Universität Bielefeld

Heavy quarks in a Quark Gluon Plasma

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University of Bielefeld & CCNU Wuhan

I) Light quark vector meson spectral function

- thermal photon & dilepton rates, electrical conductivity

[J.Ghiglieri, OK, M.Laine, F.Meyer, PRD94(2016)016005]

[H-T.Ding, F.Meyer, OK, PRD94 (2016) 034504]

II) Heavy quark momentum diffusion coefficient

[A.Francis, OK, et al., PRD92(2015)116003]

III) Thermal quarkonium physics in the pseudoscalar channel

[Y. Burnier, H.-T. Ding, OK et al. JHEP11 (2017) 206]

CRC-TR 211
Strong-interaction matter under extreme conditions

High Performance Computing in High Energy Physics
CCNU Wuhan, 19.-21.09.2018

Spectral and transport properties in the QGP

Thermal dilepton rate

$$\frac{\mathrm{d}W}{\mathrm{d}\omega\mathrm{d}^3p} = \frac{5\alpha^2}{54\pi^3}\frac{1}{\omega^2(e^{\omega/T}-1)}\ \rho_{\mathbf{V}}(\omega,\mathbf{T})$$

Thermal photon rate

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

Transport coefficients are encoded in the same spectral function

→ Kubo formulae

Diffusion coefficients:

$$DT = \frac{T}{2\chi_q}\lim_{\omega\to 0}\frac{\rho_{\mathrm{ii}}(\omega)}{\omega}$$

On the lattice only correlation functions can be calculated

→ spectral reconstruction required

This talk: continuum extrapolated lattice correlation functions compared to perturbation theory

for a comparison of Bayesian and stochastic reconstructions of spectral functions see

[H.-T. Ding, OK, S. Mukherjee, H. Ohno, H.-T. Shu, PRD97(2018)094503]

$$G(\tau,\vec{p},T) = \int_0^\infty \frac{\mathrm{d}\omega}{2\pi}\rho(\omega,\vec{p},T)K(\tau,\omega,T)$$

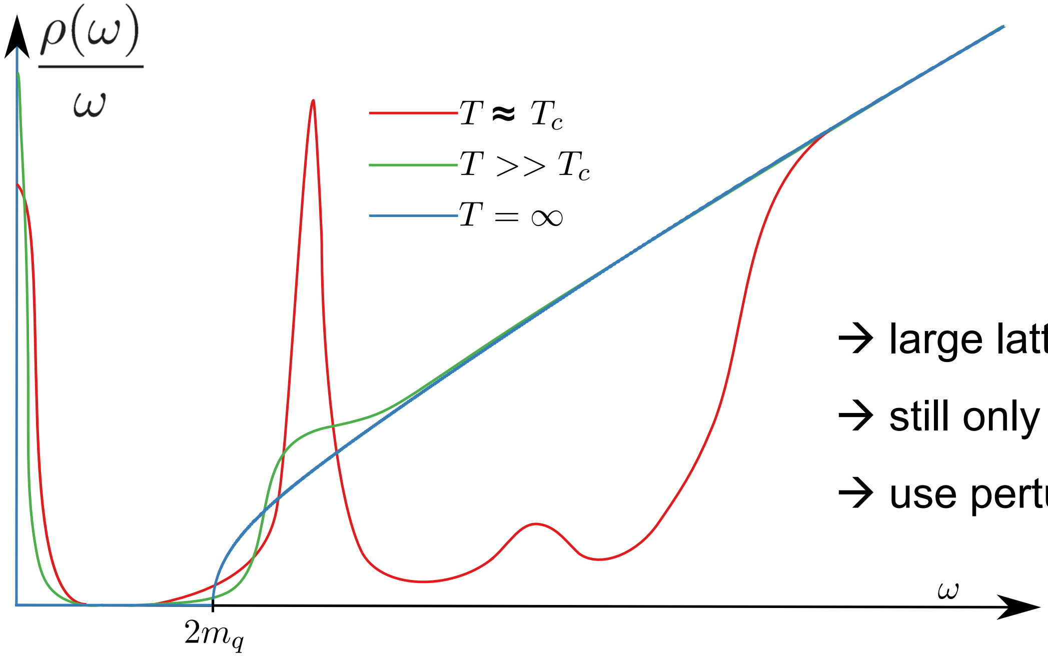
$$K(\tau,\omega,T) = \frac{\cosh\left(\omega(\tau-\frac{1}{2T})\right)}{\sinh\left(\frac{\omega}{2T}\right)}$$

Different contributions and scales enter in the spectral function

- continuum at large frequencies
- possible bound states at intermediate frequencies
- transport contributions at small frequencies
- in addition cut-off effects on the lattice

notoriously difficult to extract from correlation functions

Spectral functions in the QGP



$$G_{\mu\nu}(\tau,\vec{x}) = \langle J_\mu(\tau,\vec{x})J_\nu^\dagger(0,\vec{0})\rangle$$
$$J_\mu(\tau,\vec{x}) = 2\kappa Z_V\bar{\psi}(\tau,\vec{x})\Gamma_\mu\psi(\tau,\vec{x})$$

→ large lattices and continuum extrapolation needed

→ still only possible in the quenched approximation

→ use perturbation theory to constrain the UV behavior

(narrow) transport peak at small ω: $\rho(\omega \ll T) \simeq 2\chi_{00}\frac{T}{M}\frac{\omega\eta}{\omega^2+\eta^2}\,, \qquad \eta = \frac{T}{MD}$

Vector-meson correlators for light quarks on large & fine lattices

[H-T.Ding, F.Meyer, OK, PRD94(2016)034504, H.T.Ding, A.Francis, OK et al., PRD83(2011)034504]

quenched SU(3) gauge configurations (separated by 500 updates)

non-perturbatively O(a) clover improved Wilson fermion valence quarks

non-perturbative renormalization constants and quark masses close to the chiral limit

	N_τ	N_σ	β	κ	$T\sqrt{t_0}$	$T/T_c\vert_{t_0}$	Tr_0	$T/T_c\vert_{r_0}$	confs
	32	96	7.192	0.13440	0.2796	1.12	0.8164	1.09	314
1.1 T_c	48	144	7.544	0.13383	0.2843	1.14	0.8169	1.10	358
	64	192	7.793	0.13345	0.2862	1.15	0.8127	1.09	242
	28	96	7.192	0.13440	0.3195	1.28	0.9330	1.25	232
1.3 T_c	42	144	7.544	0.13383	0.3249	1.31	0.9336	1.25	417
	56	192	7.793	0.13345	0.3271	1.31	0.9288	1.25	273
	24	128	7.192	0.13440	0.3728	1.50	1.0886	1.46	340
1.5 T_c	32	128	7.457	0.13390	0.3846	1.55	1.1093	1.49	255
	48	128	7.793	0.13340	0.3817	1.53	1.0836	1.45	456

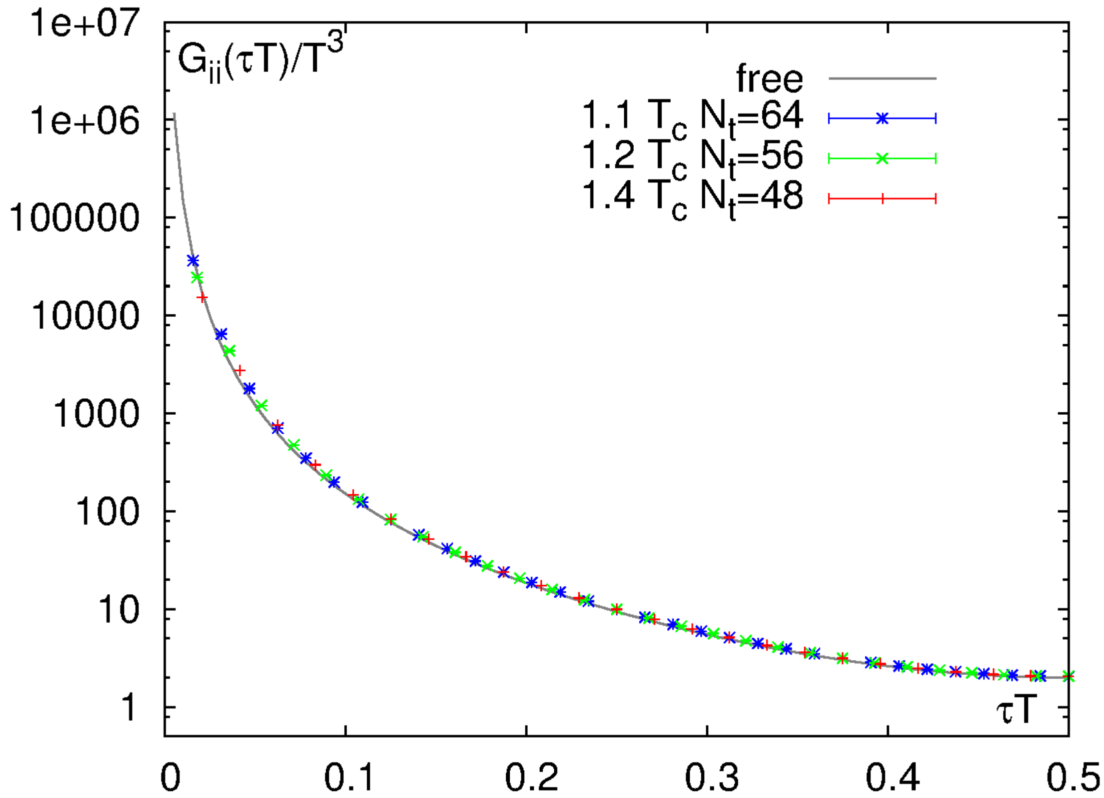
Scale setting using r_0 and t_0 [A.Francis, M.Laine, T.Neuhaus, H.Ohno PRD92(2015)116003]

fixed aspect ratio N_σ/N_τ = 3 and 3.43 to allow continuum limit at finite momentum:

$$\frac{\vec{p}}{T} = 2\pi\vec{k}\frac{N_\tau}{N_\sigma}$$

constant physical volume $(1.9\text{fm})^3$

Vector-meson correlation function

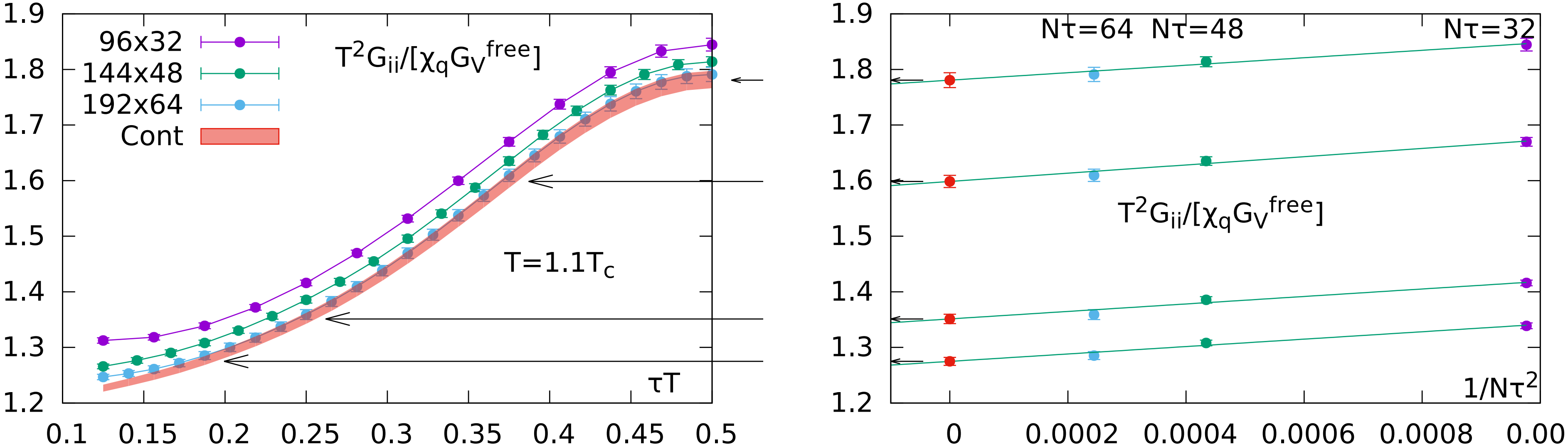


compared to free (non-interacting) correlator:

$$G_V^{free}(\tau) = 6T^2 \left(\pi(1-2\tau T)\frac{1+\cos^2(2\pi\tau T)}{\sin^3(2\pi\tau T)} + 2\frac{\cos(2\pi\tau T)}{\sin^2(2\pi\tau T)} \right)$$

hard to distinguish differences due to different orders of magnitude in the correlator

→ in the following we will use $G_V^{free}(\tau)$ as a normalization



correlators normalized by quark number susceptibility χ_q independent of renormalization

and by the free non-interacting correlator $G_V^{free}(\tau)$

we interpolate the correlator for each lattice spacing

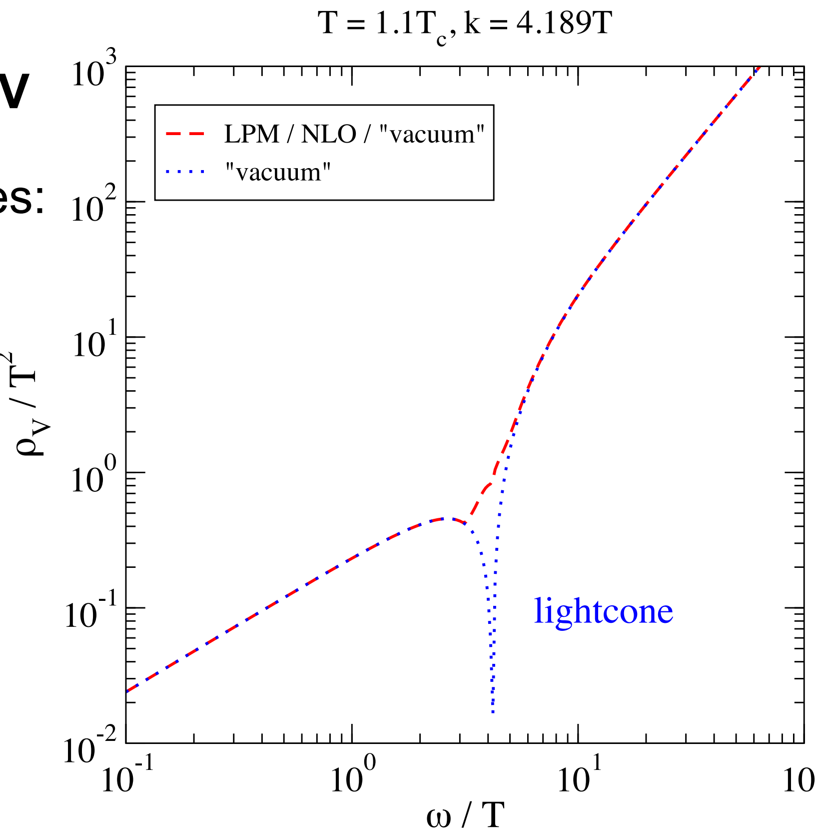
and perform the continuum limit a→0 at each distance τT

cut-off effects are visible at all distances on finite lattices

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

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

pQCD spectral function used to constrain the UV



interpolation between different (perturbative) regimes:

3T < ω < 10T: [J.Ghiglieri, G.D.Moore, JHEP 1412 (2014) 029]

ω > 10T: [I. Ghisoiu, M.Laine, JHEP 10 (2014) 84]

ω >> 10T: [M.Laine, JHEP 1311 (2013) 120]

to allow for non-perturbative effects

and to analyze how far pQCD can be trusted

we model the infrared behavior assuming smoothness at the light cone

and fit to continuum extrapolated lattice correlators

Vector spectral function in the hydrodynamic regime for $\omega, k \lesssim \alpha_s^2 T$:

$$\frac{\rho_{\mathrm{V}}(\omega,\mathbf{k})}{\omega} = \left(\frac{\omega^2 - k^2}{\omega^2 + D^2 k^4} + 2\right)\chi_{\mathrm{q}} D$$

with the quark number susceptibility: $\chi_{\mathrm{q}} \equiv \int_0^\beta \mathrm{d}\tau \int_{\mathbf{x}} \langle V^0(\tau,\mathbf{x}) V^0(0)\rangle$

and the diffusion coefficient: $D \equiv \frac{1}{3\chi_{\mathrm{q}}} \lim_{\omega\to 0^+} \sum_{i=1}^{3} \frac{\rho^{ii}(\omega,\mathbf{0})}{\omega}$

which relate to the electric conductivity: $\sigma = e^2 \sum_{f=1}^{N_{\mathrm{f}}} Q_f^2 \chi_{\mathrm{q}} D$

In this limit the (soft) photon rate becomes: $\frac{\mathrm{d}\Gamma_\gamma(\mathbf{k})}{\mathrm{d}^3\mathbf{k}} \overset{k \lesssim \alpha_s^2 T}{\approx} \frac{2T\sigma}{(2\pi)^3 k}$

In the AdS/CFT framework the vector spectral function has the same infrared structure

and here numerical result can make predictions beyond the hydro regime

[S.Caron-Huot, JHEP12 (2006) 015]

Although not QCD, it may give qualitative insight into the structures at small ω and k

$(5+2\ n_{max})^{th}$ order polynomial Ansatz at small ω:

$$\rho_{\rm fit} \equiv \frac{\beta\,\omega^3}{2\omega_0^3}\left(5-\frac{3\omega^2}{\omega_0^2}\right)-\frac{\gamma\,\omega^3}{2\omega_0^2}\left(1-\frac{\omega^2}{\omega_0^2}\right)+\sum_{n=0}^{n_{\rm max}}\frac{\delta_n\omega^{1+2n}}{\omega_0^{1+2n}}\left(1-\frac{\omega^2}{\omega_0^2}\right)^2$$

with the constraints to match smoothly with pQCD at ω_o

$$\rho_{\rm V}(\omega_0,\mathbf{k}) \equiv \beta\,, \quad \rho_{\rm V}'(\omega_0,\mathbf{k}) \equiv \gamma\,,$$

and n_{max}+1 free parameters

starting with a linear behavior at $\omega \ll$ T

smoothly matched to the perturbative spectral function at $\omega_0 \simeq \sqrt{k^2+(\pi T)^2}$

In the following we will use n_{max} = 0 and n_{max} = 1 for the fits to the lattice data

and to estimate the systematic uncertainties

Continuum lattice correlators vs. perturbation theory

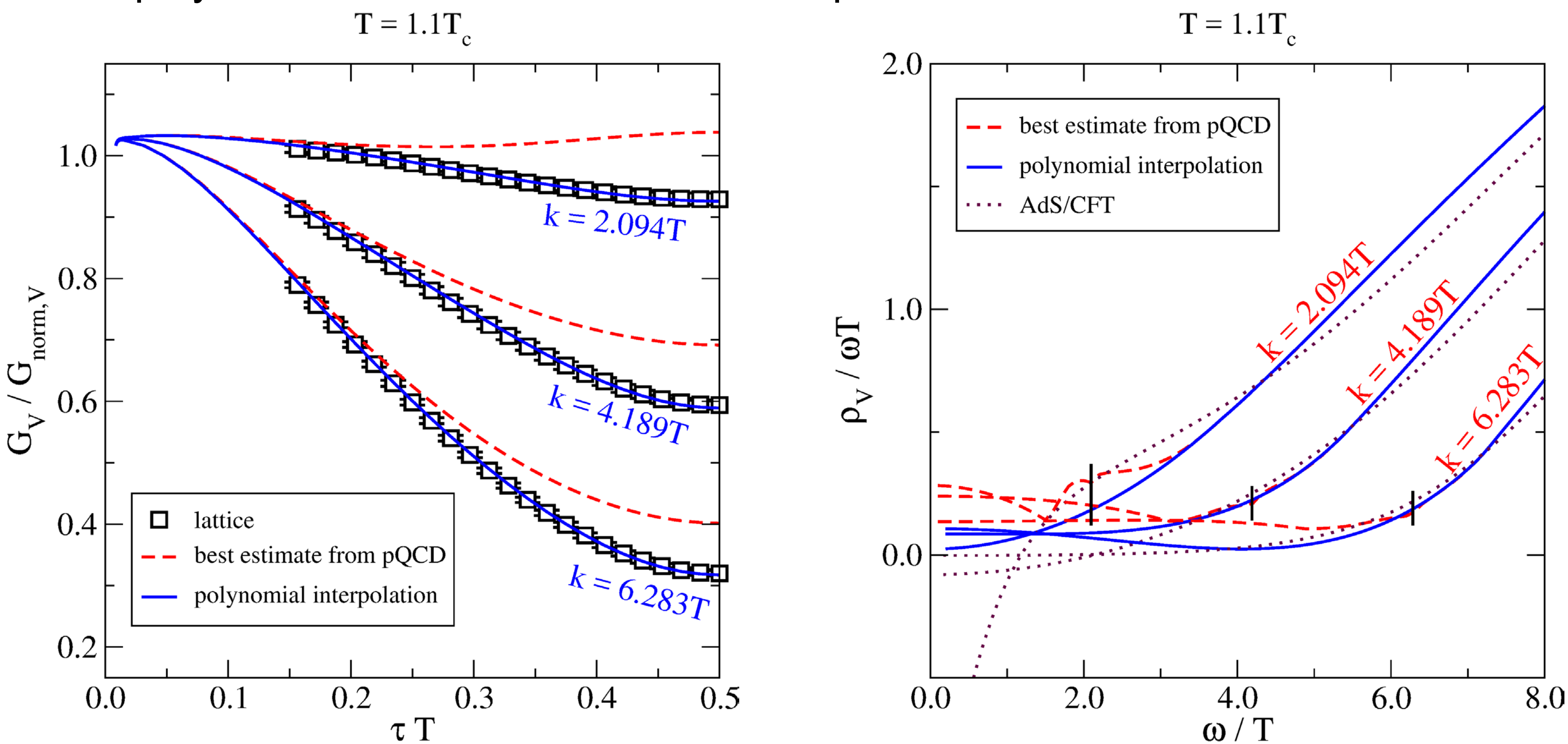
[J.Ghiglieri, OK, M.Laine, F.Meyer, PRD94(2016)016005]

Fixed aspect ratio used to perform continuum extrapolation at finite p

$$\frac{\vec{p}}{T} = 2\pi \vec{k} \frac{N_\tau}{N_\sigma}$$

β_0	$N_s^3 \times N_\tau$	confs	$T\sqrt{t_0}$	$T/T_c\|_{t_0}$	Tr_0	$T/T_c\|_{r_0}$
7.192	$96^3 \times 32$	314	0.2796	1.12	0.816	1.09
7.544	$144^3 \times 48$	358	0.2843	1.14	0.817	1.10
7.793	$192^3 \times 64$	242	0.2862	1.15	0.813	1.09
7.192	$96^3 \times 28$	232	0.3195	1.28	0.933	1.25
7.544	$144^3 \times 42$	417	0.3249	1.31	0.934	1.25
7.793	$192^3 \times 56$	273	0.3271	1.31	0.929	1.25

use perturbation theory at large ω and fit a polynomial at small ω to extract the spectral function



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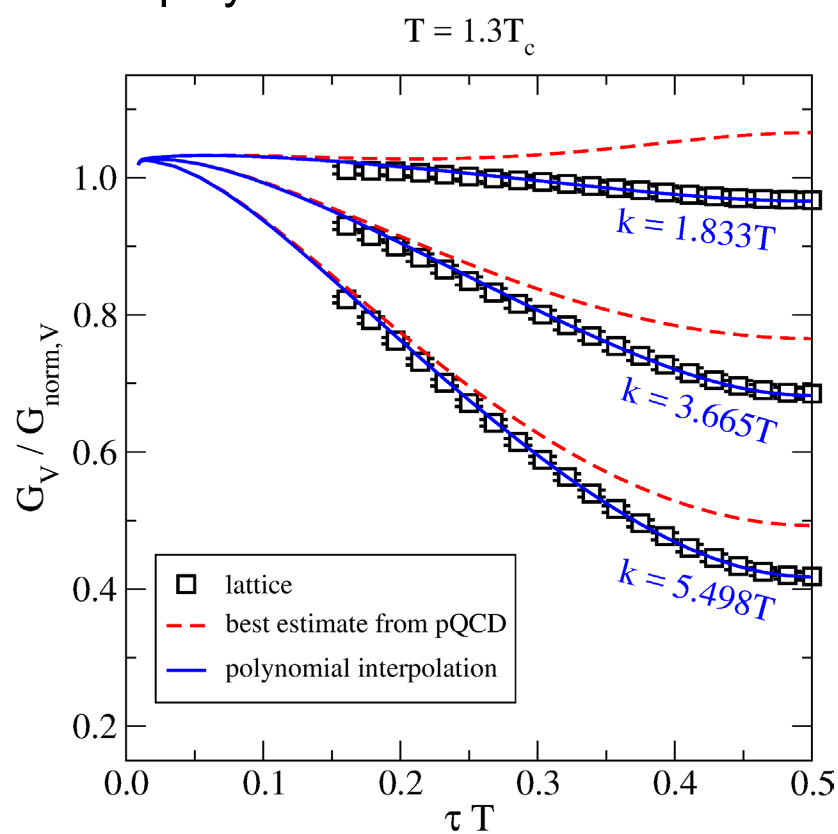
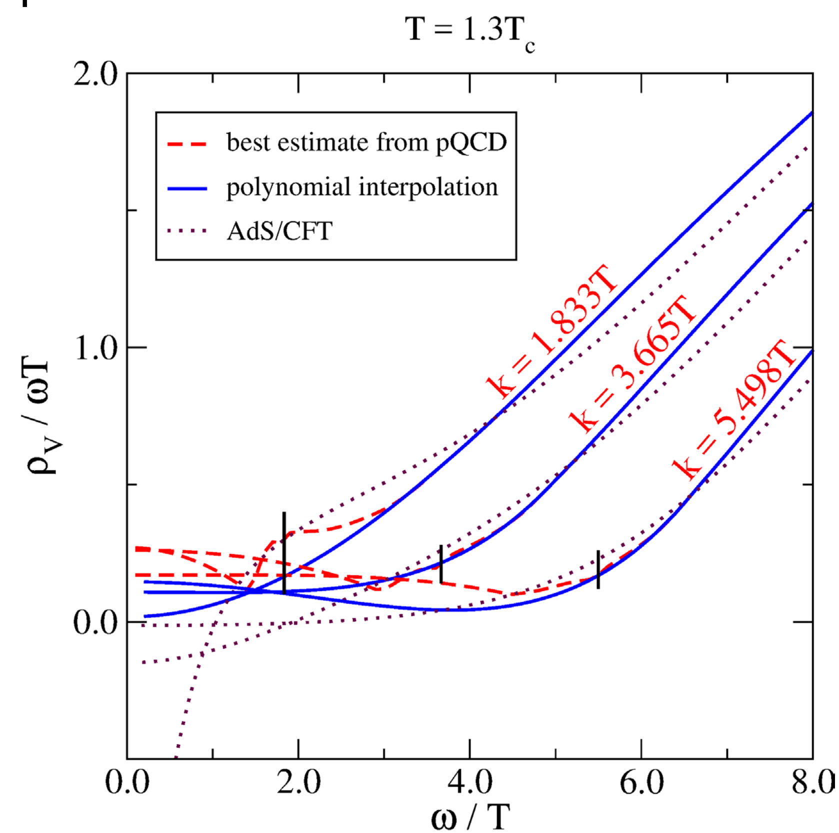




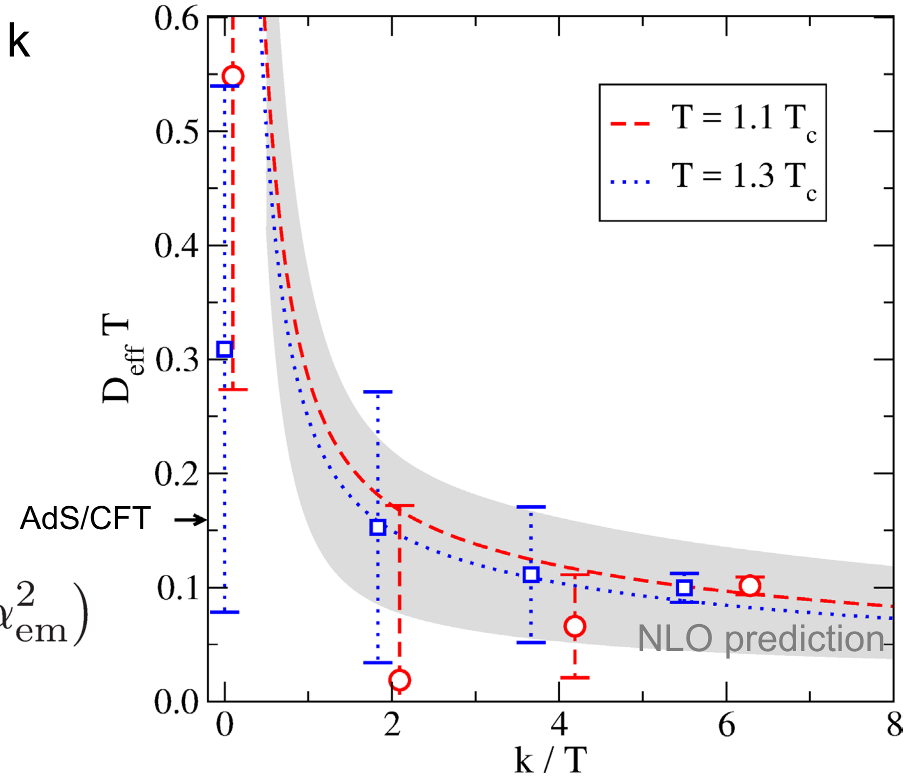
[J.Ghiglieri, OK, M.Laine, F.Meyer, PRD94(2016)016005]

The spectral function at the photon point ω = k

$$D_{\rm eff}(k) \equiv \begin{cases} \dfrac{\rho_{\rm V}(k,\mathbf{k})}{2\chi_{\rm q}k} & , \quad k>0 \\ \lim\limits_{\omega\to0^+} \dfrac{\rho^{ii}(\omega,\mathbf{0})}{3\chi_{\rm q}\omega} & , \quad k=0 \end{cases} .$$

can be used to calculate the photon rate

$$\frac{d\Gamma_\gamma(\mathbf{k})}{d^3\mathbf{k}} = \frac{2\alpha_{\rm em}\chi_{\rm q}}{3\pi^2} n_{\rm B}(k) D_{\rm eff}(k) + \mathcal{O}\left(\alpha_{\rm em}^2\right)$$



becomes more perturbative at larger k, approaching the NLO prediction (valid for k>>gT)

[J. Ghiglieri, G.D. Moore, JHEP12 (2014) 029]

but non-perturbative for k/T < 3

Electrical conductivity obtained in the limit k→0 between the results from

AdS/CFT: $DT = \dfrac{1}{2\pi}$

[G.Policastro, D.T.Son,A.O.Starinets, JHEP09(2002)043]

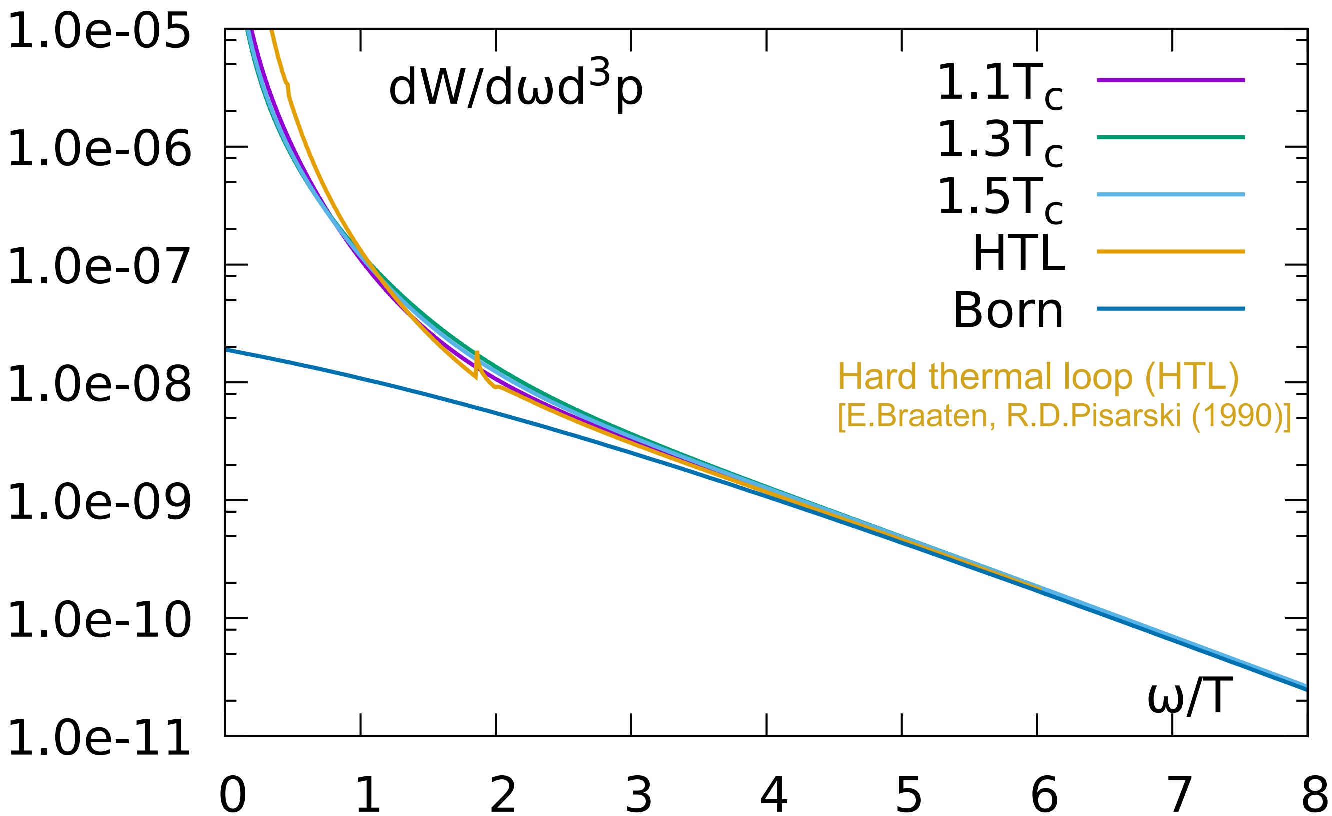
LO perturbation theory [Arnold, Moore Yaffe, JHEP 05 (2003)]

using lattice value for χ_q/T^2 : $DT = 2.9 - 3.1$

[H-T.Ding, F.Meyer, OK, PRD94(2016)034504]

Dileptonrate directly related to vector spectral function:

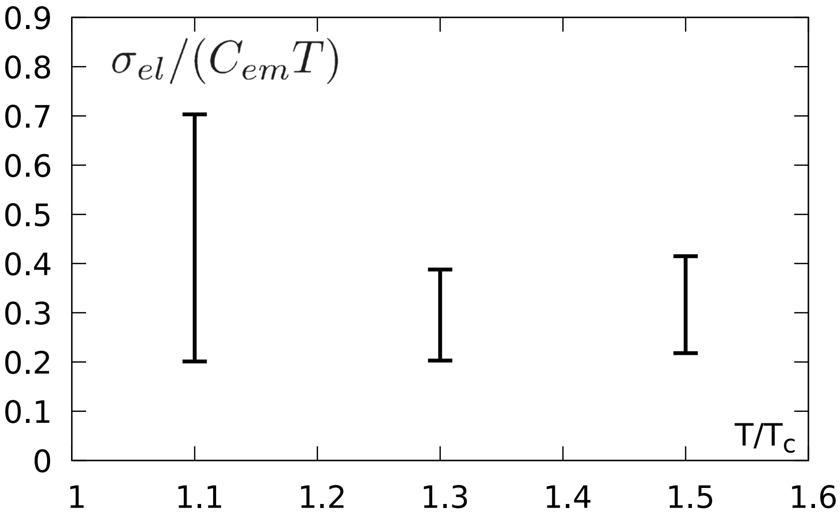
$$\frac{\mathrm{d}W}{\mathrm{d}\omega \mathrm{d}^3p} = \frac{5\alpha^2}{54\pi^3}\frac{1}{\omega^2(e^{\omega/T}-1)}\ \rho_{\mathbf{V}}(\omega,\mathbf{T})$$



continuum estimate for the of the electrical conductivity

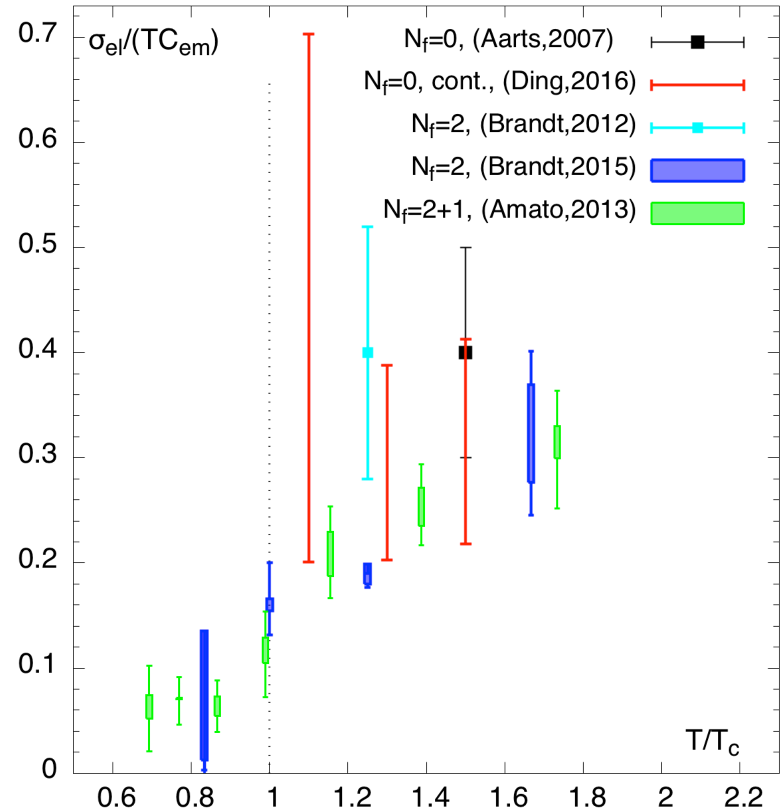
lower and upper limits from analysis of different classes of spectral functions:

$$\frac{\sigma_{el}}{C_{em}T} = \frac{1}{6}\lim_{\omega\to 0}\frac{\rho_{ii}(\omega,\vec{p}=0,T)}{\omega T}$$



[H-T.Ding, F.Meyer, OK, PRD94(2016)034504]

comparison of different lattice results
(Plot courtesy of A.Francis)



[G.Aarts et al., PRL 99 (2007) 022002,
H-T.Ding, F.Meyer, OK, PRD94(2016)034504,
B.B.Brandt et al., JHEP 1303 (2013) 100,
Brandt et al., PRD93 (2016) 054510,
A.Amato et al., PRL 111 (2013) 172001]

Progress in determining transport coefficients, although systematic uncertainties still need to be reduced in the future.

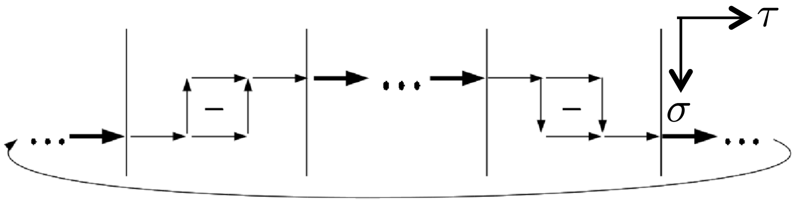
Heavy Quark Effective Theory (HQET) in the large quark mass limit

for a single quark in medium

leads to a (pure gluonic) "color-electric correlator"

[J.Casalderrey-Solana, D.Teaney, PRD74(2006)085012, S.Caron-Huot,M.Laine,G.D. Moore,JHEP04(2009)053]

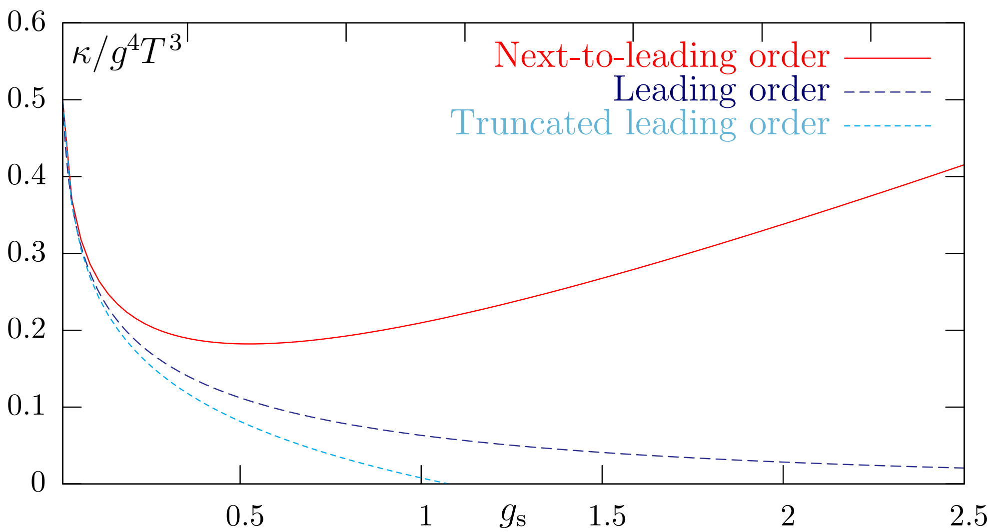
$$G_E(\tau) \equiv -\frac{1}{3}\sum_{i=1}^{3} \frac{\left\langle \mathrm{Re\,Tr}\left[U(\tfrac{1}{T};\tau)\, g\, E_i(\tau,\mathbf{0})\, U(\tau;0)\, g\, E_i(0,\mathbf{0})\right]\right\rangle}{\left\langle \mathrm{Re\,Tr}[U(\tfrac{1}{T};0)]\right\rangle}$$



$$\kappa = \lim_{\omega\to 0} \frac{2T\rho_E(\omega)}{\omega}$$

NLO perturbative calculation:

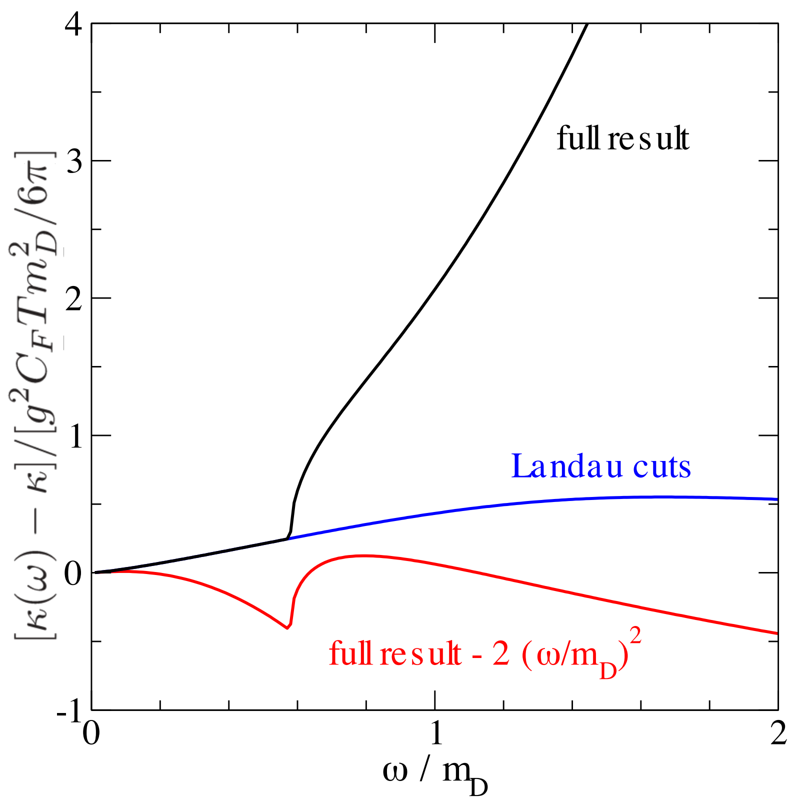
[Caron-Huot, G. Moore, JHEP 0802 (2008) 081]



→ large correction towards strong interactions

→ non-perturbative lattice methods required

NLO spectral function in perturbation theory: [Caron-Huot, M.Laine, G.Moore, JHEP 0904 (2009) 053]



in contrast to a narrow transport peak, from this a smooth limit

$$\kappa/T^3 = \lim_{\omega\to 0} \frac{2T\rho_{\mathrm{E}}(\omega)}{\omega}$$

is expected

qualitatively similar behavior also found in AdS/CFT [S.Gubser, Nucl.Phys.B790 (2008)175]

Heavy Quark Momentum Diffusion Constant – Lattice results

[A.Francis, OK, M.Laine, T.Neuhaus, H.Ohno, PRD92(2015)116003]

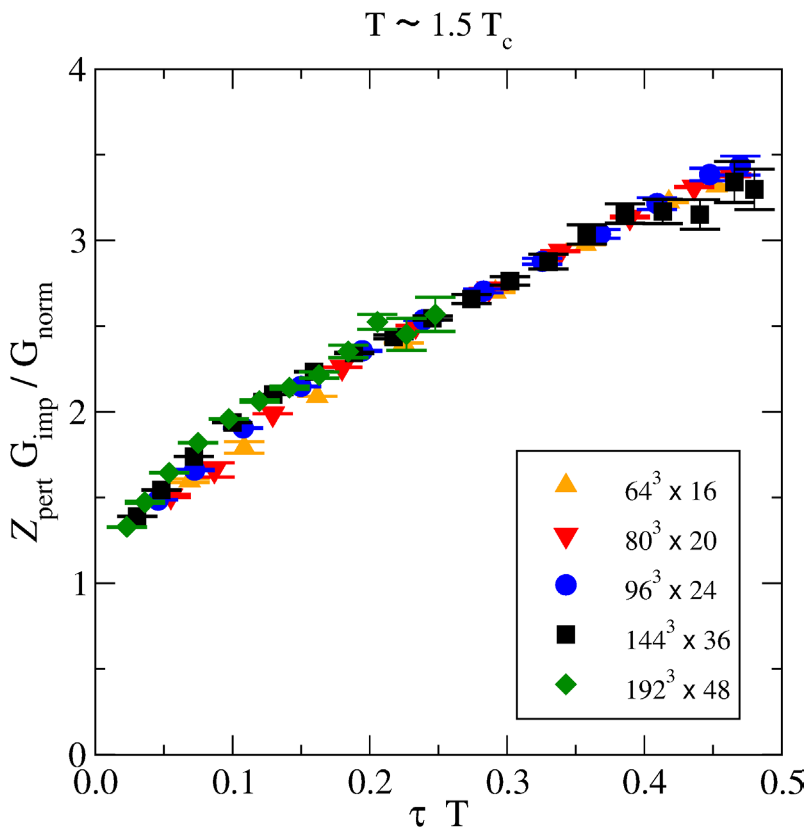
Quenched Lattice QCD on large and fine isotropic lattices at $T \simeq 1.5\, T_c$

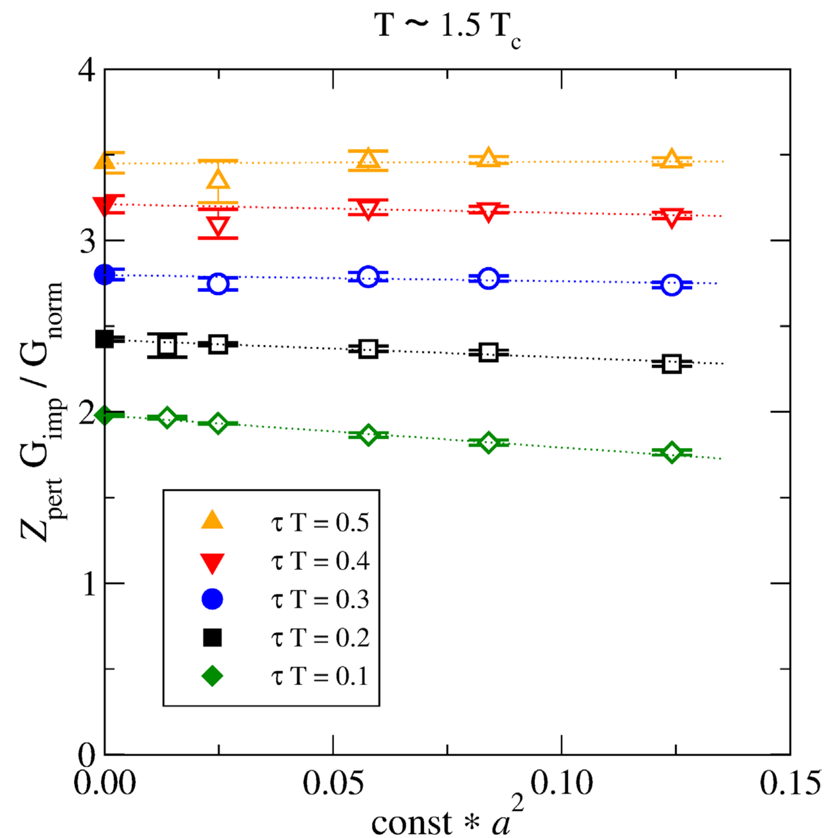
- standard Wilson gauge action
- algorithmic improvements to enhance signal/noise ratio
- fixed aspect ration $N_s/N_t = 4$, i.e. fixed physical volume $(2\text{fm})^3$
- perform the continuum limit, $a \to 0 \;\leftrightarrow\; N_t \to \infty$
- determine κ in the continuum using an Ansatz for the spectral fct. $\rho(\omega)$
- scale setting using r_0 and t_0 scale [A.Francis,OK,M.Laine, T.Neuhaus, H.Ohno, PRD91(2015)096002]

β_0	$N_s^3 \times N_\tau$	confs	$T\sqrt{t_0}^{(\text{imp})}$	$T/T_c\|_{t_0}^{(\text{imp})}$	$T\sqrt{t_0}^{(\text{clov})}$	$T/T_c\|_{t_0}^{(\text{clov})}$	Tr_0	$T/T_c\|_{r_0}$
6.872	$64^3 \times 16$	172	0.3770	1.52	0.3805	1.53	1.116	1.50
7.035	$80^3 \times 20$	180	0.3693	1.48	0.3739	1.50	1.086	1.46
7.192	$96^3 \times 24$	160	0.3728	1.50	0.3790	1.52	1.089	1.46
7.544	$144^3 \times 36$	693	0.3791	1.52	0.3896	1.57	1.089	1.46
7.793	$192^3 \times 48$	223	0.3816	1.53	0.3955	1.59	1.084	1.45

similar studies by [Banerjee,Datta,Gavai,Majumdar, PRD85(2012)014510]
and [H.B.Meyer, New J.Phys.13(2011)035008]

we performed a continuum extrapolation, $a \to 0 \leftrightarrow N_t \to \infty$ **, at fixed** $T=1/a\,N_t$





well behaved continuum extrapolation for $0.05 \leq \tau T \leq 0.5$

finest lattice already close to the continuum

coarser lattices at larger τT show almost no cut-off effects

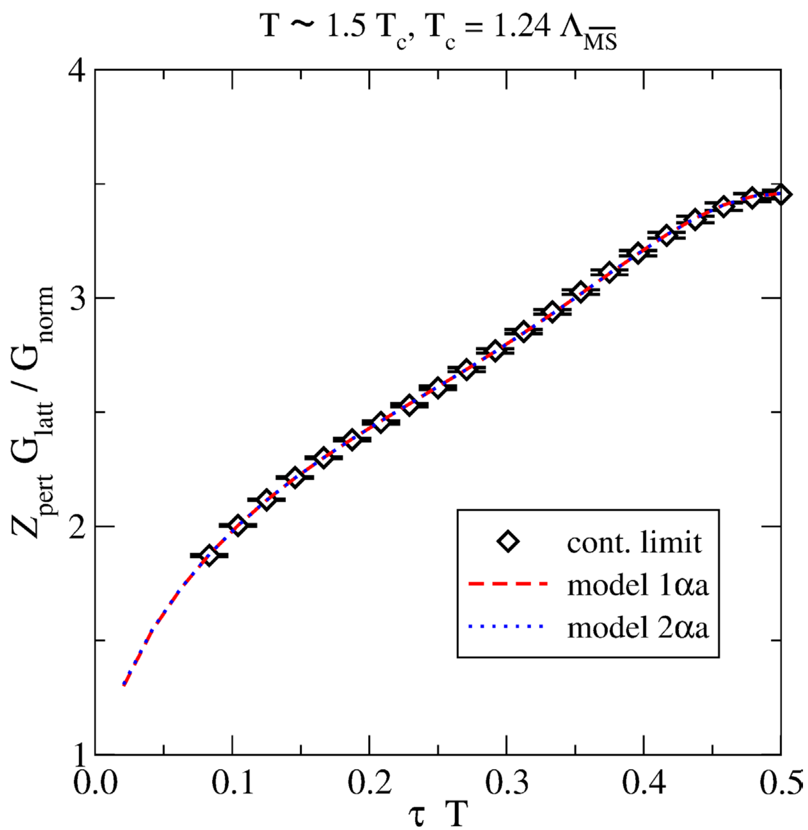
how to extract the spectral function from the correlator?

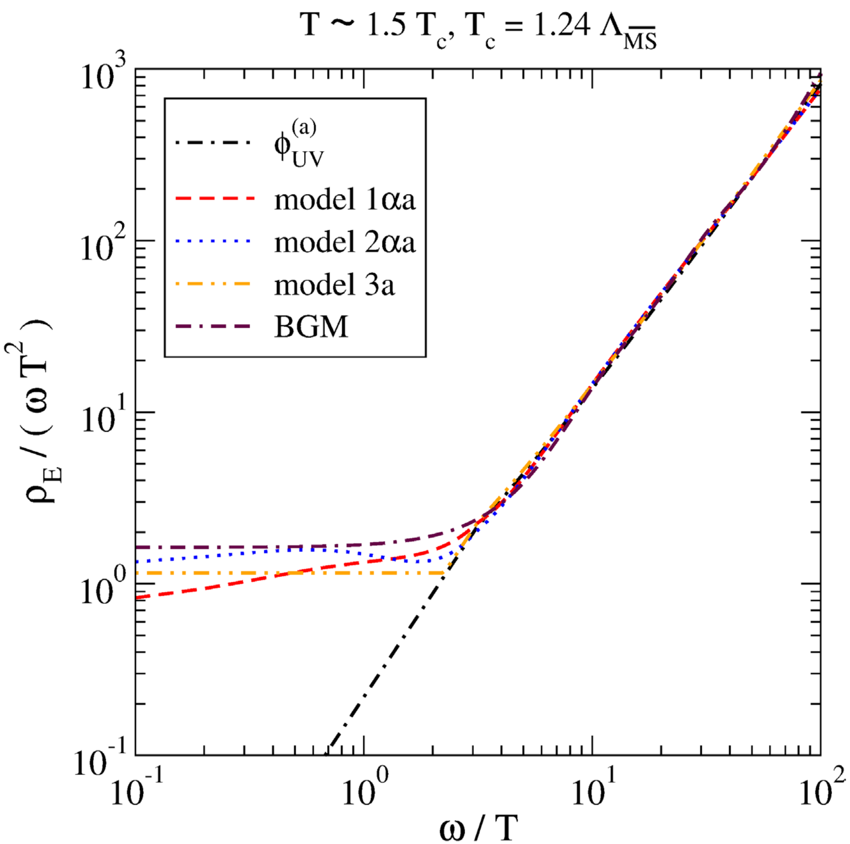
Spectral function models with correct asymptotic behavior

$$\rho_{\mathrm{UV}}(\omega) = \frac{g^2(\bar{\mu}_\omega) C_F \omega^3}{6\pi}$$

modeling corrections to ρ_{IR} by a power series in ω

$$\rho_{\mathrm{IR}}(\omega) = \frac{\kappa\omega}{2T}$$

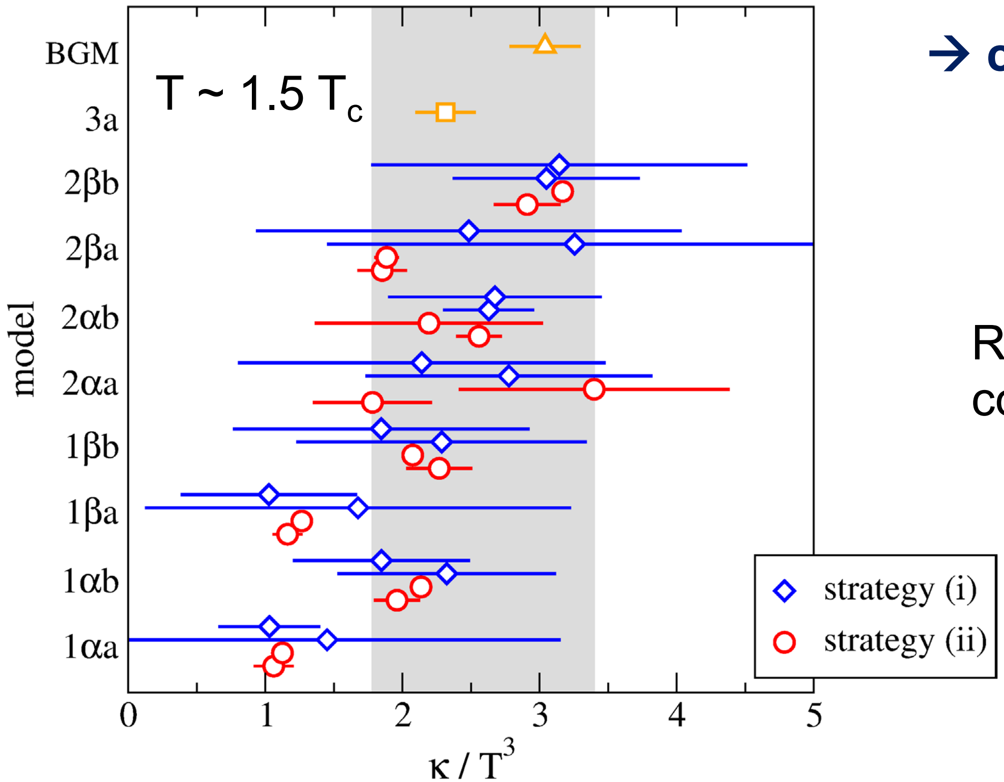




$$G_{\mathrm{model}}(\tau) \equiv \int_0^\infty \frac{\mathrm{d}\omega}{\pi} \rho_{\mathrm{model}}(\omega) \frac{\cosh\left(\frac{1}{2} - \tau T\right)\frac{\omega}{T}}{\sinh\frac{\omega}{2T}}$$

$$\kappa/T^3 = \lim_{\omega\to 0} \frac{2T\rho_{\mathrm{E}}(\omega)}{\omega}$$

[A.Francis, OK et al., PRD92(2015)116003]



Detailed analysis of systematic uncertainties

→ continuum estimate of κ :

$$\kappa/T^3 = \lim_{\omega\to 0} \frac{2T\rho_E(\omega)}{\omega} = 1.8...3.4$$

Related to diffusion coefficient D and drag coefficient η_D (in the non-relativistic limit)

$$2\pi T D = 4\pi \frac{T^3}{\kappa} = 3.7...7.0$$

$$\eta_D = \frac{\kappa}{2M_{kin}T}\left(1 + O\left(\frac{\alpha_s^{3/2}T}{M_{kin}}\right)\right)$$

time scale associated with the kinetic equilibration of heavy quarks:

$$\tau_{\mathrm{kin}} = \frac{1}{\eta_D} = (1.8\ldots3.4)\left(\frac{T_c}{T}\right)^2\left(\frac{M}{1.5\ \mathrm{GeV}}\right)\ \mathrm{fm/c}$$

→ close to T_c, $\tau_{kin} \simeq$ 1fm/c and therefore charm quark kinetic equilibration appears to be almost as fast as that of light partons.

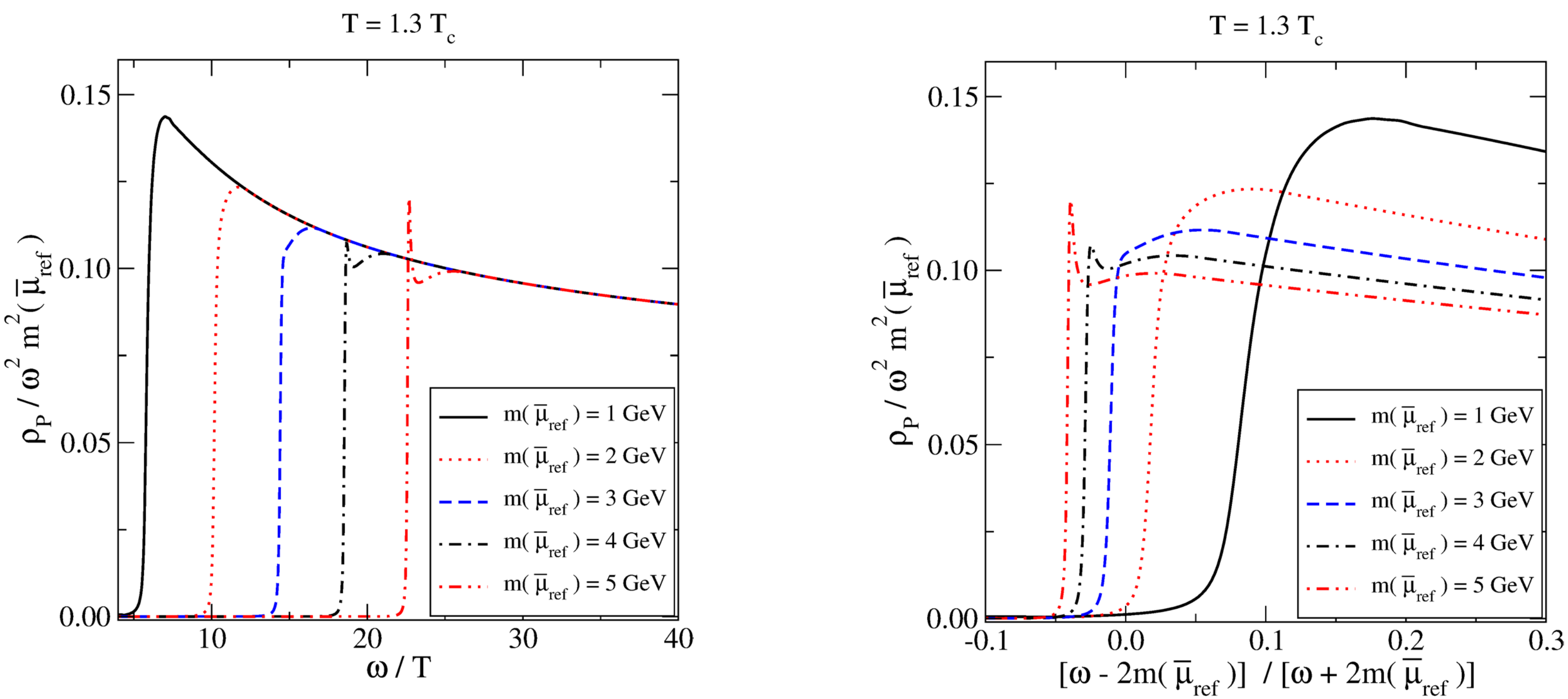
[Y. Burnier, H.-T. Ding, OK et al. JHEP11 (2017) 206]

Using **continuum extrapolated correlation functions** from Lattice QCD

$$G_{\rm P}(\tau) \equiv M_{\rm B}^2 \int_{\vec{x}} \Big\langle (\bar\psi i\gamma_5\psi)(\tau,\vec{x})\, (\bar\psi i\gamma_5\psi)(0,\vec{0}) \Big\rangle_{\rm c} , \quad 0 < \tau < \frac{1}{T} ,$$

and best knowledge on the spectral function from **perturbation theory and pNRQCD**

interpolated between different regimes



we will focus on the pseudo-scalar channel (no transport contribution in this channel)

Lattice set-up

quenched SU(3) gauge configurations (separated by 500 updates)

non-perturbatively O(a) clover improved Wilson fermion valence quarks

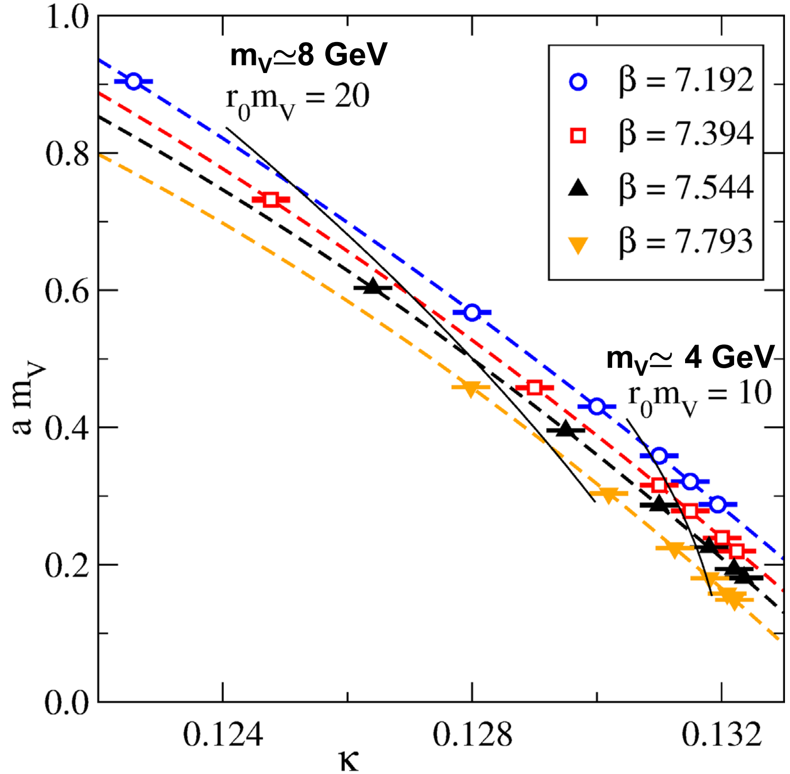
6 quark masses between charm and bottom → interpolate to physical c and b mass

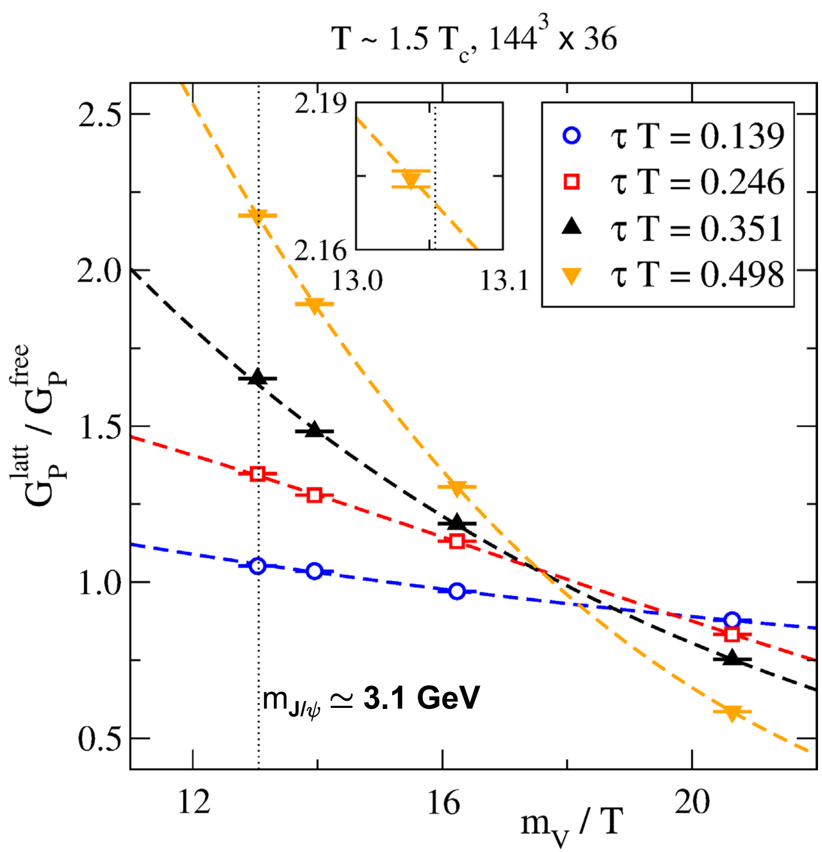
β	N_s	N_τ	confs	r_0/a	T/T_c	c_{SW}	κ_c	κ	$\frac{m^2(1/a)}{m^2(\bar{\mu}_{ref})}$
7.192	96	48	237	26.6	0.74	1.367261	0.13442	0.12257, 0.12800, 0.13000, 0.13100, 0.13150, 0.13194	0.6442
		32	476		1.12				
		28	336		1.27				
		24	336		1.49				
		16	237		2.23				
7.394	120	60	171	33.8	0.76	1.345109	0.13408	0.124772, 0.12900, 0.13100, 0.13150, 0.132008, 0.132245	0.6172
		40	141		1.13				
		30	247		1.51				
		20	226		2.27				
7.544	144	72	221	40.4	0.75	1.330868	0.13384	0.12641, 0.12950, 0.13100, 0.13180, 0.13220, 0.13236	0.5988
		48	462		1.13				
		42	660		1.29				
		36	288		1.51				
		24	237		2.26				
7.793	192	96	224	54.1	0.76	1.310381	0.13347	0.12798, 0.13019, 0.13125, 0.13181, 0.13209, 0.13221	0.5715
		64	249		1.13				
		56	190		1.30				
		48	210		1.51				
		32	235		2.27				

Interpolation to physical c + b bare quark masses required to perform continuum extrap.

→ lines of constant physics defined by vector meson mass at 0.75 T_c

→ interpolate correlators to the physical lines of constant physics



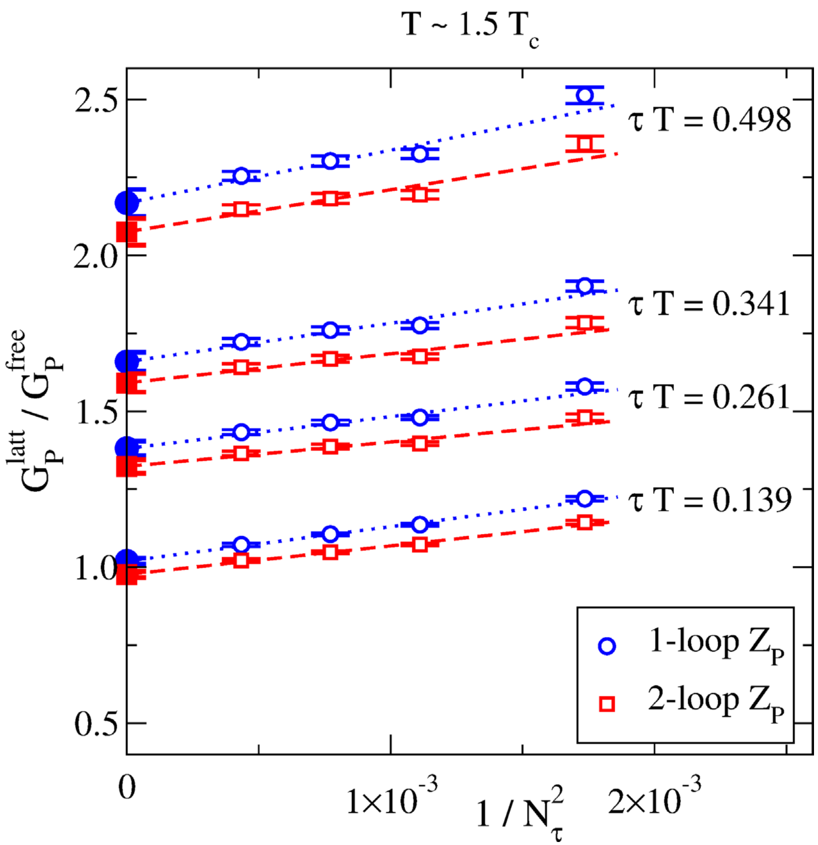


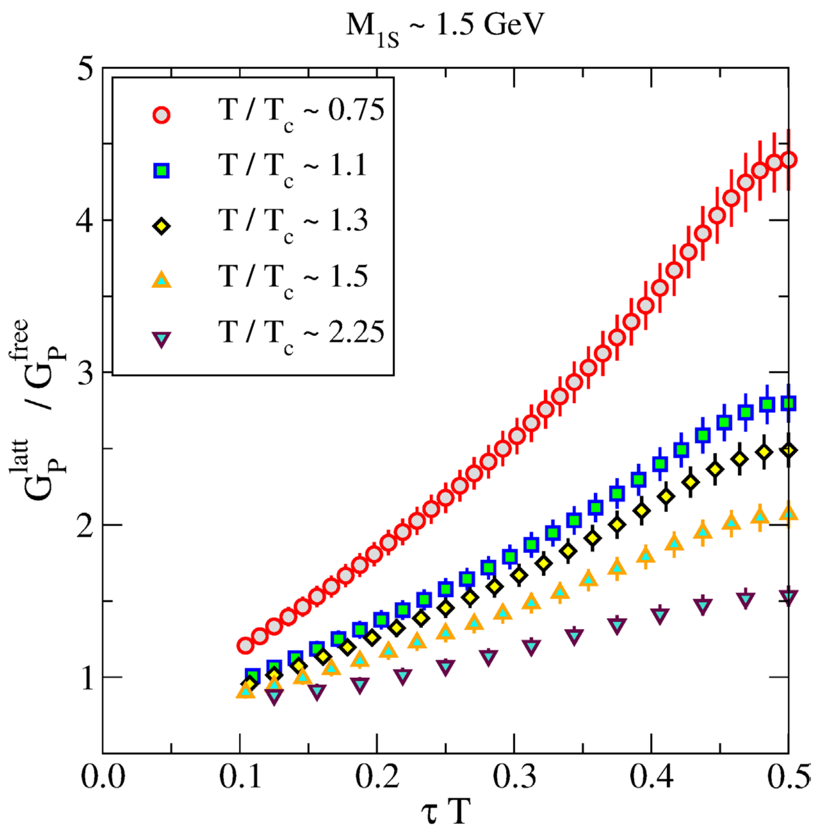
→ continuum extrapolation on lines of constant physics for c and b quark masses

Continuum limit of the correlation functions in a^2

continuum extrapolation well behaved

some uncertainty in renormalization → well defined continuum correlators





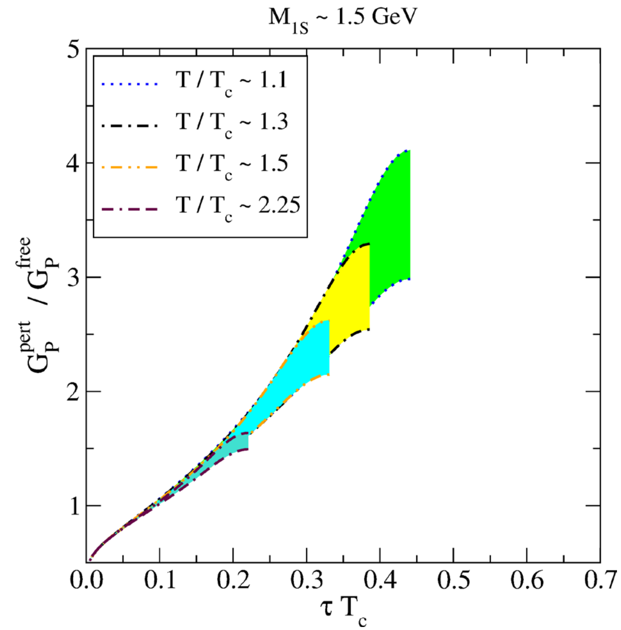
→ comparison to perturbation theory and determination of continuum spectral functions

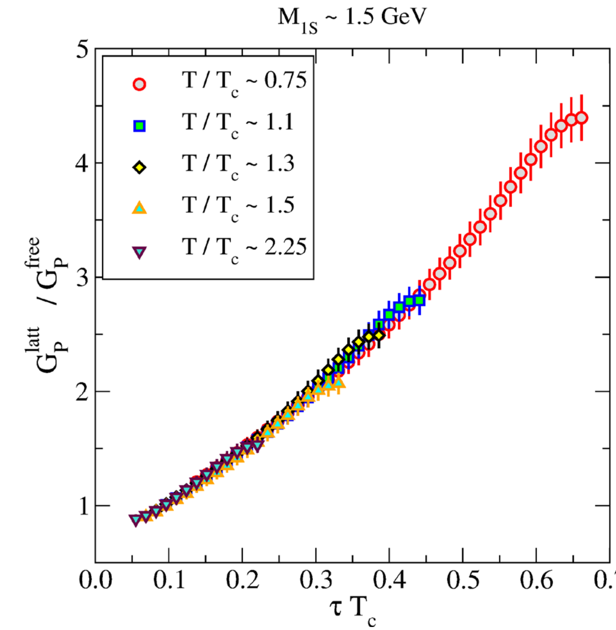
Continuum extrapolated lattice vs. perturbative correlators

perturbative correlators:

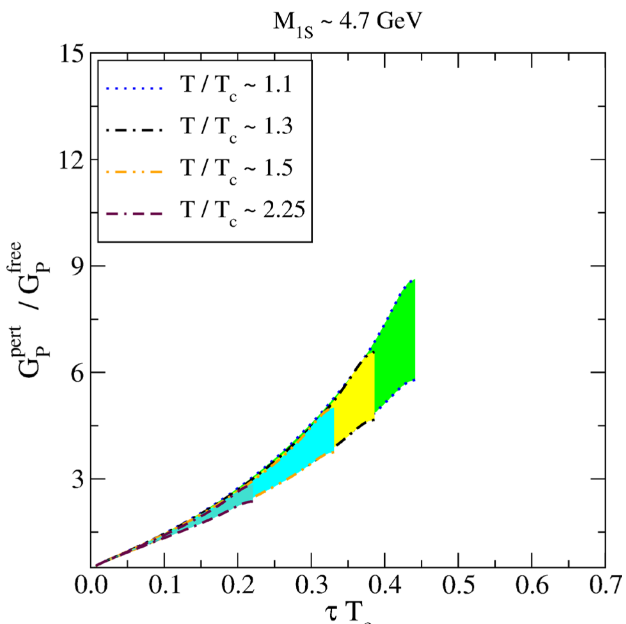
lattice correlators (continuum extrap.):

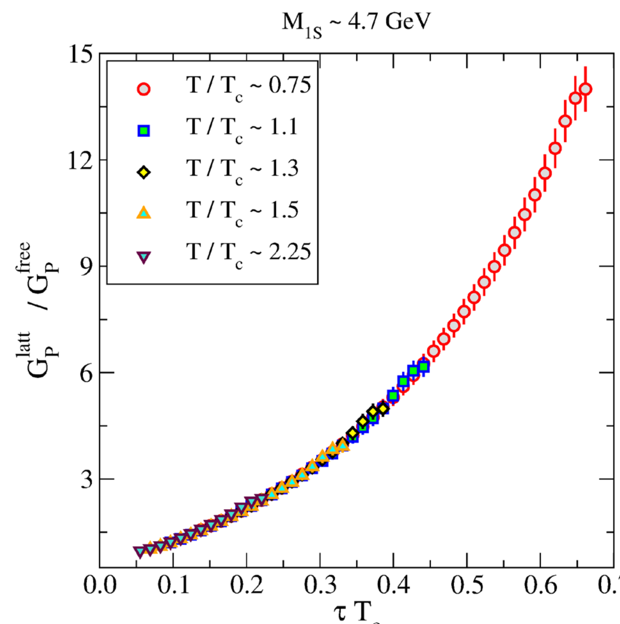
charm:



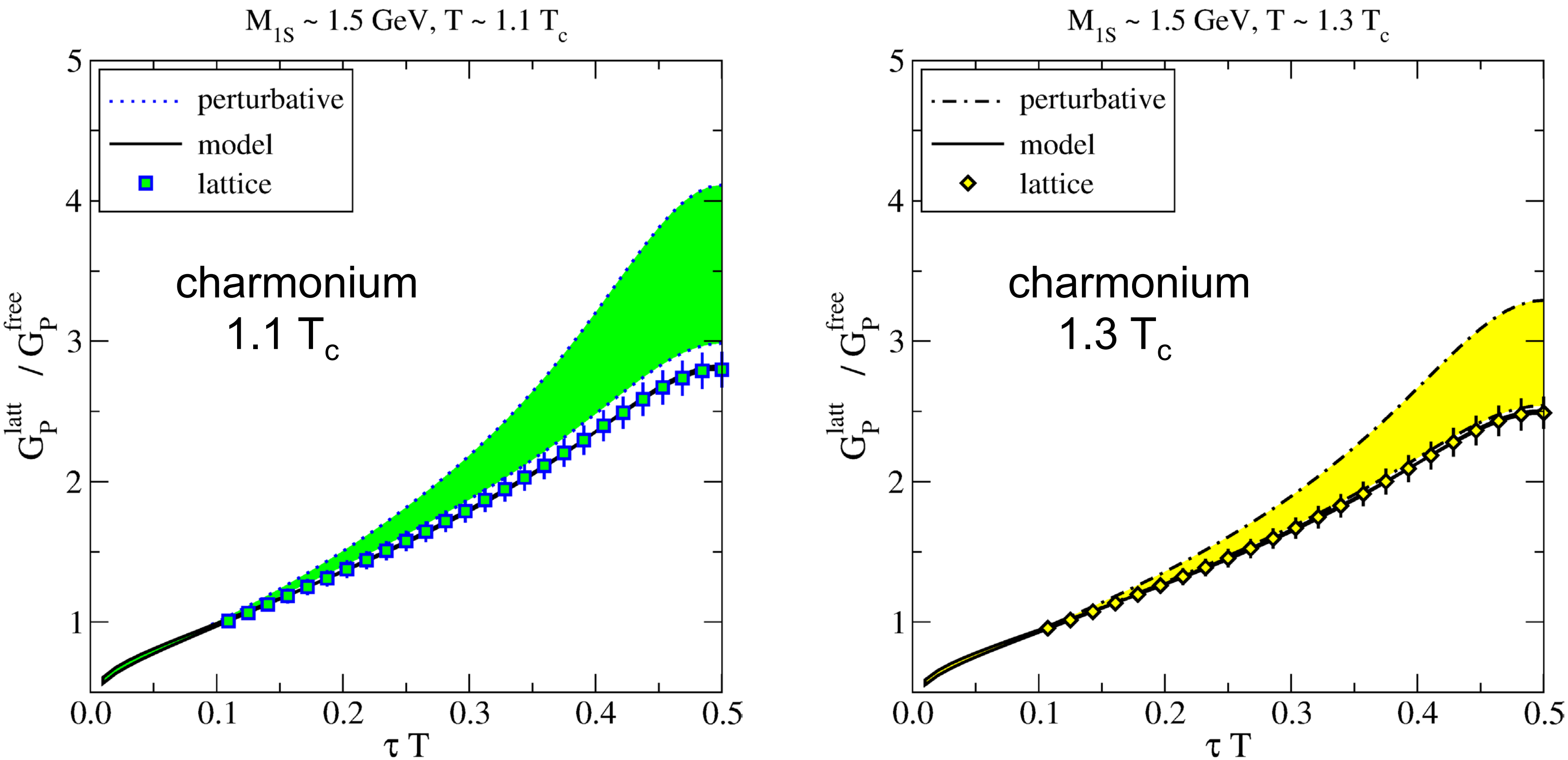


bottom:





Pseudo-scalar



differences between lattice and perturbation theory may have a simple explanation

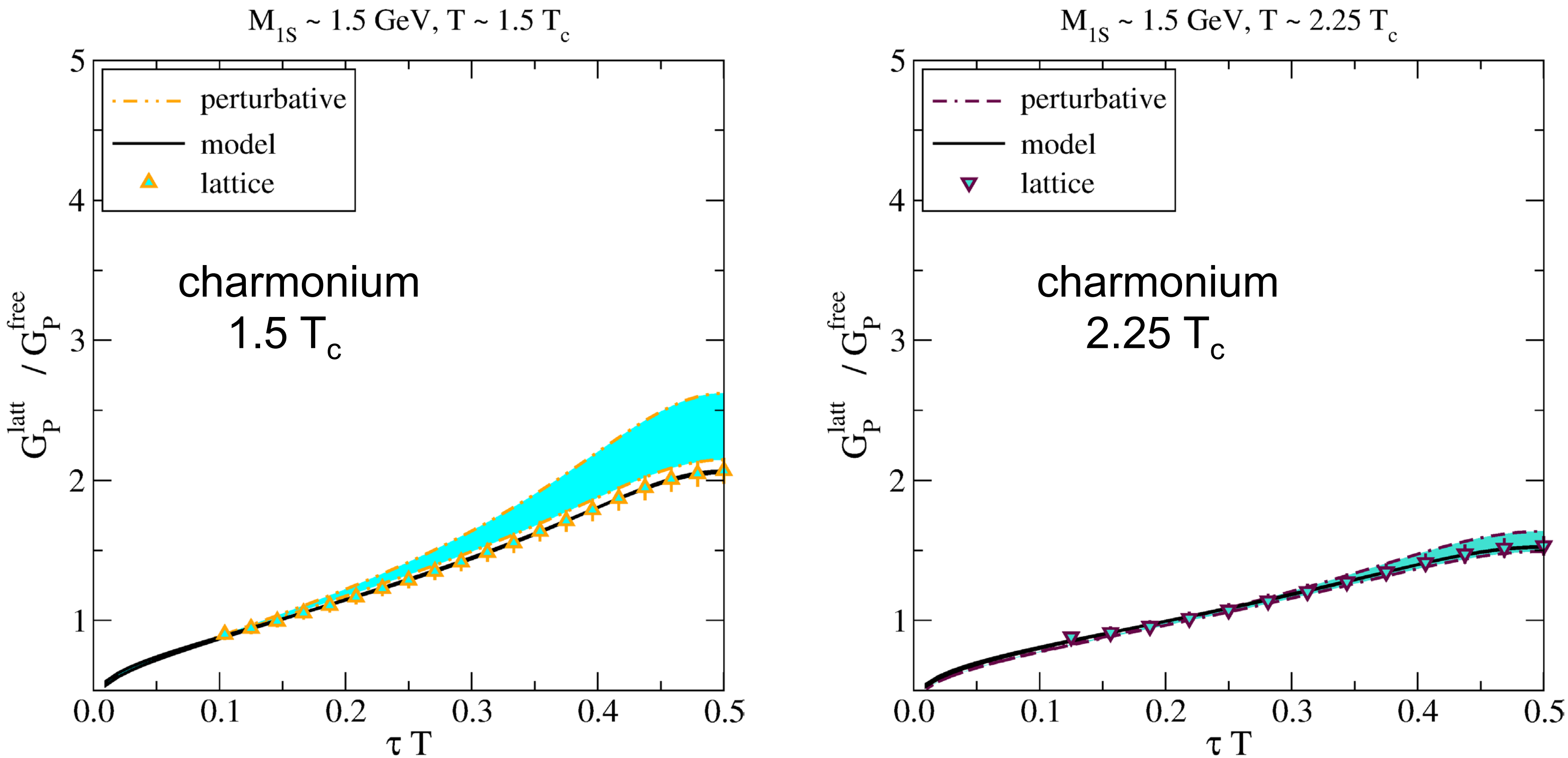
A: uncertainties related to the perturbative renormalization factors

B: non-perturbative mass shifts

$$\rho_{\rm P}^{\rm model}(\omega) \;\equiv\; A\,\rho_{\rm P}^{\rm pert}(\omega - B)\;.$$

→ continuum lattice data well described by this model with χ^2/d.o.f < 1

Modelling the spectral function



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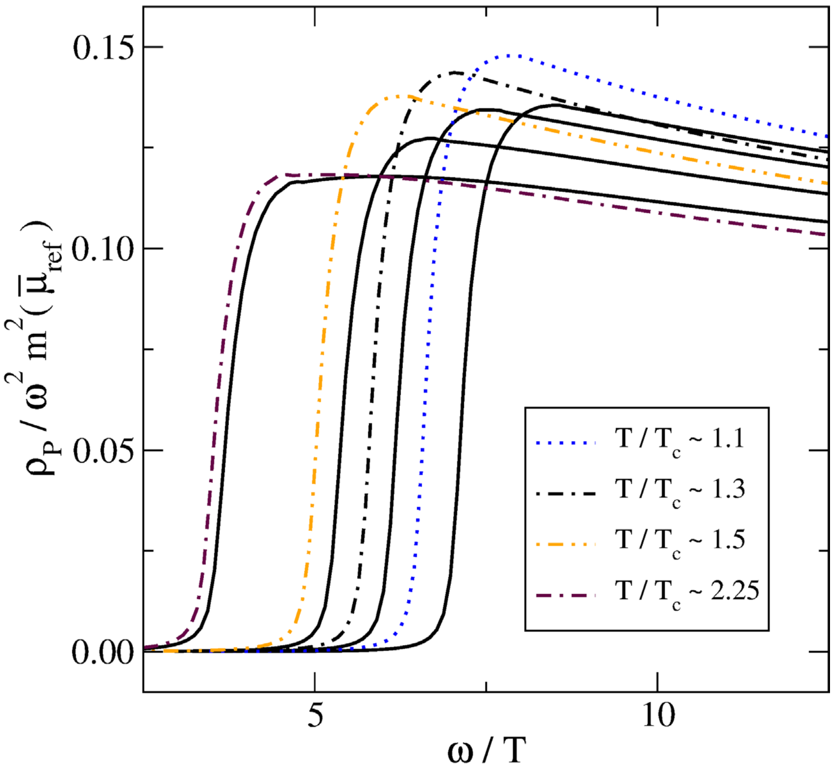
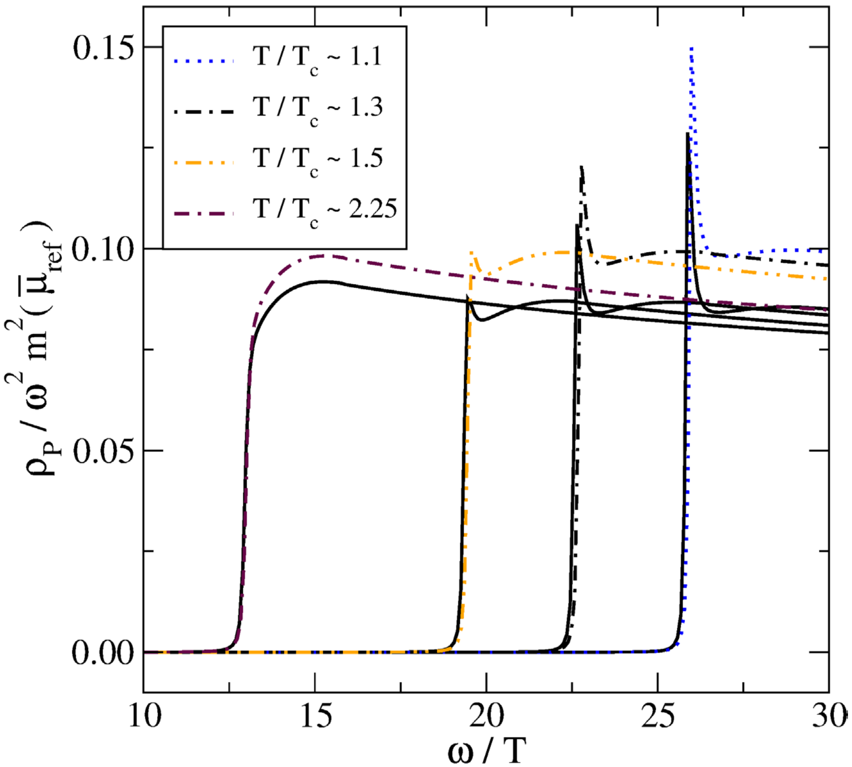
Pseudo-scalar spectral functions

charmonium: $m(\bar{\mu}_{ref}) = 1$ GeV



bottomonium: $m(\bar{\mu}_{ref}) = 5$ GeV



charmonium:

no resonance peaks are needed for representing the lattice data even for 1.1 T_c

modest threshold enhancement sufficient in the analyzed temperature region

bottomonium:

thermally broadened resonance peak present

up to temperatures around 1.5 T_c

next steps:

analysis of the vector channel

heavy quark diffusion coefficient

Conclusion – Disclaimer - Outlook

Continuum extrapolated correlators from quenched lattice QCD are well described by perturbative model spectral functions down to T $\approx$ T_c for observable with an external scale (mass, momentum) $\gtrsim \pi$T

All results in this talk were obtained in the quenched approximation

What may change when going to full QCD?

$\Lambda_{\overline{\mathrm{MS}}}\|_{N_f=0} \approx 255\mathrm{MeV}$	$\Lambda_{\overline{\mathrm{MS}}}\|_{N_f=3} \approx 340\mathrm{MeV}$
$T_c\|_{N_f=0} \approx 1.24\Lambda_{\overline{\mathrm{MS}}}\|_{N_f=0}$	$T_c\|_{N_f=3} \approx 0.45\Lambda_{\overline{\mathrm{MS}}}\|_{N_f=3}$
$\alpha_s^{EQCD}\|_{T\simeq T_c} \simeq 0.2$	$\alpha_s^{EQCD}\|_{T\simeq T_c} > 0.3$
1st order deconfinement transition	**chiral crossover transition**

Physics may become more non-perturbative, more interesting, more complicated…

Quenched theory is a nice playground but full QCD studies crucial!

Congratulations to Heng-Tong and CCNU for the opening of the NSC^3

Looking forward to many more interesting projects in the future