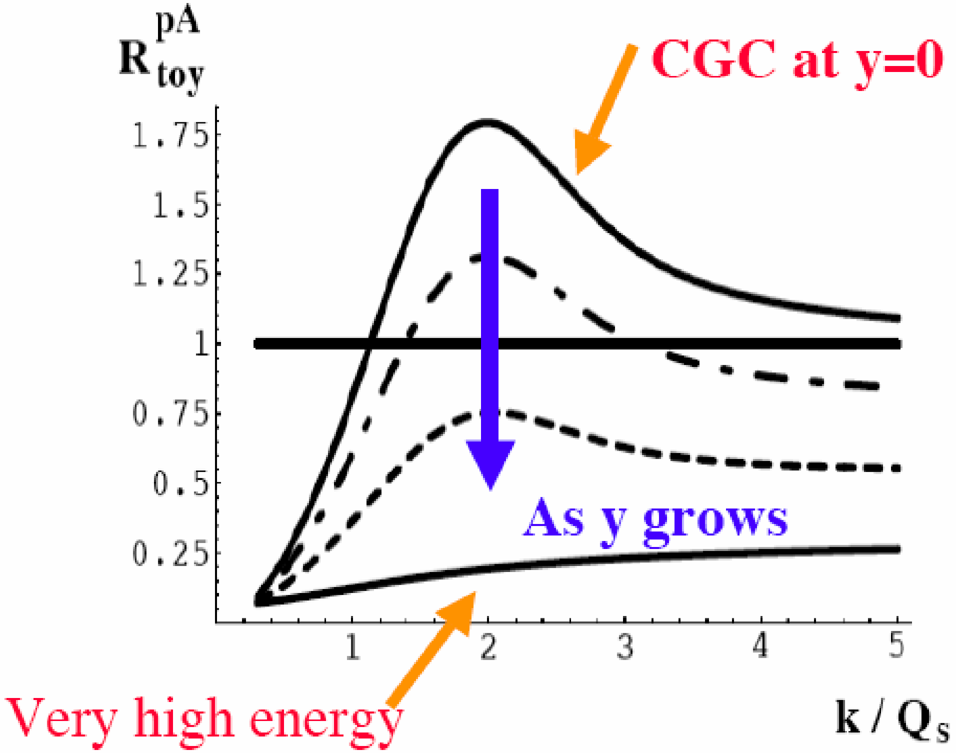
H. Satz / RHIC and LHC: physics perspectives

Figure 5: Regions of vanishing baryon number density for $\delta y = 2$ (inner white and light shaded triangles) and $\delta y = 3.5$ (inner white triangle).

Baryons
and
Recombination:
talk by R.Hwa

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Hard probes of the Color Glass Condensate

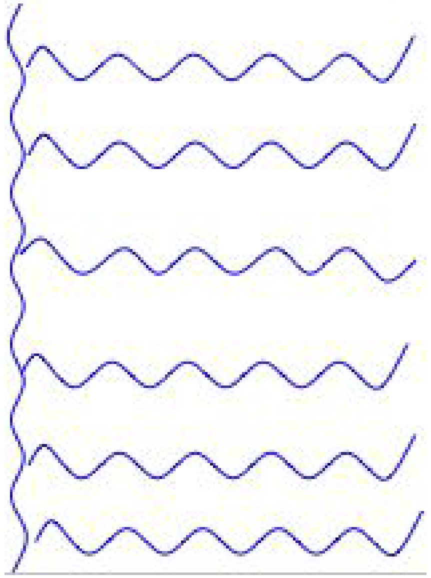


Talks by
R. Baier, H. Fujii, F. Gelis,
J. Jalilian-Marian,
G. Milhano,
A.Mueller,
D. Triantafyllopoulos,
K.Tuchin

R. Venugopalan

Quantum effects

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

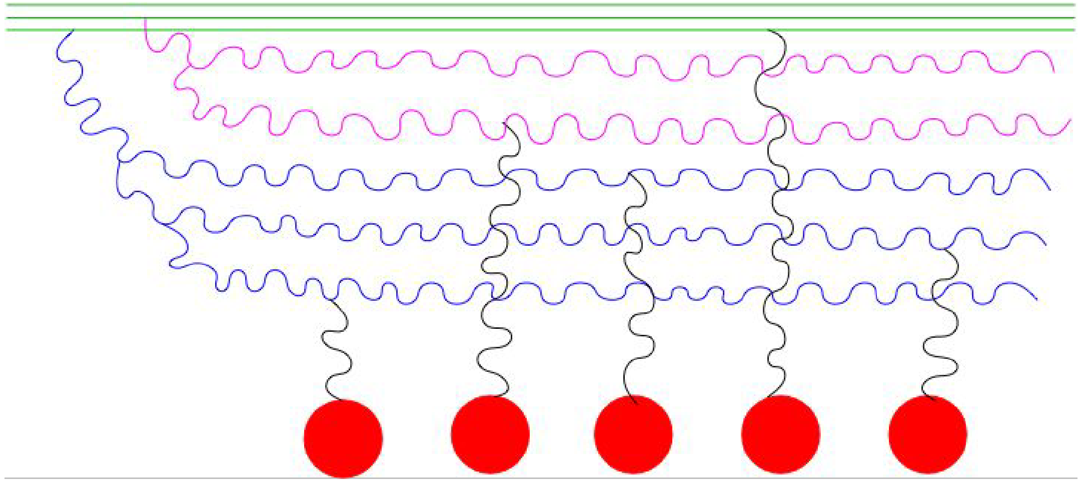


Talks by R.Baier,
J.Bartels,
B.Gay Ducati, E.Iancu,
J.Jalilian-Marian,
L.McLerran, A.Mueller,
D.Triantafyllopoulos,
K.Tuchin,
R.Venugopalan

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

Quantum CGC and hard processes on nuclei



Talks by R.Baier,
B.Gay Ducati, E.Iancu,
J.Jalilian-Marian,
L.McLerran, A.Mueller,
D.Triantafyllopoulos,
K.Tuchin, R.Venugopalan

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

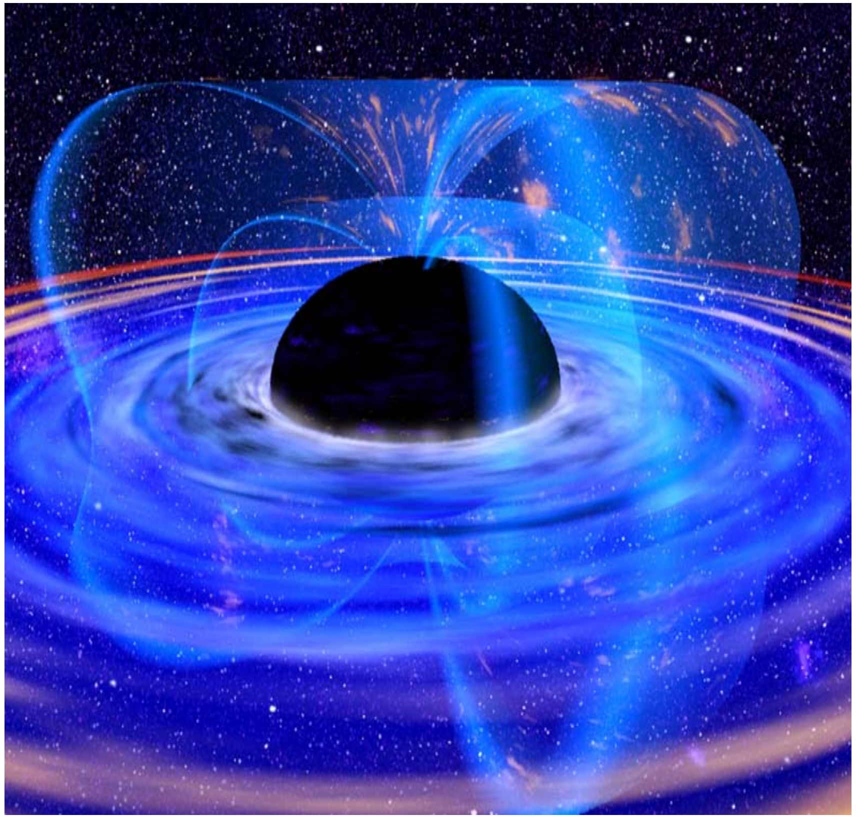
3) Since $Q_s^2 \sim A^{1/3}$ the A-dependence is changed

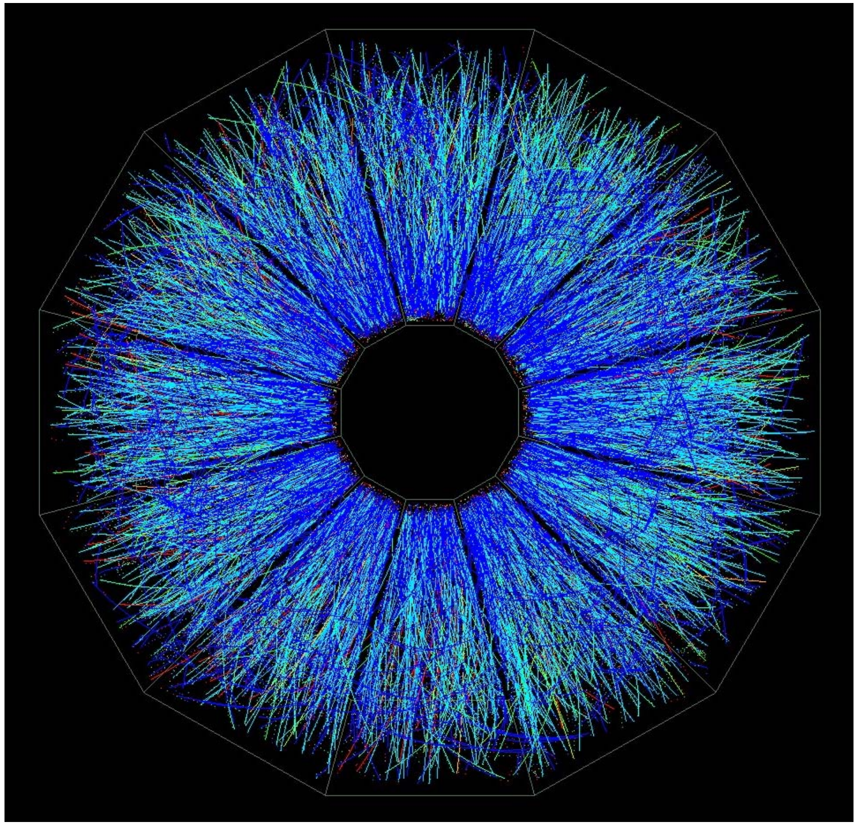
=>

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

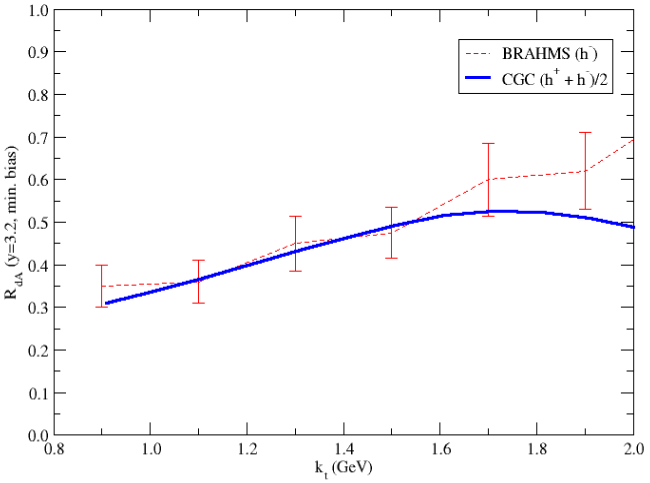
Hawking radiation

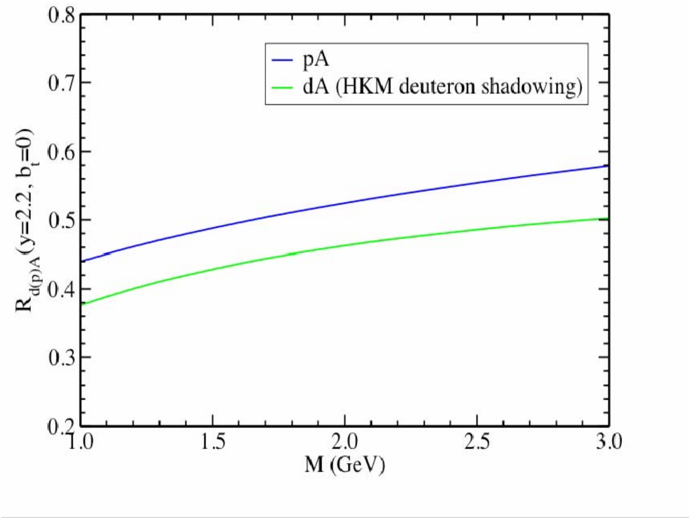




CGC confronts the data

J. Jalilian-Marian





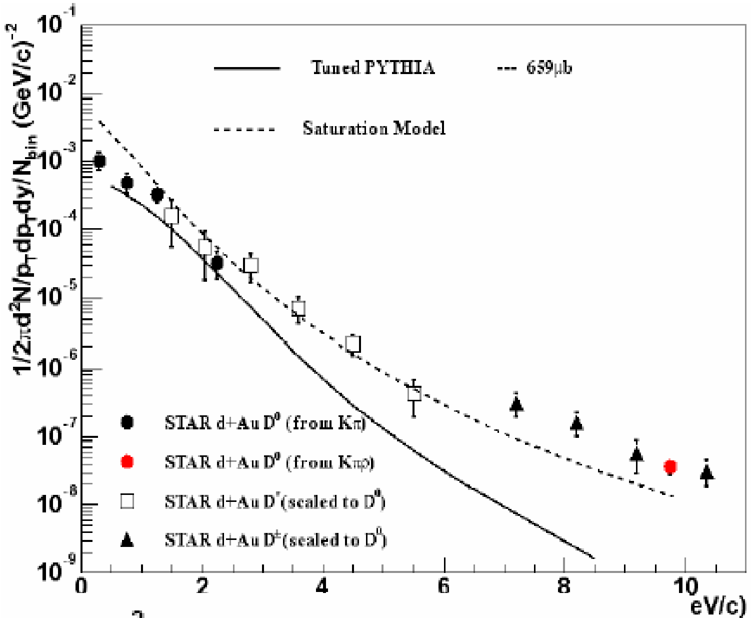
hadrons

dileptons

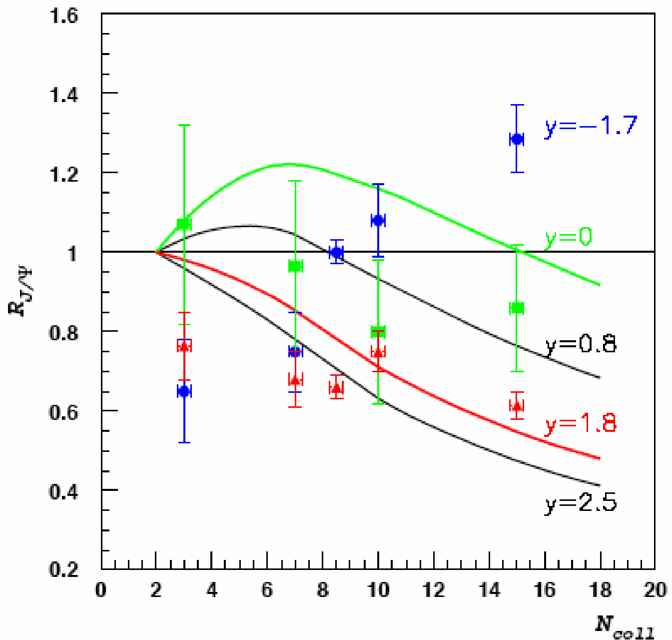
2-particle correlations:
breakdown of AGK?

CGC confronts the data

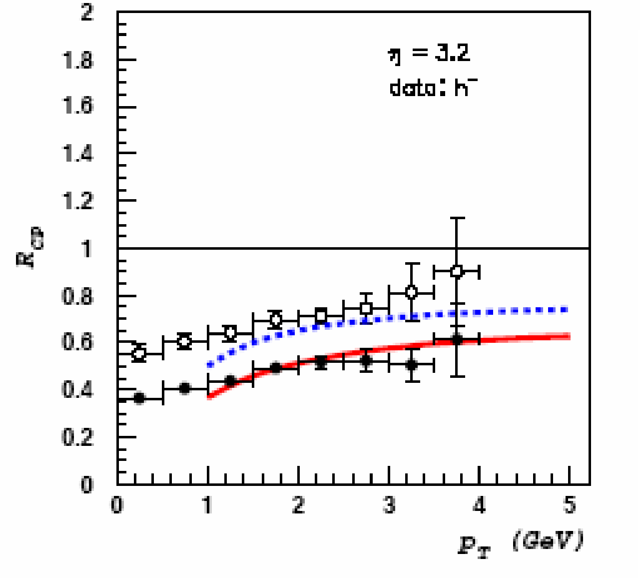
K. Tuchin



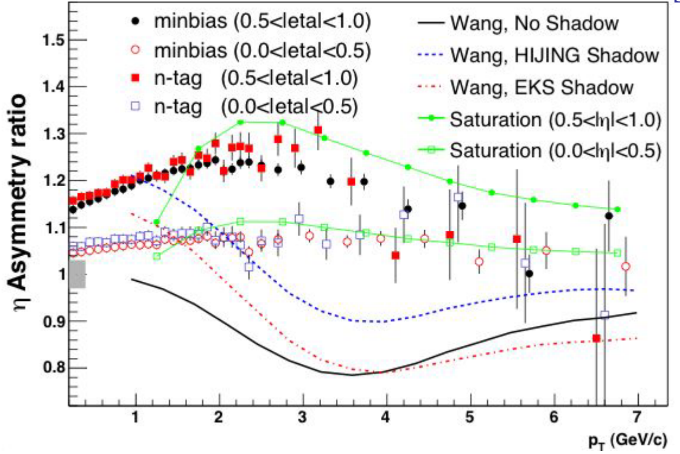
charm



charmonium

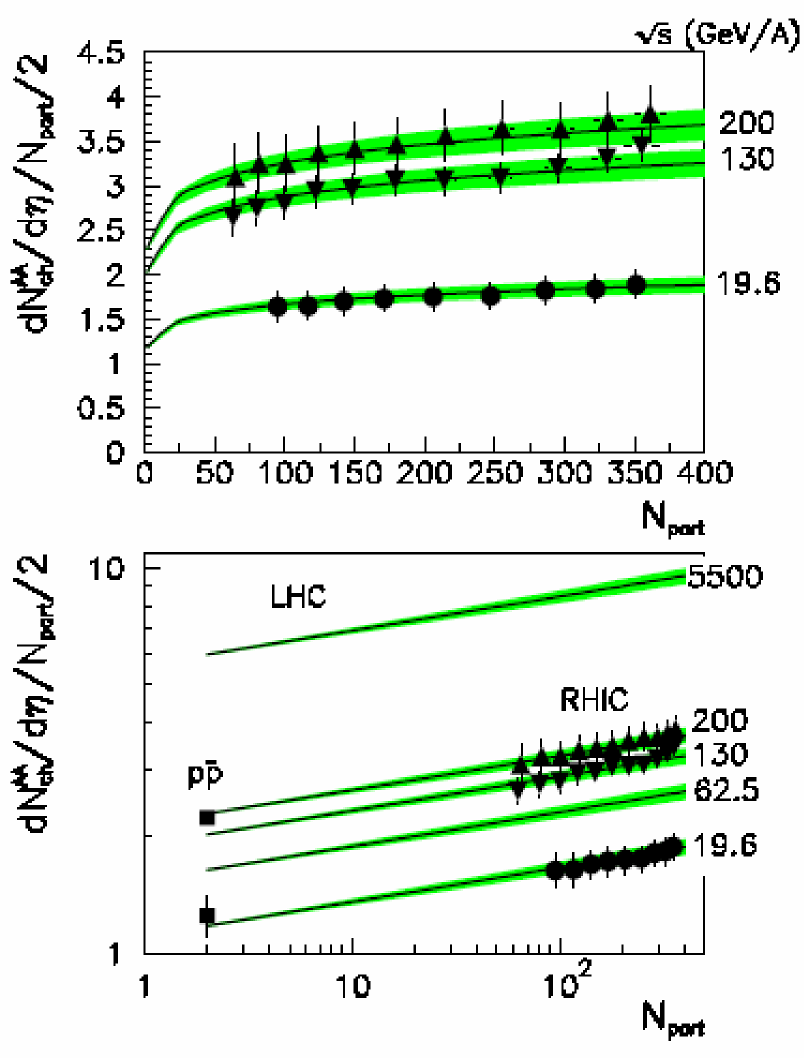


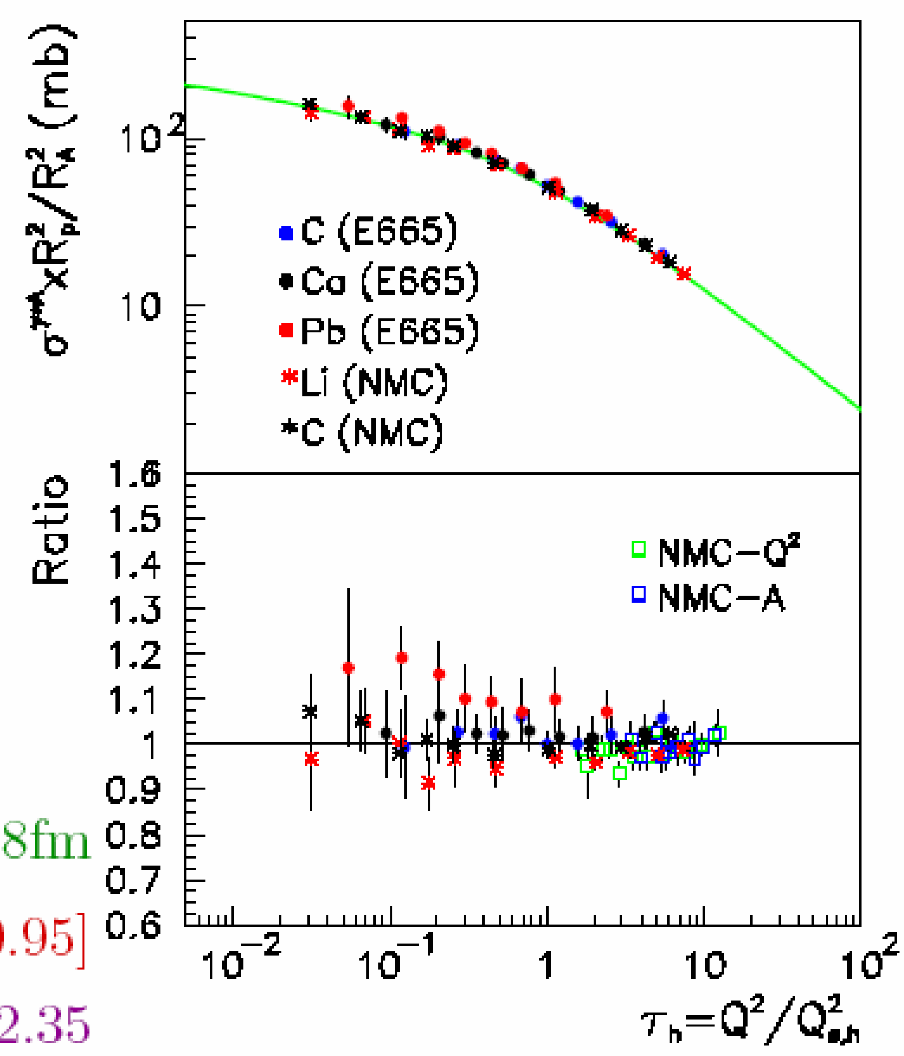
hadrons



CGC confronts the data

C. Salgado: DIS and AA





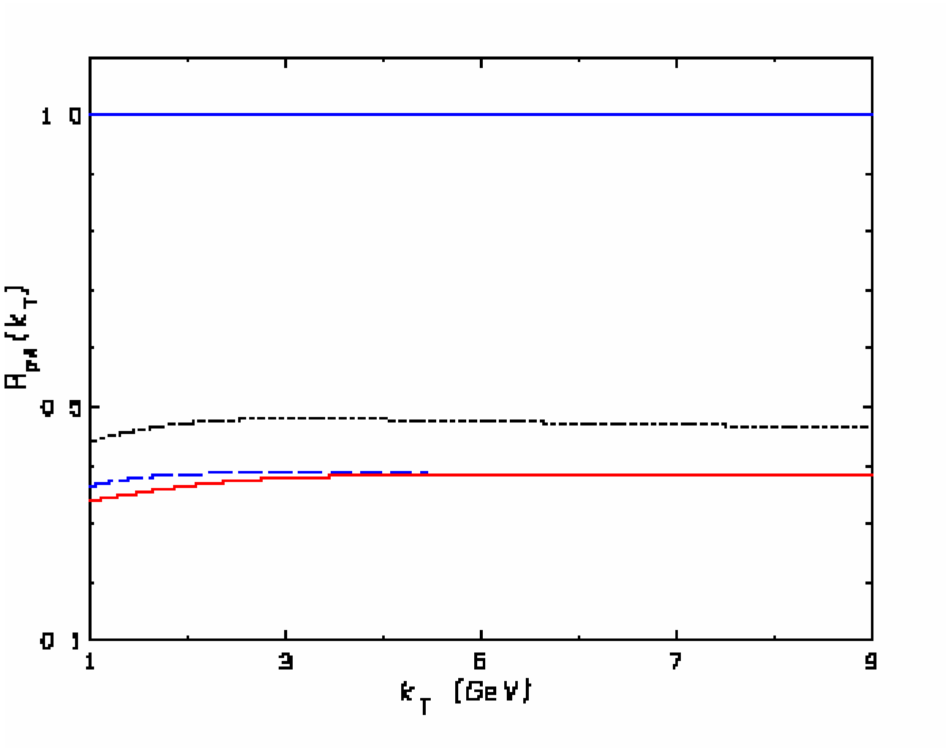
08fm

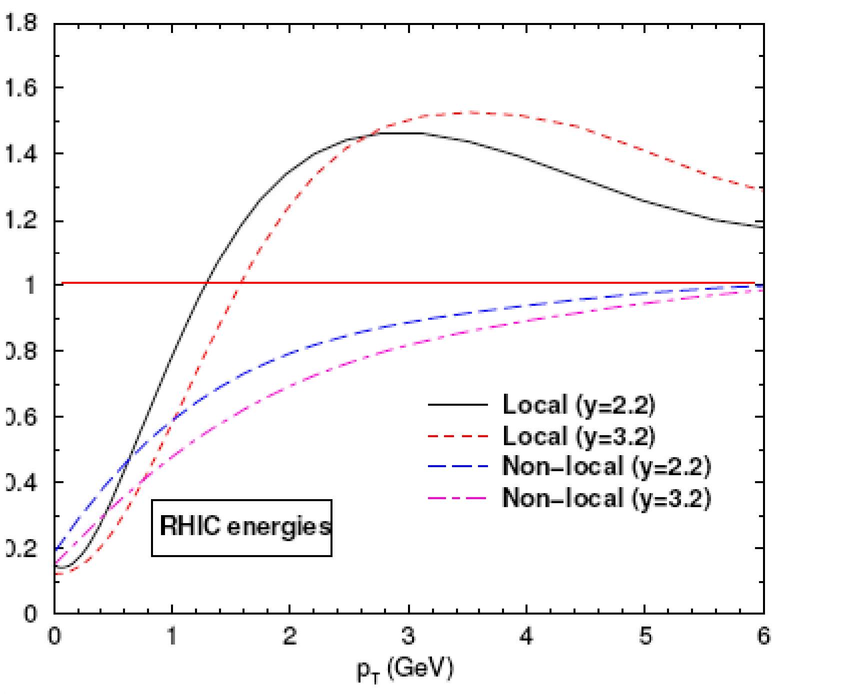
0.95]

2.35

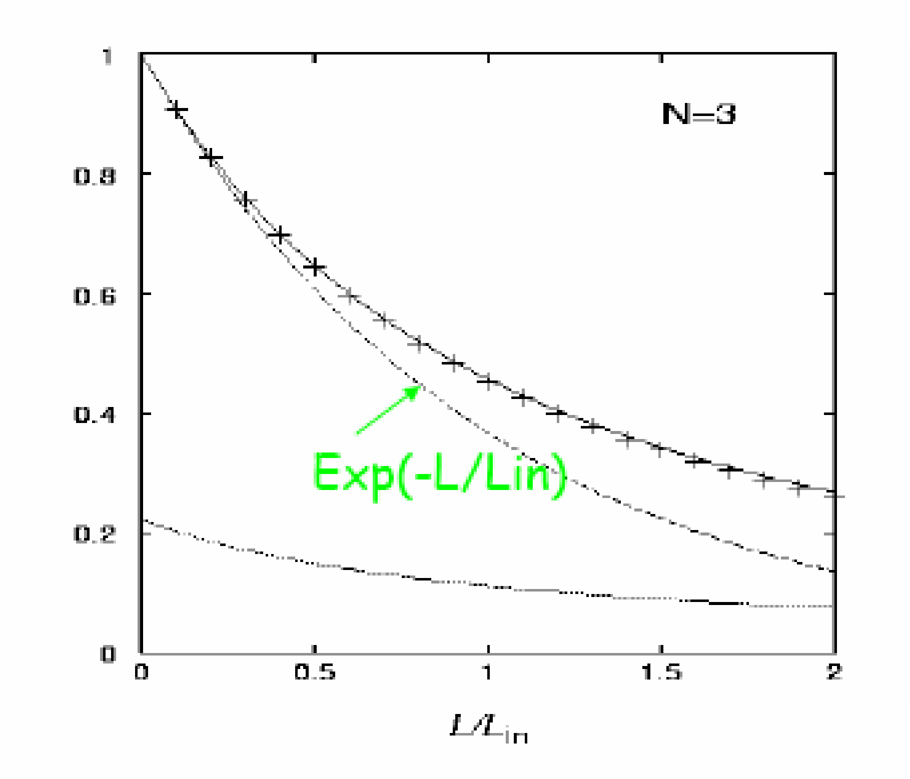
Dileptons from the CGC

R. Baier, J. Jalilian-Marian, B. Gay Ducati, F. Gelis

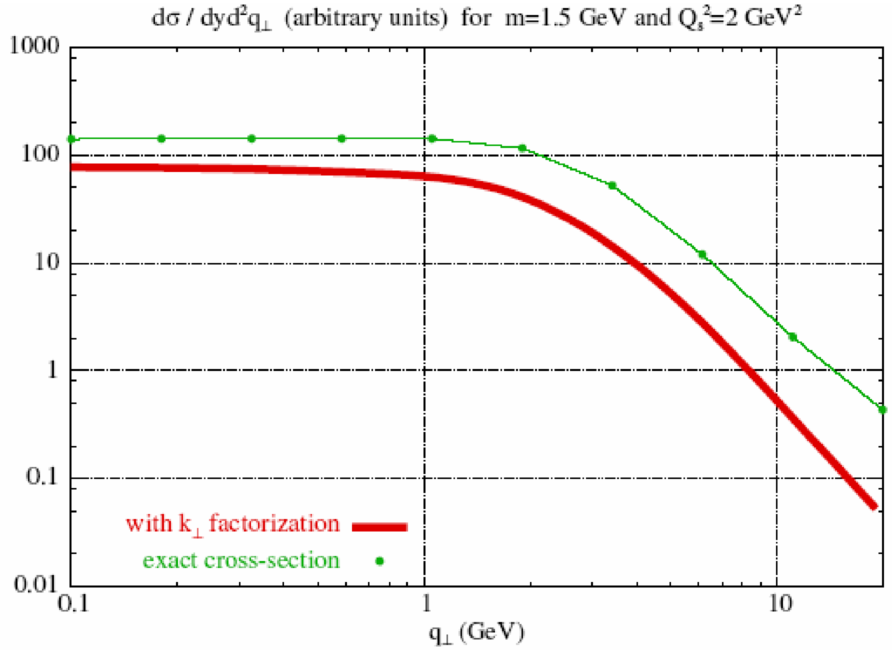




Open charm and charmonium

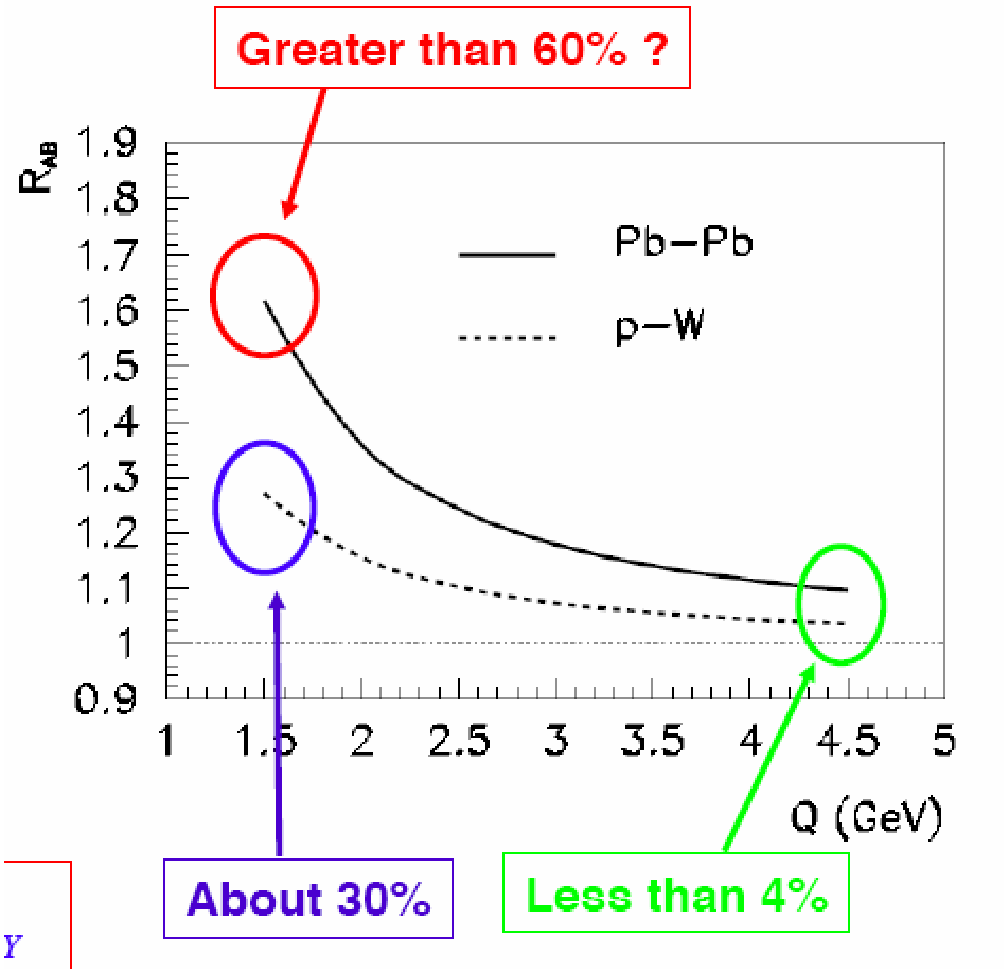


H. Fujii:
"superpenetration"



F. Gelis:
Breakdown of k_t factorization

Nuclear effects at not so small x



Greater than 60% ?

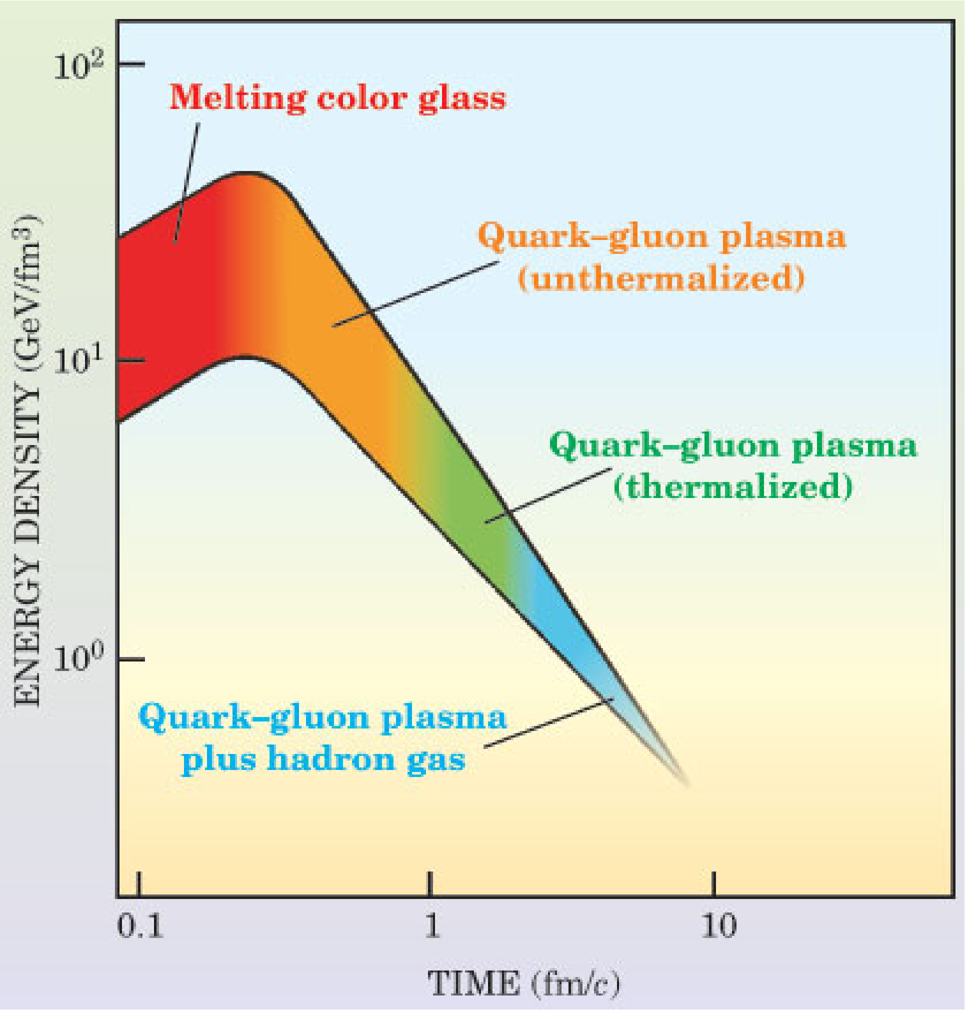
About 30%

Less than 4%

J.Qiu:
Power corrections
to Drell-Yan;
Back-to-back
correlations

L.Tolos:
Slow D-mesons
in cold nuclear matter

From CGC to Quark Gluon Plasma



Talk by
L.McLerran

How does the CGC thermalize so fast?

The Hard Probes Café
is still open…

Hard Probe
Cafe

CERN, Geneva 1994
LBL, Berkeley 1994
ECT*, Trento 1995
INT, Seattle 1996
CFIF, Lisbon 1997
INT, Seattle 1998
JYFL, Jyväskylä 1999
BNL, New York 2000
NBI, Copenhagen 2001

1st International Conference on "Hard Probes", Ericeira, 2004

2nd?

YES!
2nd "Hard Probes":
San Francisco Bay Area,
California, spring of 2006

LBL - INT - BNL
Organizers: X.N.Wang, P.Jacobs,
…

and finally…

Carlos Lourenço	Jorge Dias de Deus
Helmut Satz	João Seixas

THANK YOU!!!