Gluon propagator and gluon mass at finite temperature, measured in Landau gauge SU(3) lattice QCD

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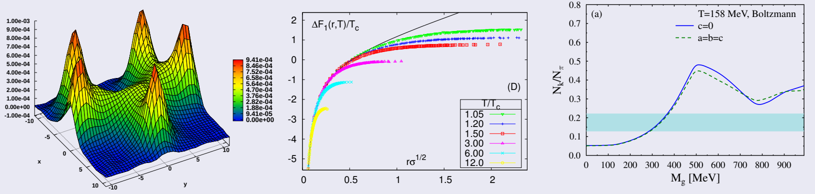
Outline

1. Why?
2. Gluon propagator with Landau gauge fixing at T=0
3. Gluon mass at finite T

Why gluon mass?



- At $T = 0$ we have colour screening and flux tubes,

J. M. Cornwall, Phys. Rev. D 26, 1453 (1982)
N. Cardoso, P. Bicudo, Phys. Rev. D 87, 034504 (2013)
N. Cardoso, M. Cardoso, P. Bicudo [arXiv:1302.3633 [hep-lat]]

- at large T Debye screening,

M. Doring, K. Hubner, O. Kaczmarek, and F. Karsch, Phys. Rev. D 75, 054504 (2007)
M. Bluhm, B. Kampfer and K. Redlich, Phys. Rev. C 84, 025201 (2011)

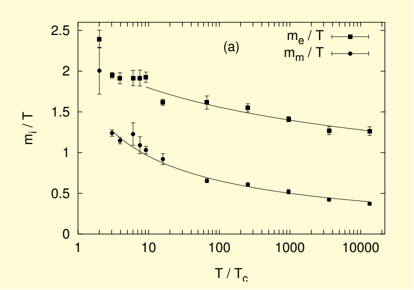
- at T_c a mass scale in the π and K multiplicities in heavy ions

P. Bicudo, F. Giacosa, E. Seel Phys.Rev. C86, 034907 (2012)

Why gluon mass?

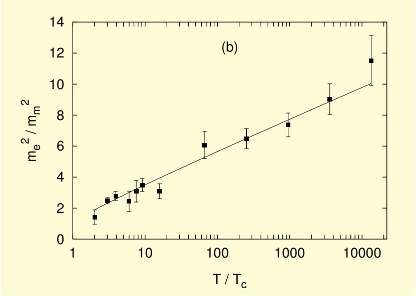
We complement the outstanding study of the gluon masses in SU(2) for $2T_c < T < 15000T_c$. Here we study $T < 2T_c$ and SU(3).

electric and magnetic masses



U.M. Heller, et al, Phys. Rev. **D57** , 1438-1448 (1998)

ratio of the masses



U.M. Heller, et al, Phys. Rev. **D57** , 1438-1448 (1998)

U.M. Heller, F. Karsch, J. Rank, Phys. Rev. **D57** , 1438-1448 (1998)

Gluon propagator with Landau gauge fixing

- Lattice QCD not only is used to compare QCD with experiment, but also is ideal to test theories, approximations and models.
- On the lattice, the Landau gauge is reached at the maximum of

$$F_U[g] = C_F \sum_{x,\mu} \mathrm{Re}\{\mathrm{Tr}[g(x)U_\mu(x)g^\dagger(x+\hat{\mu})]\}c \, ,$$

where $g(x)$ is a gauge transformation. The maximum leads to,

$$\partial_\mu A^a_\mu = 0 \, .$$

We apply a (Fourier accelerated) Steepest Descent method. We have tested this method both in CPU's and GPU's.

N. Cardoso, P. Silva, P. Bicudo, O. Oliveira Com. Phys. Com. 184, 124-129 (2013)
Mario Schrock, Hannes Vogt. [arXiv:1212.5221 [hep-lat]]

Gluon propagator with Landau gauge fixing

The $T = 0$ Landau gluon propagator reads

$$\langle A^a_\mu(p) A^b_\nu(p) \rangle = V\,\delta(p-k)\,\delta^{ab}\left(\delta_{\mu\nu} - \frac{p_\mu p_\nu}{p^2}\right) D(p^2)$$

- We compute $D(p^2)$ with pure gauge lattice simulations,

  Wilson action

- use sufficiently large volumes $V = {L_s}^3$,

  larger volume $\longrightarrow$ smaller IR $D(p^2)$

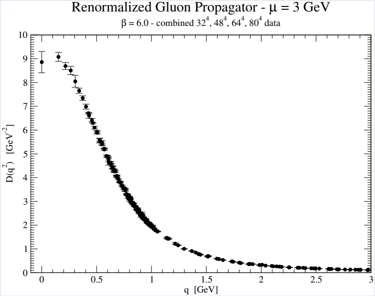
- use small lattice spacing,

  $\mathcal{O}(a^2)$ corrections effects @ IR and medium range momentum

A. Cucchieri and T. Mendes, PoS LAT 2007 (2007) 297 [arXiv:0710.0412 [hep-lat]]
I. L. Bogolubsky, E.-M. Ilgenfritz, M. Müller-Preussker, A. Sternbeck, Phys. Lett. **B676**, 69 (2009)
O. Oliveira, P. J. Silva, Phys. Rev. **D 86**, 114513 (2013)

Gluon propagator @ $T = 0$

Lattice Propagator



Interpretation

- In the UV, the propagator is massless, similar to 1-loop
- In the IR it seems massive and the simplest fit is a Yukawa up to $p \approx 600$ MeV

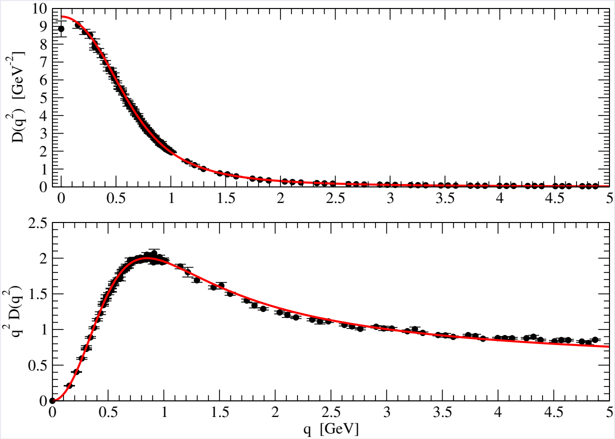
$$M_g = 648(7) MeV$$

- or complex conjugate poles

$$M_g = 626 \pm i\,362 \text{ MeV}$$

O. Oliveira, P. Bicudo, J. Phys. **G38**, 045003 (2011)
A. Bashir, C. Lei, I. C. Cloët, B. El-Bennich, L. Yu-Xin, C. D. Roberts, P. C. Tandy, Com. Theor. Phys. **58**, 79 (2012)

Gluon propagator @ $T = 0$



Interpretation

A more elaborate fit: a Running Gluon Mass

$$D(p^2) = \frac{Z(p^2)}{p^2 + M^2(p^2)}$$

O. Oliveira, P. Bicudo, J. Phys. **G38**, 045003 (2011)

Gluon propagator @ $T = 0$

The running gluon mass is fitted with a parameter $m_0 = 723(11)$ MeV

$$M^2(p^2) = \frac{m_0^4}{p^2 + m_0^2} \, , \quad Z(p^2) = \frac{z_0}{\left[\log \frac{p^2 + r\, m_0^2}{\Lambda^2}\right]^{\gamma}} \, ,$$

♡ fit works up to $p = 4.1$ GeV
♠ no log behaviour in the running mass

- similar functional form to the decoupling solution of the Dyson-Schwinger equations
- and prediction of the Refined-Zwanziger action

C. S. Fischer, A. Maas, J. M. Pawlowski, Annals Phys. **324**, 2408 (2009)
A C Aguilar, J Papavassiliou, Phys. Rev. **D81**, 034003 (2010)
D. Dudal, O. Oliveira, N. Vandersickel, Phys. Rev. **D81** 074505 (2010)
O. Oliveira, P. Bicudo, J. Phys. **G38**, 045003 (2011)

Gluon propagator @ $T > 0$

We project the Lorentz structure of the propagator $D^{ab}_{\mu\nu}(\hat{q})$ with two form factors,

$$D^{ab}_{\mu\nu}(\hat{q}) = \delta^{ab}\left(P^T_{\mu\nu} D_T(q_4^2, \vec{q}) + P^L_{\mu\nu} D_L(q_4^2, \vec{q})\right)$$

transverse D_T

longitudinal D_L

using transverse and longitudinal projectors , similar to electric and magnetic projectors, respectively, in the Landau gauge

$$P^T_{\mu\nu} = (1 - \delta_{\mu 4})(1 - \delta_{\nu 4})\left(\delta_{\mu\nu} - \frac{q_\mu q_\nu}{\vec{q}^2}\right)$$

$$P^L_{\mu\nu} = \left(\delta_{\mu\nu} - \frac{q_\mu q_\nu}{q^2}\right) - P^T_{\mu\nu}$$

Gluon propagator @ $T > 0$

Finite temperature T is simply introduced by reducing the extent of temporal direction $L_t << L_s$,

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

Moreover all lattice data is renormalized fitting the momenta in the UV region to the 1-loop inspired propagator,

$$D_{lattice}(q^2) = \frac{K}{q^2}\left(\ln\frac{q^2}{\Lambda^2}\right)^{-13/22} ,$$

- we set $D(q^2) = Z_R D_{lattice}(q^2)$; $D(\mu^2) = 1/\mu^2$ with $\mu =$4GeV
- renormalization removes the lattice spacing effects
- D_T and D_L are renormalised independently
- we observe Z_L and Z_T differ by less than 2 %

Gluon propagator @ $T > 0$

Our Lattice setup

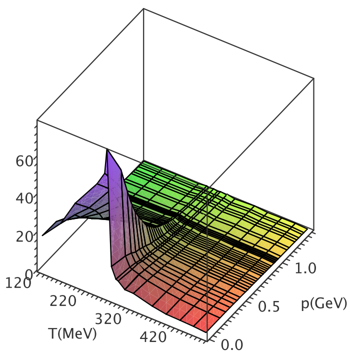
Temp. (MeV)	β	L_s	L_t	a [fm]	1/a (GeV)
121	6.0000	64	16	0.1016	1.9426
162	6.0000	64	12	0.1016	1.9426
194	6.0000	64	10	0.1016	1.9426
243	6.0000	64	8	0.1016	1.9426
260	6.0347	68	8	0.09502	2.0767
265	5.8876	52	6	0.1243	1.5881
275	6.0684	72	8	0.08974	2.1989
285	5.9266	56	6	0.1154	1.7103
290	6.1009	76	8	0.08502	2.3211
305	6.1326	80	8	0.08077	2.4432
324	6.0000	64	6	0.1016	1.9426
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	1.9426

- we utilize the same large volume with $L_s \sim 6.5$ fm for all T
- Generated at Milipeia, Centaurus at Coimbra University (Chroma and PFFT libraries)
- other recent works are,

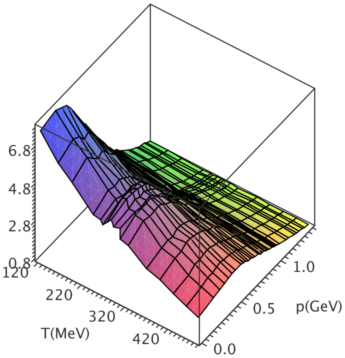
A. Cucchieri, T. Mendes, arXiv:1201.6086
A. Maas, J. M. Pawlowski, L. von Smekal, D. Spielmann, Phys. Rev. **D85**, 034037 (2012)
R. Aouane, V. Bornyakov, E.-M. Ilgenfritz, V. Mitrjushkin, M. Müller-Preussker, A. Sternbeck, Phys. Rev. **D85**, 034501 (2012)

Gluon propagator @ $T > 0$

Longitudinal component



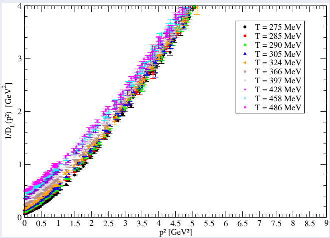
Transverse component

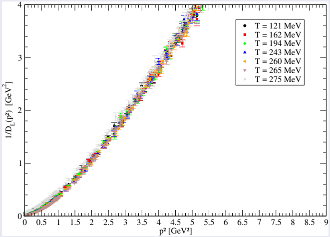


O. Oliveira, P. J. Silva, Acta Phys.Polon.Supp. 5 (2012) 1039, PoS(LATTICE2012)216

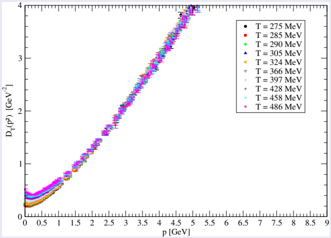
Gluon propagator @ $T > 0$

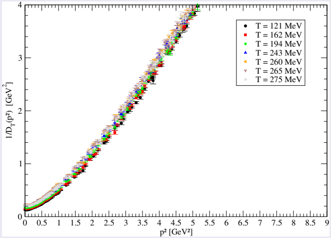
Inverse of Longitudinal D_L





Inverse of transverse D_T





- the mass should correspond to a pole
- we plot the inverse propagators
- in the IR

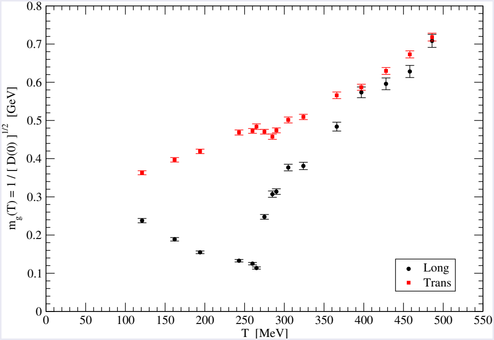
$D_L^{-1} \sim$ linear, $D_T{}^{-1}$ bends

- in the UV

$D_i{}^{-1} \sim \log$

Gluon mass @ finite T

naive M_L and M_T function of T



Interpretation

- The simplest ansatz for a massive propagator is,

$$D(p) = \frac{1}{p^2 + M^2}$$

$$\Rightarrow M = 1/\sqrt{D(0)}$$

- close to T_c, D_L signals the transition, while D_T is flat
- at $T \sim 2T_c$ we have $M_L \sim M_T$

Gluon mass @ finite T

- for a better IR ansatz, we fit D_i to a Yukawa with mass M and dressing function Z

$$D_i(p^2) = \frac{Z}{p^2 + m^2}$$

and look for the largest fitting range p_{max}

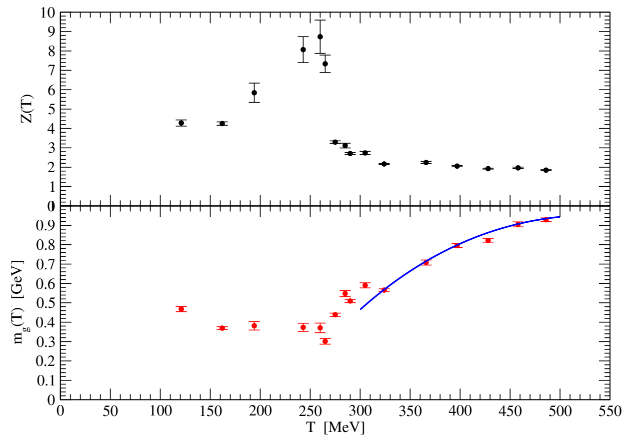
- this fits quite well D_L
- the Yukawa does not fit D_T

Fits of the longitudinal propagator

T	p_{max}	Z_L	M_L	$\chi^2/d.o.f.$
121	0.467	4.28(16)	0.468(13)	1.91
162	0.570	4.252(89)	0.3695(73)	1.66
194	0.330	5.84(50)	0.381(22)	0.72
243	0.330	8.07(67)	0.374(21)	0.27
260	0.271	8.73(86)	0.371(25)	0.03
265	0.332	7.34(45)	0.301(14)	1.03
275	0.635	3.294(65)	0.4386(83)	1.64
285	0.542	3.12(12)	0.548(16)	0.76
290	0.690	2.705(50)	0.5095(85)	1.40
305	0.606	2.737(80)	0.5900(32)	1.30
324	0.870	2.168(24)	0.5656(63)	1.36
366	0.716	2.242(55)	0.708(13)	1.80
397	0.896	2.058(34)	0.795(11)	1.03
428	1.112	1.927(24)	0.8220(89)	1.30
458	0.935	1.967(37)	0.905(13)	1.45
486	1.214	1.847(24)	0.9285(97)	1.55

Gluon mass @ finite T

Mass and dressing function fitting the longitudinal propagator



Summary

- We compute the gluon propagator in Landau gauge Lattice QCD at finite $T < 2T_c$,
- the longitudinal component D_L is peaked at $T = T_c$,
- in the infrared, we fit D_i with massive Yukawa ansatze
- the fit to D_L is more stable than the fit to D_T
- M_L is compatible with confinement screening at $T \sim 0$,
- M_L is consistent with debye screening at $T >> 0$,
- M_L is minimum at $T \sim T_c$, but finite as suggested by multiplicites of π and k production in heavy ion collisions.

to be continued ...