Constant mode in charmonium correlation functions

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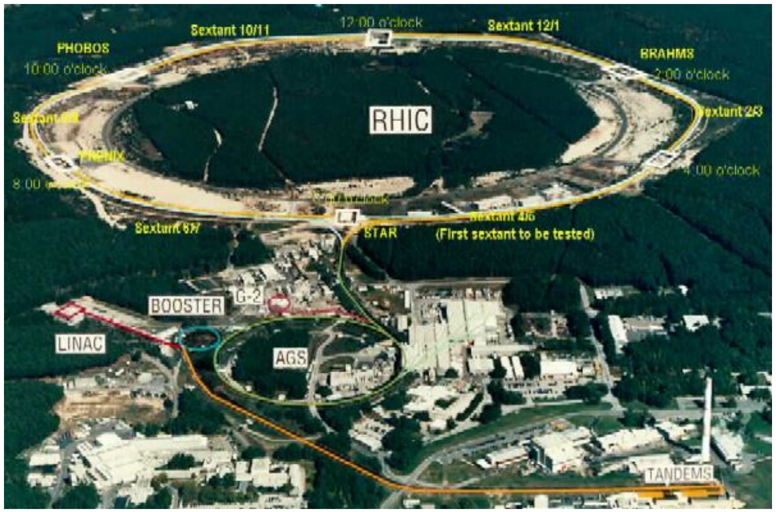
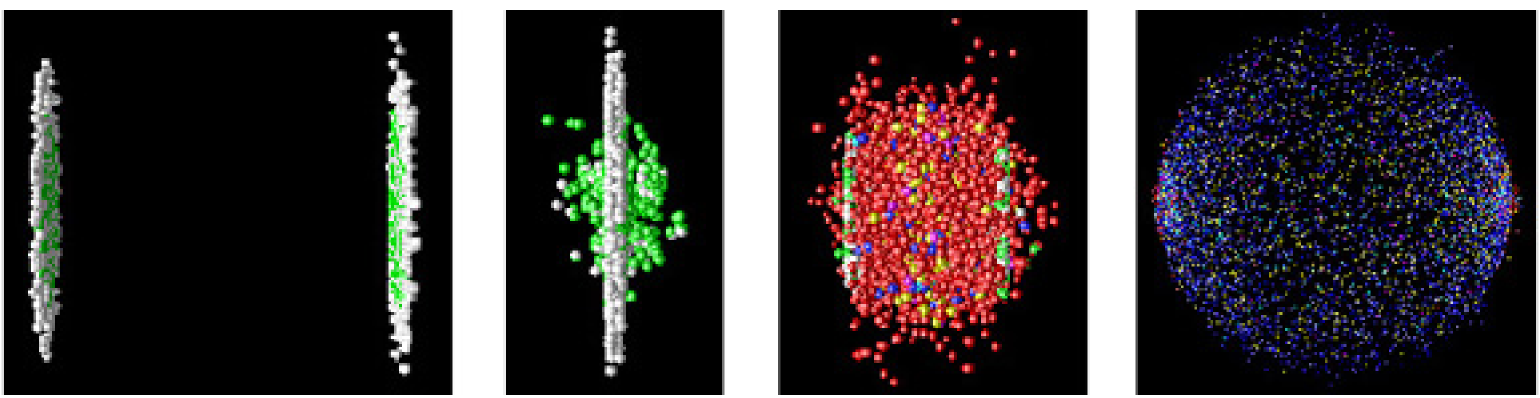
This is based on the Phys. Rev. D75 094502 (2007) [hep-lat/0701005]

Thermal Field Theory and their applications
YITP Kyoto, 5-7 September 2007

Experiments



- SPS : CERN (– 2005)
  Super Proton Synchrotron
- RHIC: BNL (2000 –)
  Relativistic Heavy Ion Collider
- LHC : CERN (2009 –)
  Large Hadron Collider



from the Phenix group web-site

First paper on the J/ψ suppression

Volume 57, Number 17 PHYSICAL REVIEW LETTERS 27 October 1986

Mass Shift of Charmonium near Deconfining Temperature and Possible Detection in Lepton-Pair Production

Takaaki Hashimoto and Osamu Miyamura
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(Received 27 May 1986)

photo : Prof. Osamu Miyamura

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in Monte Carlo analyses.[7,8] A related question is whether charmoniumlike clusters may still exist in a quark-gluon plasma. We have made tentative calculations by screened Coulombic potential and found that possibility small. Thus, contribution to lepton pair in the J/ψ mass region from the deconfinement phase would be mainly thermal quark-antiquark annihilation.[18] In connection with this point, we make a com-

lin, 1985), p. 1.
[4]R. D. Pisarski, Phys. Lett. **110B**, 155 (1982).
[5]R. D. Pisarski and F. Wilczek, Phys. Rev. D **29**, 338 (1984).
[6]L. McLerran and B. Svetitsky, Phys. Rev. D **24**, 450 (1981).
[7]M. Fukugita, T. Kaneko, and A. Ukawa, Phys. Lett. **154B**, 185 (1985).
[8]C. Dorninger, H. Leeb, and H. Markum, Z. Phys. C 29

J/ψ suppression in Exp.

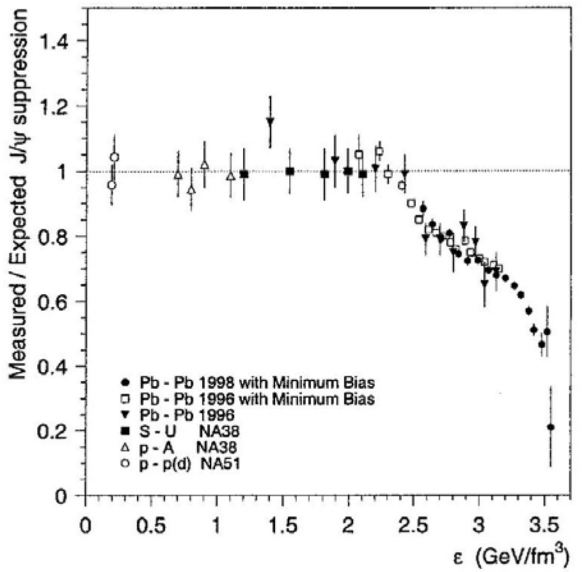


Fig. 7. Measured J/ψ production yields, normalised to the yields expected assuming that the only source of suppression is the ordinary absorption by the nuclear medium. The data is shown as a function of the energy density reached in the several collision systems.

Phys.Lett.B477(2000)28
NA50 Collaboration

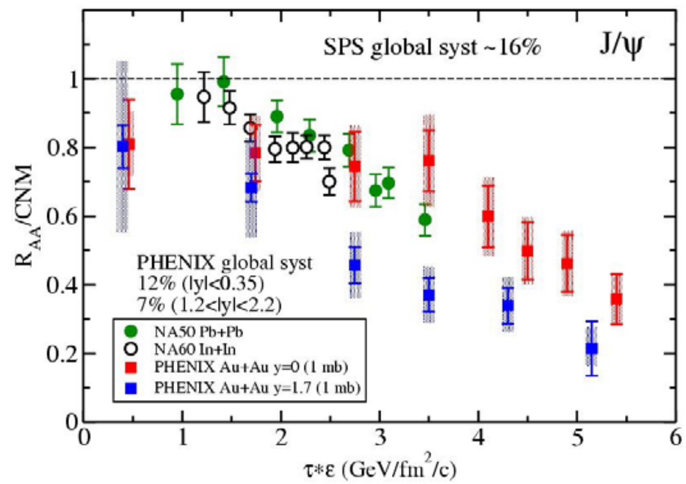


Figure 10: Survival fraction (R_{AA}/CNM) vs energy density comparison of PHENIX Au+Au suppression to that from NA38/50 at CERN.

QM2006
PHENIX Collaboration

Energy density
$0.5\text{–}1.5\,\mathrm{GeV/fm^3} = 1.0T_c$
$10\ \mathrm{GeV/fm^3} = 1.5T_c$
$30\ \mathrm{GeV/fm^3} = 2.0T_c$

"Charmonium states in QGP exist or not ?" from Lattice QCD

Charmonium in Lattice QCD

Lattice QCD enables us to perform

nonperturbative calculations of QCD

$$\langle X\rangle = \frac{1}{Z_{QCD}}\int Dq(x)D\bar{q}(x)DA_\mu(x)X(q,\bar{q},A_\mu)e^{-S_{QCD}}$$

Path integral by MC integration

QCD action on a lattice

Wilson quark,
Staggered (KS) quark,
Domain Wall quark, etc

Input parameters (lattice setup) :

(1) gauge coupling → lattice spacing (a) → continuum limit

(2) quark masses

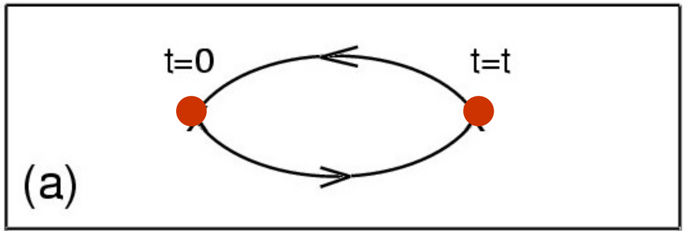
(3) (Imaginary) time extent → Temperature (T=1/Nta)

Charmonium correlation function

$$\langle X\rangle = \frac{1}{Z_{QCD}}\int Dq(x)D\bar{q}(x)DA_{\mu}(x)X(q,\bar{q},A_{\mu})e^{-S_{QCD}}$$

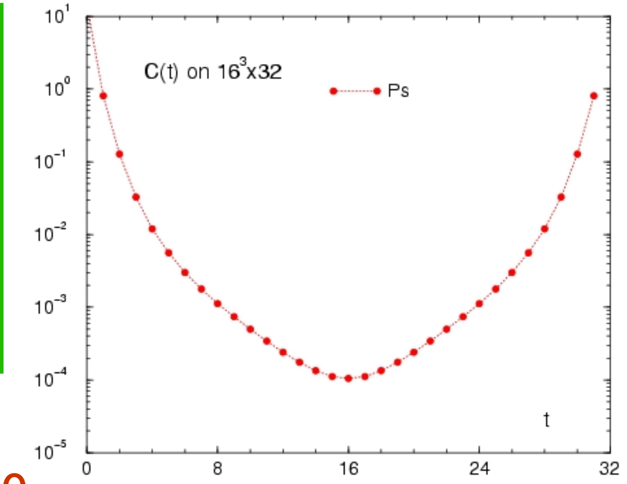
Correlation function

$$C(t) = \langle O(t)O^{\dagger}(0)\rangle$$



Charmonium operators

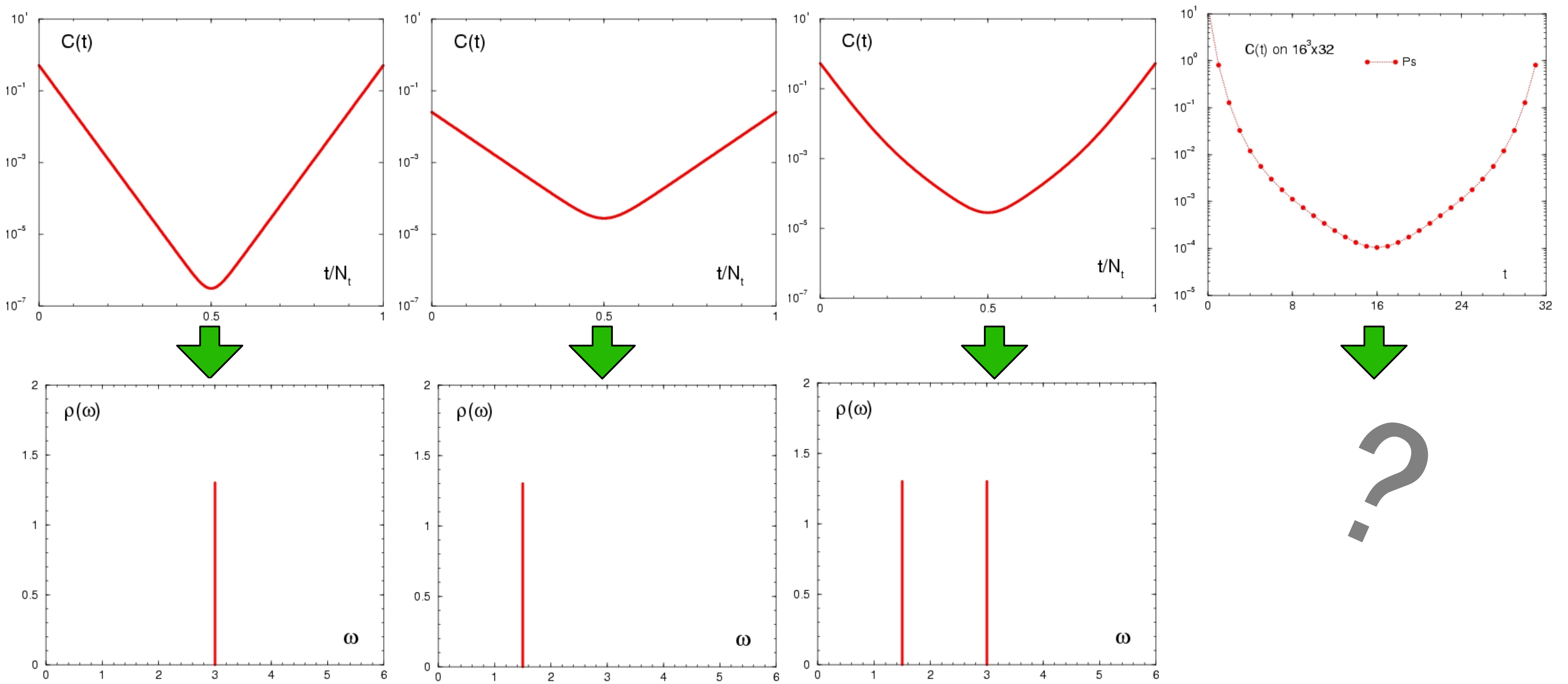
Pseudescalar(Ps)	$J^{PC} = 0-+$	η_{c}, ...
Vector (V)	$J^{PC} = 1--$	J/ψ, $\psi(2S)$, ...
Scalar (S)	$J^{PC} = 0++$	χ_{c0}, ...
Axialvector (Av)	$J^{PC} = 1++$	χ_{c1}, ...



LQCD provides C(t) of charmonium at T>0

Example of lattice results

$$\begin{aligned} C(t) &= \langle O(t) O^{\dagger}(0) \rangle \\ &= \int d\omega \rho(\omega) \frac{e^{-\omega t} + e^{-\omega(N_t - t)}}{1 - e^{-\omega N_t}} \end{aligned}$$

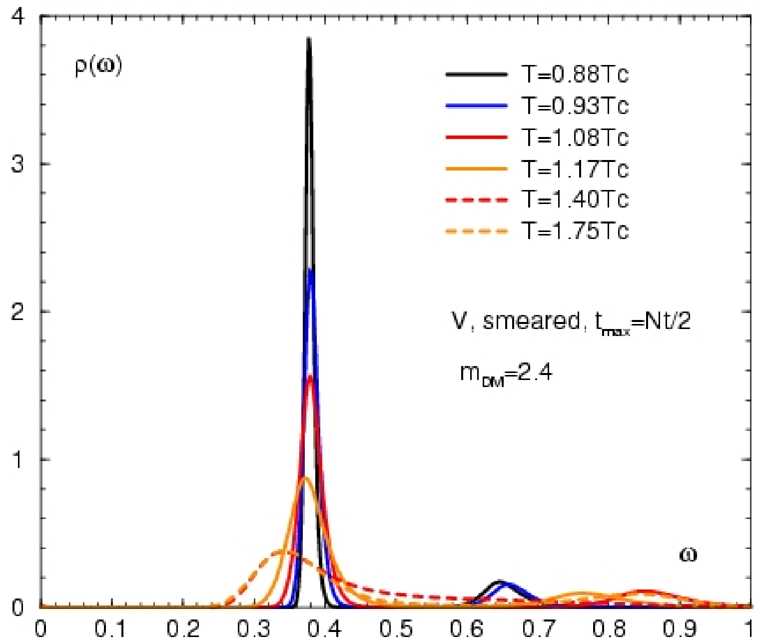


Charmonium spectral function

$$
\begin{aligned}
C(t) &= \langle O(t) O^{\dagger}(0) \rangle \\
&= \int d\omega \rho(\omega) \frac{e^{-\omega t} + e^{-\omega(N_t - t)}}{1 - e^{-\omega N_t}}
\end{aligned}
$$

Maximum entropy method

$C(t) \rightarrow \rho(\omega)$



Quenched QCD

- T. Umeda et al., EPJC39S1, 9, (2005).
- S. Datta et al., PRD69, 094507, (2004).
- T. Hatsuda & M. Asakawa, PRL92, 012001, (2004).
- A. Jakovac et al., PRD75, 014506 (2007).

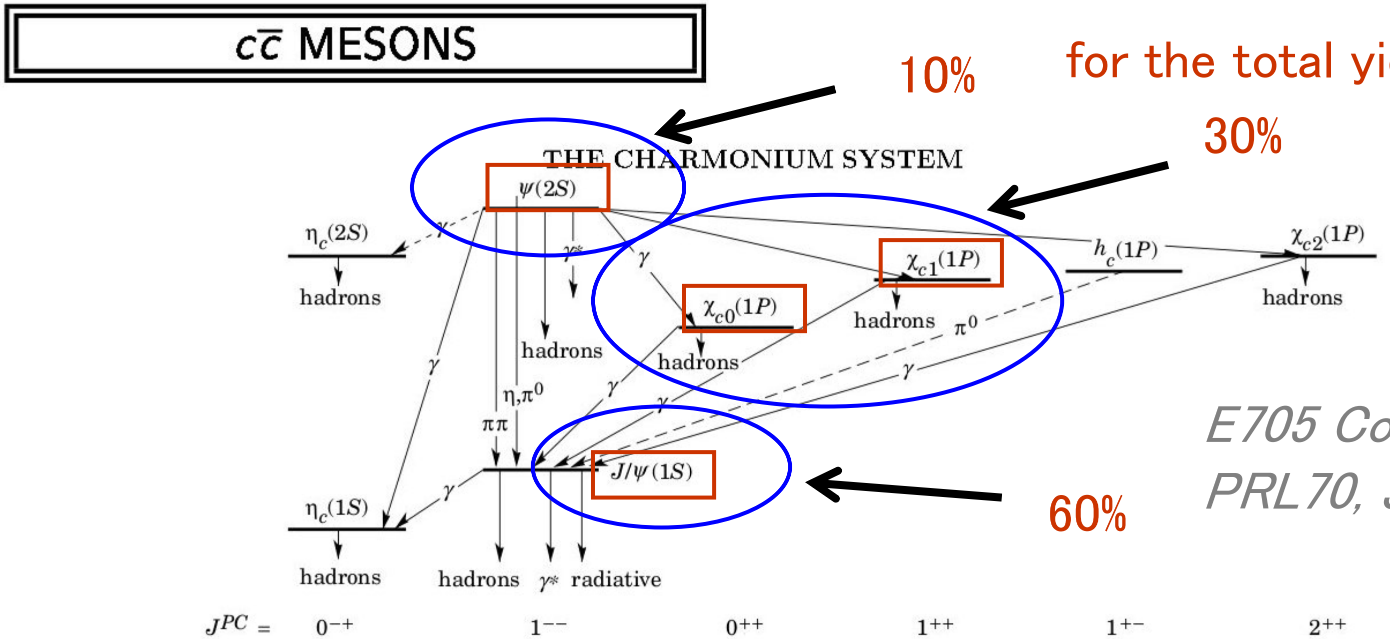
Full QCD

- G. Aarts et al., hep-lat/0610065.

All studies indicate survival of J/ψ state above T_c ($1.5T_c$?)

Sequential J/ψ suppression

Particle Data Group (2006)



10% for the total yield of J/ψ

30%

60%

Ps V S Av

E705 Collaboration, PRL70, 383, (1993).

Dissociation temperatures of J/ψ and ψ' & χ_c are important for QGP phenomenology.

Discussion

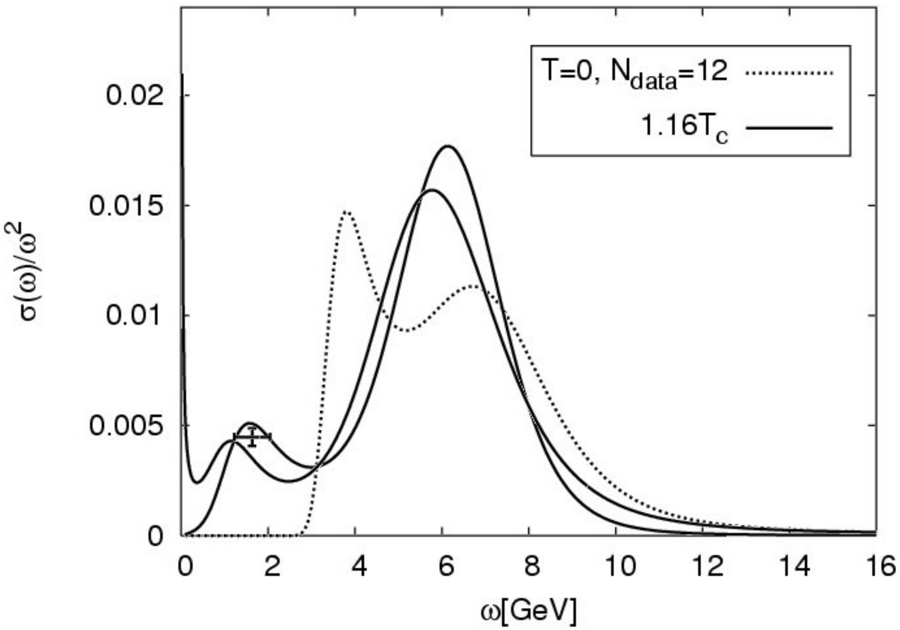


FIG. 19: The scalar spectral function for $\beta = 6.1$ at $T = 1.16T_c$ and at zero temperature reconstructed using $N_{data} = 12$. At finite temperature two default models $m(\omega) = 0.01$ and $m(\omega) = 0.038\omega^2$ have been used.

Studies for P-wave charmonium SPFs

S. Datta et al., PRD69, 094507 (2004).

A.Jakovac et al., PRD75, 014506 (2007).

(*) They concluded that

- the results of SPFs for P-states are not so reliable.
  e.g. large default model dep.
- the drastic change just above Tc is reliable results.

Lattice QCD results

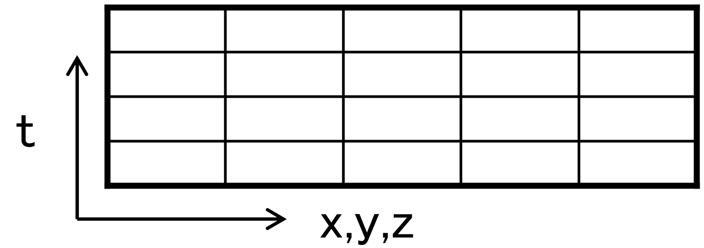
Lattice setup

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

  lattice size : 20^3 x N_t

  lattice spacing : $1/a_s$ = 2.03(1) GeV,

  anisotropy : $a_s/a_t = 4$



- Quark mass

  charm quark (tuned with J/ψ mass)

N_τ	160	32	26	20
T/T_c	~ 0	0.88	1.08	1.4
# of conf.	60	300	300	300

Effective mass (local mass)

Definition of effective mass

$$\begin{aligned} C(t) &= A_0 e^{-m_0 t} + A_1 e^{-m_1 t} + \cdots \\ &\equiv A e^{-m_{eff}(t) t} \end{aligned}$$

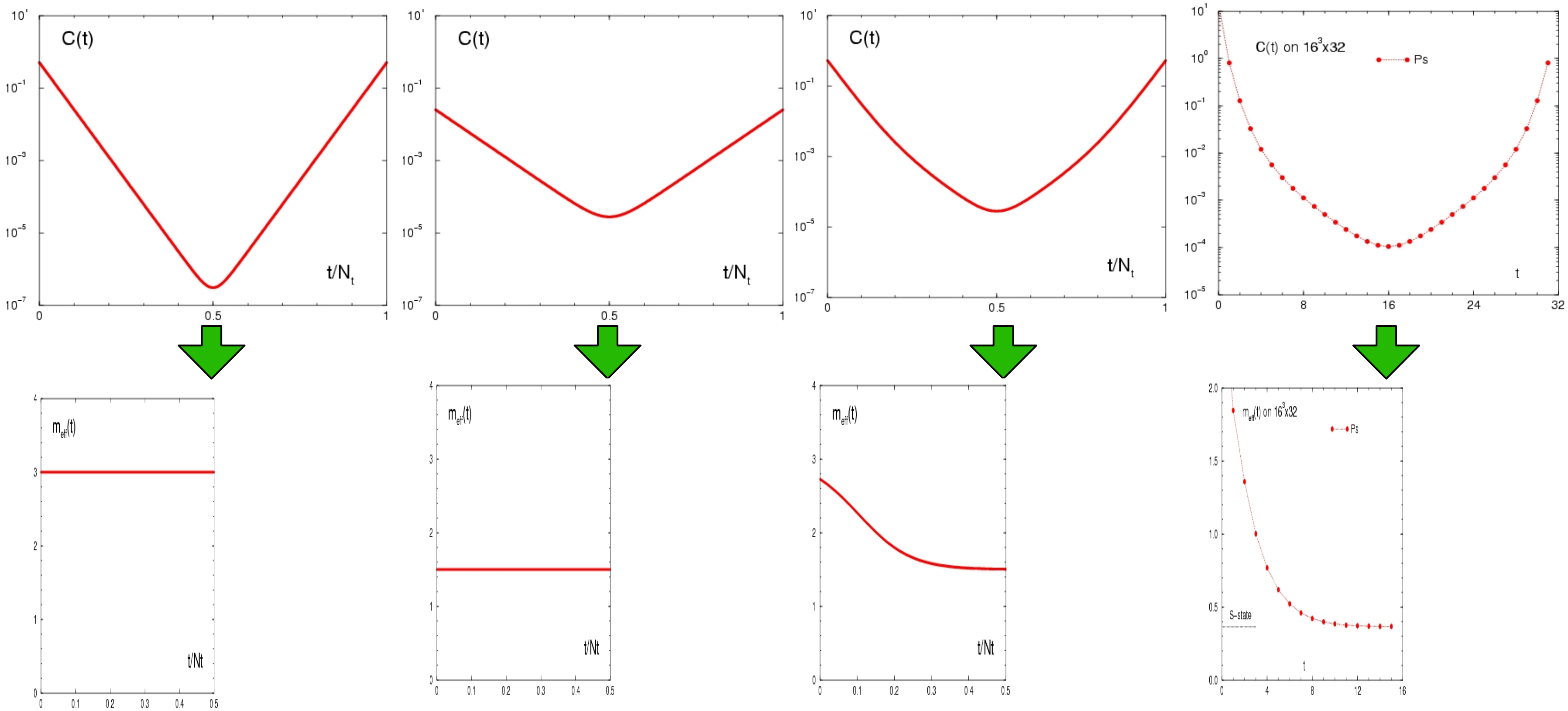
$$\frac{C(t)}{C(t+1)} = e^{-m_{eff}(t)}$$

$$m_{eff}(t) \to m_0 \quad \text{when} \quad (m_1 - m_0)t \gg 1$$

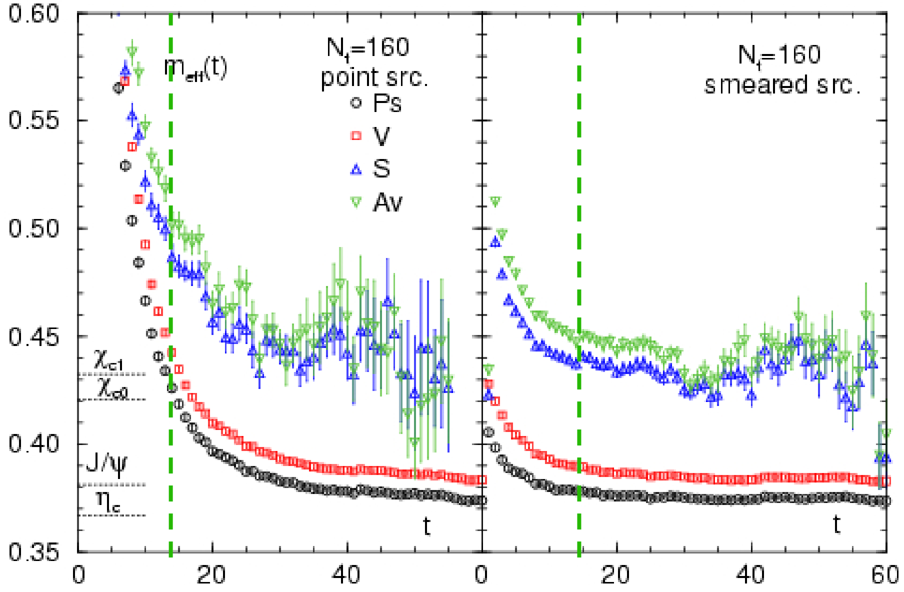
In the (anti) periodic b.c.

$$\frac{C(t)}{C(t+1)} = \frac{\cosh[m_{eff}(t)(N_t/2 - t)]}{\cosh[m_{eff}(t)(N_t/2 - t - 1)]}$$

Effective mass (local mass)



At zero temperature



(our lattice results)

M_{PS} = 3033(19) MeV

M_V = 3107(19) MeV

(exp. results from PDG06)

$M_{\eta c}$ = 2980 MeV

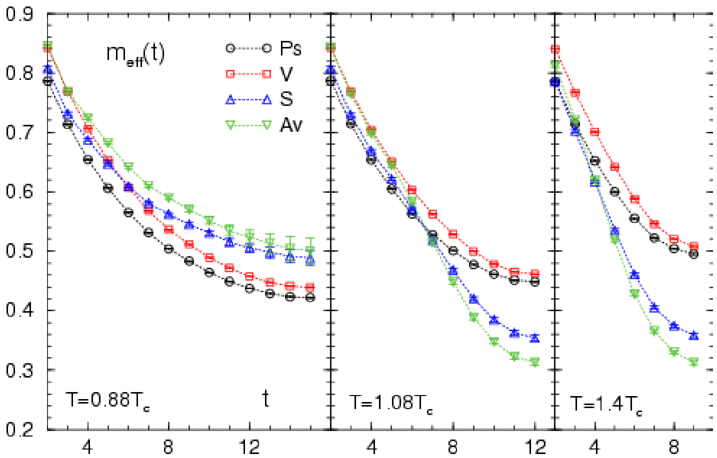
$M_{J/\psi}$ = 3097 MeV

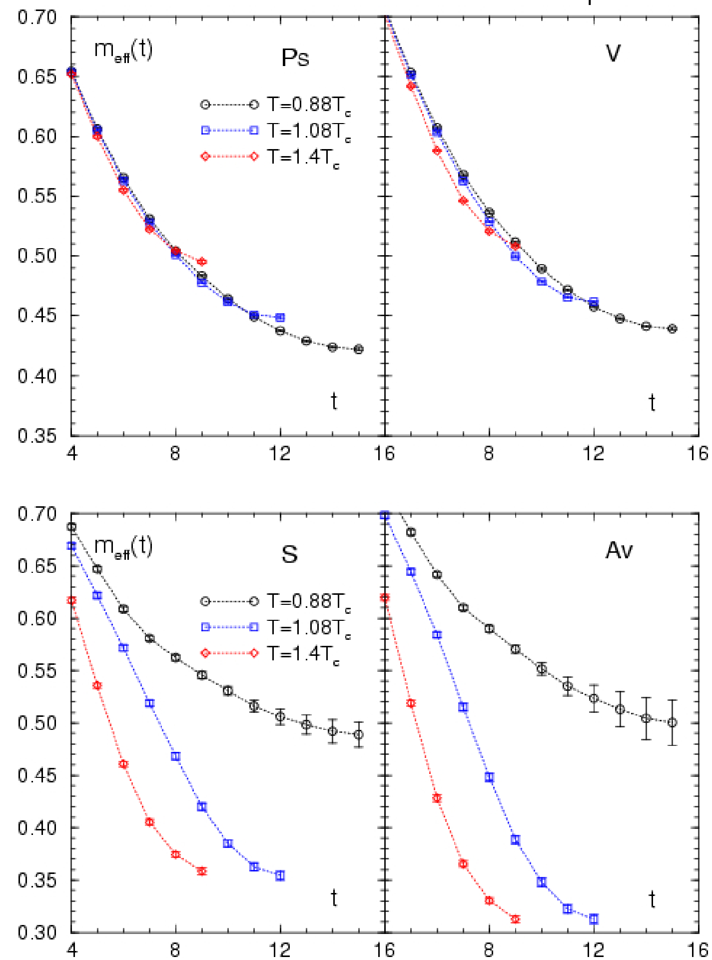
$M_{\chi c0}$ = 3415 MeV

$M_{\chi c1}$ = 3511 MeV

- In our lattice $N_t \simeq 28$ at T_c
  $t = 1 - 14$ is available near T_c
- Spatially extended (smeared) op. is discussed later

Quenched QCD at T>0

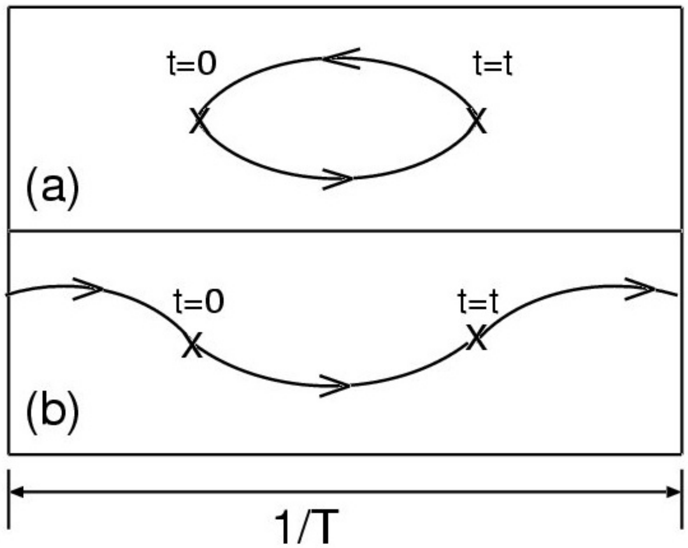




- small change in S-wave states
  → survival of J/ψ & η_c at $T>T_c$
- drastic change in P-wave states
  → dissociation of χ_c just above Tc (?)

S. Datta et al.,
PRD69, 094507 (2004). etc…

Constant mode



$\exp(-m_q t) \times \exp(-m_q t)$
$= \exp(-2m_q t)$

m_q is quark mass
or single quark energy

$\exp(-m_q t) \times \exp(-m_q(L_t-t))$
$= \exp(-m_q L_t)$

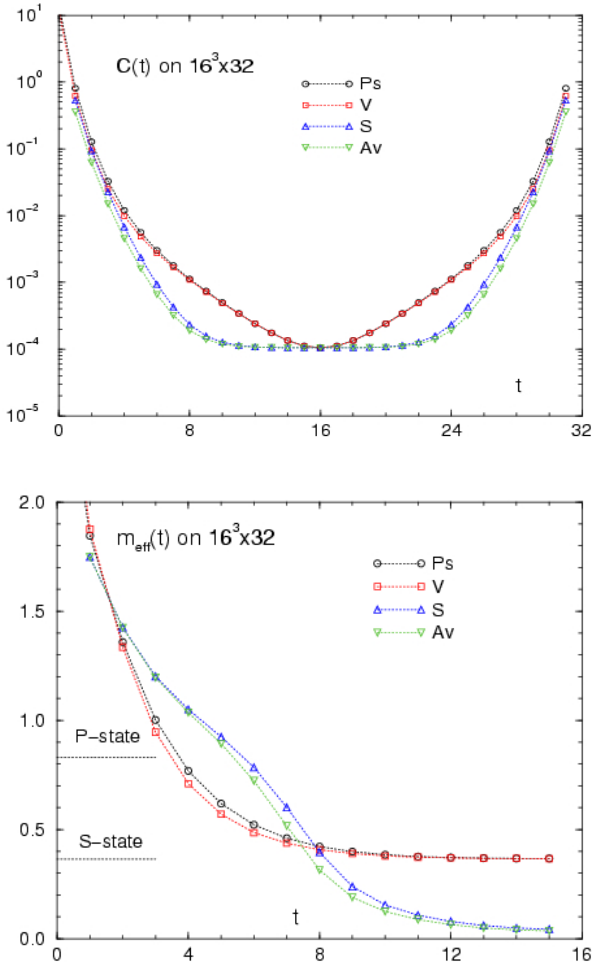
L_t = temporal extent

- in imaginary time formalism
  $L_t = 1/\text{Temp.}$
  gauge field : periodic b.c.
  quark field : anti-periodic b.c.
- in confined phase: m_q is infinite

→ the effect appears
only in deconfined phase

Pentaquark (KN state):
two pion state:
→ Dirichlet b.c.
c.f. *T.T.Takahashi et al., PRD71, 114509 (2005).*

Free quark calculations



Continuum form of the correlators

calculated by S. Sasaki

$$C(t) = \sum_{\vec{p}} \frac{4}{\cosh(E_p N_t/2)} \times$$

$$\begin{cases} \left(E_p^2 \cosh[2E_p(t - N_t/2)]\right) & \text{for } \Gamma = \gamma_5 \\ \left((E_p^2 - p_i^2)\cosh[2E_p(t - N_t/2)] + p_i^2\right) & \text{for } \Gamma = \gamma_i \\ -\left(p^2 \cosh[2E_p(t - N_t/2)] + (E_p^2 - p^2)\right) & \text{for } \Gamma = 1 \\ -\left((p^2 - p_i^2)\cosh[2E_p(t - N_t/2)] + (E_p^2 - p^2 + p_i^2)\right) & \text{for } \Gamma = \gamma_i\gamma_5 \end{cases}$$

where

E_p : single quark energy with relative mom. p

$$p^2 = \sum_i p_i^2$$

Physical interpretation

$$
\begin{aligned}
\rho_\Gamma(\omega) \;=\; & \Theta(\omega^2-4m_q^2)\frac{N_c}{8\pi\omega}\sqrt{\omega^2-4m_q^2}[1-2n_F(\omega/2)] \\
& \times[\omega^2(a_H^{(1)}-a_H^{(2)})+4m^2(a_H^{(2)}-a_H^{(3)})] \\
& +2\pi\omega\delta(\omega)N_c[(a_H^{(1)}+a_H^{(2)})I_1+(a_H^{(2)}-a_H^{(3)})I_2]
\end{aligned}
$$

F. Karsch et al., PRD68, 014504 (2003).
G. Aarts et al., NPB726, 93 (2005).

constant contribution remains
in the continuum form & infinite volume

The constant term is related to some transport coefficients.

From Kubo–formula, for example, a derivative of the SPF
in the V channel is related to the electrical conductivity σ.

$$\sigma = \frac{1}{6}\frac{\partial}{\partial\omega}\rho_V(\omega)\Big|_{\omega=0}$$

Without constant mode

How much does SPF change at the region $\omega \gg T$

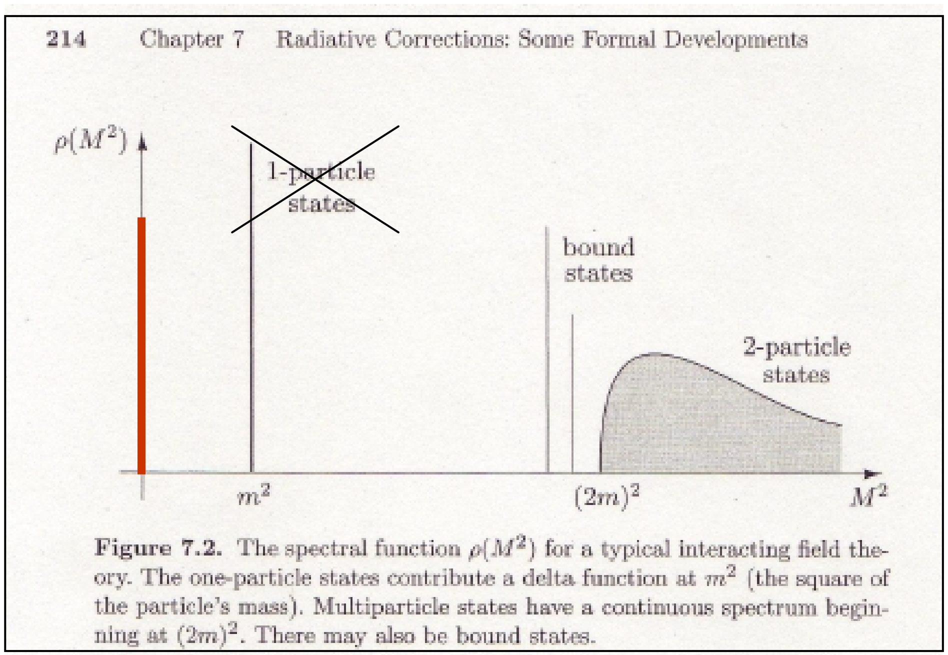

214 Chapter 7 Radiative Corrections: Some Formal Developments

Figure 7.2. The spectral function $\rho(M^2)$ for a typical interacting field theory. The one-particle states contribute a delta function at m^2 (the square of the particle's mass). Multiparticle states have a continuous spectrum beginning at $(2m)^2$. There may also be bound states.

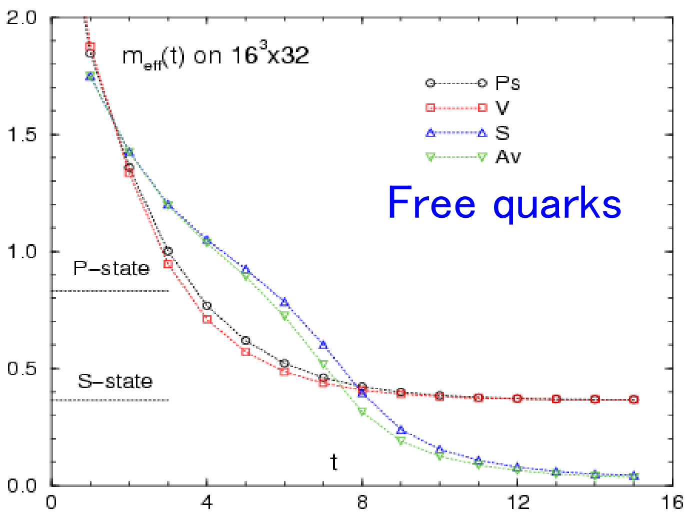
from "An Introduction to Quantum Field Theory"
Michael E. Peskin, Perseus books (1995)

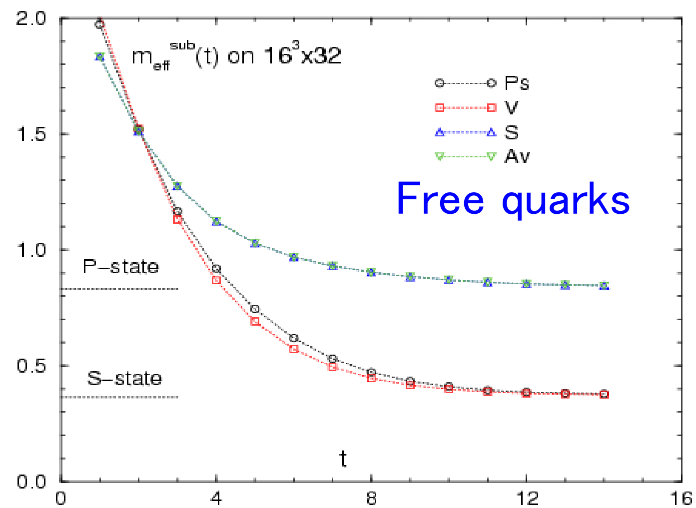
Midpoint subtraction

An analysis to avoid the constant mode

Midpoint subtracted correlator

$$\bar{C}(t) = C(t) - C(N_t/2) \quad \Rightarrow \quad \frac{\bar{C}(t)}{\bar{C}(t+1)} = \frac{\sinh^2\left[\frac{1}{2}m_{eff}^{sub}(t)(N_t/2-t)\right]}{\sinh^2\left[\frac{1}{2}m_{eff}^{sub}(t)(N_t/2-t-1)\right]}$$

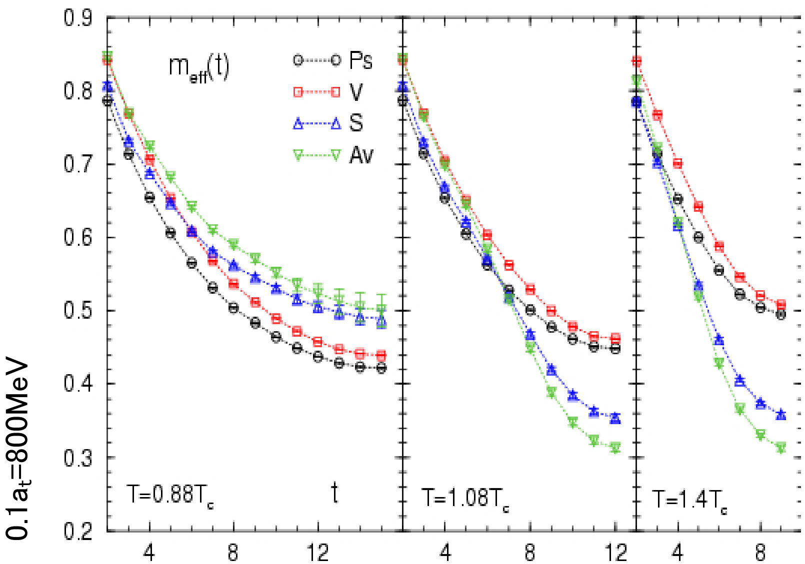




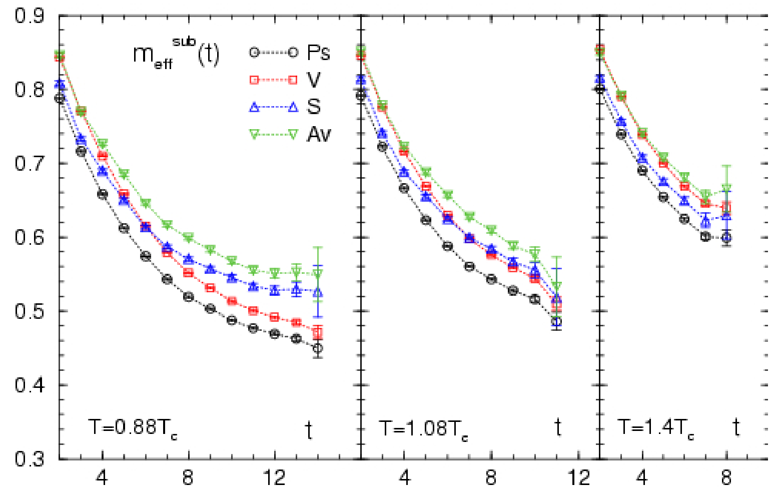
Midpoint subtraction analysis

$$\bar{C}(t) = C(t) - C(N_t/2) \qquad \frac{\bar{C}(t)}{\bar{C}(t+1)} = \frac{\sinh^2\left[\frac{1}{2}m_{eff}^{sub}(t)(N_t/2-t)\right]}{\sinh^2\left[\frac{1}{2}m_{eff}^{sub}(t)(N_t/2-t-1)\right]}$$

usual effective masses at T>0



subtracted effective mass

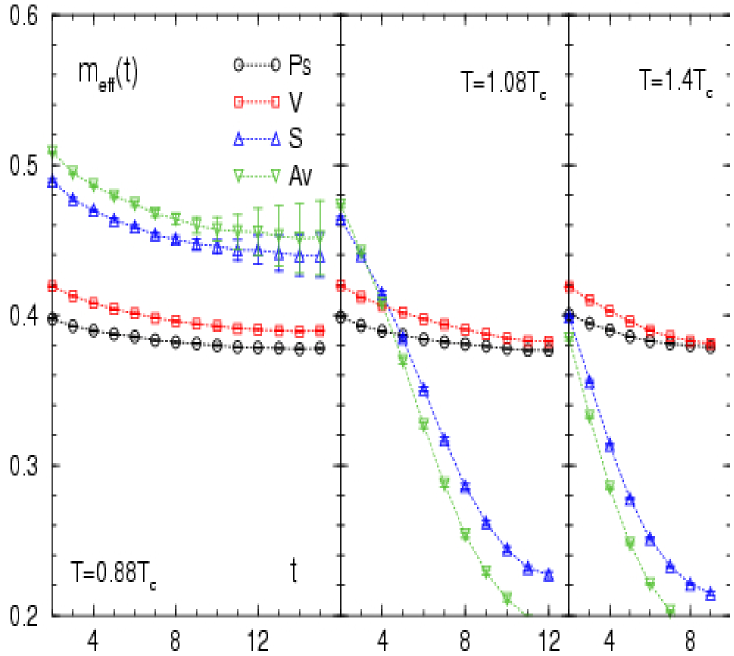


the drastic change in P-wave states disappears in $m_{eff}^{sub}(t)$

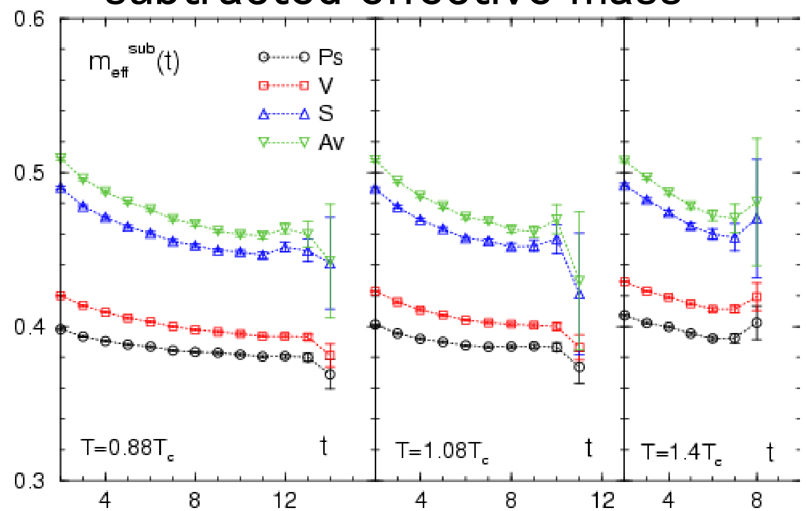
→ the change is due to the constant mode

Results with extended op.

usual effective mass



subtracted effective mass



Spatially extended operators:

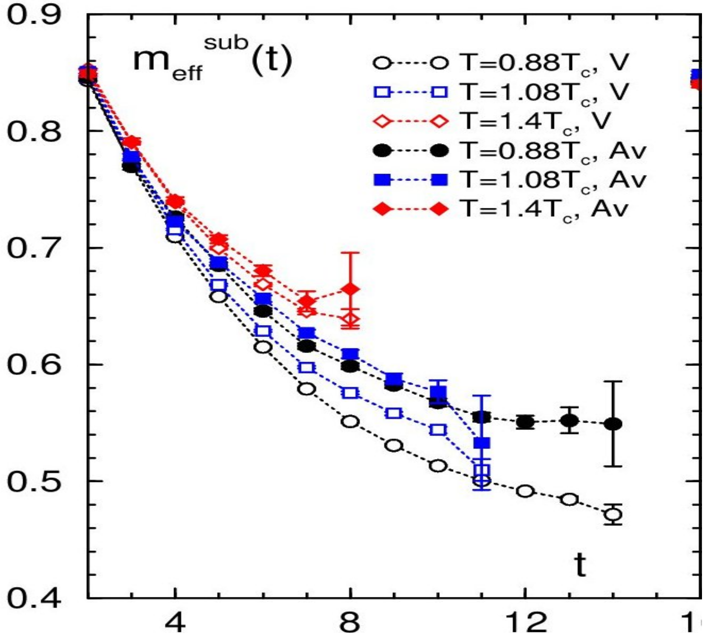
$$O_\Gamma(\vec{x},t) = \sum_{\vec{y}} \phi(\vec{y})\bar{q}(\vec{x}-\vec{y},t)\Gamma q(\vec{x},t)$$

with a smearing func. ϕ(x)
in Coulomb gauge

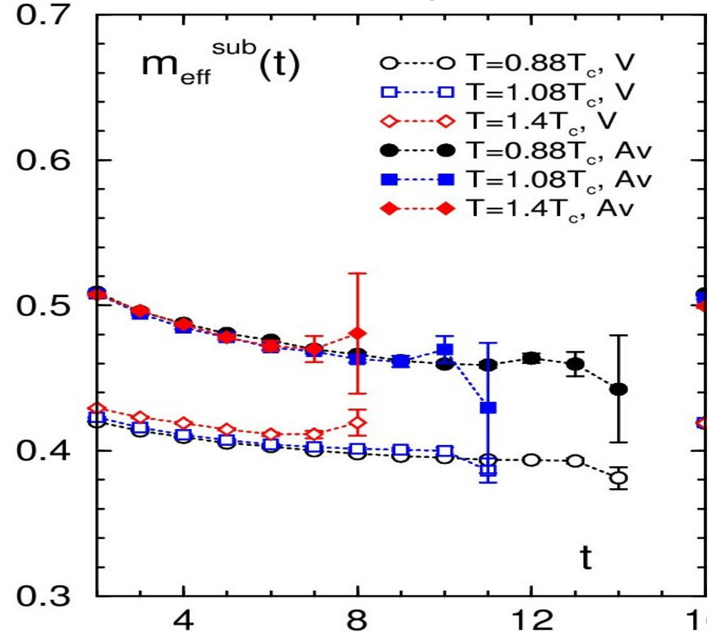
- extended op. enhances overlap
- small constant effect in V channel
- no large change above T_c in $m_{eff}^{sub}(t)$

Discussion

point operators



extended operators



The drastic change of P−wave states is due to the const. contribution.

→ There are small changes in SPFs (except for ω=0 peak).

Why several MEM studies show the dissociation of χ_c states ?

Conclusion

- There is the constant mode in charmonium correlators above T_c
- The drastic change in χ_c states is due to the constant mode

➔ the survival of χ_c states above T_c, at least $T=1.4T_c$.

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

In the MEM analysis,
one has to check consistency of the results at $\omega \gg T$
using, e.g., midpoint subtracted correlators.

$$\bar{C}(t) = C(t) - C(N_t/2)$$

$$\bar{C}(t) = \int_0^\infty d\omega \rho_\Gamma(\omega) K^{sub}(\omega,t),$$

$$K^{sub}(\omega,t) = \frac{\sinh^2(\frac{\omega}{2}(N_t/2-t))}{\sinh(\omega N_t/2)}$$