Stabilizing Yang-Mills thermodynamics with Gribov quantization

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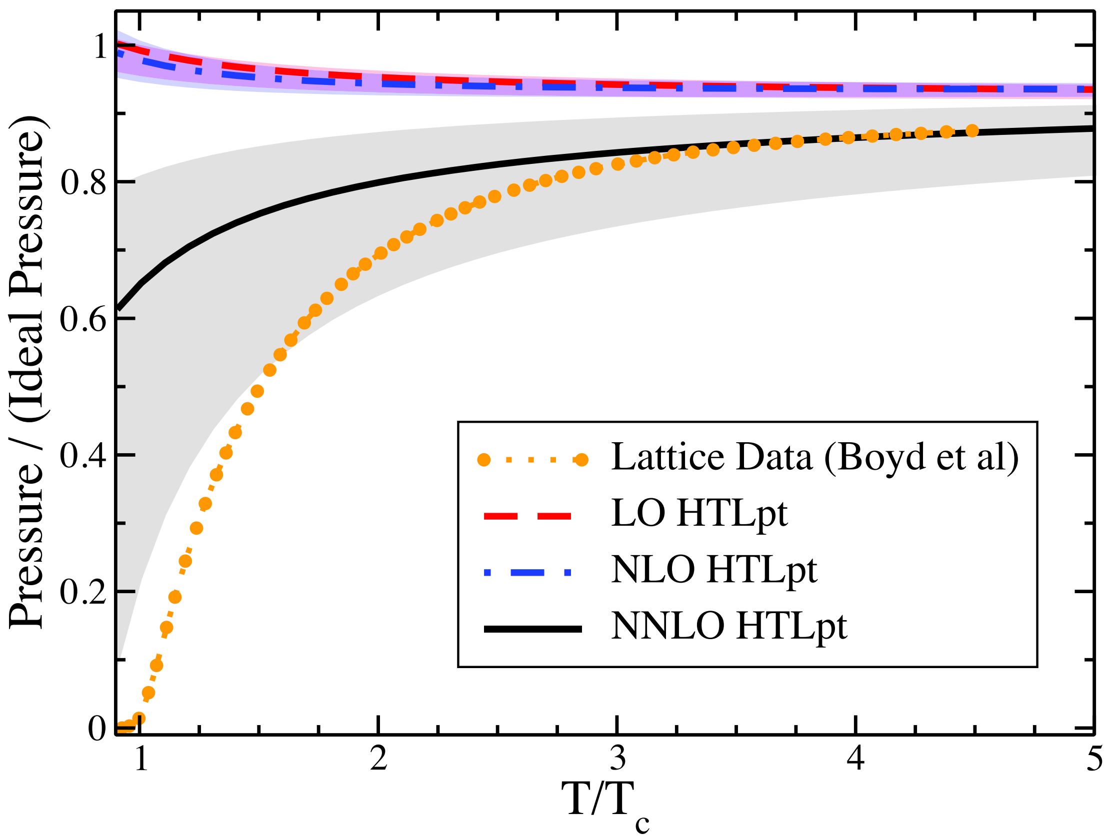
Introduction: Heavy ion collisions $\rightarrow g_s \sim \mathcal{O}(1)$

- RHIC: $T_0 \sim$ 350 MeV $\sim 2\,T_c$; LHC: $T_0 \sim$ 600 MeV $\sim 4\,T_c$
- Quark Gluon Plasma (QGP) vs Quark Gluon Liquid (QGL)
- Running coupling expected: $g_s \sim \mathcal{O}(1)$
- Neither tiny, nor huge: INTERMEDIATE coupling!
- Conventional QFT ($g_s \ll 1$, scale separation...): INAPPLICABLE!
- How to approach it?!
- A first try with Yang-Mills thermodynamics – Simplest test bench

Introduction – Resummed Yang-Mills free energy



HTLpt YM free energy with vs temperature.

$\pi T \leq \mu \leq 4\pi T$ and $\alpha_s = g^2/4\pi$

- Naive perturbative expansion of YM free energy is not convergent!
- Resummation of electric gluons $\sim gT$.
- NNLO HTLpt free energy agrees with lattice for $T \gtrsim 3\,T_c$ [1]. Similar results from DR [2] and DRSPT [3].
- Fail to produce SHARP RISING near T_c: Nonpert release of new d.o.f.!

[1] Andersen, Strickland, NS, 09/10

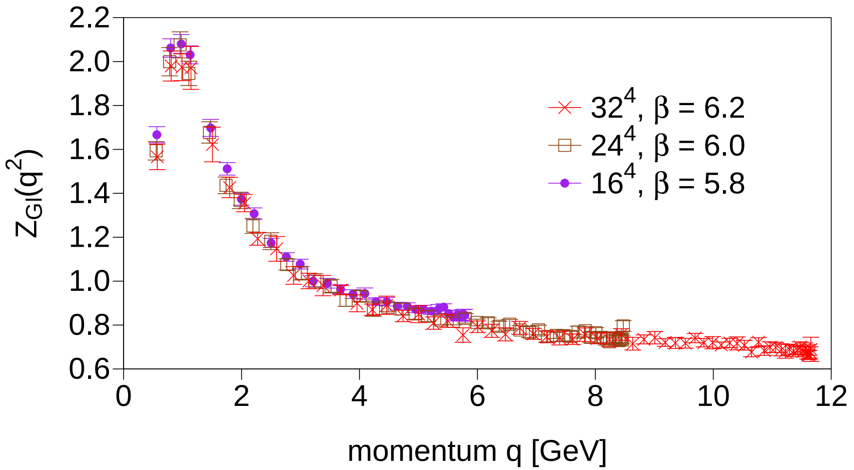
[2] Hietanen, Kajantie, Laine, Rummukainen, Schröder, 08

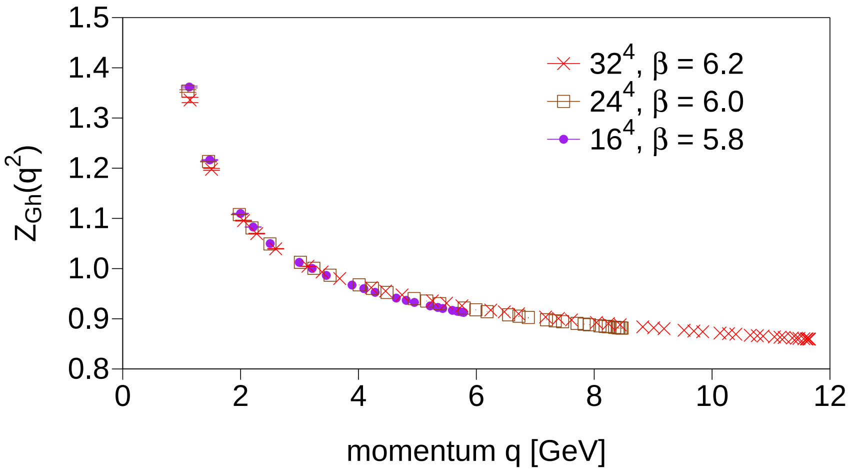
[3] Blaizot, Iancu, Rebhan, 03

Introduction – Missing ingredients in pert. theory!

- Nonpert. magnetic scale g^2T – Linde problem
- IR gauge fixing: Gluons SUPPRESSED; Ghosts ENHANCED

Features of confinement (Landau gauge)





Ilgenfritz *et al.*, arXiv:1010.5120

- Topological d.o.f.: Polyakov loops, monopoles, instantons...

Gribov quantization (Landau gauge)

- For YM, after Faddeev-Popov, there are residue gauge transformations in IR, i.e. Gribov copies (Gribov, 78; Singer, 78)
- Gribov quantization: Nonpert. gauge fixing in IR
- Gluons are IR suppressed

$$D_A = \left\langle A_\mu^a(P) A_\nu^b(-P) \right\rangle = \delta^{ab} \frac{P^2}{P^4+m_G^4} \left(\delta_{\mu\nu} - \frac{P_\mu P_\nu}{P^2} \right)$$

- Ghosts are IR enhanced

$$D_c = \left\langle \bar{c}^a(P) c^b(-P) \right\rangle = \frac{\delta^{ab}}{P^2} \frac{1}{1-\sigma(P)} \approx \frac{\delta^{ab}}{P^4} \frac{128\pi m_G^2}{N_c g^2} \quad (P \to 0)$$

- Gap eq. for m_G: $\frac{d}{d+1} N_c g^2 \int_P \frac{1}{P^4+m_G^4} = 1$
  - $T=0$: $m_G^2 = \mu^2 \exp\left(\frac{5}{6} - \frac{64\pi^2}{3N_c g^2} \right)$ (Gribov, 78)
  - $T \to \infty$: $m_G \to \frac{d}{d+1} \frac{N_c}{4\sqrt{2}\pi} g^2 T$ (Zwanziger, 07)

Gribov free energy in a nutshell

- LO 2PI (quasiparticle approximation)

$$\Gamma = \frac{1}{2}\mathrm{tr}\log G^{-1} - \frac{1}{2}\mathrm{tr}\,\Pi G + \Gamma_2[G]$$

- Gluon loop

$$\frac{1}{2}\mathrm{tr}\log D_A^{-1} = \frac{1}{2}(N_c^2-1)\sum\!\!\!\!\!\!\!\int_P \left\{3\log\frac{P^4+m_G^4}{P^2} + \ln P^2\right\}$$

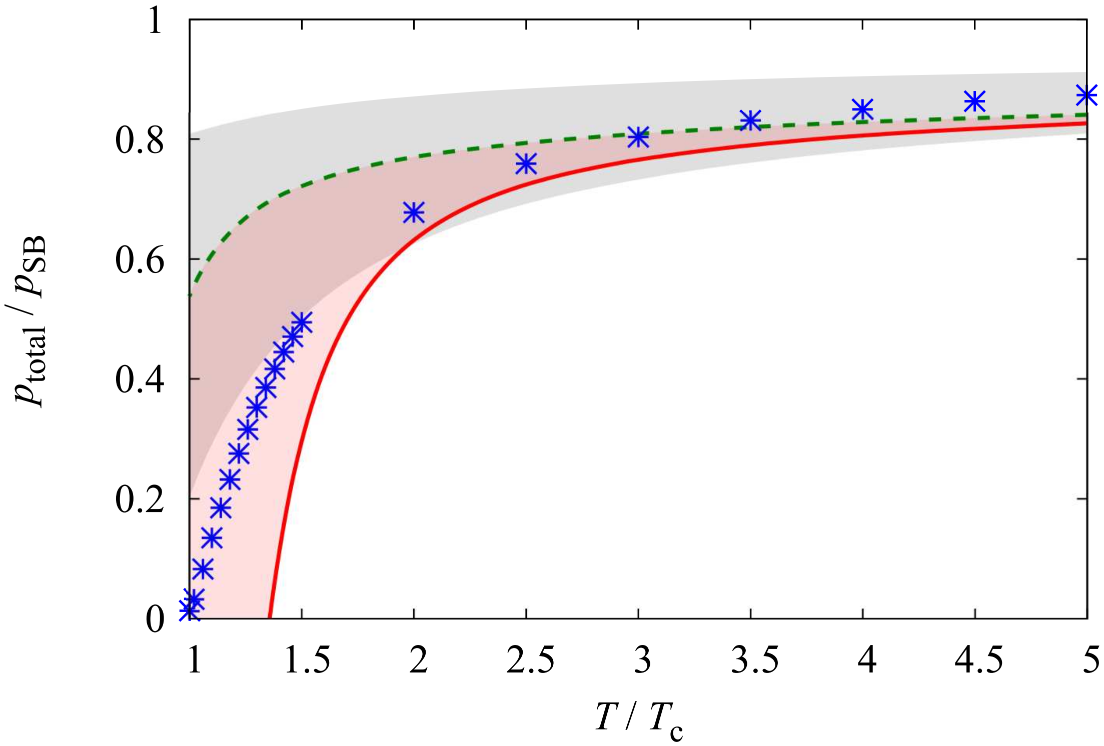
- Ghost loop

$$-\mathrm{tr}\log D_c^{-1} = -(N_c^2-1)\sum\!\!\!\!\!\!\!\int_P \left\{\log P^2 + \log\left[1-\sigma(P)\right]_{T=0}\right\}$$

- $\mu^2 = 2.86\,\mathrm{GeV}^2$ fixed by $[1-\sigma(P)]^{\mathrm{lat}}_{T=0}$ (Sternbeck *et al.*, 06)
  – In contrast to conventional thermal field theory!

Free energy from Gribov quantization

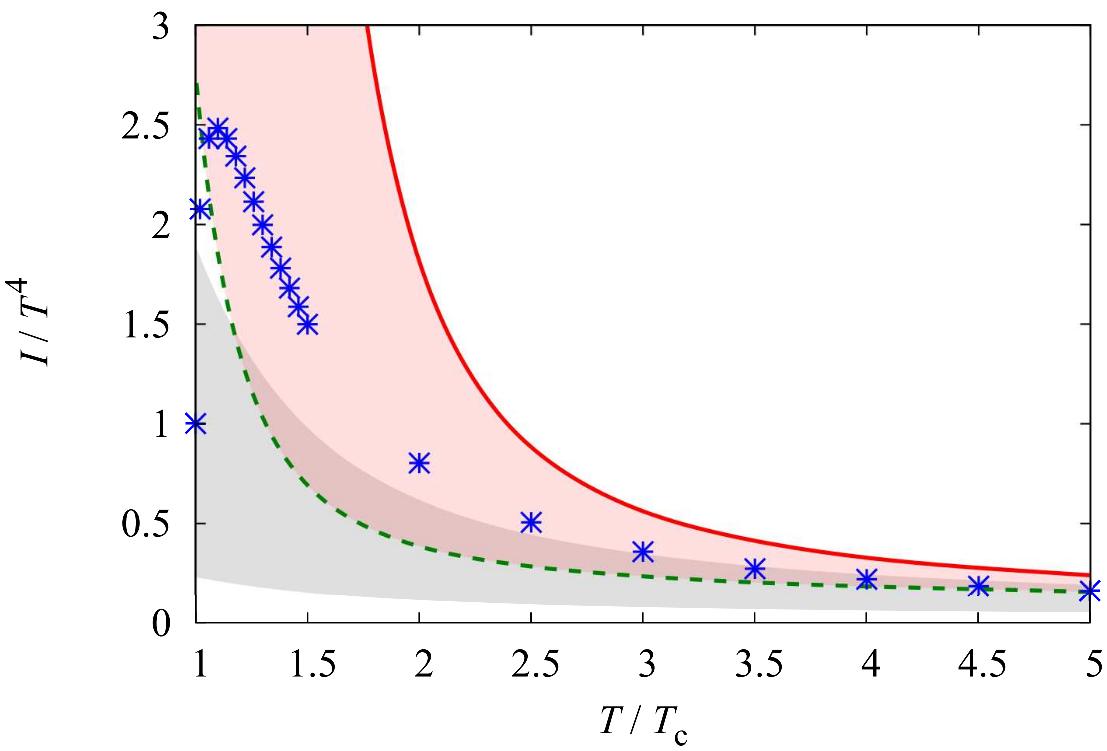
Fukushima, NS, arXiv:1304.8004



Lattice (Blue): W-B, arXiv:1204.6184
HTLpt (grey): Andersen, Strickland, NS, arXiv:0911.0676
Lattice $\alpha_s(T)$: Kaczmarek *et al.*, hep-lat/0406036

- Nonpert. $\alpha_s(T)$ from lattice
- $m_G \sim 400 - 500\,\mathrm{MeV}$
- In good agreement with lattice
- Lattice uncertainty highly suppressed above $2.5\,T_c$, ROBUST!
- Uncertainty comparing to 3-loop HTLpt:
  - 35% at $2.5\,T_c$
  - 15% at $5\,T_c$
- SHARP RISING near T_c!!!
- FRG running consistent with lattice, wouldn't be qualitative change

Interaction measure from Gribov quantization



Lattice (Blue): W-B, arXiv:1204.6184
HTLpt (grey): Andersen, Strickland, NS, arXiv:1005.1603
Lattice $\alpha_s(T)$: Kaczmarek *et al.*, hep-lat/0406036

- $I = \epsilon - 3p = T^5 \frac{d}{dT} \frac{p}{T^4}$
- Similar to pressure, in line with lattice
- Sizable contributions from $m_G \sim g^2 T$ in low T, in contrast to HTLpt
- Nonpert gauge fixing is crucial even at high T deconfined phase!
- Including Polyakov loop to tackle phase transition (Fukushima, Kashiwa, arXiv:1206.0685)

Outlook

What does it mean if it "COSTS" energy to excite gluons in IR?

- Impacts on QCD under extreme conditions:
  - Chiral spirals (Kojo, Hidaka, McLerran, Pisarski, arXiv:0912.3800; Kojo, Hidaka, Fukushima, McLerran, Pisarski, arXiv:1107.2124)
  - Strong magnetic fields – IR dynamics of LLL (Kojo, NS, arXiv:1211.7318, arXiv:1305.4510)

- Impacts on realtime dynamics and phenomenology:
  - Transport coefficients: $\hat{q}$, η/s, ...
  - Magnetic screening in initial state (Dumitru, Nara, Petreska, arXiv:1211.7318; Dumitru, Fujii, Nara, arXiv:1305.4510)
  - BEC far from equilibrium