Quarkonium correlators at finite temperature

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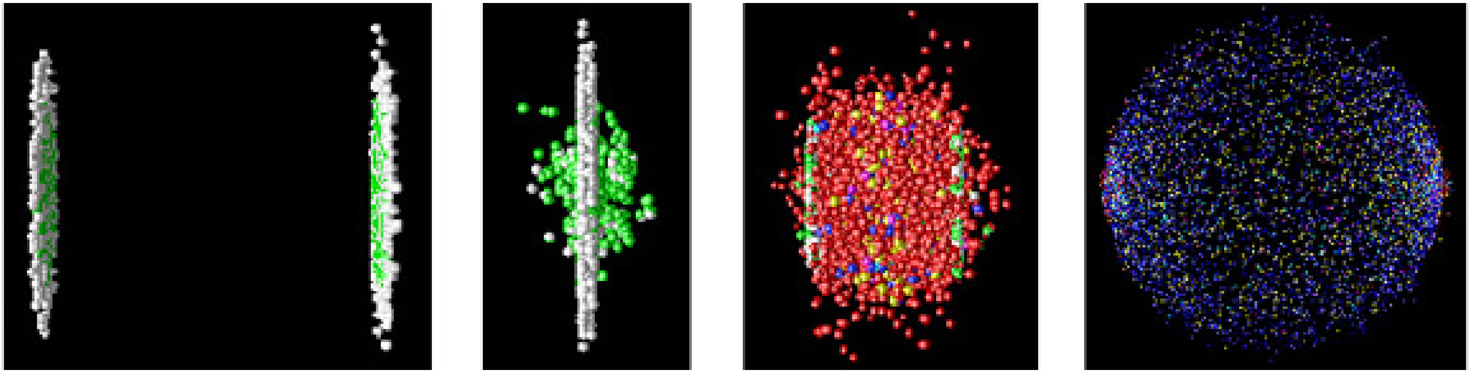
Nara Women's University, Nara, Japan , December 2nd 2008

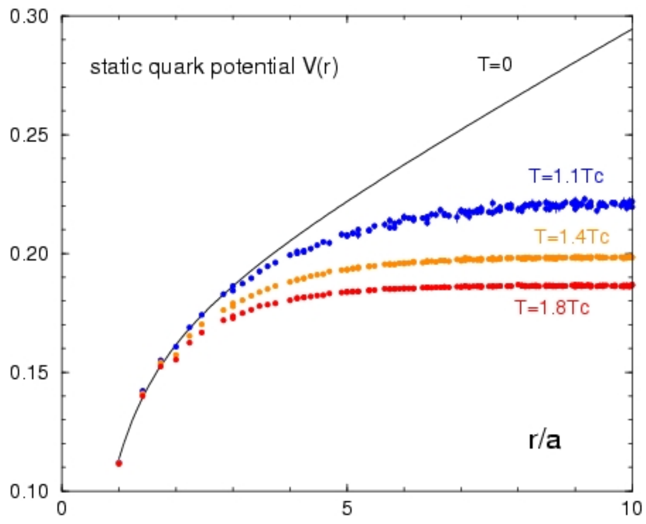
Contents of this talk

from the Phenix group web-site



- Introduction
  - -- Quark Gluon Plasma & J/ψ suppression
  - -- Lattice studies on J/ψ suppression
- Our approach to study charmonium dissociation
- Charmonium wave functions at T>0
- Summary & future plan

J/ψ suppression as a signal of QGP



Confined phase:
linear raising potential
→ bound state of c - $\bar{c}$

De-confined phase:
Debye screening
→ scattering state of c - $\bar{c}$

T.Hashimoto et al.('86), Matsui&Satz('86)

Lattice QCD calculations:

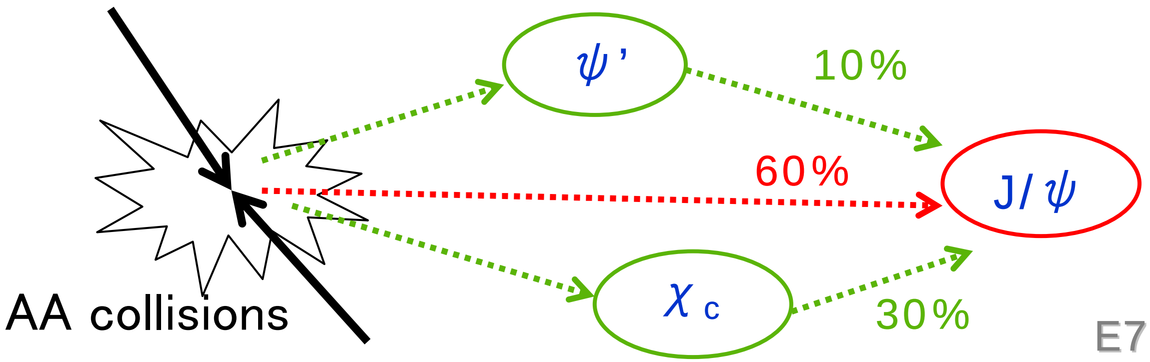
Spectral function by MEM: T.Umeda et al.('02), S.Datta et al.('04), Asakawa&Hatsuda('04), A.Jakovac et al.('07), G.Aatz et al.('06)

Wave func.: T.Umeda et al.('00)

B. C. dep.: H.Iida et al. ('06)

→ all calculations indicate that J/ψ survives till 1.5T_c or higher

Sequential J/ψ suppression scenario



E705 Collab.('93)

J/ψ (1S)	:	$J^{PC} = 1^{--}$	M=3097MeV	(Vector)
ψ (2S)	:	$J^{PC} = 1^{--}$	M=3686MeV	(Vector)
χ_{c0} (1P)	:	$J^{PC} = 0^{++}$	M=3415MeV	(Scalar)
χ_{c1} (1P)	:	$J^{PC} = 1^{++}$	M=3511MeV	(AxialVector)

PDG('06)

It is important to study dissociation temperatures for not only J/ψ but also ψ(2S), χ_c's

Current status on charmonium T_{dis}

- Lattice QCD studies (by MEM analysis) indicate
  - J/ψ may survive up to $T=1.5T_c$ or higher
  - χ_c may dissolve just above T_c
    e.g. A.Jakovac et al. (2007)
  - no results on excited states, ψ'
- The 2nd statement may be misleading (!)
  small change even in P-wave correlators
  up to $3T_c$ w/o the constant mode
- On the other hand,
  potential model studies suggest
  charmonium dissociation may also
  provide small change in the correlators
  e.g. A.Mocsy et al. (2007)

Therefore we would like to investigate T_{dis}
using new approaches in Lattice QCD
without Bayesian analyses

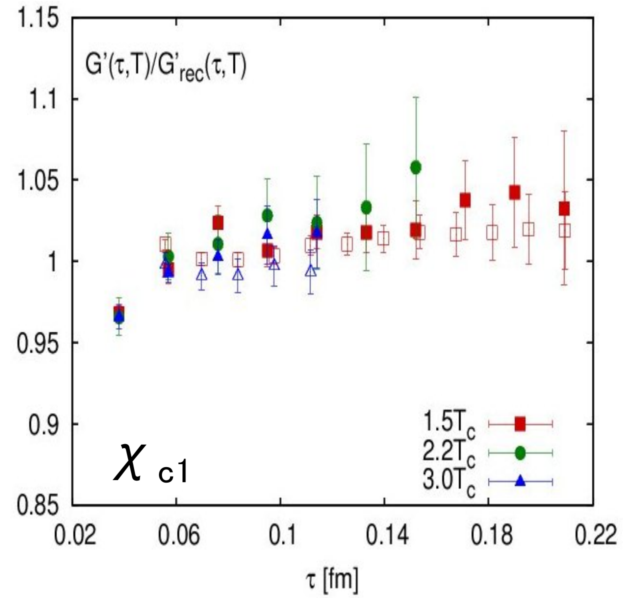
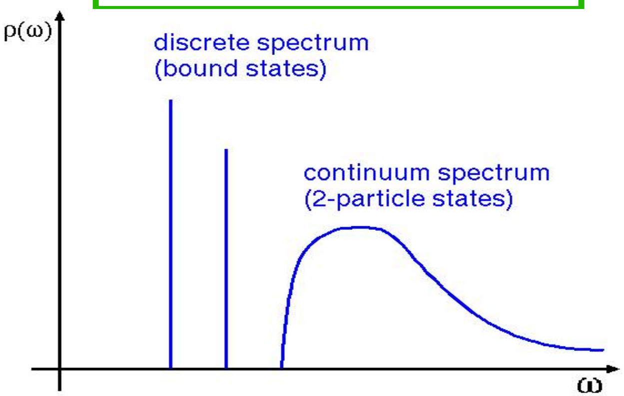


Fig. 3. The ratio of the derivatives $G'(\tau,T)/G'_{rec}(\tau,T)$ in the scalar channel (top) and axial-vector channel (bottom) calculated at $\beta = 7.192$. The results from anisotropic lattice calculations at $\beta = 6.5$ [26] are also shown (open symbols).

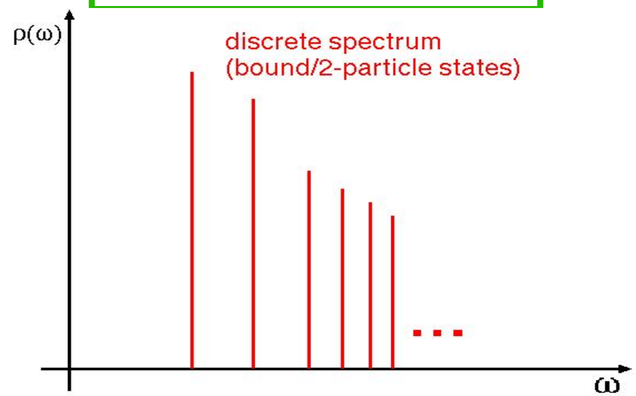
P.Petreczky (2008)

Spectral functions in a finite volume box

infinite volume case



finite volume case



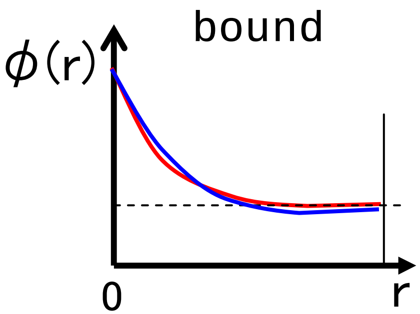
In a finite volume,
discrete spectra does not always indicate bound states !

In order to study a few lowest states,
the variational analysis is one of the most reliable approaches !

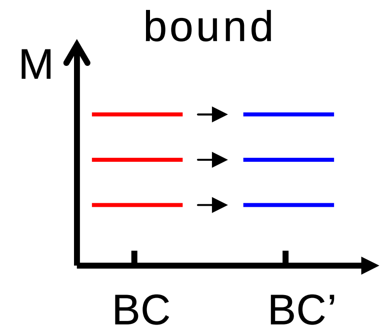
N x N correlation matrix : C(t)

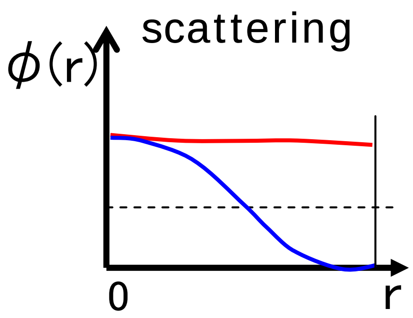
$$C(t)\psi = \lambda(t,t_0)C(t_0)\psi \qquad \lambda_i(t,t_0) = e^{-E_i(t-t_0)}$$

Boundary condition dependence

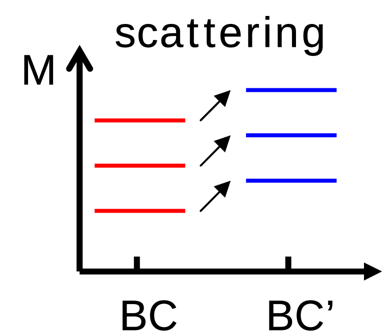


The wave functions are localized,
their energies are insensitive to B.C.





The momenta depends on B.C.,
the scattering state energies
are sensitive to B.C.



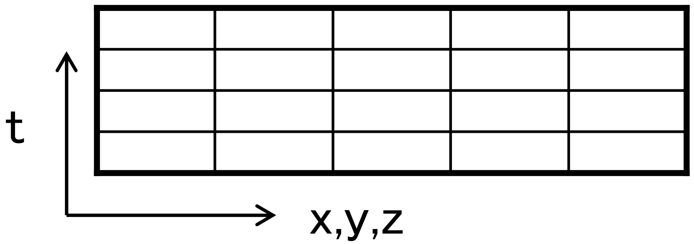
The idea has been already applied to the charmonium study in H. Iida et al., PRD74, 074502 (2006).

Lattice setup

- Quenched approximation (no dynamical quark effect)
- Anisotropic lattices

  lattice spacing : a_s = 0.0970(5) fm

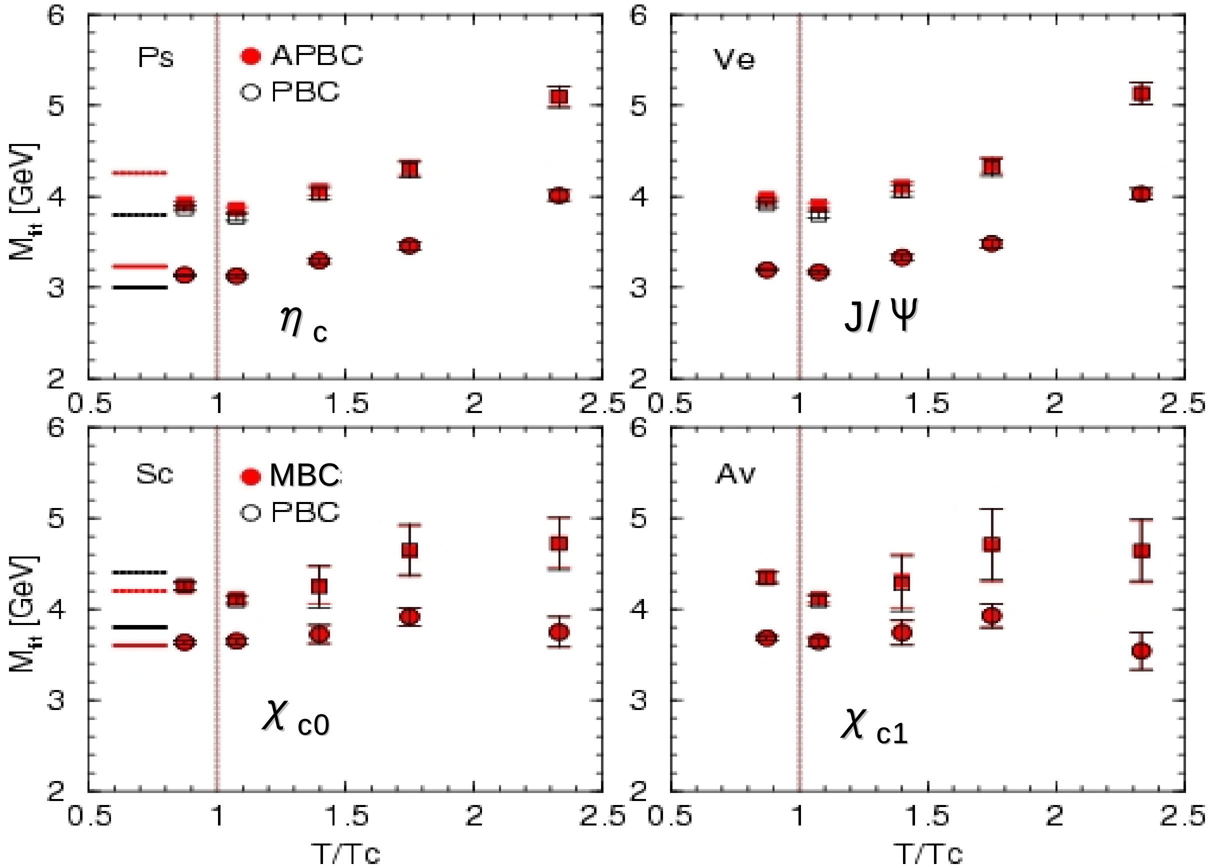
  anisotropy : $a_s/a_t = 4$



- r_s=1 to suppress doubler effects
- Variational analysis with 4 x 4 correlation matrix

N_t	32	26	20	16	12
T/T_c	0.88	1.08	1.40	1.75	2.33
# of conf.					
$V=16^3$	300	300	300	300	300
$V=20^3$	300	300	300	300	300
$V=32^3$	—	—	—	—	100

Temperature dependence of charmonium spectra



$$q(x_i + L_i) = b_i q(x_i)$$

$b_i = 1$: periodic

$b_i = -1$: anti-periodic

PBC : b=(1, 1, 1)

APBC : b=(-1,-1,-1)

MBC : b=(-1, 1, 1)

an expected shift in $V=(2fm)^3$ (free quark case) ~ 200MeV

- No significant mass shift in the different B.C.s
- only statistical error (large systematic error at higher temp.)

Wave functions at finite temperature

Temp. dependence of (Bethe-Salpeter) “Wave function”

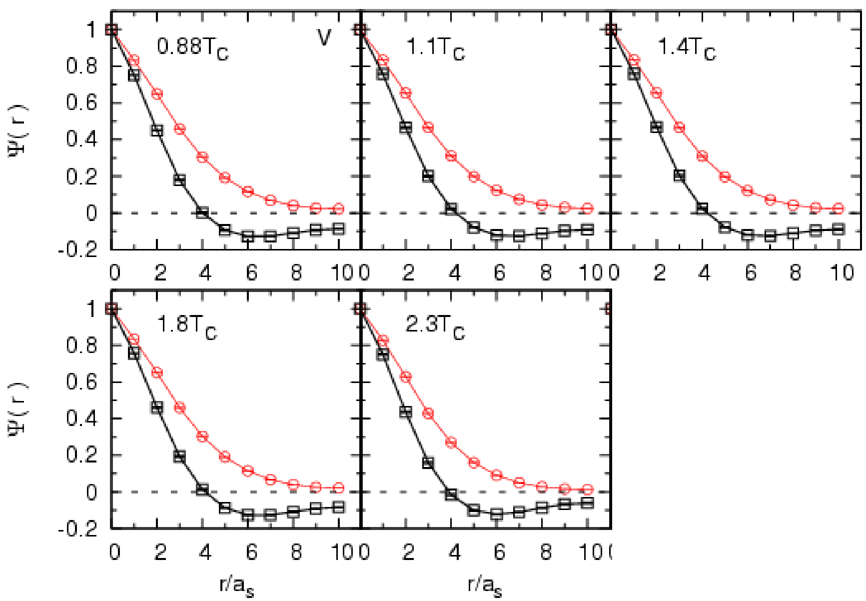
$$BS(\vec{r},t) = \sum_{\vec{x}} \langle \bar{q}(\vec{x}+\vec{r},t)\Gamma q(\vec{x},t)\bar{q}(\vec{0},0)\Gamma q(\vec{0},0)\rangle$$
$$\Psi(|\vec{r}|,t) = BS(\vec{r},t)/BS(\vec{r}_0,t)$$

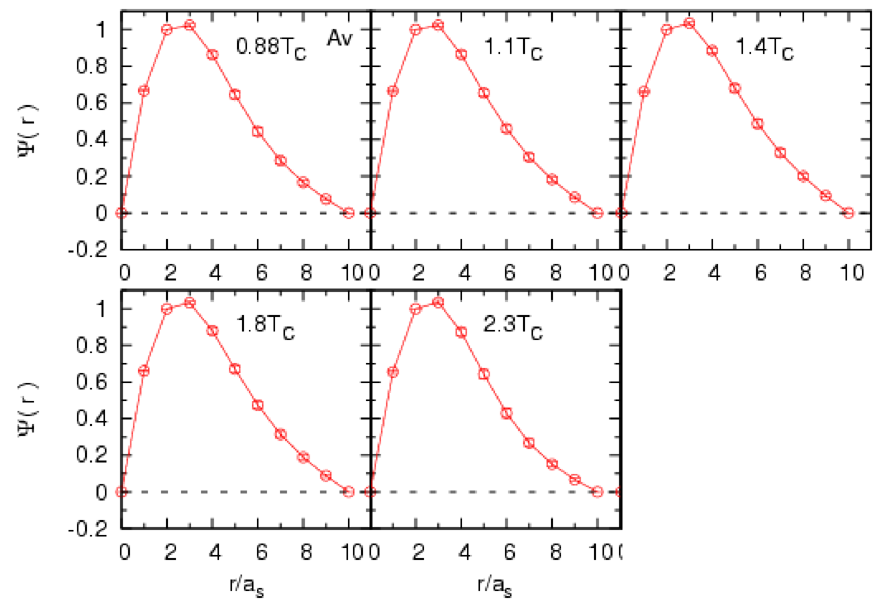
$$\Gamma = \begin{cases} \gamma_5 & \text{(Ps)} \\ \gamma_i & \text{(Ve)} \quad (i=1,2,3) \\ \sum_j \left(\overrightarrow{\partial}_j\gamma_j - \overleftarrow{\partial}_j\gamma_j\right) & \text{(Sc)} \\ \sum_{j,k}\epsilon_{ijk}\left(\overrightarrow{\partial}_j\gamma_k - \overleftarrow{\partial}_j\gamma_k\right) & \text{(Av)} \quad (i=1,2,3) \end{cases}$$

using the eigen functions of the variational analysis

→ we can extract the wave functions of each states

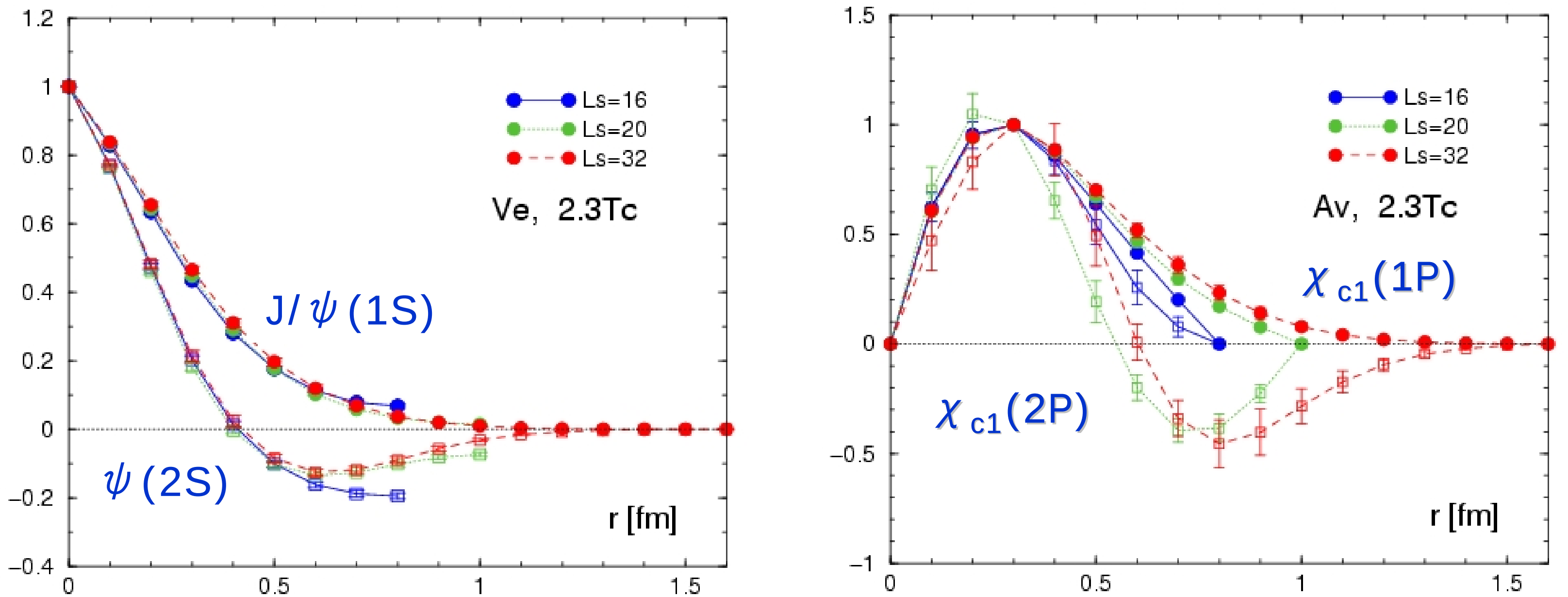
Charmonium wave functions at finite temperatures





- Small temperature dependence in S- and P-wave states
- No signal of scattering states even at T=2.3Tc
- Large volume is necessary for P-wave states.

Volume dependence at T=2.3Tc



- No signal of scattering states even at T=2.3Tc
- P-wave state W.F. depends on volume,
  but these are well localized.

Summary and future plan

We investigated T_{dis} of charmonia from Lattice QCD
using another approach to study charmonium at T>0
without Bayesian analysis

- boundary condition dependence
- Wave function (Volume dependence)

No hint for unbound c-$\bar{c}$ quarks up to T = 2.3 Tc

→ The result may affect the scenario of J/ψ suppression.

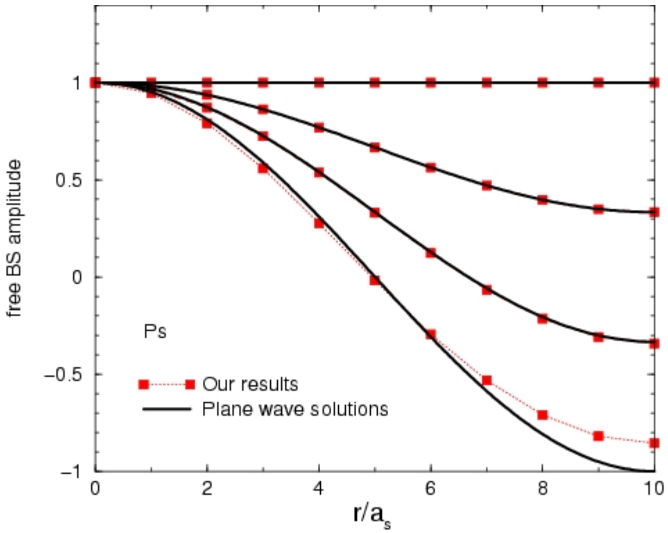
Future plan

- Interpretations of the experimental results on J/ψ suppression
- Full QCD calculations (Nf=2+1 Wilson is now in progress)

Thank you very much !!

Wave functions in free quark case

Test with free quarks ($L_s/a=20$, $ma=0.17$)
in case of S-wave channels

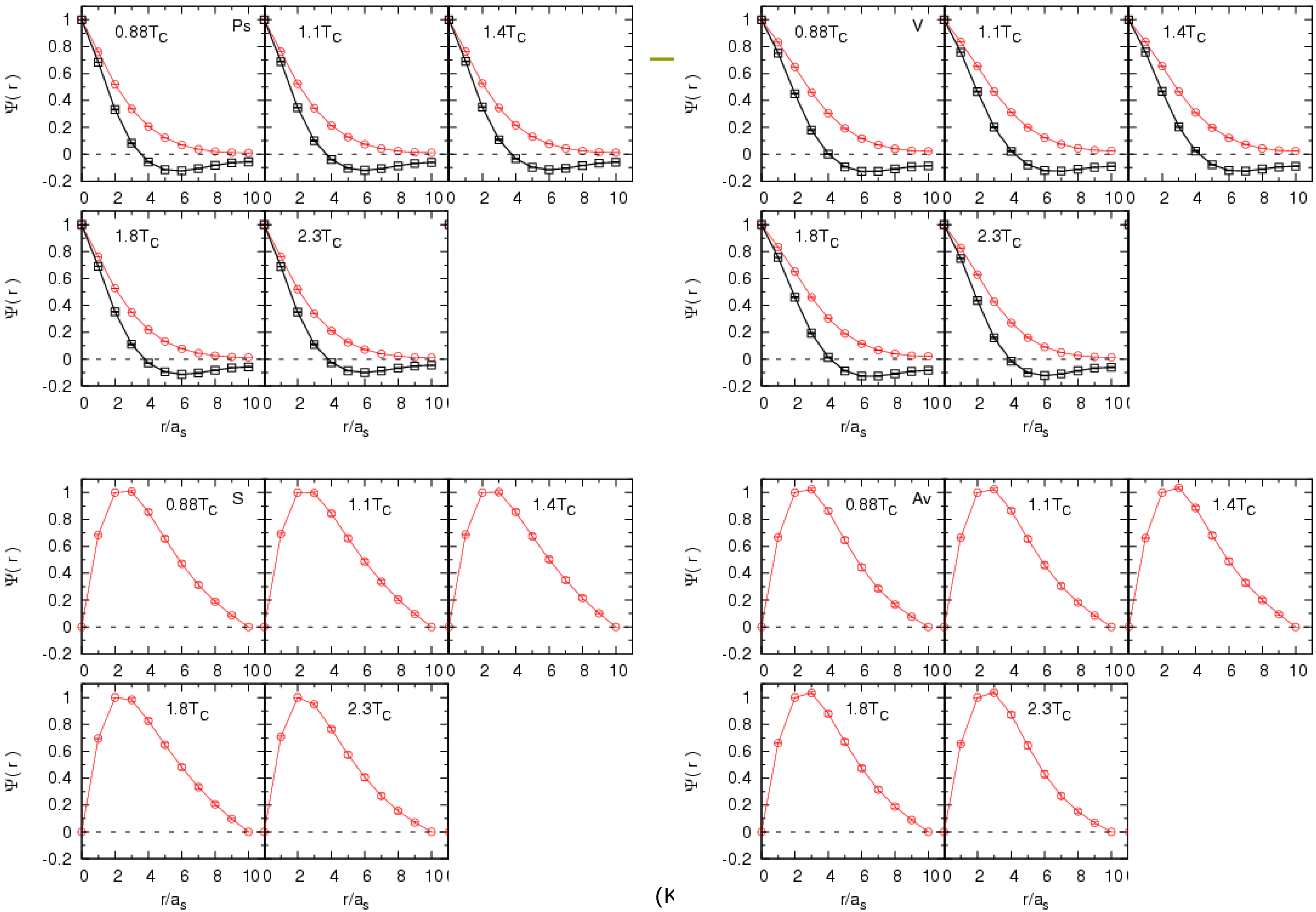


- Free quarks make trivial waves with an allowed momentum in a box

$$\Psi_k(|\vec{r}|,t) = \frac{\sum_{\vec{p}=\vec{k}} \cos(p_1 r_1)\cos(p_2 r_2)\cos(p_3 r_3)}{\sum_{\vec{p}=\vec{k}} 1}$$

- The wave function is constructed with eigen functions of 4 x 4 correlators

- Our method well reproduces the analytic solutions (!)



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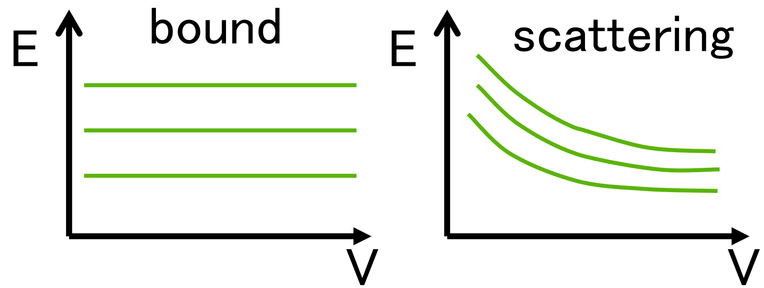
Bound state or scattering state ?

We know three ways to identify the state in a finite volume

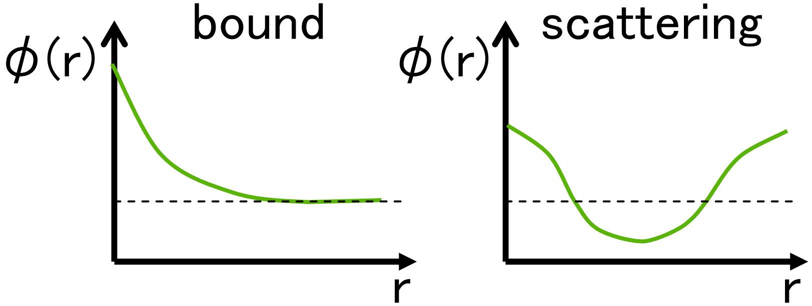
■ Volume dependence



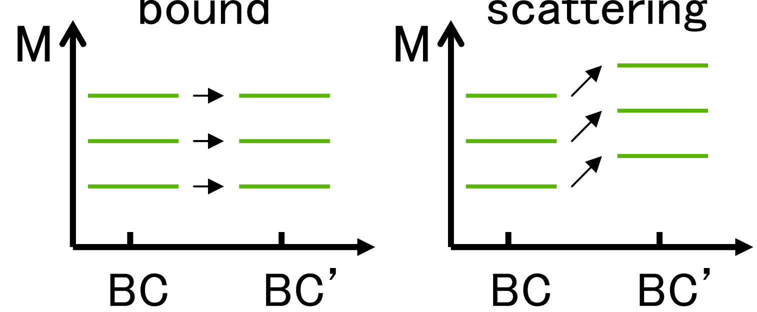
E : energy
V : volume

Φ(r): wave function
r : c - c̄ distance

■ Wave function



■ Boundary Condition (B.C.) dep.



H.Iida et al.('06), N.Ishii et al.('05)

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  - no results on excited states, ψ'
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  small change even in P-wave state
  up to $1.4T_c$ w/o the constant mode
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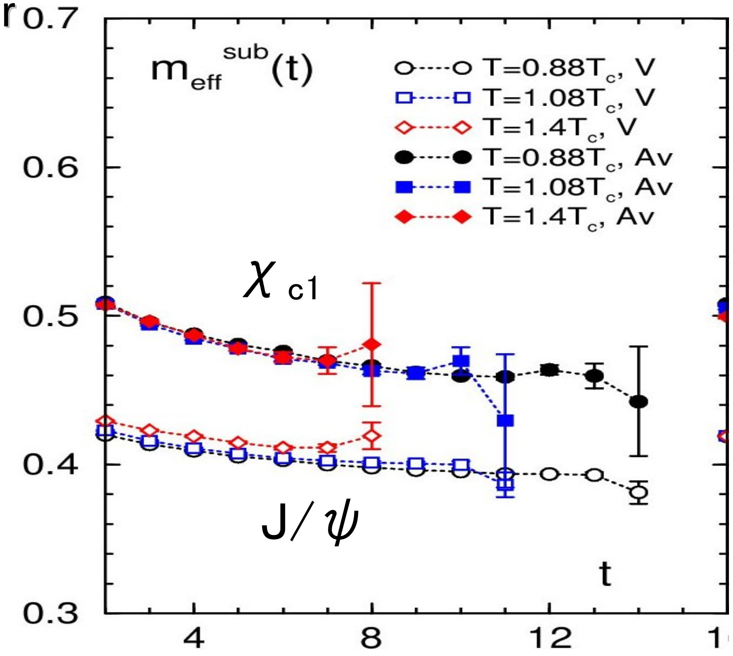

Fig: Temp. dependence of $M_{eff}(t)$ for J/ψ, χ_{c1} w/o constant mode.
T.Umeda (2007)