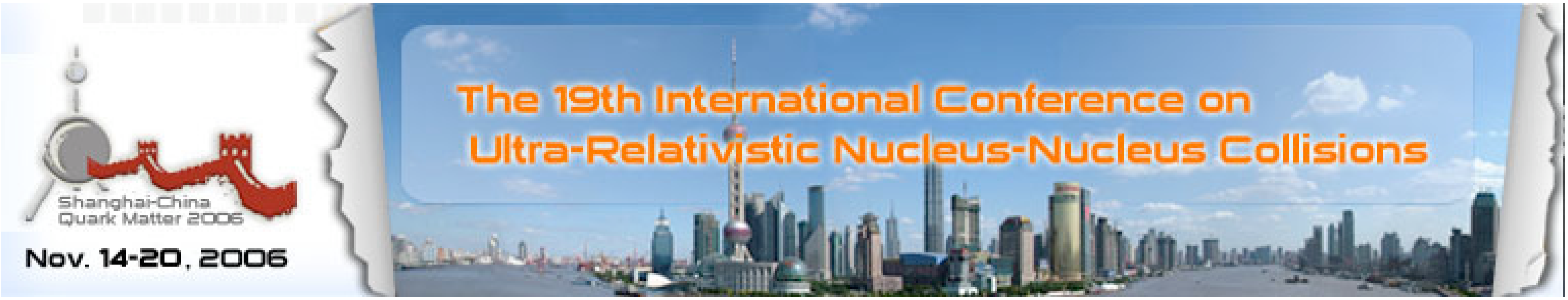


Theoretical issues in J/ψ suppression

D. Kharzeev

BNL

BROOKHAVEN
NATIONAL LABORATORY

This week 32 years ago: November revolution

VOLUME 33, NUMBER 23 PHYSICAL REVIEW LETTERS 2 DECEMBER 1974

Experimental Observation of a Heavy Particle J†

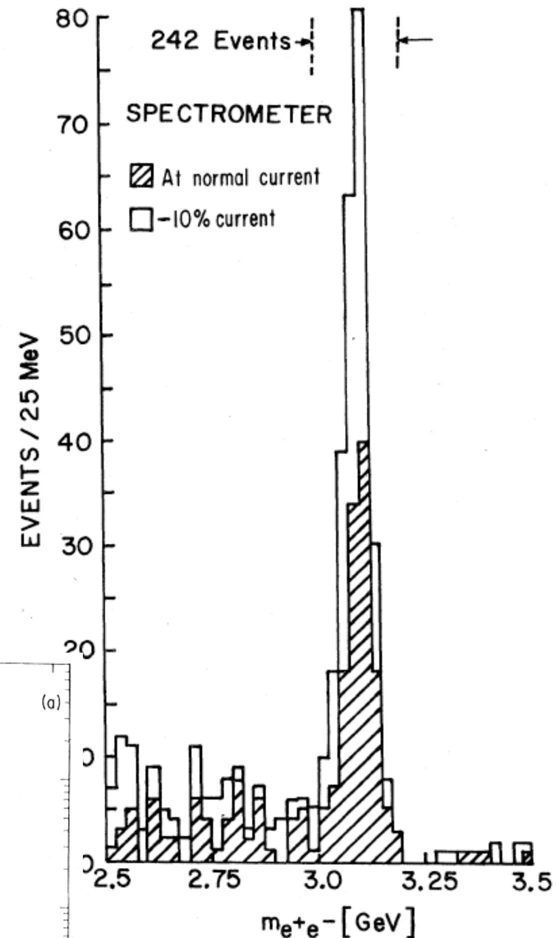
J. J. Aubert, U. Becker, P. J. Biggs, J. Burger, M. Chen, G. Everhart, P. Goldhagen, J. Leong, T. McCorriston, T. G. Rhoades, M. Rohde, Samuel C. C. Ting, and Sau Lan Wu
Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

and

Y. Y. Lee
Brookhaven National Laboratory, Upton, New
(Received 12 November 1974)

12 November

We report the observation of a heavy particle J, with mass $m = 3.1$ GeV and width approximately zero. The observation was made from the reaction $p + \mathrm{Be} \to e^+ + e^- + x$ by measuring the e^+e^- mass spectrum with a precise pair spectrometer at the Brookhaven National Laboratory's 30-GeV alternating-gradient synchrotron.

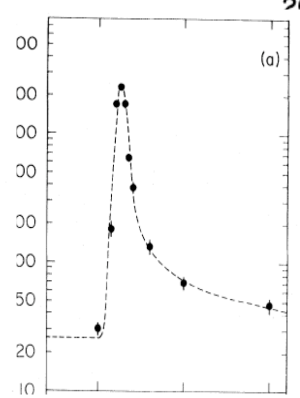


Discovery of a Narrow Resonance in e^+e^- Annihilation*

J.-E. Augustin,† A. M. Boyarski, M. Breidenbach, F. Bulos, J. T. Dakin, G. J. Feldman, G. E. Fischer, D. Fryberger, G. Hanson, B. Jean-Marie,† R. R. Larsen, V. Lüth, H. L. Lynch, D. Lyon, C. C. Morehouse, J. M. Paterson, M. L. Perl, B. Richter, P. Rapidis, R. F. Schwitters, W. M. Tanenbaum, and F. Vannucci‡
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

and

G. S. Abrams, D. Briggs, W. Chinowsky, C. E. Friedberg, G. Goldhaber, R. J. Hollebeek, J. A. Kadyk, B. Lulu, F. Pierre,§ G. H. Trilling, J. S. Whitaker, J. Wiss, and J. E. Zipse
Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720
(Received 13 November 1974)



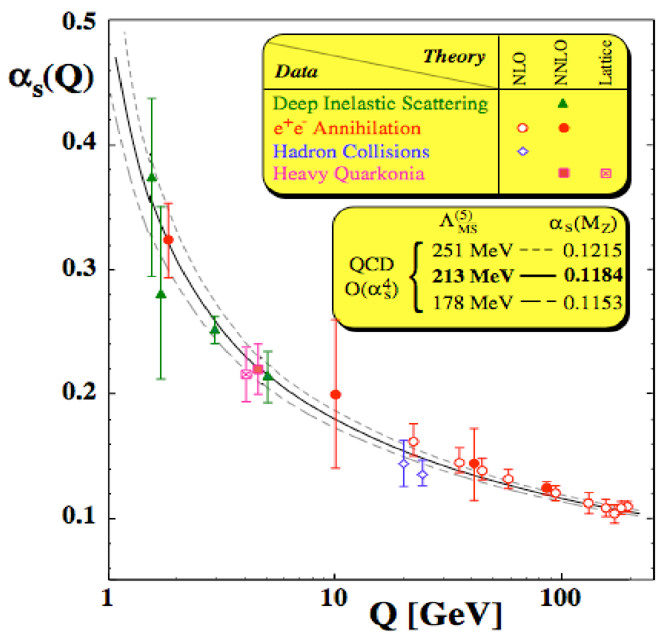
We have observed a very sharp peak in the cross section for $e^+e^- \to$ hadrons, e^+e^-, and possibly $\mu^+\mu^-$ at a center-of-mass energy of 3.105 ± 0.003 GeV. The upper limit to the full width at half-maximum is 1.3 MeV.

Why are heavy quarks so important?

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}:

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



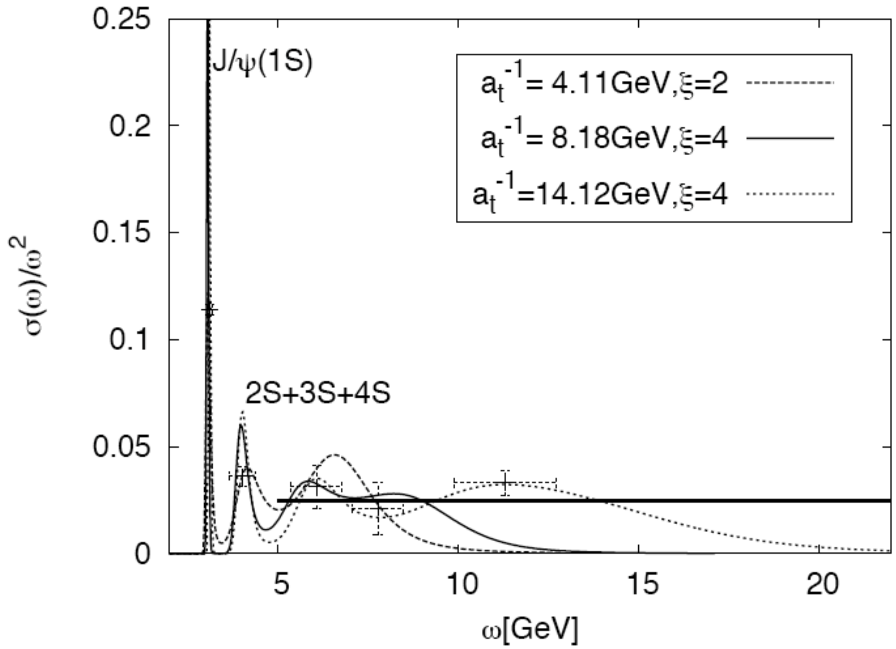
coupling is small → narrow width

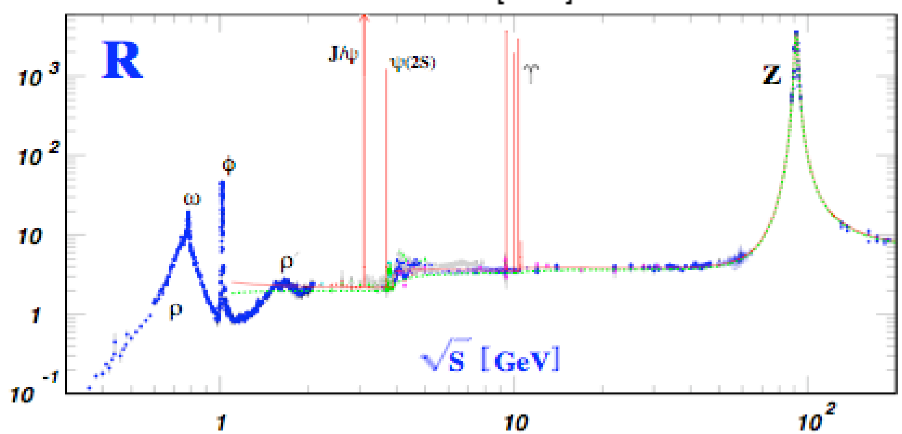
$$\alpha_s(M_H) \ll 1$$

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

vacuum fields are weak on the heavy quark scale: may be treated as perturbation

Why are heavy quarkonia so special?

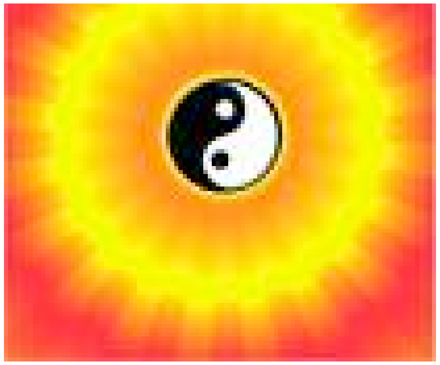




Heavy quarks =
small velocities,
small size,
tight binding,
weak coupling
to light hadrons…
all "relatively"

Lattice results: A.Jakovac, P.Petreczky, K.Petrov, A.Velytsky, hep-lat/0611017, November 13

20 years ago: J/Ψ in the plasma



Volume 178, number 4 PHYSICS LETTERS B 9 October 1986

J/ψ SUPPRESSION BY QUARK–GLUON PLASMA FORMATION ☆

T. MATSUI
Center for Theoretical Physics, Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

and

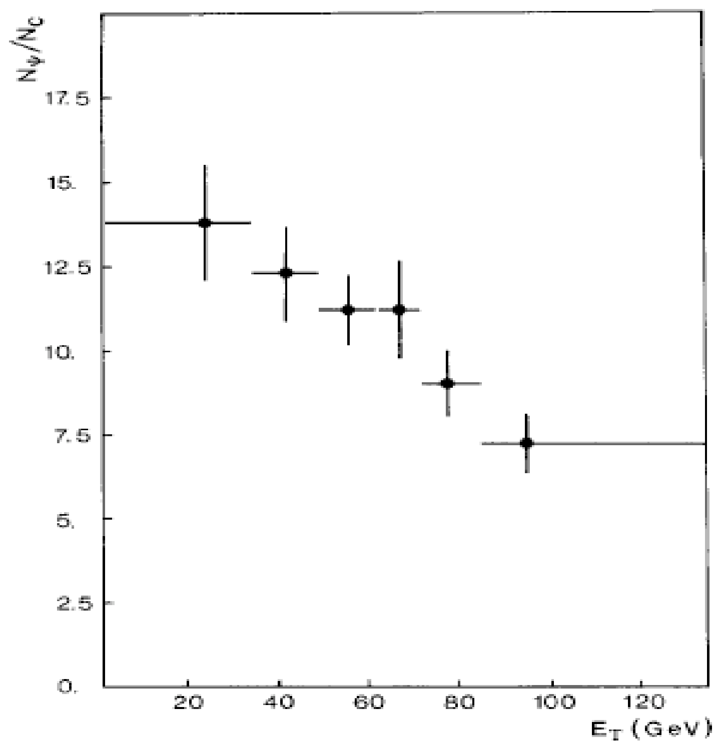
H. SATZ
Fakultät für Physik, Universität Bielefeld, D-4800 Bielefeld, Fed. Rep. Germany and Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA

Received 17 July 1986

If high energy heavy ion collisions lead to the formation of a hot quark–gluon plasma, then colour screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region. To study this effect, the temperature dependence of the screening radius, as obtained from lattice QCD, is compared with the J/ψ radius calculated in charmonium models. The feasibility to detect this effect clearly in the dilepton mass spectrum is examined. It is concluded that J/ψ suppression in nuclear collisions should provide an unambiguous signature of quark–gluon plasma formation.

T. Matsui & H. Satz:

We thus conclude, that there appears to be no mechanism for J/ψ suppression in nuclear collisions except the formation of a deconfining plasma, and if such a plasma is produced, there seems to be no way to avoid J/ψ suppression.



NA38: the first observation of J/Ψ suppression

6 April 1989

THE PRODUCTION OF J/Ψ
IN 200 GeV/NUCLEON OXYGEN-URANIUM INTERACTIONS

NA38 Collaboration

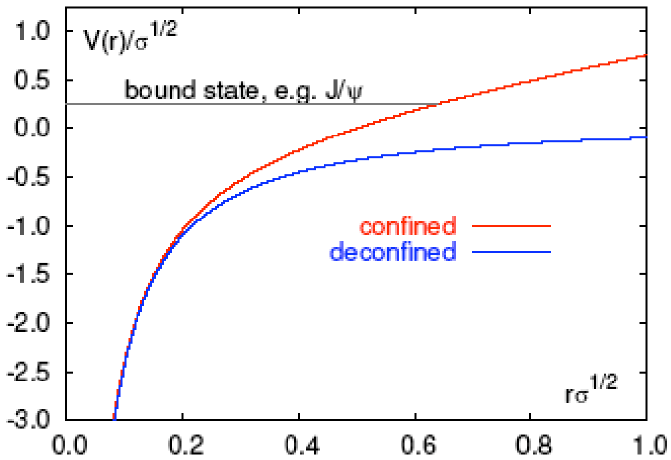
And so the story began…

Heavy quarkonium as a probe

The Matsui-Satz argument:

- deconfinement $\Rightarrow$ screening

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



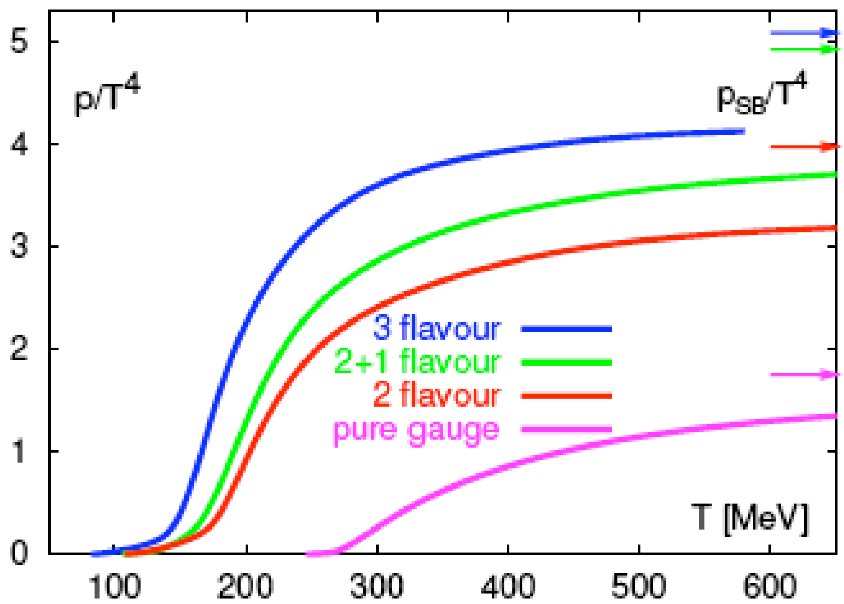
$V_{\bar{q}q}(r,T) \to \infty$ confinement

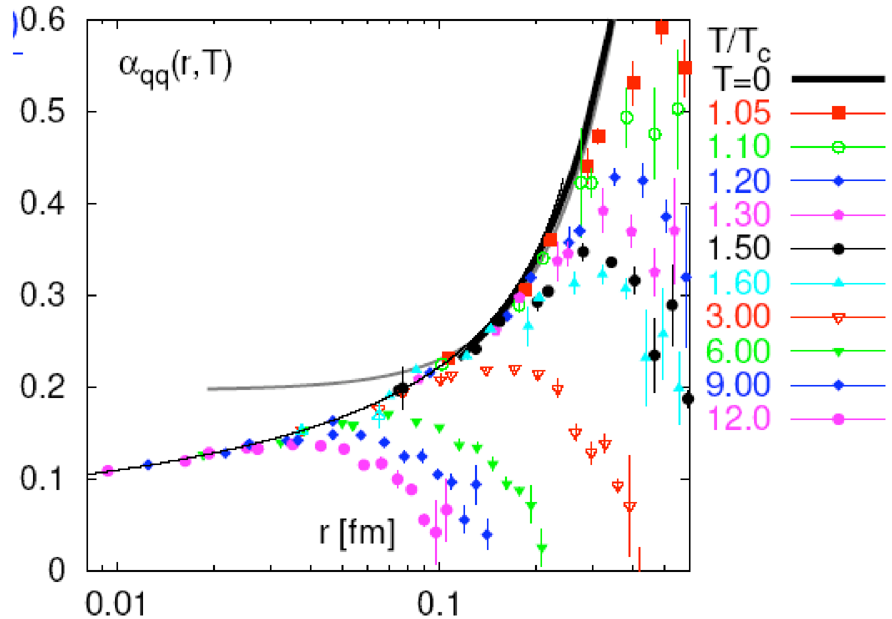
$V_{\bar{q}q}(r,T) < \infty$ deconfinement

F.Karsch

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

QCD plasma



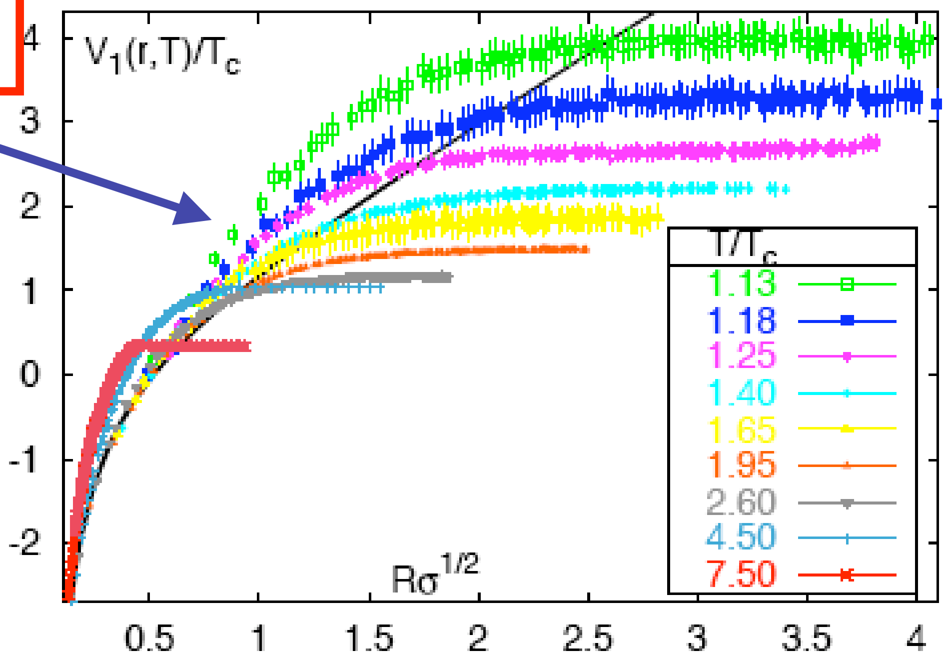


Talks by T. Hatsuda, F. Karsch

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

Heavy quark internal energy above T

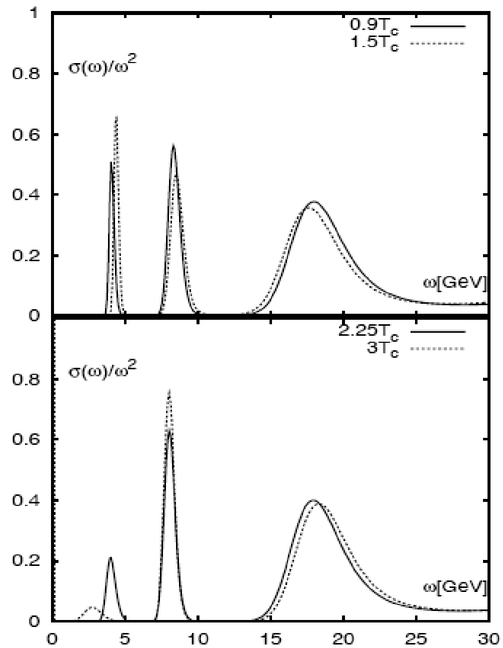
Remnants
of confinement?



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

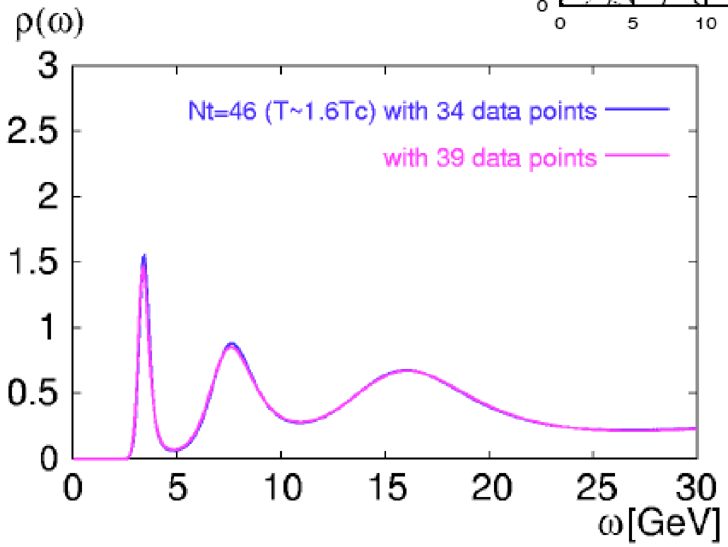
J/Ψ above T_c: alive and well?

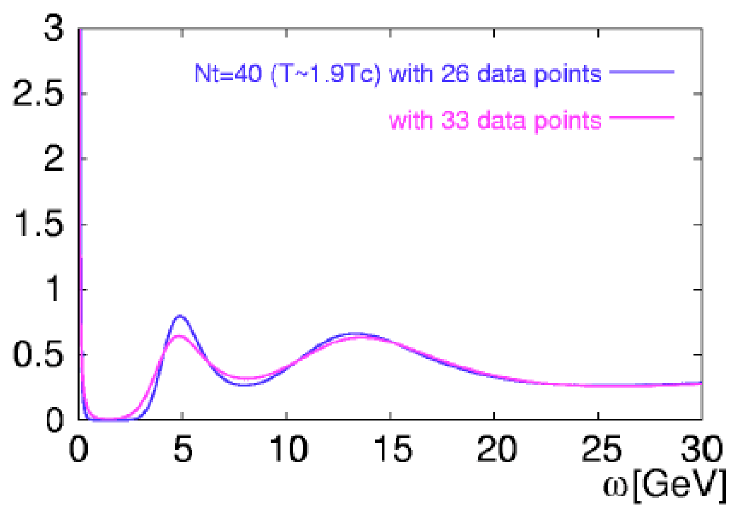
Talks by
T.Hatsuda,
K.Petrov



J/Ψ survives
in the plasma
up to ~ 2 T_c

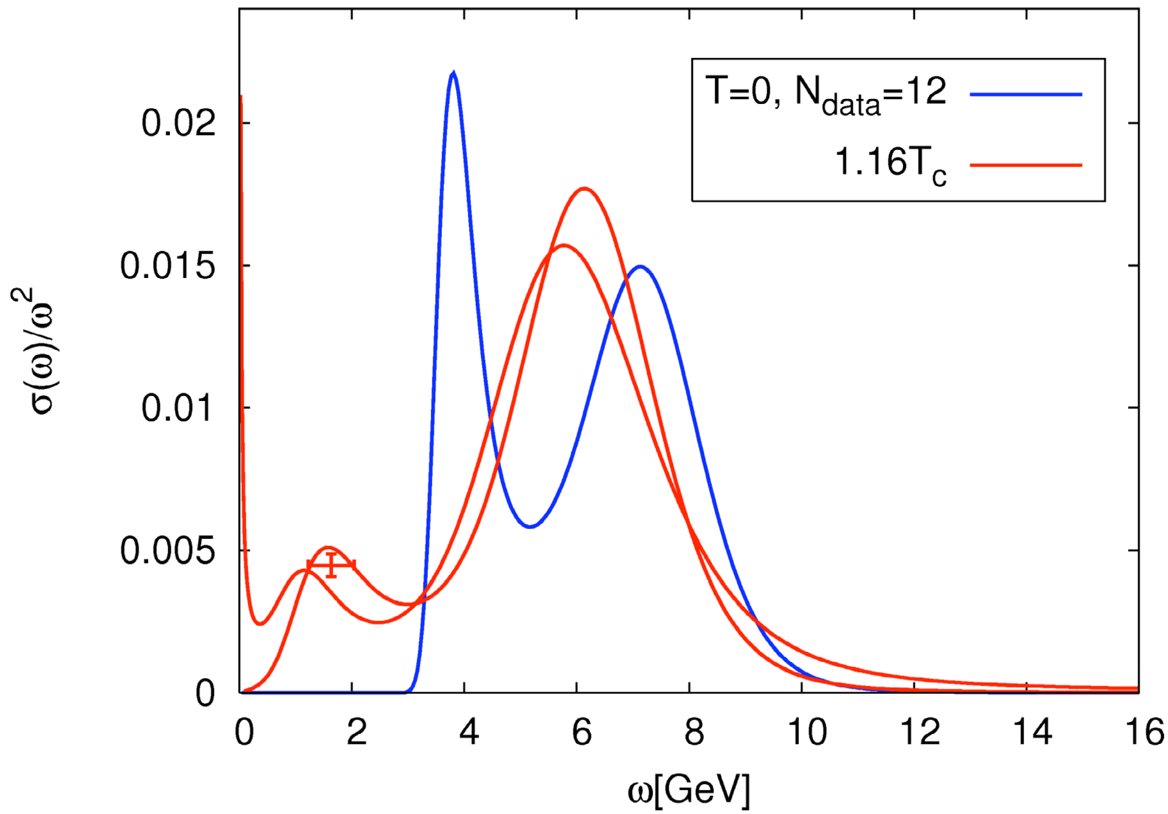
S.Datta,
F.Karsch,
P.Petreczky,
I.Wetzorke





M.Asakawa,
T.Hatsuda

Excited states dissapear at $T \sim T_c$



Scalar channel; from A.Jakovac et al., hep-lat/0611017

Screening at finite momentum

* Weak coupling: enhanced screening in the direction of momentum

M.Chu & T.Matsui '89, M.Mustafa et al '04

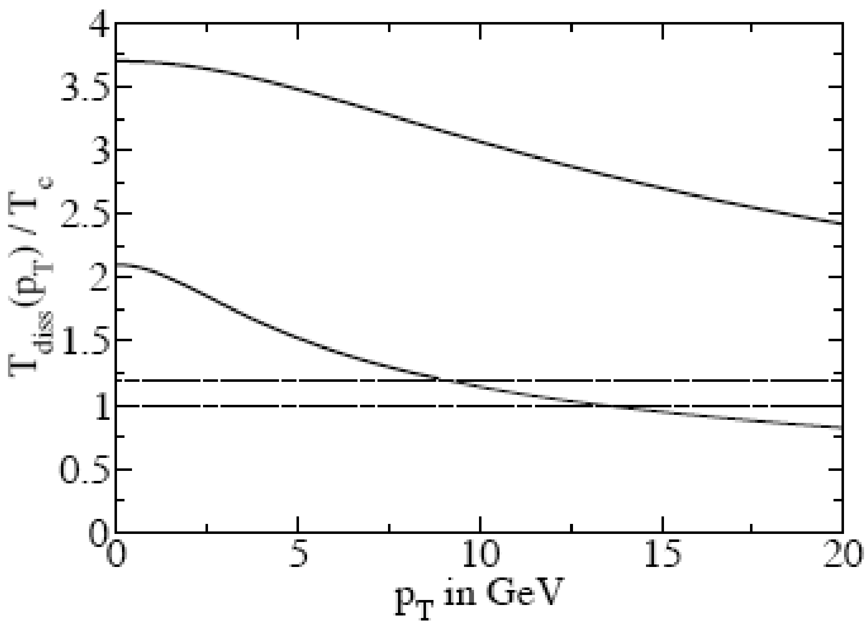


FIG. 3: A $1/\sqrt{\gamma}$-velocity scaling of the screening length in QCD would imply that the J/Ψ dissociation temperature $T_{\rm diss}(p_T)$ decreases significantly with transverse momentum.

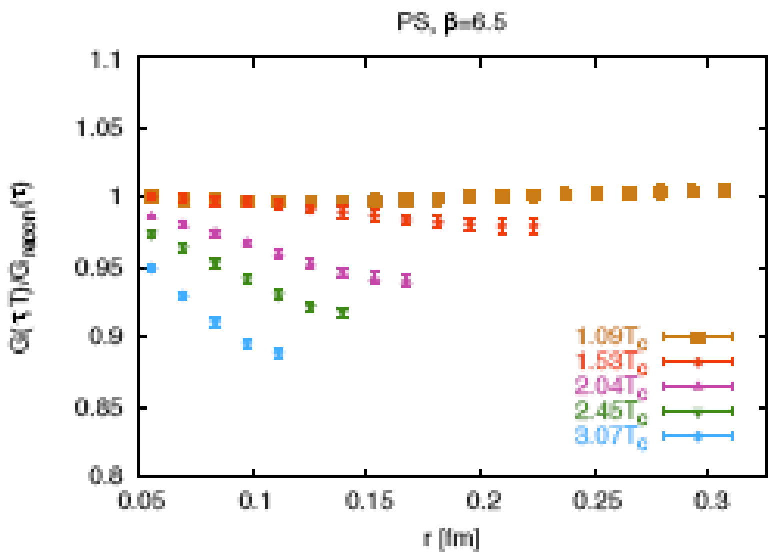
* AdS/CFT: Lorentz contraction of the screening length, enhanced screening

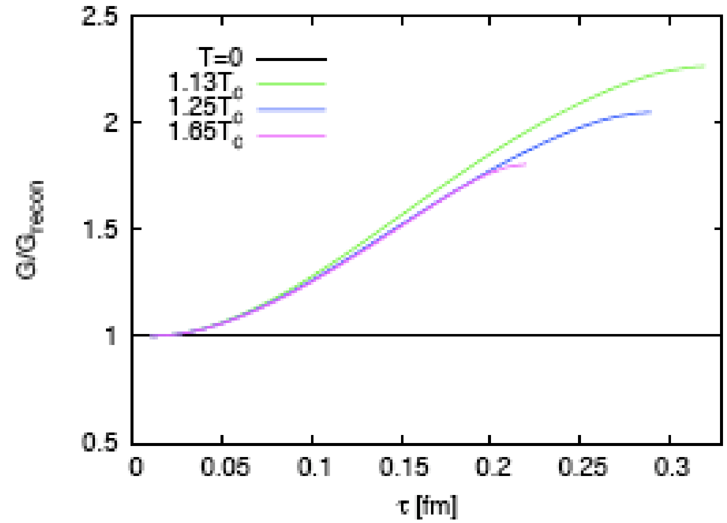
H.Liu, K.Rajagopal, U.Wiedemann '06

* Lattice calculations so far limited to p/T < 5;

* Experiment: how to disentangle from the suppression due to gluon fragmentation?

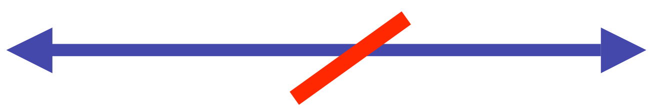
The potential model





A. Mocsy,
P. Petreczky
hep-ph/0606053

Lattice



Potential

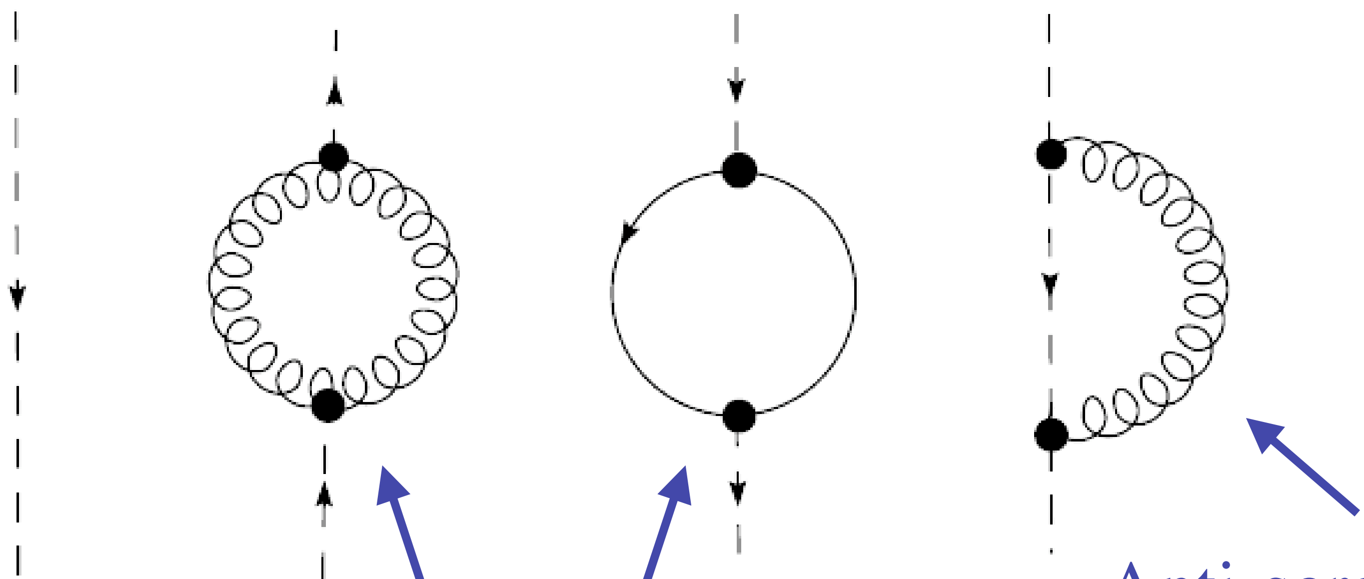
Talk by A.Mocsy

Potential models, even fitted to static lattice potentials, fail to describe the behavior of quarkonium correlators and spectral densities - screening sets in too early

Why?

Space-time picture of $\bar{Q}Q$ interaction

(Coulomb gauge)



Coulomb; instantaneous

Screening; not instantaneous

$$V(R) = \sum_m \sigma(m^2)\ \frac{\exp(-mR)}{R}$$

Anti-screening, and possibly confinement;
Gribov, Zwanziger,..
instantaneous

Difficulties of the potential model

Potential model is based on the assumption
that the interaction is instantaneous, or
at least much faster than the typical revolution
time of heavy quarks in quarkonium, $\tau \sim 1/\varepsilon$.

OK for the Coulomb potential;

Fails for soft vacuum fields;

Fails for the screened gluon exchange as well -

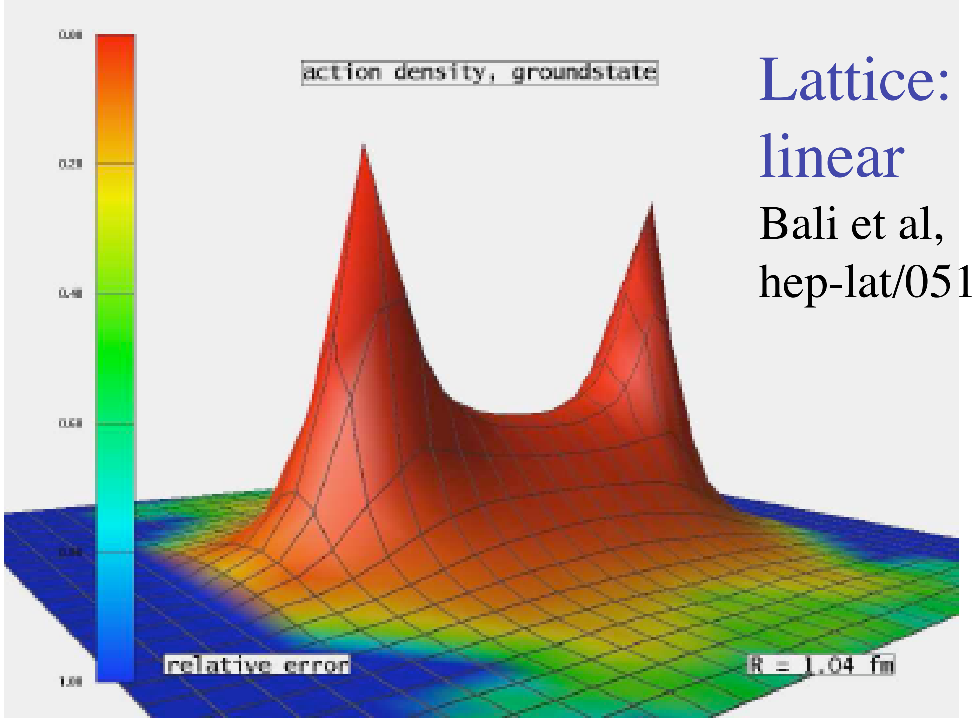
Retardation effects are crucial: 

Can quarkonium at finite T elucidate the nature of confinement?

Potential in the Operator Product Expansion:

$$\lim_{r\to 0} V(r) \approx -\frac{(N_c^2-1)}{2N_c}\frac{\alpha_s(r)}{r}\left(1 + \sum_n a_n \alpha_s^n(r) + c_3 \Lambda_{QCD}^3 r^3\right)$$

Confining, but: quadratic, not linear!



Lattice: linear

Bali et al, hep-lat/0512018

energy shift due to quadratic Stark effect in the vacuum field with $E^2<0$ ("gluon condensate")

SVZ, Voloshin, Leutwyler, …

Is confinement a "short-distance" phenomenon?

OPE sums leading large-distance contributions;
are we missing an important short-distance non-perturbative physics?
If yes, it would not be immediately screened away above T_c…

Perhaps, infrared-finite QCD coupling? (strings, monopoles,…)

$$\alpha_s(Q^2) \Longrightarrow \alpha_s(Q^2) = \frac{4\pi}{b_0}\left(\frac{1}{\ln(Q^2/\Lambda^2_{QCD})} + \frac{\Lambda^2_{QCD}}{\Lambda^2_{QCD} - Q^2}\right)$$

"Coulomb confinement" ?
=> Linear confining potential

Gribov; Zwanziger; Zakharov; Narison; Shirkov;…

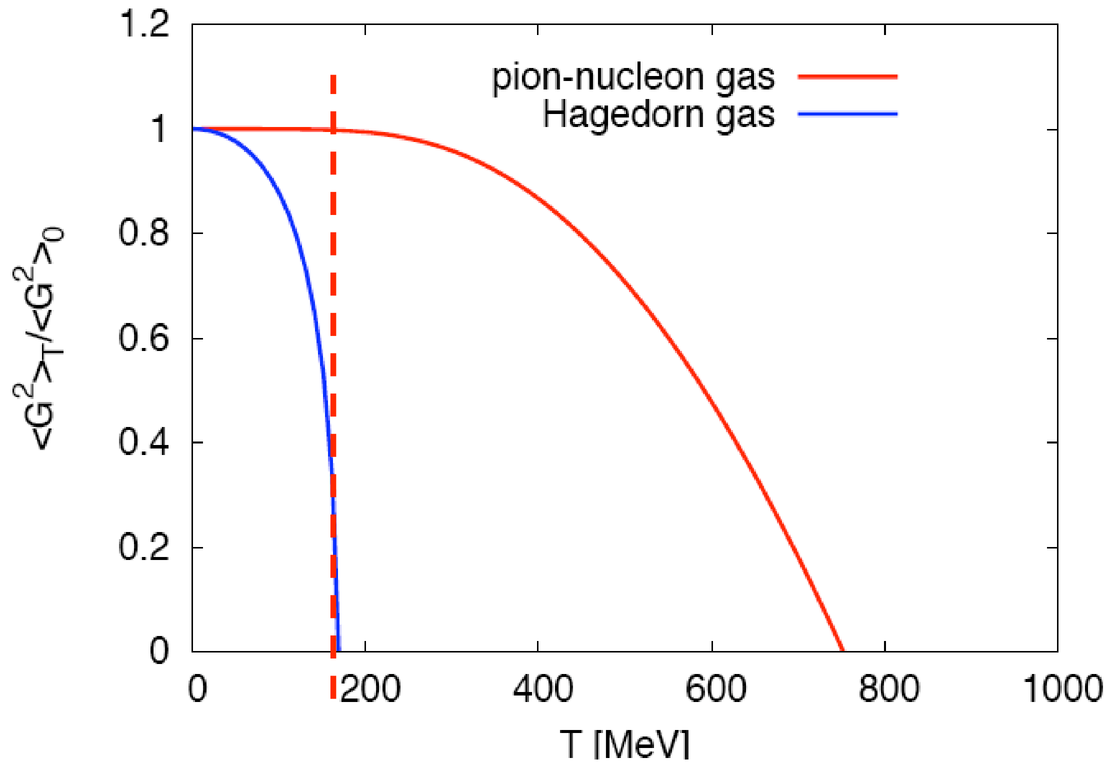
Review: Dokshitzer, DK, hep-ph/0404216

How to tell? Vary the strength of vacuum fields by raising T and look at quarkonium spectral functions

Do vacuum fields change around T_c?

YES

$$\langle \frac{\alpha_s}{\pi} G^2 \rangle_T = \langle \frac{\alpha_s}{\pi} G^2 \rangle_0 + \sum_h g_h \int \frac{d^3p}{2E_\pi (2\pi)^3} n(E_h) \langle h(\mathbf{p}) | \frac{\alpha_s}{\pi} G^2 | h(\mathbf{p}) \rangle$$



resonance contributions reduce the gluon condensate dramatically at high temperatures, would lead to quarkonium mass shifts incompatible with the lattice - the remnants of confinement should originate somewhere else;

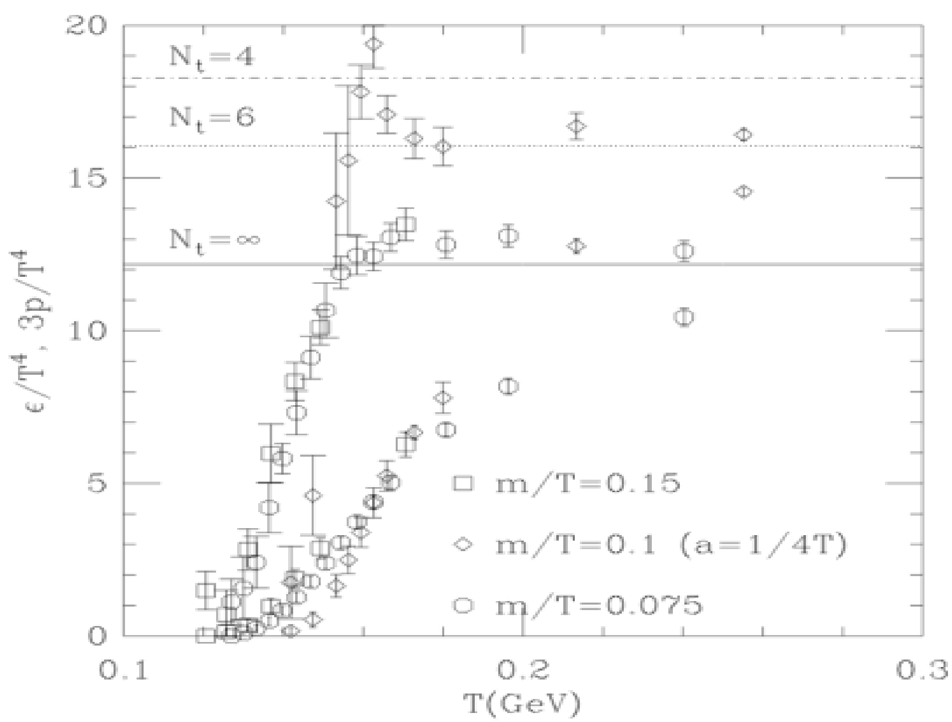
"Coulomb confinement" at short time scales?

A.Mocsy, DK

Do vacuum fields change around T_c?

YES

$$\langle \frac{\alpha_s}{\pi} G^2 \rangle_T = \langle \frac{\alpha_s}{\pi} G^2 \rangle_0 + \sum_h g_h \int \frac{d^3p}{2E_\pi (2\pi)^3} n(E_h) \langle h(\mathbf{p}) | \frac{\alpha_s}{\pi} G^2 | h(\mathbf{p}) \rangle$$



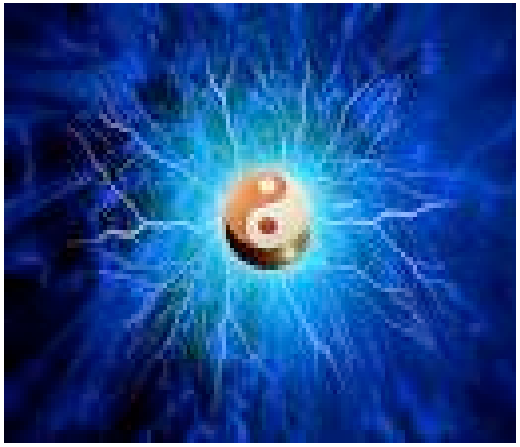
+ lattice data on (ε – 3 p) above T_c

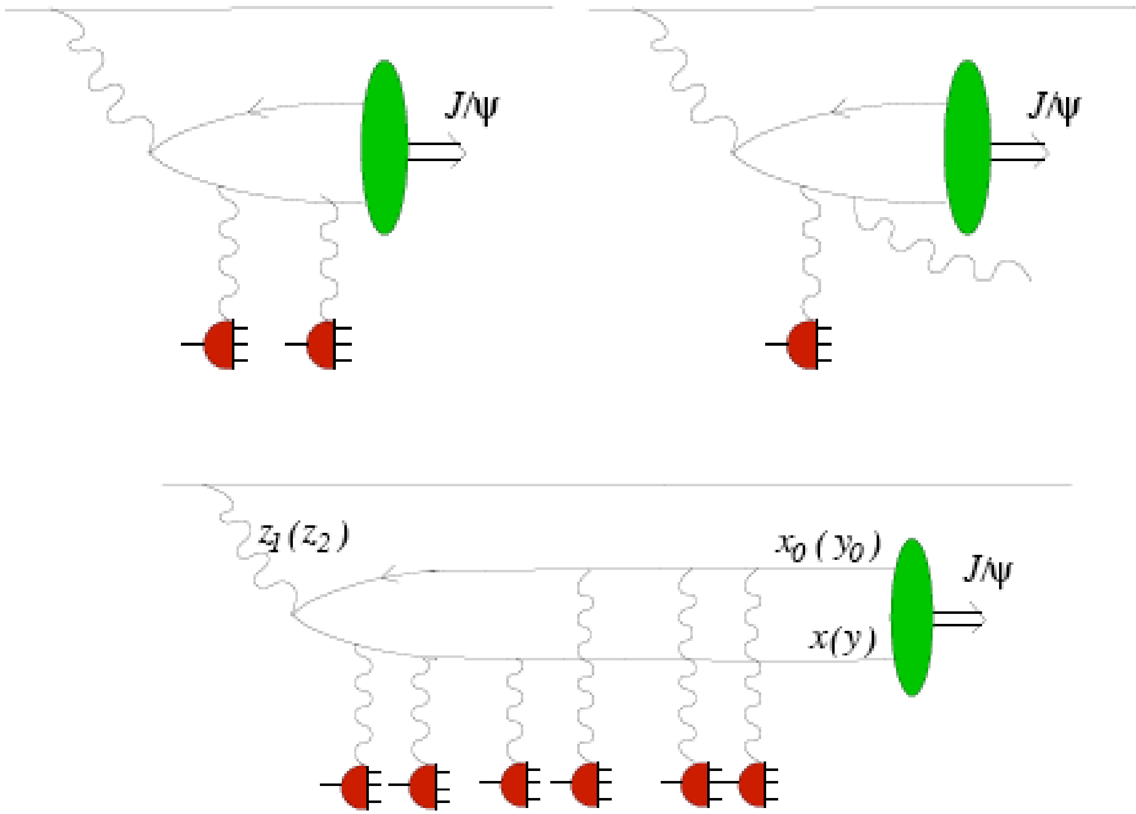
resonance contributions reduce the gluon condensate dramatically at high temperatures, would lead to quarkonium mass shifts incompatible with the lattice - the remnants of confinement should originate somewhere else;

"Coulomb confinement" at short time scales?

A.Mocsy, DK

J/Ψ in strong color fields: "initial state effects"

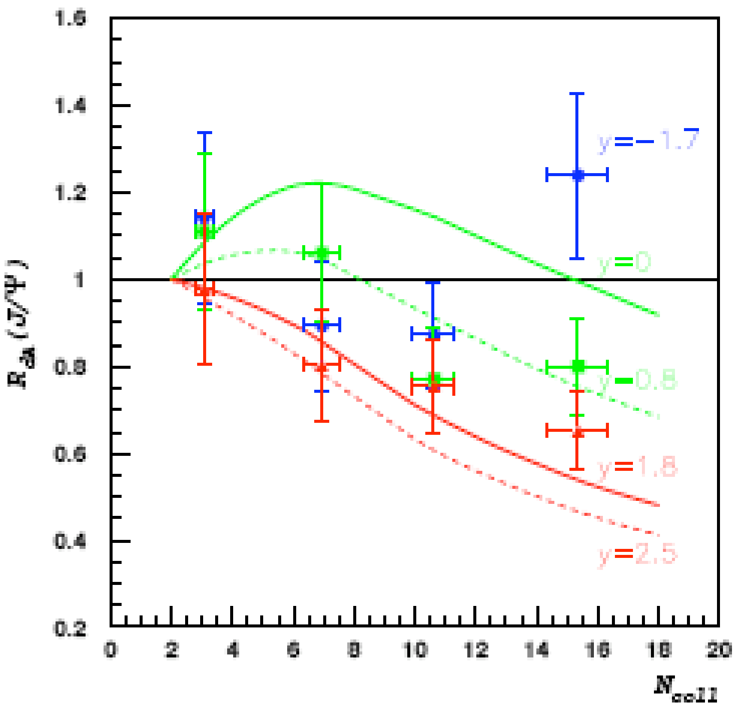


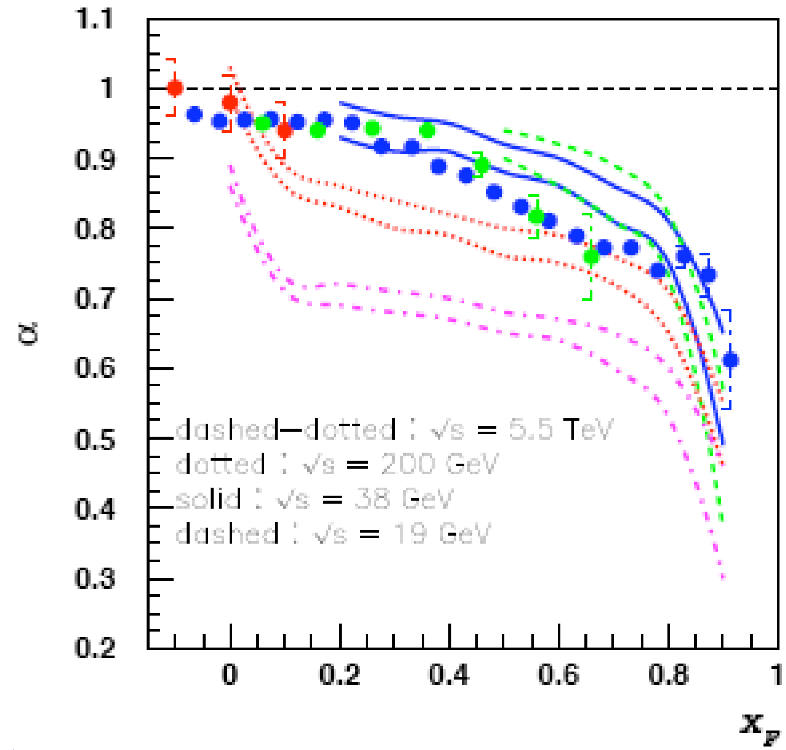


J/Ψ suppression in the Color Glass Condensate

Somewhat like screening in the plasma, $Q_s \leftrightarrow 2\pi T$

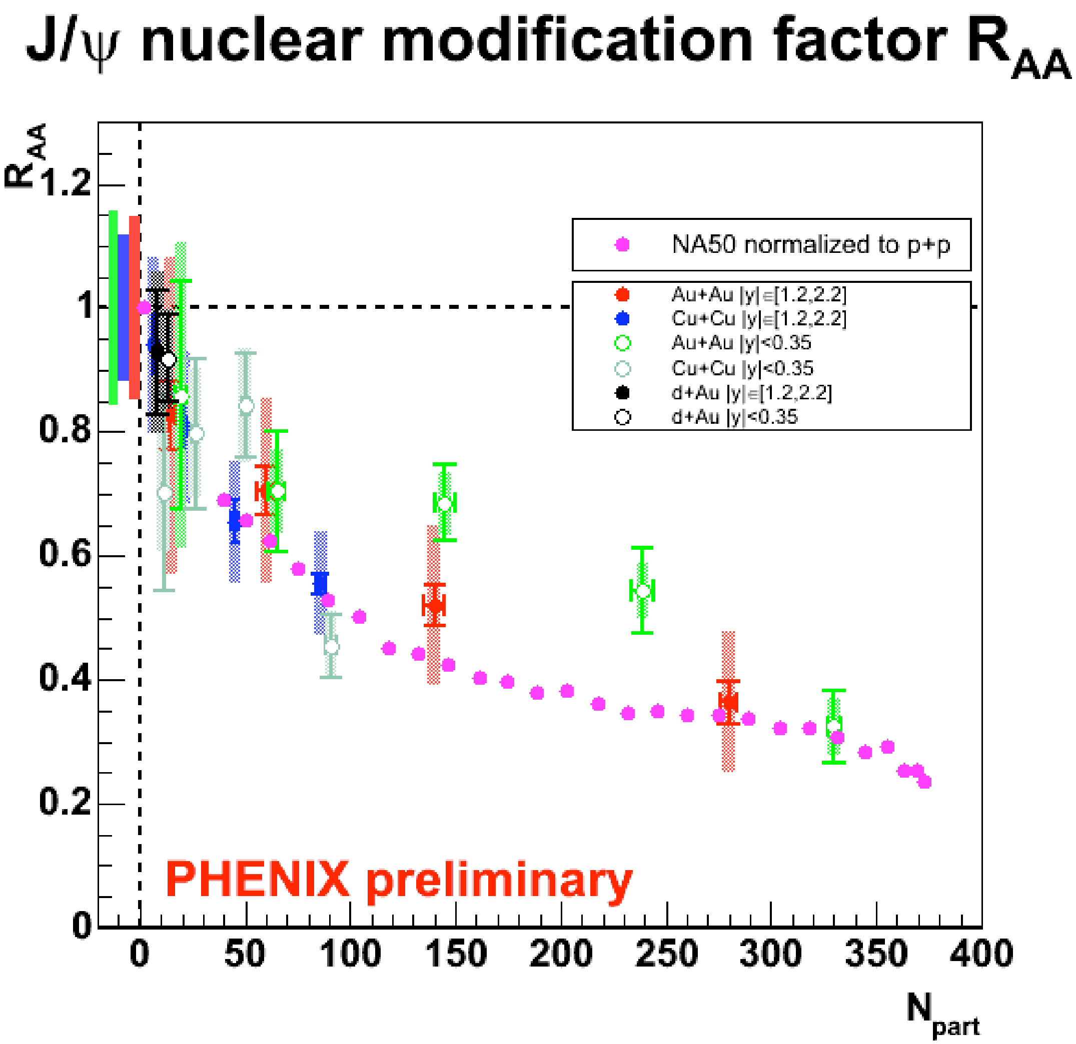
"x_F scaling"





Data: PHENIX Coll., nucl-ex/0507032
DK, K.Tuchin, hep-ph/0510358

J/ψ suppression at RHIC



"same as at SPS"?

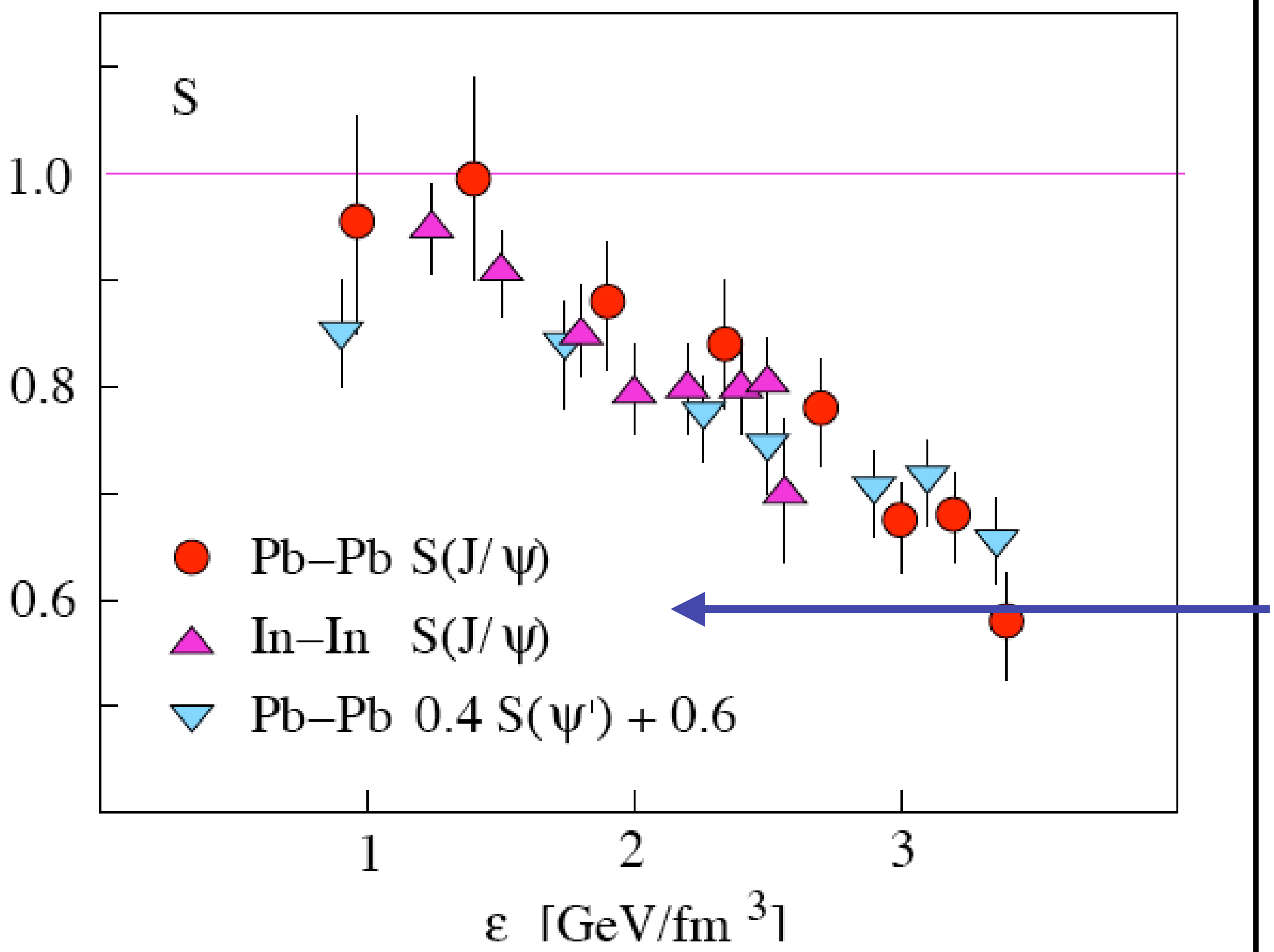
Sequential charmonium dissociation?

Both the absence of J/ψ suppression up to ~ 2 T_c in
the lattice QCD data and
the apparent similarity of the magnitude of suppression
at RHIC and SPS are puzzling;

However, the two puzzles may be consistent with each other

F.Karsch, DK, H.Satz,
hep-ph/0512239

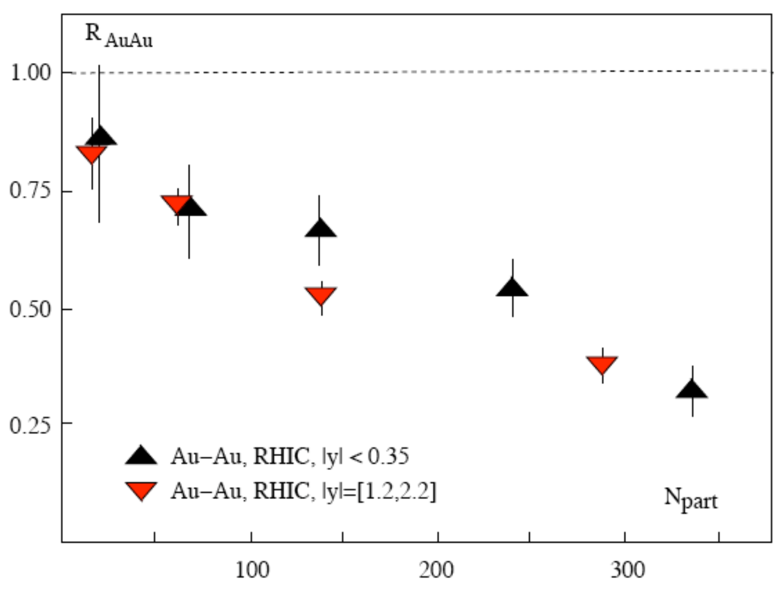
Is there a “direct” J/ψ suppression at SPS?

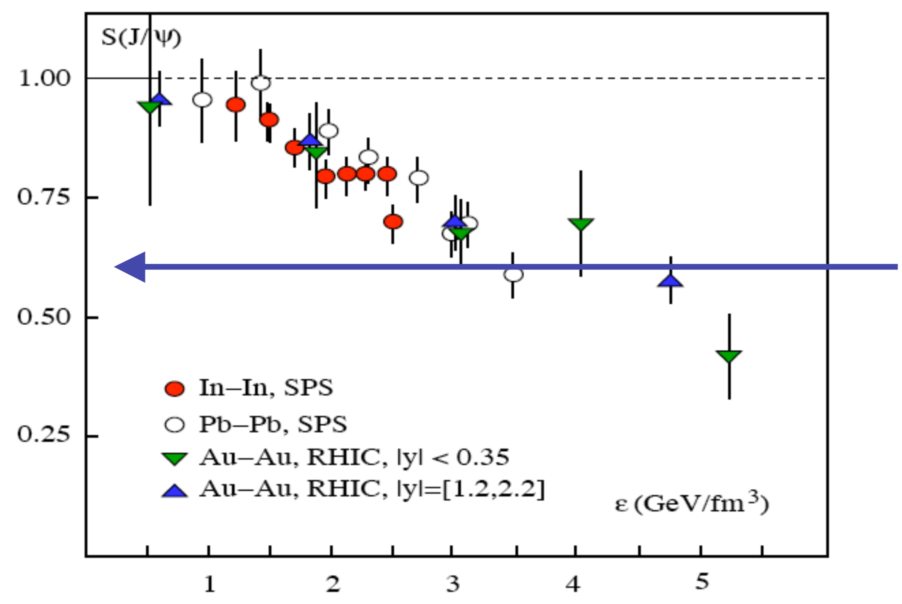


~ 40% of observed J/ψ ‘s originate from χ and ψ decays; they should be gone above T_c

(S has been corrected for initial state suppression)

Is there a “direct” J/ψ suppression at RHIC?

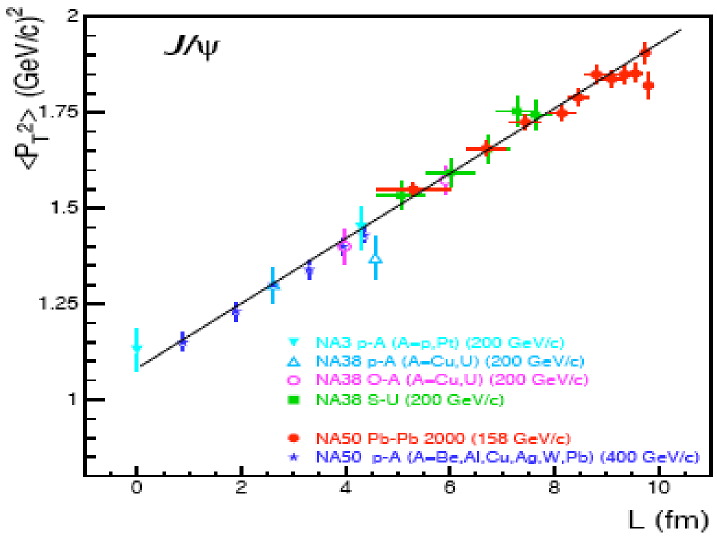


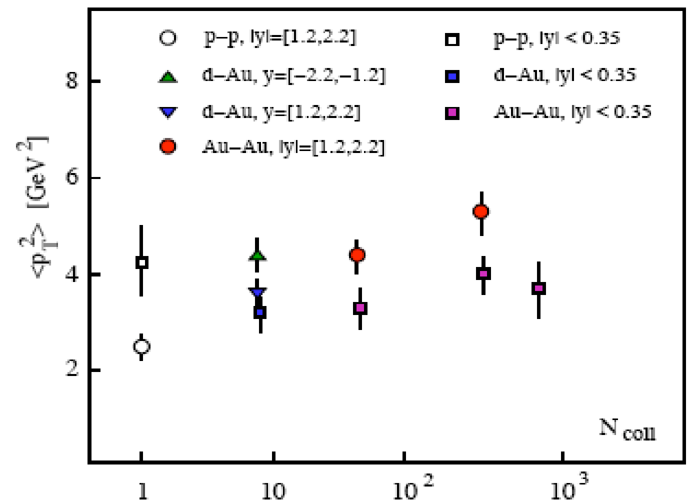


Data: PHENIX, NA50, NA60

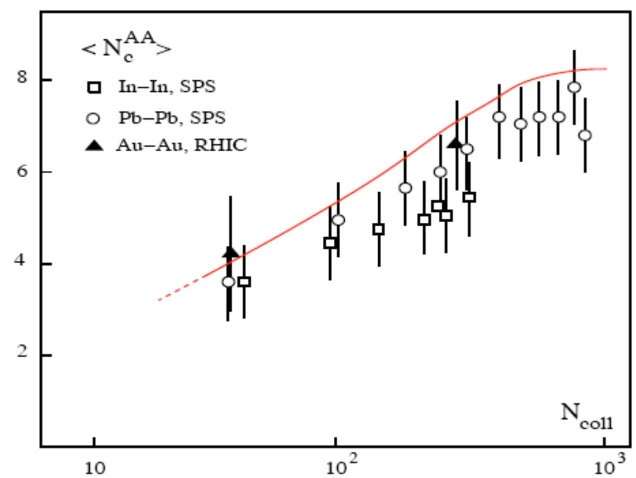
Energy density at the time J/ψ is formed - assumed $\tau = 1$ fm/c

Transverse momentum distributions



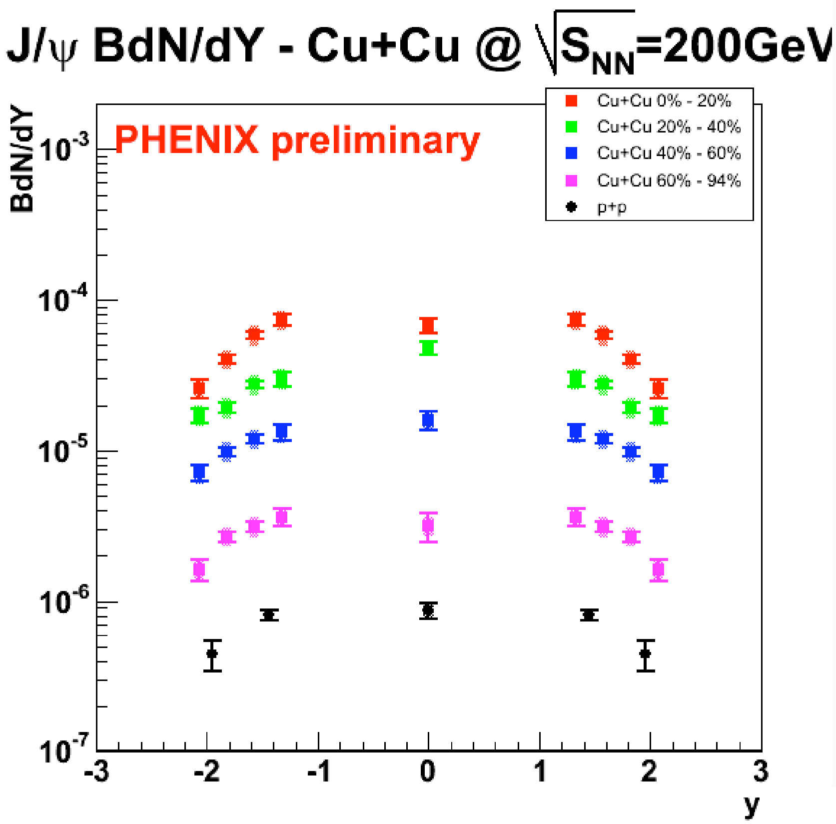


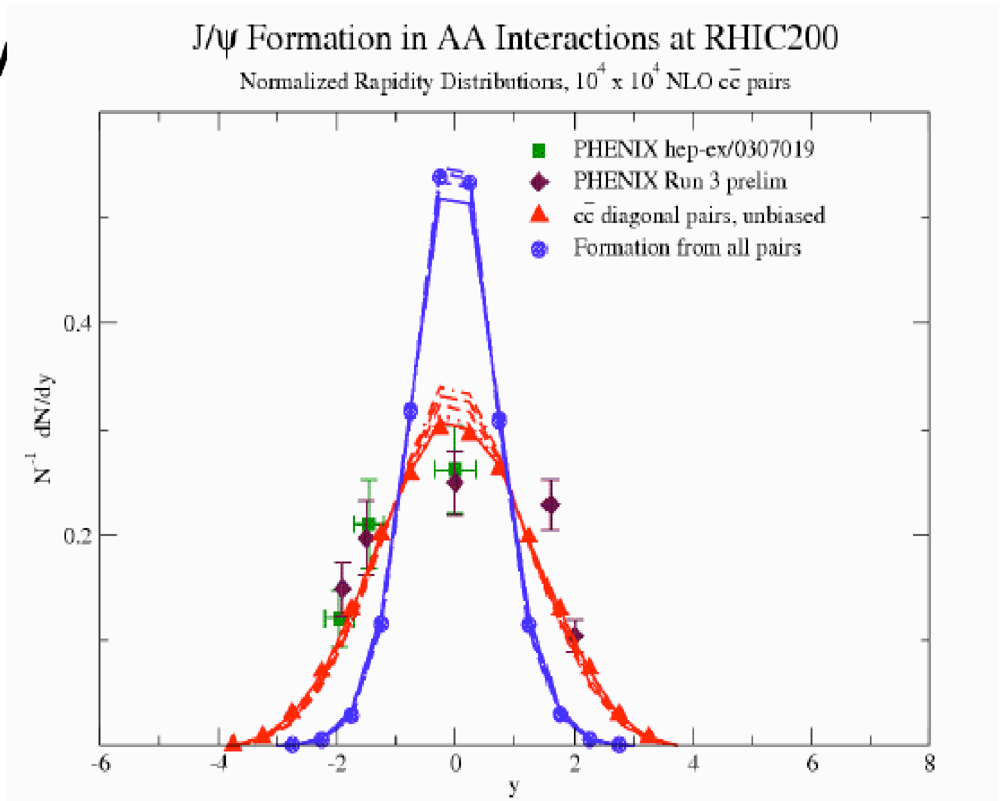
"Secondary" J/ψ's have softer p_T distributions + Cronin effect => suppression mostly at small p_T



Glauber model analysis

Recombination of charm quarks?





R.Thews,R.Rapp,…

Recombination narrows the rapidity distribution beyond what is expected from the initial state effects; is this seen?

Summary

1. 20 years later, the problem of J/ψ behavior in quark-gluon plasma remains in the focus of attention

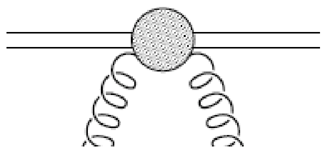
2. This problem may well keep the key to understanding both the nature of the plasma and the properties of confinement in QCD

More work has to be done…

Additional slides

Quarkonium in the hadron gas

Quarkonium-hadron scattering amplitude



$$\mathcal{M}^{kl}(P',p';P,p) = -\bar{d}_2 \frac{a_0^2}{\epsilon_0} \langle \pi^k(p')| \frac{1}{2} g^2 \mathbf{E}^{a2}(0) | \pi^l(p) \rangle$$

can be expressed through the matrix element of the trace of the energy-momentum tensor:

$$\langle \pi^k(p')| \frac{1}{2} g^2 \mathbf{E}^{a2}(0) | \pi^l(p) \rangle = \frac{4\pi^2}{b} \langle \pi^k(p') | \theta^\mu_\mu(0) | \pi^l(p) \rangle$$

Therefore, the coupling of heavy quarkonium to hadrons at low energy is analogous to the coupling of the Higgs boson -

$$\Theta^\alpha_\alpha = \frac{\tilde{\beta}(g)}{2g} G^{\alpha\beta a} G^a_{\alpha\beta} + \sum_{l=u,d,s} m_l \bar{q}_l q_l$$

it is proportional to the hadron mass (squared); decoupling of pions!

$$\langle h | \Theta^\alpha_\alpha | h \rangle = 2 M_h^2$$

DK, nucl-th/9601029

H.Fujii,DK, hep-ph/9903495

Quarkonium in hadron gas: recent lattice results

K.Yokokawa, S.Sasaki, T.Hatsuda,A.Hayashigaki, hep-lat/0605009

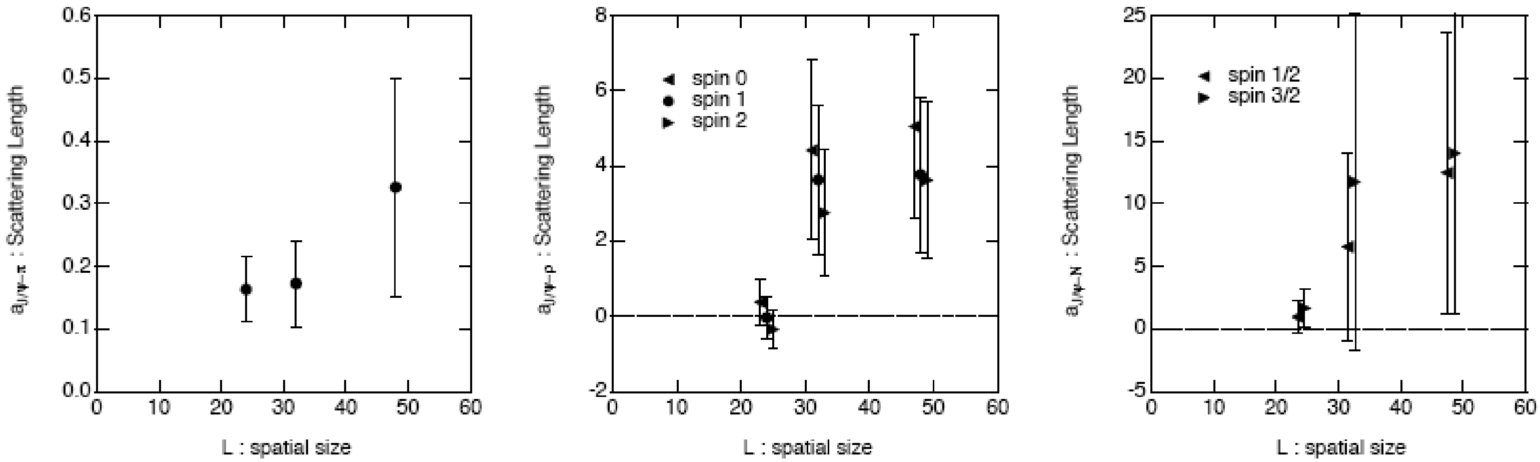


FIG. 4: The scattering lengths as a function of the spatial size L in lattice units for physical pion mass ($M_\pi = 140$ MeV). Left (middle, right) panel is for the J/ψ-π (J/ψ-ρ, J/ψ-N) channel.

$$a_{\psi\pi} : a_{\psi\rho} : a_{\psi N} \simeq 0.3 \pm 0.15 : 4 \pm 1.5 : 15 \pm 10 \sim m_\pi^2 : m_\rho^2 : m_N^2 \simeq 0.3 : 9 : 13$$

Pion "decoupling" seen in the data! J/ψ is safe in the pion gas