Quarkonia as Probe of Deconfinement

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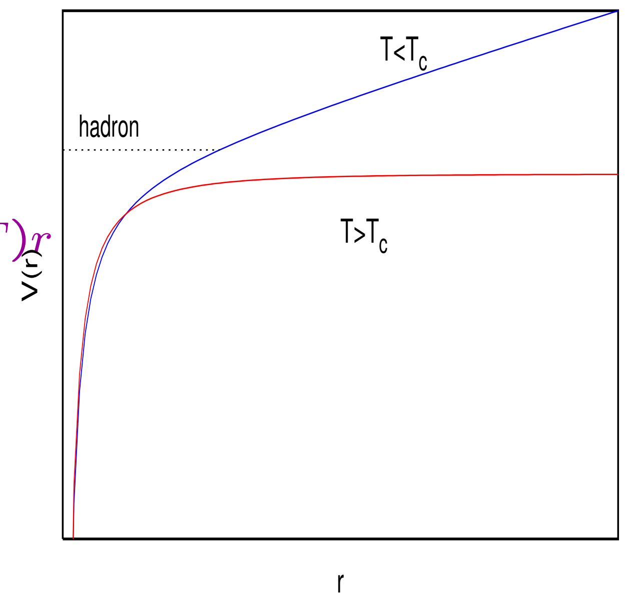
J/ψ as probe of deconfinement

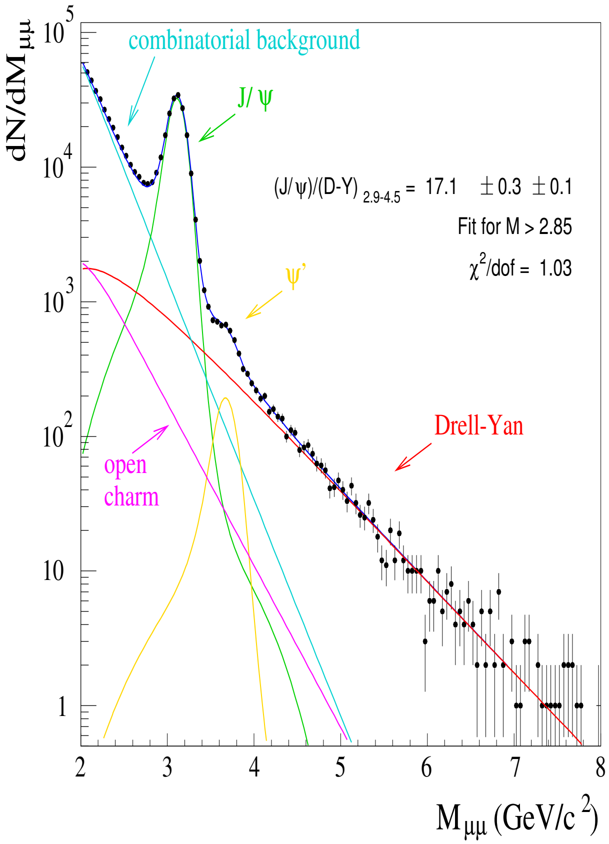
T. Matsui & H. Satz, Phys. Lett. B178, 416 ('86)

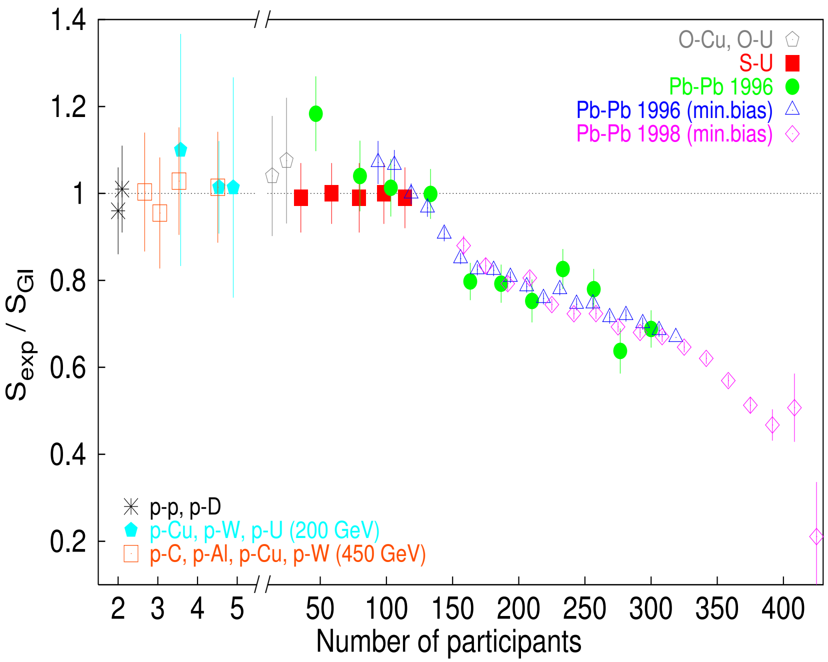
- Screening in plasma
  $\Longrightarrow$ reduced binding between $\bar{c}c$

$$T < T_c : \qquad V(r) \sim -\frac{\alpha}{r} + \sigma r$$
$$T > T_c : \qquad V(r) \sim -\frac{\alpha(T)}{r} e^{-\mu(T) r}$$



J/ψ was estimated to dissolve at around 1.1 T_c
large branching into dileptons $\longrightarrow$ suitable as probe for deconfinement transition





Evidence for Deconfinement of Quarks and Gluons at CERN SPS

NA50 Collab., Phys. Lett. B477, 28 (2000)

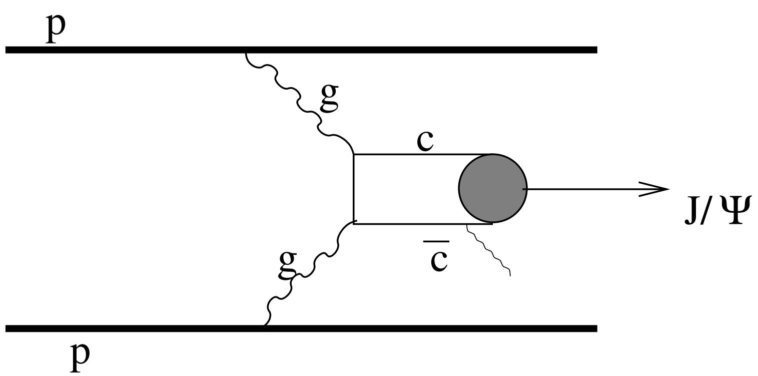
- Production
  - Production in pp collision

    Benchmarking with pp collision at 200 GeV
  - Effect of nucleus
- Absorption in nucleus ("Normal nuclear absorption")

  Study these two effects from d-Au collisions
- Absorption in hadronic medium ("Comover suppression")
- Fate in partonic medium

Quarkonium Working Group report, hep-ph/0412158

Production



- Production in pp collision:

$gg -> c\bar{c}$ Perturbative QCD

$c\bar{c} -> J/\psi, \chi_c, ...$ Nonperturbative

Color Evaporation Model: $\sigma_{h_i}(s) = f_i \sigma_{c\bar{c}}(s)|_{\sqrt{s}<2m_D}$

$(J/\psi) \Longleftarrow 60\%(\text{direct}) + 30\%(\chi_{c_1} \rightarrow J/\psi) + 10\%(\psi' \rightarrow J/\psi)$

In a nucleus, the quark and gluon fragmentation functions get modified from that in a nucleon. “Nuclear shadowing”

M. Arneodo, Phys.Rep.240,301 ('94)

Overlaping partons fuse, to enhance distribution at large momentum fraction

Eskola et al., hep-ph/0104124

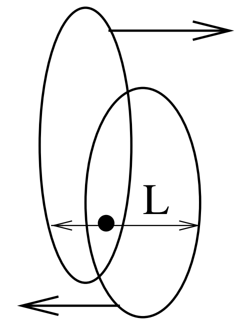
$$d\sigma^{J/\psi}_{dAu} \approx f_{J/\psi} \int dz dz' \int^{2m_D} \frac{dM}{M} \rho_d(s) f_g(x,Q^2) \rho_A(s') S_g(A,x,Q^2,r',z') f_g(x,Q^2) \sigma_{gg}(Q^2) + q\bar{q} \text{ terms}$$

Normal Nuclear Absorption

Calculated in Glauber model

$$S_{AB} = exp(-L(= L_A + L_B)\rho_0 \sigma_{abs})$$

$$L_A = \frac{2\pi}{3} R_A^3 \int db (T_A(b_A))^2 \frac{A-1}{A}$$

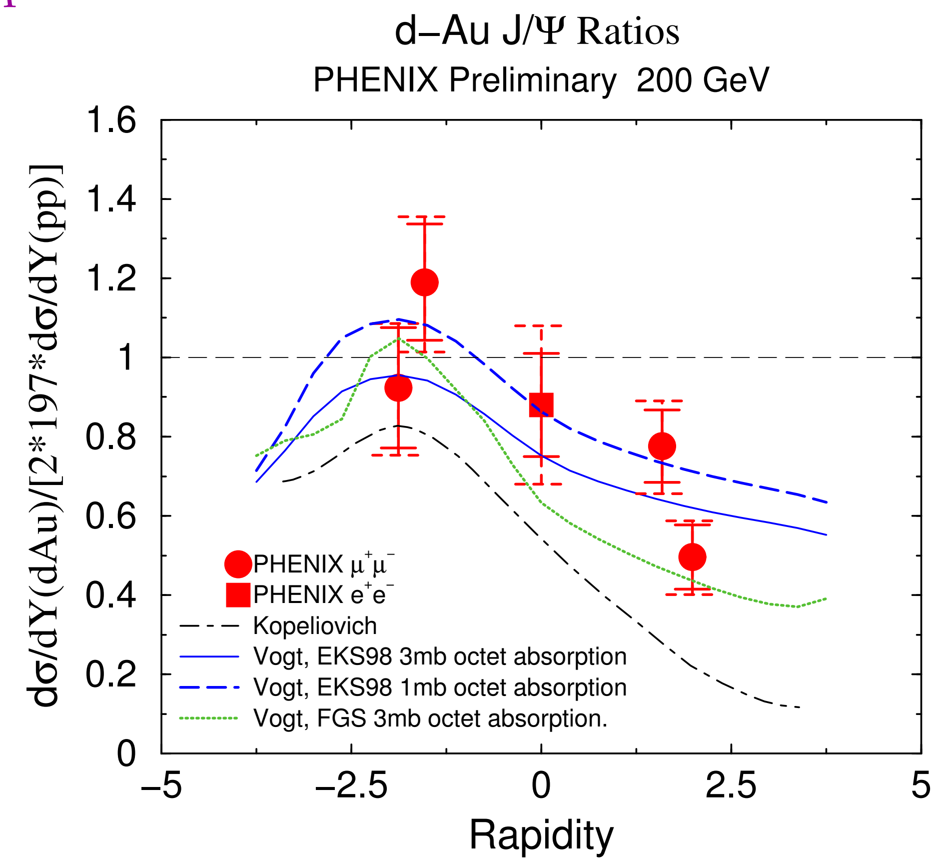


SPS: from pA,200 MeV

$\sigma_{abs} \approx 4.18 \pm 0.35$ mb

RHIC: from dA, 200MeV

$\sigma_{abs} \approx$ 1-3 mb



Comover Absorption

If the medium is *not deconfined* but hadron gas, what is the extent of J/ψ suppression?

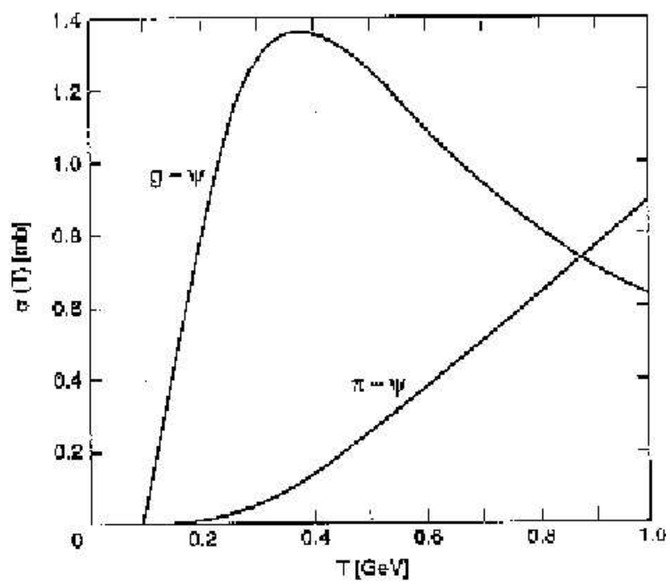
Need $\pi J/\psi$, $\rho J/\psi$, ... cross section

Coulombic quarkonia: $\sigma_{g\Phi} = \frac{2\pi}{3}(\frac{32}{3})^2(\frac{m_Q}{\epsilon_0})^{\frac{1}{2}}(\frac{1}{m_Q^2})\frac{(k-\epsilon_0)^{3/2}}{(k/\epsilon_0)^5}$

Bhanot & Peskin, NPB 156,391('79)

Pion gas: $|p| \sim 0.6T$
cross section very small

gluon gas: $|p| \sim 3T$
Kharzeev & Satz, PLB 334,155('94)



Other models (meson exchange model, QCD sum rule, chiral lagrangian, ...) give higher cross-sections $\approx \mathcal{O}$(mb)

- Fit to Pb-Pb and S-U data in SPS:

A. Capella et al., nucl-th/0303055

Fail to explain the NA60 In-In data

NA60: R. Arnaldi, Quark Matter ’05

- If hadron gas taken as resonance gas $\longrightarrow$ cannot fit NA50 data in central region

L. Maiani et al., NP A 741, 273 (’04)

Quarkonia in deconfined medium

Early results: potential model calculations

A sample of potential model values for T_d/T_c

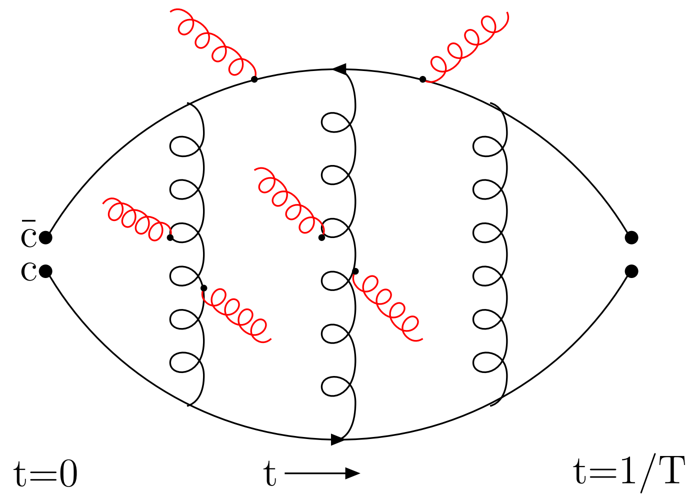
	J/ψ	ψ'	χ_c	υ	χ_b
Karsch & Satz '91	1.17	1.0	1.0	2.62	1.0
Digal *et al.* '01	1.1	0.1-0.2	0.74	2.31	1.13
Wong '01	0.99	0.50	0.90	1.11	1.00

$\longrightarrow$ May act as a thermometer for the plasma

Direct Lattice Study

Matsubara Correlator $G_H(\tau, T) = \langle J_H(\tau) J_H(0) \rangle_T$

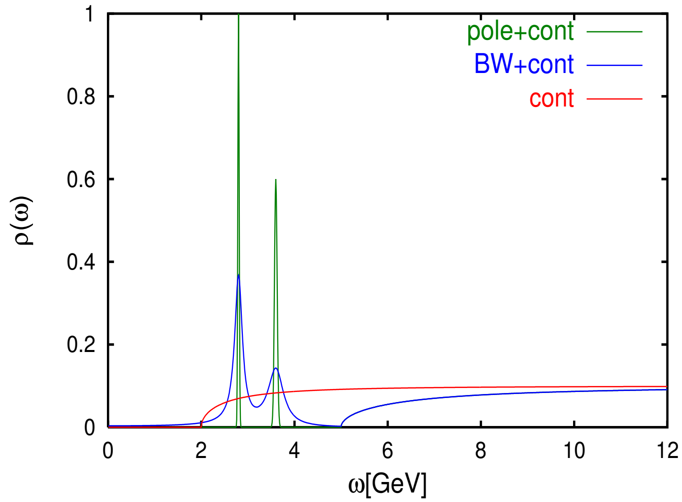
$J_H =$	$\bar{c}c$	${}^3P_0$	χ_{c_0}
	$\bar{c}\gamma_5 c$	${}^1S_0$	η_c
	$\bar{c}\gamma_i c$	${}^3S_1$	J/ψ
	$\bar{c}\gamma_i\gamma_5 c$	${}^3P_1$	χ_{c_1}



$$G(\tau, T) = \int_0^\infty d\omega \sigma(\omega, T) \frac{\cosh(\omega(\tau - 1/(2T))}{\sinh(\omega/(2T))}$$

$$\text{Bound state} \approx \omega^4 \delta(\omega^2 - m^2)$$
$$\text{resonance} \approx \frac{\omega^2 m \Gamma}{(\omega^2 - m^2)^2 + \Gamma^2 m^2}$$
$$\text{cut} \approx \omega^2$$

$$\rho(\omega) = \frac{\sigma(\omega)}{\omega^2}$$



Incorporate prior information: in entropy form
(Maximum entropy method)

Maximize $F = \alpha S - \chi^2$

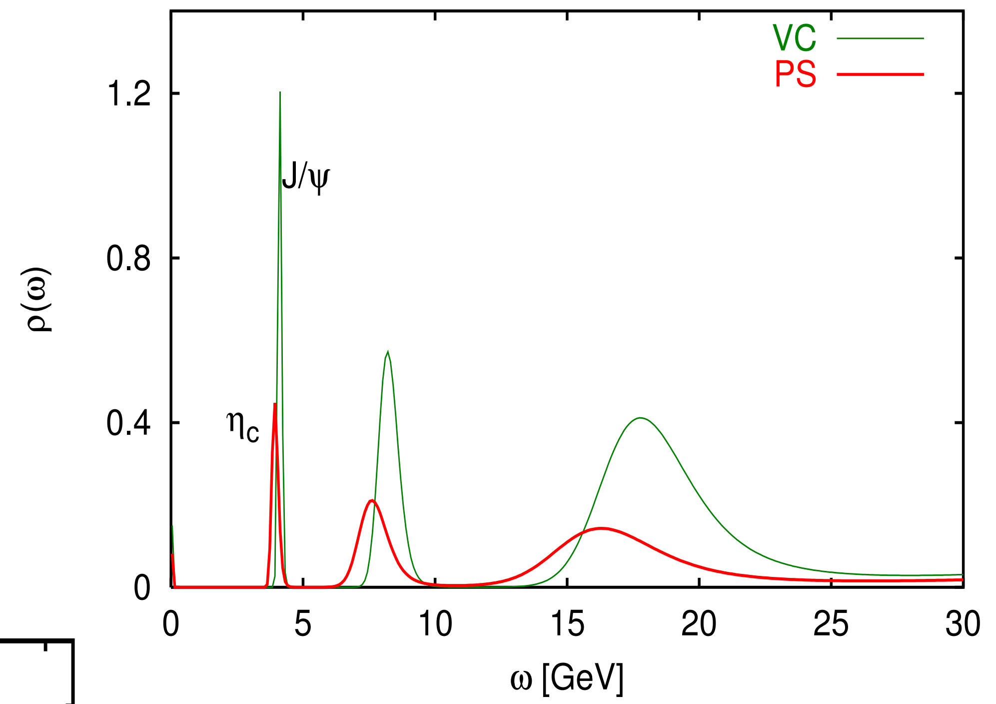
Average over α with weight $\sim e^F$

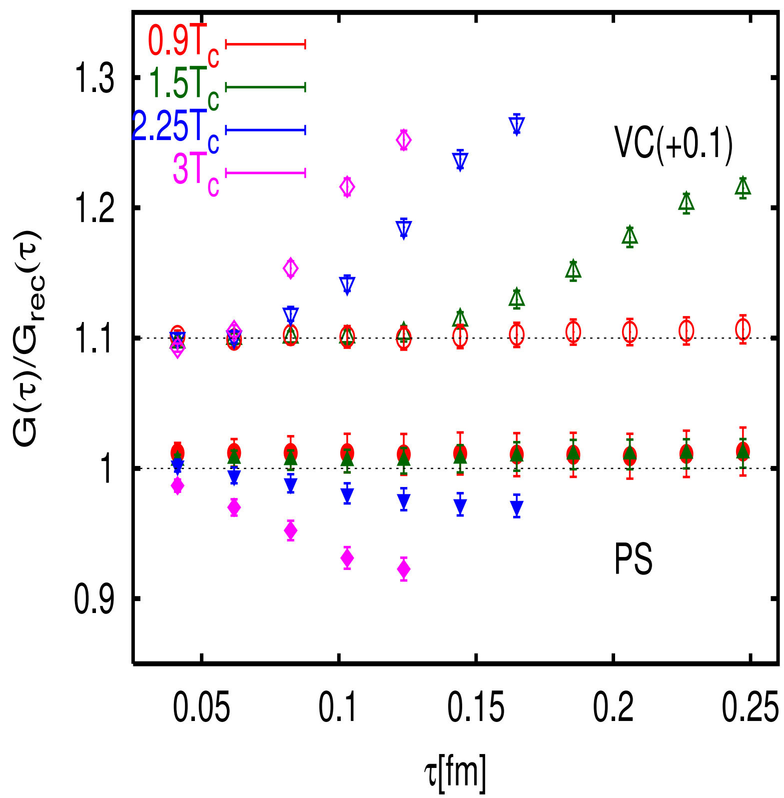
M. Asakawa *et al.*, Prog. Part. Nucl. Phys. 46, 459 (2001)
R.K.Bryan, Eur. Biophys. J.18:165 (1990)

1S states J/ψ, η_c

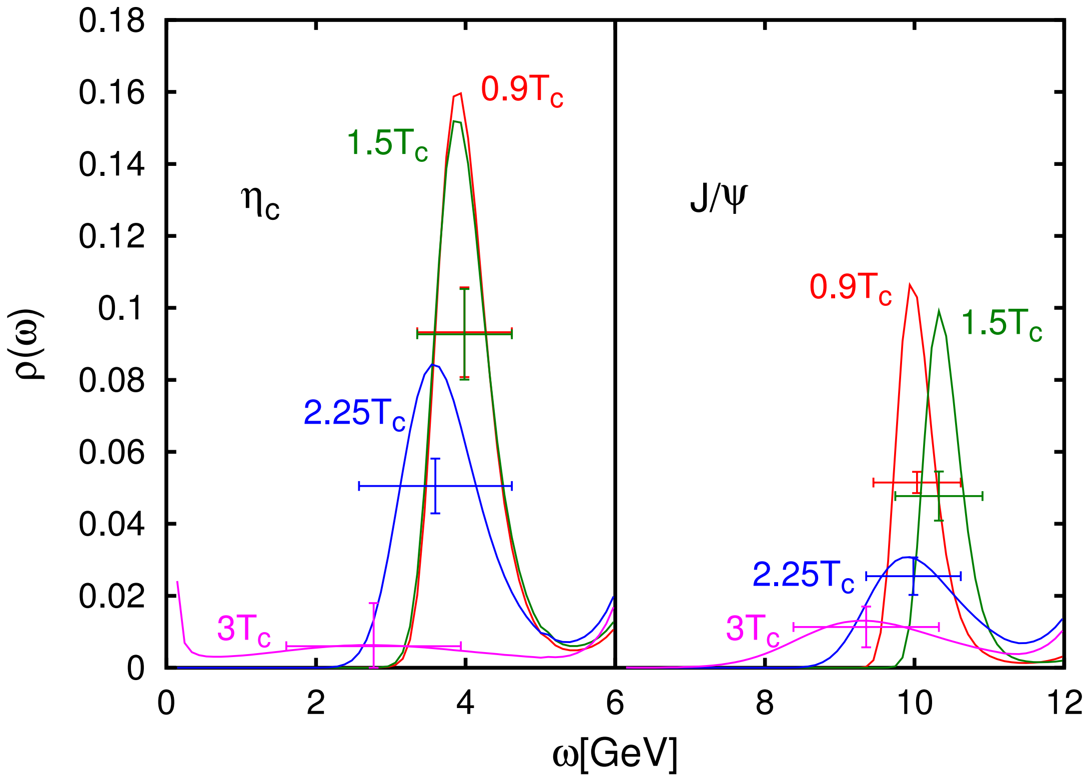
a^{-1} = 0.02fm lattices

N_τ	40	24	16	12
T/T_c	0.90	1.5	2.25	3





$$G_{\mathrm{recon},T^*}(\tau,T) = \int d\omega\, \sigma(\omega,T^*)\, K(\omega,\tau,T)$$

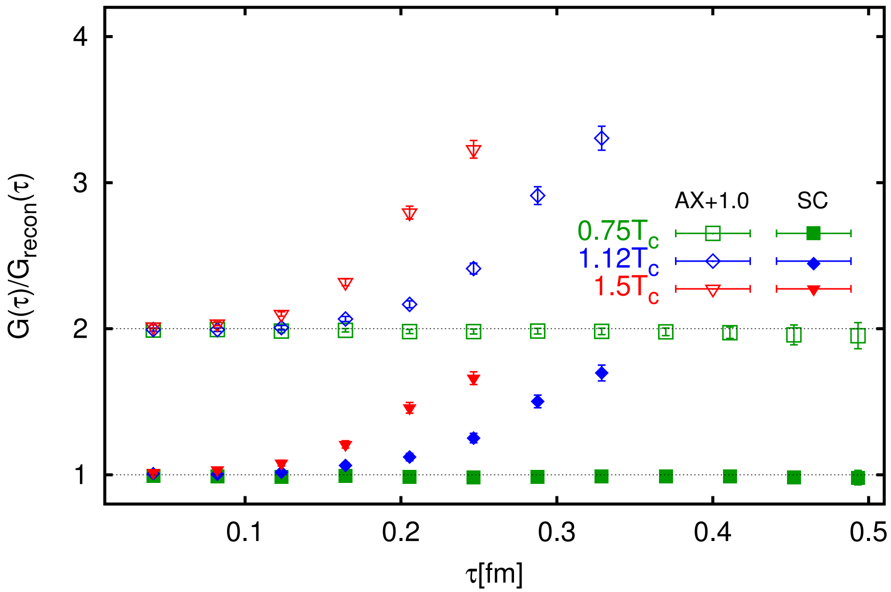


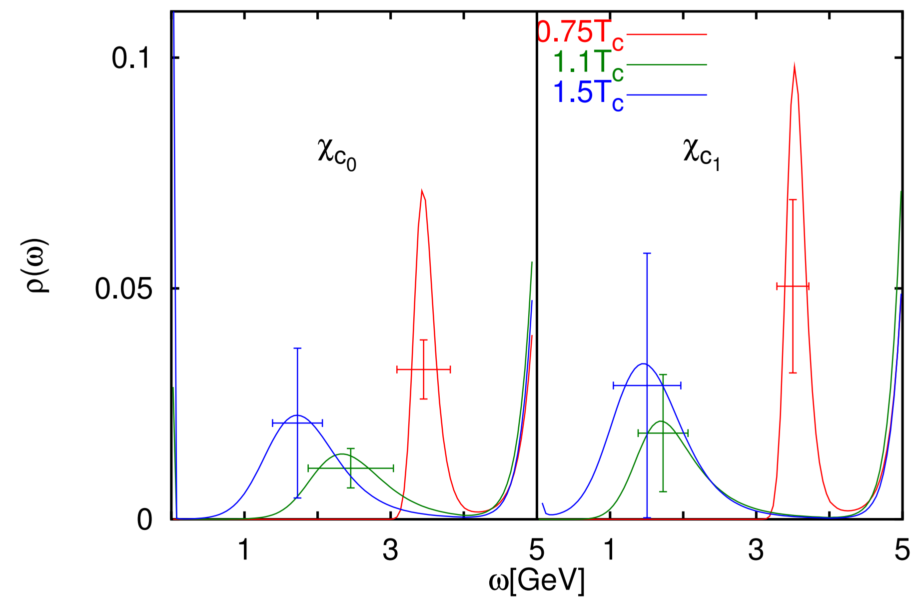
1S States survive upto 2.25 T_c

- η_c shows no change upto 1.5 T_c
- Weakening (and possibly broadening) at 2.25 T_c
- No significant resonance seen at 3 T_c

- J/ψ shows no weakening upto 1.5 T_c
- Weakening (and possibly broadening) at 2.25 T_c
- No significant resonance seen at 3 T_c

1P states χ_{c_0}, χ_{c_1}





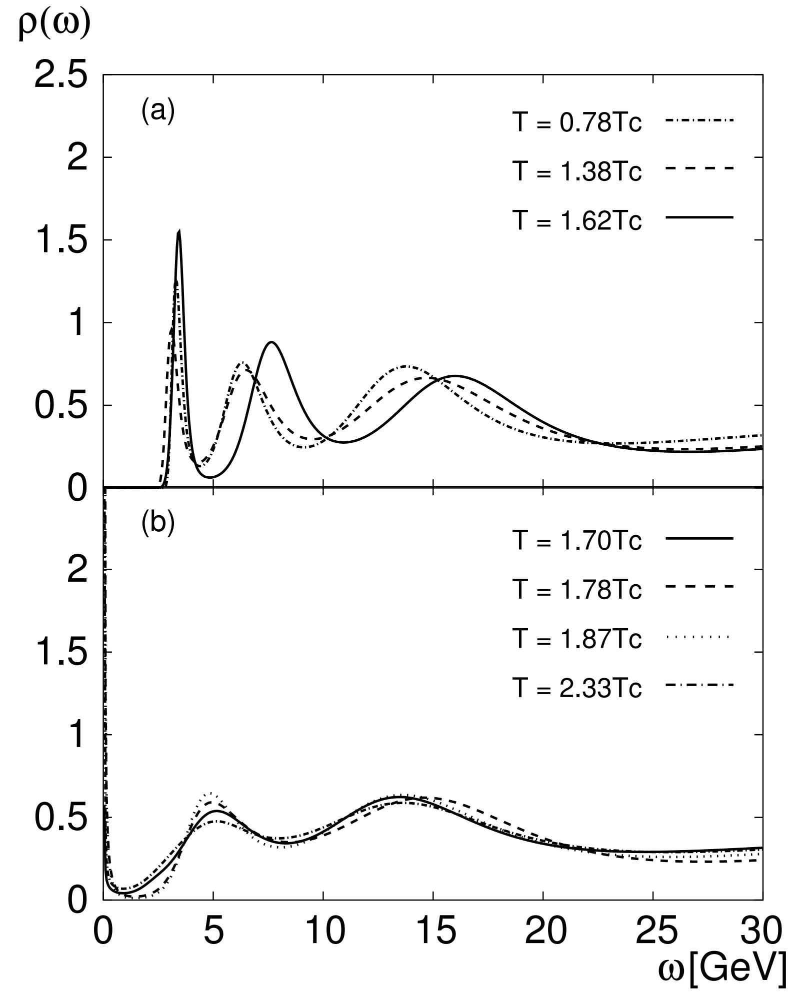
1P states seriously modified, possibly dissolved, already at 1.1 T_c

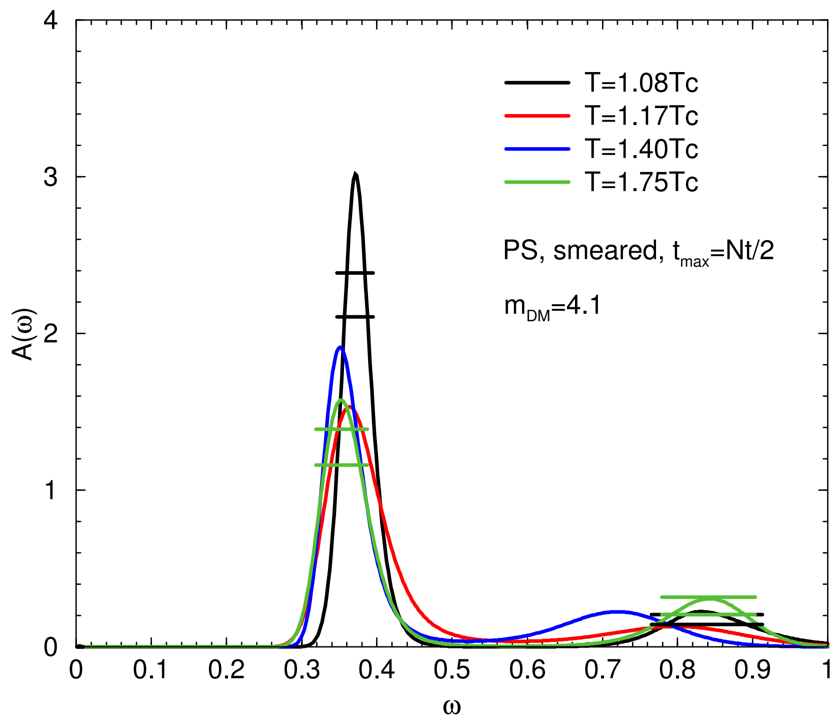
Datta,Karsch,Petreczky,Wetzorke, PRD69,094507('04);NP(PS)119,487('03)

Space-time asymmetric lattice,
a_t = 0.01 fm, ξ=4

No modification till $\sim\ 1.6T_c$
Disappearance between 1.6-1.7 T_c

Asakawa & Hatsuda, J.Ph.G30,S1337('04)





Smeared operators

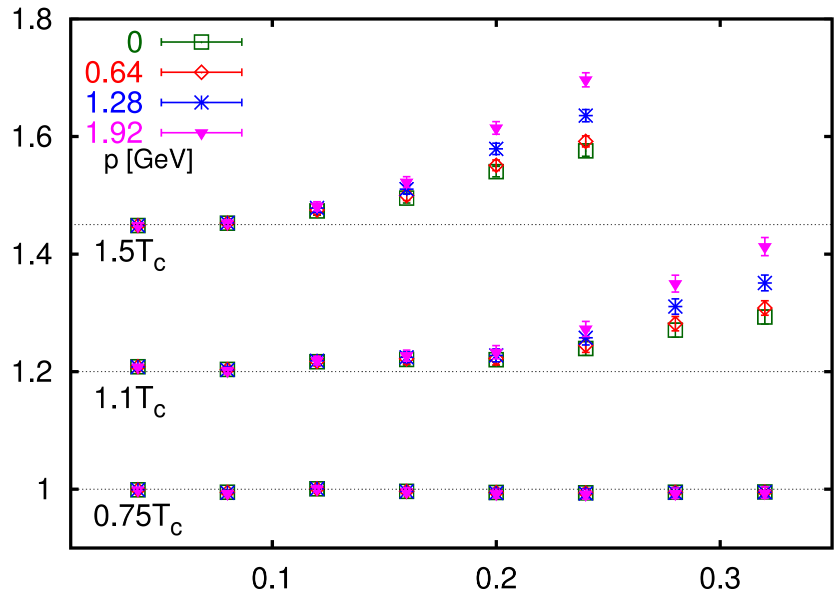
Gradual change
Peak till 1.75 T_c

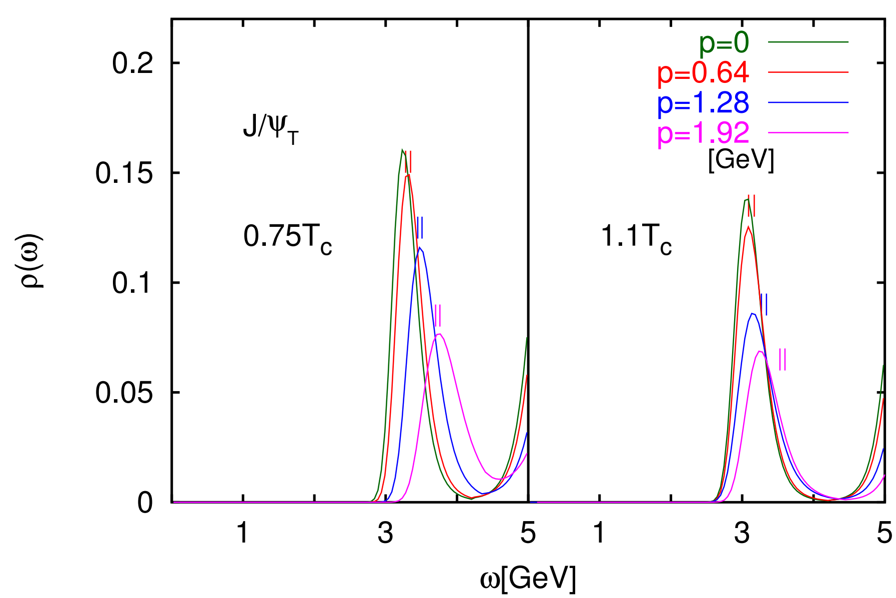
Umeda et al., in:
QWG Report, hep-th/0412158

J/ψ moving in heatbath frame

sees more energetic gluons

$$\sigma_{g\Phi} \sim (k-\epsilon_0)^{3/2} \qquad k \to k(\sqrt{1+p^2/m_\Phi^2}+p/m_\Phi)$$

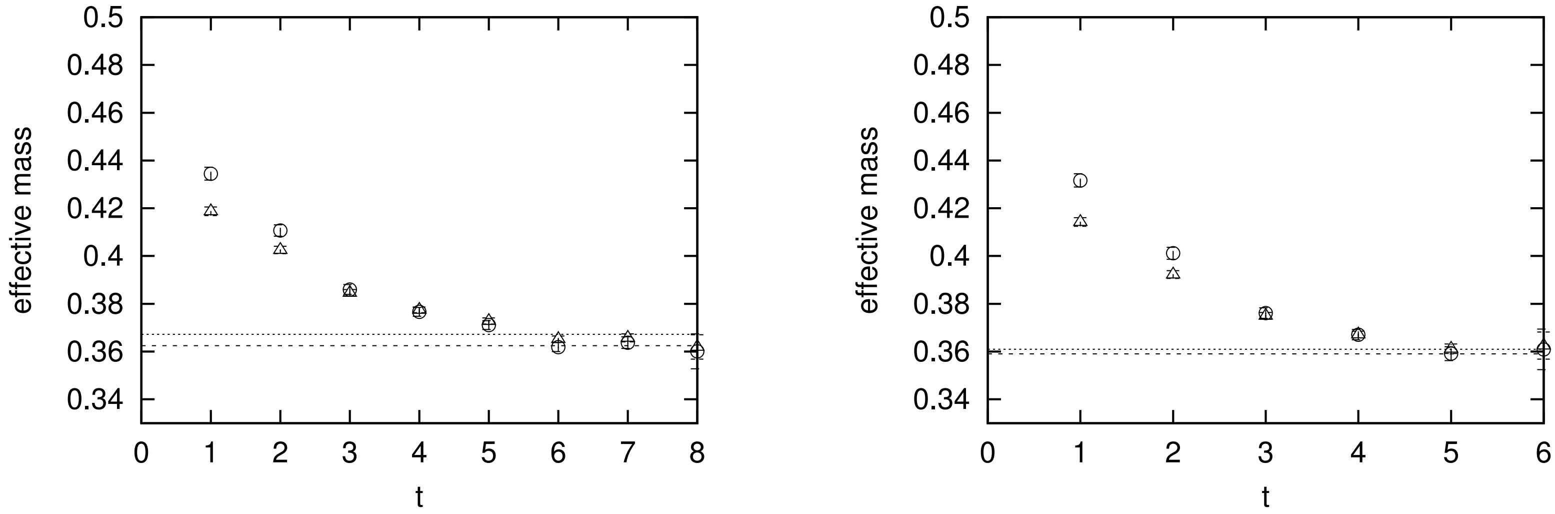




Datta et al., SEWM'04,hep-lat/0409147

Mass of state, with periodic and antiperiodic spatial boundary conditions

H. Iida *et al.*, PoS(LAT2005) 184 (*hep-lat*/0509129)



"J/Ψ and η_c survive... for $T = (1.11 - 2.07)T_c$."

"our preliminary lattice results show a large spatial b.c. dependence for the $c\bar{c}$ system in the χ_{c1} ($J^P = 1^+$) channel even near T_c"

What about quenching effect?

Below T_c effect may be significant: excitation of thermal pions

In particular, the possibility of excited charmonia decaying before T_c
Mass modification of D mesons $\rightarrow$ low T_d for 1P, 2S states

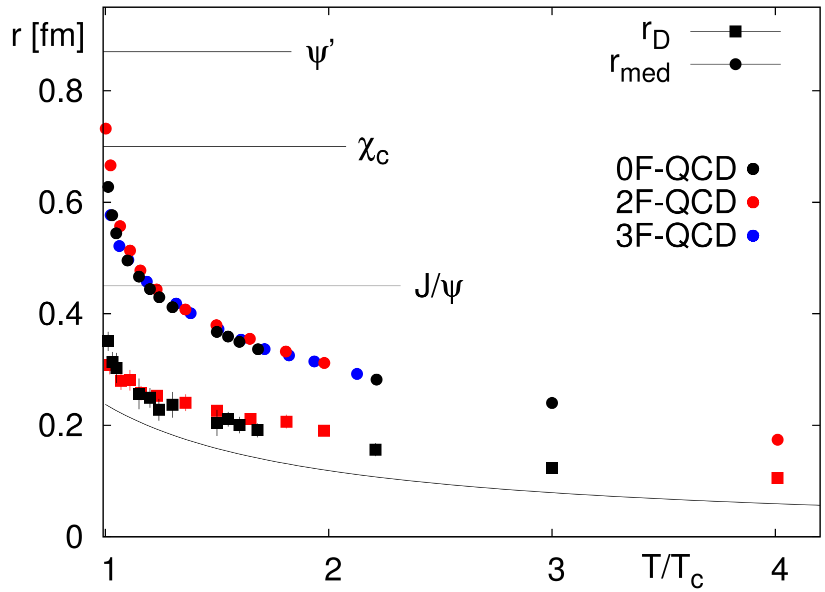
Digal, Petreczky and Satz, Phys. Rev. D 64, 094015 (2001)

Above T_c effect of quenching
may not be so significant for J/ψ decay, since

- Effect of gluon from $q \rightarrow q + g \Longrightarrow \langle p_g^q \rangle \approx \frac{3}{4}T$

D. Kharzeev & H. Satz, Phys. Lett. B334, 155 (1994)

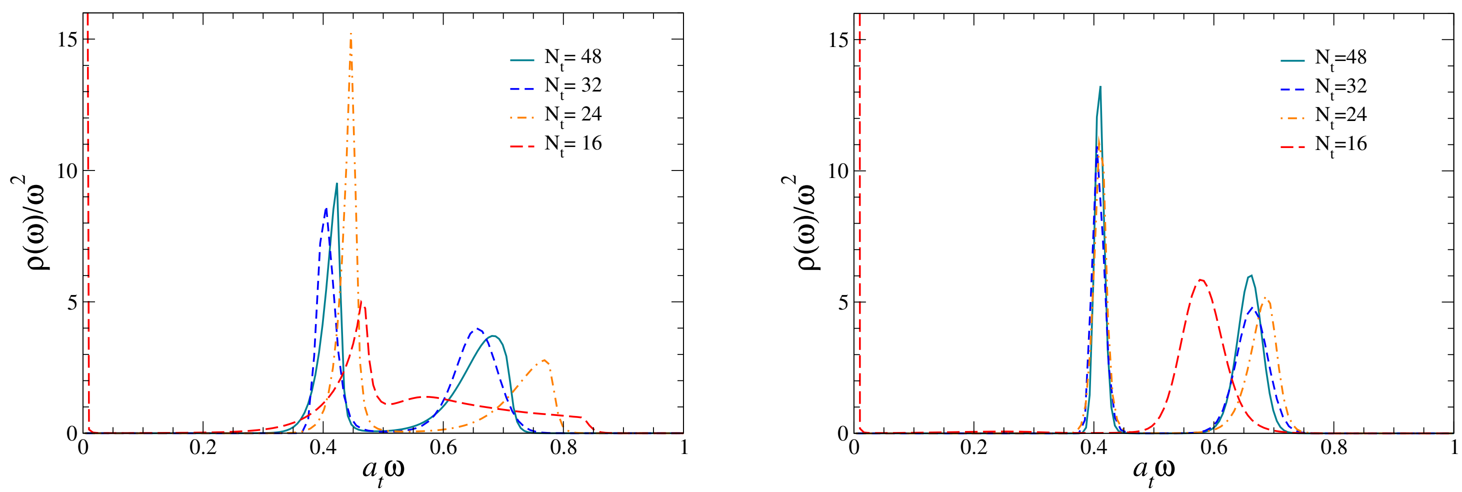
• Screening radius similar for gluonic plasma and n_f=2,3 QCD



O. Kaczmarek and F. Zantow, Eur. Phys. J. C 43, 63 (2005)

Calculation in full theory required.

Calculations for 2-flavor QCD with VERY anisotropic lattice:



J.I. Skullerud & Collaborators, PoS(LAT2005) 176 (*hep-lat*/0509115)

- $T/Tc \approx$ 0.75, 1.1, 1.5, 2.2, resp.
- ξ = 8
- $a_{\text{spatial}} \approx$ 1 GeV, rather coarse
- Tuning problem: "Quark anisotropy is significantly larger than gluon anisotropy... quarks feeling a higher temperature than the gauge fields."

For SPS and RHIC temperatures, 1S states not modified
Excited states significantly modified, maybe dissolved

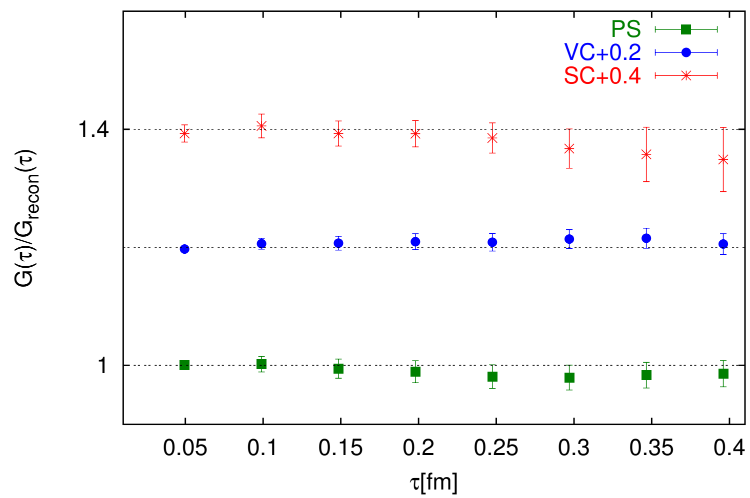
$\Longrightarrow$ $\boxed{\sim 40\%\text{ suppression of } J/\psi}$

signal of deconfinement **if** medium modification of excited states not significant below T_c

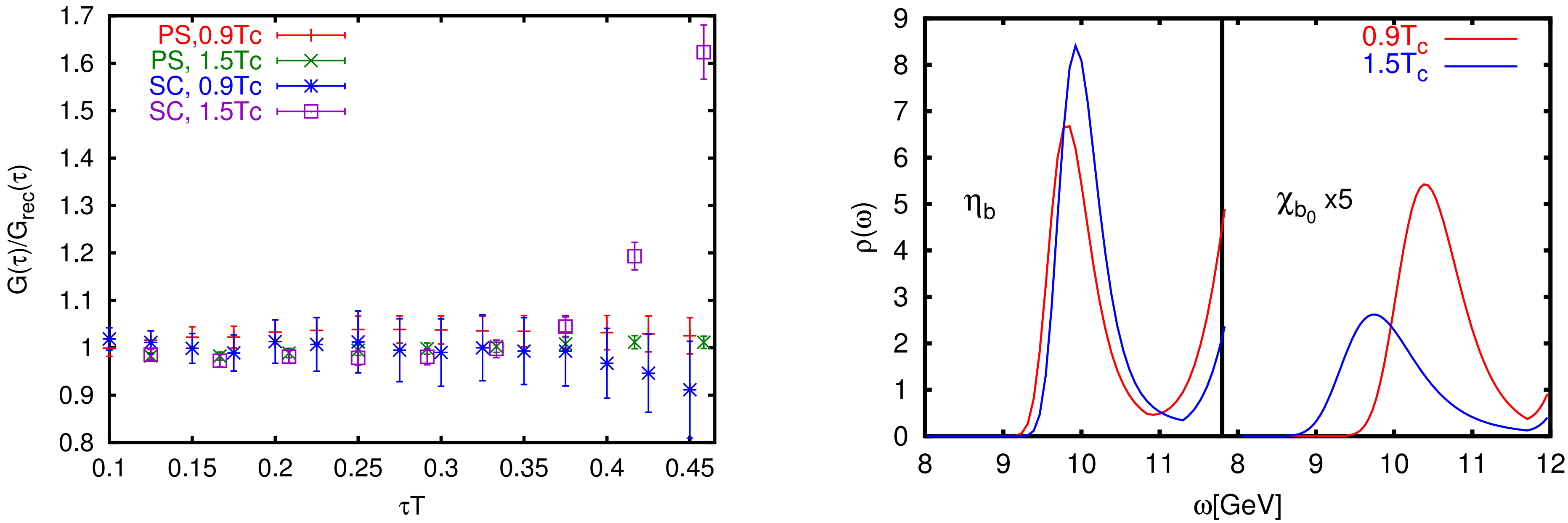
True for quenched

Datta et al., PRD 69,094507('04)

Unquenched study needed.



Preliminary results for Bottomonia:



Significant modification of χ_b states already at 1.5 T_c

Consistent with the results of Petrov *et al.*, hep-lat/0509138

A Note on Potential Model Studies:

Color averaged free energy

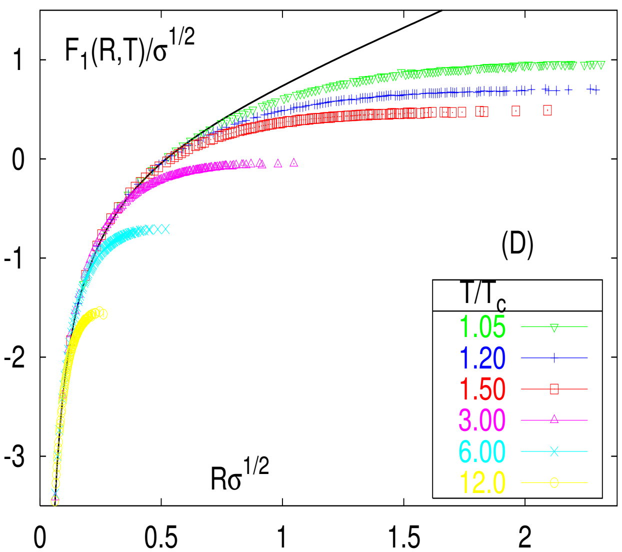
$$\exp(-F_{\mathrm{av}}(r,T)/T) = \langle \mathrm{Tr}(L_{\vec{r}})\mathrm{Tr}(L_0^\dagger)\rangle$$

Perturbatively, $V_1(r,T) = -8V_8(r,T) \sim -\frac{4}{3}\frac{\alpha(T)}{r}e^{-\mu(T)r}$

not valid close to T_c

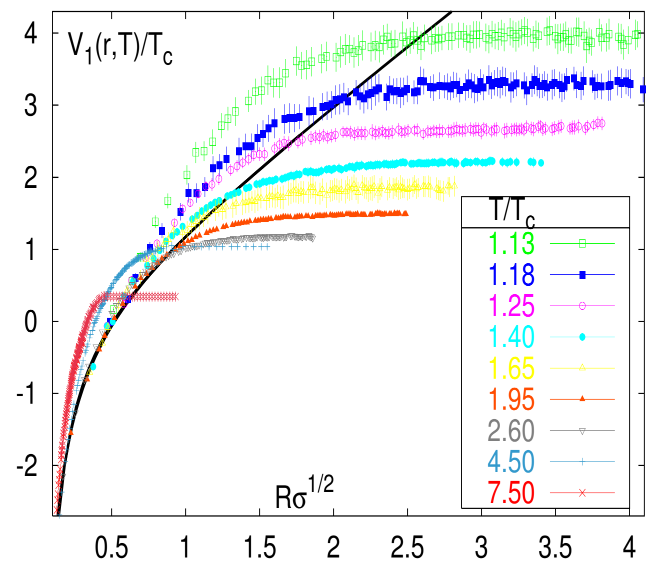
Recent results for color singlet free energy and internal energy:

O. Kaczmarek *et al.*, *hep-lat*/0309121



$$e^{-F_1(r,T)/T} = \langle \mathrm{Tr} L_{\vec{r}} L_0^\dagger \rangle$$

$$V_1(r,T) = \frac{\partial F_1(r,T)/T}{\partial T}$$



J/ψ(1S)	χ_c(1P)	ψ'(2S)	Υ(1S)	χ_b (1P)	Υ (2S)	
2.10	1.16	1.12	$>$ 4.0	1.76	1.60	Satz et al.'05
$\sim$ 2.3	1.15	1.15	-	-	-	Alberico et al. '05
2.60	1.19	1.2	$\sim$ 5	1.73	2.28	Wong '04

Satz et al. find free energy fit well to Debye-Hueckel screened form

$$F_s(r,T) = \frac{\sigma}{\mu}\left[\frac{\Gamma(1/4)}{2^{3/2}\Gamma(3/4)} - \frac{\sqrt{x}}{2^{3/4}\Gamma(3/4)} K_{\frac{1}{4}}(x^2+\kappa x^4)\right] - \frac{\alpha}{r}[e^{-x}+x]$$

V. Dixit, Mod. Phys. A ('90)

Such approaches will predict a mass reduction

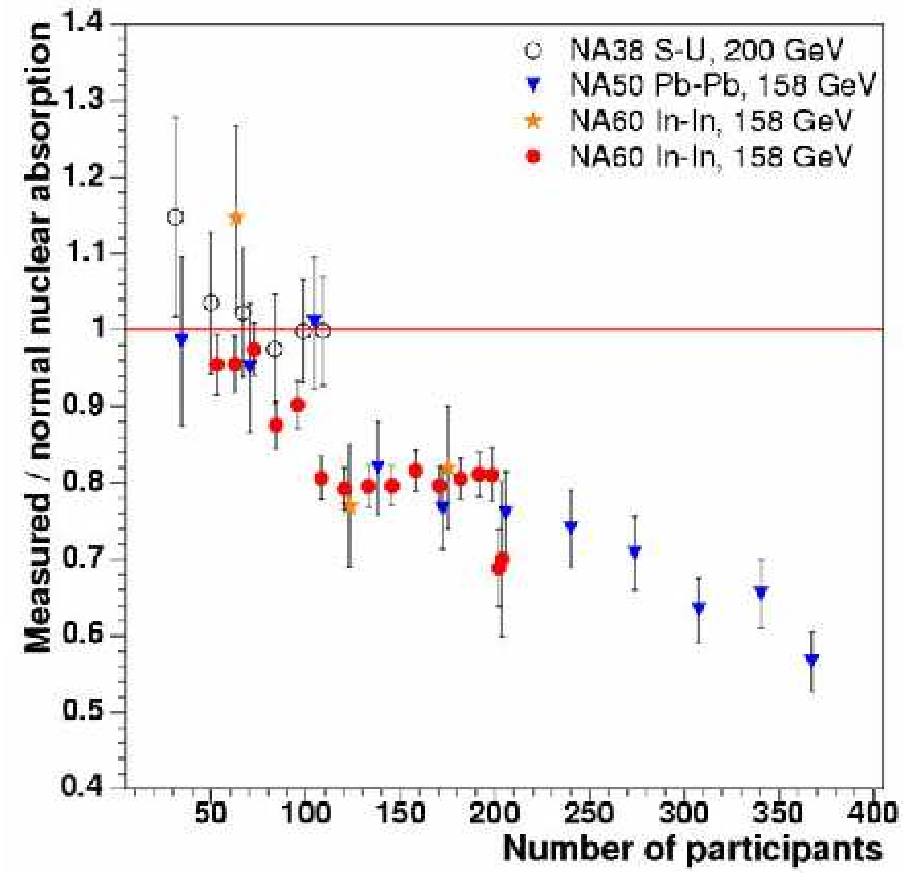
Other details of the correlator not reproduced by lattice data

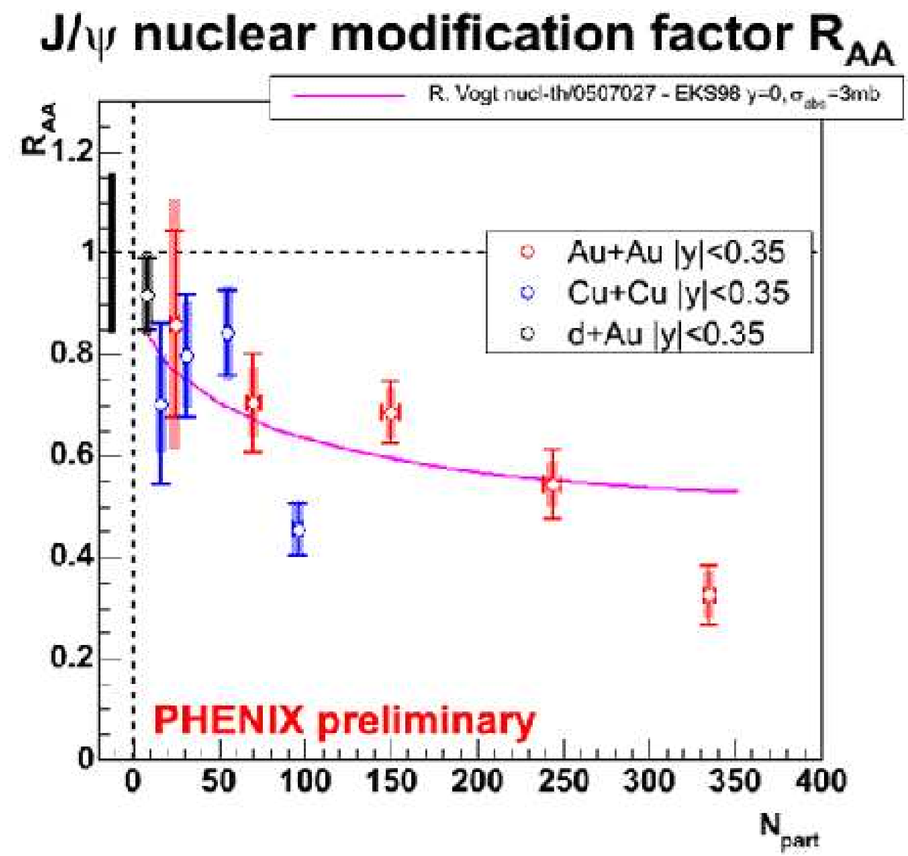
Petreczky & Mocsy, Eur.Phys.J. C43:77 ('05)

- 1S states $J/\psi, \eta_c$ largely unmodified till $\gtrsim 1.5T_c$
- Excited states χ_{c_0}, χ_{c_1} seriously modified / dissolved at $\lesssim 1.1T_c$
- $\Longrightarrow$ $\lesssim 40\%$ suppression of J/ψ in RHIC

  Signal of deconfinement if

  - Excited states not modified below T_c
    Unquenched study important
    No large mass drop of D meson
  - Nuclear absorption small
- Similar onset of suppression of J/ψ, χ_c
- *Similar for Υ, χ_b?*





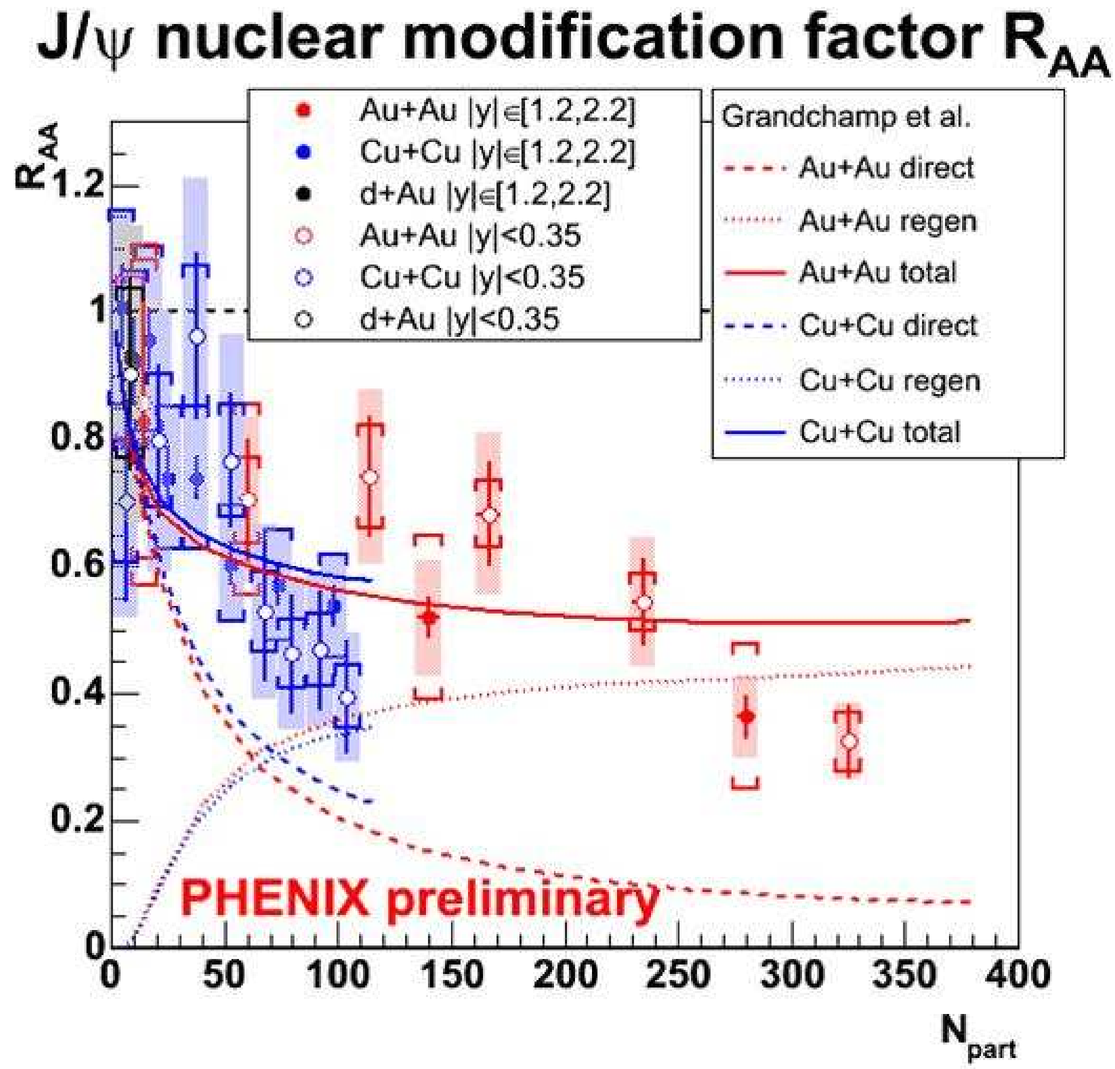
Quark Matter '05 NA60: Scomparin; Phenix: Pereira da Costa (nucl-ex/0510051)

For complete suppression scenario, RHIC suppression too small
Not inconsistent with only excited state suppression

F.Fleuret, IGS-Bielefeld, Sept.'05

Regeneration of J/ψ from $c\bar{c}$ pair

May be significant at RHIC



- p_T spectra
- rapidity distribution
- J/ψ flow

Phenix: V. Cianciolo, Quark Matter '05

	Obtained	RHIC1	RHIC2
$J/\psi \to ee$	$\sim$ 80	3300	4.3M
$J/\psi \to \mu\mu$	$\sim$ 7000	29000	4.3M
$\Upsilon \to ee$	-	830	39000
$\Upsilon \to \mu\mu$	- 80	1040	39000
$\chi_c \to ee\gamma$	-	220	0.67M
$\chi_c \to \mu\mu\gamma$	-	8600	0.67M

- charmonia suppression pattern. Study suppression of J/ψ, ψ', χ_c
- Study of Υ suppression
- Open charm – energy loss
- charm flow
- J/ψ flow