Baryons across the deconfinement transition

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Introduction

QCD phase diagram:

- $T \neq 0$: from hadronic to quark-gluon plasma
- standard observables:
  - pressure, entropy, fluctuations
  - confinement, chiral symmetry
  - light mesons, quarkonia
  - ...
- less standard observables:
  - transport
  - ...
  - baryons

Mesons/baryons in a medium

mesons in a medium very well studied

- thermal broadening and mass shift in hadronic phase
- deconfinement/melting in the QGP
- quarkonia survival as thermometer
- conductivity/dileptons from vector current
- chiral symmetry restoration

relatively easy on the lattice

- high-precision correlators

what about baryons?

Outline

baryons across the deconfinement transition:

three parts:

- medium effects and parity doubling
- nucleon spectral functions at very high temperature
- baryon spectral functions from lattice correlators

Outline

baryons across the deconfinement transition:

- anisotropic $N_f = 2 + 1$ Wilson-clover ensembles

FASTSUM collaboration

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Outline

baryons across the deconfinement transition:

- anisotropic $N_f = 2 + 1$ Wilson-clover ensembles

this work:

GA, Chris Allton, Simon Hands, Benjamin Jäger, Kristi Praki and Jonivar Skullerud

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$+$ Davide de Boni

in preparation

Baryons in a medium

lattice studies of baryons at finite temperature very limited

- screening masses De Tar and Kogut 1987
- ... with a small chemical potential QCD-TARO: Pushkina, de Forcrand, Kim, Nakamura, Stamatescu et al 2005
- temporal correlators Datta, Gupta, Mathur et al 2013

not much more (afaik) . . . but what about:

- in-medium modification?
- chiral symmetry?
- parity doubling?
- spectral functions?
- ...

Nucleons in a medium

- simplest nucleon operator

$$O_N(\mathbf{x},\tau) = \epsilon_{abc} u_a(\mathbf{x},\tau) \left[u_b^T(\mathbf{x},\tau) \mathcal{C} \gamma_5 d_c(\mathbf{x},\tau) \right]$$

- essential difference with mesons: role of parity

$$\mathcal{P} O_N(\mathbf{x},\tau) = \gamma_4 O_N(-\mathbf{x},\tau)$$

- positive/negative parity operators

$$O_{N_\pm}(\mathbf{x},\tau) = P_\pm O_N(\mathbf{x},\tau) \qquad\qquad P_\pm = \frac{1}{2}(1 \pm \gamma_4)$$

- euclidean correlators (zero momentum)

$$G_\pm(\tau) = \int d^3x \, \left\langle \mathrm{tr}\, O_{N_\pm}(\mathbf{x},\tau) \overline{O}_{N_\pm}(\mathbf{0},0) \right\rangle$$

Mesons/baryons in a medium

meson versus baryon correlators

- meson correlators symmetric around $\tau = 1/2T$
- baryon correlators not symmetric

for $G_+(\tau)$:

- positive parity state propagates with τ
- negative parity state propagates with $1/T - \tau$
- one correlator contains both the positive and negative parity channel
- follows from discrete symmetries
- minimum typically not at $\tau = 1/2T$

Nucleons in a medium

- example: nucleon ground state

$$G_\pm(\tau) = A_\pm e^{-m_\pm \tau} + A_\mp e^{-m_\mp (1/T - \tau)}$$

- nucleon: $m_+ = m_N \ = 0.939$ GeV
  $m_- = m_{N^*} = 1.535$ GeV
- no parity doubling: manifestation of chiral symmetry breaking

parity doubling:

- sufficient condition is unbroken chiral symmetry
- degeneracy between $+/-$ parity channels

$$G_\pm(\tau) = G_\mp(\tau) = G_\pm(1/T - \tau)$$

On the lattice

FASTSUM ensembles

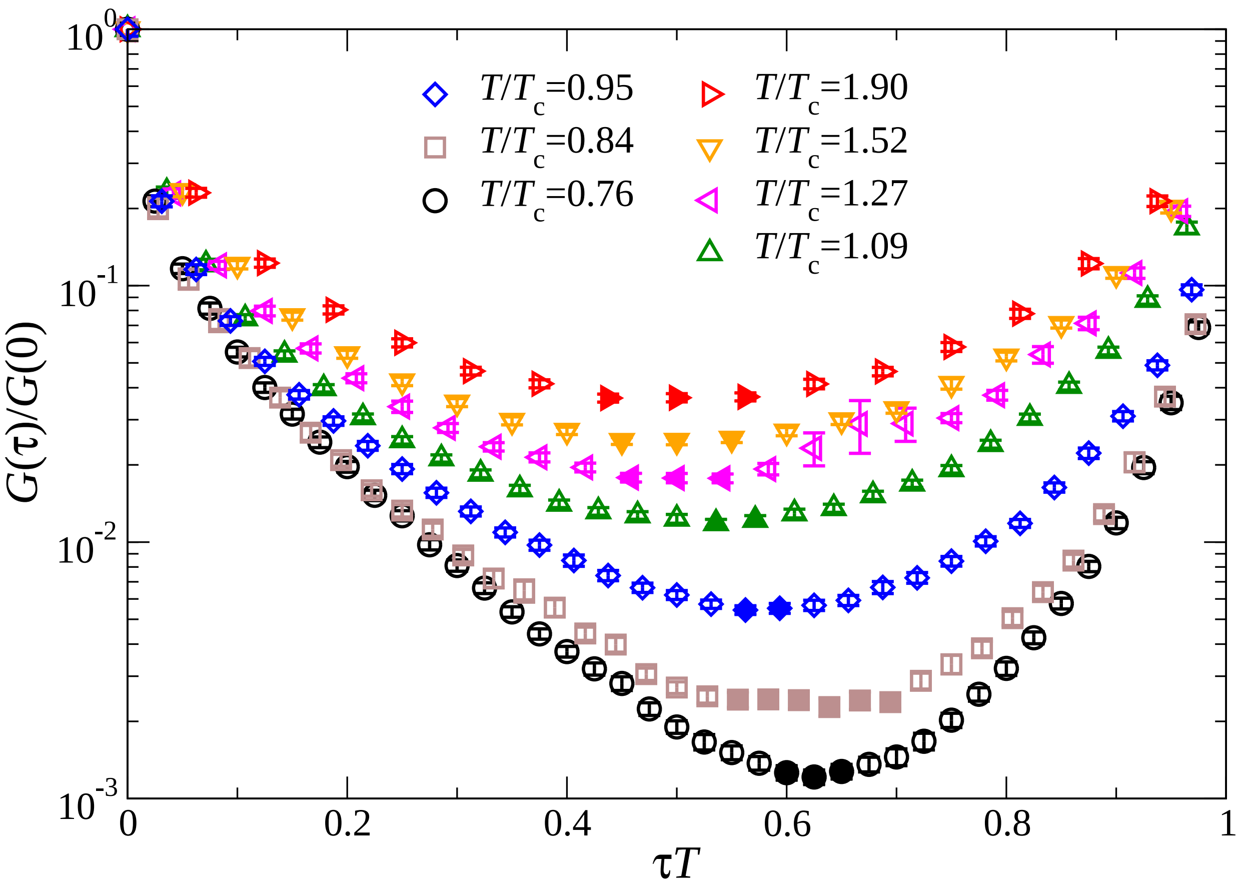
- $N_f = 2+1$ dynamical quark flavours, Wilson-clover
- many temperatures, below and above T_c
- anisotropic lattice, $a_s/a_\tau = 3.5$, many time slices
- strange quark: physical value
- two light flavours: somewhat heavy $m_\pi = 384(4)$ MeV

N_s	24	32	24	24	32/24	32/24	32/24	24	32/24
N_τ	128	48	40	36	32	28	24	20	16
T/T_c	0.24	0.63	0.76	0.84	0.95	1.09	1.27	1.52	1.90
$N_{\rm cfg}$	400	600	500	500	500	500	500	1000	1000

- tuning and $N_\tau = 128$ data from HadSpec collaboration

Lattice correlators

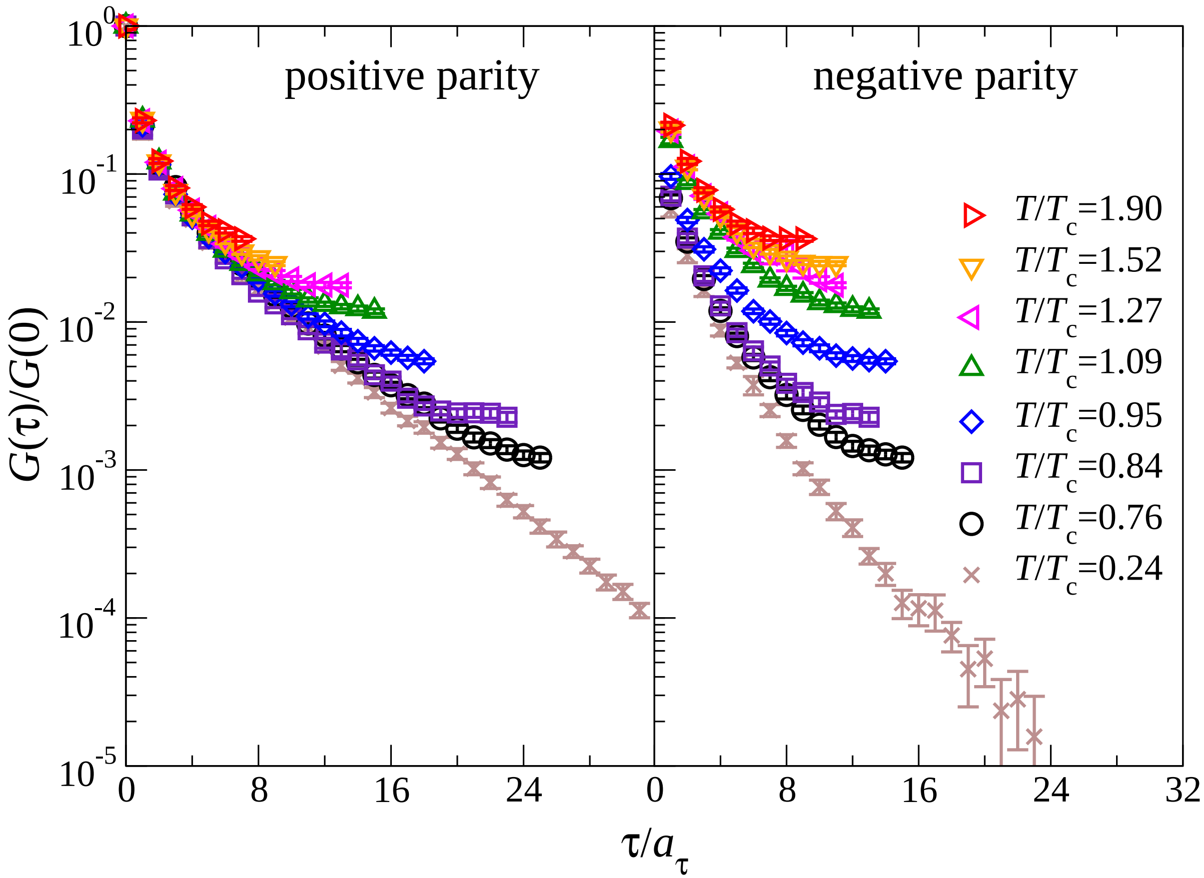
- euclidean correlator $G_+(\tau)$



- not symmetric around $\tau = 1/2T$ below T_c
- more symmetric as temperature increases

Nucleons in a medium

- separate positive and negative parity channels



- below T_c: $m_- > m_+$ $\qquad m_+ = m_N \qquad m_- = m_{N*}$
- much more T dependence in negative-parity channel

Nucleons in a medium

- exponential fits/effective masses below T_c

T/T_c	$a_\tau m_N$	$a_\tau m_{N^*}$	m_N [GeV]	m_{N^*} [GeV]
0.24	0.213(5)	0.33(5)	1.20(3)	1.9(3)
0.76	0.209(16)	0.28(3)	1.18(9)	1.6(2)
0.84	0.192(17)	0.28(2)	1.08(9)	1.6(1)
0.95	0.198(25)	0.22(4)	1.12(14)	1.3(2)

- $m_\pm$ larger than in Nature (probably $\sim$ heavy pions)
- mass splitting $m_{N^*} - m_N \sim 700$ MeV (600 in Nature)
- nucleon ground state largely T independent
- N^* ground state significant temperature dependence
- relevant for heavy-ion phenomenology?

Nucleons in a medium

parity doubling

- correlator ratio

$$R(\tau) = \frac{G_+(\tau) - G_+(1/T - \tau)}{G_+(\tau) + G_+(1/T - \tau)}$$

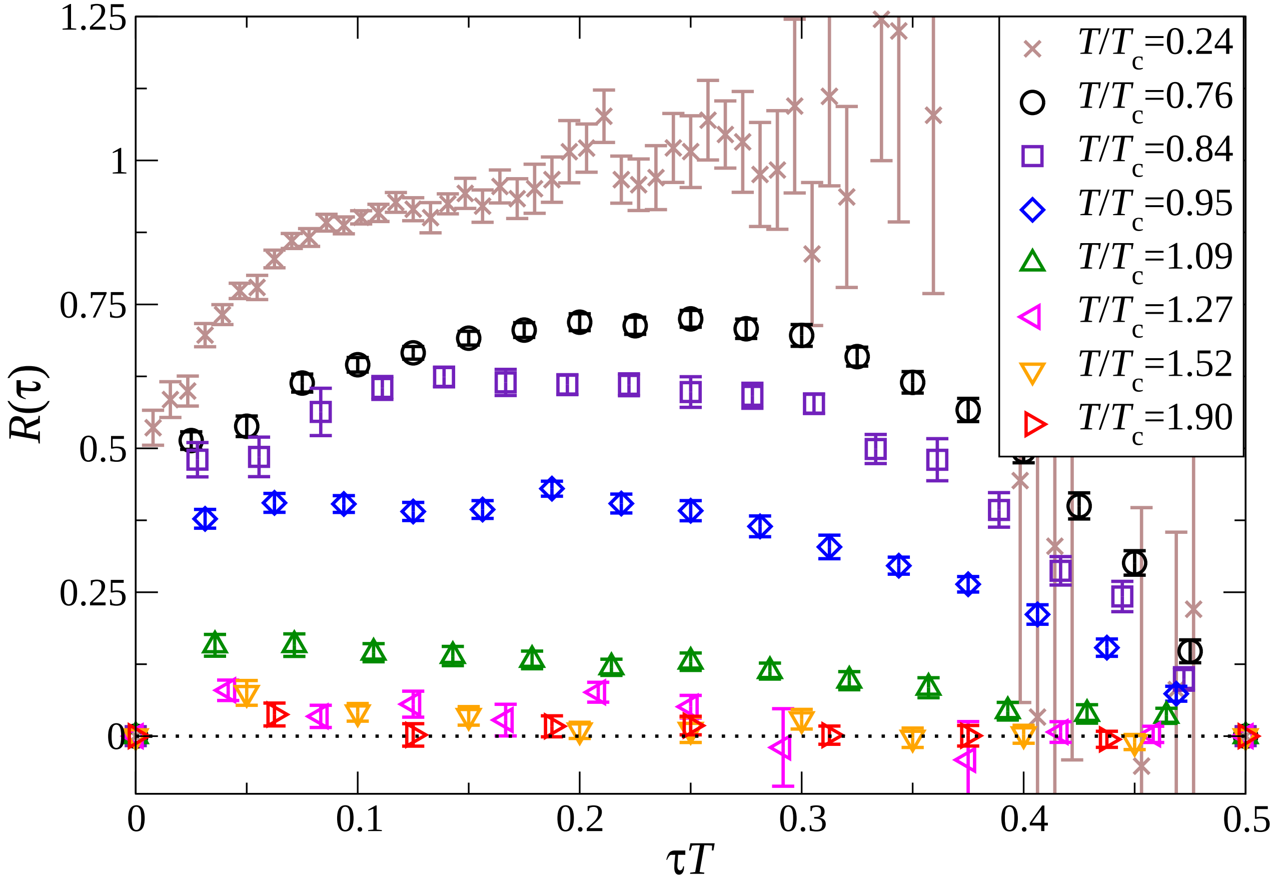
if

- no parity doubling and $m_- \gg m_+$: $R(\tau) = 1$
- parity doubling: $R(\tau) = 0$

note

- $R(1/T - \tau) = -R(\tau)$ and $R(1/2T) = 0$

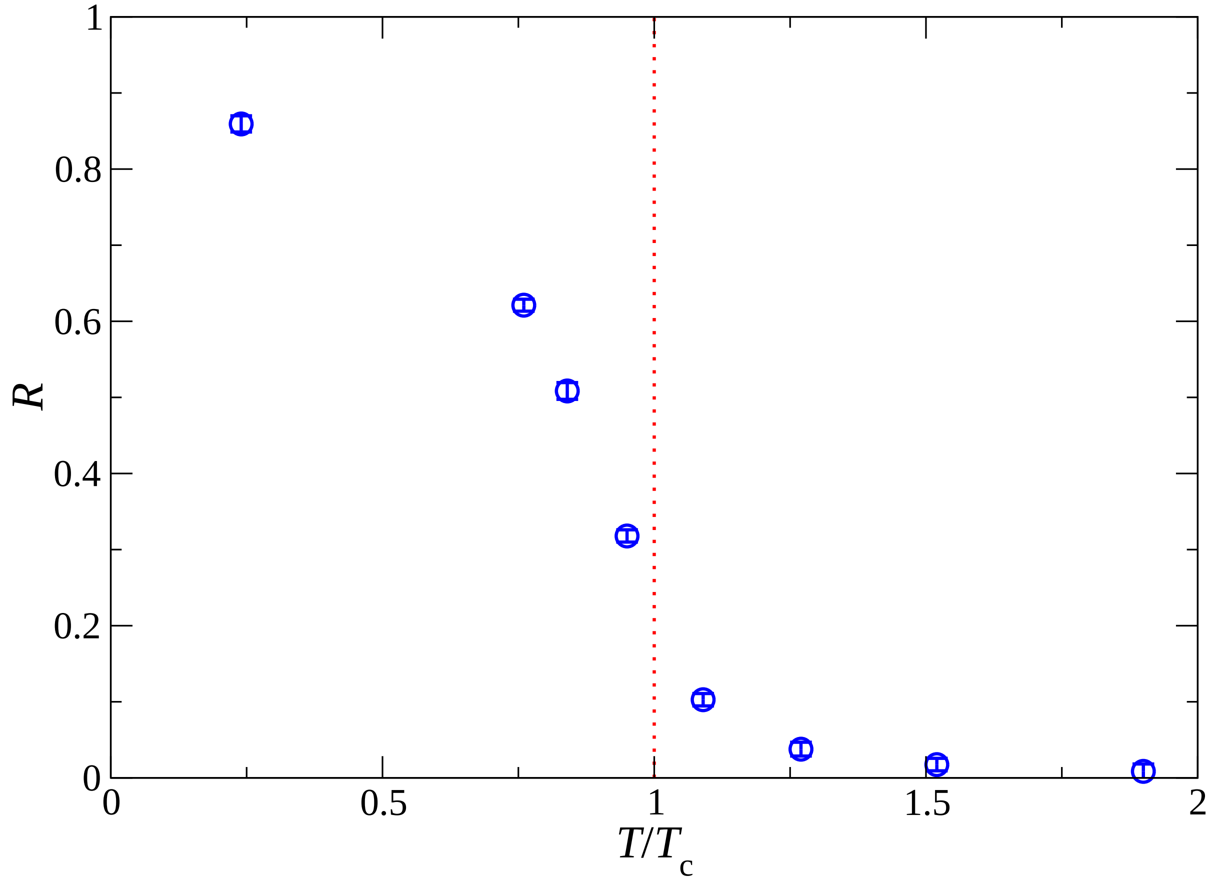
Parity doubling



- ratio close to 1 below T_c, decreasing uniformly
- ratio close to 0 above T_c, parity doubling
- technical note: smearing essential

Quasi-order parameter

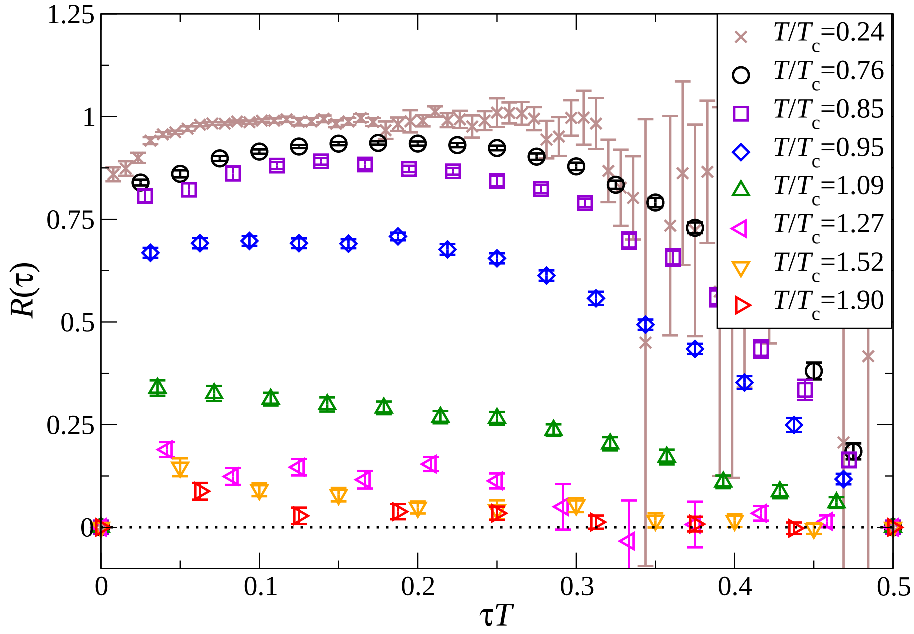
- integrated ratio $$R = \frac{\sum_{n=1}^{\frac{1}{2}N_\tau - 1} R(\tau_n)/\sigma^2(\tau_n)}{\sum_{n=1}^{\frac{1}{2}N_\tau - 1} 1/\sigma^2(\tau_n)}$$

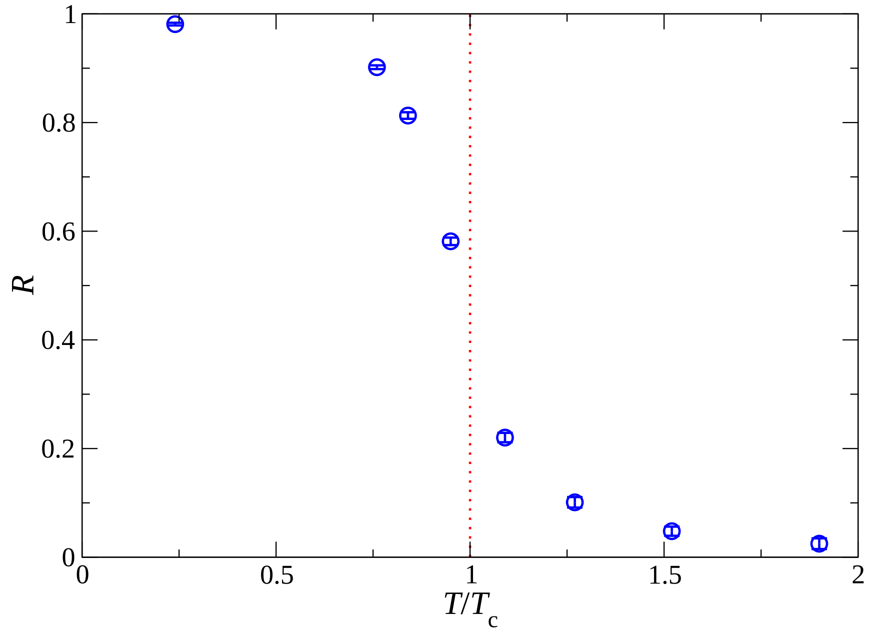


- crossover behaviour, tied with deconfinement transition

Quasi-order parameter

- signal depends quantitatively on interpolating operator
- different (more complicated) operator
- more suppression of excited states





- but semi-quantitative agreement
- parity doubling coincides with deconfinement transition: tied to restoration of chiral symmetry

Spectral functions

- mesons/bosonic operators $\tilde{\tau} = \tau - 1/2T$

$$G(\tau, \mathbf{p}) = \int \frac{d\omega}{2\pi} K(\tau, \omega) \rho(\omega, \mathbf{p}) \qquad K(\tau, \omega) = \frac{\cosh(\omega\tilde{\tau})}{\sinh(\omega/2T)}$$

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- baryons are fermionic: matrix in Dirac space

$$G(x) = \langle O(x)\overline{O}(0)\rangle = \sum_\mu \gamma_\mu G_\mu(x) + 1\!\!1 G_m(x)$$

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- spectral relations (dropping momentum dependence)

$$G_4(\tau) = \int \frac{d\omega}{2\pi} K_{\rm e}(\tau,\omega)\rho_4(\omega), \qquad K_{\rm e}(\tau,\omega) = \frac{\cosh(\omega\tilde{\tau})}{\cosh(\omega/2T)}$$

$$G_{i,m}(\tau) = \int \frac{d\omega}{2\pi} K_{\rm o}(\tau,\omega)\rho_{i,m}(\omega), \qquad K_{\rm o}(\tau,\omega) = -\frac{\sinh(\omega\tilde{\tau})}{\cosh(\omega/2T)}$$

Kernels

- mesons/bosonic operators $\tilde{\tau} = \tau - 1/2T$

$$K(\tau, \omega) = \frac{\cosh(\omega\tilde{\tau})}{\sinh(\omega/2T)} = [1 + n_B(\omega)]\, e^{-\omega\tau} + n_B(\omega) e^{\omega\tau}$$

- baryons/fermionic operators

$$K_{\rm e}(\tau, \omega) = \frac{\cosh(\omega\tilde{\tau})}{\cosh(\omega/2T)} = [1 - n_F(\omega)]\, e^{-\omega\tau} + n_F(\omega) e^{\omega\tau}$$

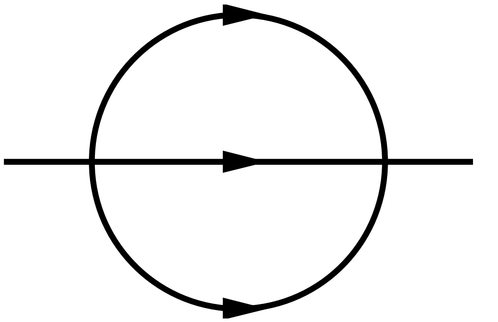
$$K_{\rm o}(\tau, \omega) = -\frac{\sinh(\omega\tilde{\tau})}{\cosh(\omega/2T)} = [1 - n_F(\omega)]\, e^{-\omega\tau} - n_F(\omega) e^{\omega\tau}$$

- at $T = 0$: all kernels $e^{-\omega\tau}$

Free spectral functions

lowest order in perturbation theory

$G(x) = \langle O(x)\overline{O}(0)\rangle$ $\qquad O(x) \sim uu^T \mathcal{C}\gamma_5\, d(x)$



two-loop diagram $\qquad (c = 4, i, m)$

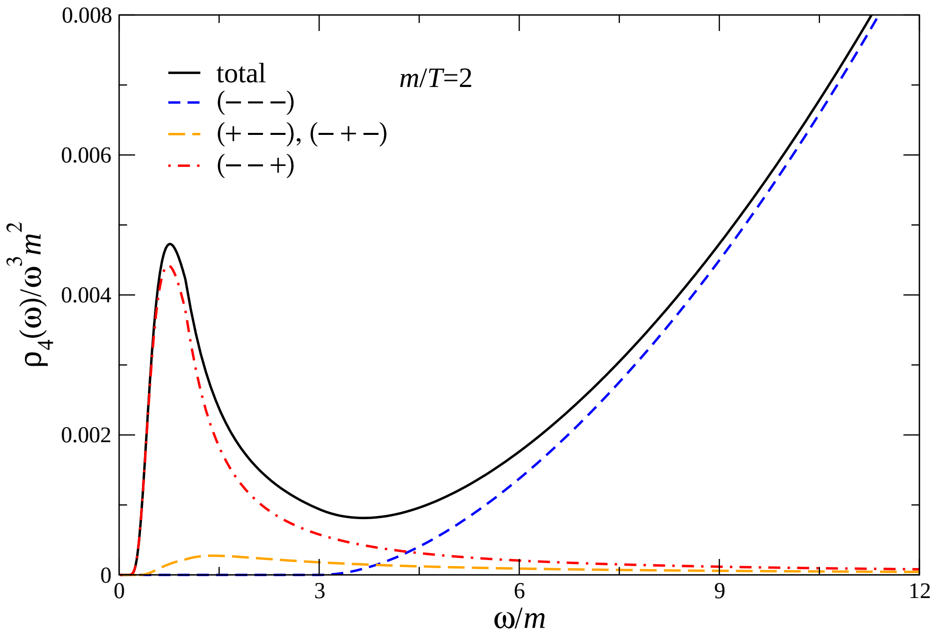
$$\rho_c(\omega) = 3\int_{\mathbf{k}_{1,2,3}} d\Phi_{123} \sum_{s_j=\pm} 2\pi\delta\left(\omega + \sum\nolimits_j s_j\omega_{\mathbf{k}_j}\right)[\text{stat.}]f_c(\omega, s_i, \mathbf{k}_i)$$

with

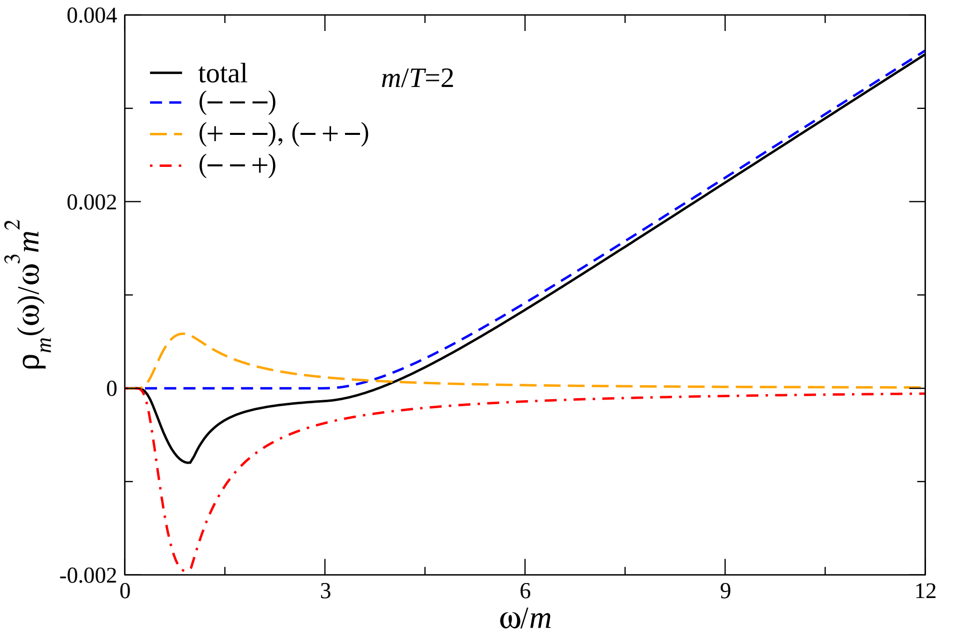
$$d\Phi_{123} = \prod_{j=1}^{3} \frac{d^3k_j}{(2\pi)^3 2\omega_{\mathbf{k}_j}}(2\pi)^3\delta(\mathbf{k}_1 + \mathbf{k}_2 + \mathbf{k}_3)$$

$$[\text{stat.}] = n_F(s_1\omega_{\mathbf{k}_1})n_F(s_2\omega_{\mathbf{k}_3})n_F(s_3\omega_{\mathbf{k}_3}) + n_F(-s_1\omega_{\mathbf{k}_1})n_F(-s_2\omega_{\mathbf{k}_3})n_F(-s_3\omega_{\mathbf{k}_3})$$

Free spectral functions



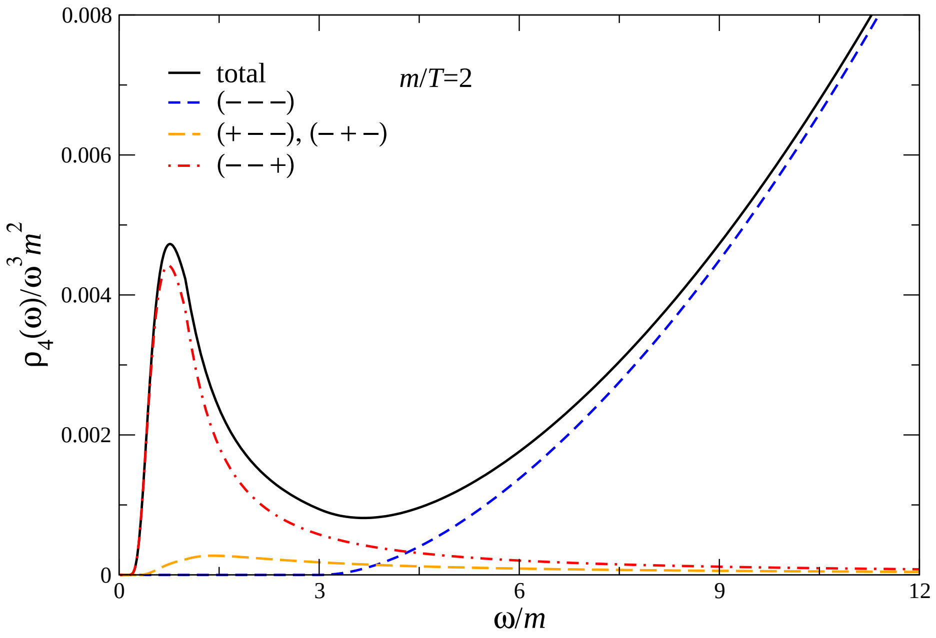
$\rho_4(\omega)$



$\rho_m(\omega)$

- decay: $\omega > 3m$ with m quark mass
- at $T > 0$ scattering contributions for all ω
- large ω: thermal contributions suppressed
- $\rho_m(\omega)$ not positive definite

Free spectral functions



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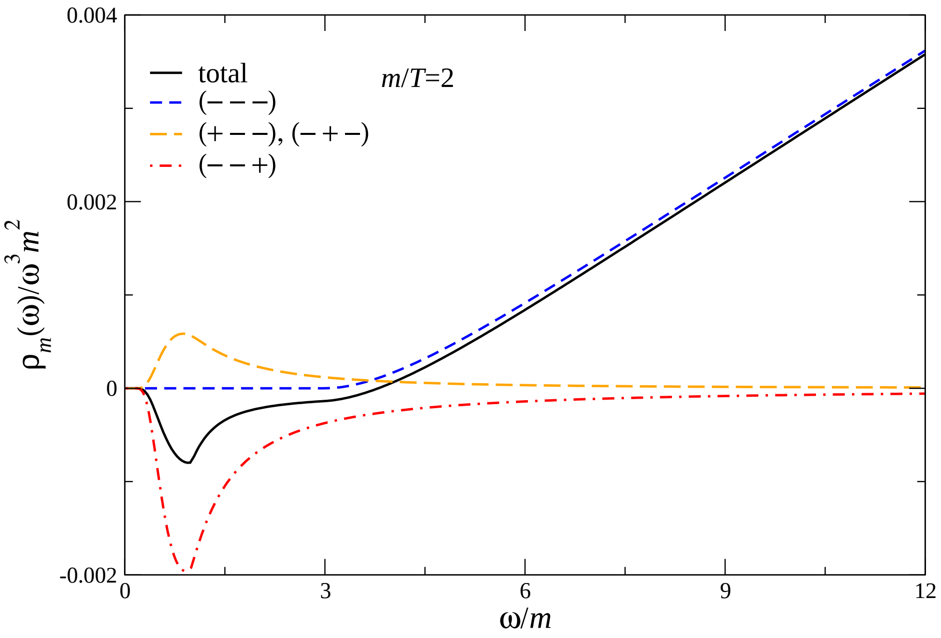


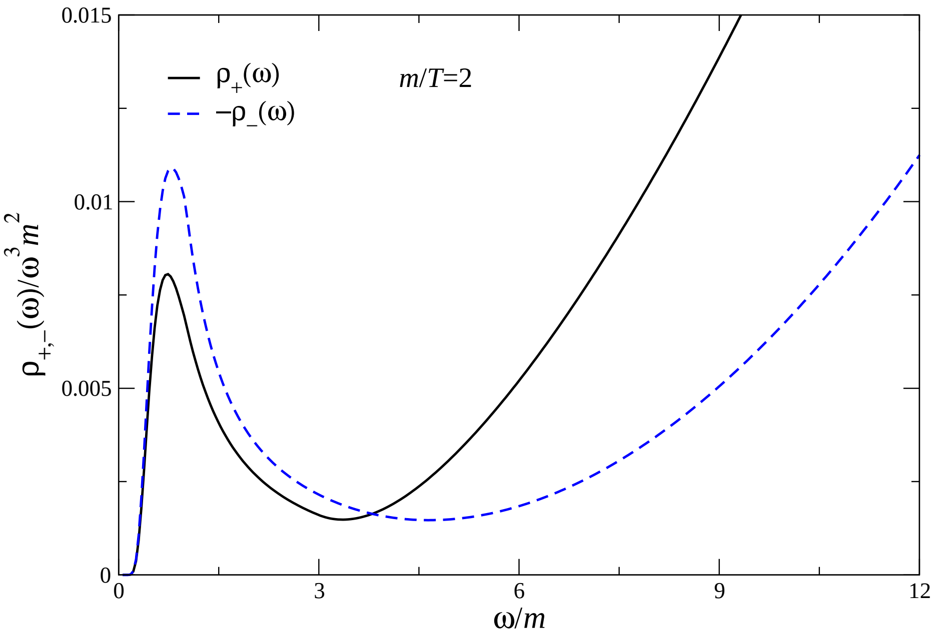
$\rho_m(\omega)$

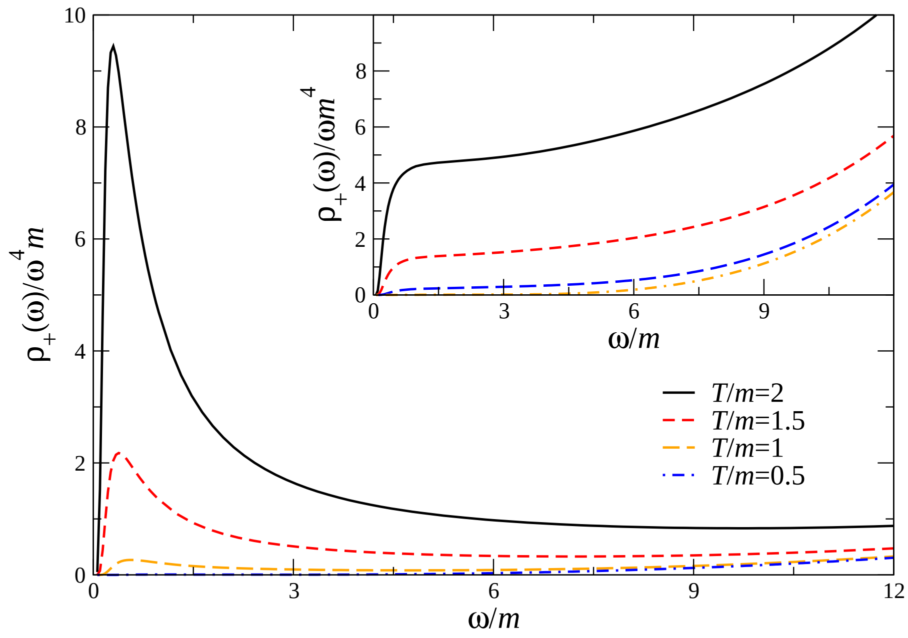
$\omega \gg T \gg m$

$$\rho_4(\omega) = \frac{5\omega^5}{2048\pi^3}\left(1 + \frac{112\pi^4}{3}\frac{T^4}{\omega^4} + \ldots\right)$$

$$\rho_m(\omega) = \frac{7m\omega^4}{512\pi^3}\left(1 - 4\pi^2\frac{T^2}{\omega^2} + \ldots\right)$$

Free spectral functions





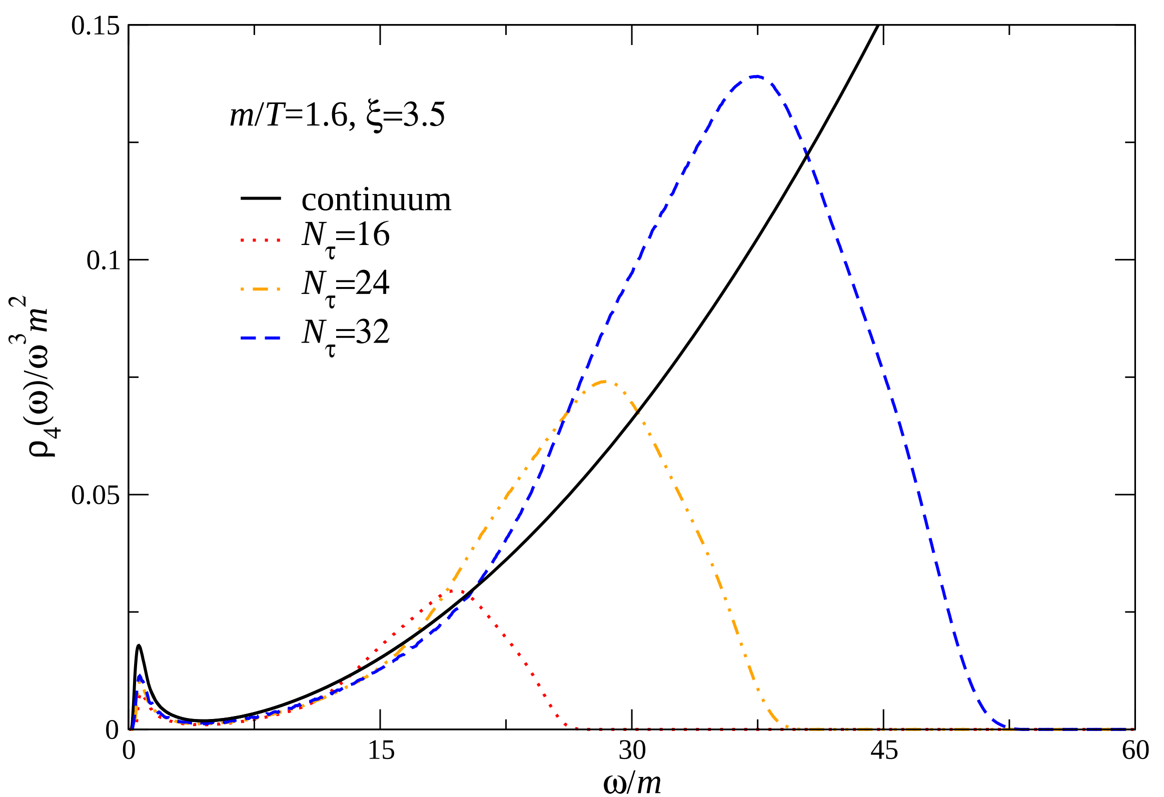
$$\rho_\pm(\omega) = \frac{1}{2}\left[\rho_m(\omega) \pm \rho_4(\omega)\right]$$

$$\rho_+(\omega)$$

- thermal enhancement at $\omega \sim T \sim m$
- apparent peak depends on presentation/normalisation
- exponentially suppressed as $\omega \to 0$
- $\pm\rho_\pm(\omega) \geq 0$ $\qquad \rho_-(\omega) = -\rho_+(-\omega)$

Lattice free spectral functions

- lattice dispersion relation, sum over Brillouin zones
- maximal energy $\omega = 3\omega_{\mathbf{k},\mathrm{max}}$
- similar to mesons Karsch et al 03, GA & Martínez Resco 05
- no cusps due to two-loop Brillouin sum



Nucleon spectral functions

construct spectral functions from euclidean correlator

Nucleon spectral functions

construct spectral functions from euclidean correlator

- interested in $\rho_\pm(\omega)$ note: $\rho_+(-\omega) = -\rho_-(\omega)$
- spectral relation

$$G_+(\tau) = 2\int_{-\infty}^{\infty} \frac{d\omega}{2\pi}\left[K_{\rm o}(\tau,\omega)\rho_m(\omega) + K_{\rm e}(\tau,\omega)\rho_4(\omega)\right]$$

$$= 2\int_{-\infty}^{\infty} \frac{d\omega}{2\pi}\,\frac{e^{-\omega\tau}}{1+e^{-\omega/T}}\,\rho_+(\omega)$$

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$$= 2\int_{-\infty}^{\infty} \frac{d\omega}{2\pi} \frac{e^{-\omega\tau}}{1+e^{-\omega/T}}\,\rho_+(\omega)$$

- all information contained in $\rho_+(\omega)$:
  - positive parity channel at $\omega > 0$
  - negative parity channel at $\omega < 0$
- $\rho_4(\omega)$, $\rho_+(\omega)$, $-\rho_-(-\omega) \geq 0$ for all ω

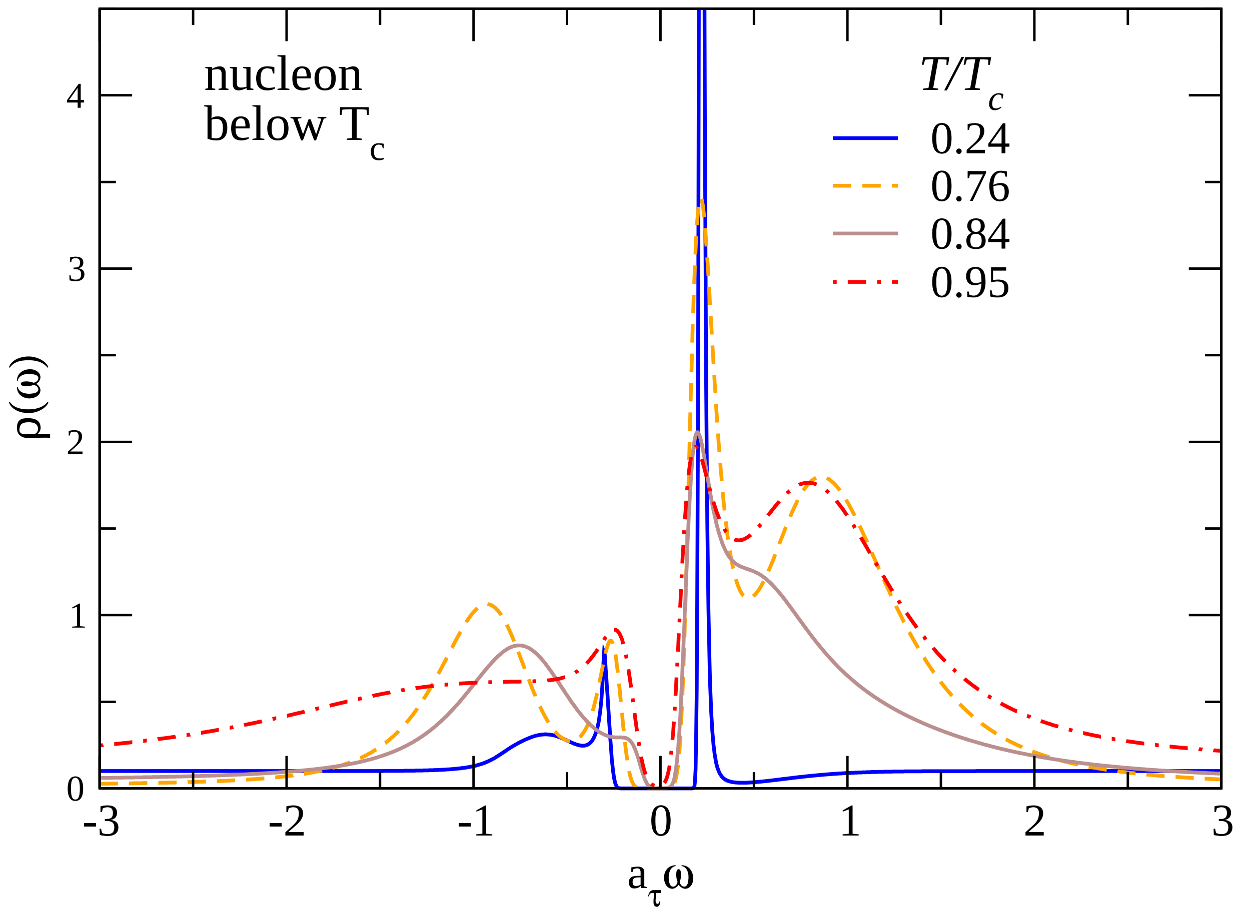
Nucleon spectral functions

construct spectral functions from euclidean correlator

- use maximal entropy method
- previously applied to a variety of problems (quarkonia, transport)
- depends on high statistics, many time slices (anisotropic lattice)
- default model: no features put in, $\rho(\omega) = m_0$

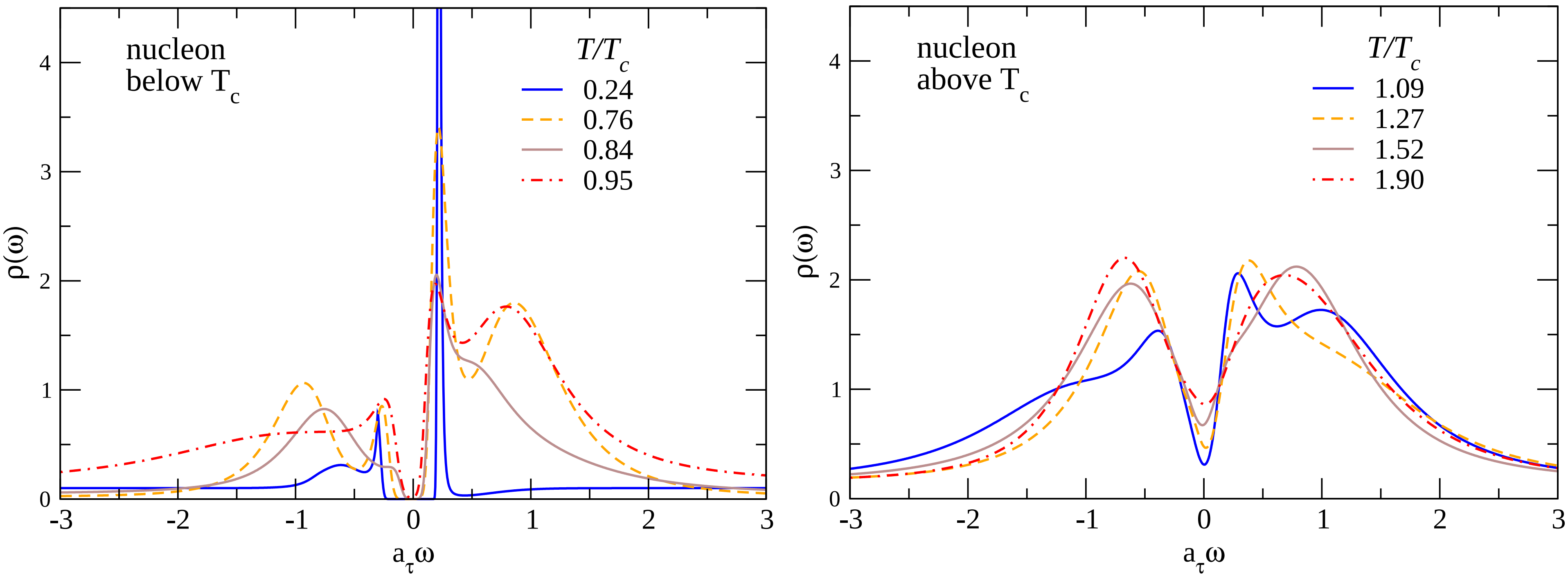
`all results preliminary`

Nucleon spectral functions



- $\omega > 0$ positive parity: nucleon stable below T_c
- $\omega < 0$ negative parity: parity partner visible, spectral weight moves inwards, towards parity doubling

Nucleon spectral functions



- above T_c: degeneracy in spectral functions emerges
- consistent with correlator analysis
- lattice artefacts (from free analysis) when $a_\tau|\omega| \gtrsim 1.4$
- larger ω not constrained by data

Baryon spectral functions

other channels: $\Delta_+(1232)$, $\Delta_-(1700)$ $\quad \delta_\Delta \equiv \frac{(m_- - m_+)}{(m_- + m_+)} = 0.16$

Baryon spectral functions

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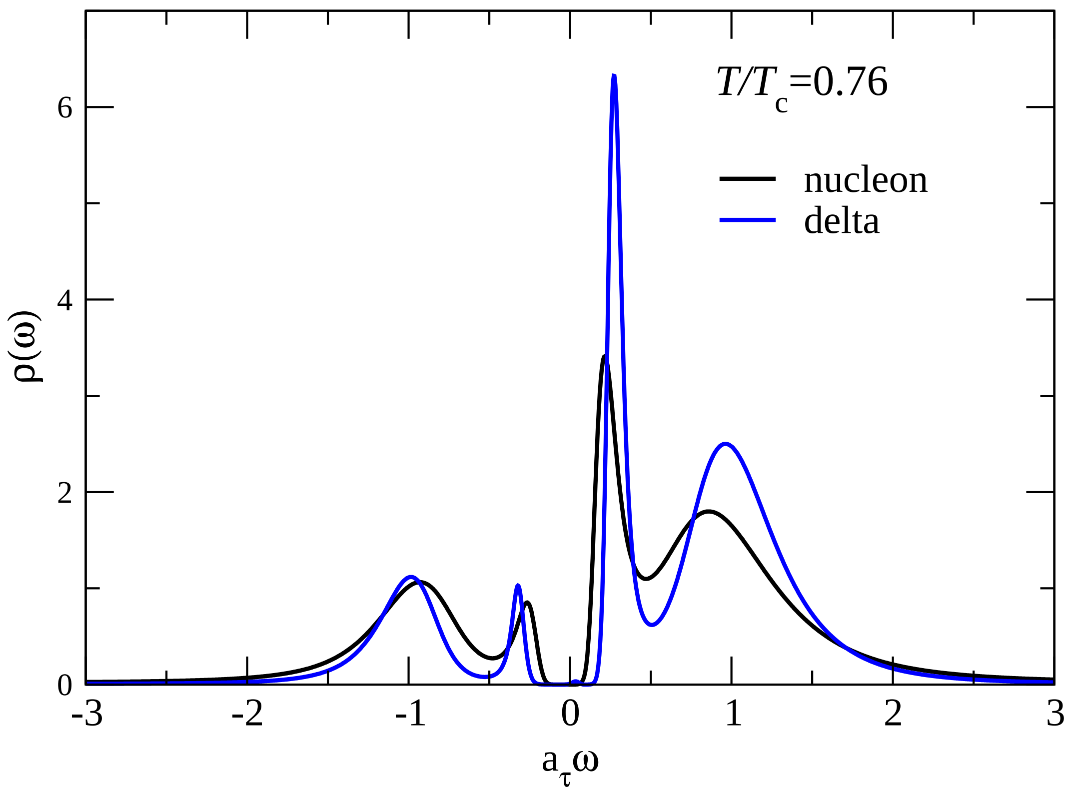
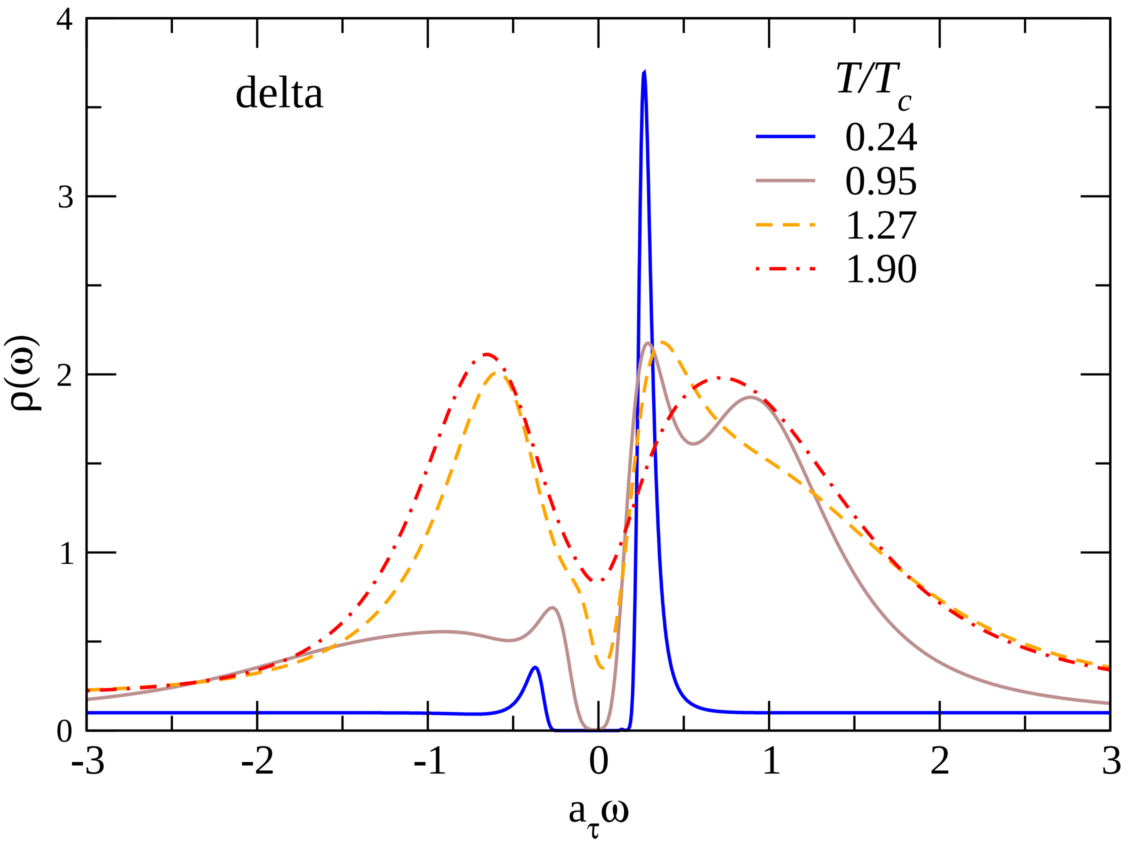


- both $\pm$ parity groundstates present
- fit: $m_+ = 1.47$ GeV, $m_- = 2.08$ GeV, $\delta_\Delta = 0.17$
- $m_\Delta - m_N = 270$ MeV (here) and 294 MeV (Nature)

Baryon spectral functions

parity doubling in the Δ channel



- full lines: below T_c
- dashed lines: above T_c

same qualitative behaviour as for the nucleons

Summary: baryons in medium

- N mostly temperature independent below T_c
- significant T dependence in N^* channel
  reduction in mass
- parity doubling above T_c
- closely linked to deconfinement transition and chiral symmetry restoration
- consistent with spectral function analysis

outlook:

- phenomenological consequences?
- Wilson fermions: no chiral symmetry at short distances
- what happens with manifestly chiral fermions?