Across the deconfinement transition: parity doubling in the nucleon sector & diffusion of light quarks

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Introduction

QCD phase diagram:

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

Outline

across the deconfinement transition:

- nucleons: medium effects and parity doubling

- conductivity and charge diffusion

all results:

- anisotropic $N_f = 2 + 1$ ensembles with Wilson-clover fermions
- part of *FASTSUM* collaboration

nucleons across the deconfinement transition

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

arXiv:1502.03603 [hep-lat]

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?

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?
- ...

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

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

Mesons/baryons in a medium

meson versus baryon correlators

- meson correlators symmetric around $\tau = 1/2T$
- baryon correlators not symmetric
- contain both positive and negative parity channels

for $G_+(\tau)$:

- positive parity state propagates with τ
- negative parity state propagates with $1/T - \tau$
- minimum typically not at $\tau = 1/2T$

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

Baryons 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:

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

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

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_{cfg}	400	600	500	500	500	500	500	1000	1000

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

Nucleons in a medium

- various interpolation operators, here simplest one

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

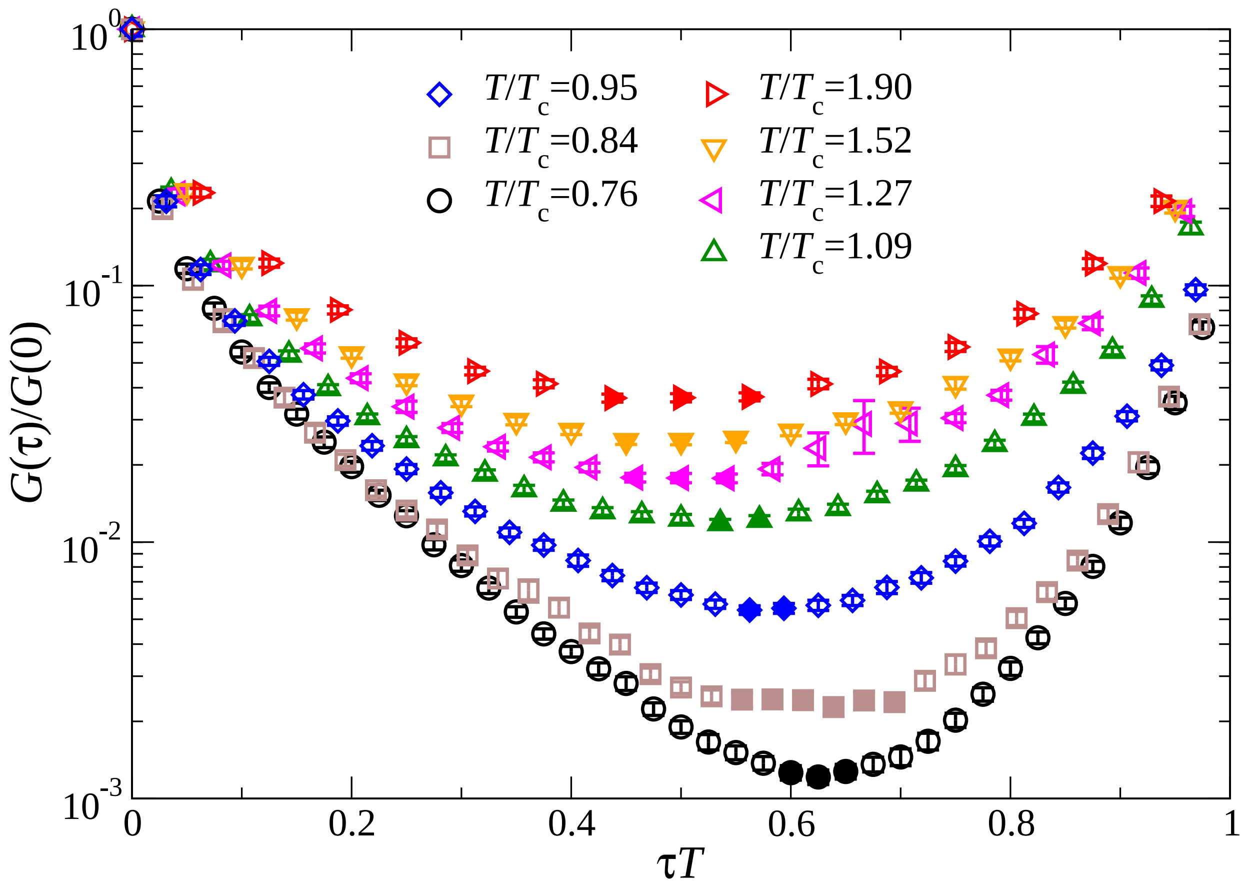
- Gaussian smearing for multiple sources and sinks
- same smearing parameters at all temperatures

questions:

- in-medium effects below T_c
- parity doubling
- deconfinement transition, chiral symmetry

Lattice correlators

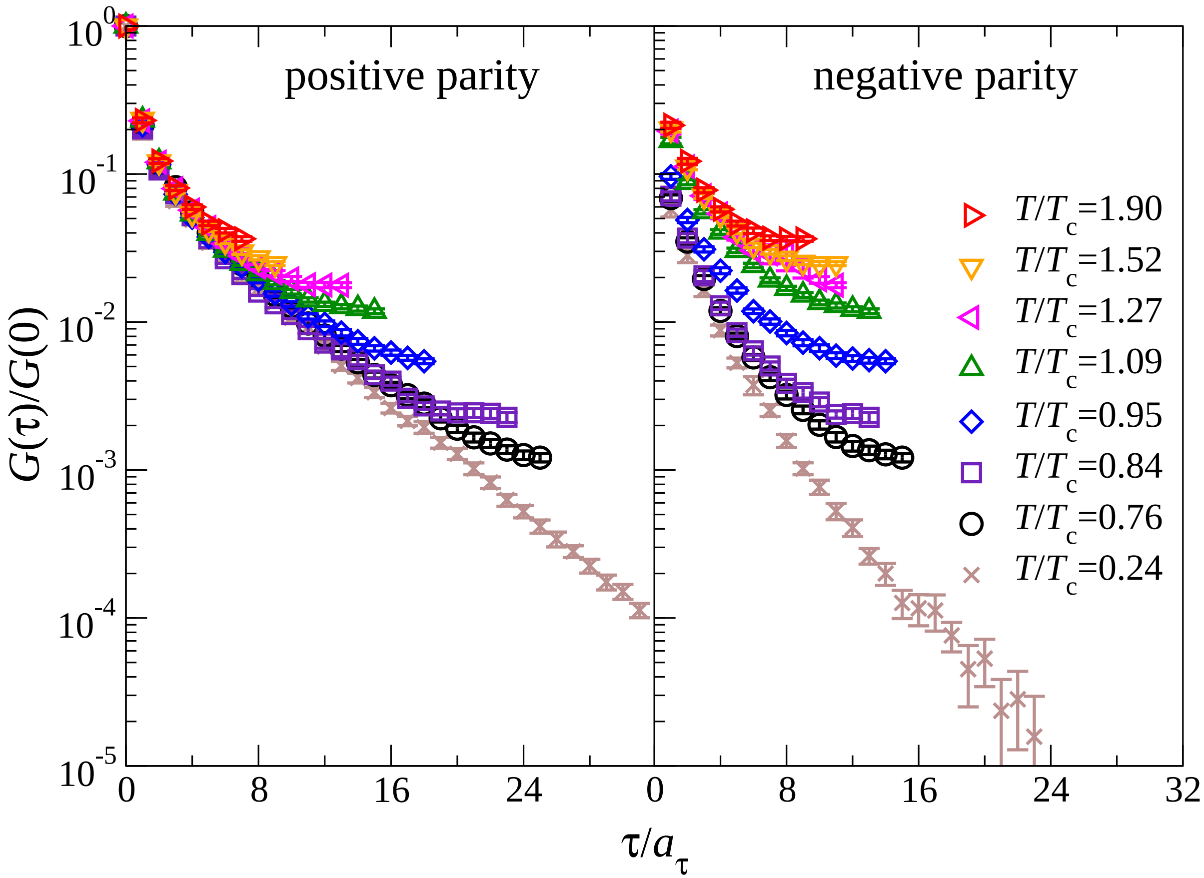
- euclidean correlator $G_+(\tau)$



- 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: $m_- > m_+$ $\qquad m_+ = m_N, m_- = m_{N*}$
- 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
- 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

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

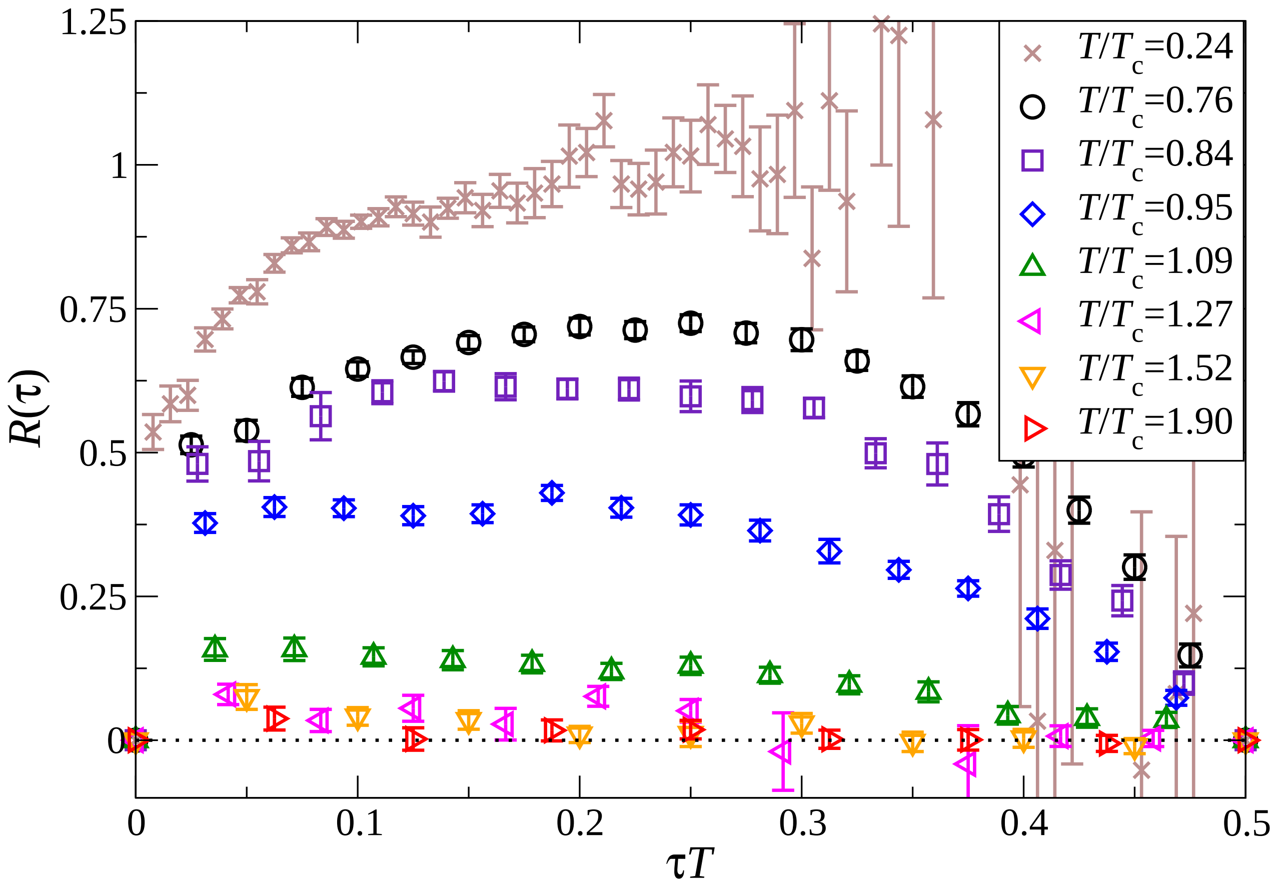
if

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

note

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

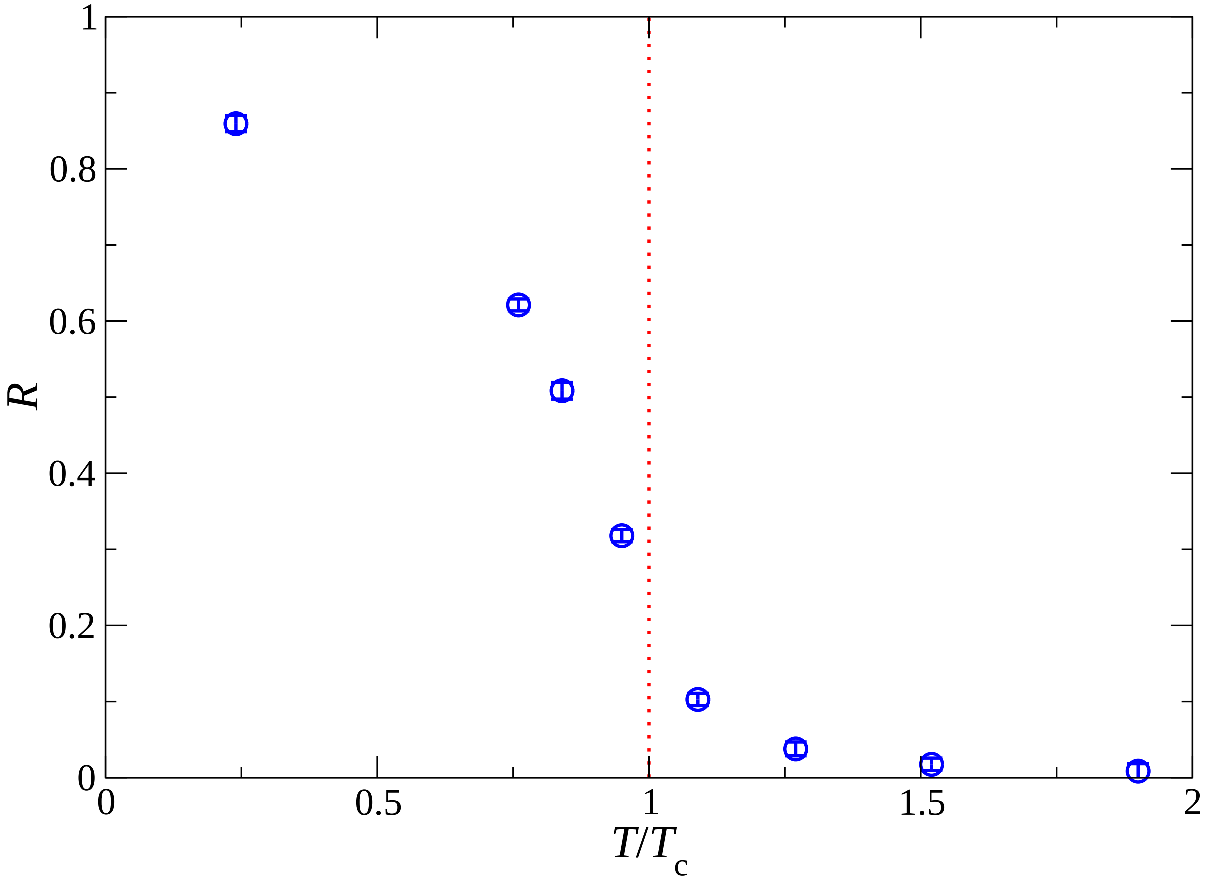
Parity doubling



- 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

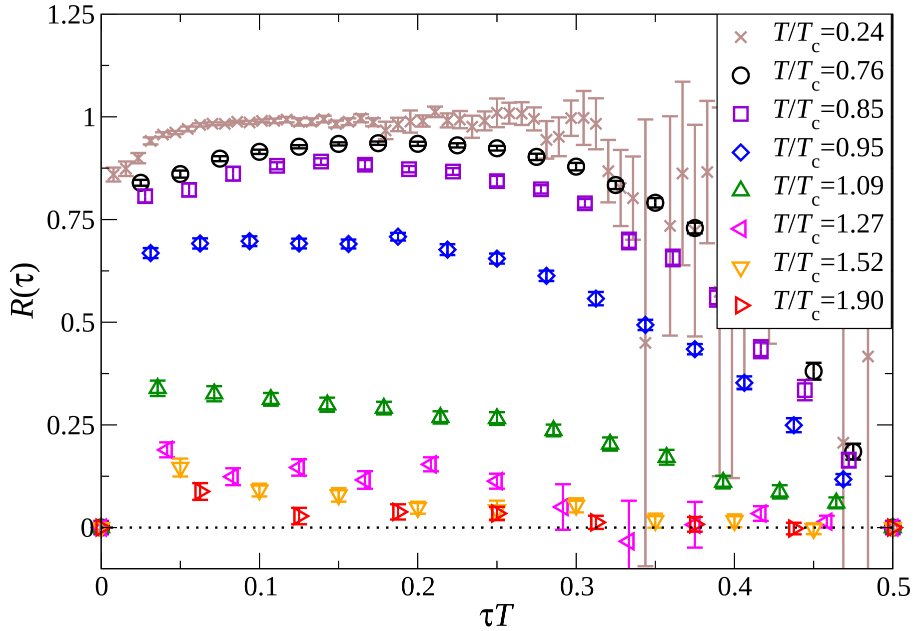
- integrated ratio $$R = \frac{\sum_{n=1}^{\frac{1}{2}N_\tau - 1} R(\tau_n)/\sigma^2(\tau_n)}{\sum_{n=1}^{\frac{1}{2}N_\tau - 1} 1/\sigma^2(\tau_n)}$$

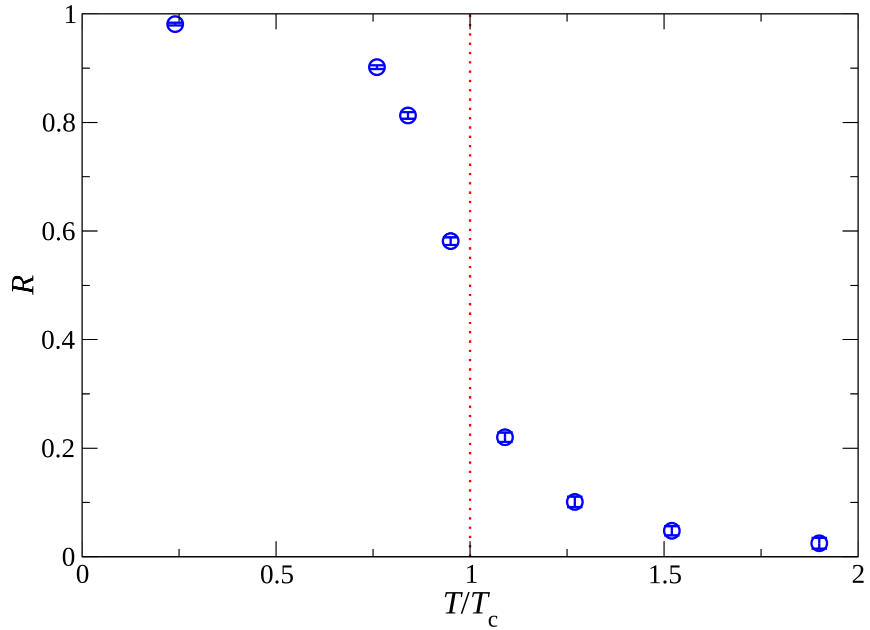


- crossover behaviour, tied with deconfinement transition

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

Summary: nucleons 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

outlook

- baryons with strange quarks
- role of smearing
- use chiral fermions

diffusion and conductivity

Alessandro Amato, **Pietro Giudice**, GA, Chris Allton, Simon Hands and Jonivar Skullerud

arXiv:1307.6763 [hep-lat] (PRL), arXiv:1412.6411 [hep-lat] (JHEP)

Transport coefficients

dynamics on long length and timescales:

- effective theory: hydrodynamics
- ideal hydrodynamics: equation of state
- viscous hydro: transport coefficients

shear/bulk viscosity, conductivity, $\ldots$

- depend on underlying microscopic theory
- typically:
  - large in weakly interacting theory
  - small in strongly coupled systems

perfect-fluid paradigm: $\eta/s = 1/4\pi$ (holography)

Transport coefficients

in the past

- emphasis on viscosity
- bound from holography $\eta/s = 1/4\pi$
- scale invariance and bulk viscosity

recently

- more interest in electrical conductivity
- role in heavy-ion collisions
- charge density fluctuations
- strong magnetic fields
- ...

Conductivity/diffusion

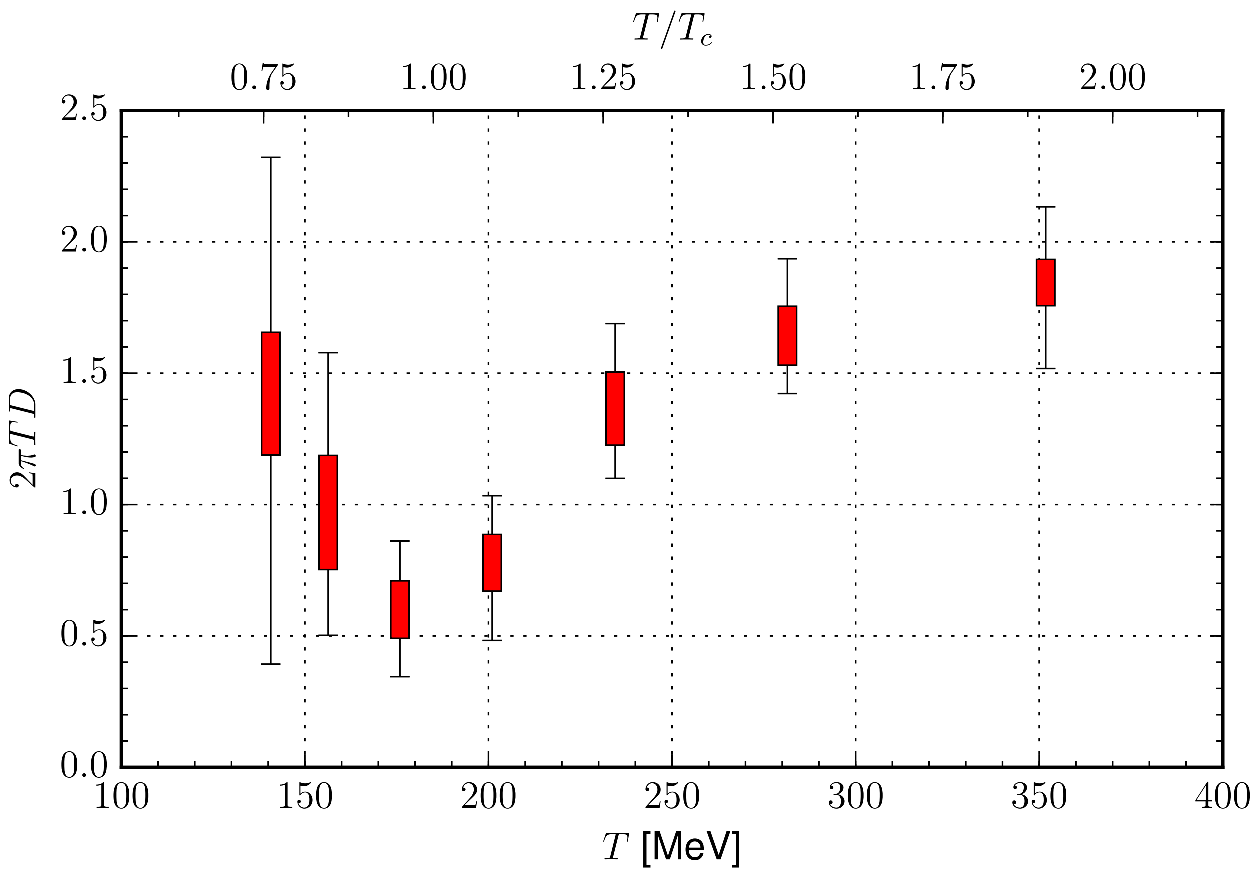
- electrical conductivity σ
- charge susceptibility χ
- both σ and χ proportional to EM factor

$$C_{\rm em} = e^2 \sum_f q_f^2 \qquad\qquad q_f = \frac{2}{3}, -\frac{1}{3}$$

- diffusion coefficient $D = \sigma/\chi$
- $C_{\rm em}$ cancels
- finite large N_c limit
- weak coupling: $D \sim 1/g^4T$
- strong coupling: $D = 1/2\pi T$ (holography)

Diffusion coefficient

- new result: D across the deconfinement transition



- minimal around T_c
- order of magnitude $D \sim 1/2\pi T$

Conductivity/diffusion

linear response: Kubo relation

$$\sigma = \lim_{\omega \to 0} \frac{1}{6\omega} \rho_{ii}(\omega, \mathbf{0})$$

where $$\rho_{\mu\nu}(x) = \langle [j_\mu(x), j_\nu(0)] \rangle_{\rm eq}$$

is current-current spectral function, j_μ is EM current

- real-time correlator in equilibrium
- on the lattice: euclidean correlator
- related to spectral function

$$G(\tau) = \int d\omega \, K(\tau, \omega) \rho(\omega) \qquad K(\tau, \omega) = \frac{\cosh[\omega(\tau - 1/2T)]}{\sinh(\omega/2T)}$$

- inversion/analytical continuation

Conductivity from the lattice

- use same ensembles

$$T/T_c = 0.24, 0.76, 0.84, 0.95, 1.09, 1.27, 1.52, 1.90$$

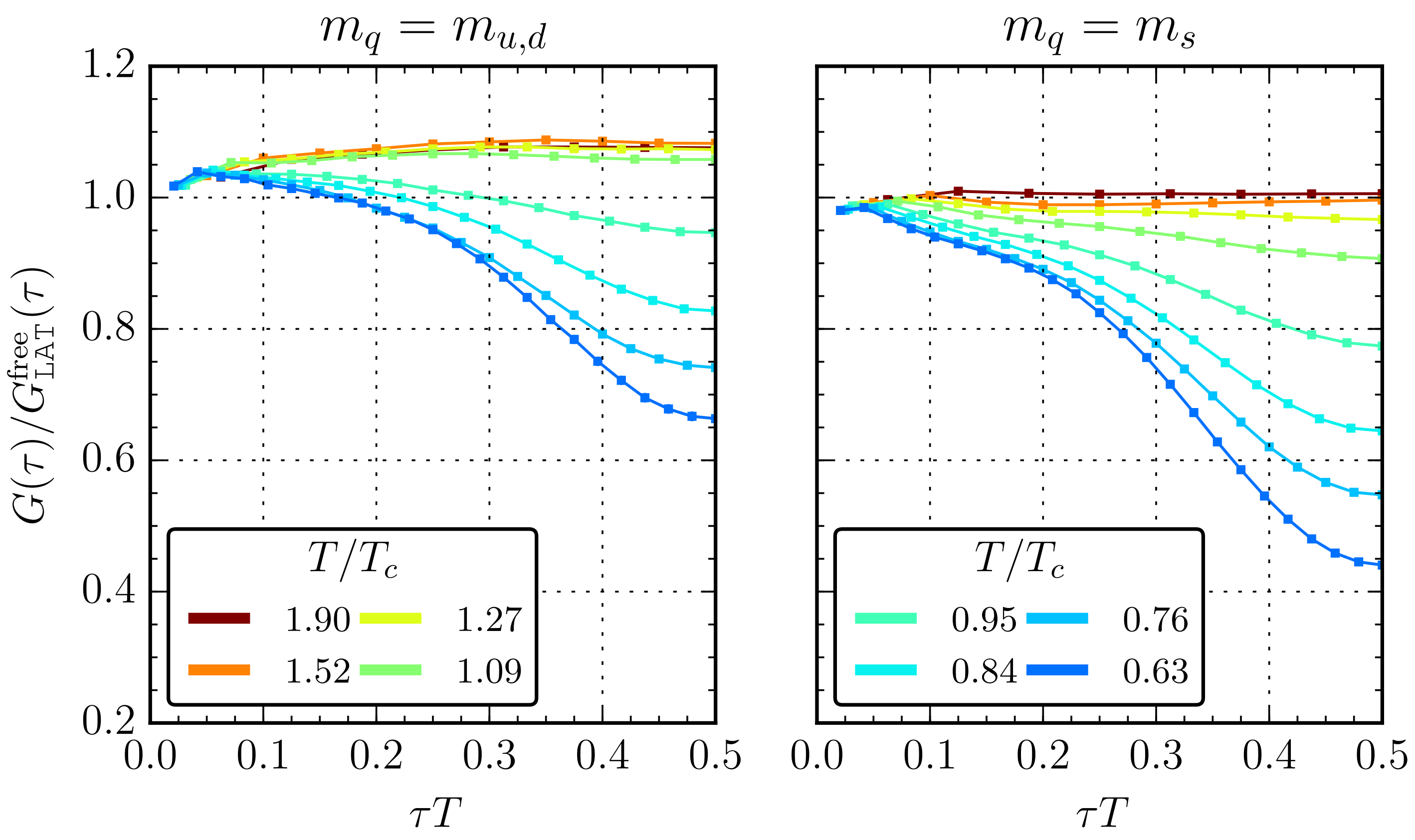
- $N_f = 2 + 1$ dynamical quark flavours
- conserved lattice current (no renormalisation required)

$$j_\mu^{\mathrm{em}} = \frac{2e}{3} j_\mu^u - \frac{e}{3} j_\mu^d - \frac{e}{3} j_\mu^s$$

- strange and up/down quarks: mass effect in
  - correlators
  - spectral functions
  - flavour susceptibilities
  - conductivity

Conserved current-current correlator

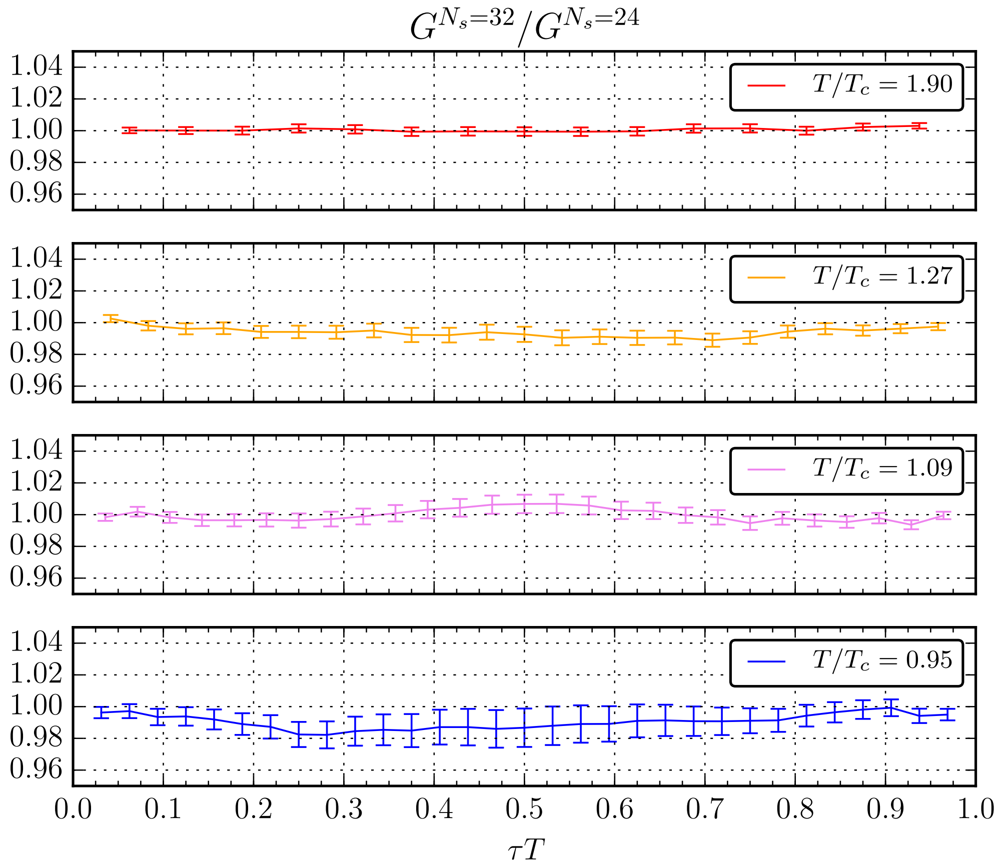
- ratio with *free* massless lattice correlator



- distinction between below/above T_c
- quark mass dependence

Conserved current-current correlator

- finite-size effects?



- only change is in spatial volume, $L_s = 2.9$ and 3.9 fm
- no finite-size effects

Spectral functions

- from correlator to spectral function

$$G(\tau) = \int d\omega\, K(\tau,\omega)\rho(\omega) \qquad K(\tau,\omega) = \frac{\cosh[\omega(\tau - 1/2T)]}{\sinh(\omega/2T)}$$

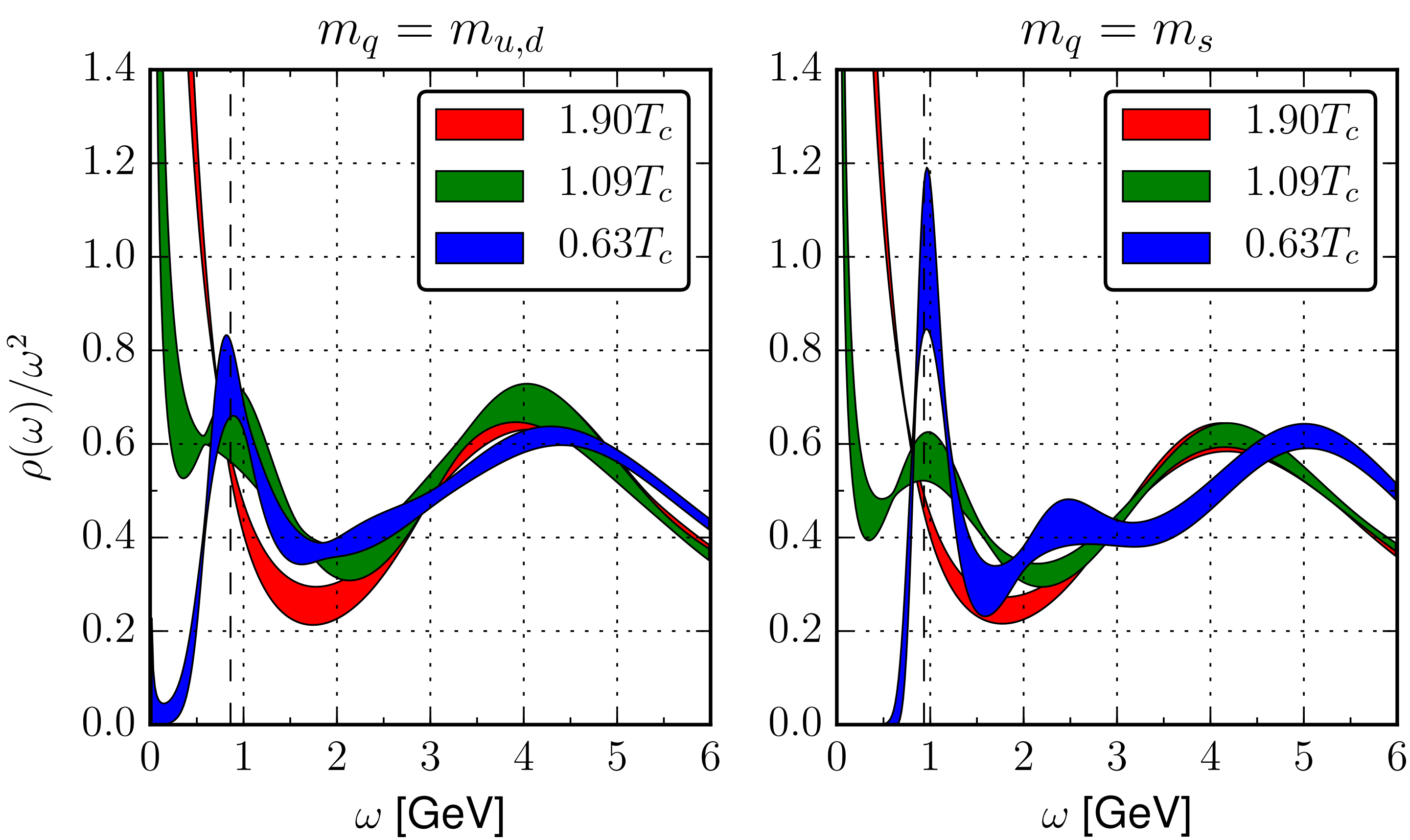
- inversion/analytical continuation
- use Maximal Entropy Method (MEM)

  Asakawa, Hatsuda & Nakahara 2001
- with $1/\omega$ instability fixed

  GA, Allton, Foley, Hands & Kim 2007
- many systematic checks (see below)

Spectral functions

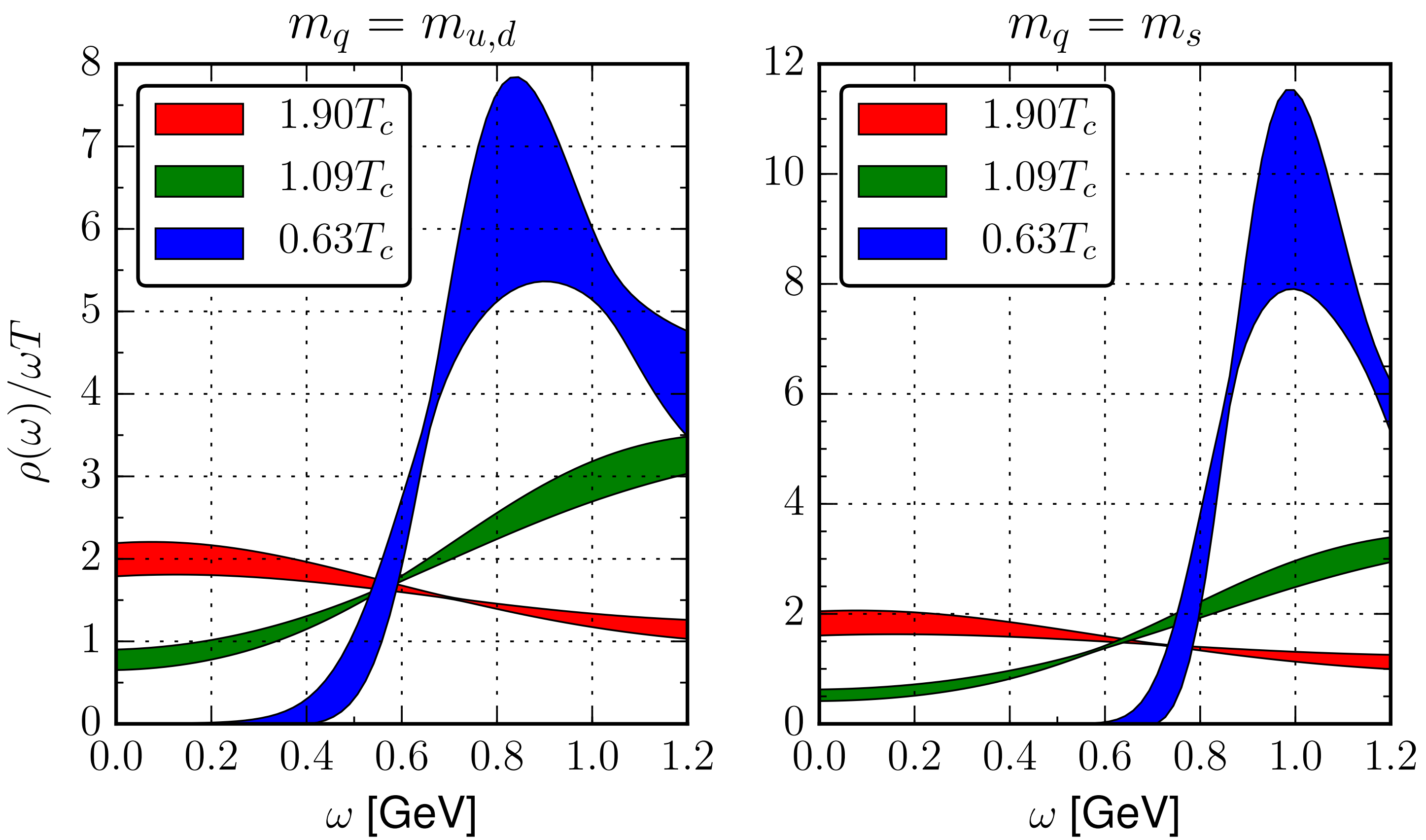
- $\rho(\omega)/\omega^2$



- peak below T_c corresponds to ρ, ϕ particle
- divergence as $\omega \to 0$ corresponds to transport peak

Spectral functions

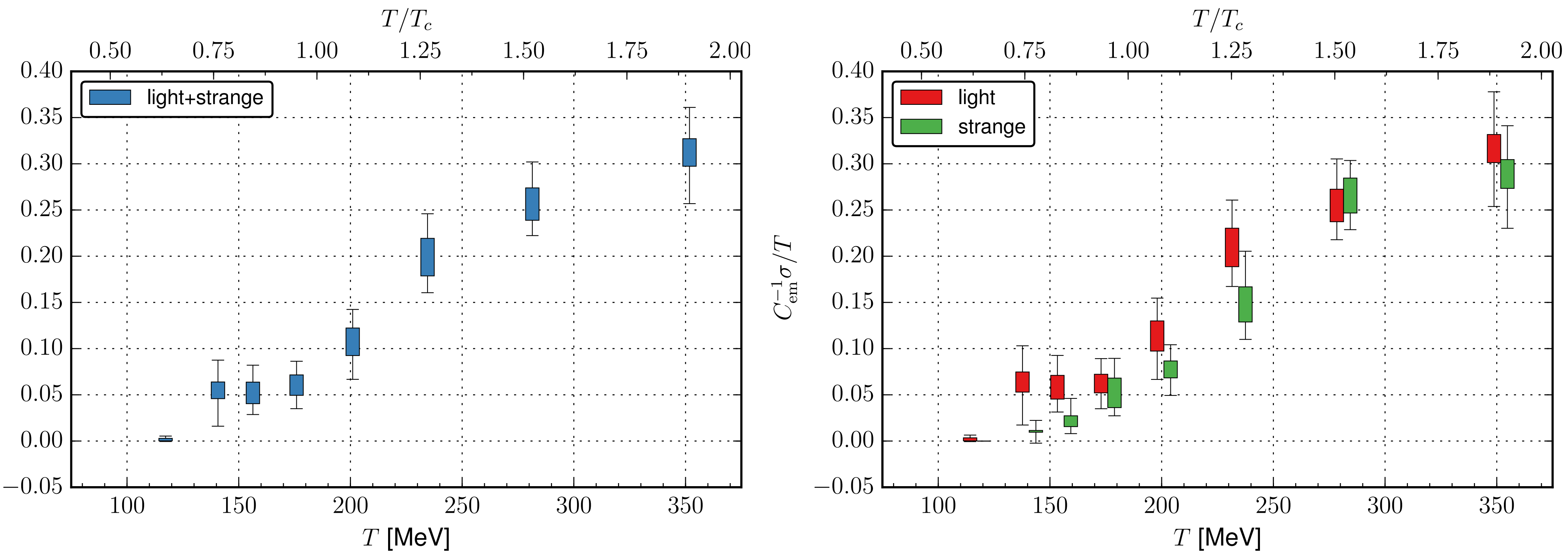
- $\rho(\omega)/\omega T$



- intercept: conductivity
- temperature and mass dependent

Conductivity

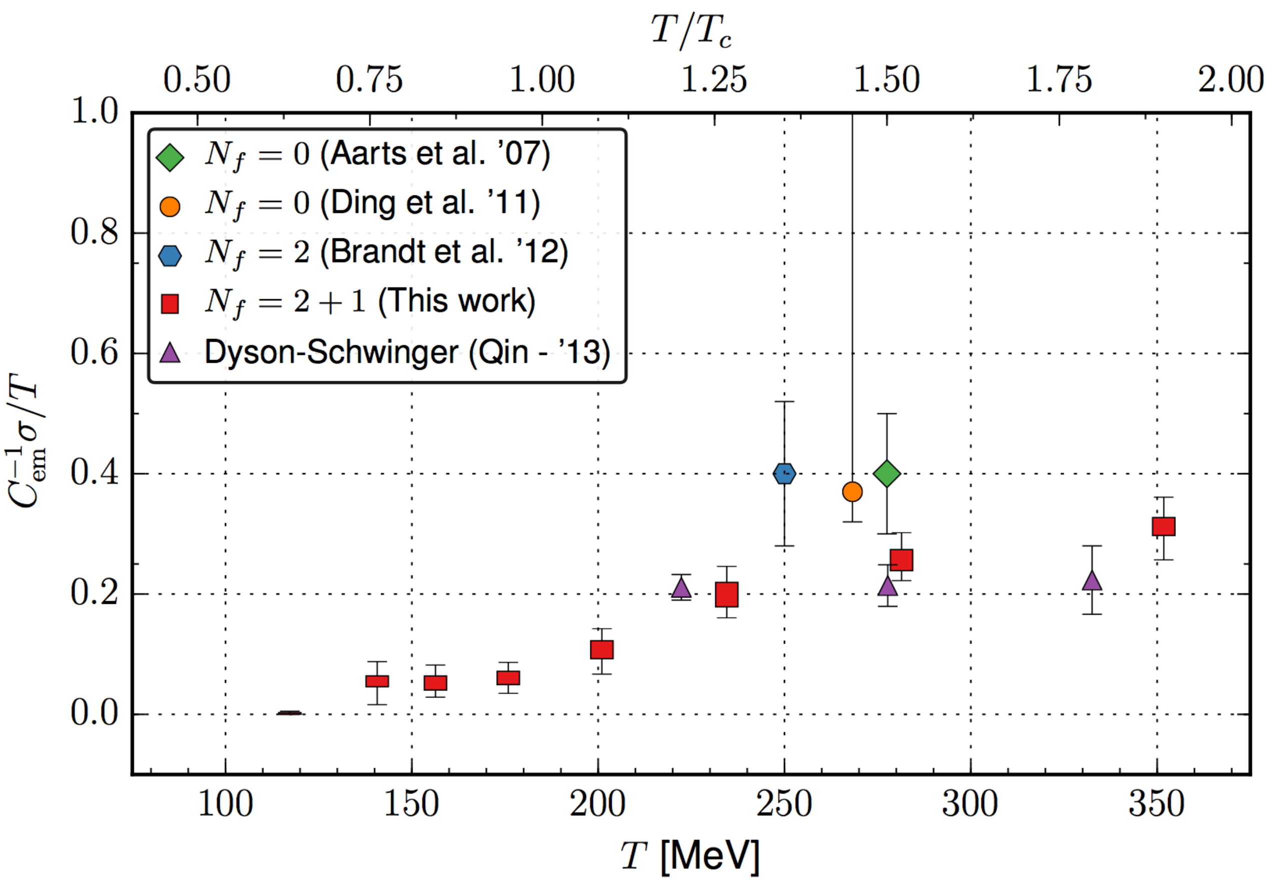
- conductivity $C_{\rm em}^{-1}\sigma/T$



- temperature and mass dependent
- agreement with previous results above T_c

Conductivity

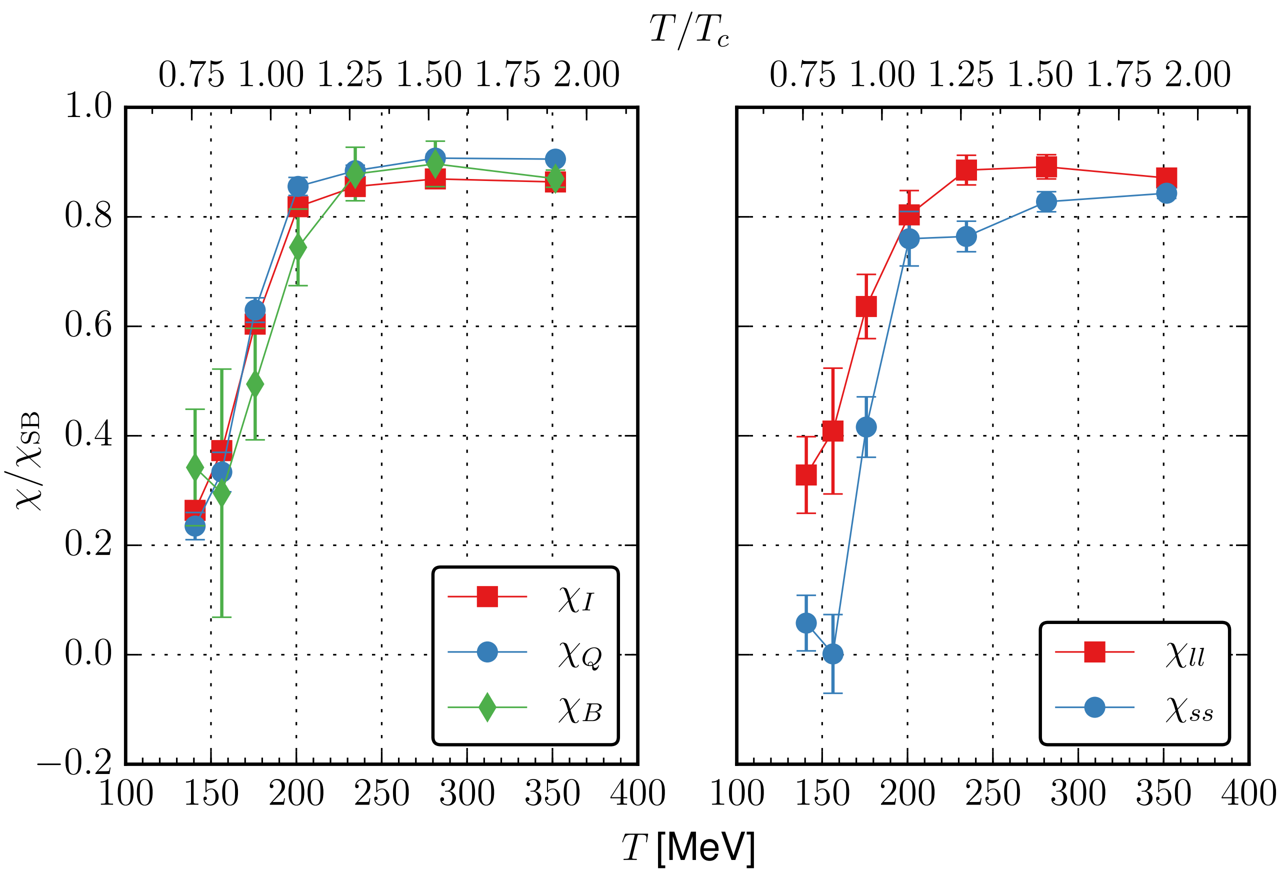
- conductivity $C_{\text{em}}^{-1}\sigma/T$



- agreement with previous results above T_c

Susceptibilies

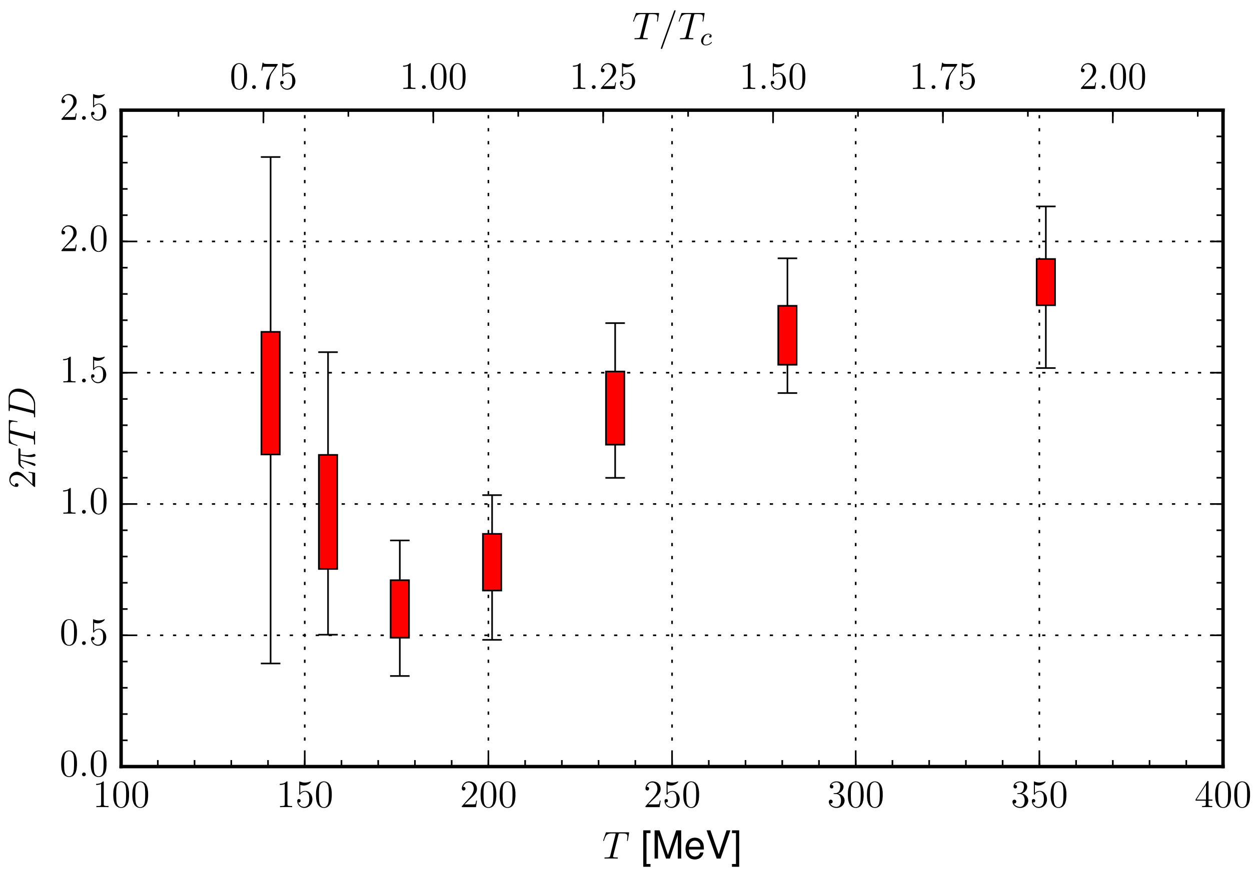
- fluctuations of isospin, electrical charge, baryon number, flavour



- agreement with previous (mostly staggered) results
- some flavour dependence

Diffusion coefficient

- combination of results: $D = \sigma/\chi_Q$



- consistent with strongly coupled plasma

Systematic checks

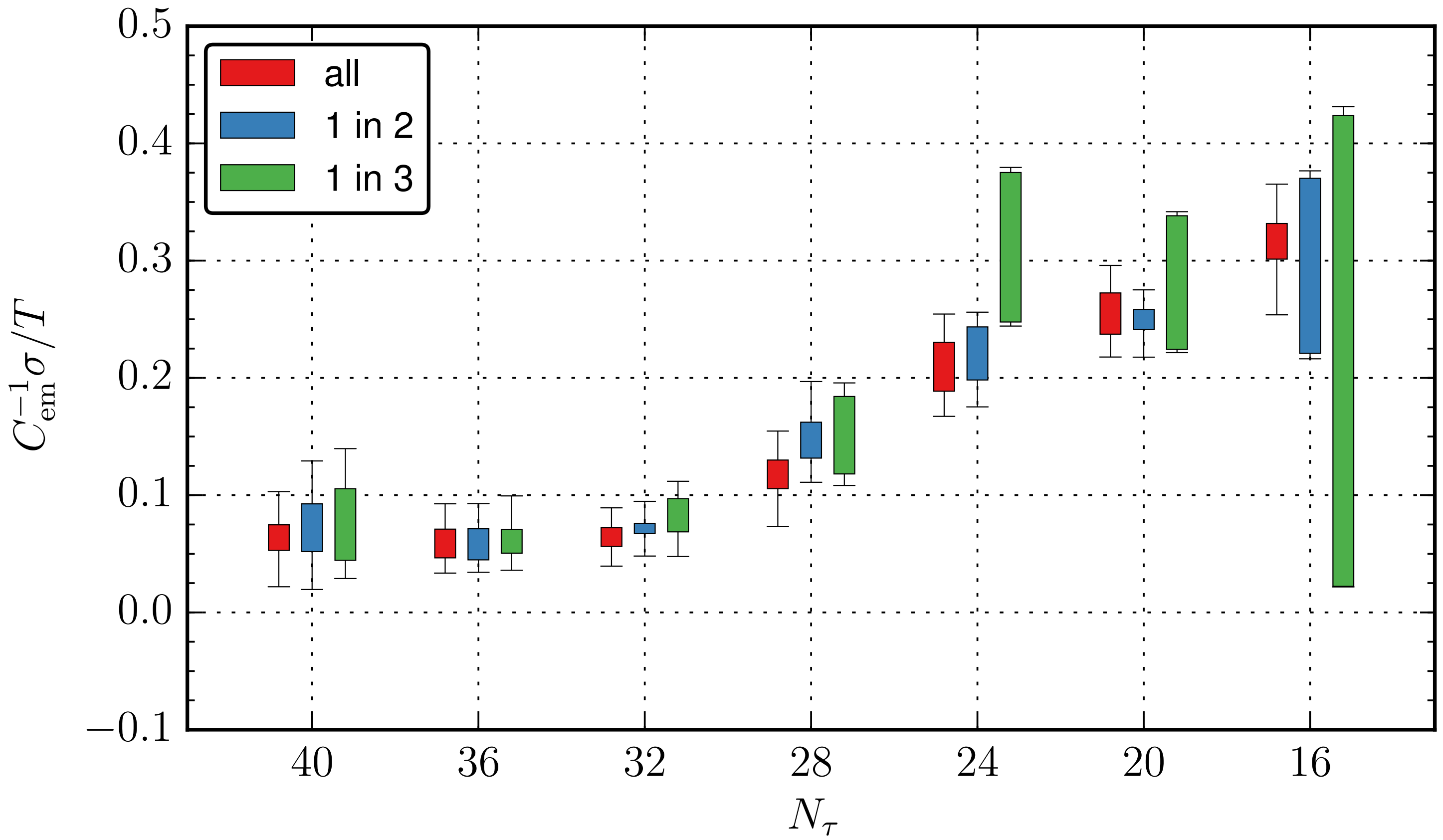
results stable against variations in MEM?

- default model
- euclidean time range
- discretisation
- ...

some illustrations

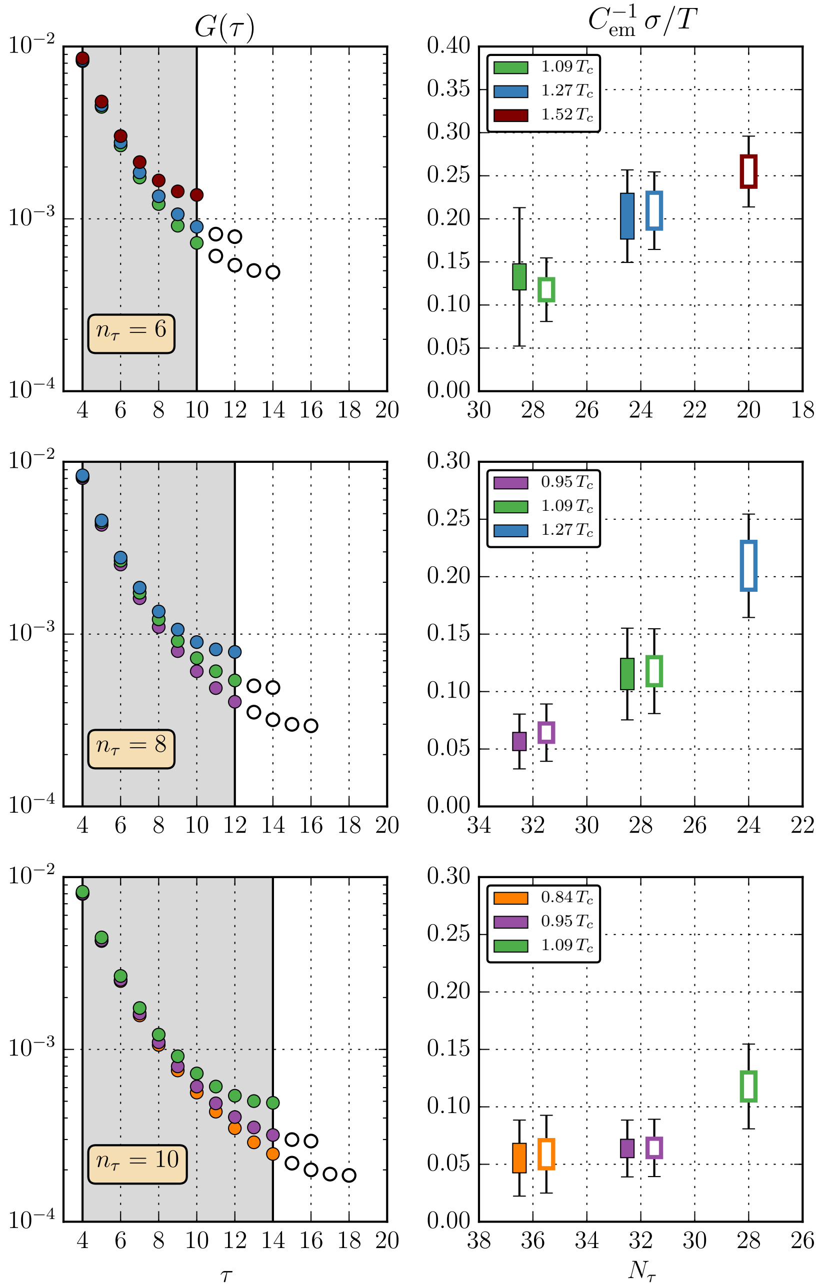
MEM stability

- anisotropic lattice, $a_s/a_\tau = 3.5$
- use all or 1 in 2 or 1 in 3



- stable at larger N_τ – anisotropy beneficial at smaller N_τ

MEM stability



use restricted time range

compare with maximal time range

robust signal

Summary

conductivity/diffusion:

- computed across deconfinement transition
- D minimum around T_c, $D \sim 1/2\pi T$
- consistent with strongly coupled plasma
- quark mass dependence

nucleons:

- N largely T independent below T_c
- N^* substantial T dependence
- parity doubling above T_c