

Lattice Landau gauge quark propagator at finite temperature

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Outline

- 1 Introduction and Motivation
 - QCD phase diagram, center symmetry and Green's functions
 - Gluon propagator @ finite T
 - Z_3 dependence
- 2 Quark propagator finite T
- 3 Conclusions and Outlook

QCD phase diagram

- study of the phase diagram of QCD relevant e.g. for heavy ion experiments
- QCD has phase transition where quarks and gluons become deconfined for sufficiently high T
- Polyakov loop
 - order parameter for the confinement-deconfinement phase transition
 - $L = \langle L(\vec{x}) \rangle \propto e^{-F_q/T}$
 - Definition on the lattice:

$$L(\vec{x}) = \text{Tr} \prod_{t=0}^{N_t-1} \mathcal{U}_4(\vec{x}, t)$$

- $T < T_c$: $L = 0$ (center symmetry)
- $T > T_c$: $L \neq 0$ (spontaneous breaking of center symmetry)

Center symmetry

- Wilson gauge action is invariant under a center transformation
- temporal links on a hyperplane $x_4 = \text{const}$ multiplied by

$$z \in Z_3 = \{e^{-i2\pi/3}, 1, e^{i2\pi/3}\}$$

- Polyakov loop $L(\vec{x}) \rightarrow zL(\vec{x})$
- $T < T_c$
 - local P_L phase equally distributed among the three sectors

$$L = \langle L(\vec{x}) \rangle \approx 0$$

- $T > T_c$
 - Z_3 sectors not equally populated: $L \neq 0$

G. Endrödi, C. Gattringer, H.-P. Schadler, arXiv:1401.7228
C. Gattringer, A. Schmidt, JHEP **01**, 051 (2011)
C. Gattringer, Phys. Lett. **B 690**, 179 (2010)

F. M. Stokes, W. Kamleh, D. B. Leinweber, arXiv:1312.0991

QCD Green's functions

- In a Quantum Field Theory, knowledge of all Green's functions allows a complete description of the theory
- In QCD, propagators of fundamental fields (e.g. quark, gluon and ghost propagators) encode information about non-perturbative phenomena
 - gluon propagator encodes information about confinement/deconfinement
 - quark propagator: chiral symmetry breaking
- Since propagators are gauge dependent quantity, we need to choose a gauge
 - in our works: Landau gauge

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Gluon propagator at finite temperature

$$D_{\mu\nu}^{ab}(\hat{q}) = \delta^{ab} \left(P_{\mu\nu}^T D_T(q_4, \vec{q}) + P_{\mu\nu}^L D_L(q_4, \vec{q}) \right)$$

- Two components:
 - transverse D_T
 - longitudinal D_L

$$D_{ii}^{aa}(q) = \frac{2}{V} \left\langle \text{Tr} \left[A_i(\hat{q}) A_i^\dagger(\hat{q}) \right] \right\rangle = \delta^{aa} \left(P_{ii}^T D^T + P_{ii}^L D^L \right)$$

$$D_{44}^{aa}(q) = \frac{2}{V} \left\langle \text{Tr} \left[A_4(\hat{q}) A_4^\dagger(\hat{q}) \right] \right\rangle = \delta^{aa} \left(P_{44}^T D^T + P_{44}^L D^L \right)$$

- Finite temperature on the lattice: $L_t \ll L_s$

$$T = \frac{1}{aL_t}$$

Lattice setup finite T

Temp. (MeV)	β	L_s	L_t	a [fm]	1/a (GeV)
121	6.0000	64	16	0.1016	1.943
162	6.0000	64	12	0.1016	1.943
194	6.0000	64	10	0.1016	1.943
243	6.0000	64	8	0.1016	1.943
260	6.0347	68	8	0.09502	2.0767
265	5.8876	52	6	0.1243	1.5881
275	6.0684	72	8	0.08974	2.1989
285	5.9266	56	6	0.1154	1.7103
290	6.1009	76	8	0.08502	2.3211
305	5.9640	60	6	0.1077	1.8324
305	6.1326	80	8	0.08077	2.4432
324	6.0000	64	6	0.1016	1.943
366	6.0684	72	6	0.08974	2.1989
397	5.8876	52	4	0.1243	1.5881
428	5.9266	56	4	0.1154	1.7103
458	5.9640	60	4	0.1077	1.8324
486	6.0000	64	4	0.1016	1.943

- Simulations: use of Chroma and PFFT libraries
- keep a constant (spatial) physical volume $\sim (6.5\text{fm})^3$
- all data renormalized at $\mu = 4\text{GeV}$

O. Oliveira, PJS, PoS(LATTICE2012)216

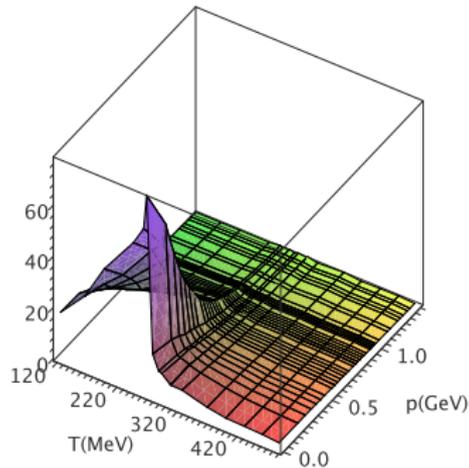
Acta Phys.Polon.Supp. 5 (2012) 1039

PoS(Confinement X)045

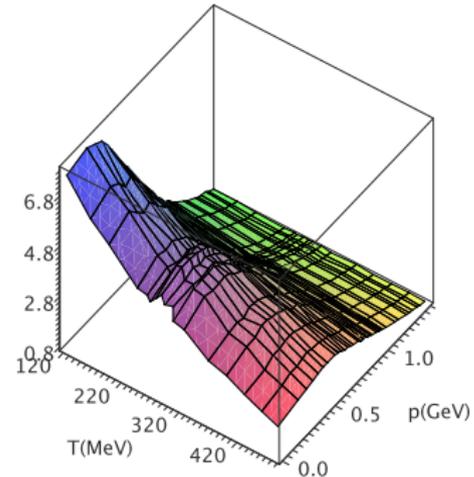


Surface plots ($q_4 = 0$)

Longitudinal component



Transverse component



PJS, O. Oliveira, P. Bicudo, N. Cardoso, Phys.Rev. D89 (2014) 074503

Outline

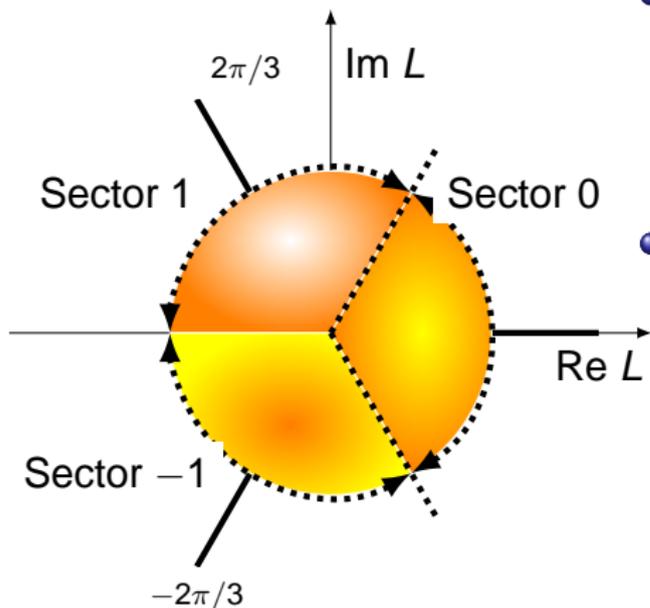
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Z_3 dependence

- D_L and D_T show quite different behaviours with T
- Usually, the propagator is computed such that $\arg(P_L) < \pi/3$ (Z_3 sector 0)
- what happens in the other sectors?

PJS, O. Oliveira, PRD **93** (2016) 114509

Z_3 dependence



- for each configuration, 3 gauge fixings after a Z_3 transformation

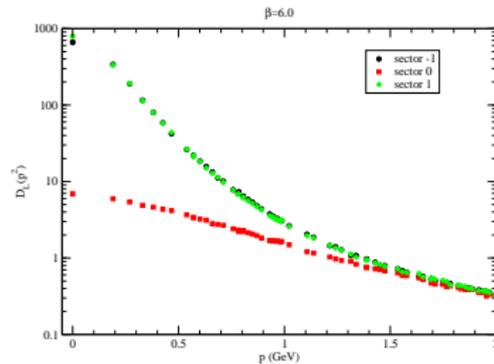
$$\mathcal{U}'_4(\vec{x}, t = 0) = z \mathcal{U}_4(\vec{x}, t = 0)$$

- configurations classified according to $\langle L \rangle = |L| e^{i\theta}$

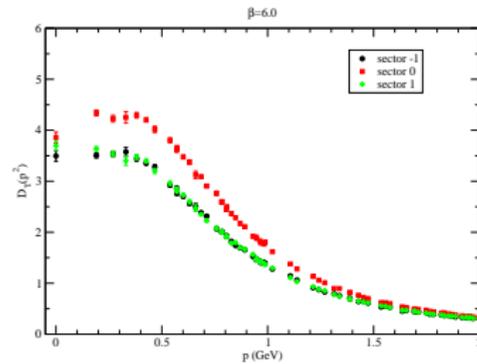
$$\theta = \begin{cases} -\pi < \theta \leq -\frac{\pi}{3}, & \text{Sector -1,} \\ -\frac{\pi}{3} < \theta \leq \frac{\pi}{3}, & \text{Sector 0,} \\ \frac{\pi}{3} < \theta \leq \pi, & \text{Sector 1} \end{cases}$$

Typical result at high T (324 MeV)

Longitudinal component



Transverse component



What happens near T_c ?

- spatial physical volume $\sim (6.5\text{fm})^3$
- 100 configs per ensemble

Coarse lattices $a \sim 0.12\text{fm}$

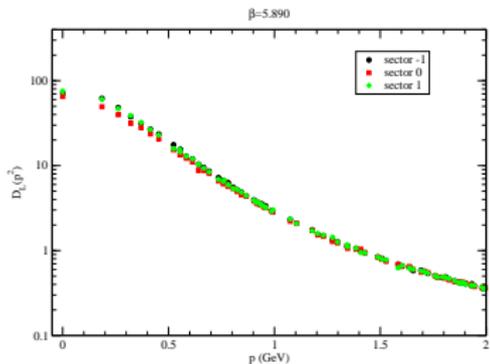
Temp. (MeV)	$L_s^3 \times L_t$	β	a (fm)	$L_s a$ (fm)
265.9	$54^3 \times 6$	5.890	0.1237	6.68
266.4	$54^3 \times 6$	5.891	0.1235	6.67
266.9	$54^3 \times 6$	5.892	0.1232	6.65
267.4	$54^3 \times 6$	5.893	0.1230	6.64
268.0	$54^3 \times 6$	5.8941	0.1227	6.63
268.5	$54^3 \times 6$	5.895	0.1225	6.62
269.0	$54^3 \times 6$	5.896	0.1223	6.60
269.5	$54^3 \times 6$	5.897	0.1220	6.59
270.0	$54^3 \times 6$	5.898	0.1218	6.58
271.0	$54^3 \times 6$	5.900	0.1213	6.55
272.1	$54^3 \times 6$	5.902	0.1209	6.53
273.1	$54^3 \times 6$	5.904	0.1204	6.50

Fine lattices $a \sim 0.09\text{fm}$

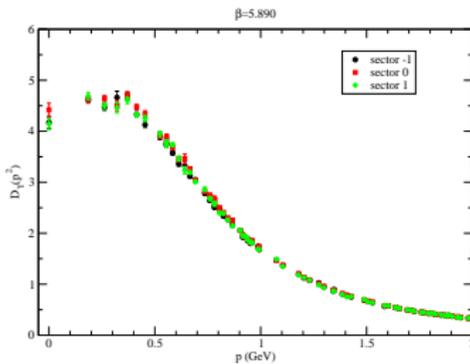
Temp. (MeV)	$L_s^3 \times L_t$	β	a (fm)	$L_s a$ (fm)
269.2	$72^3 \times 8$	6.056	0.09163	6.60
270.1	$72^3 \times 8$	6.058	0.09132	6.58
271.0	$72^3 \times 8$	6.060	0.09101	6.55
271.5	$72^3 \times 8$	6.061	0.09086	6.54
271.9	$72^3 \times 8$	6.062	0.09071	6.53
272.4	$72^3 \times 8$	6.063	0.09055	6.52
272.9	$72^3 \times 8$	6.064	0.09040	6.51
273.3	$72^3 \times 8$	6.065	0.09025	6.50
273.8	$72^3 \times 8$	6.066	0.09010	6.49

Coarse lattices, below T_C

Longitudinal component

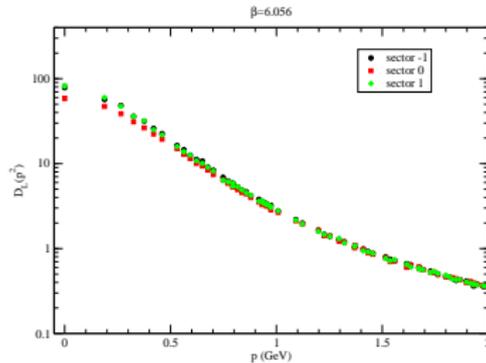


Transverse component

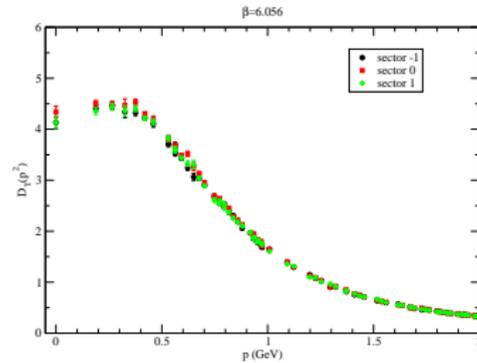


Fine lattices, below T_C

Longitudinal component

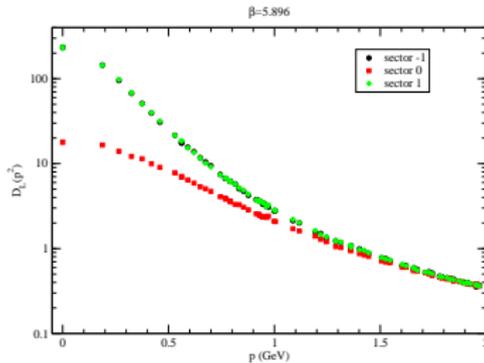


Transverse component

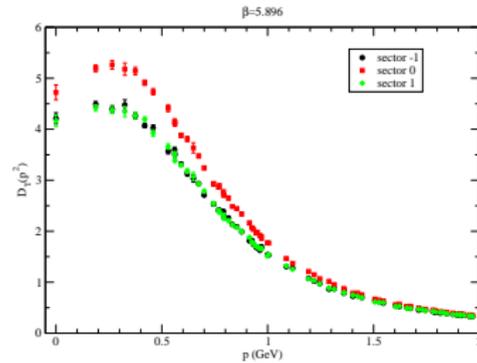


Coarse lattices, above T_C

Longitudinal component

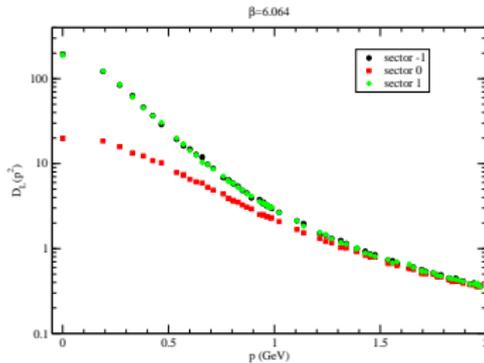


Transverse component

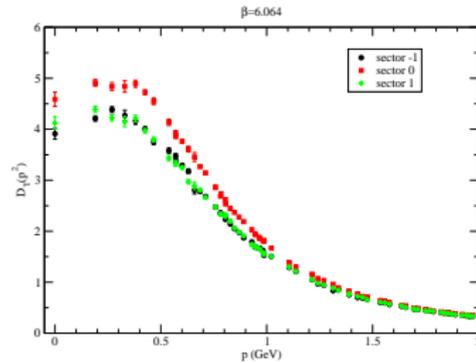


Fine lattices, above T_c

Longitudinal component

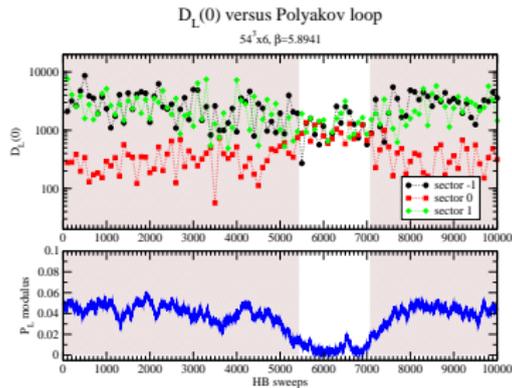


Transverse component

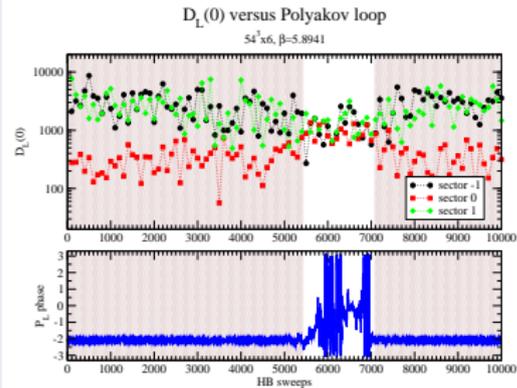


(bare) Polyakov loop history

Modulus

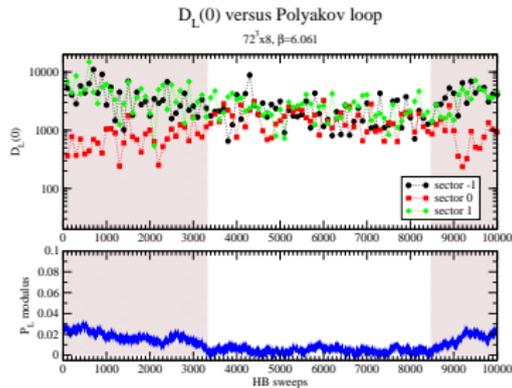


Phase

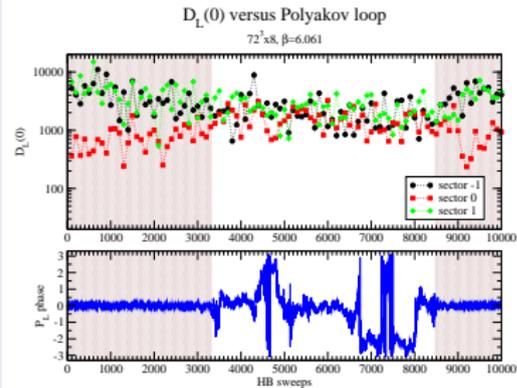


(bare) Polyakov loop history

Modulus

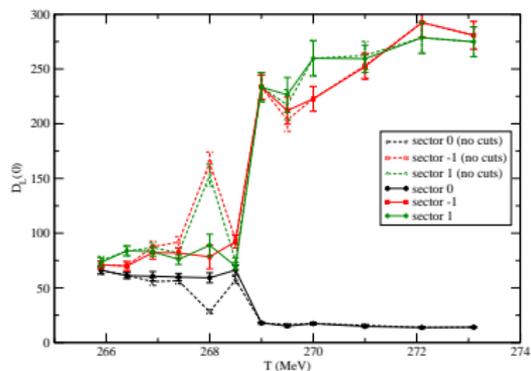


Phase

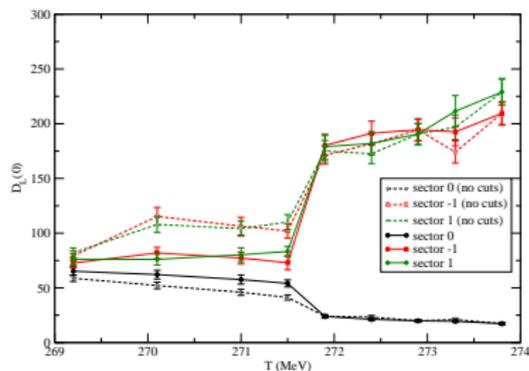


Removing configurations in wrong phase

Coarse lattices



Fine lattices



Gluon propagator at finite temperature

- Longitudinal component signals deconfinement phase transition
- Propagators in various Z_3 sectors differ above T_c
- what about the quark propagator?

Quark propagator at finite temperature

- At finite T, quark propagator is described by three form factors in momentum space

$$S(p_t, \vec{p}) = \frac{1}{i\gamma_t p_t \omega(p_t, \vec{p}) + i\vec{\gamma} \cdot \vec{p} Z(p_t, \vec{p}) + \sigma(p_t, \vec{p})}$$

$$S(p_t, \vec{p}) = \frac{-i\gamma_t p_t \omega(p_t, \vec{p}) - i\vec{\gamma} \cdot \vec{p} Z(p_t, \vec{p}) + \sigma(p_t, \vec{p})}{p_t^2 \omega^2(p_t, \vec{p}) + (\vec{p} \cdot \vec{p}) Z^2(p_t, \vec{p}) + \sigma^2(p_t, \vec{p})}$$

- Clover fermions, rotated sources

Sheikholeslami, Wohlert, Nucl. Phys. B259 (1985) 572

Heatlie et al, Nucl. Phys. B352 (1991) 266

A few previous works in Landau gauge (I)

- M. Hamada *et al*, PoS (LAT2006) 136
 - quark propagator in momentum space
 - Wilson fermions: mass function changes across the phase transition
 - a test using Clover fermions shows qualitative agreement with Wilson (not quantitative)
- M. Hamada *et al*, PRD81 (2010) 094506
 - Clover fermions
 - temporal correlation functions
 - no qualitative change across T_c ,
 - although value of effective quark mass changes

$$m_{\text{eff}}^{\text{above}T_c} \sim \frac{1}{2} m_{\text{eff}}^{\text{below}T_c}$$

A few previous works in Landau gauge (II)

- F. Karsch and M. Kitazawa, PRD80 (2009) 056001
 - quark spectral functions above and below T_c
 - $T > T_c$ — data well described by a two-pole approximation
 - $T < T_c$ — two-pole ansatz fails: violation of positivity?

- all works used quenched configurations
- no systematic study has been done with Clover fermions in momentum space

Quark propagator finite T

- focus on the region around T_c
- 3 temperatures, 2 point sources so far

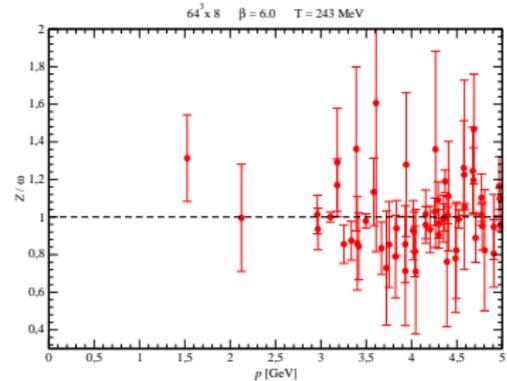
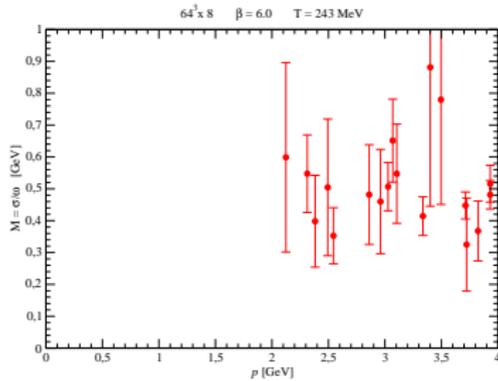
T(MeV)	β	$L_s^3 \times L_t$	κ	m_{bare} (MeV)	c_{SW}
243	6.0000	$64^3 \times 8$	0.1350	10	1.769
260	6.0347	$68^3 \times 8$	0.1351	11	1.734
275	6.0684	$72^3 \times 8$	0.1352	12	1.704

Luscher et al, Nucl. Phys. B491 (1997) 323

- cylinder cuts; analysis of lattice artifacts still to be done

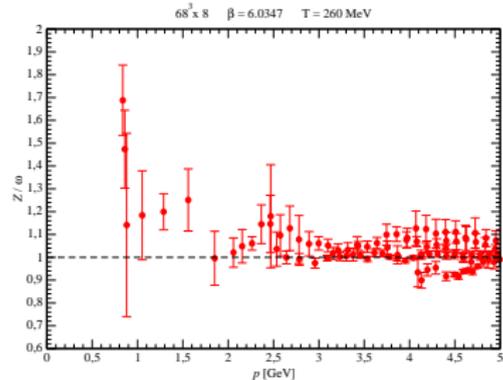
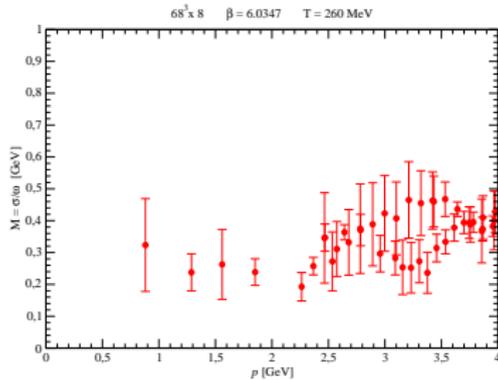
T=243 MeV

Preliminary!



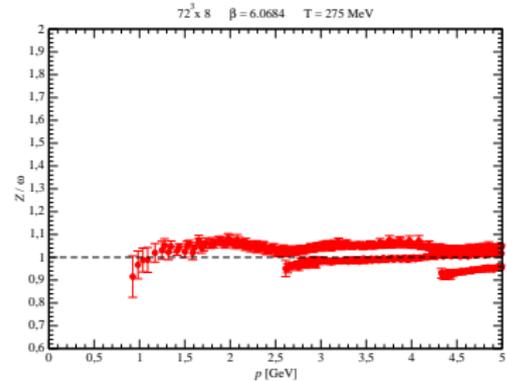
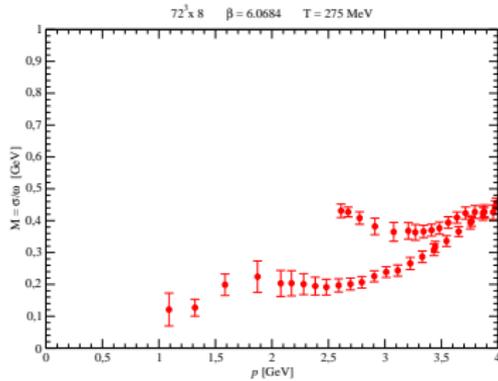
T=260 MeV

Preliminary!



T=275 MeV

Preliminary!



Conclusions and Outlook

- Review of our results for the gluon propagator at finite temperature
 - Z_3 dependence
- preliminary results for the quark propagator
 - behaviour across T_c not clear yet
 - increase statistics, improve analysis
- Outlook:
 - other temperatures
 - dynamical simulations



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