Hadronic Correlation and Spectral Functions at Finite Temperature

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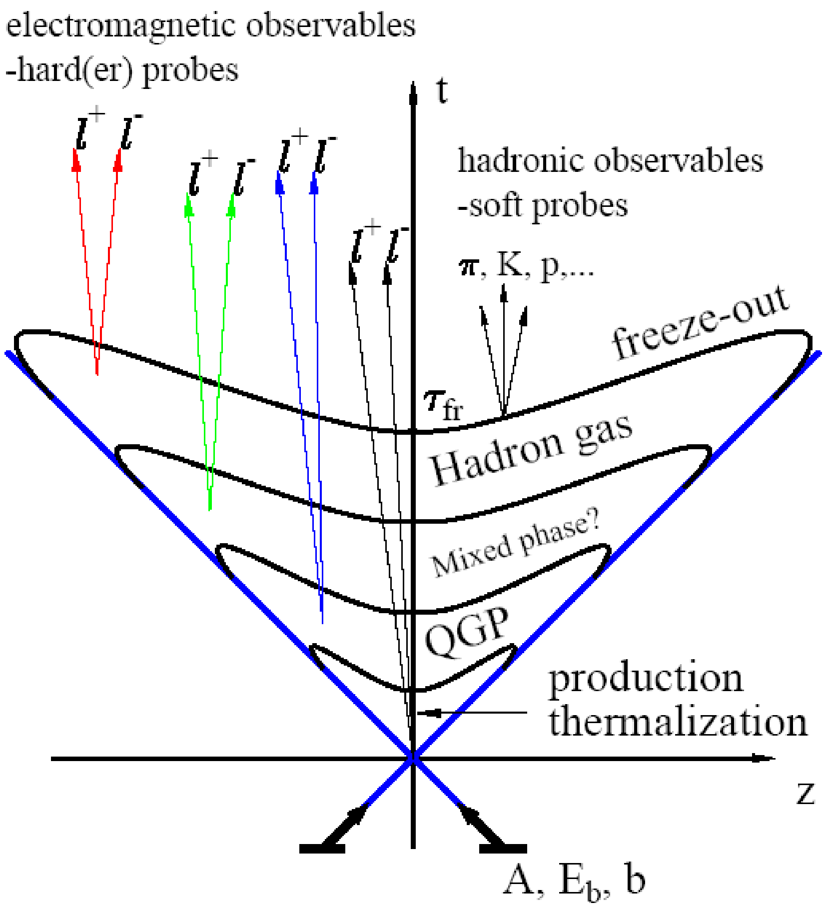
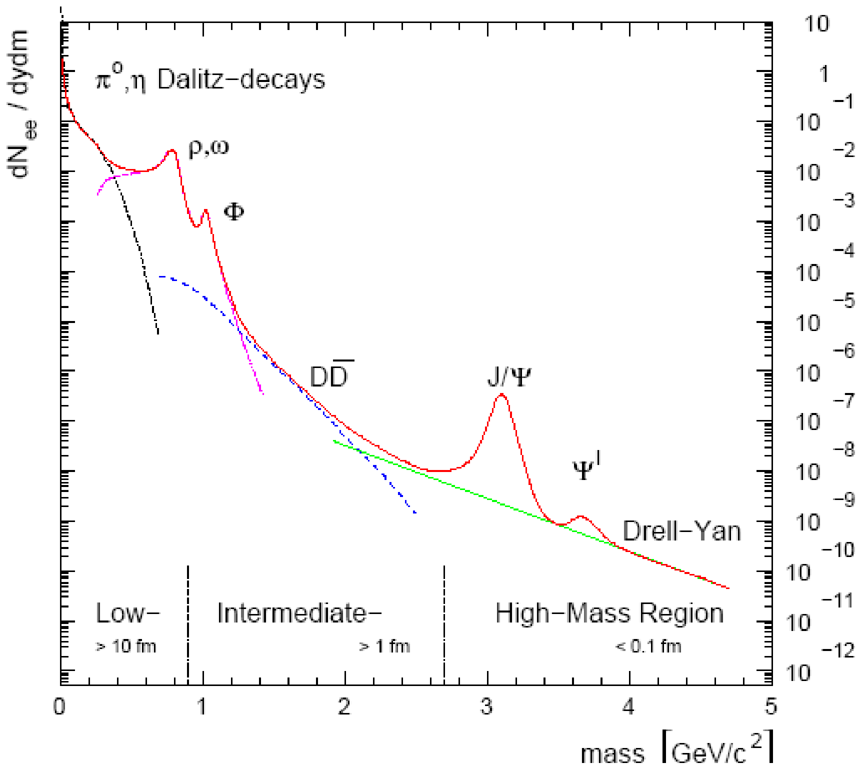
Hard Probes in Heavy Ion Collisions - Dileptons





Dileptonrate directly related to vector spectral function:

$$\frac{dW}{d\omega d^3p} = \frac{5\alpha^2}{27\pi^2}\frac{1}{\omega^2(e^{\omega/T}-1)}\sigma_V(\omega,\vec{p},T)$$

Hard Probes in Heavy Ion Collisions – RHIC results

pp-data well understood by hadronic cocktail

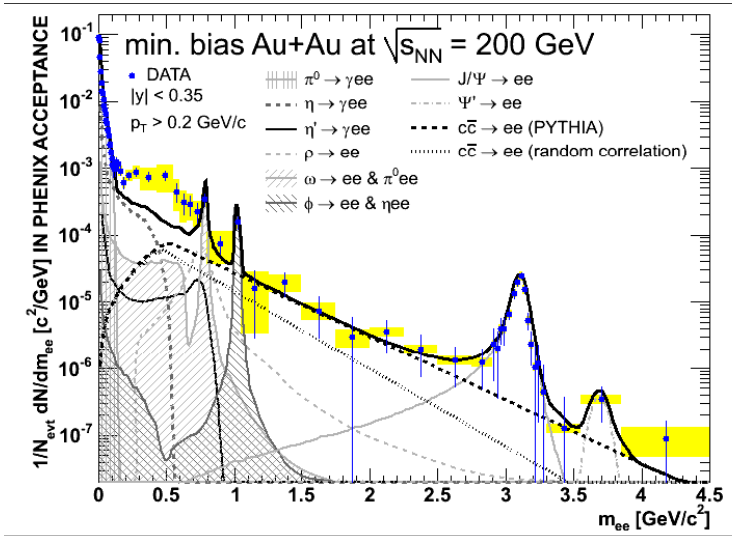
low invariant mass region <150 MeV similar in Au-Au

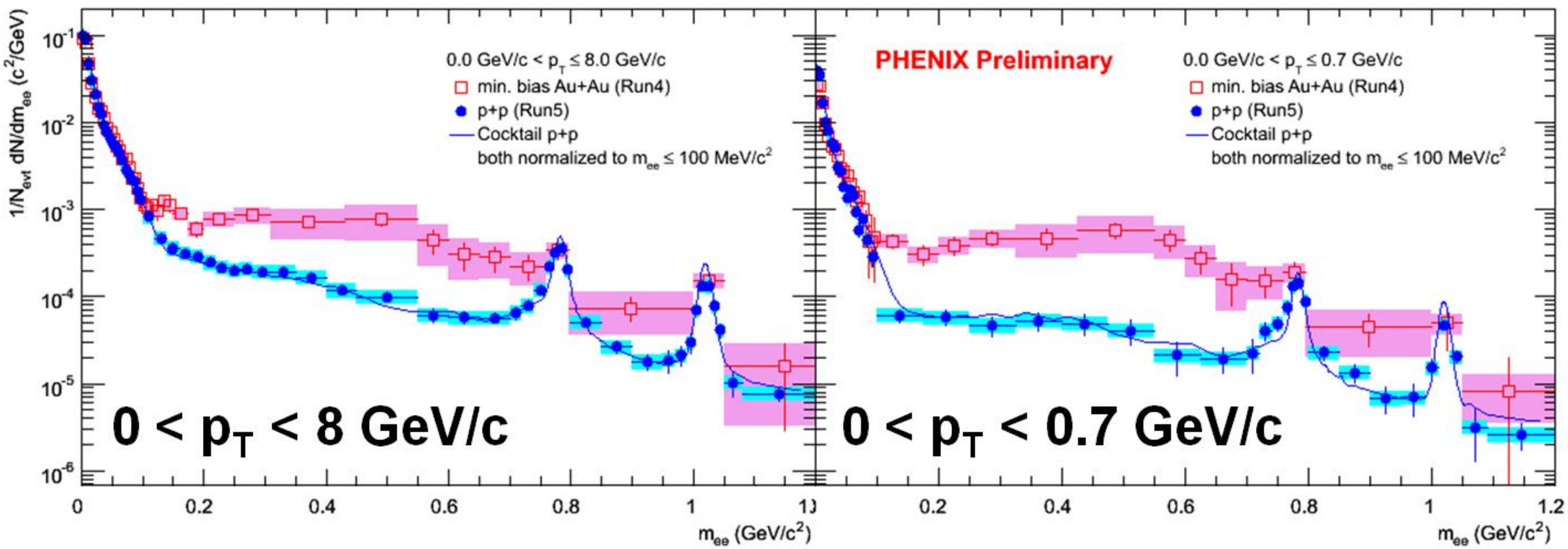
large enhancement between 150-750 MeV

indications for thermal effects!? Also at higher m_{ee}?

Need to understand the contribution from QGP!

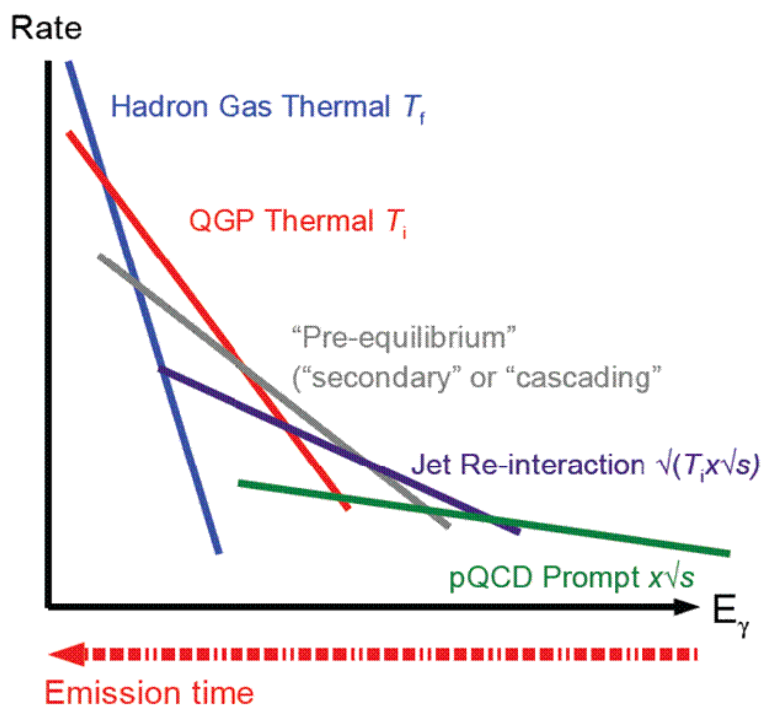
$\rightarrow$ spectral functions from lattice QCD



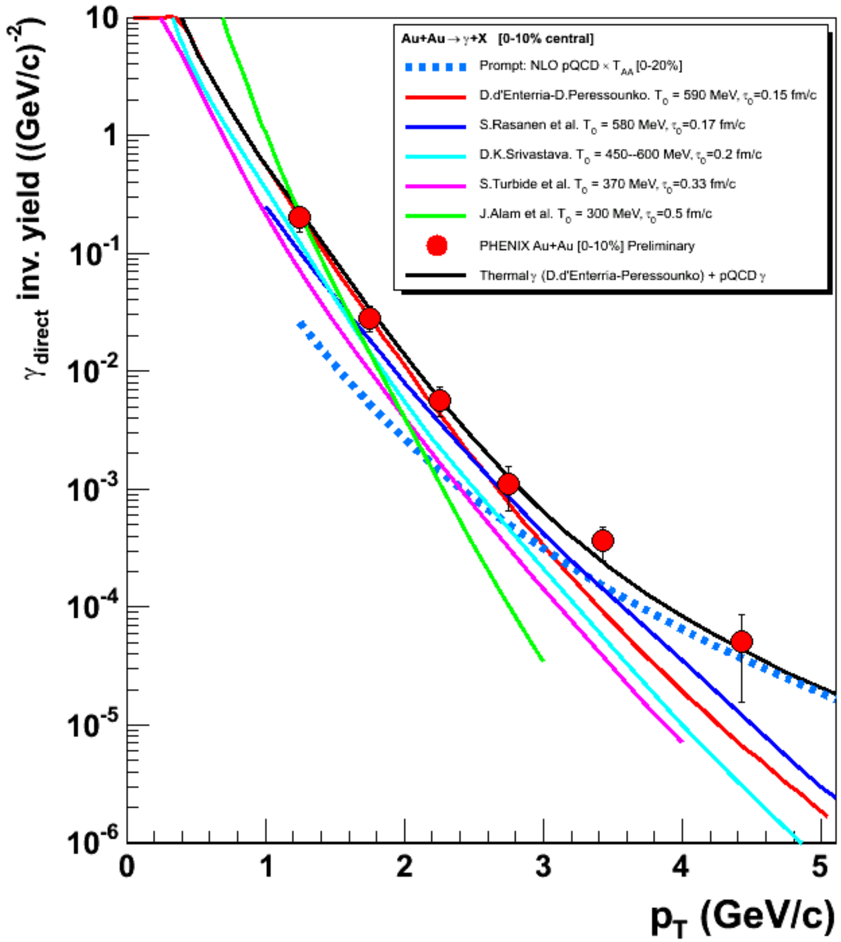


Hard Probes in Heavy Ion Collisions - Photons

Direct and fragmentation photon relative contribution



[Fleuret 2009]



Photonrate directly related to vector spectral function (at finite momentum):

$$\omega \frac{dN_\gamma}{d^4x d^3q} = \frac{5\alpha}{6\pi^2} \frac{1}{e^{\omega/T} - 1} \sigma_V(\omega = |\vec{p}|, T)$$

Transport Coefficients

The small ω limit of σ_V is related to transport coefficients (Kubo-Formulas)

Light quark sector $\rightarrow$ **electrical conductivity**:

$$\sigma_{el} = \lim_{\omega \to 0} \frac{\sigma_V^{ii}(\omega, \vec{p} = 0, T)}{6\omega}$$

Heavy quark sector $\rightarrow$ **heavy quark diffusion constant**:

$$D = \frac{1}{3\chi^{00}} \lim_{\omega \to 0} \frac{\sigma_V^{ii}(\omega, \vec{p} = 0, T)}{\omega}$$

Free (non-interacting) spectral function [Karsch et al. 03, Aarts et al. 05]

$$\sigma_H = \frac{N_c}{8\pi^2} \Theta(\omega^2 - 4m^2)\ \omega^2\ \tanh(\frac{\omega}{4T}) \times \sqrt{1 - (\frac{2m}{\omega})^2} \left[a_H + (\frac{2m}{\omega})^2\ b_H \right] + \frac{N_c}{3}\ \frac{T^2}{2}\ f_H\ \omega \delta(\omega)$$

with interactions:

$$\delta(\omega) \rightarrow \frac{1}{\pi} \frac{\eta}{\omega^2 + \eta^2}$$

[Petreczky+Teaney 06 Aarts et al. 05]

Introduction

Hadronic correlators for light quarks (m_q=0)

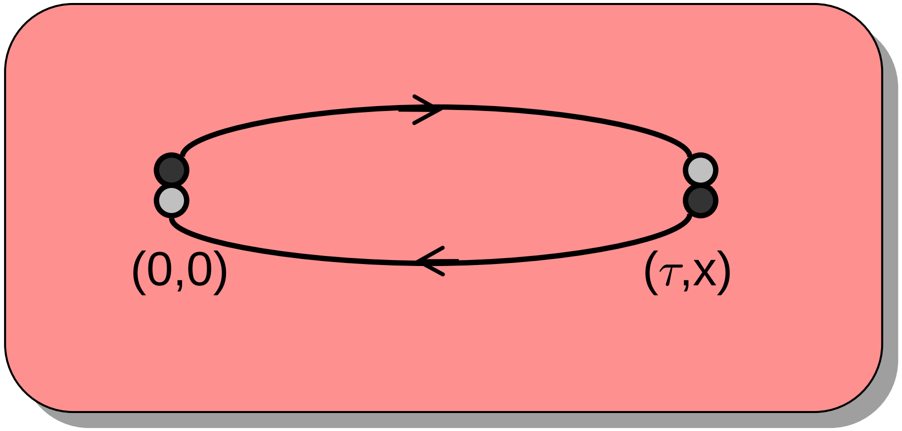
- Screening masses in the thermodynamic and continuum limit
- Temporal correlators vs. free correlators
- Spectral functions and Dilepton rates

Charmonium hadronic correlators (m_q=m_c)

- Screening Masses below and above T_c
- Temporal correlators vs. free correlators
- Spectral functions below and above T_c
- Temporal correlators vs. reconstructed correlators
- Zero mode contributions

Hadronic correlators – Lattice setup

Thermal hadronic correlation functions



$$J_H = \bar{q}(\tau,\vec{x})\Gamma_H q(\tau,\vec{x})$$

$$G_H(\tau,T,\vec{p}) = \sum_{\vec{x}} e^{-i\vec{p}\vec{x}} \langle J_H(0,0) J_H^{\dagger}(\tau,\vec{x})\rangle$$

O(a)-improved Clover improved fermionic action

on large quenched lattice configurations up to $128^3 \times 16/32/48$

includes all the relevant physics (in the quenched limit)

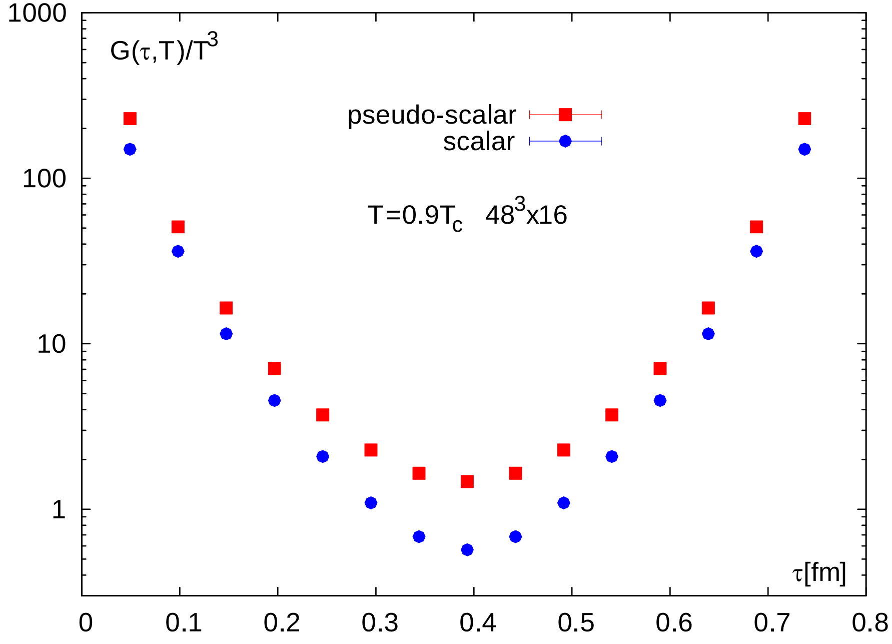
how to extract it?

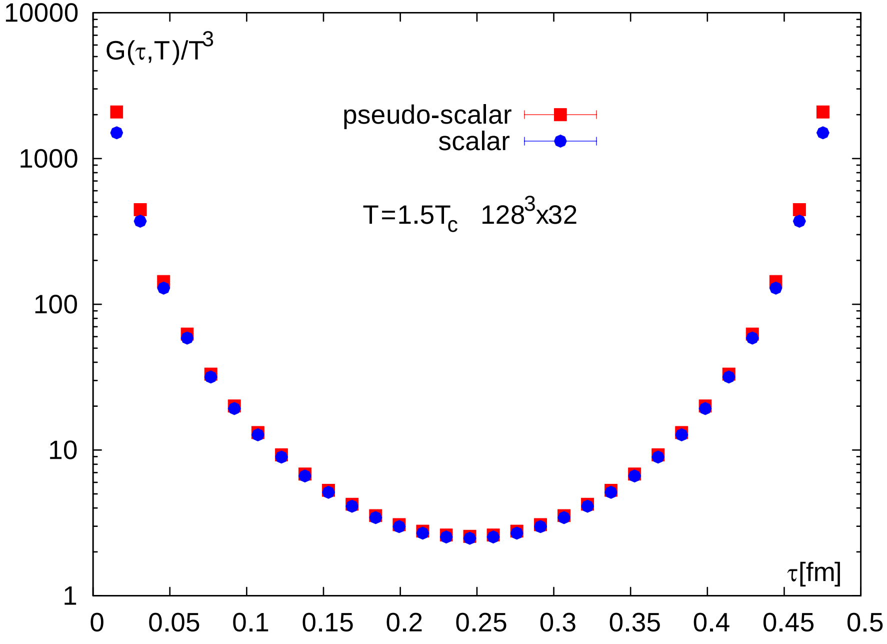
directly from the correlators?

spectral functions using MEM?

Light Quark Correlators – Chiral Symmetry

Temporal Correlators:





splitting below T_c due to

chiral and axial U(1) symmetry breaking

degenerate states at 1.5 T_c

symmetry restauration above T_c

deviations at small τ due to

different cut-off effects

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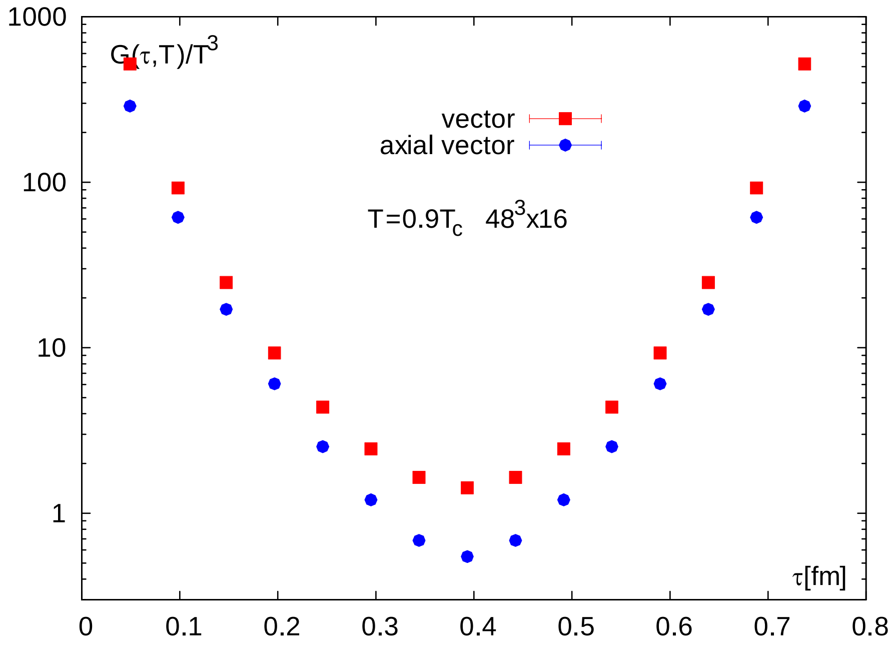

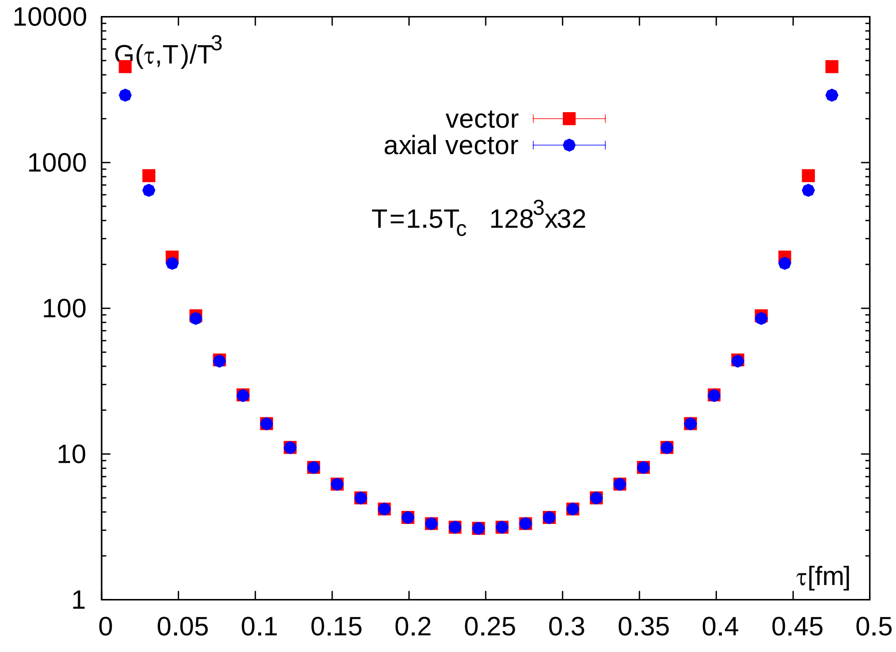

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Light Quark Screening Masses – Definition

use **Spatial Correlators**

$$G_H(z,T,\vec{p}_\perp) = \sum_{\tau,\vec{x}_\perp} e^{-i\vec{p}_\perp \vec{x}_\perp} \langle J_H(0,0) J_H^\dagger(\tau,\vec{x}) \rangle$$

correlation function depends on the same spectral density,

but the relation is more involved

$$G_H(z) = \int_{-\infty}^{+\infty} \frac{\mathrm{d}p_z}{2\pi} e^{ip_z z} \int_{-\infty}^{+\infty} \mathrm{d}p_0 \frac{\sigma_H(p_0,\vec{0}_\perp,p_z)}{p_0} \quad \overrightarrow{z \to \infty} \text{ Ampl.} \times \exp(-m_{\text{screen}}\, z)$$

however, $m_{\text{screen}}(T) \neq m_{pole}(T)$ in general :

look for zeros of $G^{-1}(p) = p_0^2 + \vec{p}^2 + m_0^2 + \Pi(p_0,\vec{p},T)$

$$\vec{p} = 0 : \qquad -p_0^2 = m_0^2 + \Pi(p_0,\vec{0},T) = (m_{pole}(T))^2$$

$$p_0 = 0 : \qquad -\vec{p}^2 = m_0^2 + \Pi(0,\vec{p},T) = (m_{\text{screen}}(T))^2$$

$$\Longrightarrow m_{screen}(T) = \frac{m_{pole}(T)}{A(T)}$$

Light Quark Screening Masses – Thermodynamic Limit, V→ ∞

large collection of lattices ranging from $16^3\times 8$ to $128^3\times 16$

allowing for thermodynamic limit $V\to\infty$ at N_t=8,12 and 16

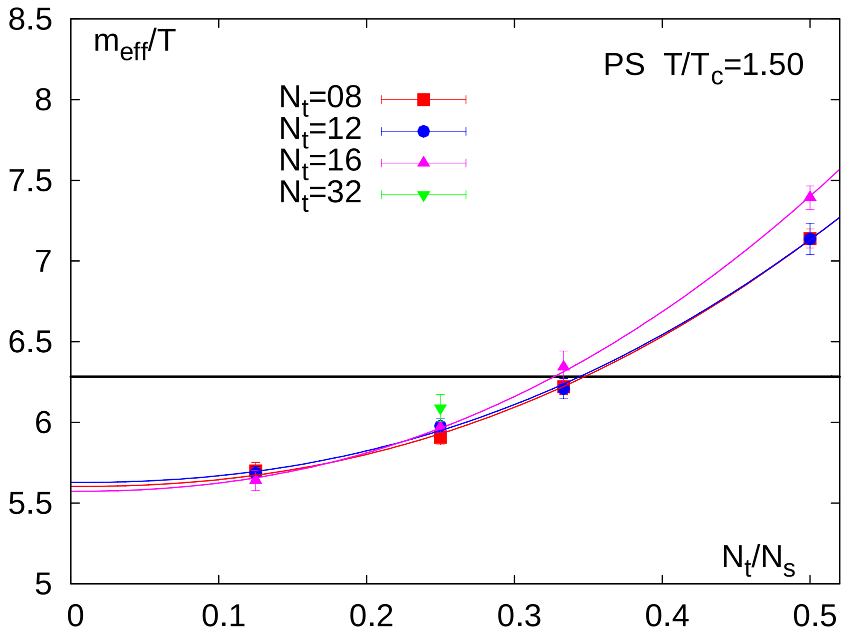
$$T \le T_c: \quad m_{\rm screen}(L,a) = m_{\rm screen}(a)\left[1+\gamma_V\left(\frac{N_\tau}{N_\sigma}\right)^3\right]$$

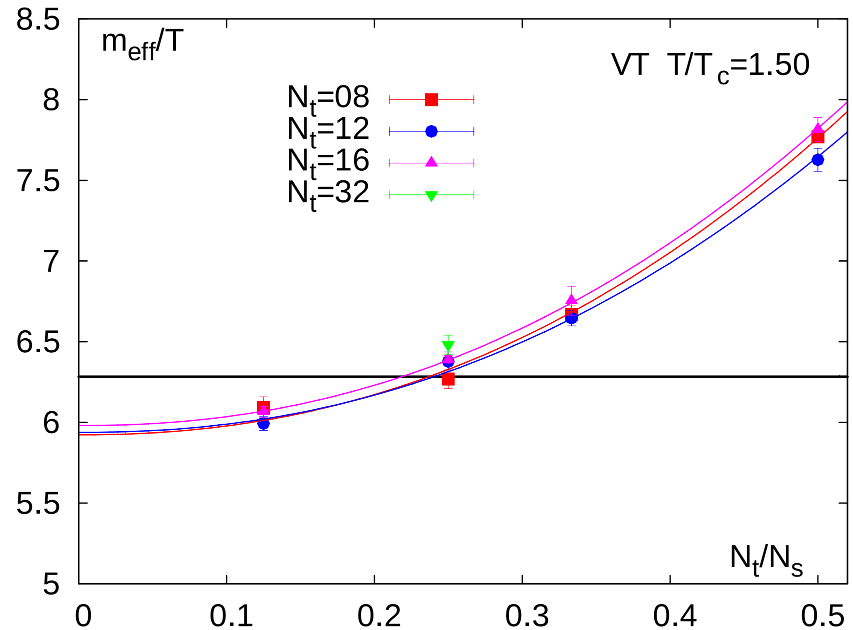
$$T > T_c: \quad m_{\rm screen}(L,a) = m_{\rm screen}(a)\left[1+\gamma_V\left(\frac{N_\tau}{N_\sigma}\right)^p\right]$$

$$T = \infty: \quad m_{\rm screen}(L,a) = m_{\rm screen}(a)\left[1+\gamma_V\left(\frac{N_\tau}{N_\sigma}\right)^1\right]$$

combined fit:

p	PS	V
1.5 Tc	2.22(10)	2.18(13)
3.0 T_c	2.06(7)	2.05(11)





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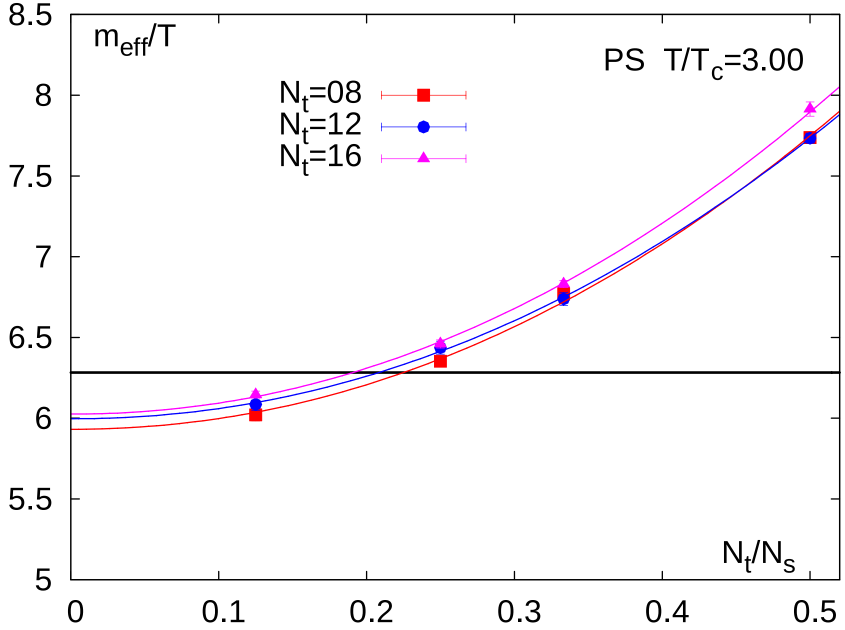
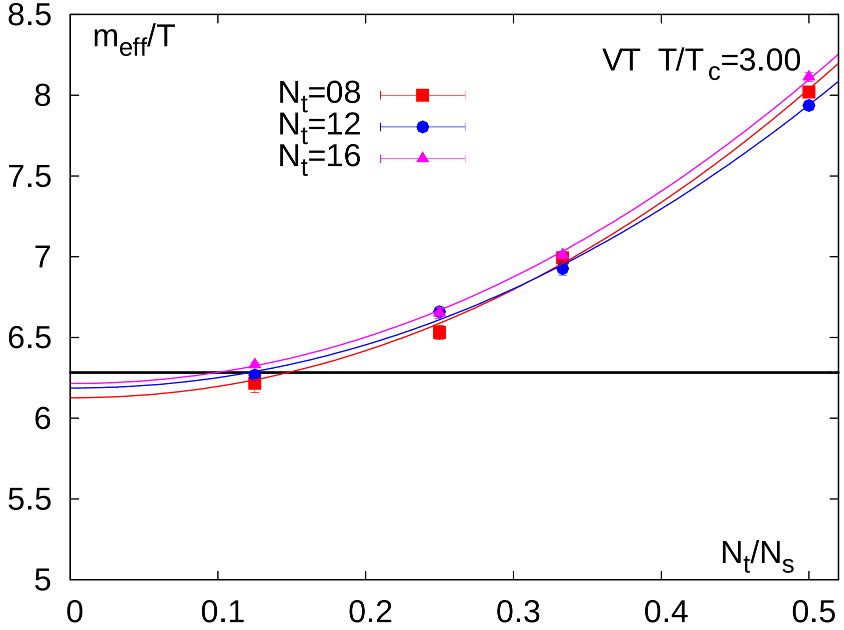




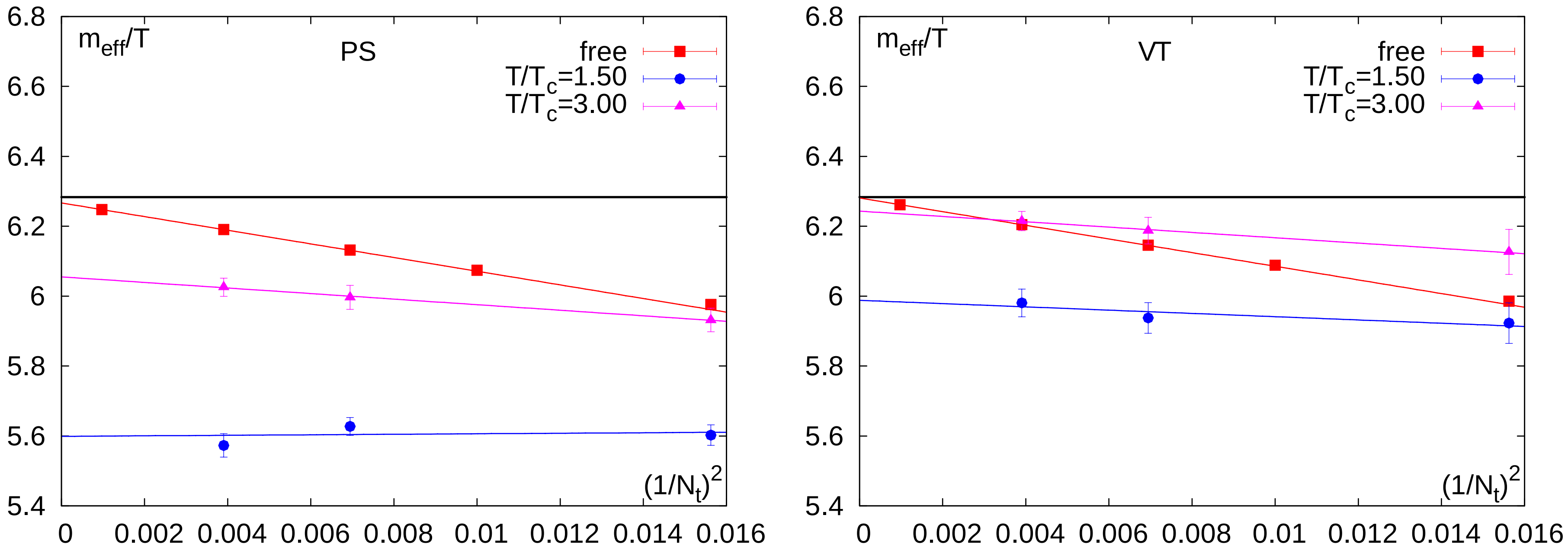
Continuum Limit

lattice spacing $a \to 0$

Non-perturbatively improved action

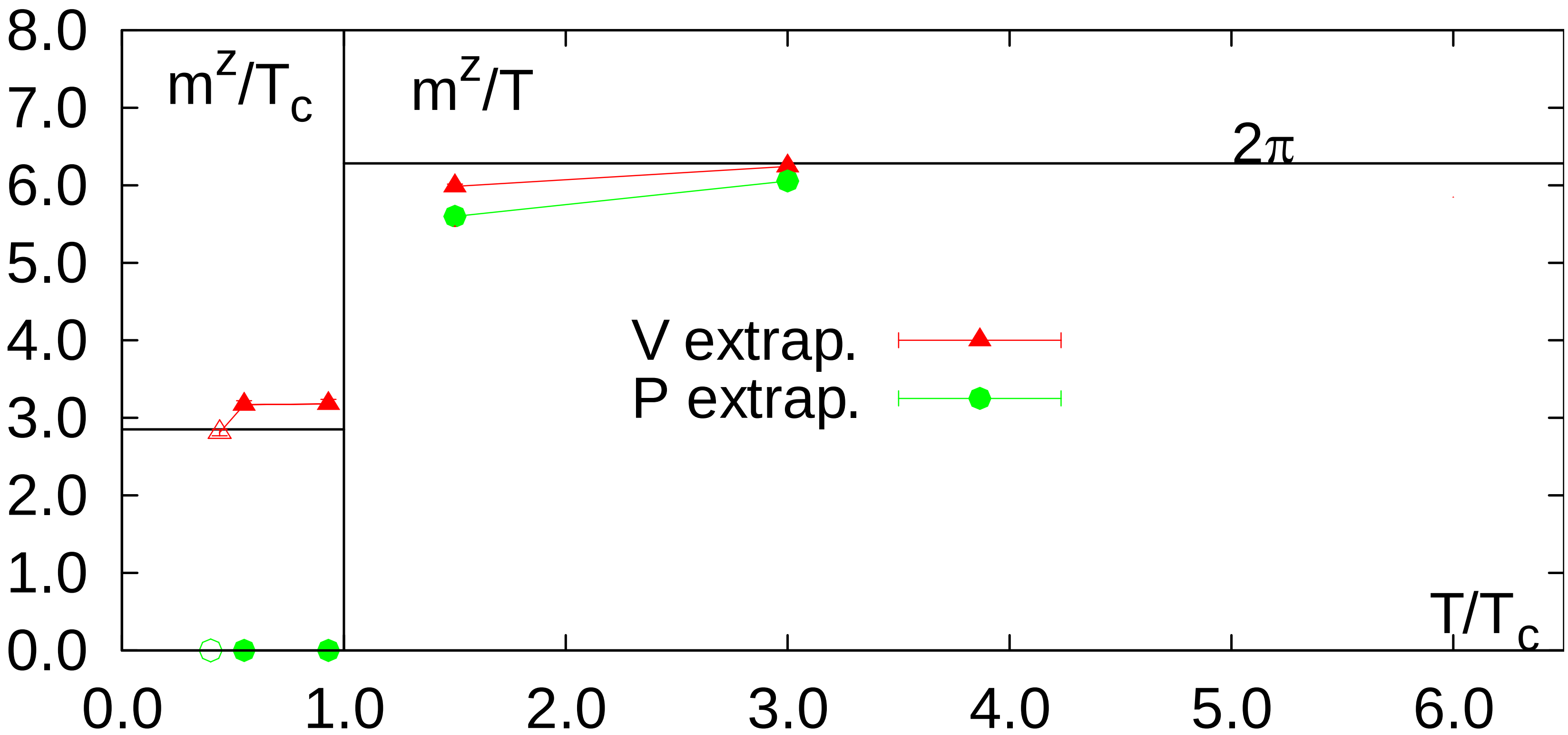
$\Rightarrow$ discretization errors O(a^2)

$$T = \infty : \quad \frac{m^z(a)}{T} = \frac{m^z}{T} - \lambda \left(\frac{1}{N_\tau}\right)^2$$



Thermodynamic and Continuum Limit:

$V \to \infty$ and $a \to 0$



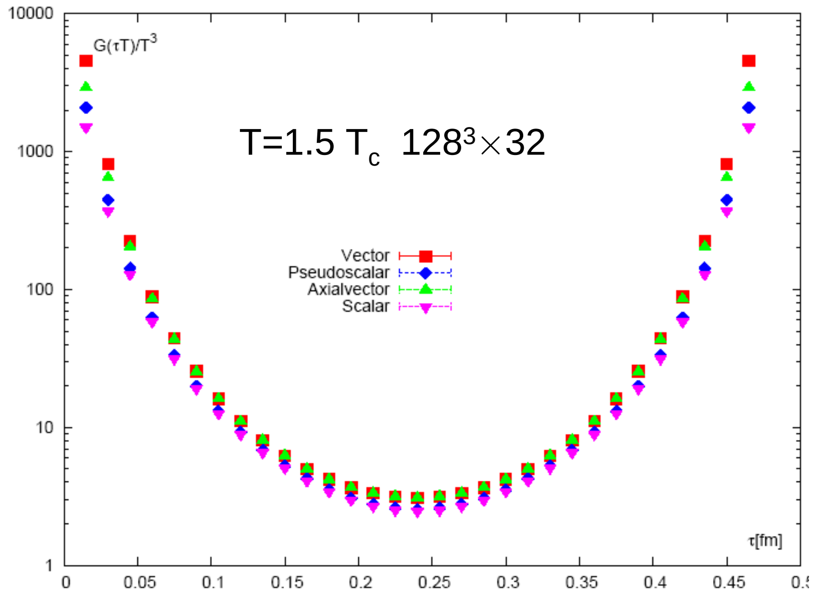
weak temperature dependence below T_c

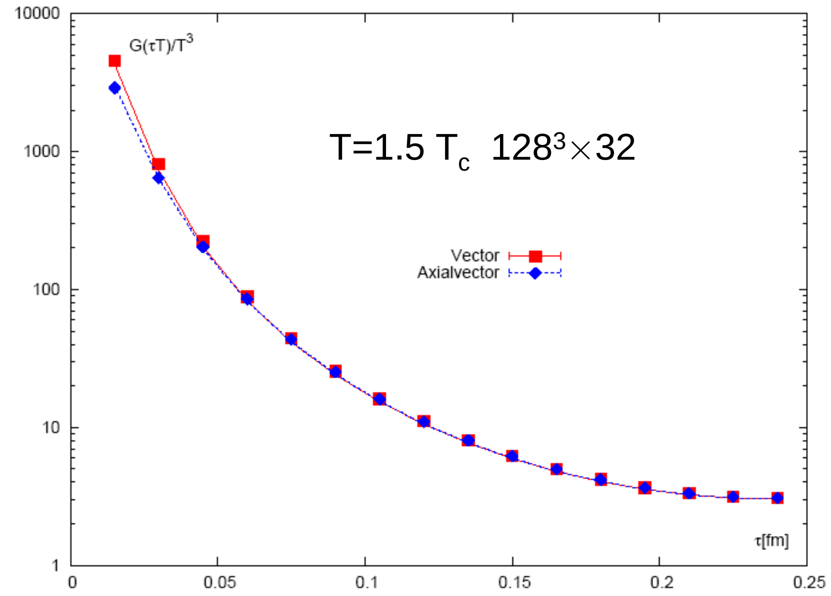
data still below free limit ($2\pi T$) at $3\,T_c$, vector closer to free case

perturbative limit reached from above [Laine, Vepsäläinen]

$\to$ need higher temperatures to verify this

Light Quark Correlators – Temporal direction





comparison with free (non-interacting) high temperature lattice correlator

vector and axial-vector close to free case

cut-off effects are well described by free lattice correlator

this explains the difference at small τ

in the following only vector and pseudo-scalar are discussed

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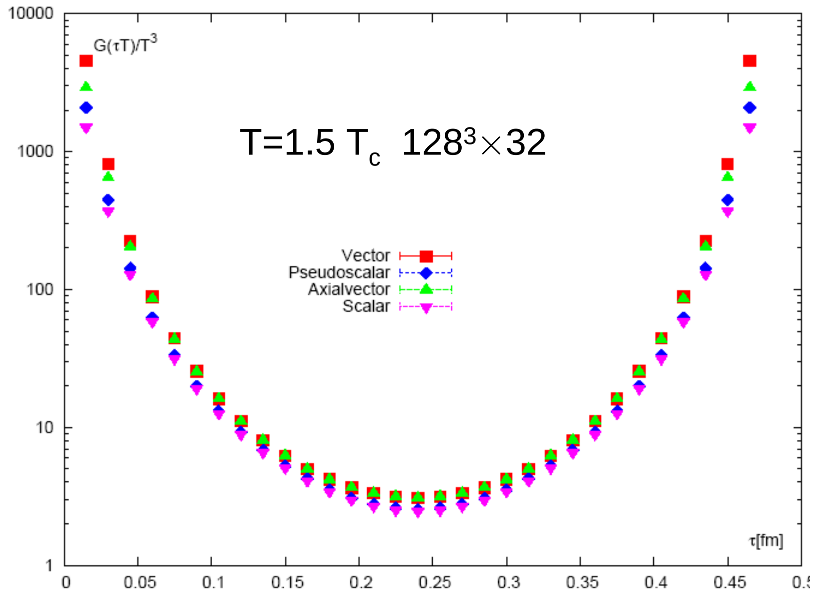

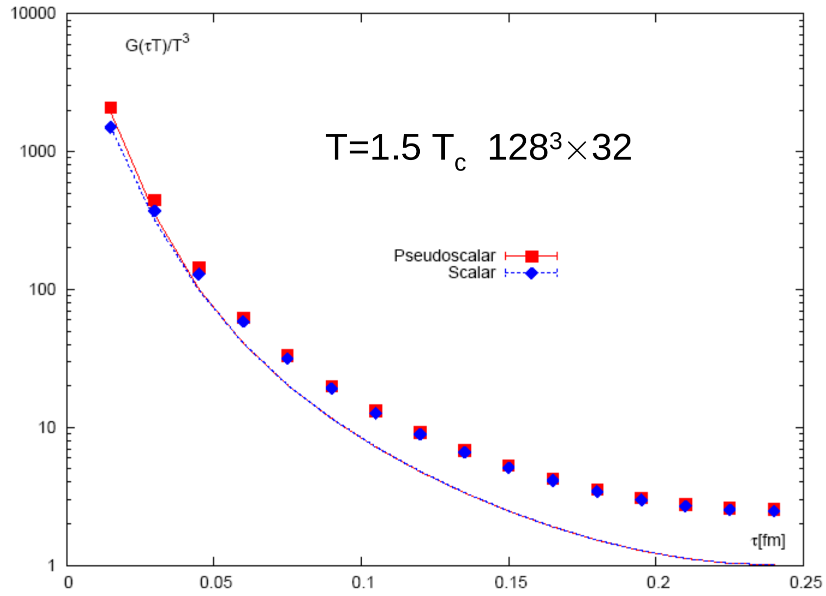

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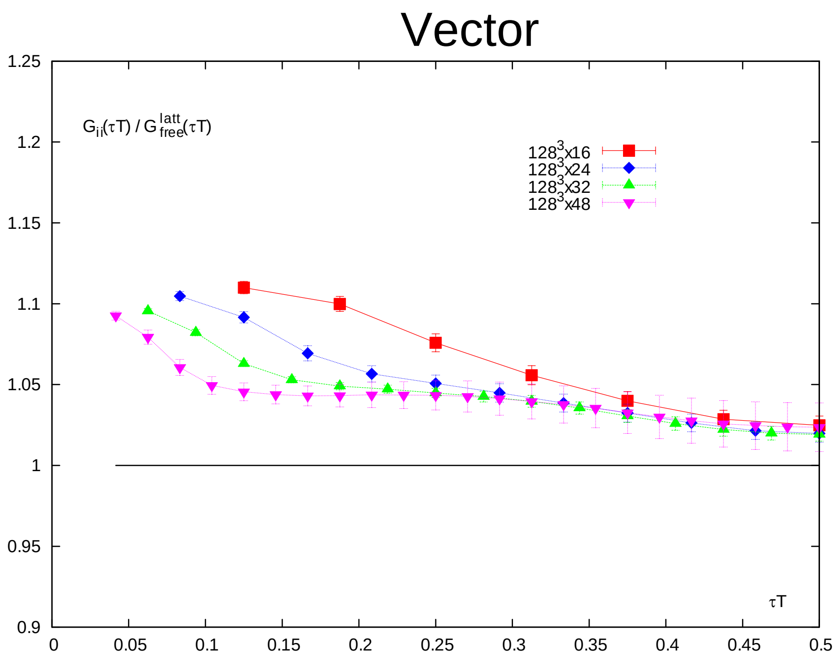
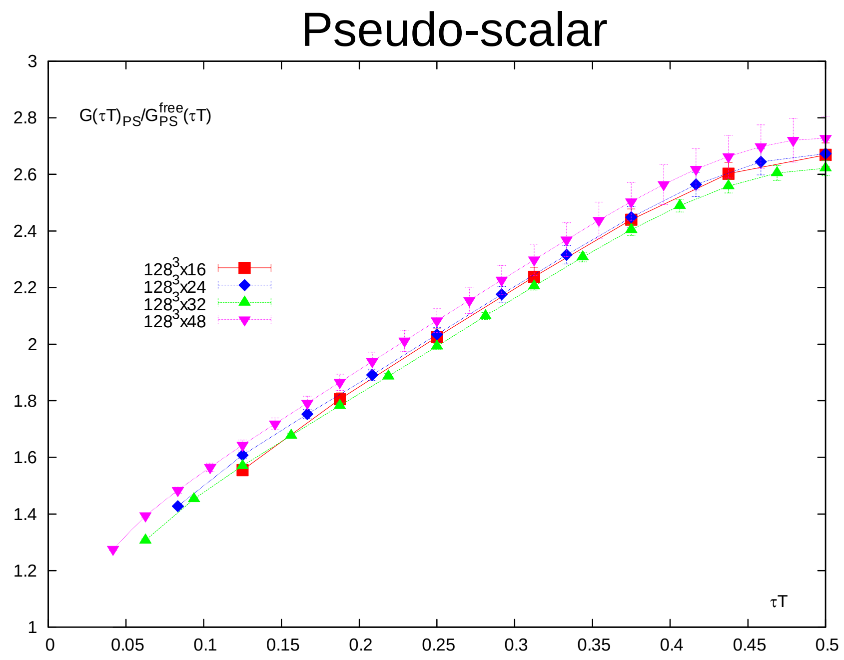
still strong correlations in scalar and pseudo-scalar channel!

Light Quark Correlators vs Free Correlators





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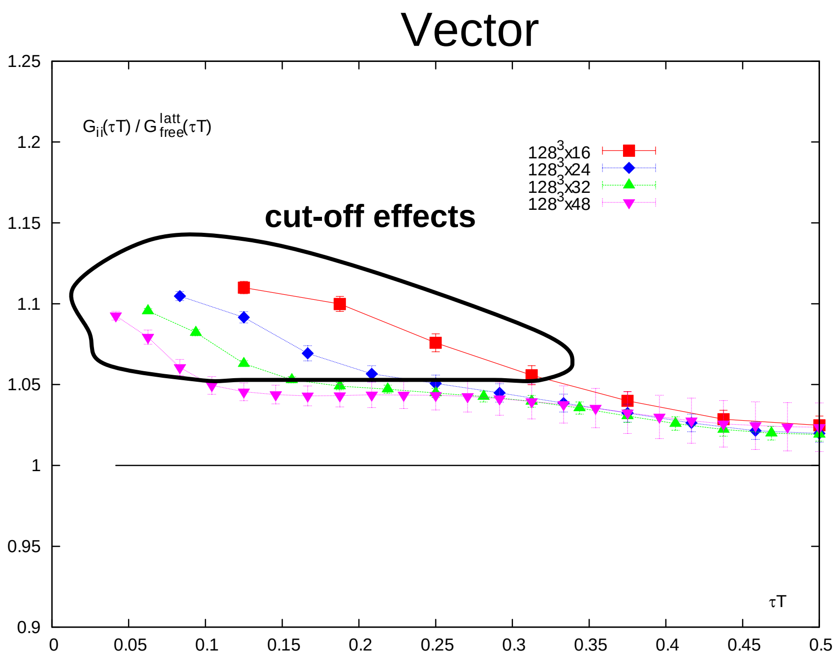
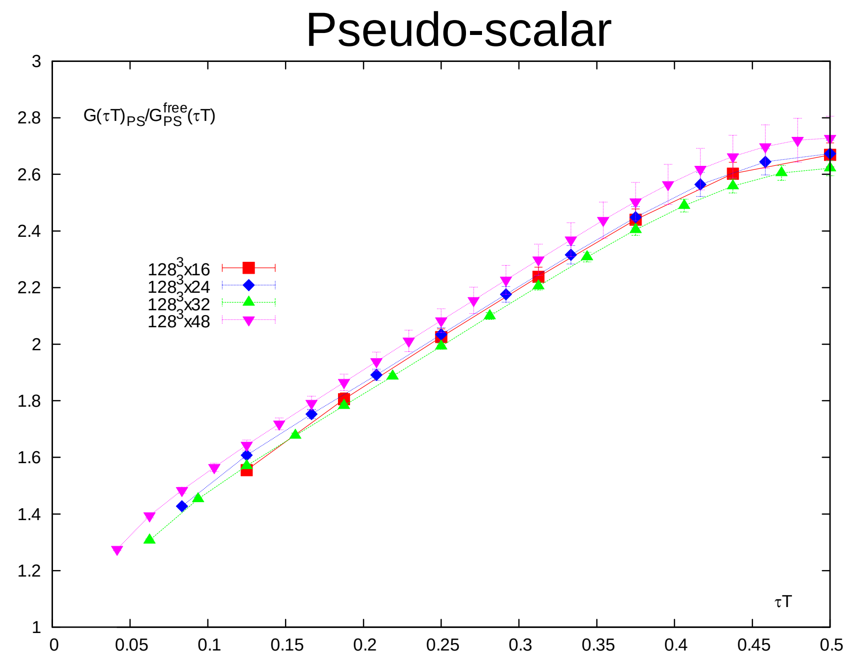




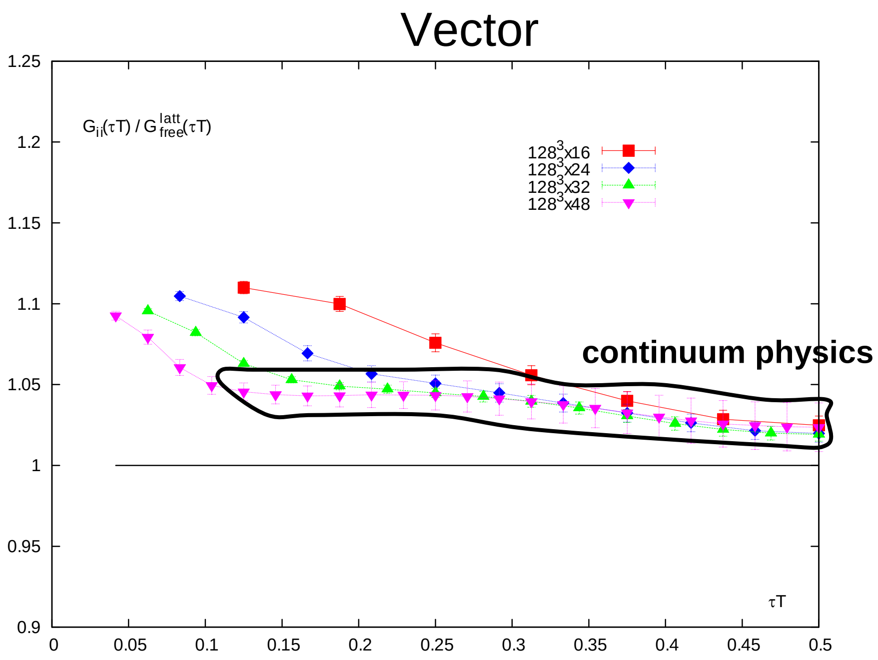
comparison with free (non-interacting) high temperature lattice correlator

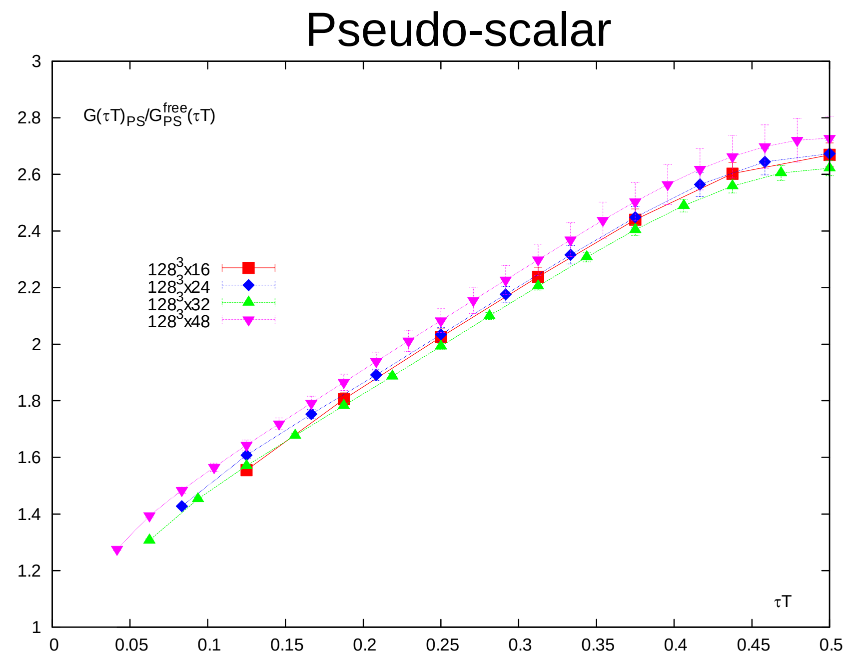
vector and axial-vector close to free case

still strong correlations in scalar and pseudo-scalar channel

first 4-5 distances still dominated by cut-off effects

Light Quark Correlators vs Free Correlators





comparison with free (non-interacting) high temperature lattice correlator

vector and axial-vector close to free case

still strong correlations in scalar and pseudo-scalar channel

first 5 points still dominated by cut-off effects!

Nt=32 and 48 needed to extract continuum physics!

Spectral Functions – Maximum Entropy Method

How to obtain continuous spectral function $\sigma(\omega,T)$

from discrete (and small) number of correlators?

$$G(\tau,T) = \int_0^\infty \mathrm{d}\omega K(\tau,\omega,T)\sigma(\omega,T)$$

$$K(\tau,\omega,T) = \frac{\cosh\left(\omega(\tau-\frac{1}{2T})\right)}{\sinh\left(\frac{\omega}{2T}\right)}$$

Best method on the market: Maximum Entropy Method (MEM)

based on Bayesian theorem [Asakawa et al. 01] $\rightarrow$ most probable spectral function

properly renormalized correlators as input

non-perturbative renormalization constants for vector [Lüscher et al. 1997]

TI perturbative renormalization constants for pseudo-scalar

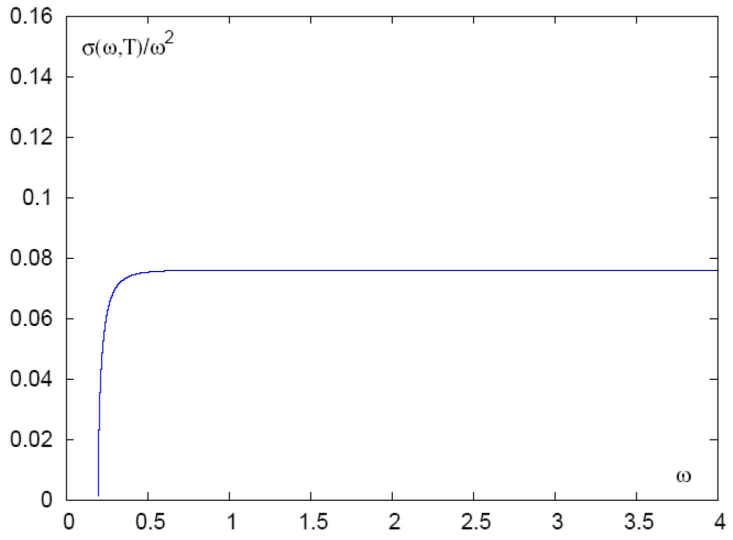
prior knowledge needed as input $\rightarrow$ default model m(ω)

result should be independent of default model $\leftarrow$ usually not the case

MEM – Free spectral function

Free (non-interacting) spectral function [Karsch et al. 03, Aarts et al. 05]

$$\sigma_H = \frac{N_c}{8\pi^2}\Theta(\omega^2 - 4m^2)\ \omega^2 \tanh(\frac{\omega}{4T}) \times \sqrt{1-(\frac{2m}{\omega})^2}\Big[a_H + (\frac{2m}{\omega})^2\ b_H\Big] + \ \frac{N_c}{3}\ \frac{T^2}{2}\ f_H\ \omega\delta(\omega)$$



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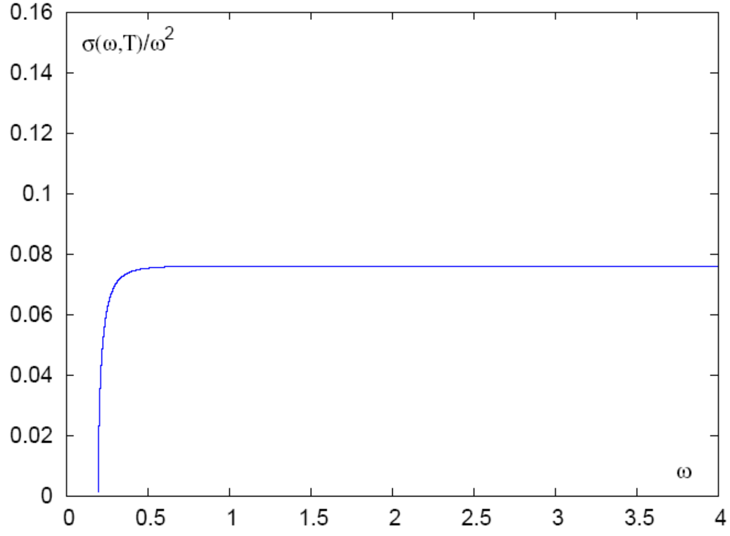
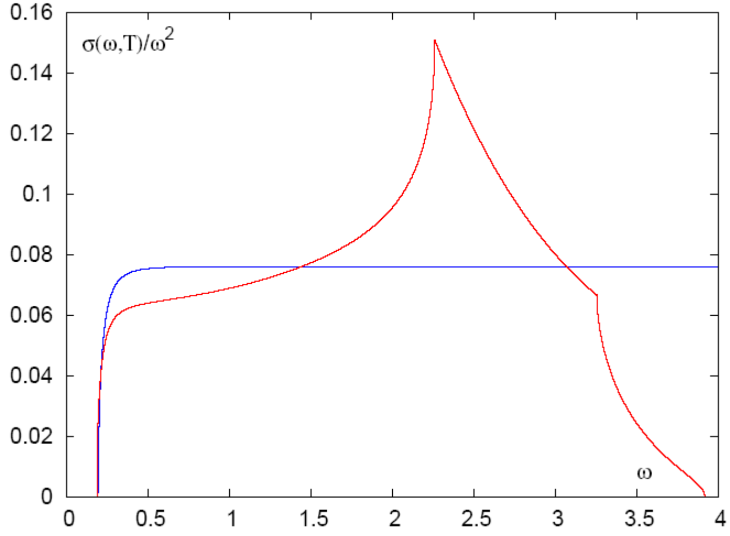
Lattice cut-off effects

$$\omega_{max} = 2\log(7+ma)$$





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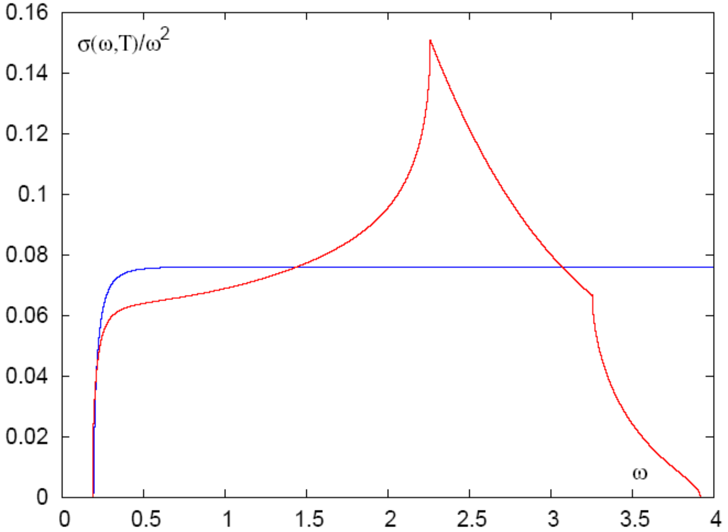
zero mode contribution at $\omega \simeq 0$ [Umeda 07]

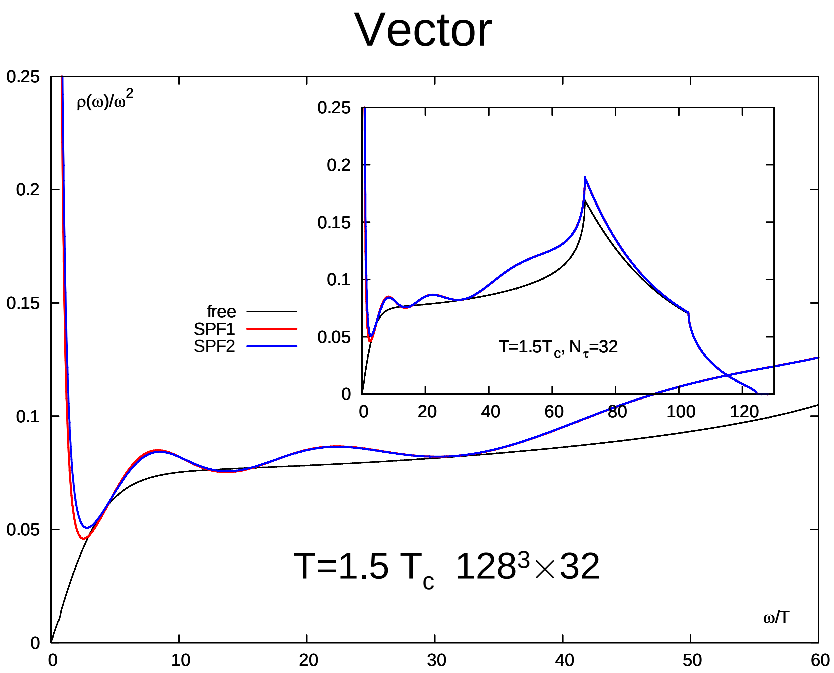
with interactions:

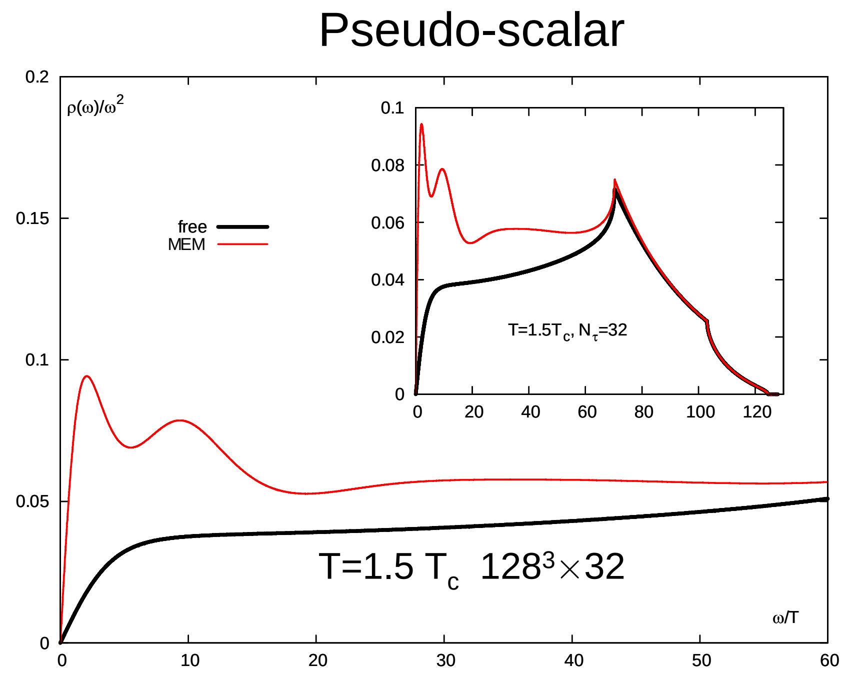
$$\delta(\omega) \to \frac{1}{\pi}\frac{\eta}{\omega^2+\eta^2}$$

[Petreczky+Teaney 06
Aarts et al. 05]



Spectral Function – Light Quark Sector





large ω behaviour well described by free lattice SPF

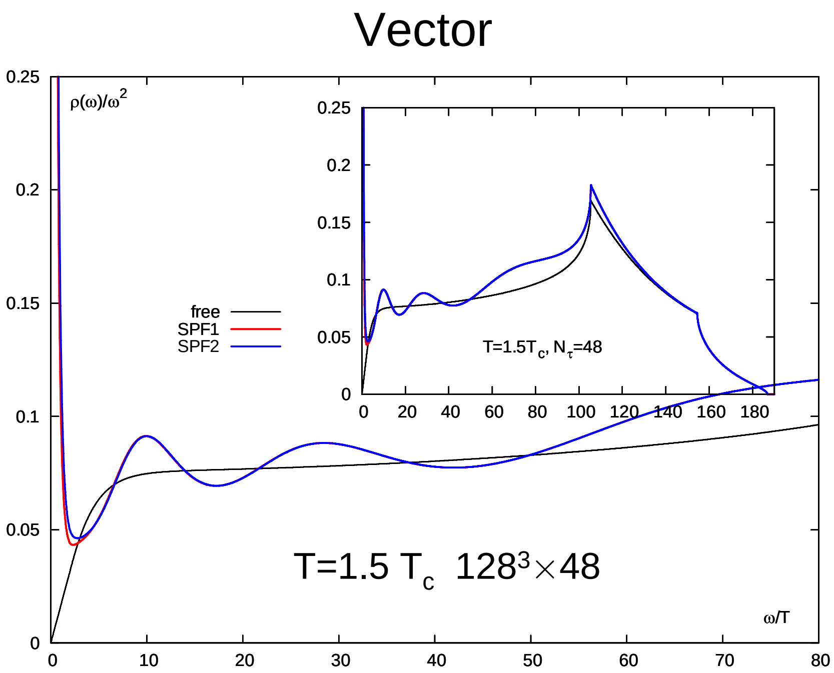
cut-Off effects are under control and well separated form physical interesting region

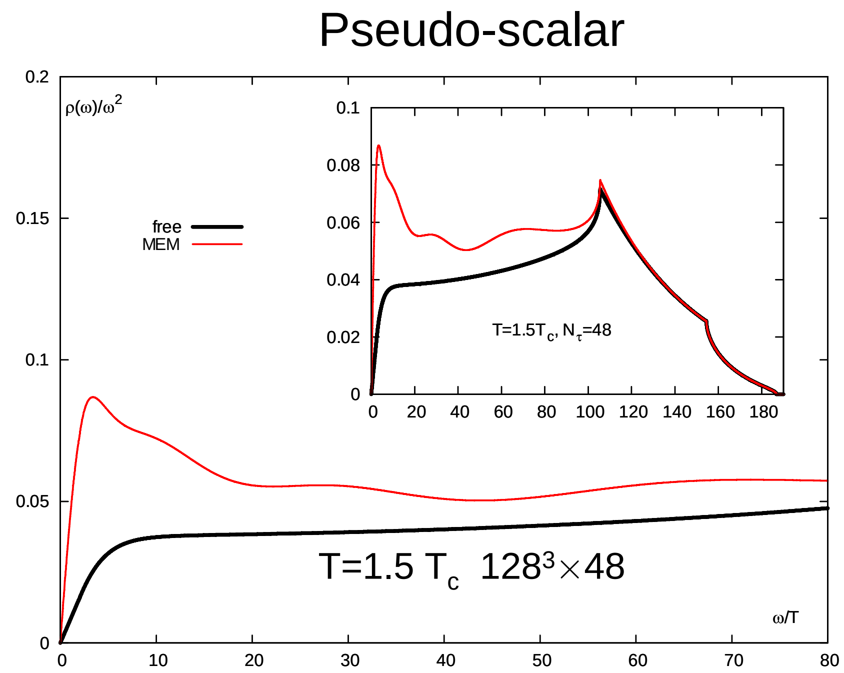
Vector SPF close to free case except at small ω

still large correlations in the Pseudoscalar sector

small ω region accessible $\rightarrow$ hope to extract transport properties
$\rightarrow$ higher statistics needed

Spectral Function – Light Quark Sector





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Dilepton Rates

Dileptonrate directly related to vector spectral function:

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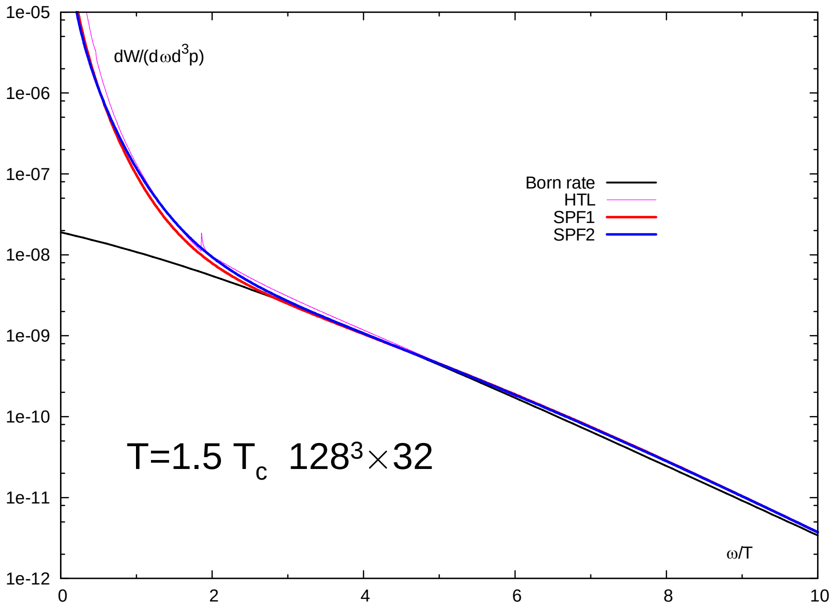
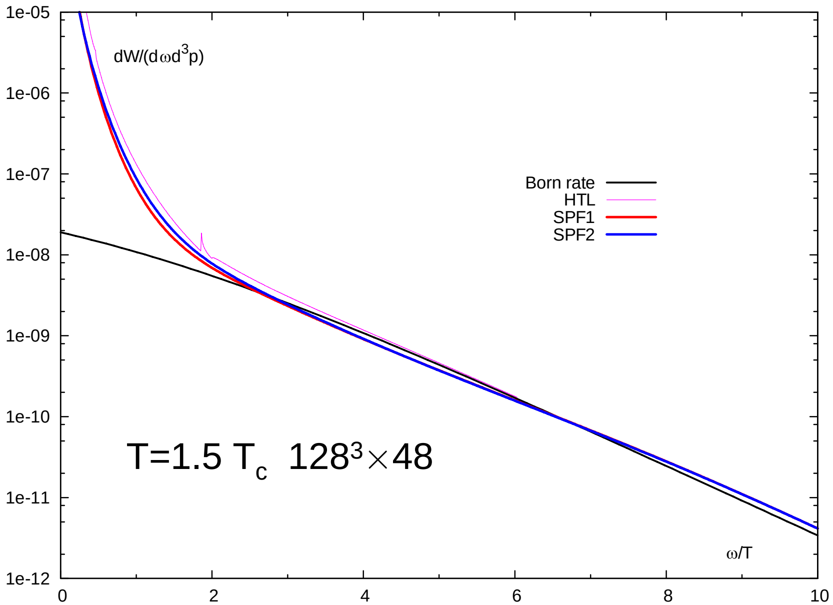




Born rate approached at large ω/T

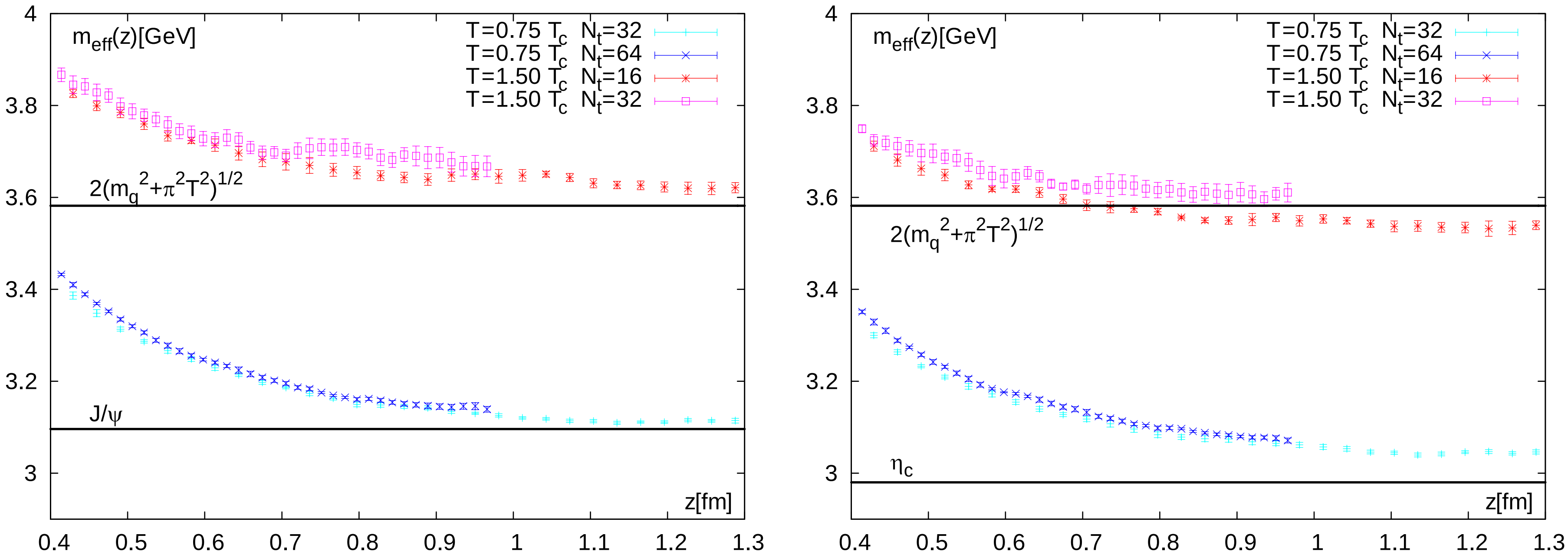
consistent with HTL calculations at intermediate ω/T

better behaved $\sim 1/\omega^2$ at small ω/T [Moore et al., Teaney, …]

higher statistics needed to resolve details at small ω/T

consistent behavior at both lattice spacings $\rightarrow$ continuum physics

Charmonium Correlators – Screening Masses



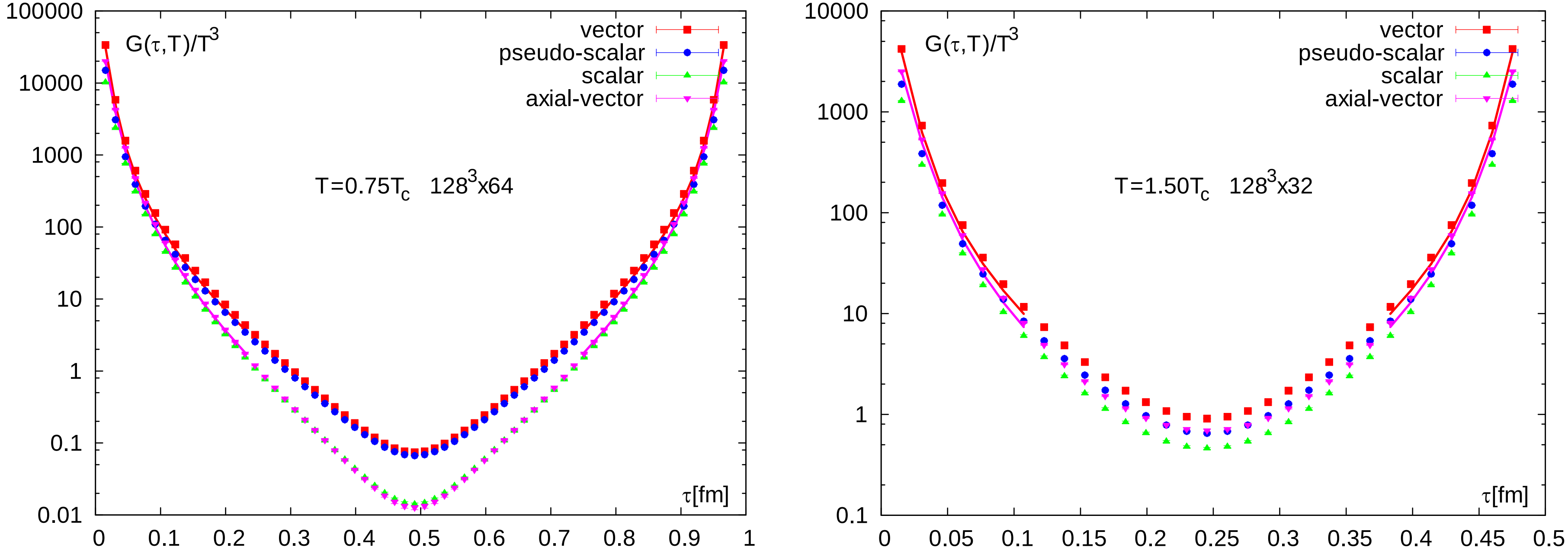
screening masses at 1.50 T_c already close to the free case $m^{scr}_{free}(T) = 2\sqrt{(\pi T)^2 + m_c^2}.$

does this tell us anything about dissociation?

need to understand the momentum dependence of $G_H(\tau,T,p)$ and $\sigma(\omega,T,p)$ in detail

thermodynamic and continuum limit not performed yet

Charmonium Correlators – Temporal Correlators



non-degenerate states still at 1.50 T_c

(almost) close to free correlators at (very) small separations

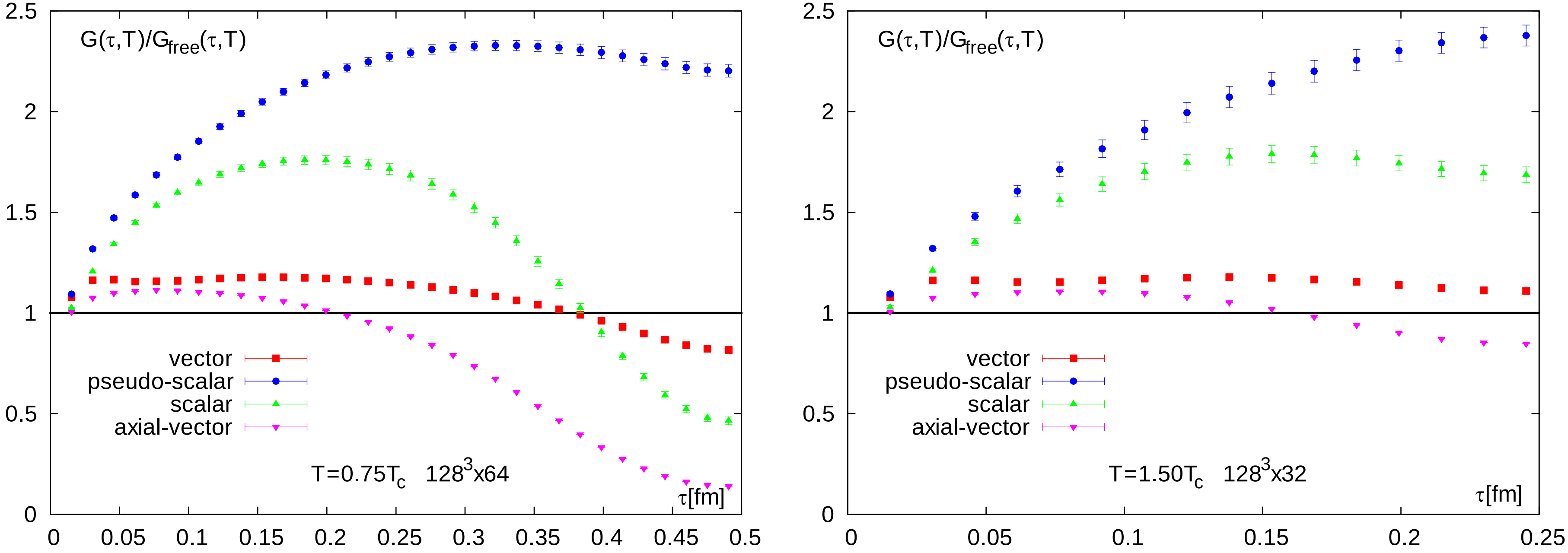
largest distance 0.25 fm due to compact temporal direction

only small distance regime (0.1-0.25 fm) relevant

for thermal effects

for bound state effects

Charmonium Correlators vs Free Correlators



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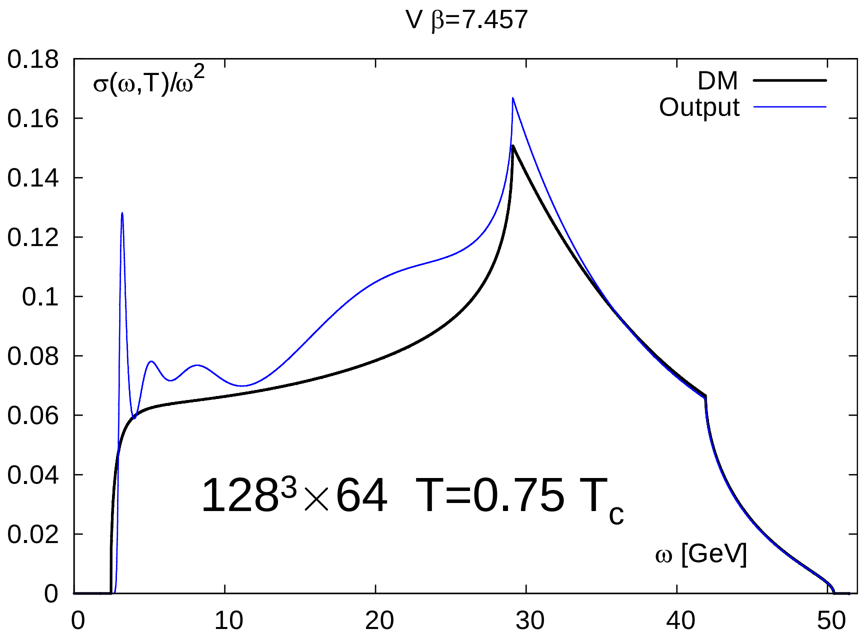
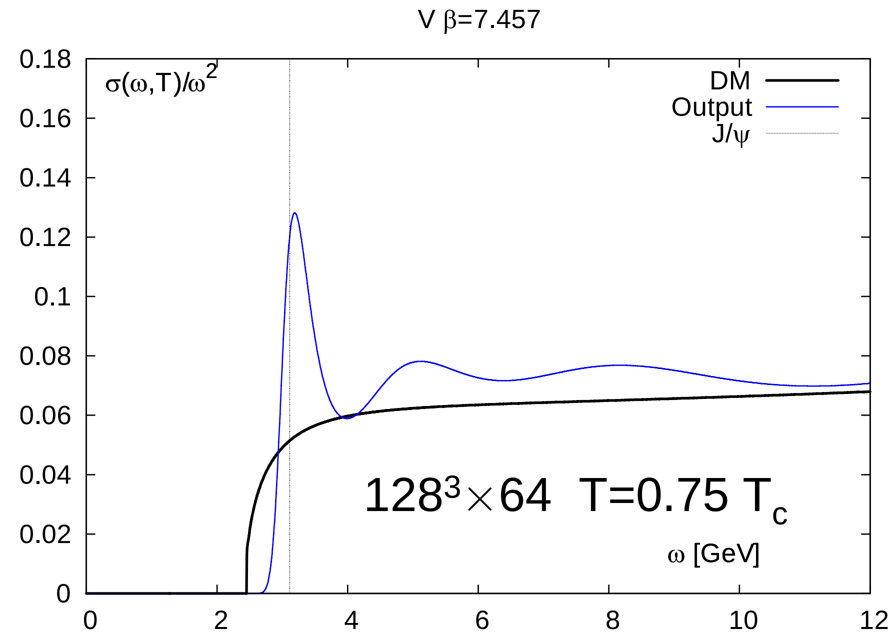
only small distance regime relevant

for thermal effects

for bound state effects

MEM – Spectral function below T_c



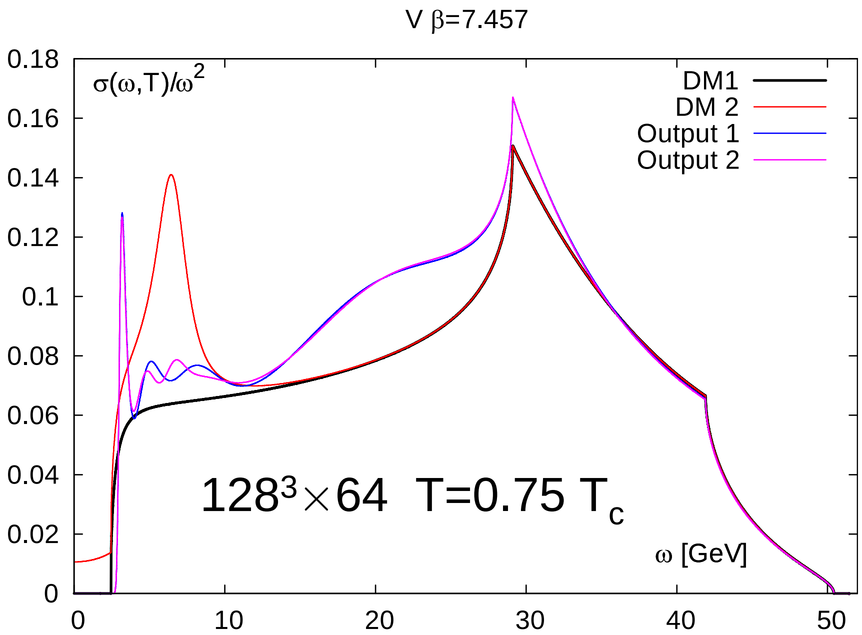


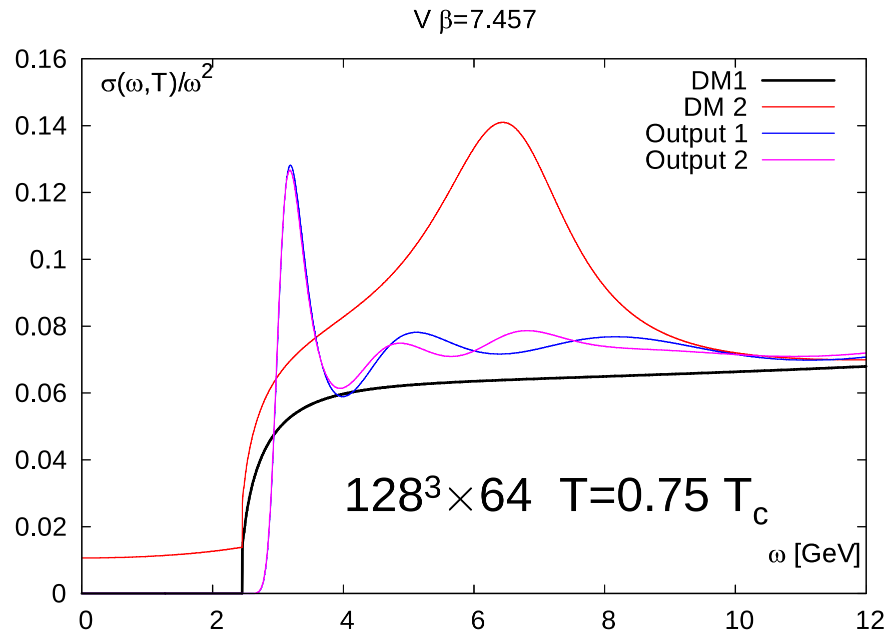
N_σ=128 and N_τ=64 ($a^{-1} \approx 13\,$GeV)$\rightarrow$ cut-off effects well separated

Pronounced ground state peak close to J/ψ mass

no zero mode contributions observed below T_c in all channels

MEM – Spectral function below T_c





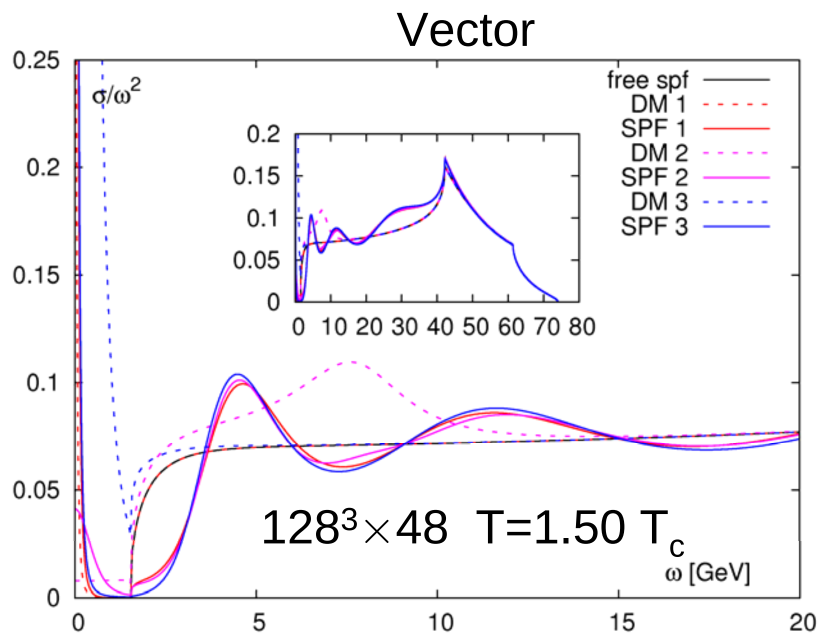
N_σ=128 and N_τ=64 ($a^{-1}\approx$13 GeV) $\rightarrow$ cut-off effects well separated

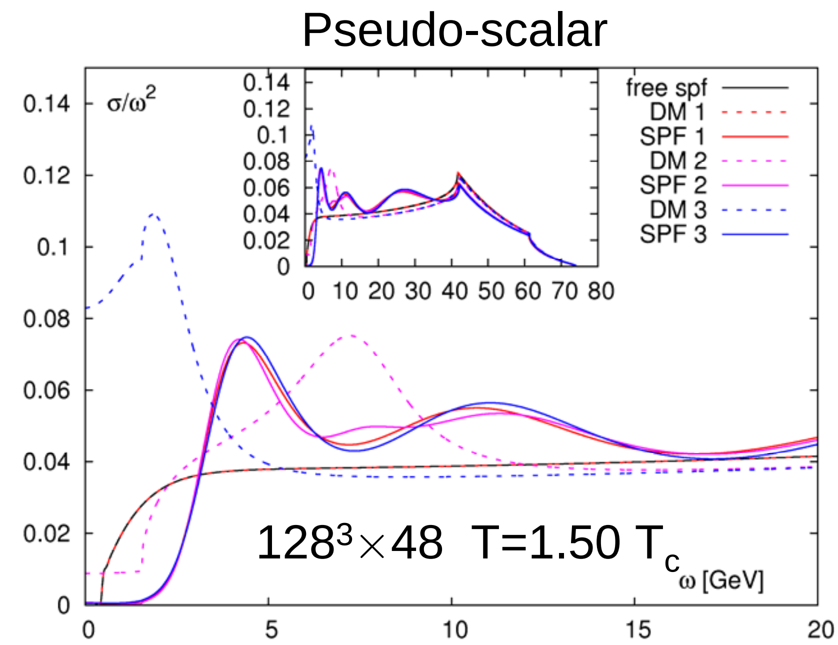
pronounced ground state peak close to J/ψ mass

no zero mode contributions observed below T_c in all channels

first peak independent of default model

MEM – Spectral function above T_c





N_σ=128 and N_τ=48 ($a^{-1}\approx$ 19 GeV) $\rightarrow$ cut-off effects well separated

small ω region accessible $\rightarrow$ hope to extract transport properties

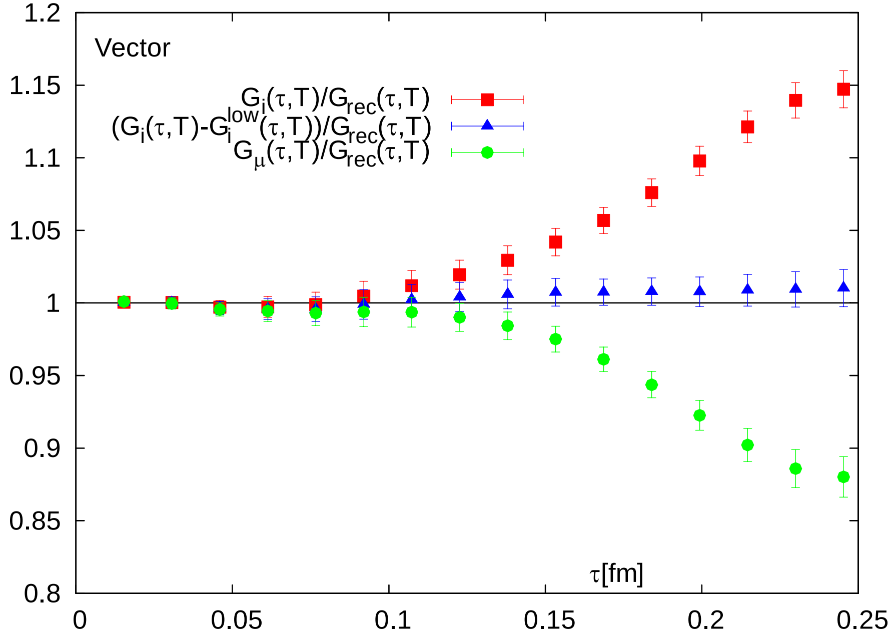
default model dependence only in small ω region $\rightarrow$ higher statistics needed

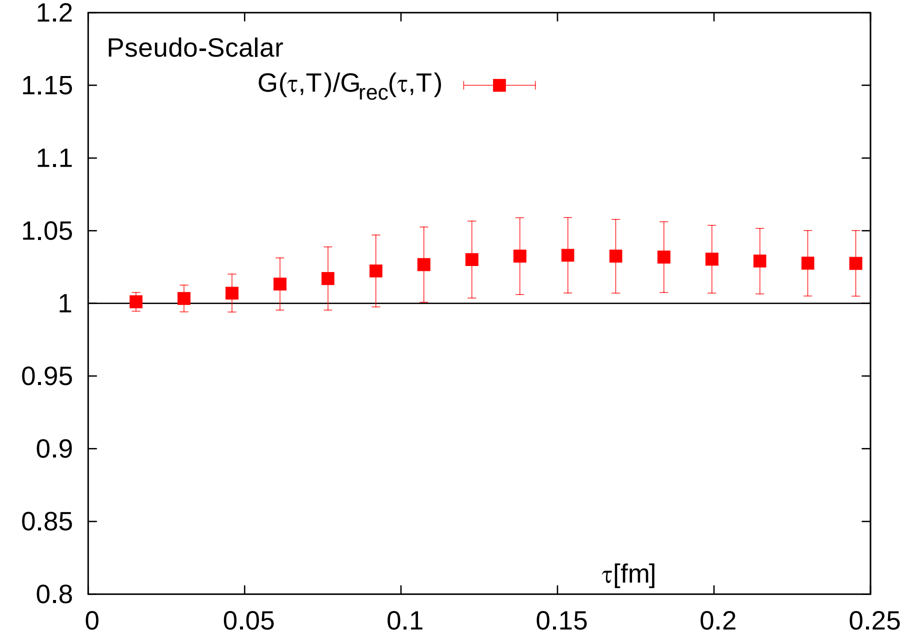
no default model dependence in the intermediate ω region

no zero-mode contribution in pseudo-scalar channel observed

no pronounced peak $\rightarrow$ bound states melted? / threshold enhancement?

Charmonium Correlators – Zero Mode Contributions





$$G_{rec}(\tau,T) = \int \sigma_0(\omega, 0.75T_c) K(\omega,\tau,T)$$

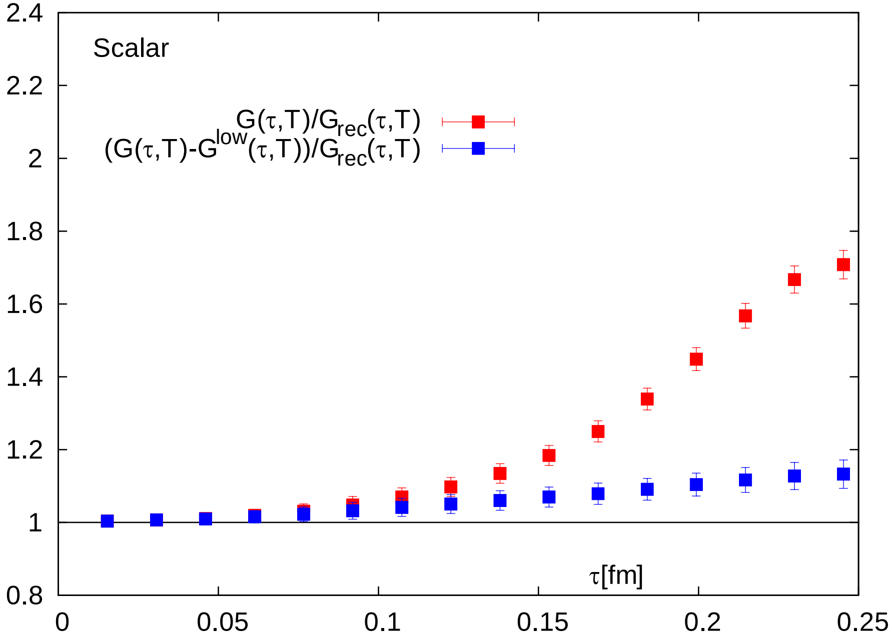
$$G_{rec}^{low}(\tau,T) = \int_0^{2m_c} \sigma_T(\omega,T) K(\omega,\tau,T)$$

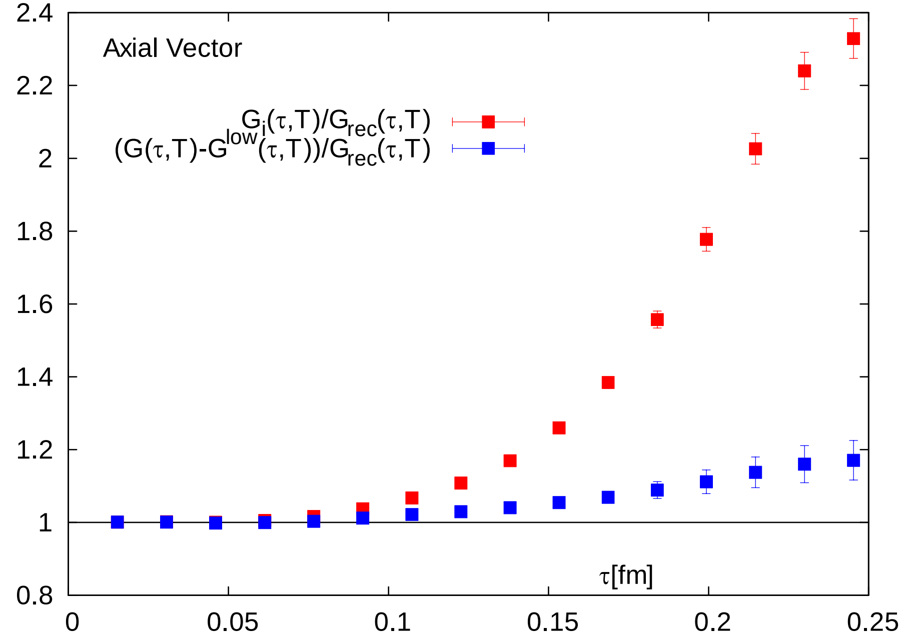
$$G_{\mu\mu}(\tau,T) = G_{ii}(\tau,T) + G_{44}(\tau,T)$$

- main T-effect due to zero-mode contribution
- well described by small ω-part of $\sigma_T(\omega$,T)
- smaller than $G_{00}(\tau$,T)=χ(T)T
- no zero-mode contribution in PS-channel

(similar to discussions by Umeda, Petreczky)

Charmonium Correlators – Zero Mode Contributions





$$G_{rec}(\tau,T) = \int \sigma_0(\omega, 0.75T_c) K(\omega,\tau,T)$$

$$G^{low}_{rec}(\tau,T) = \int_0^{2m_c} \sigma_T(\omega,T) K(\omega,\tau,T)$$

- larger zero-mode contribution in S-wave
- larger T-effect in the S-wave states

systematic uncertainties in reconstruction and low-ω part of spetral function

high quality data and small lattice spacing + large momenta (volume) needed

Conclusions and Outlook

Hadronic correlators for light quarks ($m_q=0$)

- Thermodynamic and Continuum Limit of screening masses!
- Spectral functions $\rightarrow$ Dilepton rates, Transport coefficients?
- Momentum dependence needs to be analyzed $\rightarrow$ Photonrates
- Comparison with HTL calculations and experiment

Charmonium hadronic correlators ($m_q=m_c$)

- What can we learn from Hadronic correlators on Dissociation?
- Momentum dependence vs. Spatial correlators/screening masses?
- Spectral functions $\rightarrow$ Dilepton rates, Transport coefficients?
- Momentum dependence needs to be analyzed $\rightarrow$ Photonrates
- Comparison with HTL/NRQCD calculations and experiment

Many Thanks to

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