Charmonium dissociation temperatures in lattice QCD

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

The 5th Heavy Ion Cafe, Univ. of Tokyo, 30 June 2007

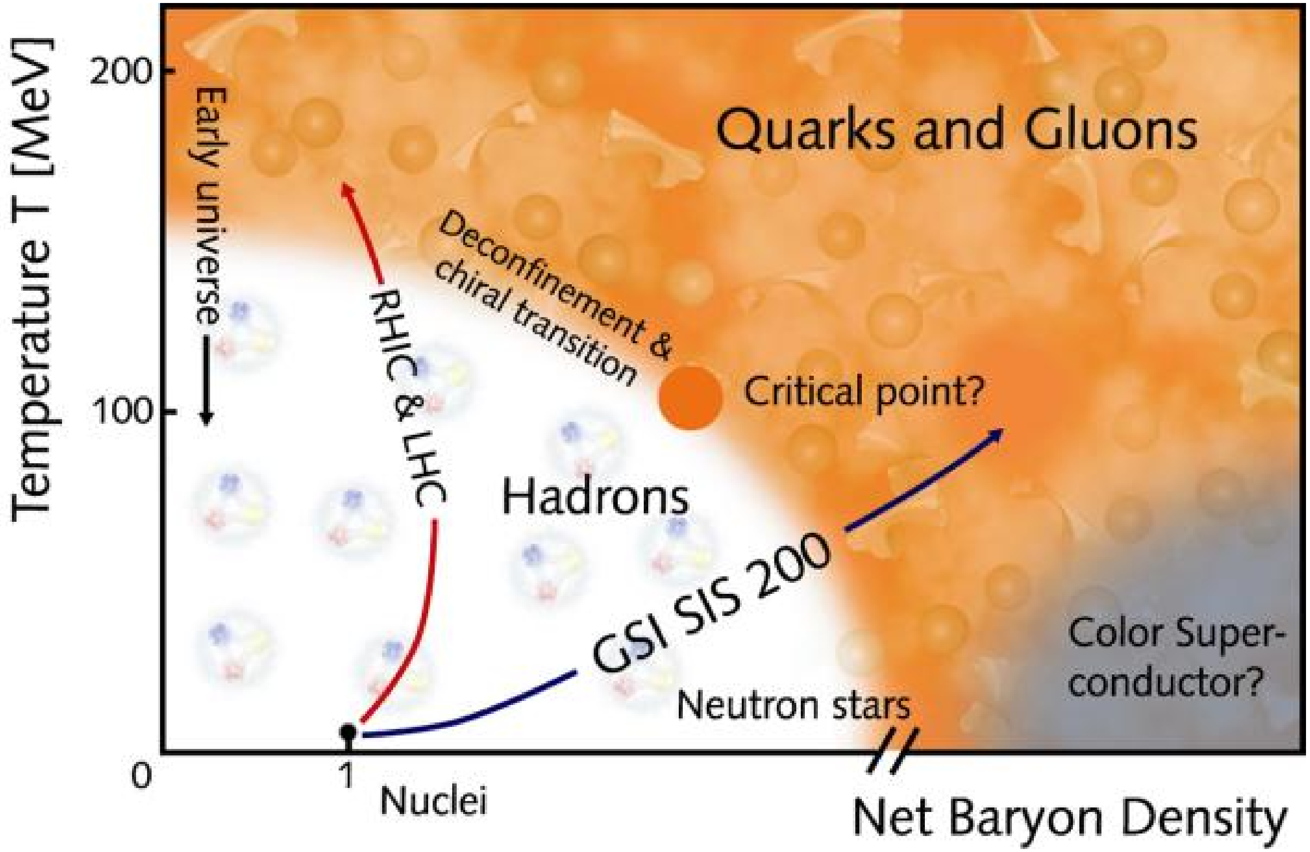
Contents

- Introduction
  - Overview
  - J/ψ suppression
  - Charmonium in Lattice QCD
  - Sequential J/ψ suppression
- Quenched QCD calculations
  - Lattice setup
  - T dependence of charmonium correlators
  - Constant mode in meson correlators
- Discussion & Conclusion

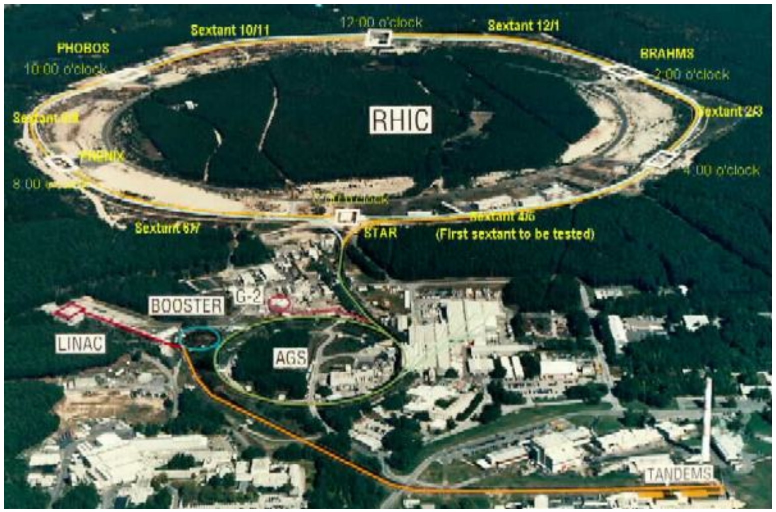
total 36 pages

Quark Gluon Plasma (QGP)

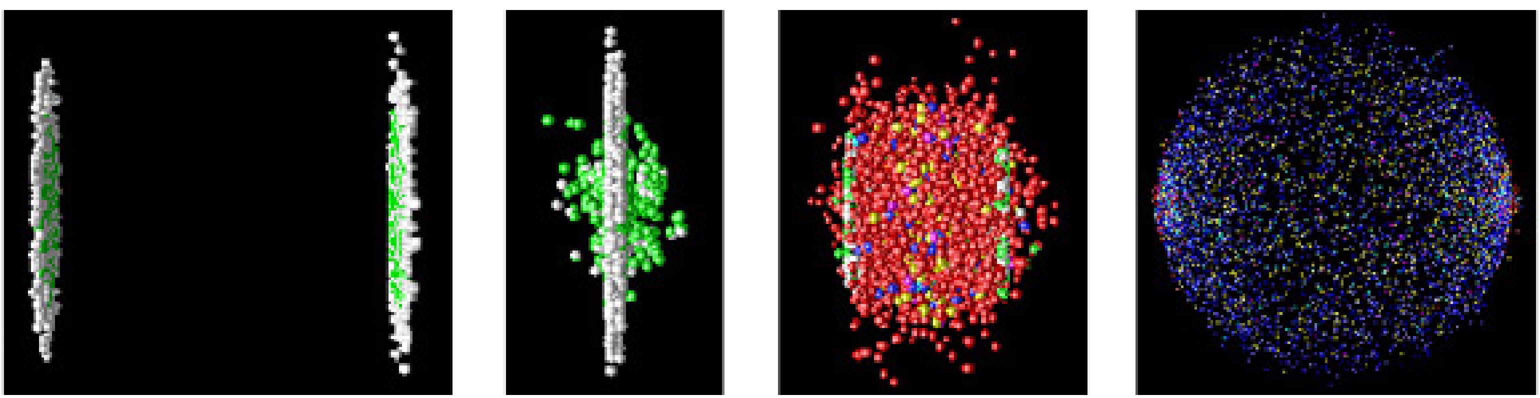
from Munster Univ. web-site



Experiments



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

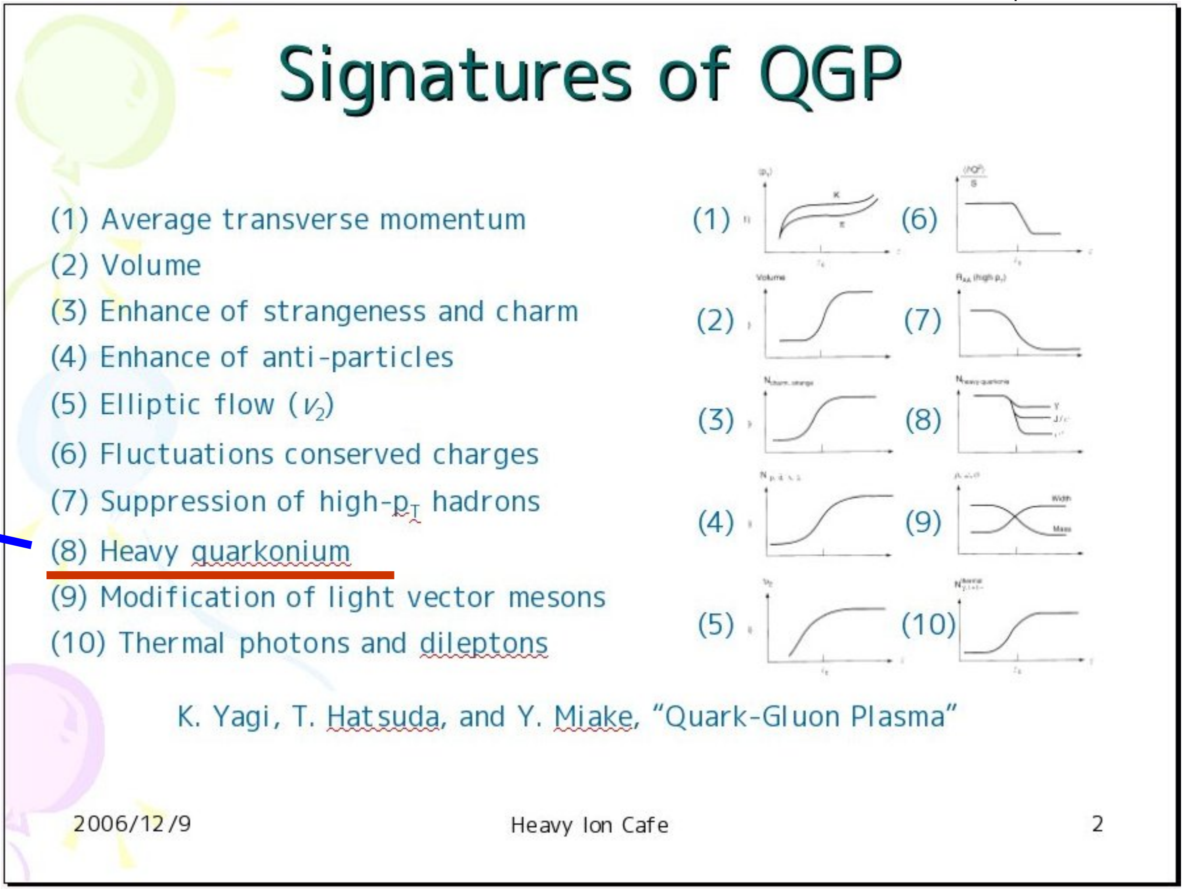


from the Phenix group web-site

Signatures of QGP

J/ψ suppression

T.Hashimoto et al., PRL57 (1986) 2123.
T.Matsui & H.Satz, PLB178 (1986) 416.



Talk by Ozawa @ Heavy Ion Cafe

J/ψ suppression in Exp.

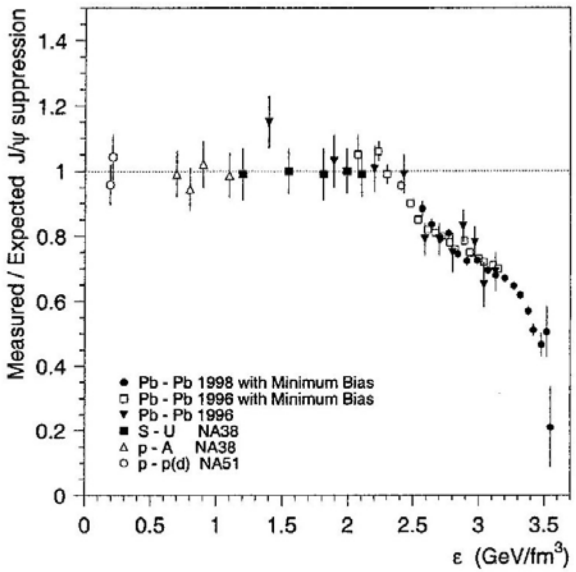


Fig. 7. Measured J/ψ production yields, normalised to the yields expected assuming that the only source of suppression is the ordinary absorption by the nuclear medium. The data is shown as a function of the energy density reached in the several collision systems.

Phys.Lett.B477(2000)28
NA50 Collaboration

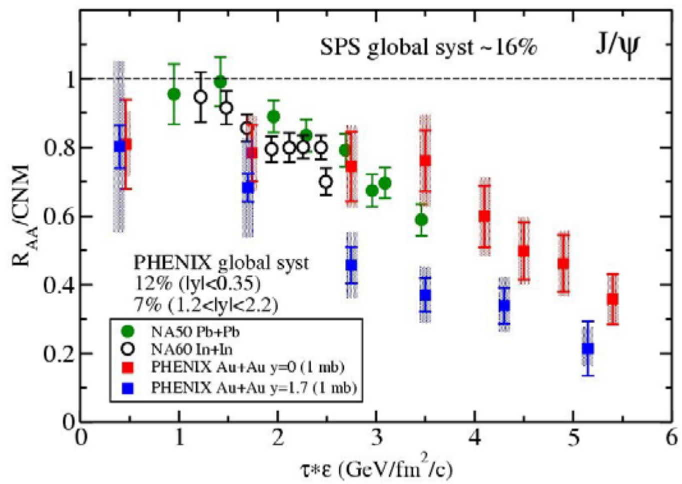


Figure 10: Survival fraction (R_{AA}/CNM) vs energy density comparison of PHENIX Au+Au suppression to that from NA38/50 at CERN.

QM2006
PHENIX Collaboration

"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) :

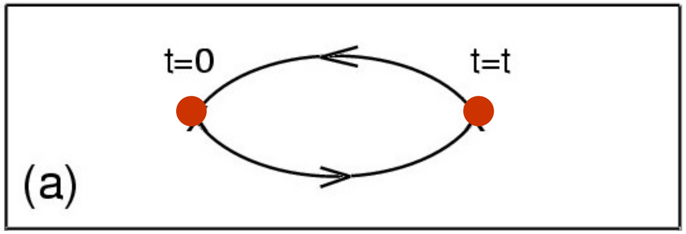
(1) gauge coupling → lattice spacing (a) → continuum limit
(2) quark masses
(3) (Imaginary) time extent → Temperature (T=1/Nta)

Charmonium correlation function

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

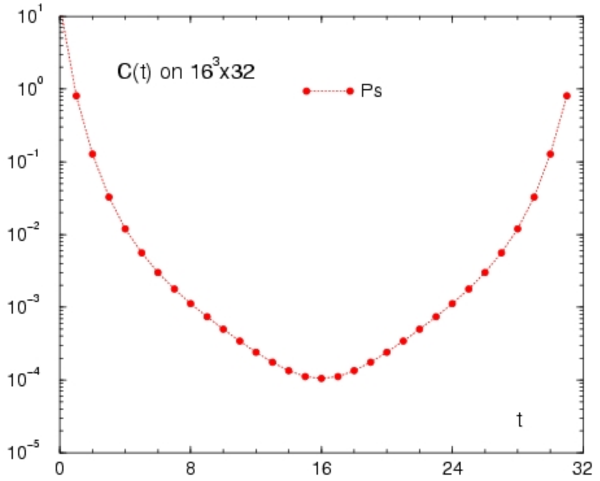
Correlation function

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



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

Charmonium spectral function

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

214 Chapter 7 Radiative Corrections: Some Formal Developments

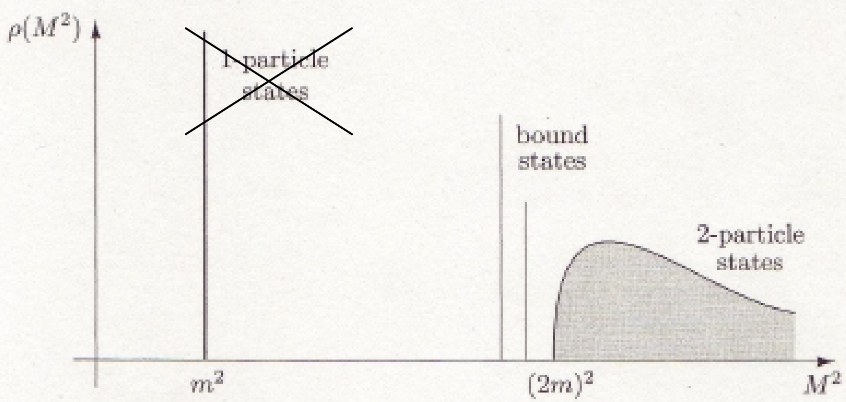
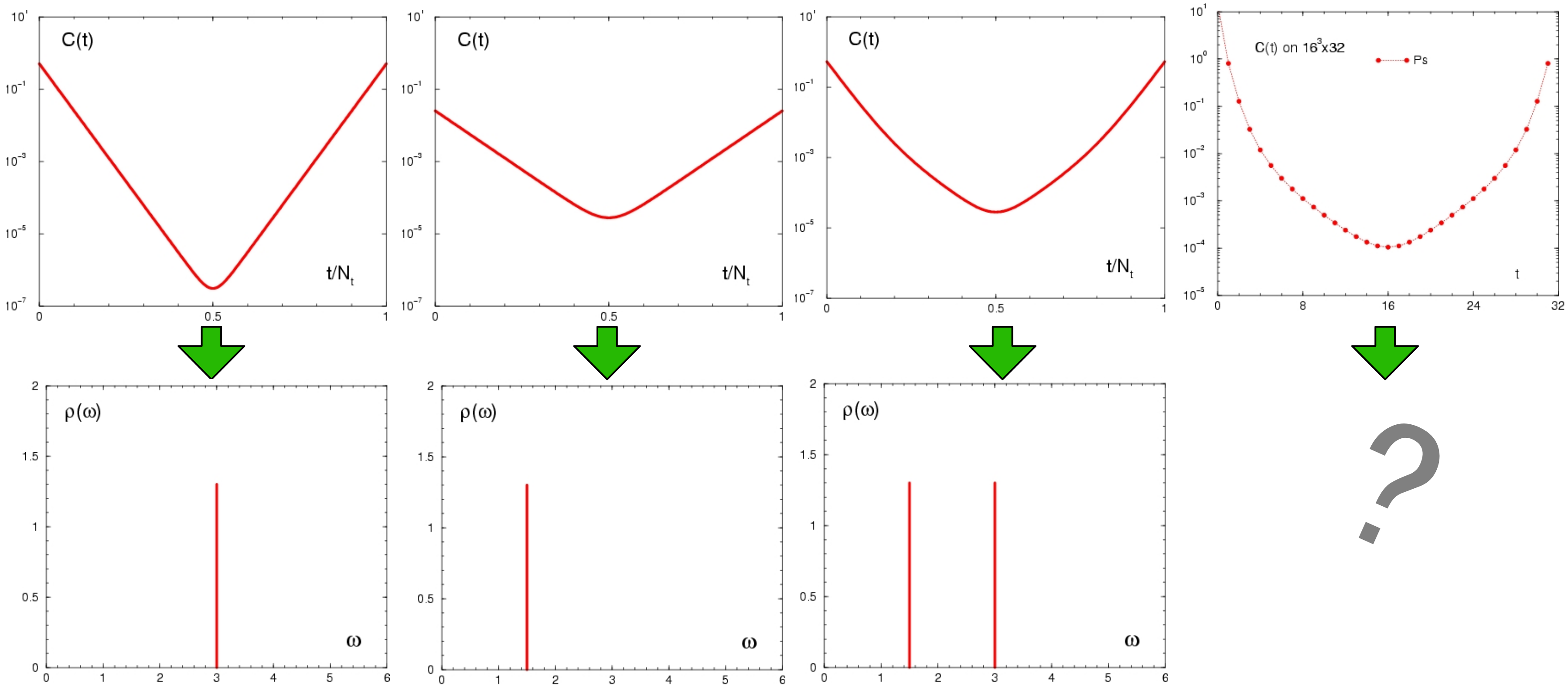


Figure 7.2. The spectral function $\rho(M^2)$ for a typical interacting field theory. The one-particle states contribute a delta function at m^2 (the square of the particle's mass). Multiparticle states have a continuous spectrum beginning at $(2m)^2$. There may also be bound states.

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

Example of lattice results

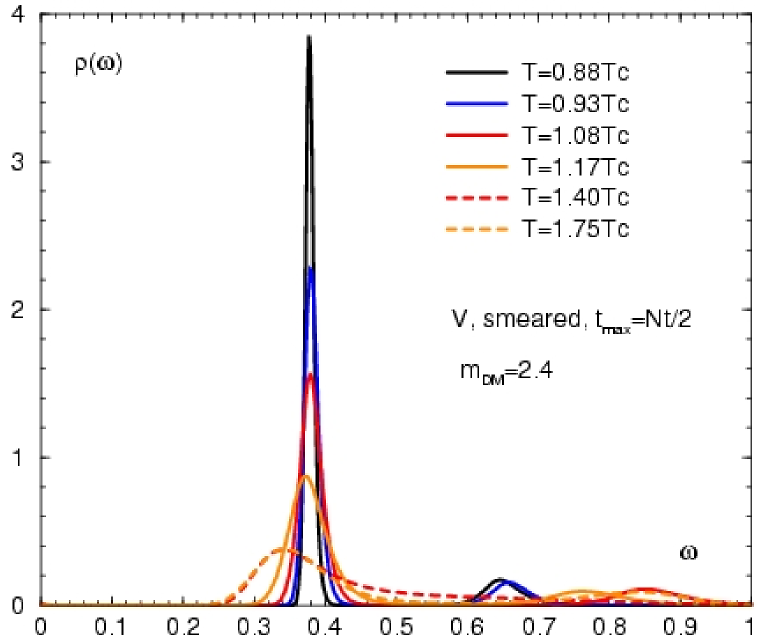
$$
\begin{aligned}
C(t) &= \langle O(t) O^\dagger(0) \rangle \\
&= \int d\omega \rho(\omega) \frac{e^{-\omega t} + e^{-\omega(N_t - t)}}{1 - e^{-\omega N_t}}
\end{aligned}
$$



Charmonium spectral function

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

Maximum entropy method
C(t) → ρ(ω)



Quenched QCD

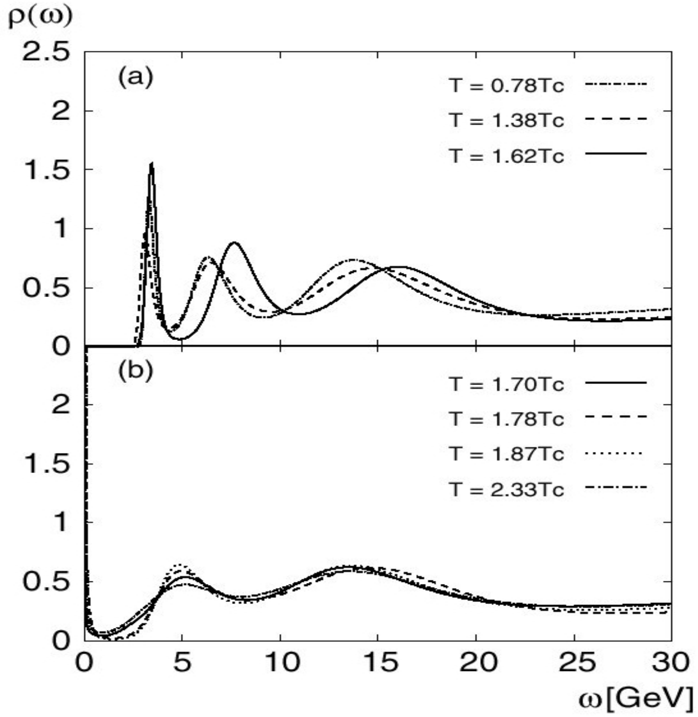
- *T. Umeda et al., EPJC39S1, 9, (2005).*
- *S. Datta et al., PRD69, 094507, (2004).*
- *T. Hatsuda & M. Asakawa, PRL92, 012001, (2004).*
- *A. Jakovac et al., PRD75, 014506 (2007).*

Full QCD

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

Charmonium spectral function

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



Maximum entropy method
C(t) → ρ(ω)

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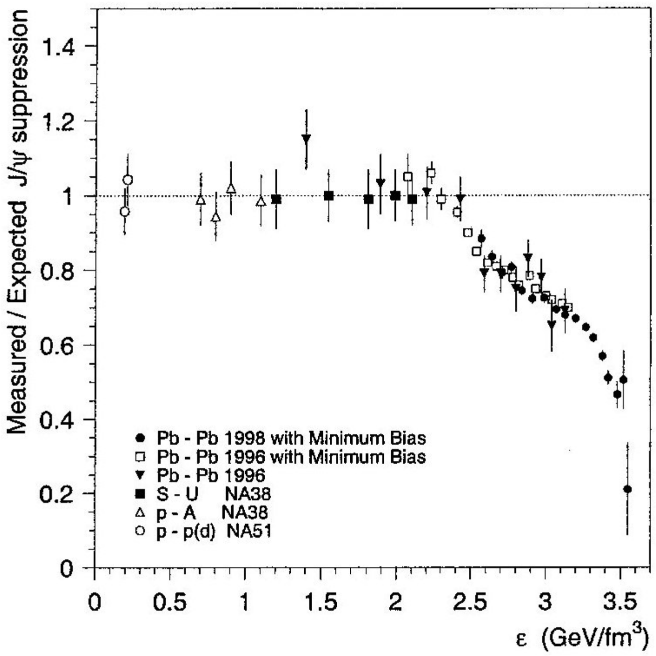
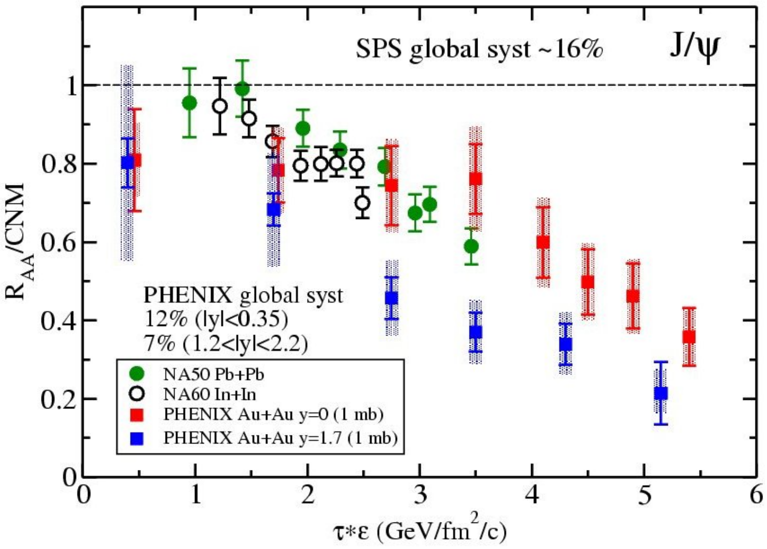
All studies indicate survival of J/ψ state above T_c (1.5T_c?)

J/ψ suppression in Exp. (?)





Energy density 0.5–1.5GeV/fm^3 = 1.0Tc

10 GeV/fm^3 = 1.5Tc

30 GeV/fm^3 = 2.0Tc

Sequential J/ψ suppression

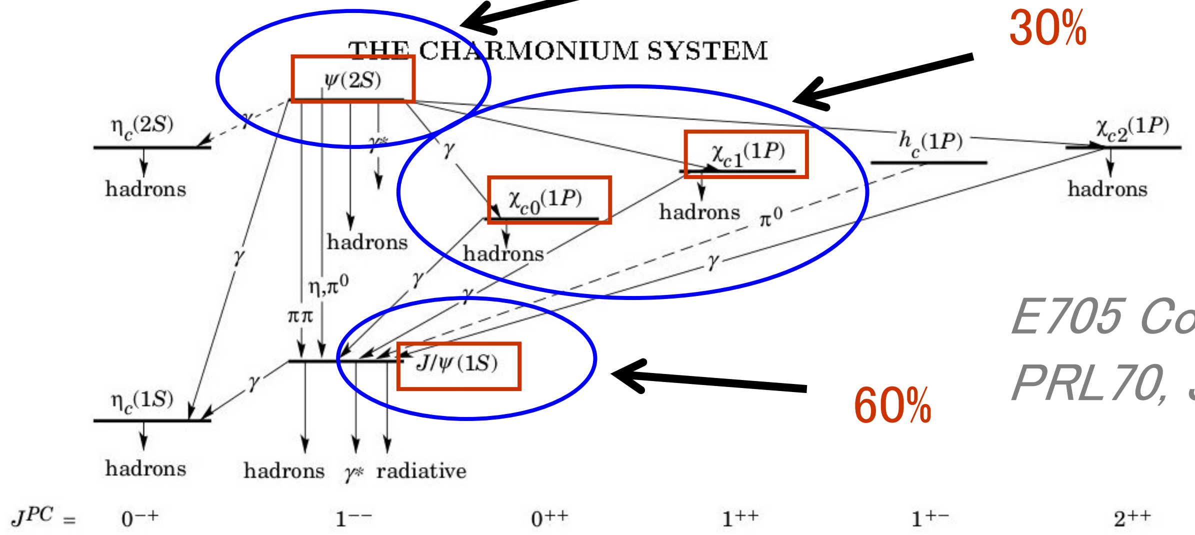
Particle Data Group (2006)

$c\bar{c}$ MESONS

10% for the total yield of J/ψ

30%

60%



E705 Collaboration, PRL70, 383, (1993).

Ps V S Av

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

χ_c states on the lattice

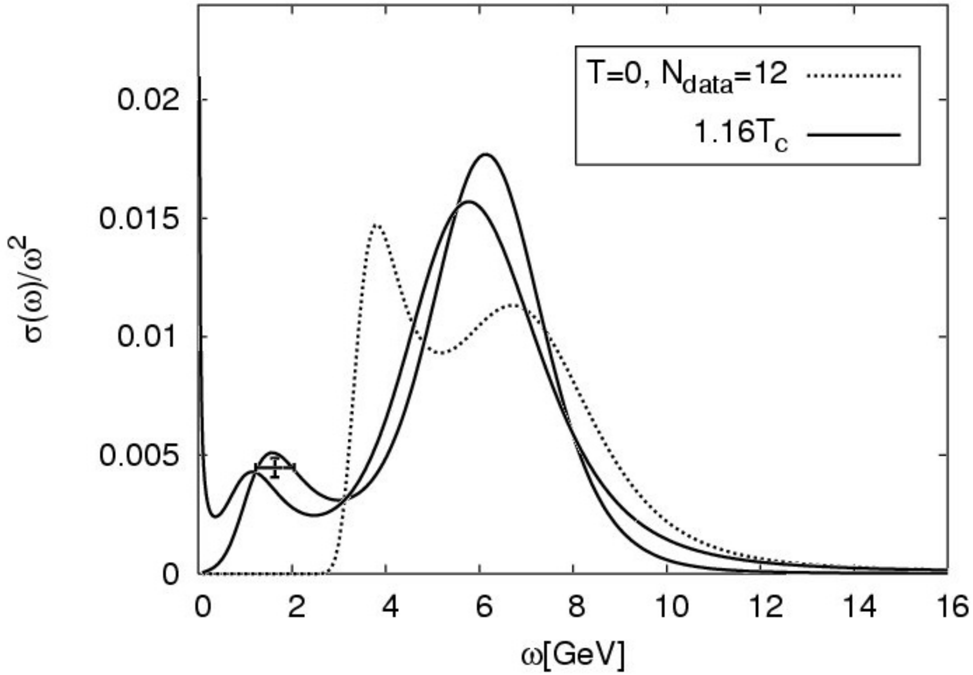


FIG. 19: The scalar spectral function for $\beta = 6.1$ at $T = 1.16T_c$ and at zero temperature reconstructed using $N_{data} = 12$. At finite temperature two default models $m(\omega) = 0.01$ and $m(\omega) = 0.038\omega^2$ have been used.

S. Datta et al., PRD69, 094507 (2004).
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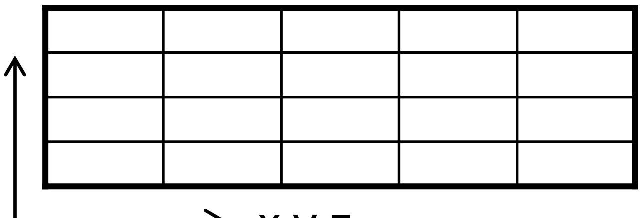
Lattice QCD results

Lattice setup

- Quenched approximation (no dynamical quark effect)
- Anisotropic lattices
  - lattice size : $20^3 \times N_t$
  - 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_T	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

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

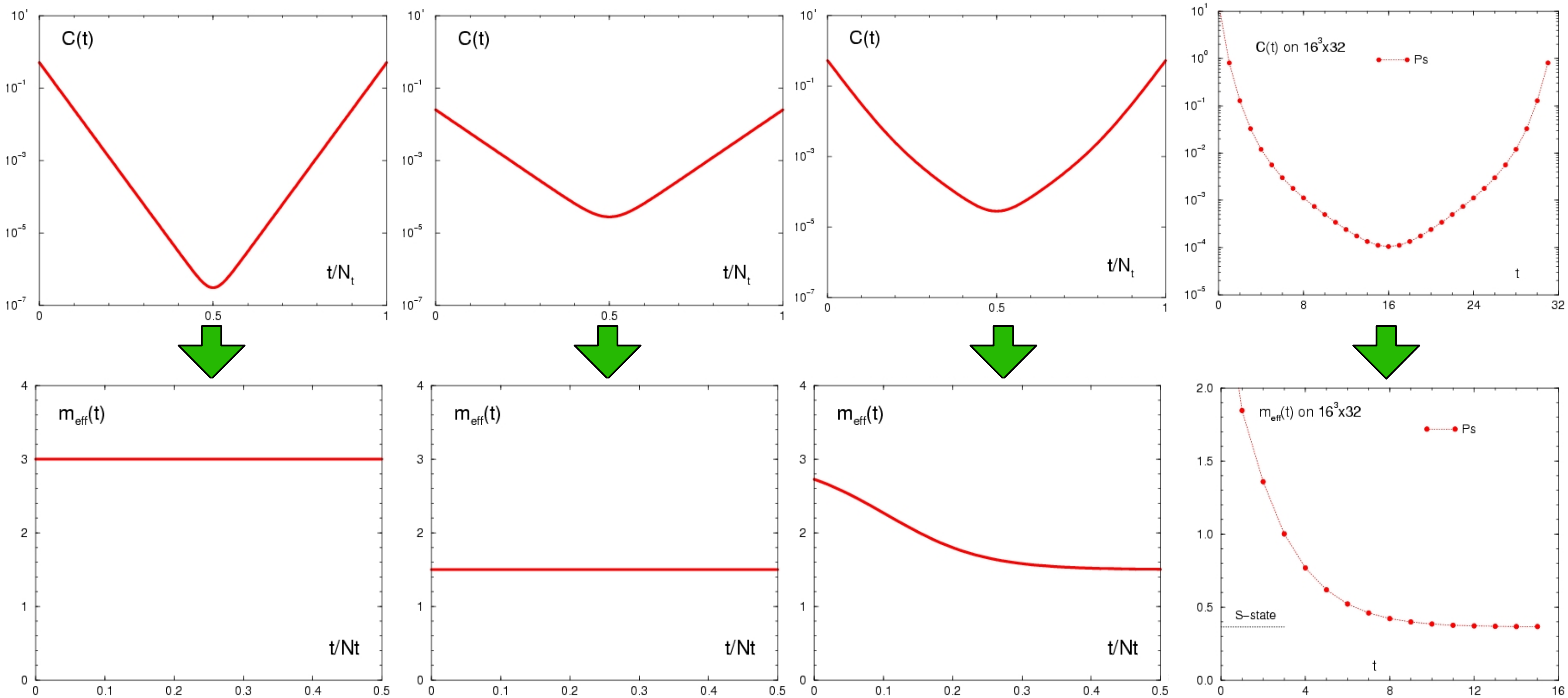
$$\frac{C(t)}{C(t+1)} = e^{-m_{eff}(t)}$$

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

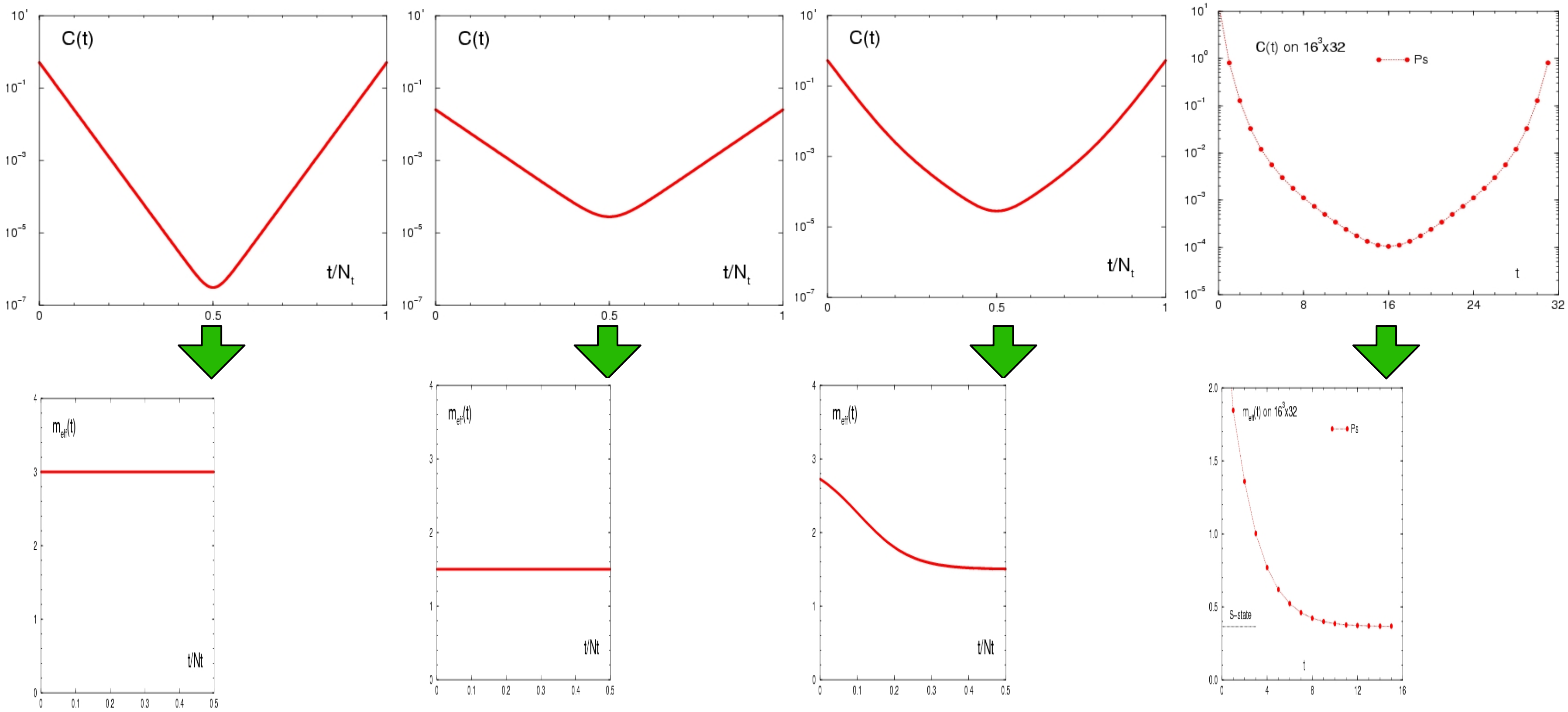
In the (anti) periodic b.c.

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

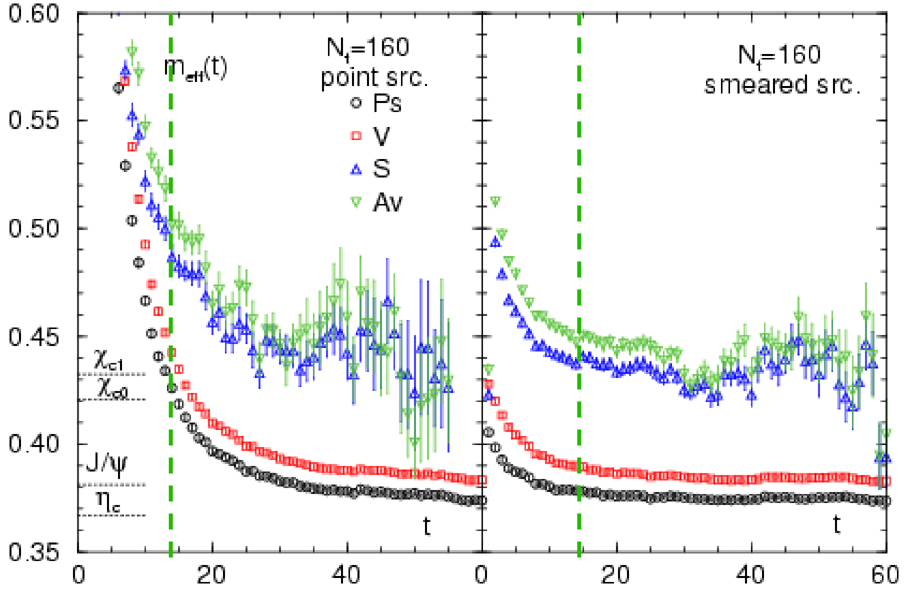
Effective mass (local mass)



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

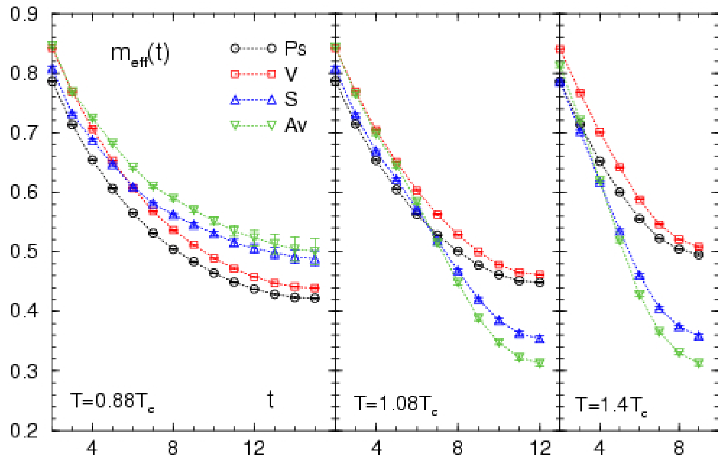
$M_{J/\psi}$ = 3097 MeV

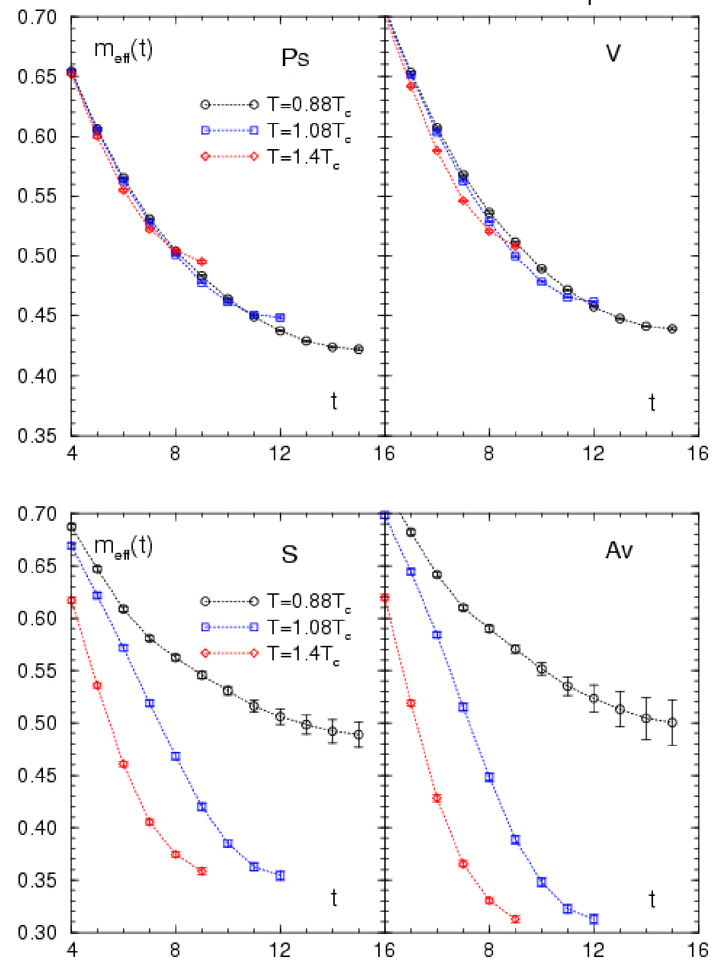
$M_{\chi c0}$ = 3415 MeV

$M_{\chi c1}$ = 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

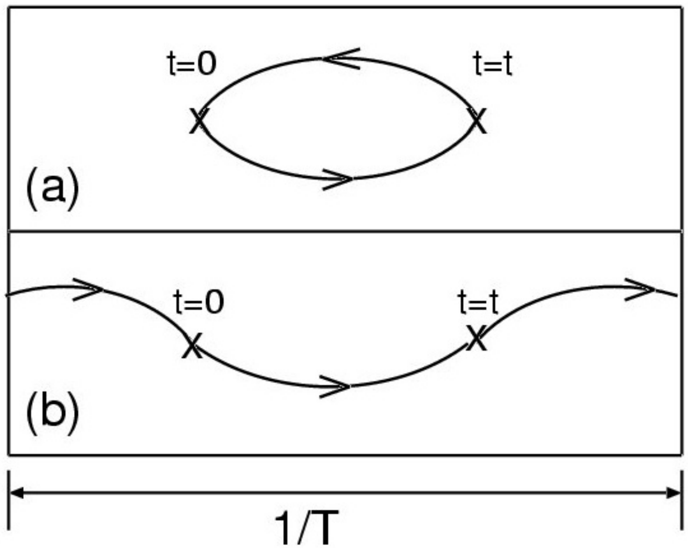




- small change in S-wave states
  - → survival of J/ψ & η_c at $T>T_c$
- drastic change in P-wave states
  - → dissociation of χ_c just above Tc (?)

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

Constant mode



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

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

m_q is quark mass
or single quark energy

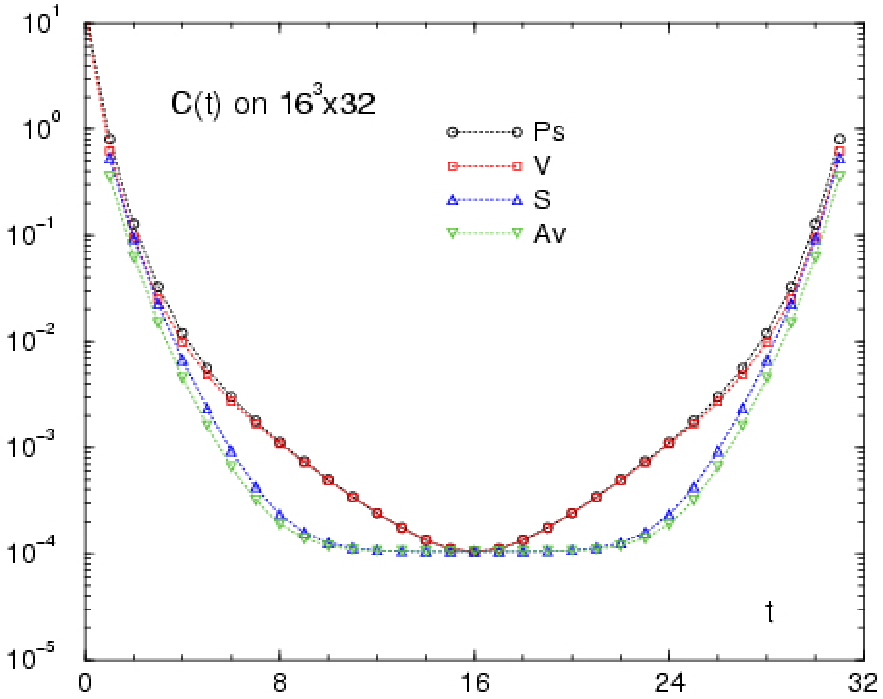
$\exp(-m_q t) \times \exp(-m_q(L_t - t))$
$= \exp(-m_q L_t)$

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

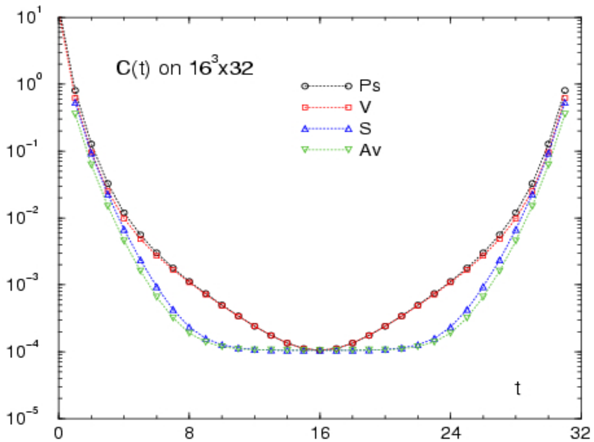
Free quark calculations

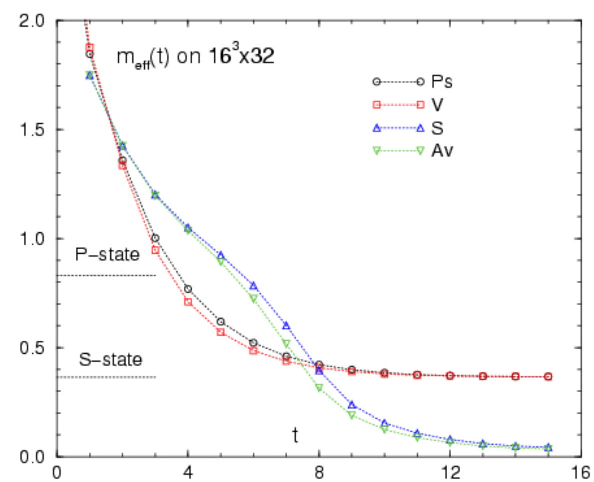


- 16^3 x 32 isotropic lattice
- Wilson quark action
  with $m_q a = 0.2$

Obvious constant contribution
in P-wave states

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

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

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 $\omega \gg T$

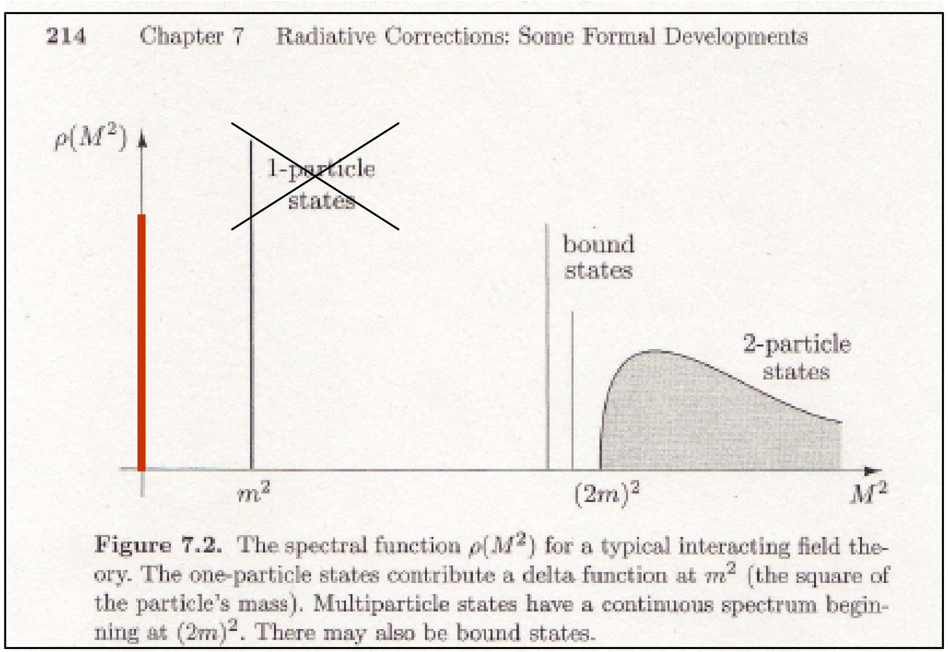


Figure 7.2. The spectral function $\rho(M^2)$ for a typical interacting field theory. The one-particle states contribute a delta function at m^2 (the square of the particle's mass). Multiparticle states have a continuous spectrum beginning at $(2m)^2$. There may also be bound states.

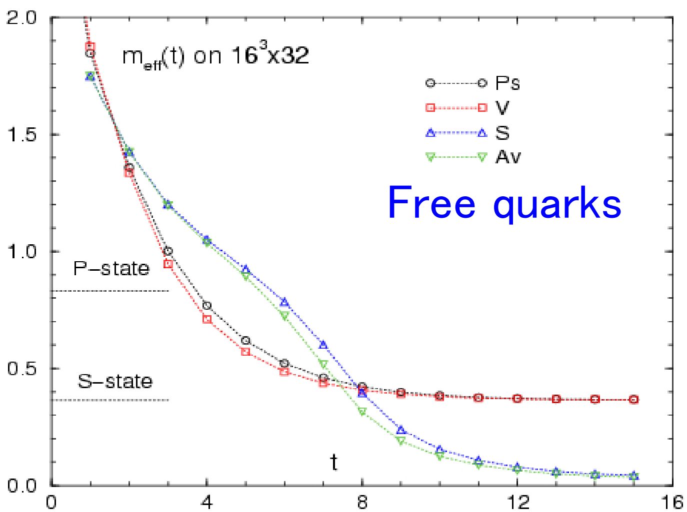
from "An Introduction to Quantum Field Theory"
Michael E. Peskin, Perseus books (1995)

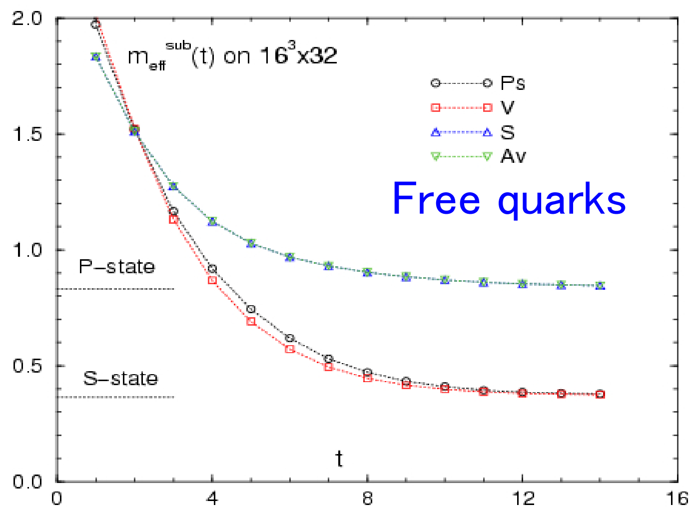
Midpoint subtraction

An analysis to avoid the constant mode

Midpoint subtracted correlator

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

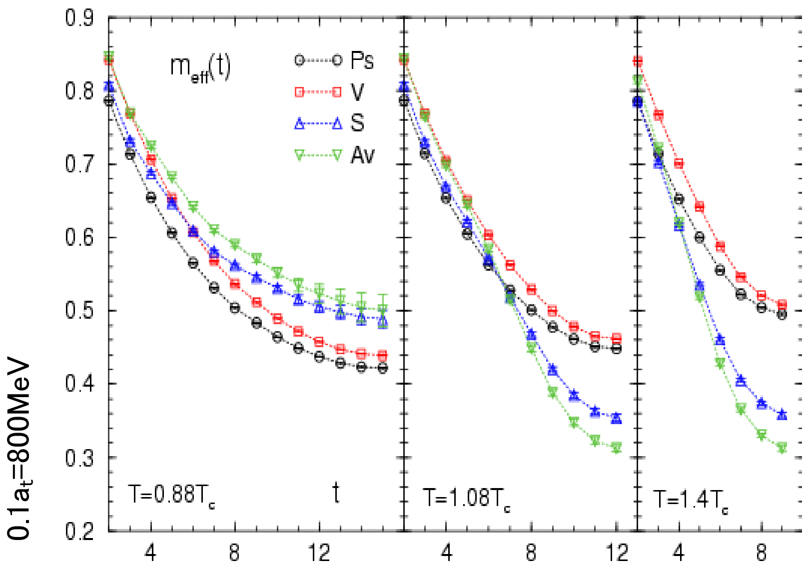




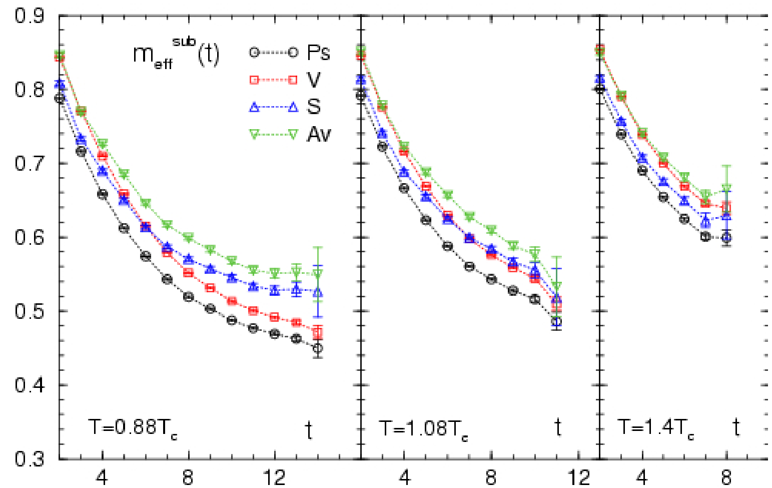
Midpoint subtraction analysis

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

usual effective masses at T>0



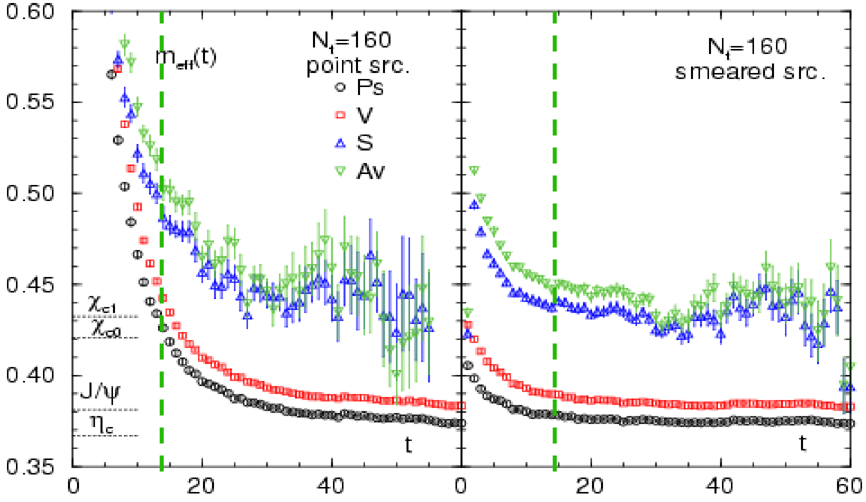
subtracted effective mass



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.

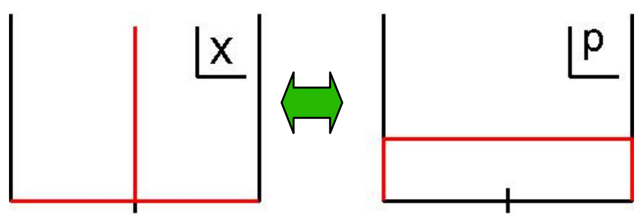


Spatially extended operators:

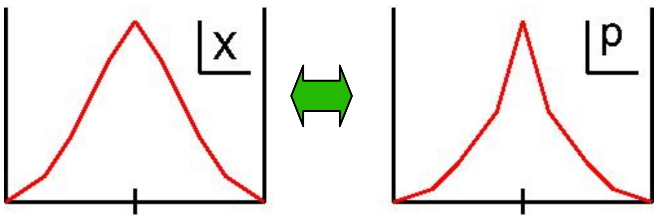
$$O_\Gamma(\vec{x},t) = \sum_{\vec{y}} \phi(\vec{y})\bar{q}(\vec{x}-\vec{y},t)\Gamma q(\vec{x},t)$$

with a smearing func. $\phi(x)$
in Coulomb gauge

point source func.



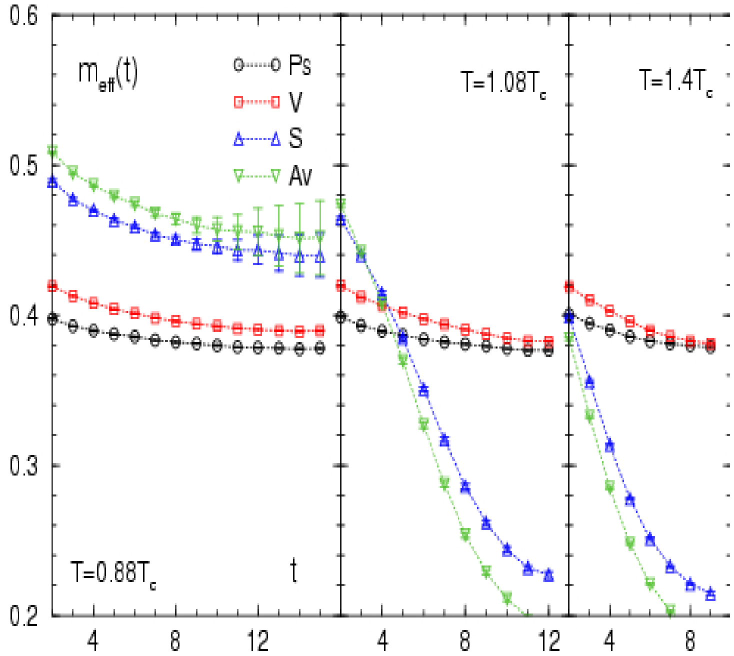
smeared source func.



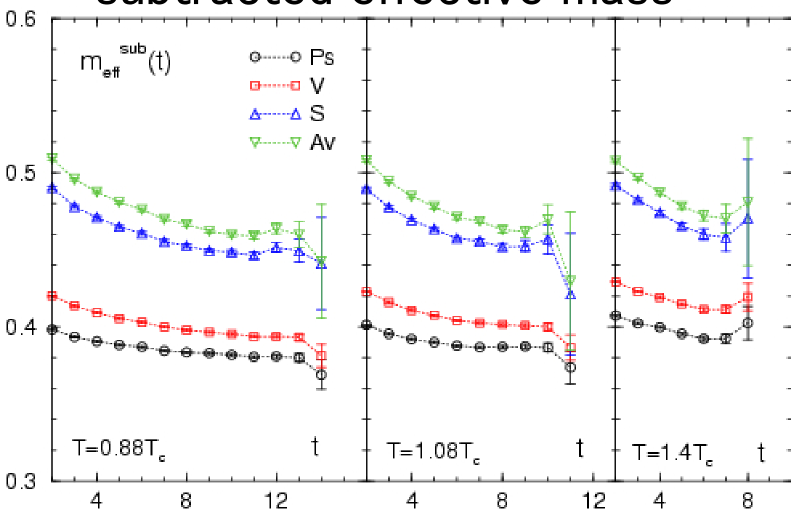
The extended op. yields large overlap with lowest states

Results with extended op.

usual effective mass



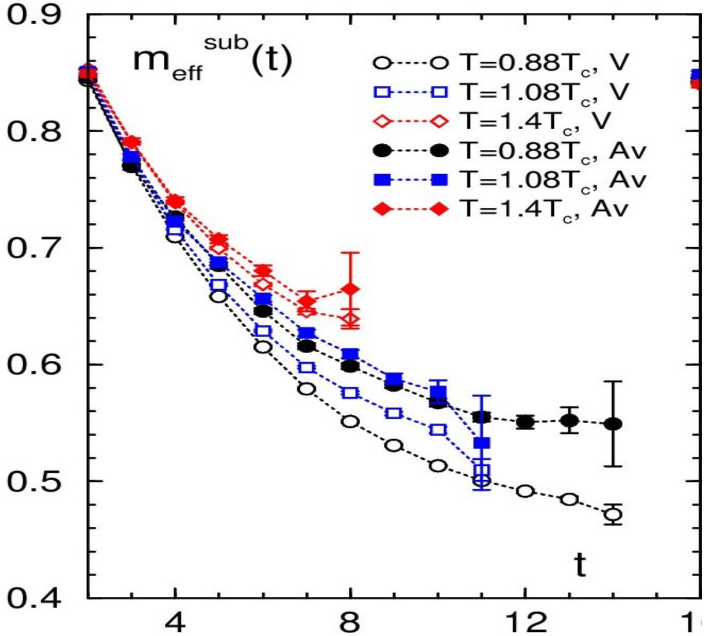
subtracted effective mass



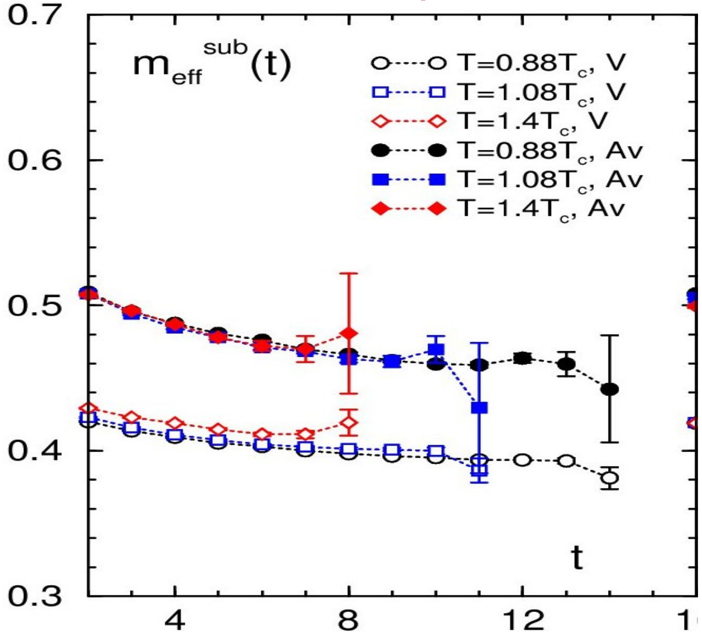
- extended op. enhances overlap with const. mode
- small constant effect is visible in V channel
- no large change above T_c in $m_{eff}^{sub}(t)$

Discussion

point operators



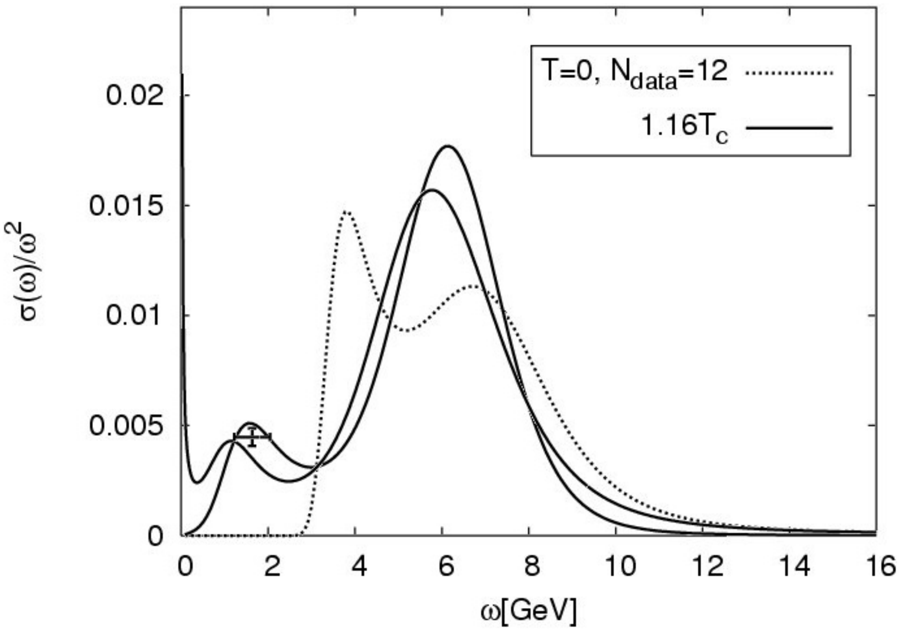
extended operators



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 ?

Discussion



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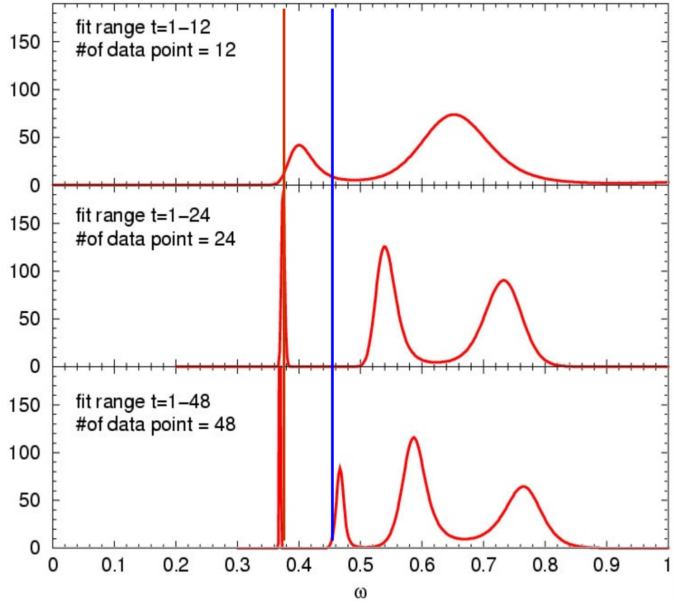
A.Jakovac et al., hep-lat/0611017.

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.

Difficulties in MEM analysis

MEM test using T=0 data



data for T/T_c=1.2

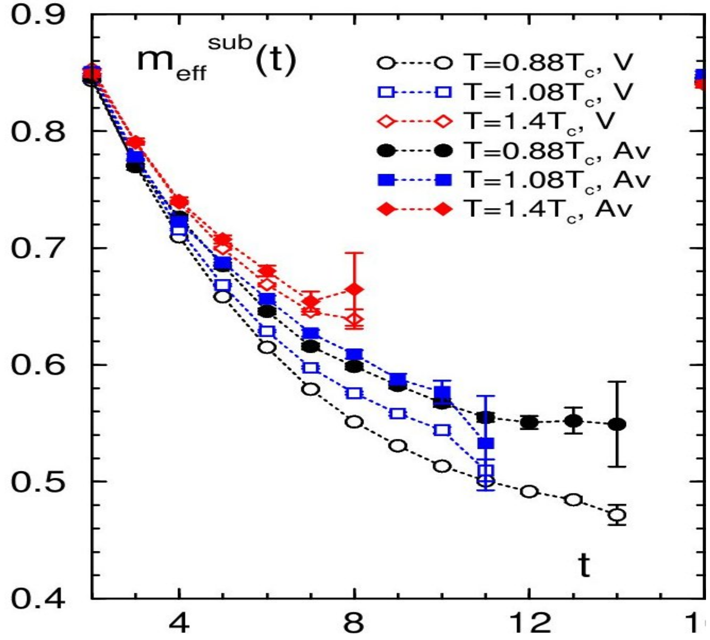
data for T/T_c=0.6

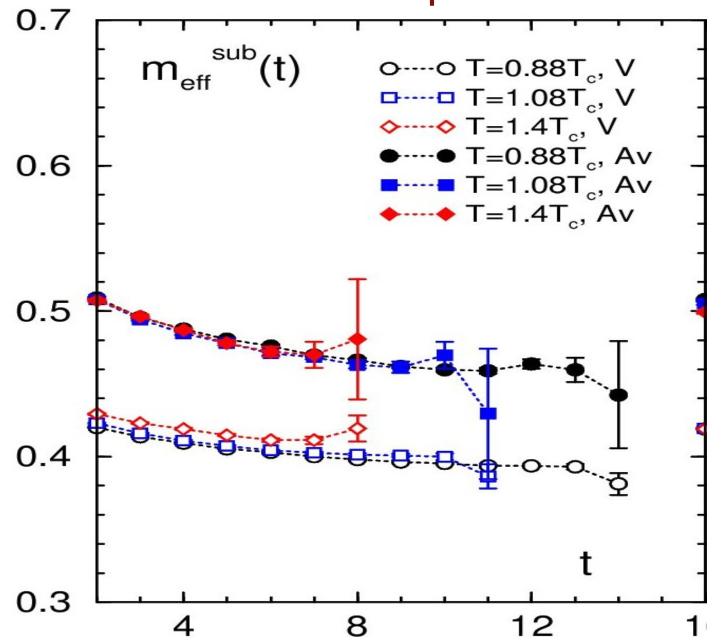
data for T/T_c=0

MEM analysis sometimes fails if data quality is not sufficient

Furthermore P−wave states have larger noise than that of S−wave states

Discussion





The drastic change of P-wave states is due to the constant mode.

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

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.

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

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

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

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

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(Received 27 May 1986)

photo : Prof. Osamu Miyamura

VOLUME 57, NUMBER 17 PHYSICAL REVIEW LETTERS 27 OCTOBER 1986

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-

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[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**

Discussion

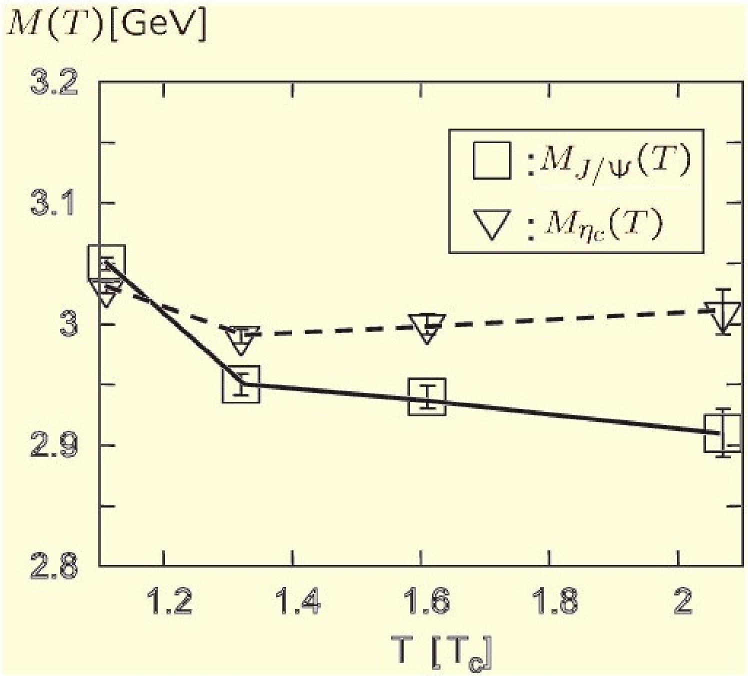


FIG. 8. Temperature dependence of the pole mass (on PBC) of J/Ψ and η_c for $(1.11\text{–}2.07)T_c$. The squares denote $M_{J/\Psi}(T)$ and the inverse triangles denote $M_{\eta_c}(T)$. There occurs the level inversion of J/Ψ and η_c above $1.3T_c$.

H. Iida et al., PRD74, 074502 (2006).

Several groups have presented

- almost no change in Ps channel
- small but visible change in V channel

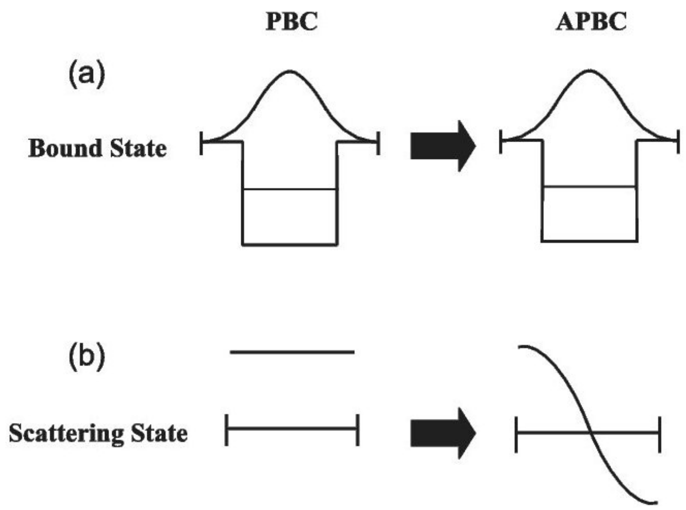
These results can be explained by the constant contribution.

- no constant in Ps channel
- small constant in V channel (proportional to p_i^2)

in free quark case

Discussion

H. Iida et al., PRD74, 074502 (2006).



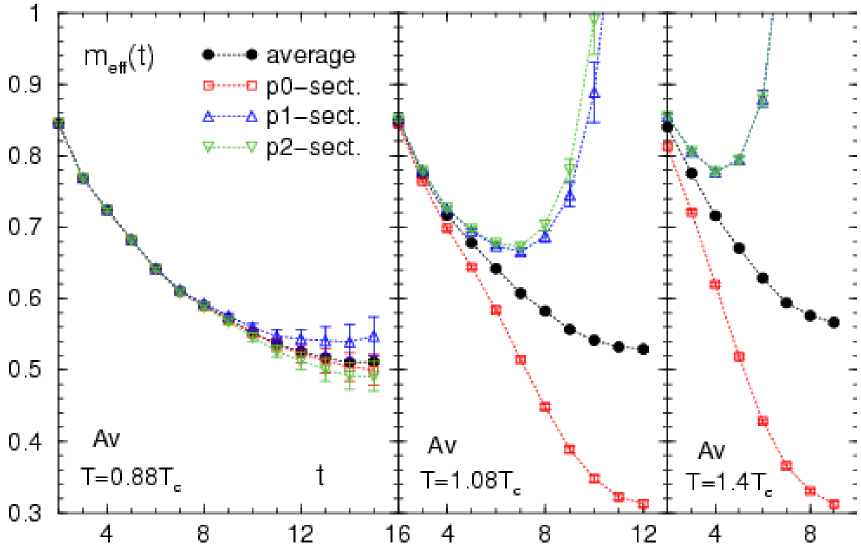
S−wave states : PBC p=(0, 0, 0) < xAPBC p=(π/L, 0, 0)

P−wave states : PBC p=(2π/L, 0, 0) > xAPBC p=(π/L, 0, 0)

P−const. : PBC p=(0, 0, 0) < xAPBC p=(π/L, 0, 0)

Discussion

Polyakov loop sector dependence



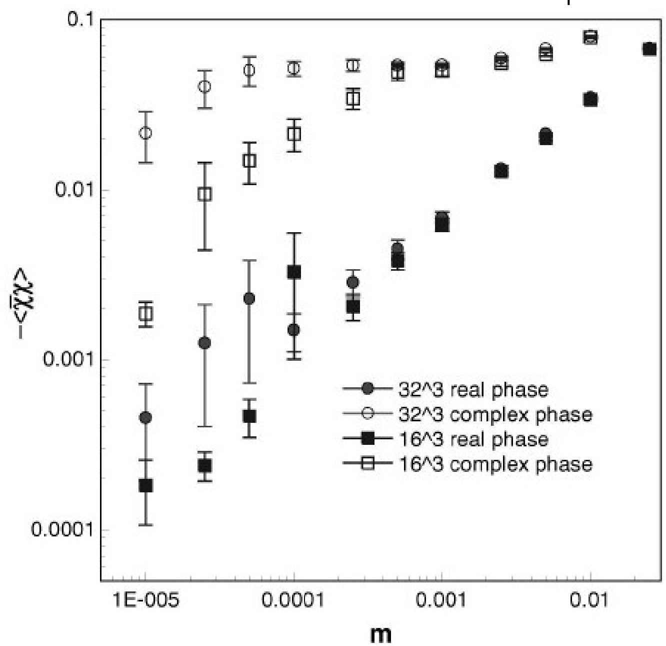


FIG. 1. The chiral condensate $\langle\bar{\chi}\chi\rangle$ plotted as a function of quark mass for a pure gauge calculation on $16^3 \times 4$ and $32^3 \times 4$ lattices. The real phase (closed points) is the most physical [$\det(D - m)$ is largest for this phase]. No evidence is seen for the expected anomalous behavior, $\langle\bar{\chi}\chi\rangle \sim m^{-1}$ as $m \to 0$.

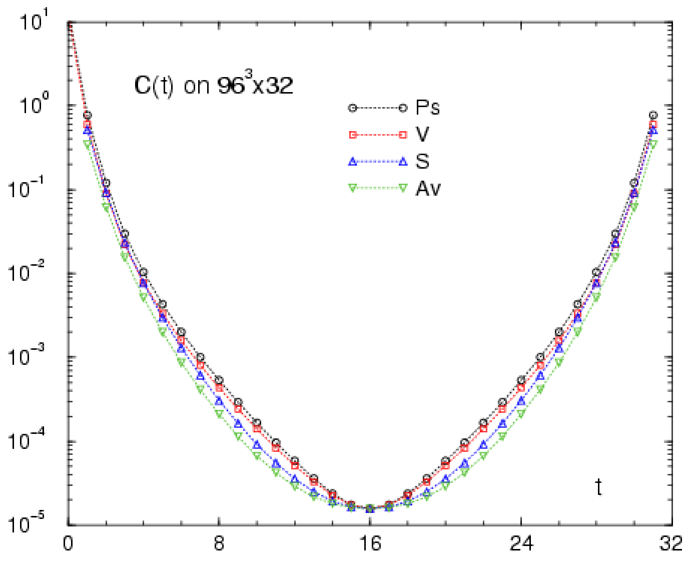
S. Chandrasekharan et al., PRL82, 2463, (1999).

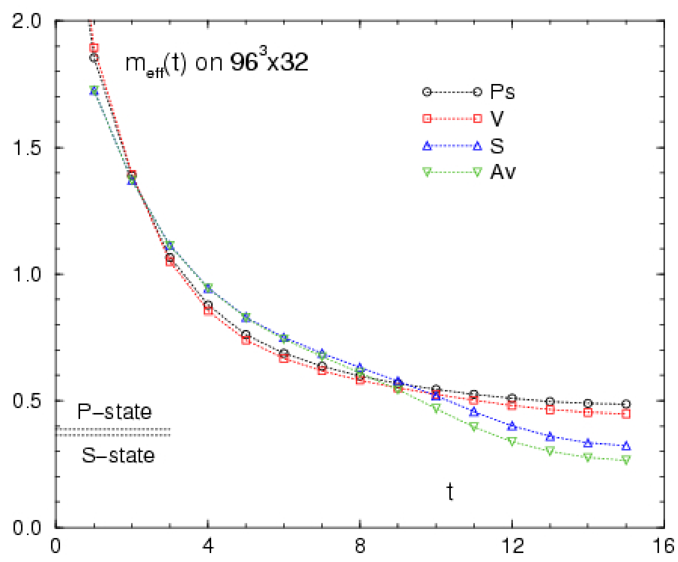
Volume dependence

Size of the constant contribution depends on the volume N_s^3

The dependence is negligible at $N_s/N_t \gtrsim 2$

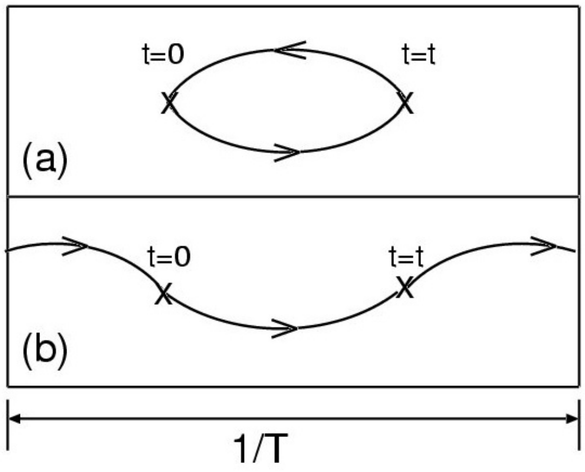
- Results on 96^3 x 32
  (N_s/N_t=3 ← similar to T>0 quench QCD calculation)





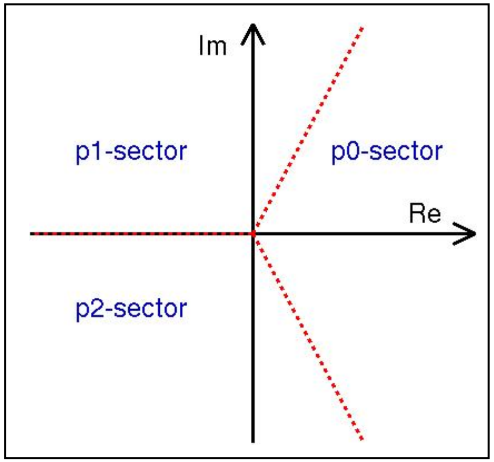
Z_3 symmetrization

Here we consider the Z_3 transformation



Z_3 symmetric

Z_3 asymmetric

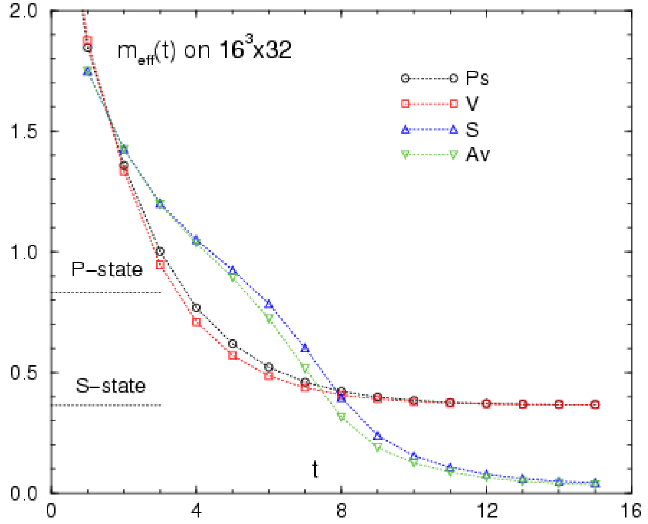


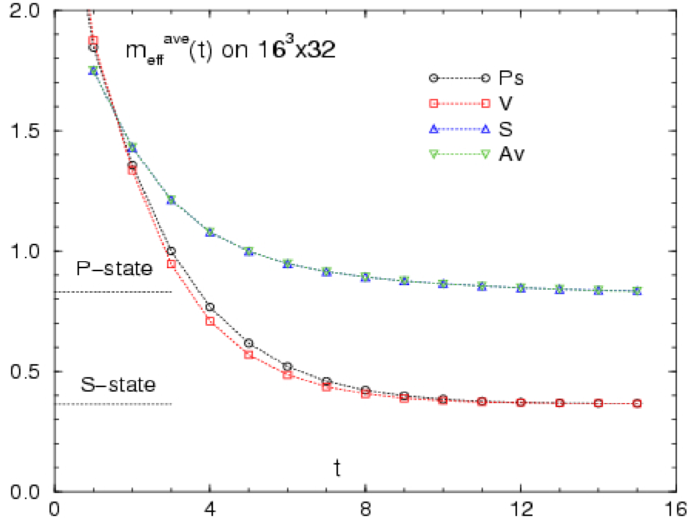
The asymmetry of diag−(b)
is coming from a factor of Re[exp(−i2 π n/3)]

$$C^{ave}(t) = \frac{1}{3}\left(C^{p0}(t) + C^{p1}(t) + C^{p2}(t)\right)$$

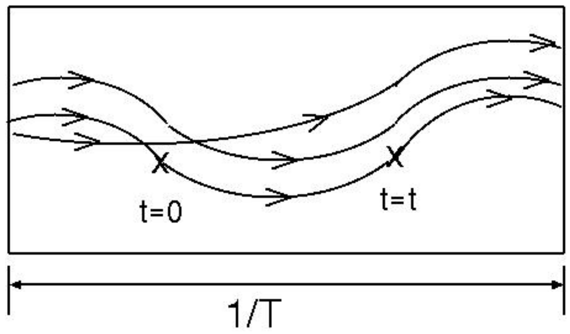
Z_3 asym. terms are removed because $\sum_{n=0}^{2} Re(e^{-i2\pi n/3}) = 0$

Averaged correlators





However, this is not an exact method to avoid the constant contribution.

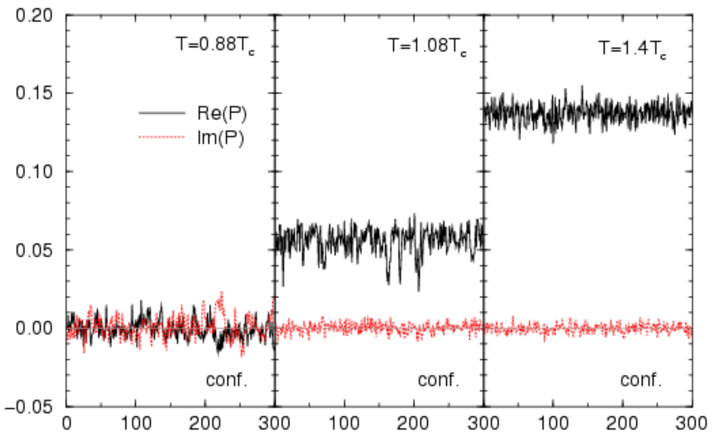


The 3 times wrapping diagram is also Z_3 symmetric.

→ the contribution is not canceled.

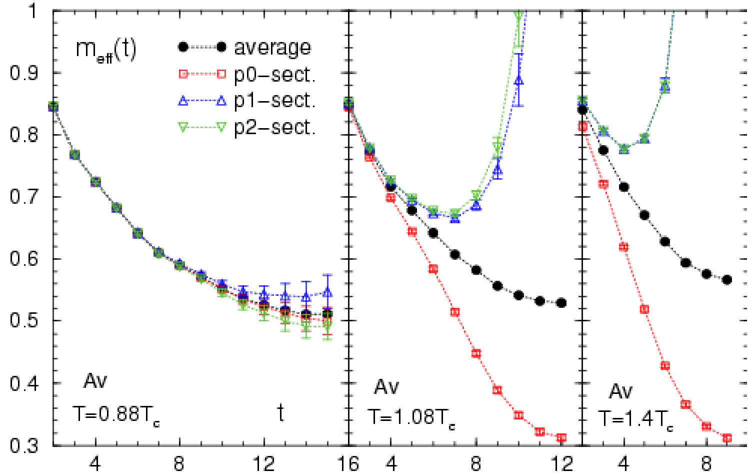
but, $O(\exp(-m_q N_t)) \gg O(\exp(-3 m_q N_t))$

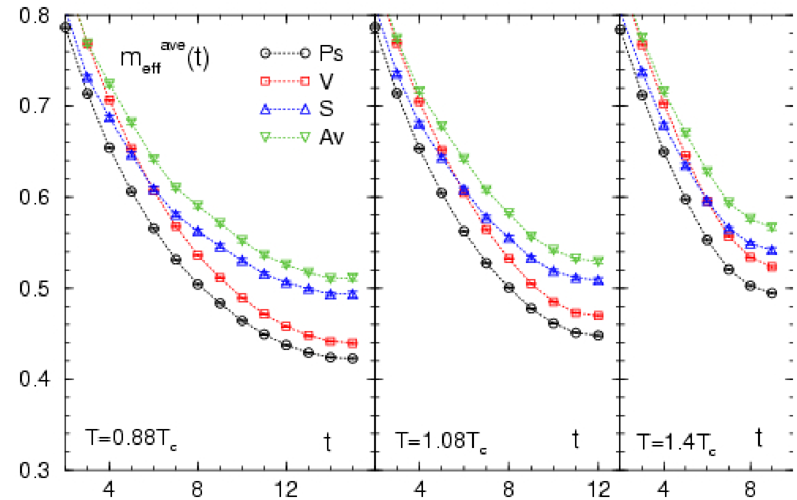
Polyakov loop sector dependence



- after Z_3 transformation
  const. → Re(exp(−i2π n/3))*const.
- even below T_c, small const. effect
  enhances the stat. fluctuation.
- drastic change in P−states disappears.

Results for Av channel

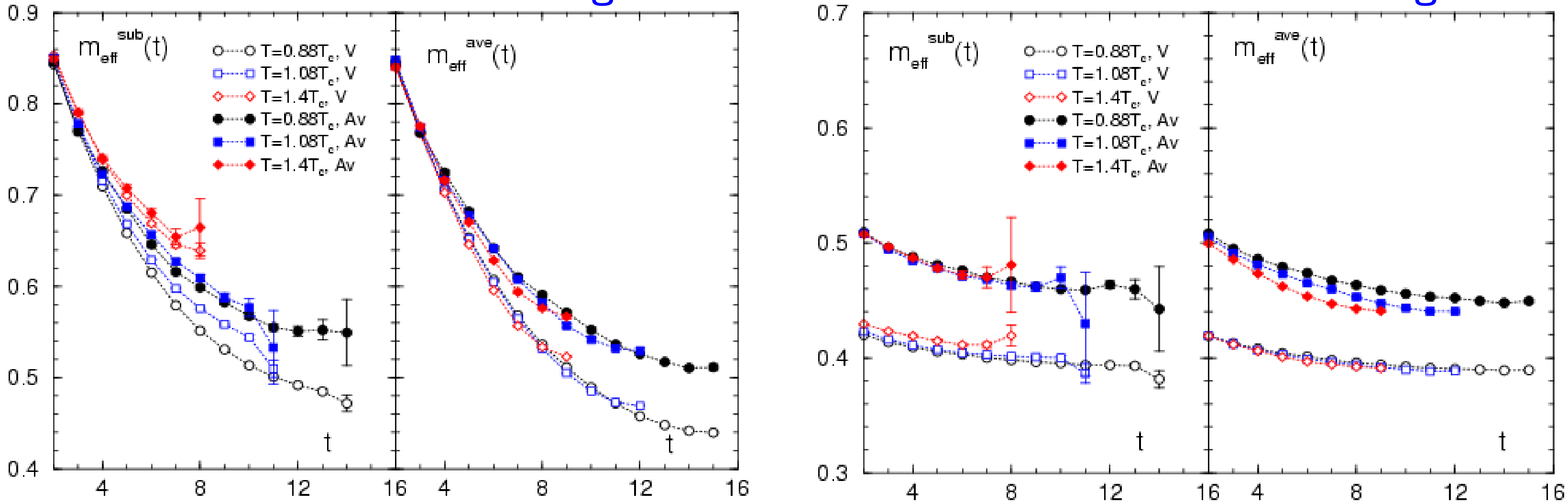




Discussion

point operators | extended operators

subtracted | averaged | subtracted | averaged



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

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

Why several MEM studies show the dissociation of χ_c states ?

Spectral representation

Spectral function of the correlator

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

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

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

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

with

$$I_1 = -2\int_{\vec{k}} n'_F(\omega_{\vec{k}})$$

$$I_2 = -2\int_{\vec{k}} \frac{k^2}{\omega_{\vec{k}}^2} n'_F(\omega_{\vec{k}})$$

	Γ	$a_H^{(1)}$	$a_H^{(2)}$	$a_H^{(3)}$	$a_H^{(1)} - a_H^{(2)}$	$a_H^{(2)} - a_H^{(3)}$	$a_H^{(1)} + a_H^{(2)}$	$a_H^{(2)} - a_H^{(3)}$
Ps	γ_5	1	-1	-1	2	0	0	0
V	γ_i	3	-1	-3	4	2	2	2
S	1	1	-1	1	2	-2	0	-2
Av	$\gamma_i\gamma_5$	3	-1	3	4	-4	2	-4

最後のテーブルいらんかも

chiral symmetry in massless limit