Collective dynamics in high-energy collisions

LBL, May 14-18, 2012

Heavy quarkonia and collective dynamics of strongly interacting matter

D. Kharzeev

Stony Brook University

BROOKHAVEN NATIONAL LABORATORY

Outline

Lecture 1: Heavy quarkonia in QCD matter

Lecture 2: New developments in relativistic hydrodynamics of strongly interacting matter (the role of quantum anomalies)

Heavy quarkonia in QCD matter

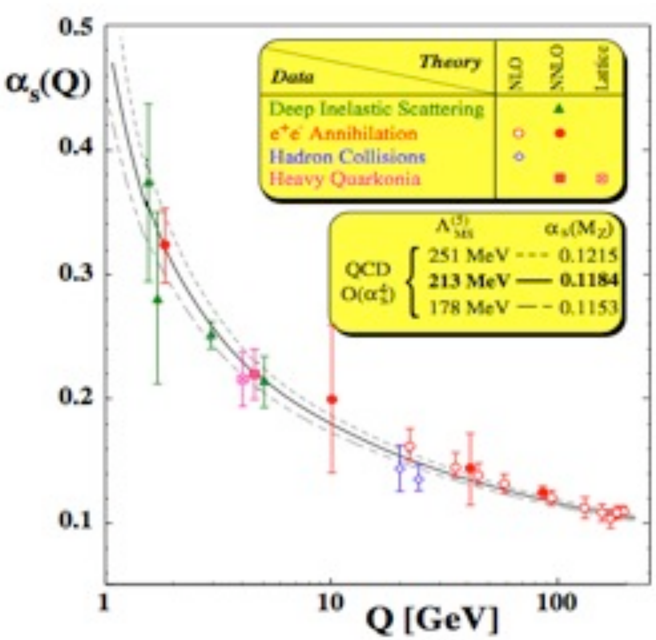
- Why heavy quarks?
- Quarkonium: the “hydrogen atom of QCD”
- Quarkonium production in strong color fields (cold nuclear matter effects in pA, AA)
- Quarkonium in quark-gluon plasma
- Confinement, holography and entanglement

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}:

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



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

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

Why heavy quarks?

QCD matter is characterized by dimensionful parameters:
saturation scale Q_S, density, transport coefficient , …

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

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

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 York 11973
(Received 12 November 1974)

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 $p + \text{Be} \to e^+ + e^- + x$ by measuring the e^+e^- mass spectrum with a precise pair spectrometer at the Brookhaven National Laboratory's 30-GeV alternating-gradient synchrotron.

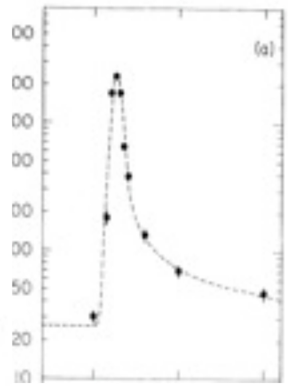
Discovery of a Narrow Resonance in e^+e^- Annihilation*

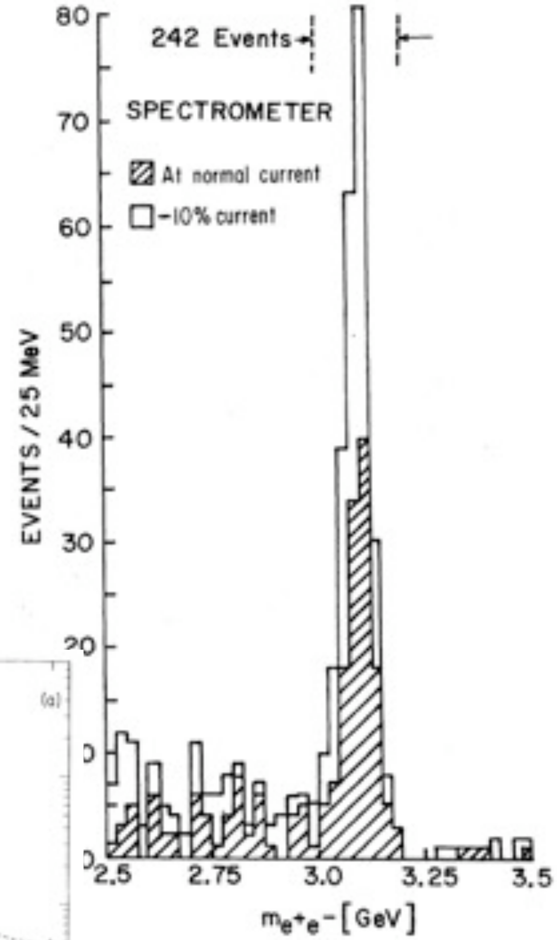
J.-E. Augustin,† A. M. Boyarski, M. Breidenbach, F. Bulos, J. T. Dakin, G. J. Feldman, G. E. Fischer, D. Fryberger, G. Hanson, B. Jean-Marie,† R. R. Larsen, V. Lüth, H. L. Lynch, D. Lyon, C. C. Morehouse, J. M. Paterson, M. L. Perl, B. Richter, P. Rapidis, R. F. Schwitters, W. M. Tanenbaum, and F. Vannucci‡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

and

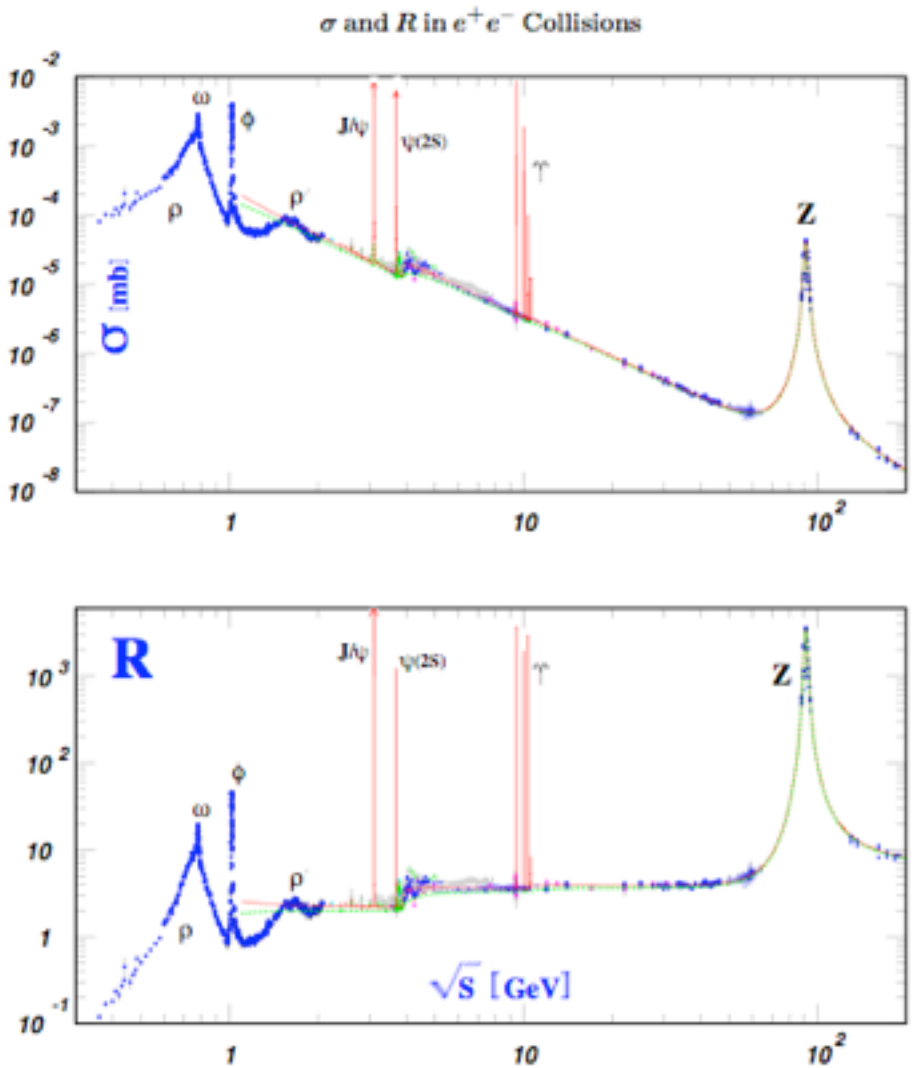
G. S. Abrams, D. Briggs, W. Chinowsky, C. E. Friedberg, G. Goldhaber, R. J. Hollebeek, J. A. Kadyk, B. Lulu, F. Pierre,§ G. H. Trilling, J. S. Whitaker, J. Wiss, and J. E. Zipse
Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720
(Received 13 November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

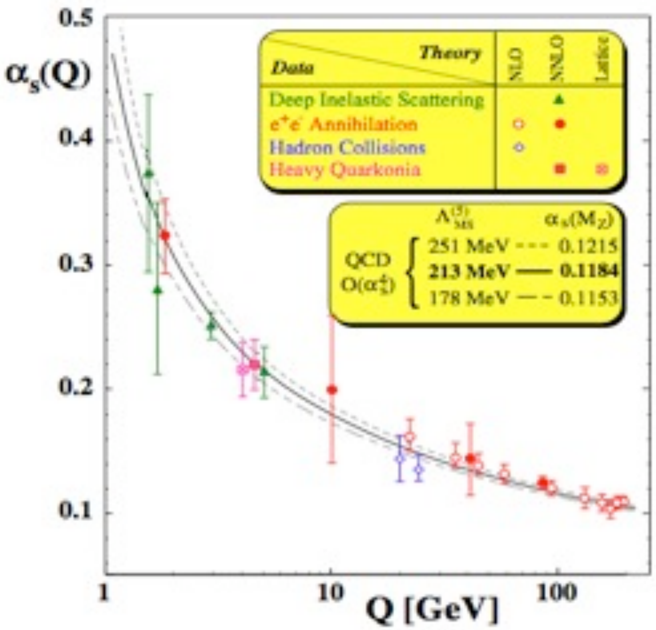


The annihilation width of heavy quarkonia is small due to the asymptotic freedom

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}:

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

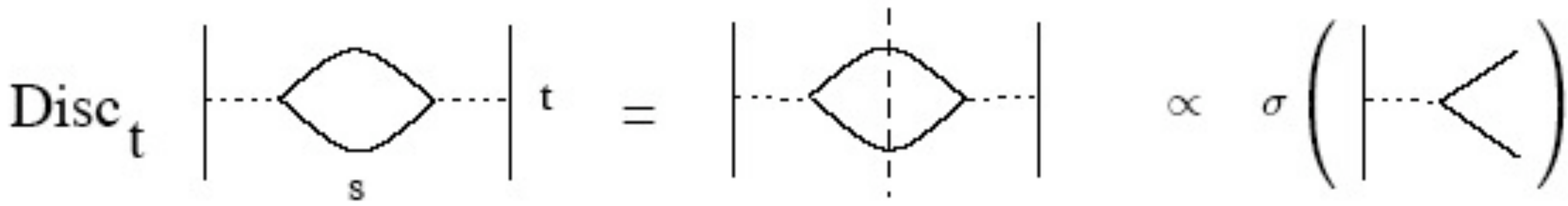


$$\alpha_s(M_H) \ll 1$$

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

Quarkonium and asymptotic freedom (Coulomb potential)

Spectral representation in the t-channel: $V(R) = \sum_m \sigma(m^2)\,\frac{\exp(-mR)}{R}$



If physical particles can be produced (positive spectral density), then unitarity implies <u>screening</u>

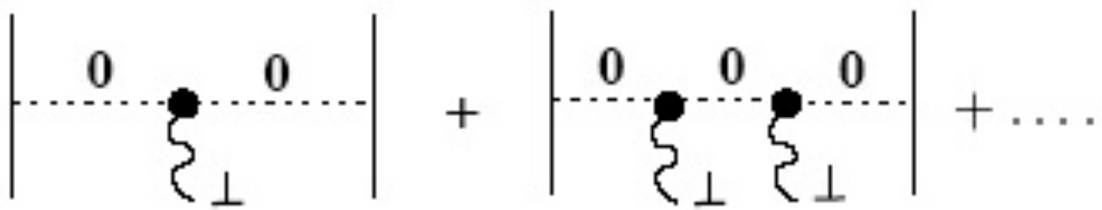
$$\left\{\frac{d\,\alpha_s^{-1}(R)}{d\ln R}\right\}^{\mathrm{phys}} \propto \frac{1}{3}N + \frac{2}{3}n_f$$

Gluons (transverse) Quarks

Coulomb potential in QCD - II

Missing non-Abelian effect: instantaneous Coulomb exchange dressed by (zero modes of) transverse gluons

$$\sum_n \left[0 + \perp \rightarrow 0\right]^n =$$



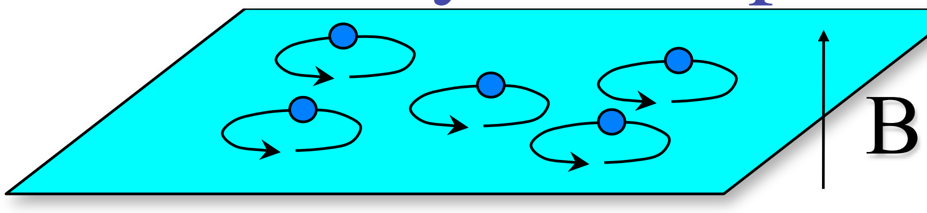
Negative sign
(the shift of the ground level
due to perturbations - unstable vacuum!):

$$\delta E \equiv E - E_0 = \sum_n \frac{|\langle 0|\delta V|n\rangle|^2}{E_0 - E_n} < 0$$

Anti-screening

$$\left\{\frac{d\,\alpha_s^{-1}(R)}{d\ln R}\right\}^{\text{stat}} \propto -4\,N$$

Asymptotic freedom and the instability of the perturbative vacuum

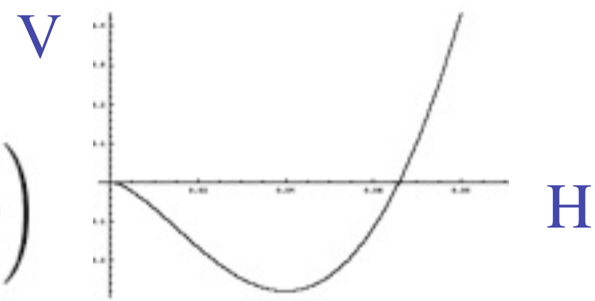


The effective potential: sum over 2D Landau levels

$$V_{\rm pert}(H) = \frac{g\,H}{4\,\pi^2}\int dp_z \sum_{n=0}^{\infty}\sum_{s_z=\pm 1}\sqrt{2\,g\,H\,(n+1/2-s_z)+p_z^2}.$$

Paramagnetic response of the vacuum:

$$\mathrm{Re}\,V_{\rm pert}(H) = \frac{1}{2}\,H^2 + (g\,H)^2\,\frac{b}{32\,\pi^2}\left(\ln\frac{g\,H}{\mu^2}-\frac{1}{2}\right)$$



1. The lowest level n=0 of radius $\sim (gH)^{-1/2}$ is unstable!

2. Strong fields ⟷ Short distances

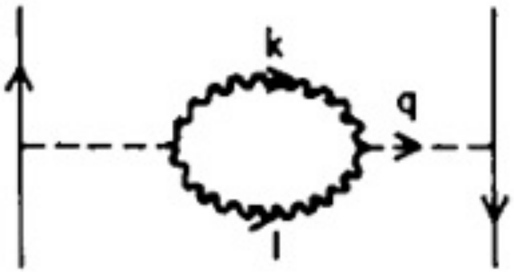
Instability of perturbative QCD vacuum;
What is the true ground state?

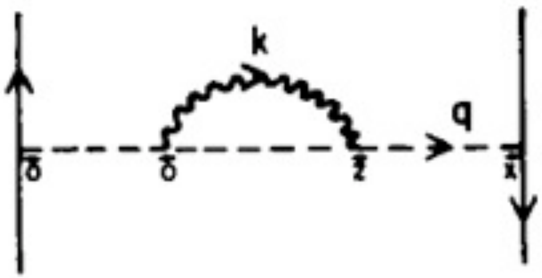
Quarkonia: the potential problems...

$$D_{\mu\nu}^{ab} = i\,\delta^{ab}\frac{1}{\bar{k}^2} \qquad \mu = \nu = 0$$

$$= i\,\delta^{ab}\left(\delta_{ij} - \frac{k_i k_j}{\bar{k}^2}\right)\frac{1}{k^2 + i\epsilon} \qquad \mu = i,\ \nu = j.$$

Coulomb gauge





Screening

Anti-Screening

THE STATIC POTENTIAL IN QUANTUM CHROMODYNAMICS

Thomas APPELQUIST[1,2] and Michael DINE[1]
J. Willard Gibbs Laboratory, Yale University, New Haven, CT 06520, USA

and

I.J. MUZINICH[3]
Brookhaven National Laboratory, Upton, N.Y. 11973, USA

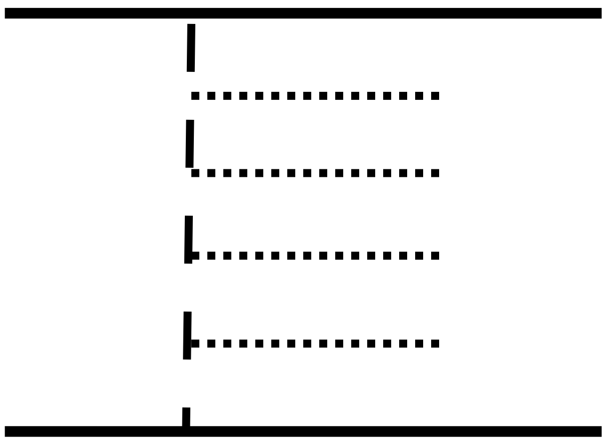
Received 18 May 1977

Quarkonia: the potential problems...

Fig. 4. A three loop graph with a singular static limit.

Higher Fock states; classified in NRQCD

Bodwin, Braaten, Lepage; ...



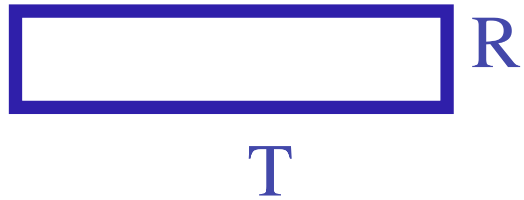
energy of transverse gluons - constant per unit of length (planar, large N limit);
... a string?

e.g., the “gluon chain” model
Greensite and Thorn

... can be seen as parts of the QCD string?

Scale invariance and confinement

Consider a rectangular Wilson loop:



$$W(C) = \exp\left(ig \int_C A_\mu dx^\mu \right)$$

It is related to the potential $V(R)$ acting between the charges Q and $\bar{Q}$:

$$W(C) \to \exp\left(-TV(R)\right)$$

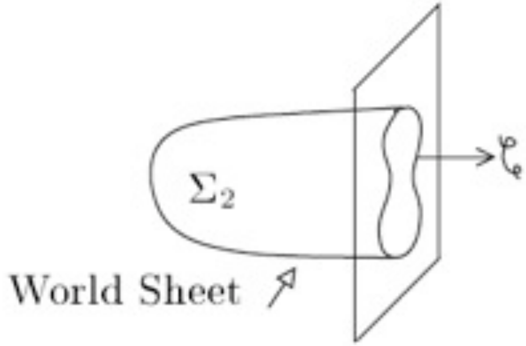
Scale transformation: $T \to \lambda T$; $R \to \lambda R$;

the only solution: Coulomb potential

$$V(R) \sim \frac{1}{R}$$

Insights from holography

$$V(L) = -\lim_{T\to\infty}\frac{1}{T}\ln\langle W(C_{L\times T})\rangle\,.$$



Of course, no confinement in N=4 SYM: scale invariance dictates that the expectation value of W must scale with T/L - thus Coulomb potential

$$V(L) \sim 1/L$$

Nevertheless, an interesting lesson: solving for the minimal surface in super-gravity and evaluating its area, one finds

$$V(L) = -\frac{4\pi^2\sqrt{\lambda}}{\Gamma^4(1/4)\,L}.$$

$$N\to\infty,\quad \lambda = g_{YM}^2 N$$

Why square root?
"not your grandfather's Coulomb potential",
a weaker one! screening?

Insights from holography

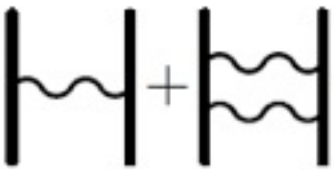
$$\alpha(\lambda) = \begin{cases} \frac{\lambda}{4\pi} + \cdots, & \text{for } \lambda \to 0; \\ \frac{4\pi^2\sqrt{2\lambda}}{\Gamma^4(1/4)} + O(1), & \text{for } \lambda \to \infty. \end{cases}$$

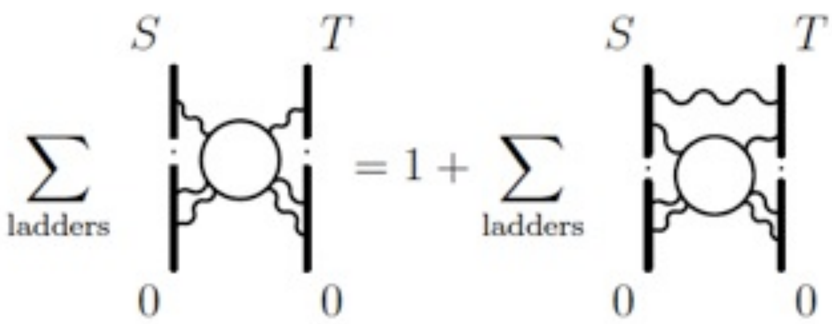
$$V(L) = -\frac{\alpha(L)}{L}$$

Indeed, the square root of the coupling (but not the pre-factor) can be reproduced on the Field Theory side by resummation of planar diagrams:

Erickson, Semenoff
Szabo, Zarembo,
hep-th/9911088

$$-\ln\left\{1 + \text{[diagram]} + \text{[diagram]} + \cdots\right\} = \frac{\lambda}{4\pi}\frac{T}{L} - \frac{\lambda^2}{(2\pi)^3}\frac{T}{L}\ln\frac{T}{L} + \cdots .$$

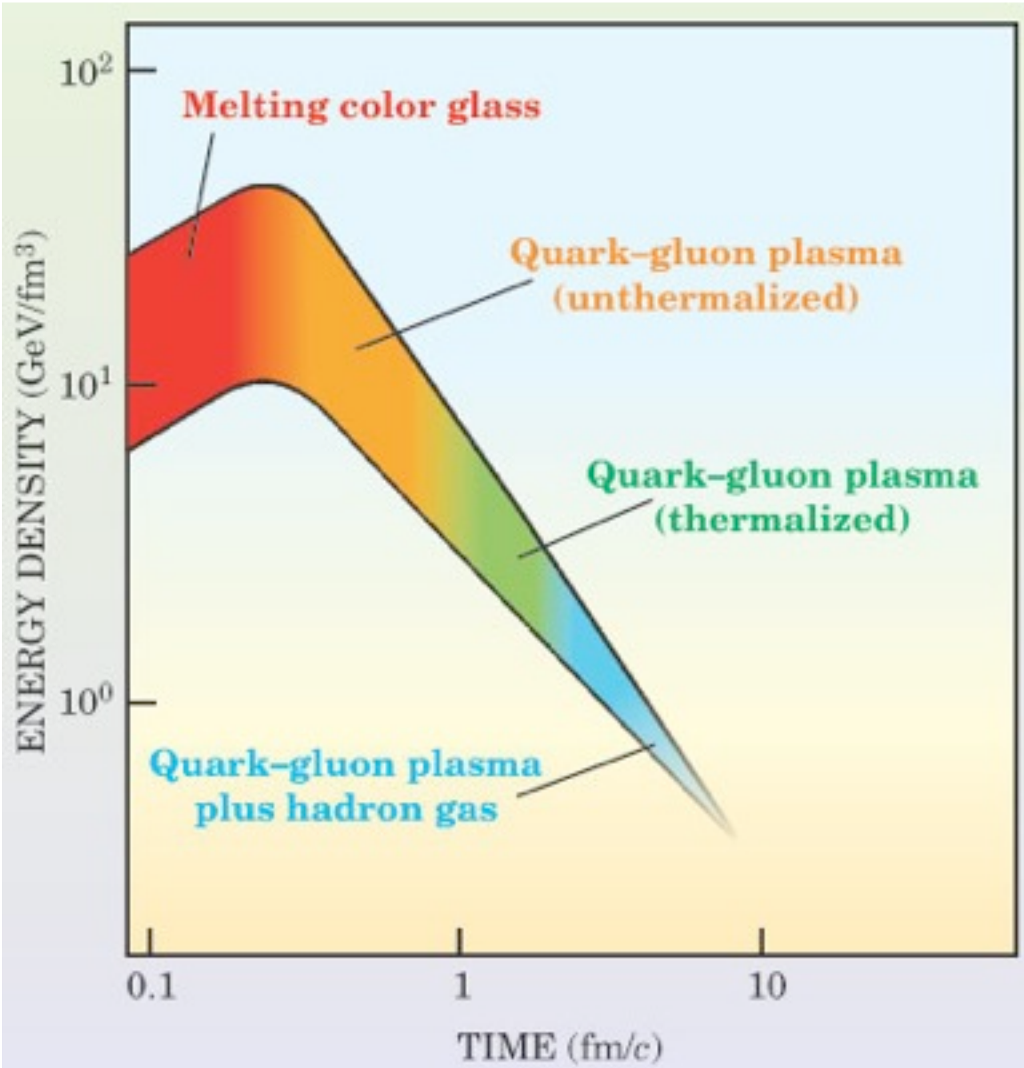




$$\alpha(\lambda) = \frac{\sqrt{\lambda}}{\pi} - 1 + O(1/\sqrt{\lambda}),$$

Infinite number of higher Fock states, but their effect may be resummed?

Quarkonium production in nuclear collisions



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

Heavy quarks and the Color Glass Condensate

Lecture by L.McLerran

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

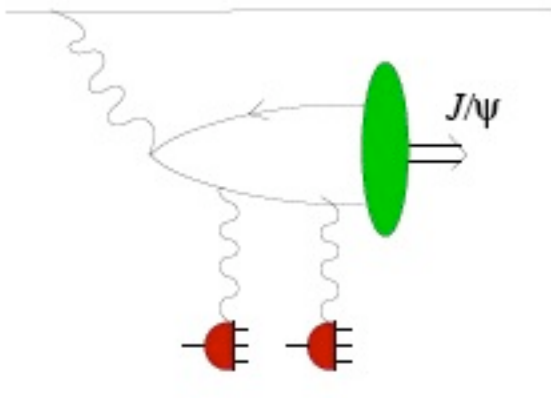
$$gE \sim \frac{M}{1/M} = M^2$$

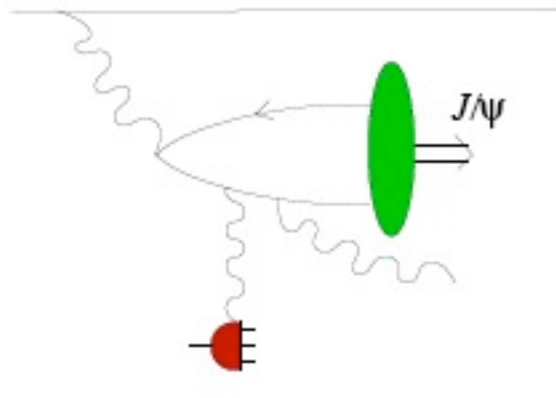
or

$$Q_s^2 \geq M^2$$

heavy quarks no longer decouple => they are not really “heavy”

J/Ψ production in strong color fields





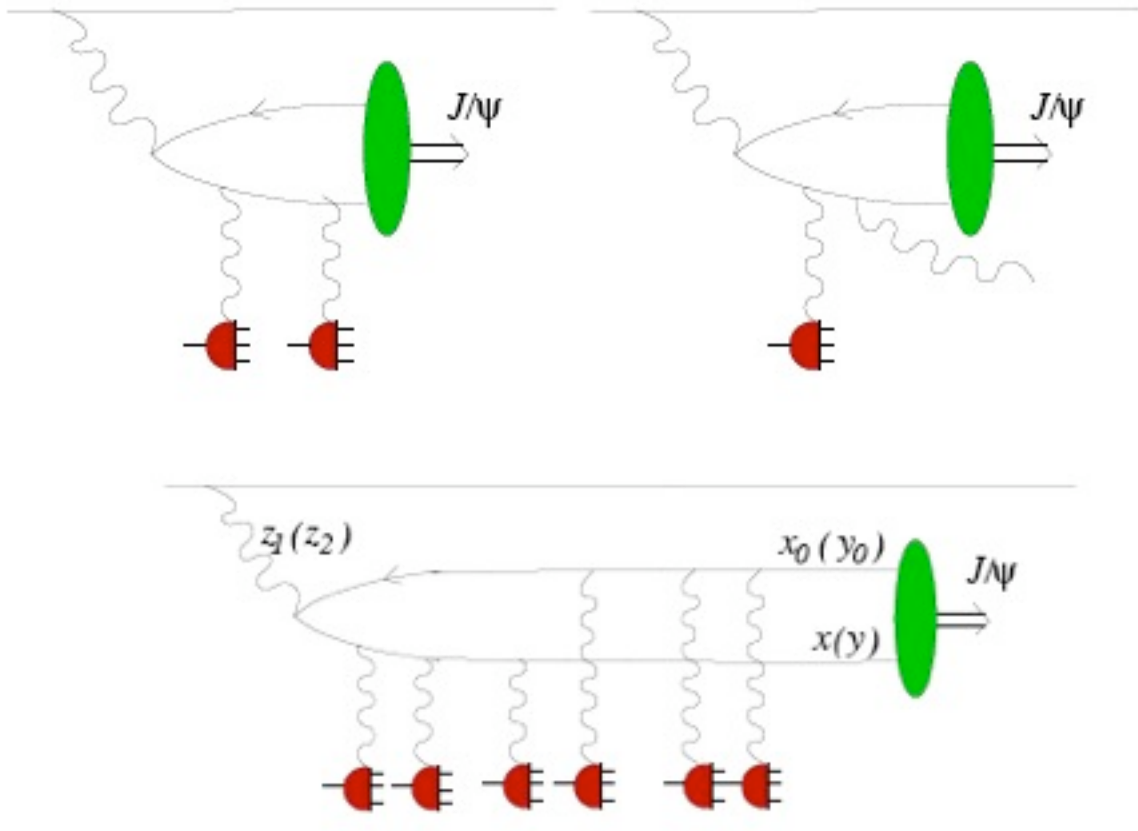
At high parton density, when $\alpha_s^2 A^{1/3} \sim 1$

$$\alpha_s^6 A^{2/3} \sim \alpha_s^2 \qquad\qquad \alpha_s^5 A^{1/3} \sim \alpha_s^3$$

this diagram is the leading one

DK, K.Tuchin, hep-ph/0510358

J/Ψ production in strong color fields



DK, K.Tuchin,
hep-ph/0510358

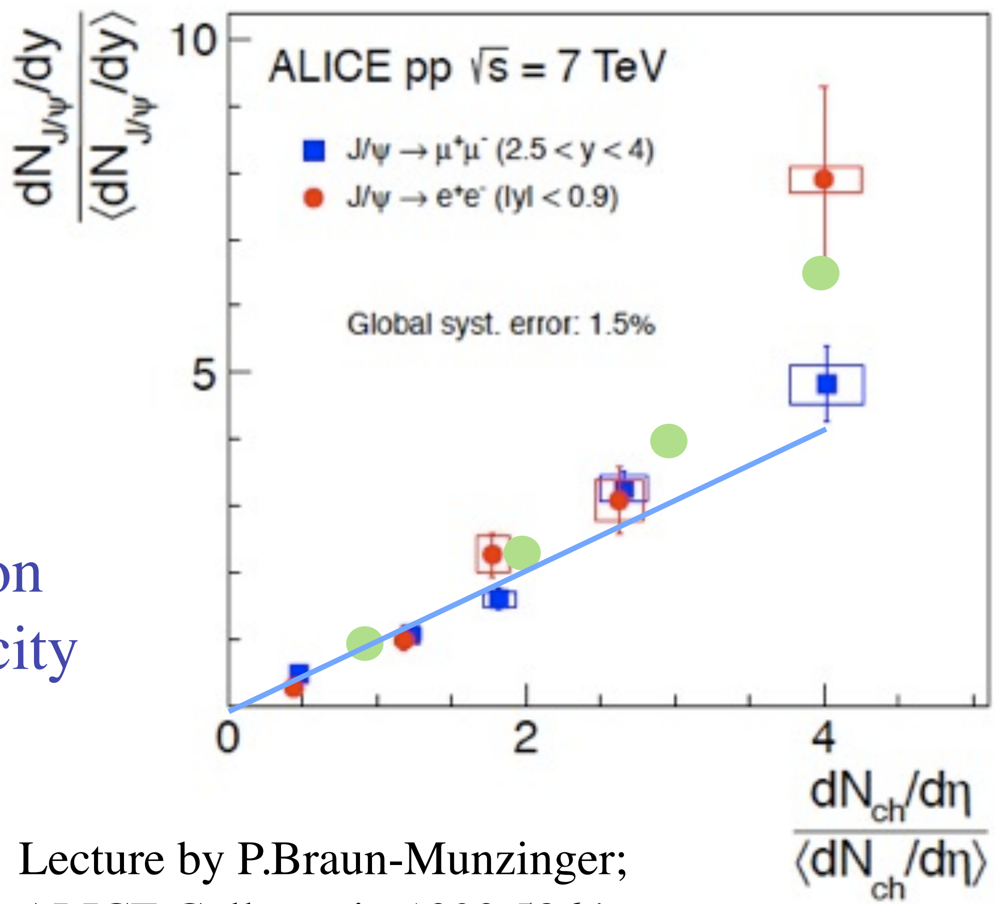
J/Ψ production in strong color fields

At high enough energy (LHC?), high parton density is reached even in pp collisions - expect the change in the scaling of J/psi yield with associated multiplicity:

$$\alpha_s^5 A^{1/3} \sim \alpha_s^3 \quad \longrightarrow \quad \alpha_s^6 A^{2/3} \sim \alpha_s^2$$

$$\frac{dn_J}{dy} \sim Q_s^2\ S \sim \frac{dn}{dy} \qquad \qquad \frac{dn_J}{dy} \sim Q_s^4\ S \sim \left(\frac{dn}{dy}\right)^{4/3}$$

J/Ψ production as a function of associated multiplicity in pp collisions: the ALICE data



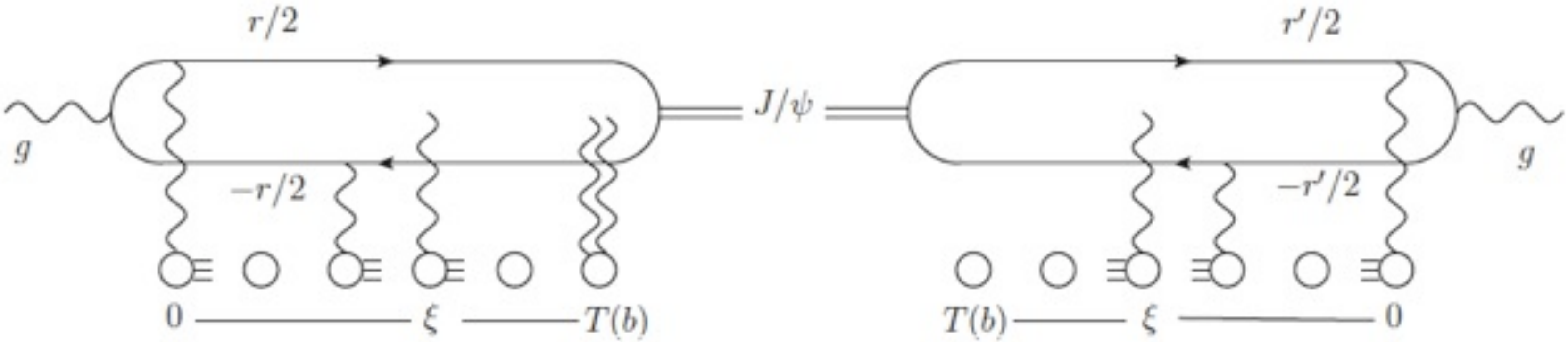
$$\frac{dn_J}{dy} \sim Q_s^4 \, S \sim \left(\frac{dn}{dy}\right)^{4/3}$$

Indication for high parton density in high multiplicity pp collisions?

$$Q_s^2 \qquad m_c^2$$

Lecture by P.Braun-Munzinger;
ALICE Coll., arxiv:1202.5864;

J/Ψ production in strong color fields



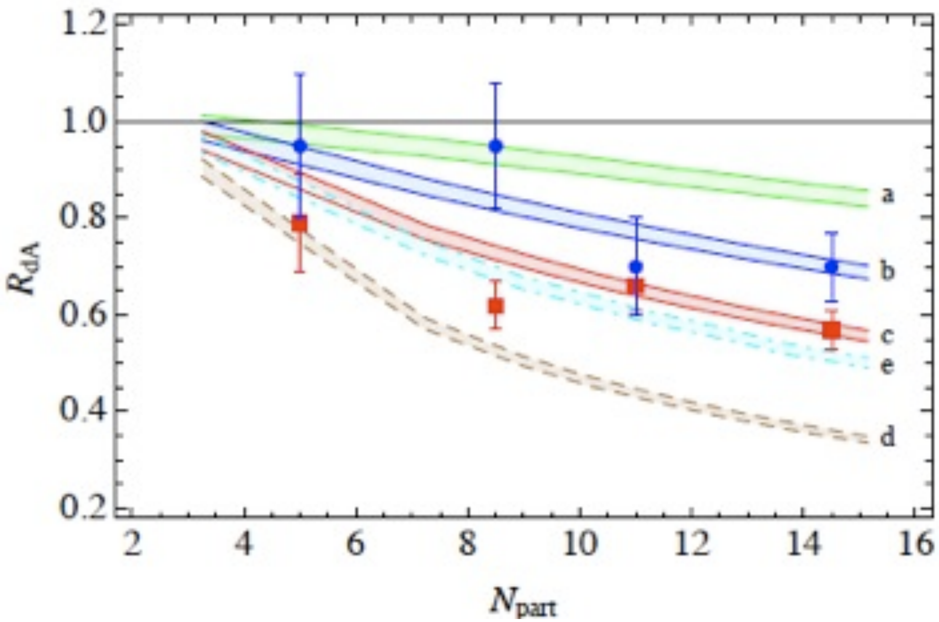
Sample diagram contributing to J/Ψ production in pA collisions

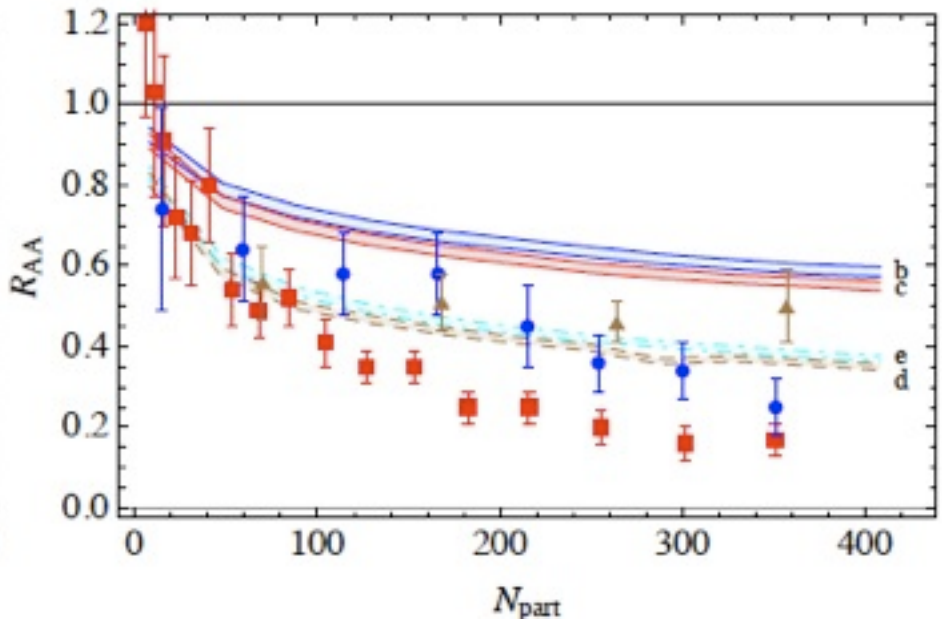
$$\frac{d\sigma_{pA\to J/\psi X}}{dy d^2 b} = x_1 G(x_1, m_c^2) \int_0^1 dz \int \frac{d^2 r}{4\pi} \Phi(\boldsymbol{r}, z) \int_0^1 dz' \int \frac{d^2 r'}{4\pi} \Phi^*(\boldsymbol{r}', z') \times \frac{4\boldsymbol{r}\cdot\boldsymbol{r}'}{(\boldsymbol{r}+\boldsymbol{r}')^2} \left(e^{-\frac{Q_s^2}{16}(\boldsymbol{r}-\boldsymbol{r}')^2} - e^{-\frac{Q_s^2}{8}(r^2+r'^2)} \right).$$

F. Dominguez,[1] D.E. Kharzeev,[2,3] E.M. Levin,[4,5] A.H. Mueller,[1] and K. Tuchin[6]

Phys. Lett. B710 (2012) 182

J/Ψ production in strong color fields





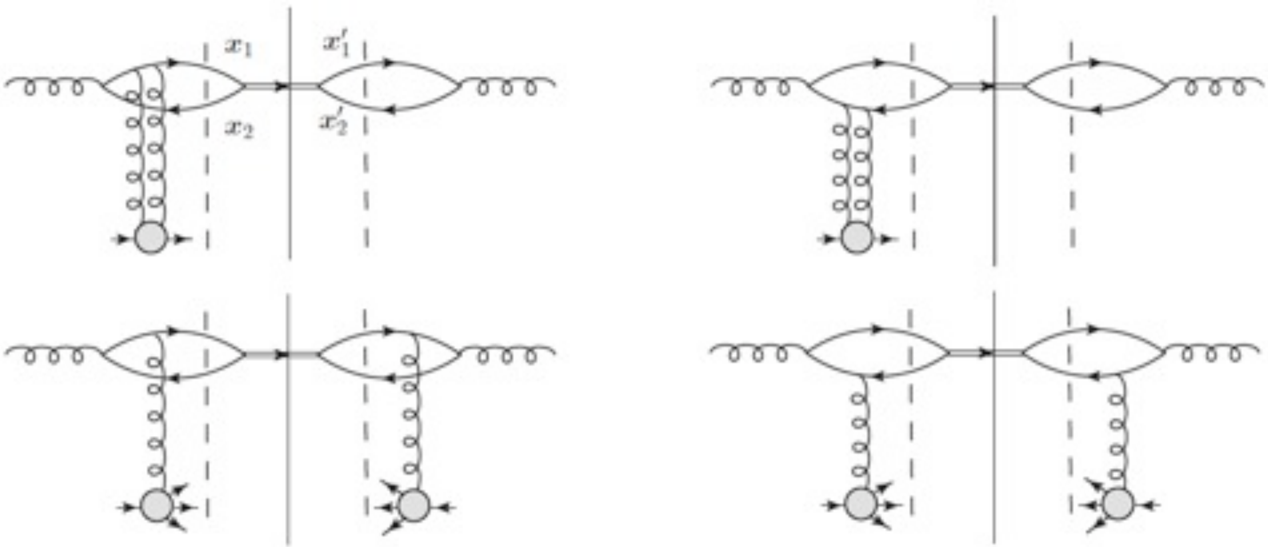
Reasonable agreement with p(d)A data

but the AA data indicate additional suppression, stronger at forward rapidity!

F. Dominguez,[1] D.E. Kharzeev,[2,3] E.M. Levin,[4,5] A.H. Mueller,[1] and K. Tuchin[6]

Phys. Lett. B710 (2012) 182

The transverse momentum spectra of J/Ψ



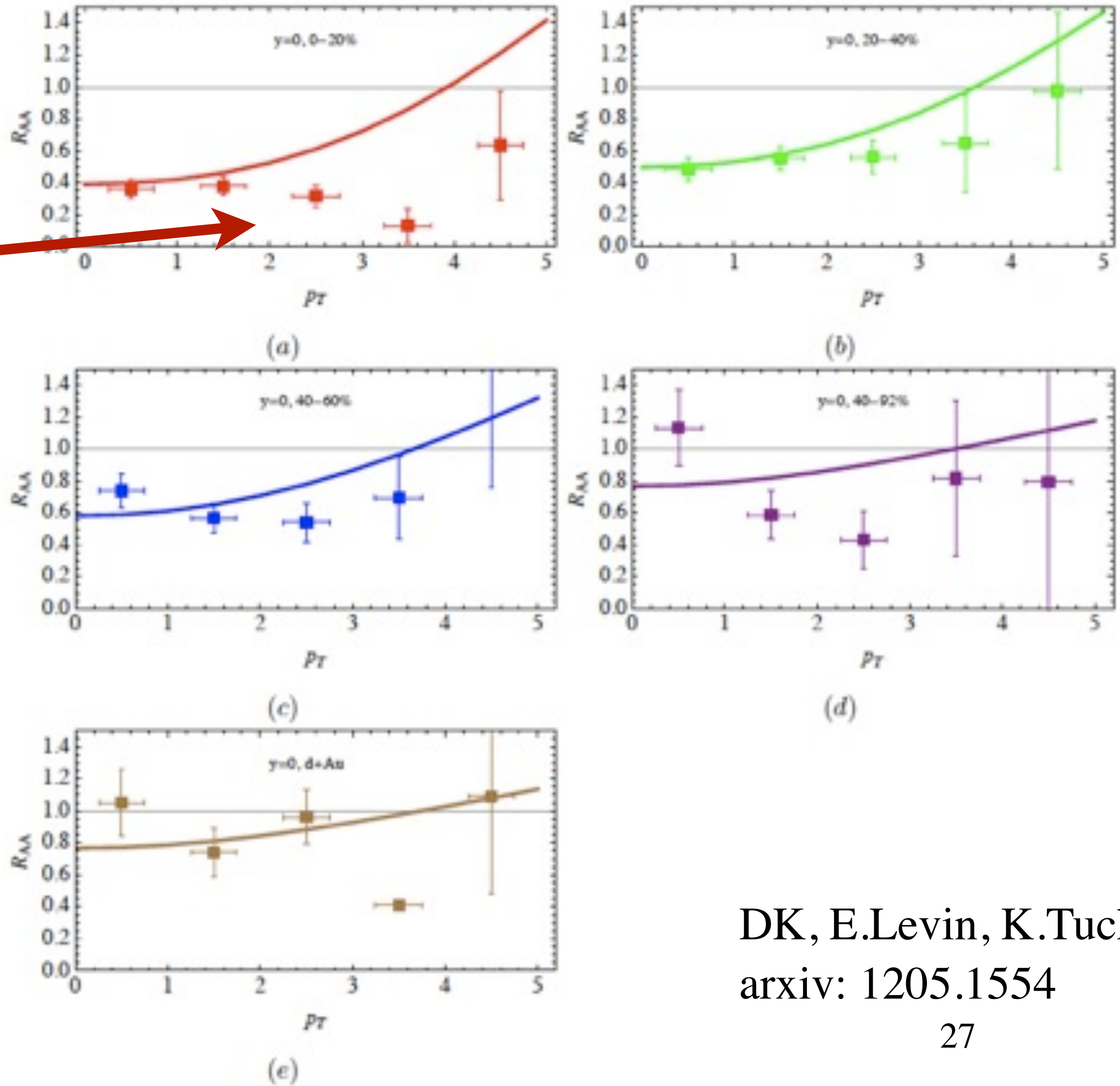
DK, E.Levin, K.Tuchin,
arxiv: 1205.1554

$$\frac{d\sigma_{A_1A_2\to J/\psi X}}{d^2p_\perp dy d^2B_1\, d^2B_2} = \int_0^1 dz \int \frac{d^2r}{4\pi}\Phi(r,z)\int_0^1 dz'\int\frac{d^2r'}{4\pi}\Phi(r',z')\int d^2k_\perp\int_0^1 d\xi'$$
$$\times \frac{C_F}{\alpha_s\pi^2}\frac{Q_{s1}^2Q_{s2}^2}{Q_{s1}^2+Q_{s2}^2}F_k \frac{\boldsymbol{r}\cdot\boldsymbol{r}'}{16\pi\xi'}\, e^{-\frac{p_\perp^2+k_\perp^2}{(Q_{s1}^2+Q_{s2}^2)\xi'}}$$
$$\times I_0\left(\frac{2p_\perp k_\perp}{(Q_{s1}^2+Q_{s2}^2)\xi'}\right) e^{-\frac{1}{4}(Q_{s1}^2+Q_{s2}^2)\frac{1}{4}(\boldsymbol{r}-\boldsymbol{r}')^2\xi'}\, e^{-\frac{1}{8}(Q_{s1}^2+Q_{s2}^2)(r^2+r'^2)(1-\xi')}$$

The transverse momentum spectra of J/Ψ comparison to the RHIC data: y=0

AuAu

Large discrepancy at semi-hard transverse momenta



dAu

PHENIX data

DK, E.Levin, K.Tuchin, arxiv: 1205.1554

The transverse momentum spectra of J/Ψ comparison to the RHIC data: y=1.7

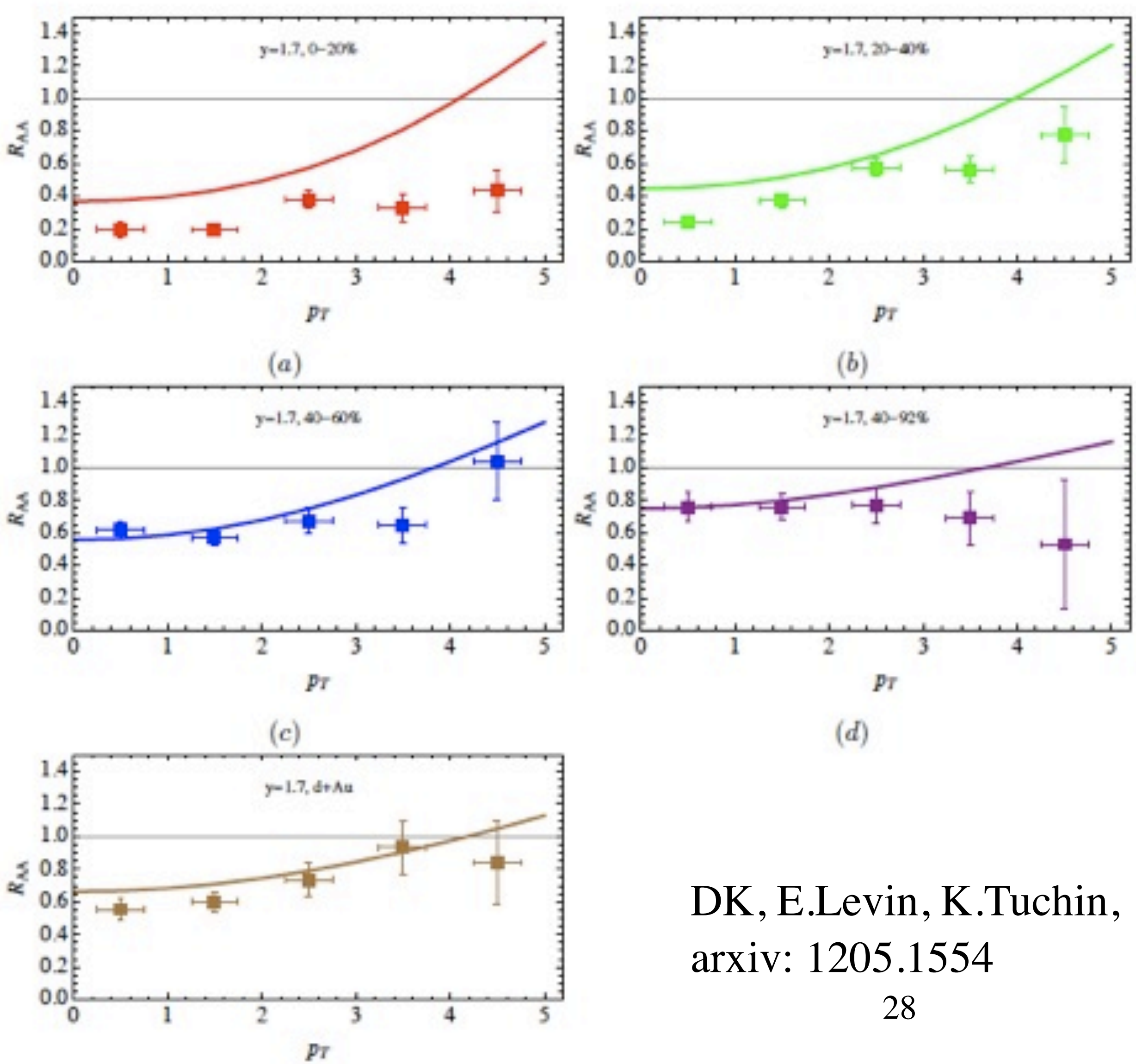
AuAu

Discrepancy increases at forward y!

dAu data described well:

dAu

PHENIX data



DK, E.Levin, K.Tuchin, arxiv: 1205.1554

The transverse momentum spectra of J/Ψ : predictions for LHC

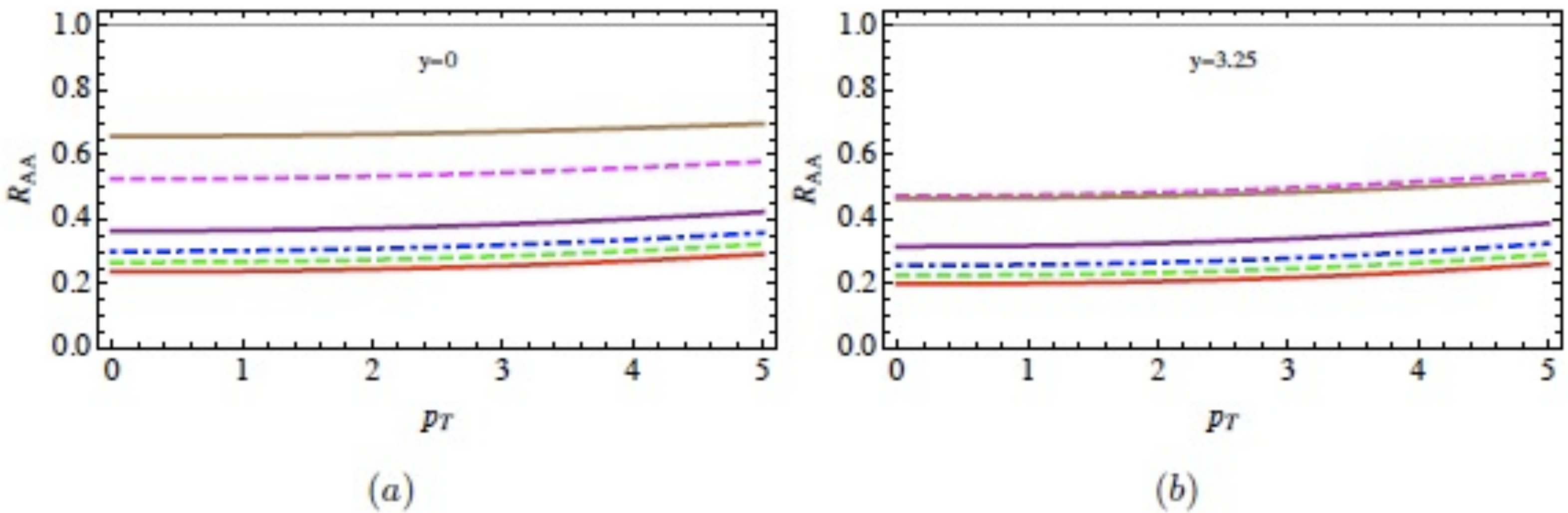


FIG. 6: (Color online). Nuclear modification factor for J/ψ's vs $p_\perp$ in GeV at $\sqrt{s} = 7$ TeV in $PbPb$ for rapidities (a) $y = 0$ and (b) $y = 3.25$. Each line corresponds to a different centrality bin; from bottom to top: 0-10% (solid red), 10-20% (dashed green), 20-30% (dash-dotted blue), 30-50% (solid purple), 50-80% (dashed magenta) and in minbias pPb (solid brown).

DK, E.Levin, K.Tuchin,
arxiv: 1205.1554

The J/Ψ production at LHC

Lecture by P. Braun-Munzinger

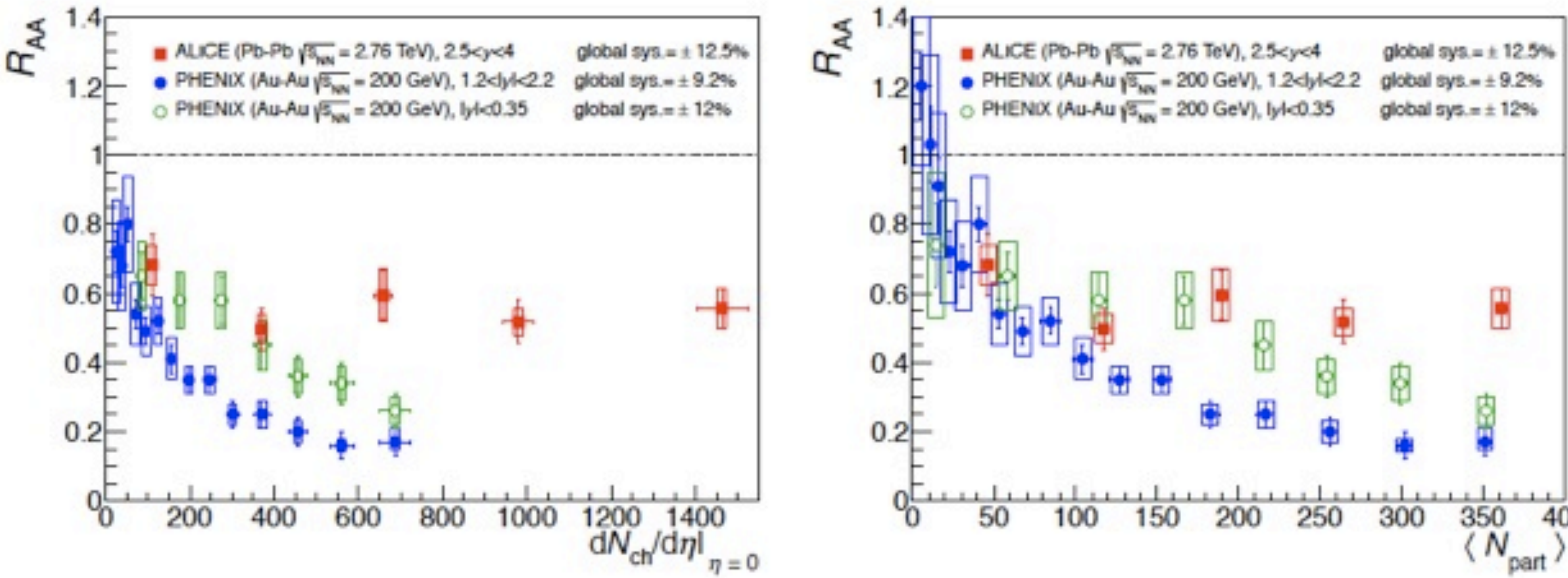


Fig. 1: (Color online) Inclusive J/ψ R_{AA} as a function of the mid-rapidity charged-particle density (left) and the number of participating nucleons (right) measured in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV compared to PHENIX results in Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV at mid-rapidity and forward rapidity [4, 5, 20].

Weaker suppression at LHC than at RHIC !?

ALICE Coll., arxiv: 1202.1383

J/Ψ as a probe of QGP

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.

Helmut Satz and Tetsuo Matsui at BNL

T. Matsui & H. Satz:

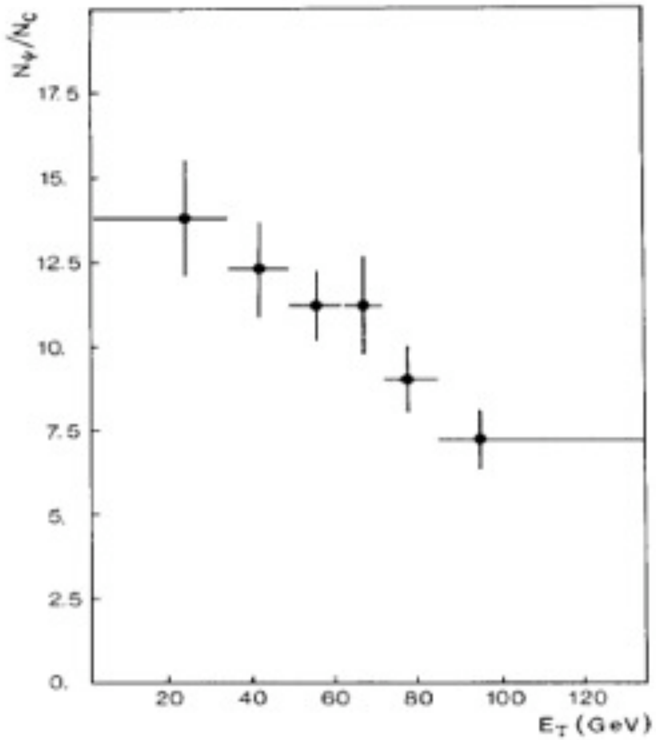
We thus conclude, that there appears to be no mechanism for J/ψ suppression in nuclear collisions except the formation of a deconfining plasma, and if such a plasma is produced, there seems to be no way to avoid J/ψ suppression.

NA38: the first observation of J/Ψ suppression

6 April 1989

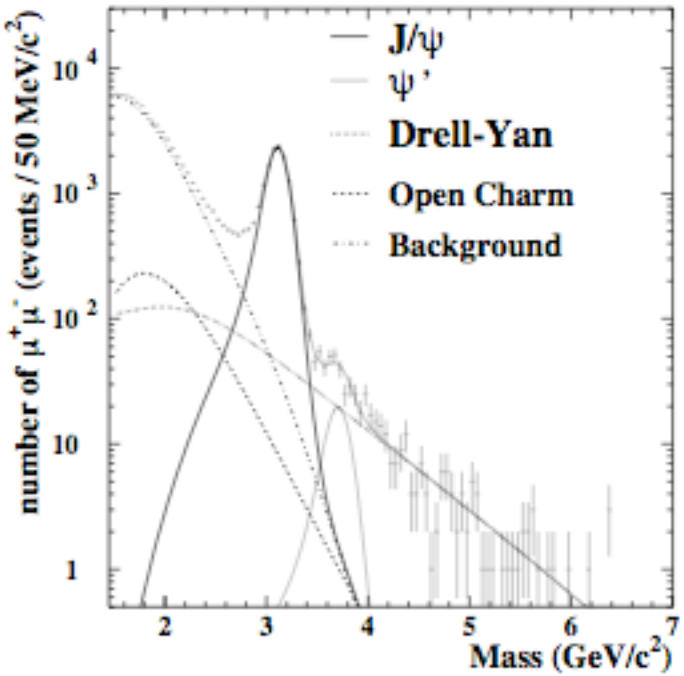
THE PRODUCTION OF J/Ψ IN 200 GeV/NUCLEON OXYGEN–URANIUM INTERACTIONS

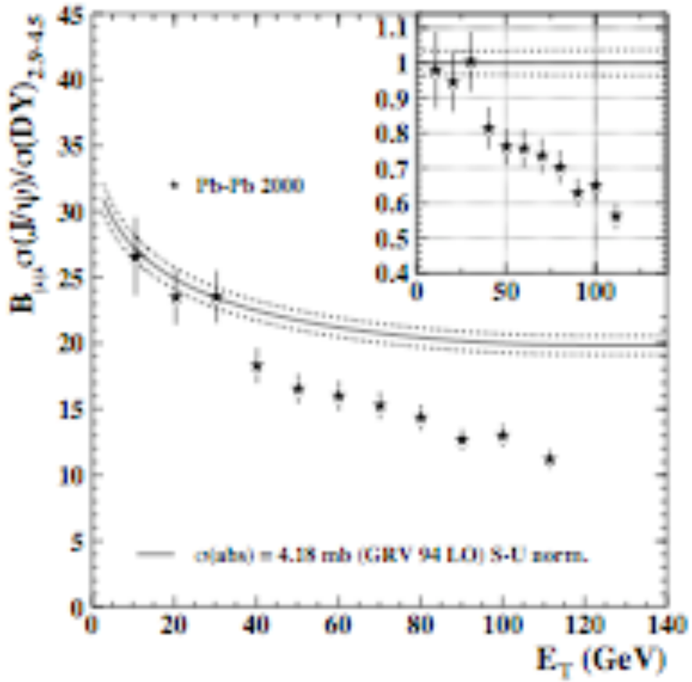
NA38 Collaboration



Experimental information

CERN: NA38/50/60 experiments





NA50 Coll., hep-ex/0412036

J/Ψ suppression in the plasma

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 can be dissociated due to thermal activation

What is the mechanism of dissociation?

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

DK & H. Satz '94

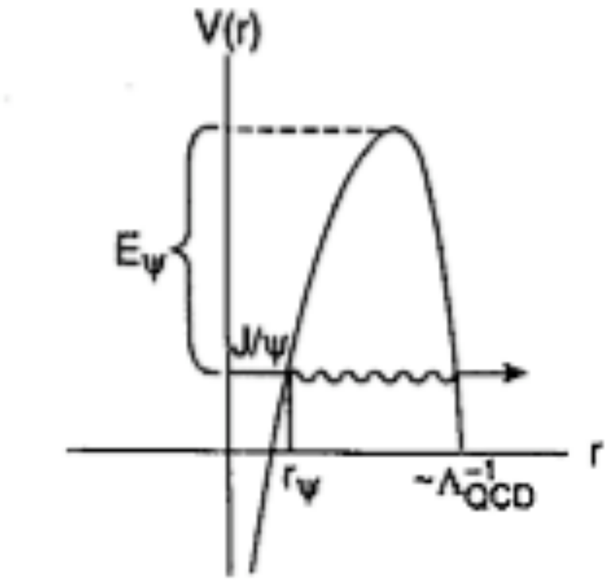
Dissociation mechanism - gluo-effect

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)

What mechanism is more important?



DK, L.McLerran, H.Satz
hep-ph/9504338

$$R_{act} = \frac{1}{Z(T)} \frac{V}{L} \left(\frac{c}{\pi^2} MT^2 \right) e^{\frac{-E_{J/\psi}}{T}}$$

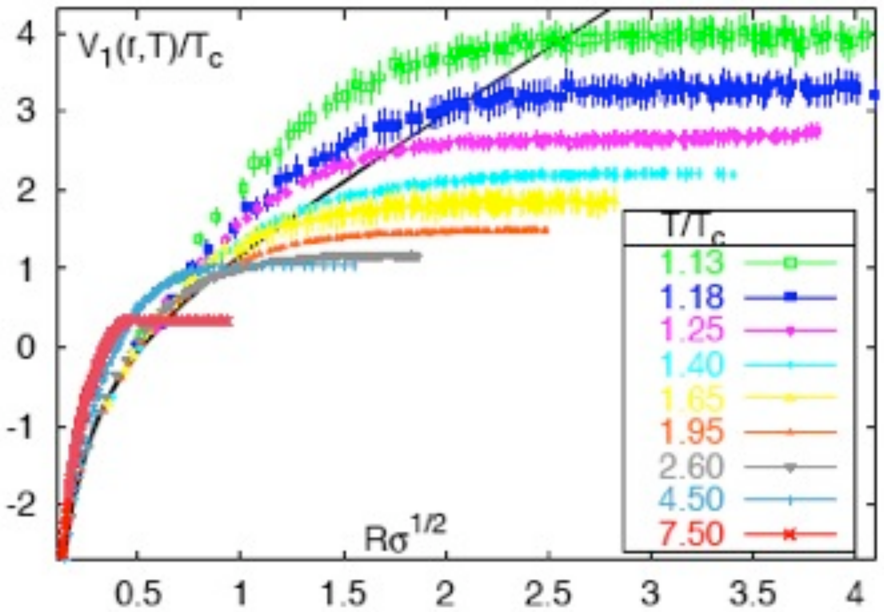
Weak coupling:

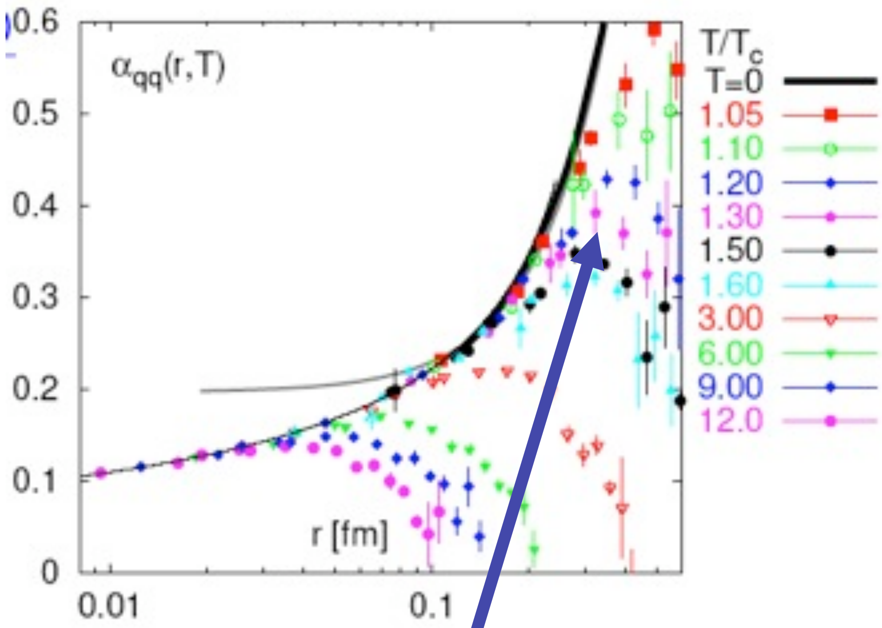
$$R_{act} = \frac{4}{L} \sqrt{\frac{T}{2\pi M}} = \frac{v(T)}{L}$$

Strong coupling:

$$R_{act} = \frac{(LT)^2}{3\pi} \; M e^{-E_{J/\psi}/T}$$

Color screening and J/Ψ suppression: lattice QCD results

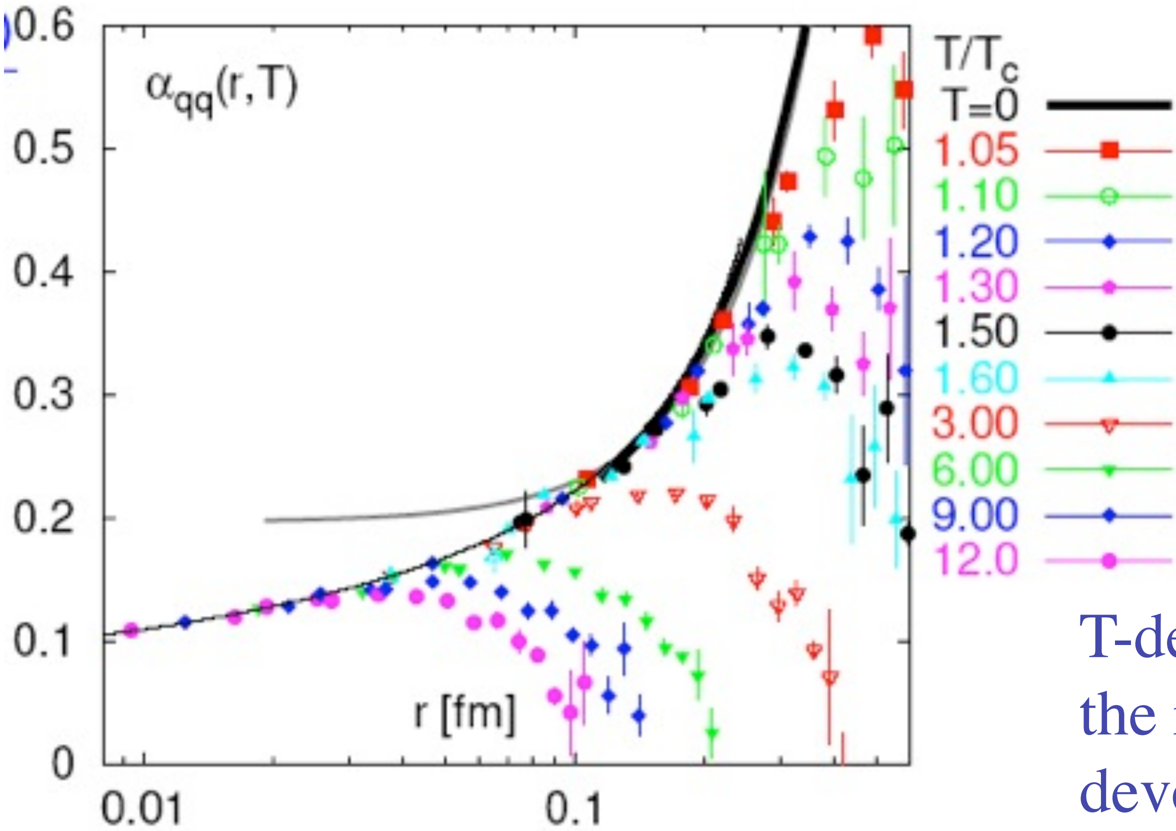




O.Kaczmarek, F. Karsch, P.Petreczky, F. Zantow, hep-lat/0309121

Interaction energy exceeds the temperature - strong coupling!

Screening in QGP

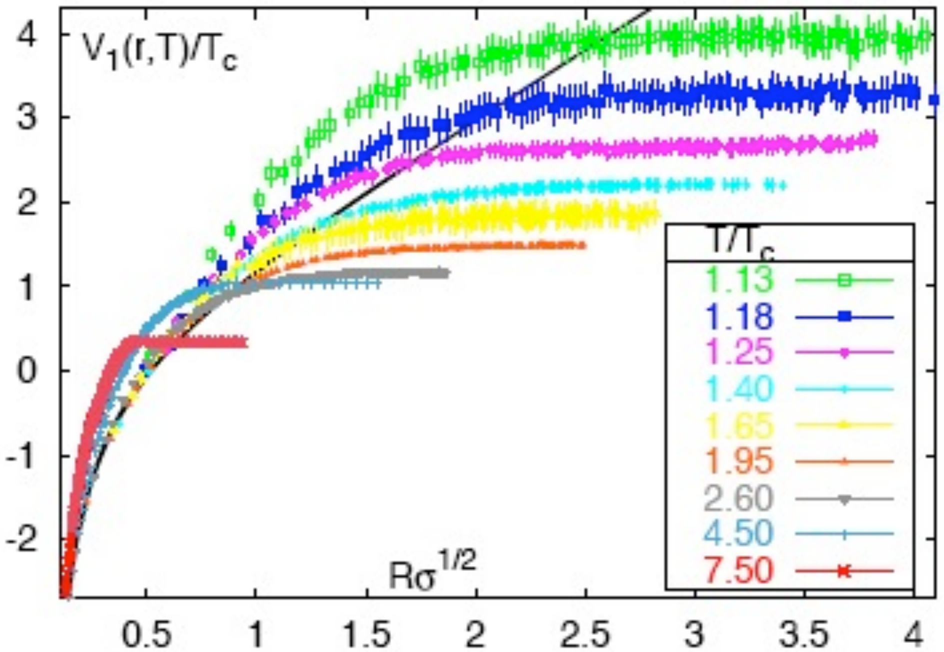


Strong force is screened by the presence of thermal gluons and quarks

T-dependence of the running coupling develops in the non-perturbative region at $T < 3\ T_c$; $\Delta E/T > 1$ - "cold" plasma

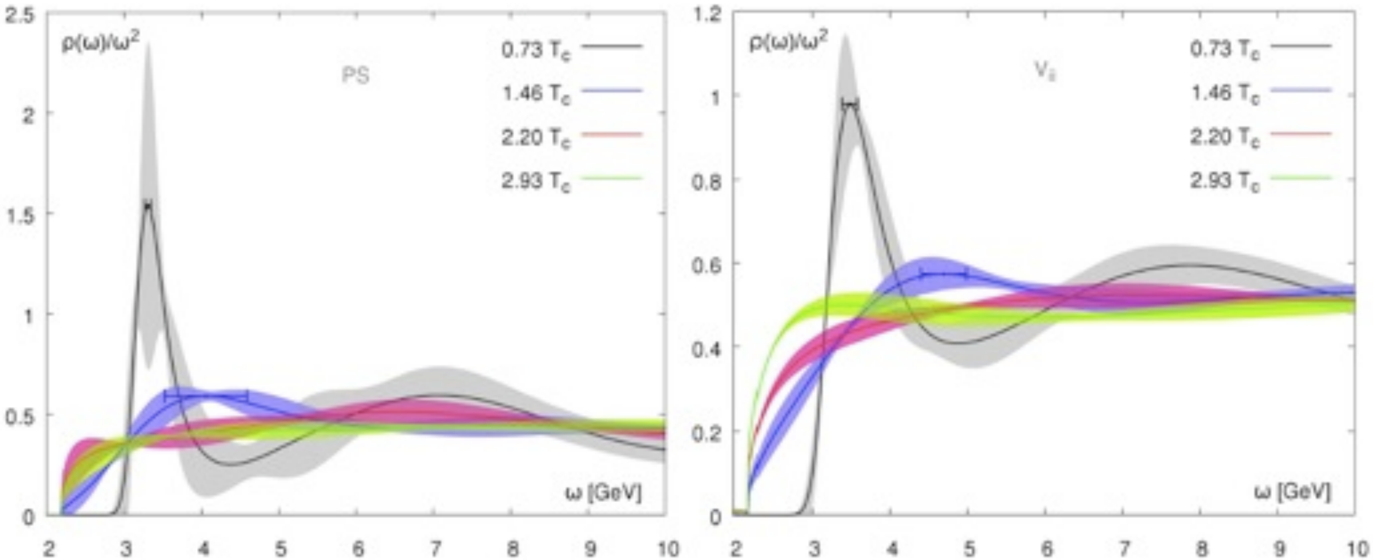
O.Kaczmarek, F. Karsch, P.Petreczky, F. Zantow, hep-lat/0309121

Heavy quark internal energy above T



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

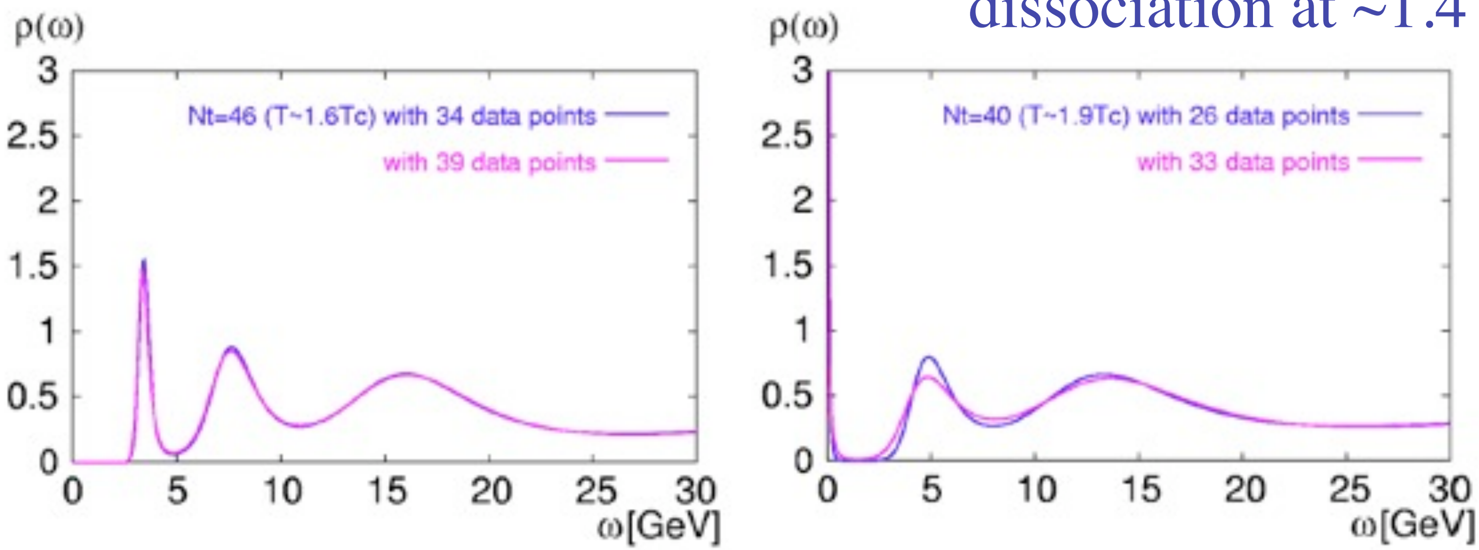
J/Ψ above T_c: lattice QCD



Lectures by H.-T. Ding, F.Karsch

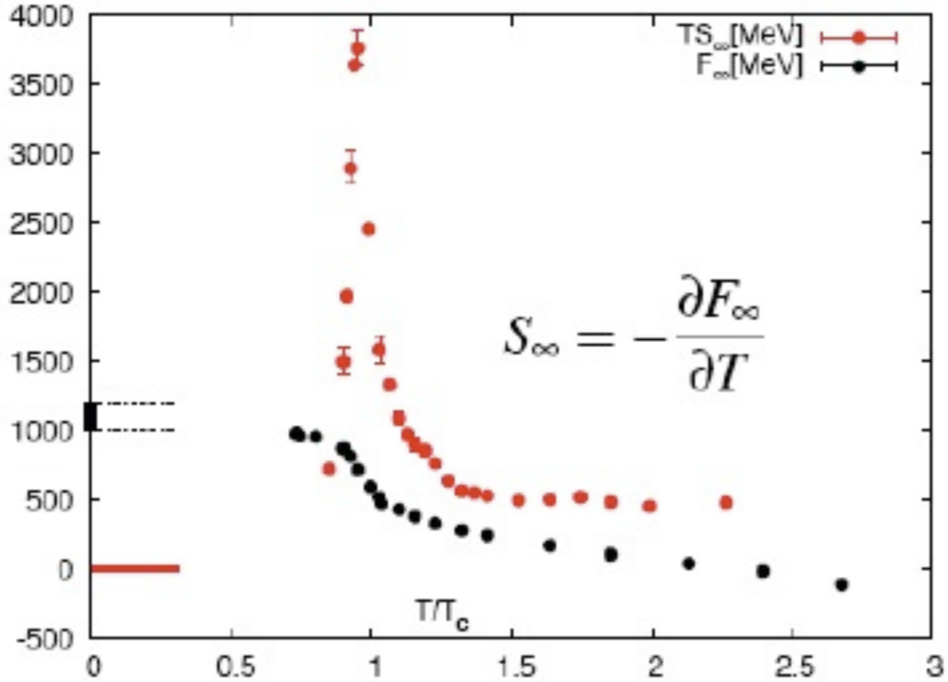
H.T.Ding et al, arxiv:1204.4945

dissociation at ~1.4 T_c ?



M.Asakawa, T.Hatsuda

Entropy: coupling to real states =>
non-instantaneous, non-local effective potential

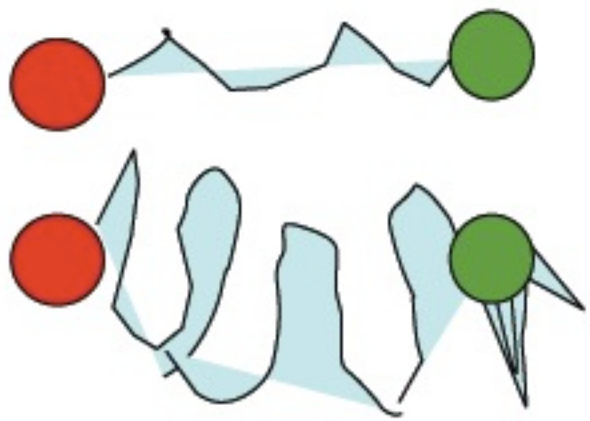


String contribution to the black hole entropy: a hint for understanding better quarkonia in the QCD plasma?

$$F = U - TS$$

$$\delta F = \left(\frac{\partial U}{\partial l} - T\frac{\partial S}{\partial l}\right)\,\delta l = 0$$

Kosterlitz-Thouless phase transition:
Frautschi, Polyakov



AdS/CFT Correspondence: Conformal gauge theory is dual to gravity

The chain of ideas:

1. String model pre-dates QCD as a description of hadron spectrum and hadron scattering amplitudes (Regge poles, Veneziano amplitude, Hagedorn spectrum,…)

2. Quantum theory of strings cannot be made consistent in (3+1) dimensions; the minimum number of dimensions is 5. Also: massless spin 2 state - graviton?

3. It has long been expected that QCD in the strong coupling and large N is described by string theory (at large N, planar diagrams dominate; they describe worldsheets of strings)

4. How to make this string description consistent
on the quantum level?
Add a 5th dimension to QCD and let gravity live there
BUT: what is the metric?

$$ds^2 = R^2 \; w^2(z) \; (dx^2_{3+1} + dz^2)$$

what is the form of w(z)?

5. Consider instead a conformal theory, such as maximally super-symmetric N=4 Yang-Mills; then the requirement of conformal invariance fixes the metric of the 5th dimension uniquely - it is an Anti- de Sitter space AdS_5:
invariance w.r.t. $x \to \lambda x$ fixes $w(z) = \frac{1}{z}$

supersymmetry - S_5, so the theory lives in $AdS_5 \times S_5$

J.Maldacena

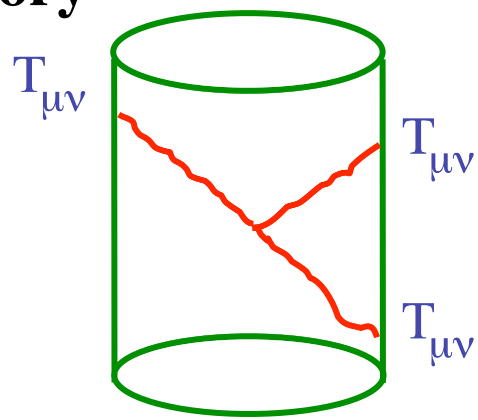
$\mathcal{N}=4$ SU(N) Yang-Mills theory	=	String theory on $AdS_5 \times S^5$

Radius of curvature $$R_{S^5} = R_{AdS_5} = \left(g_{YM}^2 N\right)^{1/4} l_s$$

Duality:

$g^2 N$ small → R small → perturbation theory

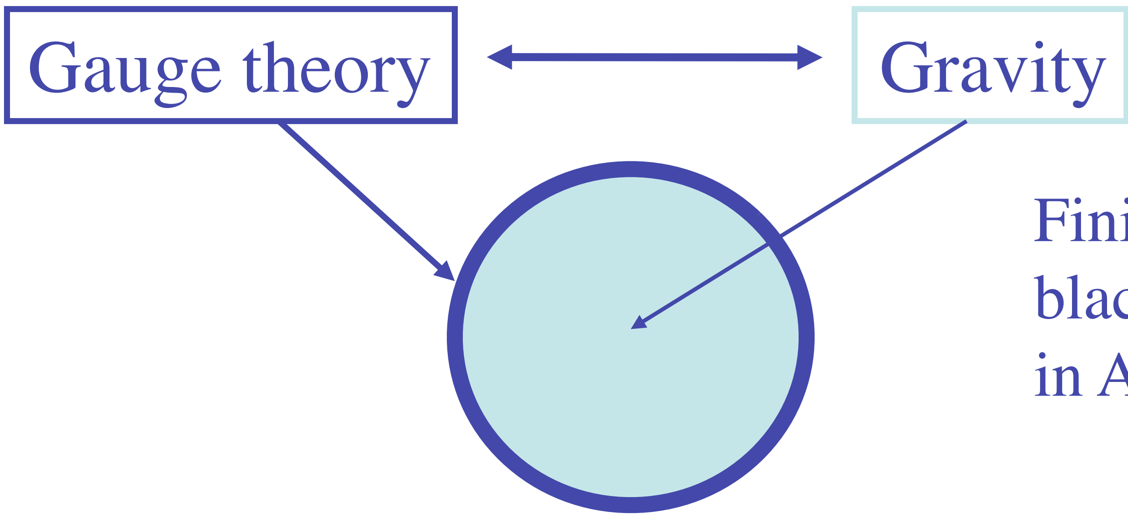
$g^2 N$ large → R large → classical gravity



Color screening and black holes?

One new idea: use a mathematical correspondence between
a conformal gauge theory and gravity in AdS space

Maldacena



Finite T -
black hole
in $AdS_5 x S_3 x T$ space

boundary

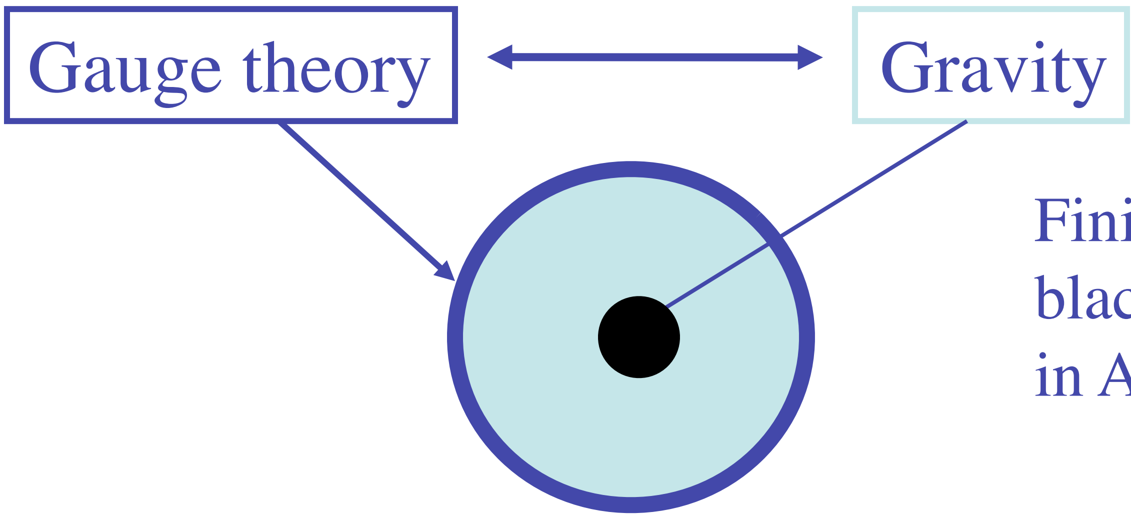
Witten; Polyakov;
Gubser, Klebanov;
Son, Starinets, Kovtun…

Anti de Sitter space - solution of Einstein's equations
with a negative cosmological constant Λ
(de Sitter space - solution with a positive Λ (inflation))

Color screening and black holes?

One new idea: use a mathematical correspondence between
a conformal gauge theory and gravity in AdS space

Maldacena



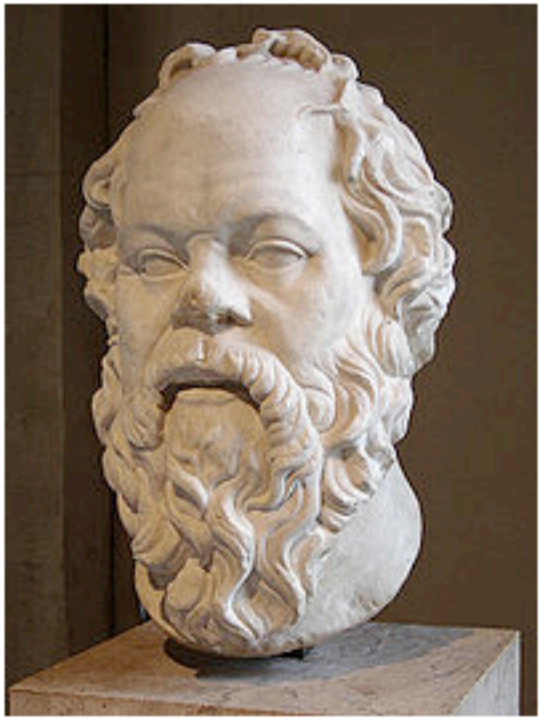
Finite T -
black hole
in $AdS_5 x S_3 x T$ space

boundary

Witten; Polyakov;
Gubser, Klebanov;
Son, Starinets, Kovtun…

Anti de Sitter space - solution of Einstein's equations
with a negative cosmological constant Λ
(de Sitter space - solution with a positive Λ (inflation))

The metaphor of the cave, 380 B.C.



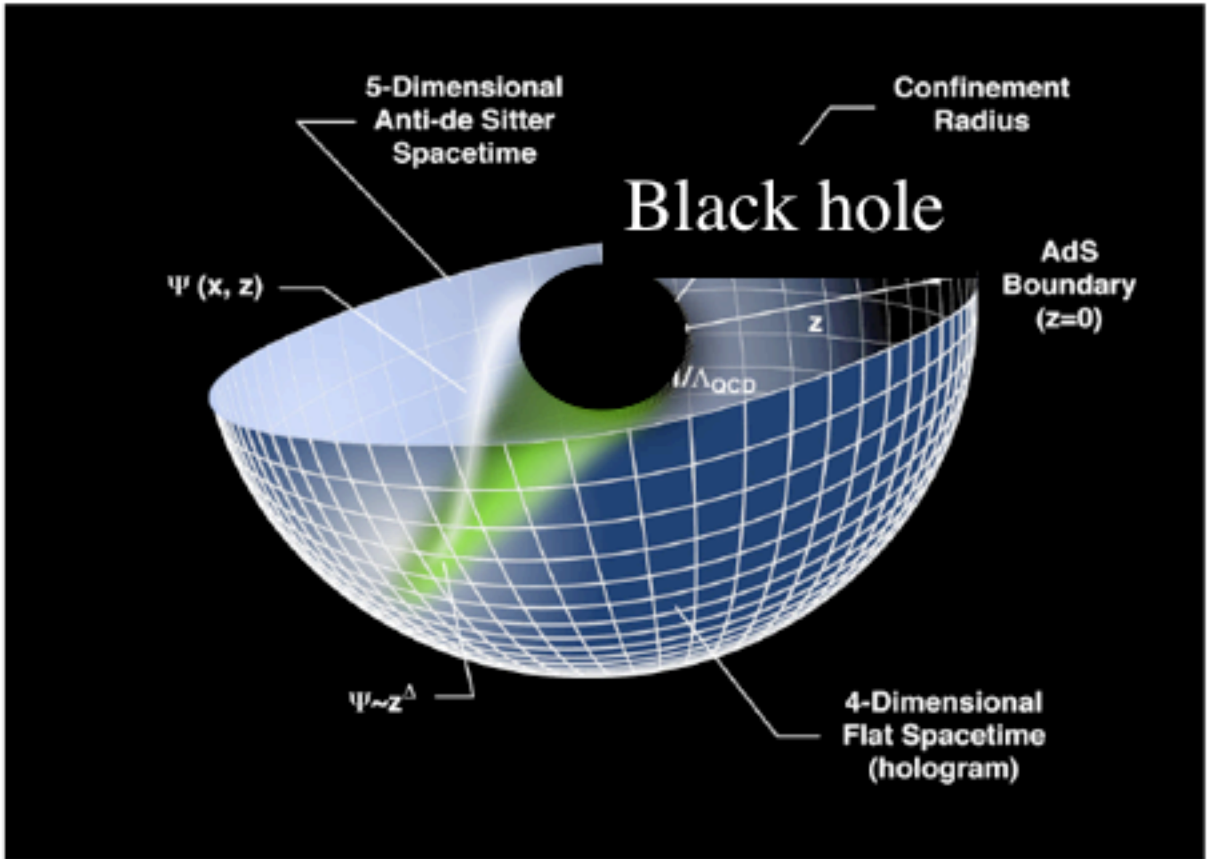
Socrates (Σωκράτης)
469 - 399 B.C.

“Physical objects and physical events are only "shadows" of their ideal or perfect forms, and exist only to the extent that they instantiate the perfect versions of themselves”

Socrates, in Plato’s “Republic”

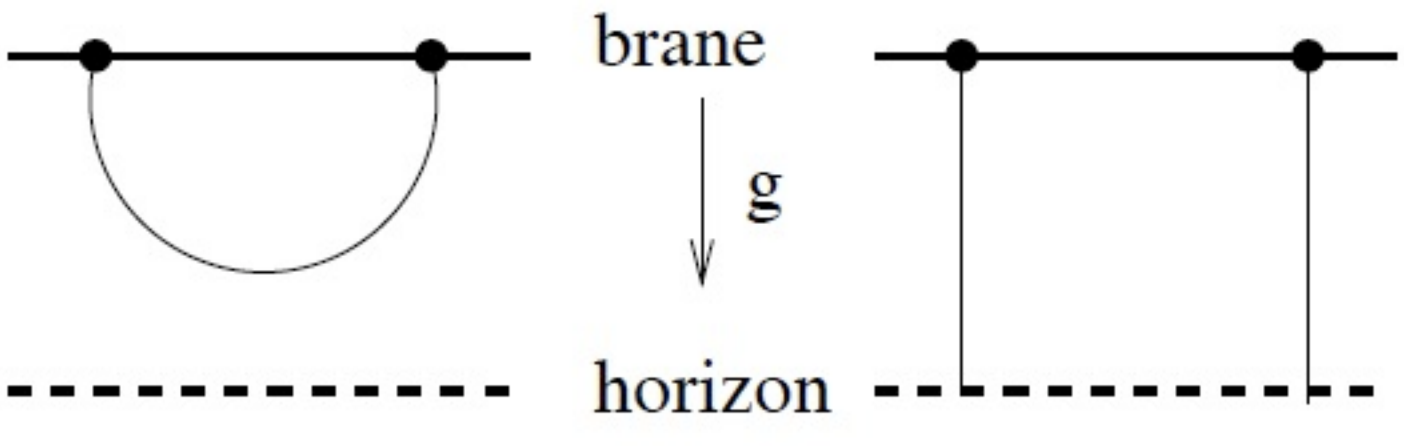
“The prisoners would take the shadows to be real things and the echoes to be real sounds, not just reflections of reality, since they are all they had ever seen or heard.”

The metaphor of the cave, 2011 A.D.



"The prisoners would take the shadows to be real things and the echoes to be real sounds, not just reflections of reality, since they are all they had ever seen or heard."

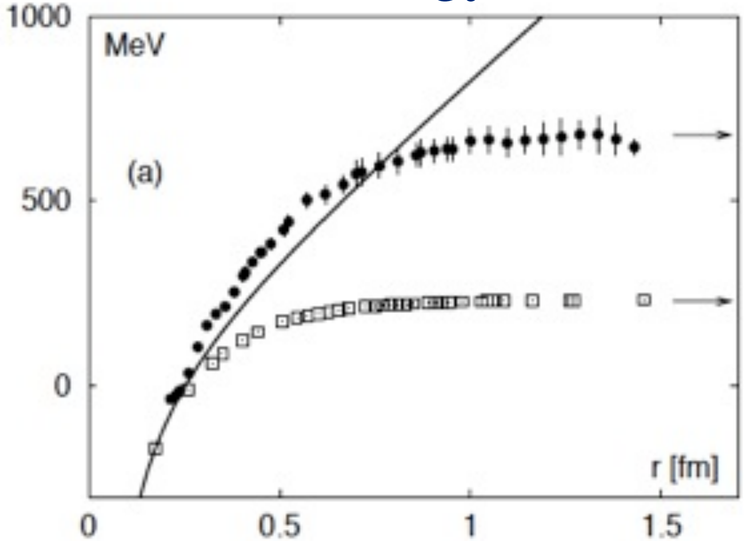
Entropy and color screening: an insight from holography



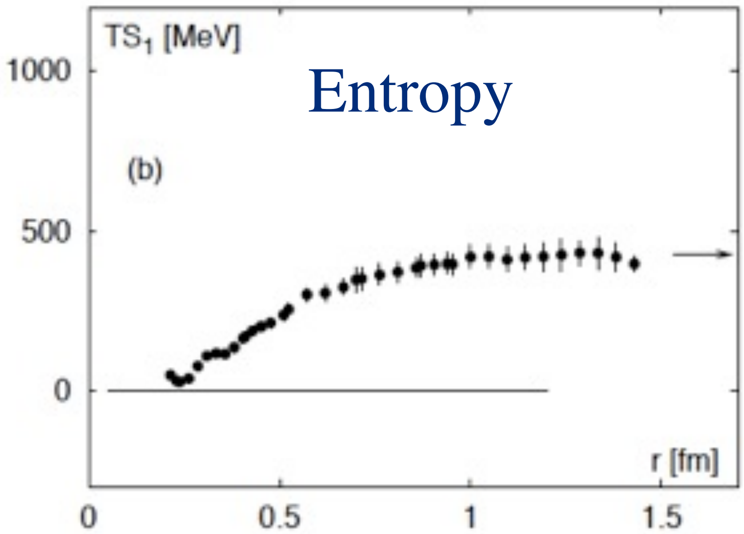
e.g., Shuryak, Zahed

Color screening and entropy

Internal energy



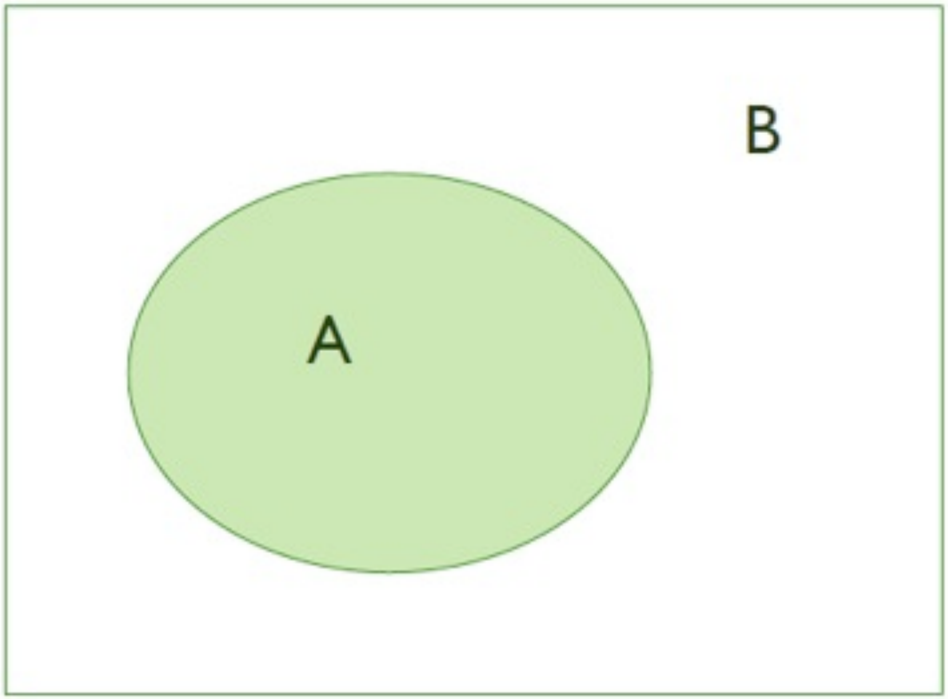
Entropy



Kaczmarek, Zantow,
arxiv:0506019

Confinement and entanglement entropy

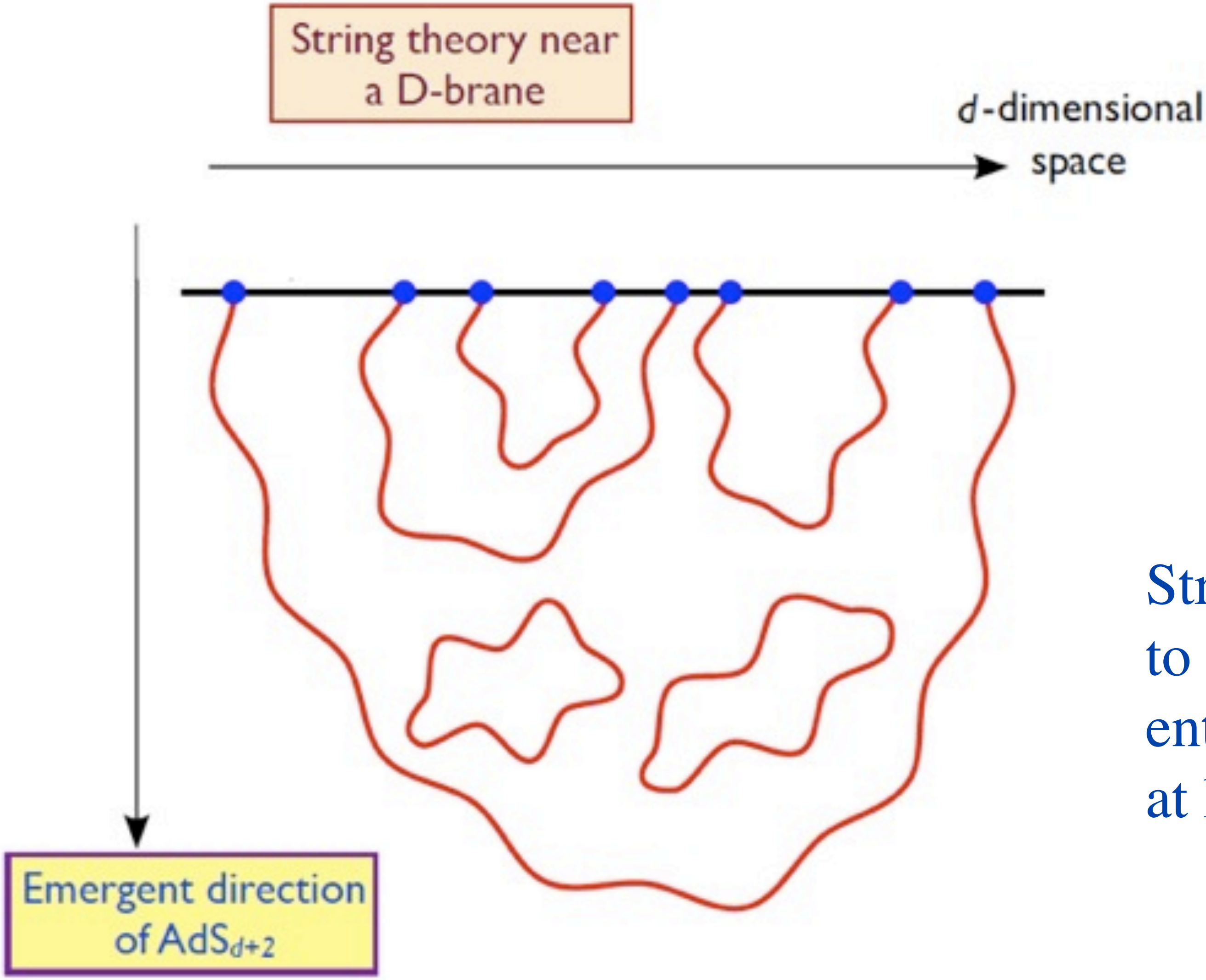
$$\rho_A = \mathrm{Tr}_B \rho, \text{ where } \rho = |\Psi\rangle\langle\Psi|$$



Entanglement entropy:

$$S_E = -\mathrm{Tr}\left(\rho_A \ln \rho_A\right)$$

Entanglement entropy and holography

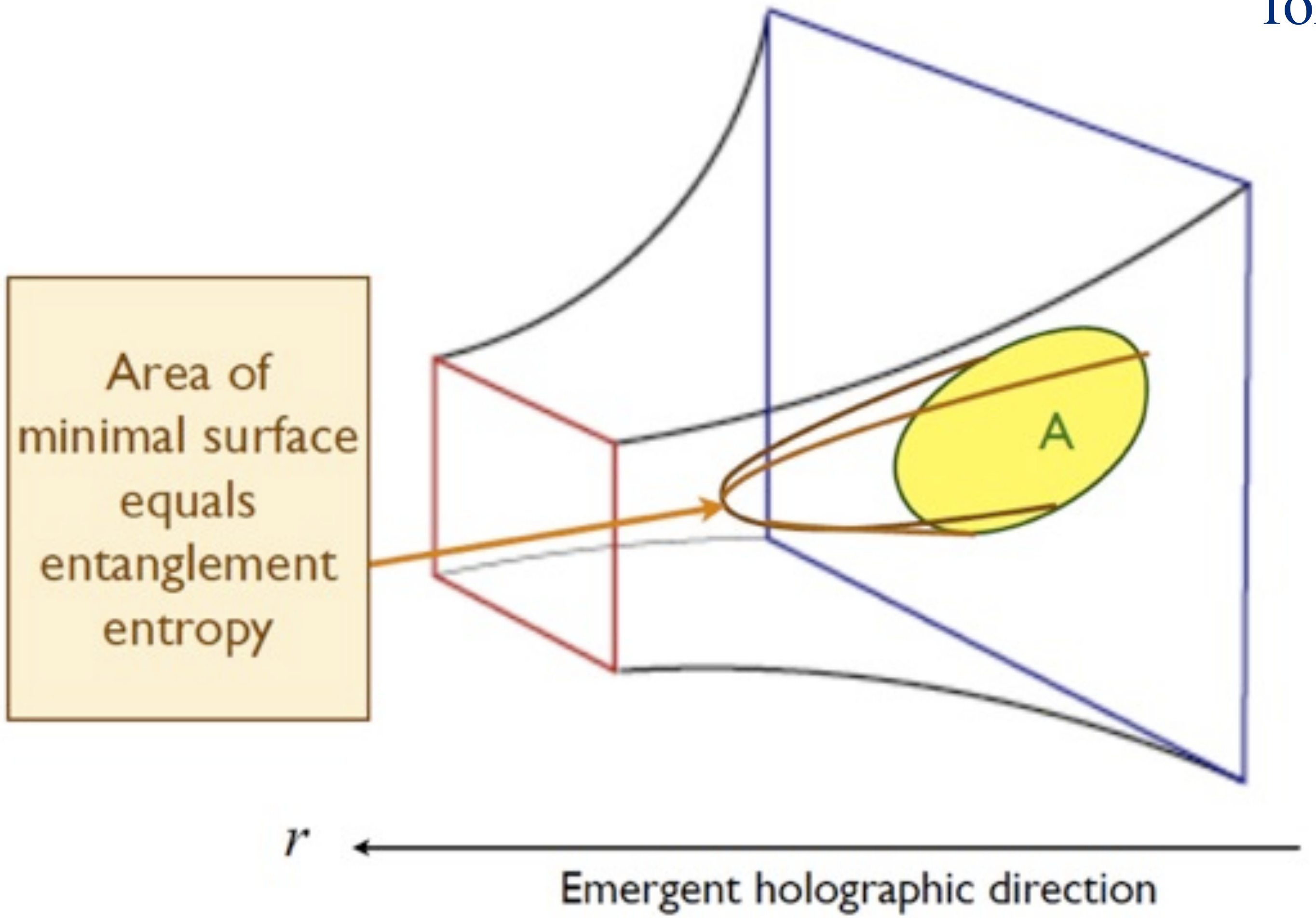


Strings lead
to quantum
entanglement
at large distances

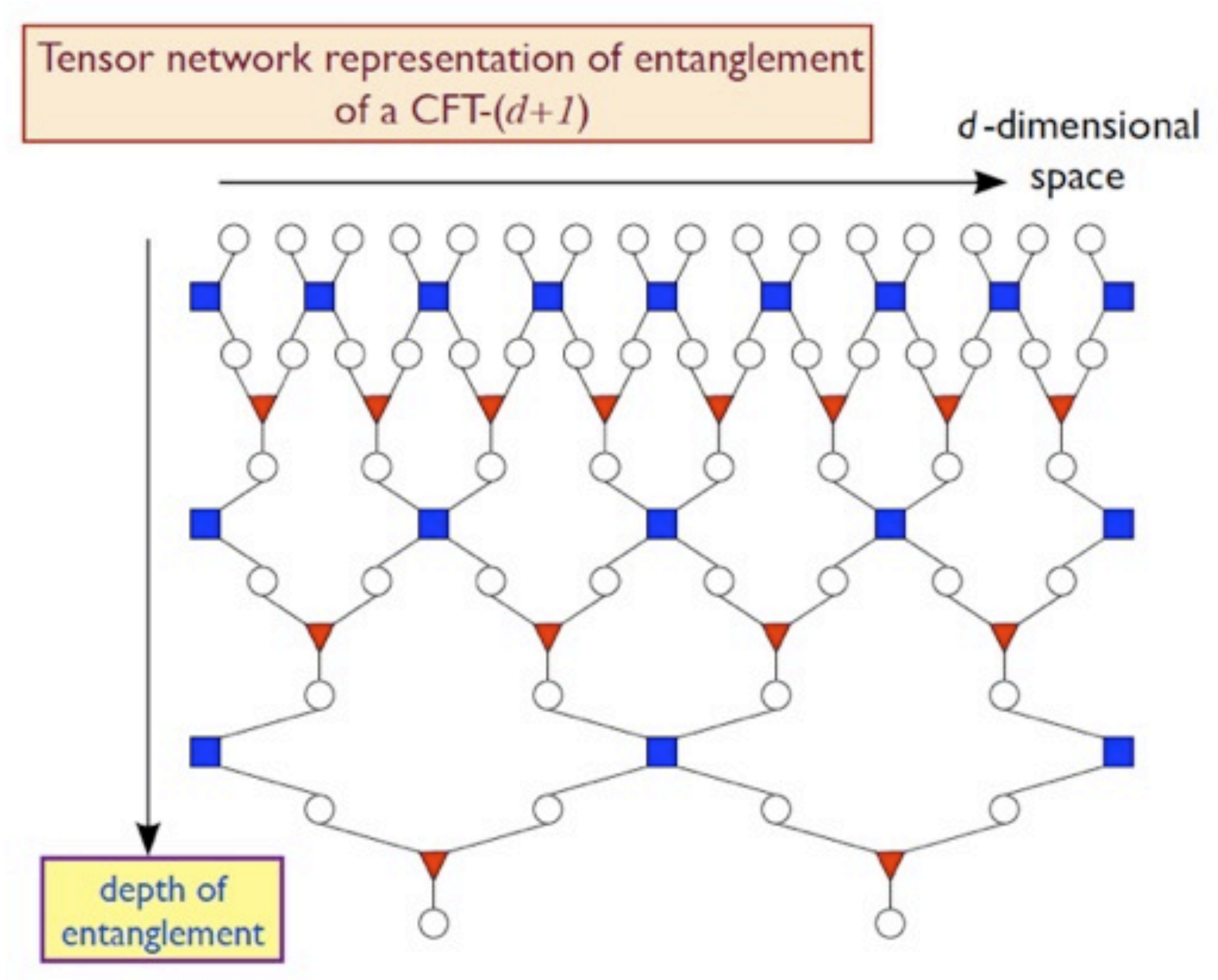
S. Sachdev, arxiv:1203.4565

Entanglement entropy and holography

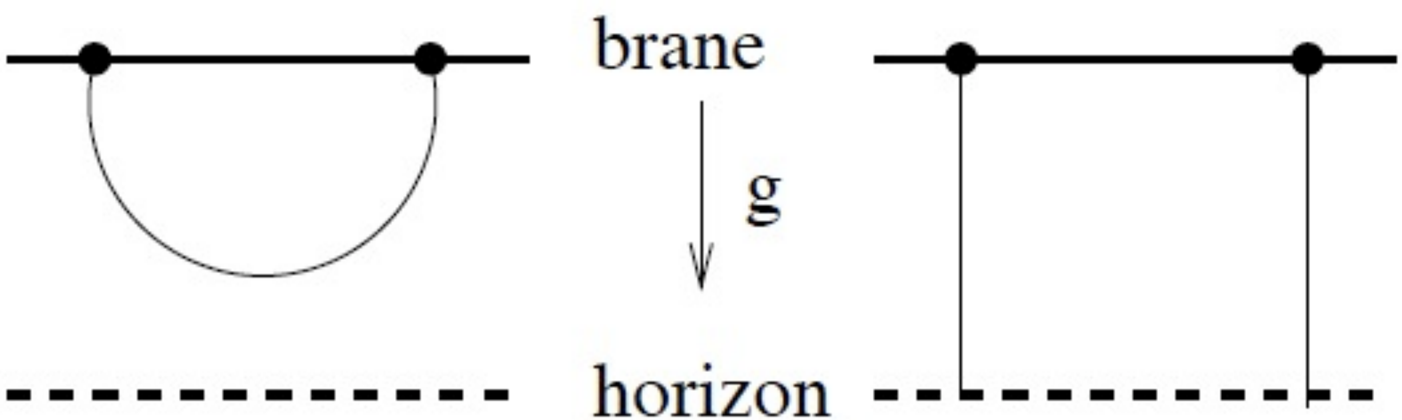
Ryu-Takanayagi formula

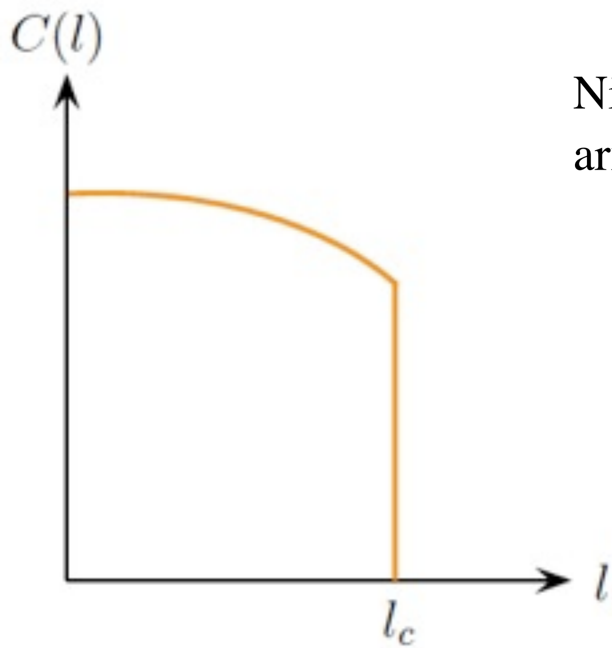


Entanglement entropy and holography



Entanglement entropy and color screening

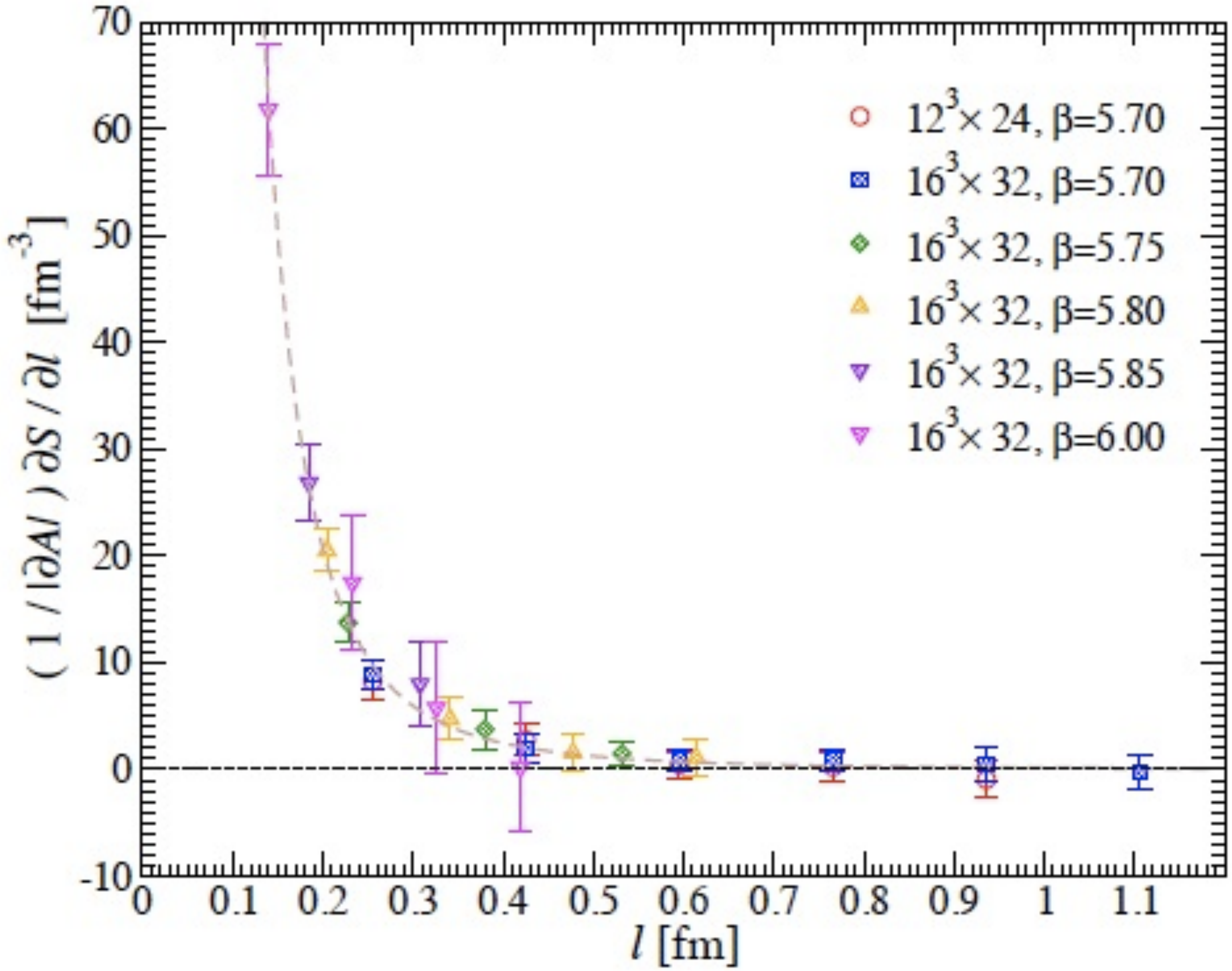




Nishioka,Ryu,Takayanagi, arxiv:0905.0932

$$C(l) \equiv \frac{l^d}{V}\frac{dS_A(l)}{dl}$$

Entanglement entropy and deconfinement

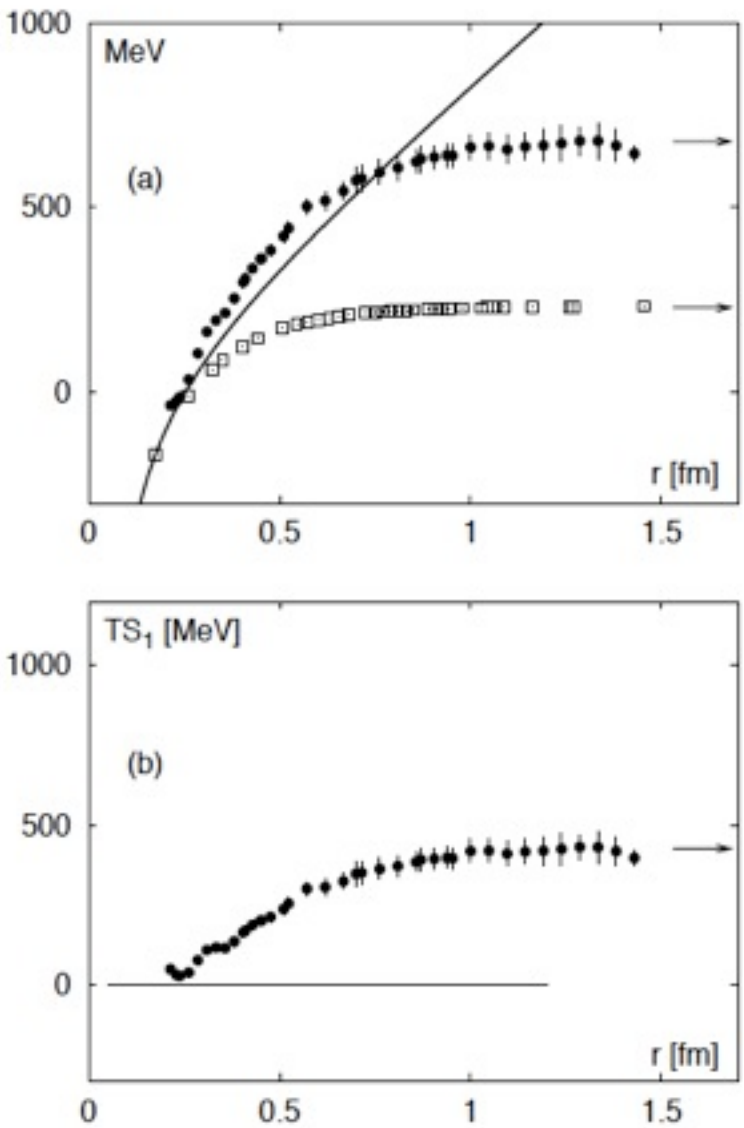


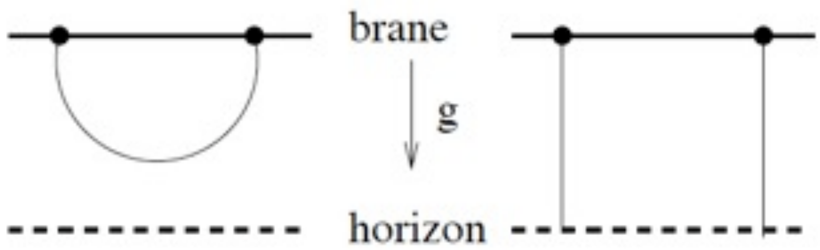
Nakagawa, Nakamura, Motoki, Zakharov, arxiv:0911.2596

also:
Buividovich, Polikarpov;

Velytsky; ....

Entanglement entropy and deconfinement





Summary

- Using the heavy quarkonium as a probe of QCD matter appeared to be a very productive idea
- 25 years later, still a very active field of research

Summary

- Using the heavy quarkonium as a probe of QCD matter appeared to be a very productive idea
- 25 years later, still a very active field of research

In other words, we still do not understand a thing....
but we are not losing hope!