Implications of Poincaré symmetry for thermal field theories

Leonardo Giusti

University of Milano-Bicocca

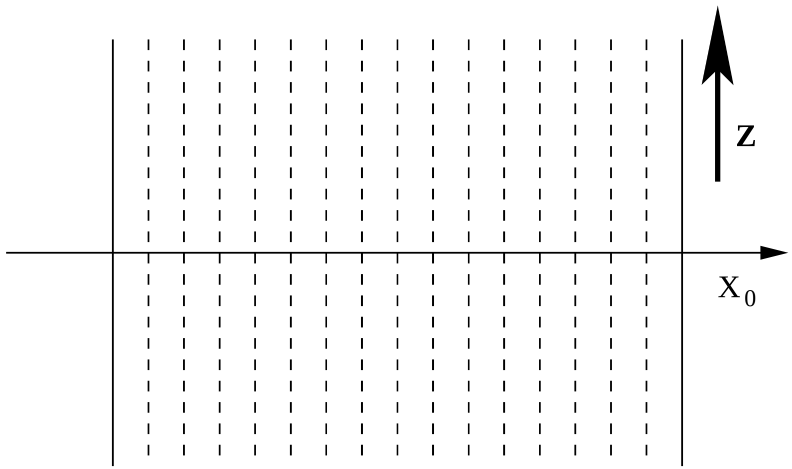
Based on: L. G. and H. B. Meyer 2011-2013; L. G. and M. Pepe 2014-2015

Outline

- Introduction
- Free-energy density with "shifted" boundary conditions

$$f\left(\sqrt{L_0^2 + \boldsymbol{z}^2}\right) = -\lim_{V\to\infty} \frac{1}{L_0 V} \ln Z(L_0, \boldsymbol{z})$$

$$\phi(L_0, \boldsymbol{x}) = \phi(0, \mathbf{x} - \boldsymbol{z})$$



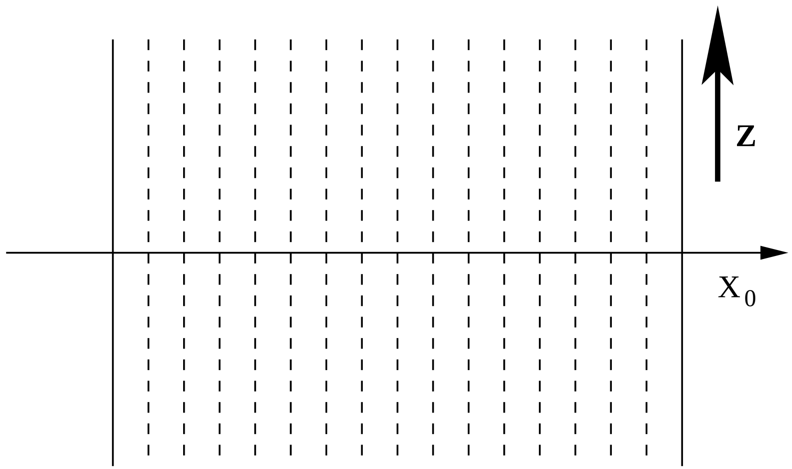
- Ward Identities for $T_{\mu\nu}$
- Definition of $T_{\mu\nu}$ on the lattice
- Non-perturbative measure of the entropy density
- Conclusions and outlook

Outline

- Introduction
- Free-energy density with "shifted" boundary conditions

$$f\left(L_0\sqrt{1+\boldsymbol{\xi}^2}\right) = -\lim_{V\to\infty}\frac{1}{L_0 V}\ln Z(L_0,\boldsymbol{\xi})$$

$$\phi(L_0,\boldsymbol{x}) = \phi(0,\boldsymbol{x}-L_0\boldsymbol{\xi})$$



- Ward Identities for $T_{\mu\nu}$
- Definition of $T_{\mu\nu}$ on the lattice
- Non-perturbative measure of the entropy density
- Conclusions and outlook

Thermal field theories in the Euclidean path integral formalism

- From textbooks

$$\phi(x) = \phi(x + V_{\rm pbc} m) \quad m \in \mathbb{Z}^4$$

$$Z(L_0) = \mathrm{Tr}\left\{e^{-L_0 \widehat{H}}\right\}$$

$$V_{\rm pbc} = \begin{pmatrix} L_0 & 0 & 0 & 0 \\ 0 & L_1 & 0 & 0 \\ 0 & 0 & L_2 & 0 \\ 0 & 0 & 0 & L_3 \end{pmatrix}$$

where the temperature is $T = 1/L_0$

- The basic thermodynamic quantities are defined as

$$f = -\frac{1}{L_0 V} \ln Z(L_0) \qquad e = -\frac{1}{V}\frac{\partial}{\partial L_0} \ln Z(L_0) \qquad s = -\frac{L_0^2}{V}\frac{\partial}{\partial L_0}\left\{\frac{1}{L_0} \ln Z(L_0)\right\}$$

which in the thermodynamic limit lead to

$$p = -f \qquad s = L_0(e+p) \qquad c_v = -L_0 \frac{\partial}{\partial L_0} s$$

Path integrals with shifted boundary conditions: infinite-volume limit (I)

- We are interested in the partition function

$$\phi(x) = \phi(x+V_{\rm sbc} m) \quad m \in \mathbb{Z}^4$$

$$Z(L_0, \boldsymbol{\xi}) = \mathrm{Tr}\left\{ e^{-L_0(\widehat{H} - i\boldsymbol{\xi}\cdot\widehat{\boldsymbol{P}})} \right\}$$

$$V_{\rm sbc} = \begin{pmatrix} L_0 & 0 & 0 & 0 \\ L_0\xi_1 & L_1 & 0 & 0 \\ L_0\xi_2 & 0 & L_2 & 0 \\ L_0\xi_3 & 0 & 0 & L_3 \end{pmatrix}$$

Path integrals with shifted boundary conditions: infinite-volume limit (I)

- We are interested in the partition function

$$\phi(x) = \phi(x+V_{\rm sbc}m) \quad m \in \mathbb{Z}^4$$

$$Z(L_0,\boldsymbol{\xi}) = \mathrm{Tr}\left\{e^{-L_0(\widehat{H}-i\xi_1\widehat{P}_1)}\right\}$$

$$V_{\rm sbc} = \begin{pmatrix} L_0 & 0 & 0 & 0 \\ L_0\xi_1 & L_1 & 0 & 0 \\ 0 & 0 & L_2 & 0 \\ 0 & 0 & 0 & L_3 \end{pmatrix}$$

where we have chosen $\boldsymbol{\xi} = \{\xi_1, 0, 0\}$

Path integrals with shifted boundary conditions: infinite-volume limit (I)

- We are interested in the partition function

$$\phi(x) = \phi(x + V_{\rm sbc} m) \quad m \in \mathbb{Z}^4$$

$$Z(L_0, \boldsymbol{\xi}) = \mathrm{Tr}\left\{ e^{-L_0(\widehat{H} - i\xi_1 \widehat{P}_1)} \right\}$$

$$V_{\rm sbc} = \begin{pmatrix} L_0 & 0 & 0 & 0 \\ L_0\xi_1 & L_1 & 0 & 0 \\ 0 & 0 & L_2 & 0 \\ 0 & 0 & 0 & L_3 \end{pmatrix}$$

where we have chosen $\boldsymbol{\xi} = \{\xi_1, 0, 0\}$

- By making an Euclidean ”boost” rotation

$$\gamma_1 = \frac{1}{\sqrt{1+\xi_1^2}}$$

$$\Lambda = \begin{pmatrix} \gamma_1 & \gamma_1\xi_1 & 0 & 0 \\ -\gamma_1\xi_1 & \gamma_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

- We are interested in the partition function

$$\phi(x) = \phi(x+V_{\rm sbc}m) \quad m \in \mathbb{Z}^4$$

$$Z(L_0,\boldsymbol{\xi}) = {\rm Tr}\left\{e^{-L_0(\widehat{H}-i\xi_1\widehat{P}_1)}\right\}$$

$$V_{\rm sbc} = \begin{pmatrix} L_0 & 0 & 0 & 0 \\ L_0\xi_1 & L_1 & 0 & 0 \\ 0 & 0 & L_2 & 0 \\ 0 & 0 & 0 & L_3 \end{pmatrix}$$

where we have chosen $\boldsymbol{\xi} = \{\xi_1, 0, 0\}$

- By making an Euclidean ”boost” rotation

$$\gamma_1 = \frac{1}{\sqrt{1+\xi_1^2}}$$

$$\Lambda = \begin{pmatrix} \gamma_1 & \gamma_1\xi_1 & 0 & 0 \\ -\gamma_1\xi_1 & \gamma_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

Lorentz [SO(4)] invariance implies

$$Z(L_0,\boldsymbol{\xi}) = {\rm Tr}\left\{e^{-L_1\gamma_1(\widetilde{H}+i\xi_1\widetilde{P}_0)}\right\}$$

$$V'_{\rm sbc} = \Lambda\, V_{\rm sbc} = \begin{pmatrix} L_0/\gamma_1 & L_1\gamma_1\xi_1 & 0 & 0 \\ 0 & L_1\gamma_1 & 0 & 0 \\ 0 & 0 & L_2 & 0 \\ 0 & 0 & 0 & L_3 \end{pmatrix}$$

- Assuming that $\widetilde{H}$ has a translationally-invariant vacuum and a mass gap [$\boldsymbol{\xi} = \{\xi_1, 0, 0\}$]

$$Z(L_0, \boldsymbol{\xi}) = \mathrm{Tr}\left\{e^{-L_1\gamma_1(\widetilde{H}+i\xi_1\widetilde{P}_0)}\right\}$$

$$V'_{\rm sbc} = \Lambda V_{\rm sbc} = \begin{pmatrix} L_0/\gamma_1 & L_1\gamma_1\xi_1 & 0 & 0 \\ 0 & L_1\gamma_1 & 0 & 0 \\ 0 & 0 & L_2 & 0 \\ 0 & 0 & 0 & L_3 \end{pmatrix}$$

the right hand side becomes insensitive to the phase in the limit $L_1 \to \infty$ at fixed ξ_1

$$f\left(L_0\sqrt{1+\xi_1^2}\right) = -\lim_{V\to\infty} \frac{1}{L_0 V} \ln Z(L_0, \boldsymbol{\xi})$$

$$V''_{\rm sbc} = \begin{pmatrix} L_0/\gamma_1 & 0 & 0 & 0 \\ 0 & L_1\gamma_1 & 0 & 0 \\ 0 & 0 & L_2 & 0 \\ 0 & 0 & 0 & L_3 \end{pmatrix}$$

- Thanks to cubic symmetry (infinite volume)

$$f\left(L_0, \boldsymbol{\xi}\right) = f\left(L_0\sqrt{1+\boldsymbol{\xi}^2}, \mathbf{0}\right)$$

$$\phi(x_0, \boldsymbol{x}) = \phi(x_0+L_0, \boldsymbol{x}+L_0\boldsymbol{\xi})$$

for a generic shift $\boldsymbol{\xi}$

Thermal field theory in a moving frame

- If $\widehat{H}$ and $\widehat{\boldsymbol{P}}$ are the Hamiltonian and the total momentum operator expressed in a moving frame, the standard partition function is

$$\mathcal{Z}(L_0, \boldsymbol{v}) \equiv \mathrm{Tr}\left\{e^{-L_0\,(\widehat{H} - \boldsymbol{v}\cdot\widehat{\boldsymbol{P}})}\right\}$$

- If we continue $\mathcal{Z}$ to imaginary velocities $\boldsymbol{v} = i\boldsymbol{\xi}$

$$Z(L_0, \boldsymbol{\xi}) = \mathrm{Tr}\,\{e^{-L_0(\widehat{H} - i\boldsymbol{\xi}\cdot\widehat{\boldsymbol{P}})}\}$$

- The functional dependence $f(L_0\sqrt{1+\boldsymbol{\xi}^2})$ is consistent with modern thermodynamic arguments on the Lorentz transformation of the temperature and the free-energy [Ott 63; Arzelies 65; see Przanowski 11 for a recent discussion]

- In the zero-temperature limit the invariance of the theory (and of its vacuum) under the Poincaré group forces its free energy to be independent of the shift $\boldsymbol{\xi}$

- At non-zero temperature the finite length L_0 breaks SO(4) softly, and the free energy depends on the shift (velocity) but only through the combination $\beta = L_0\sqrt{1+\boldsymbol{\xi}^2}$

Euclidean Ward identities for correlators of $\overline{T}_{\mu\nu}$

- When $\boldsymbol{\xi} \neq 0$ odd derivatives in the ξ_k do not vanish anymore, and the dependence of f from the combination $L_0\sqrt{1+\boldsymbol{\xi}^2}$ implies

$$\langle T_{0k}\rangle_{\boldsymbol{\xi}} = \frac{\xi_k}{1-\xi_k^2}\left\{\langle T_{00}\rangle_{\boldsymbol{\xi}} - \langle T_{kk}\rangle_{\boldsymbol{\xi}}\right\}$$

- By deriving twice with respect to the ξ_k

$$\langle T_{0k}\rangle_{\boldsymbol{\xi}} = \frac{L_0\xi_k}{2}\sum_{ij}\left\langle \overline{T}_{0i}\, T_{0j}\right\rangle_{\boldsymbol{\xi},\,c}\left[\delta_{ij} - \frac{\xi_i\,\xi_j}{\boldsymbol{\xi}^2}\right]$$

- Note that:

  ∗ All operators at non-zero distance

  ∗ Number or components of EMT on the two sides different

  ∗ On the lattice they can be imposed to fix the renormalization of $T_{\mu\nu}$

Entropy density from the response to the shift

- The Entropy density can be computed as

$$s = -\frac{L_0\,(1+\boldsymbol{\xi}^2)^{3/2}}{\xi_k}\,\langle T_{0k}\rangle_{\boldsymbol{\xi}}$$

or as

$$s = -\frac{(1+\boldsymbol{\xi}^2)^{3/2}}{\xi_k}\,\lim_{V\to\infty}\frac{1}{V}\frac{\partial}{\partial\xi_k}\ln Z(L_0,\boldsymbol{\xi})$$

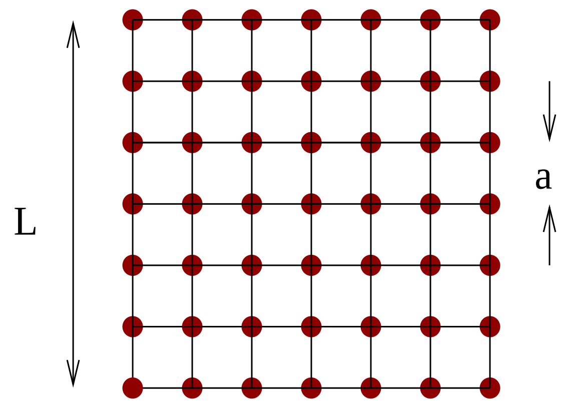
- With respect to the standard technique:

  $*$ No ultraviolet power divergent subtraction (zero temperature subtraction)

  $*$ On the lattice finite multiplicative renormalization constant fixed non-perturbatively by WIs

Lattice gauge theory [Wilson 74]

- A Yang-Mills theory can be defined on a discretized space-time so that gauge invariance is preserved



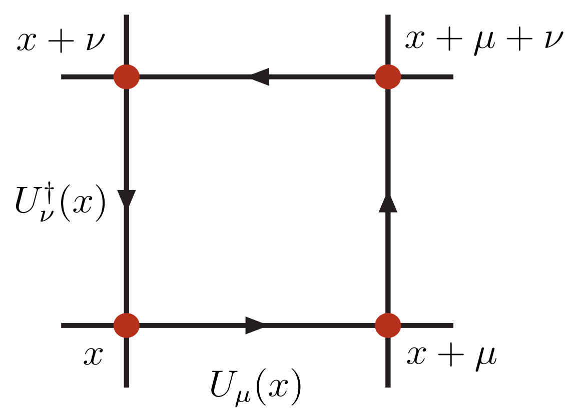
- The the gauge field $U_\mu \in \mathrm{SU}(3)$ resides on links

- The Wilson action is

$$S_G[U] = \frac{\beta}{2} \sum_x \sum_{\mu,\nu} \left[1 - \frac{1}{3} \mathrm{ReTr} \left\{ U_{\mu\nu}(x) \right\} \right]$$

where $\beta = 6/g_0^2$ and the plaquette is

$$U_{\mu\nu}(x) = U_\mu(x)\, U_\nu(x+\hat{\mu})\, U_\mu^\dagger(x+\hat{\nu})\, U_\nu^\dagger(x)$$



- Discrete shifts in the boundary conditions can be implemented straightforwardly

Non-perturbative renormalization of $T_{\mu\nu}$

- On the lattice the Poincaré group is broken down to a discrete group and standard discretizations of $T_{\mu\nu}$ acquire finite ultraviolet renormalizations

- We focus on the SU(3) Yang–Mills. The analysis applies to other theories as well

$$T^{\rm R}_{\mu\nu} = Z_T \left\{ T^{[1]}_{\mu\nu} + z_T T^{[3]}_{\mu\nu} + z_S \left[T^{[2]}_{\mu\nu} - \langle T^{[2]}_{\mu\nu} \rangle_0 \right] \right\} .$$

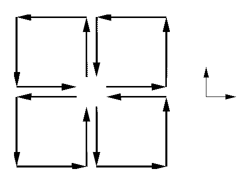
$$T^{[1]}_{\mu\nu} = (1-\delta_{\mu\nu}) \frac{1}{g_0^2} \left\{ F^a_{\mu\alpha} F^a_{\nu\alpha} \right\}$$

$$T^{[2]}_{\mu\nu} = \delta_{\mu\nu} \frac{1}{4 g_0^2} F^a_{\alpha\beta} F^a_{\alpha\beta}$$

$$T^{[3]}_{\mu\nu} = \delta_{\mu\nu} \frac{1}{g_0^2} \left\{ F^a_{\mu\alpha} F^a_{\mu\alpha} - \frac{1}{4} F^a_{\alpha\beta} F^a_{\alpha\beta} \right\}$$

where

$$F^a_{\mu\nu}(x) = -\frac{i}{4a^2} \mathrm{Tr}\left\{ \left[Q_{\mu\nu}(x) - Q_{\nu\mu}(x) \right] T^a \right\} , \qquad Q_{\mu\nu}(x) = \sum$$



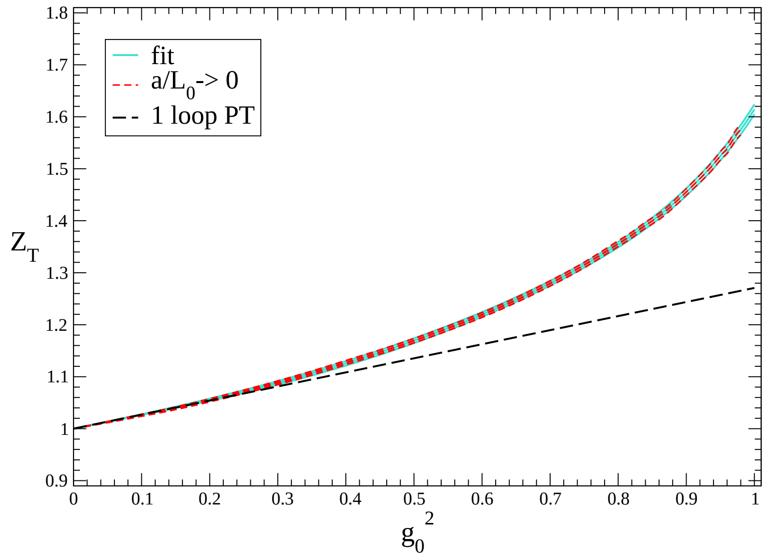
The sextet renormalization constant Z_T

- The continuum relation

$$\langle T_{0k} \rangle_{\boldsymbol{\xi}} = \frac{1}{L_0} \lim_{V\to\infty} \frac{1}{V} \frac{\partial}{\partial \xi_k} \ln Z(L_0, \boldsymbol{\xi})$$

can be imposed on the lattice to fix Z_T

$$Z_T(g_0^2) = -\frac{\Delta f}{\Delta \xi_k} \frac{1}{\langle T_{0k}^{[1]} \rangle_{\boldsymbol{\xi}}}$$



where the derivative in the shift is discretized by the symmetric finite difference

$$\frac{\Delta f}{\Delta \xi_k} = \frac{1}{2aV} \ln \left[\frac{Z(L_0, \boldsymbol{\xi} - a\hat{k}/L_0)}{Z(L_0, \boldsymbol{\xi} + a\hat{k}/L_0)} \right]$$

- The final results for $Z_T(g_0^2)$ are well represented by

$$Z_T(g_0^2) = \frac{1 - 0.4457\, g_0^2}{1 - 0.7165\, g_0^2} - 0.2543\, g_0^4 + 0.4357\, g_0^6 - 0.5221\, g_0^8$$

with the error that varies from 0.4% up 0.7% in the range $0 \leq g_0^2 \leq 1$

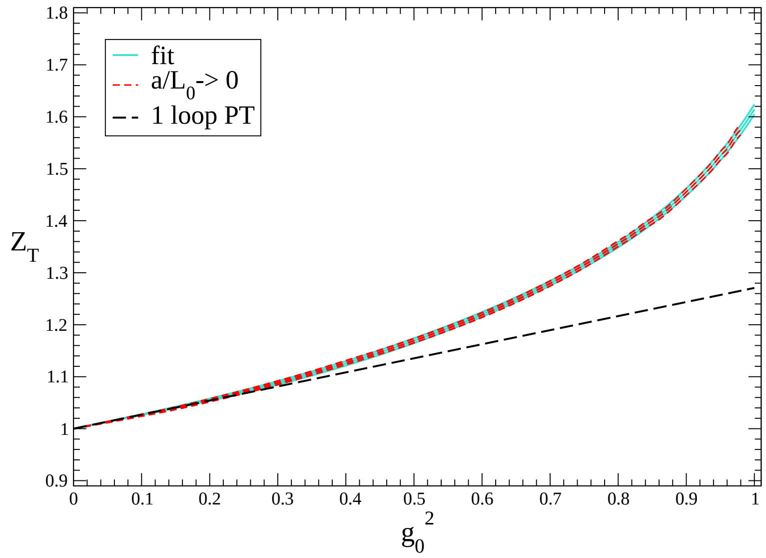
The sextet renormalization constant Z_T

- The continuum relation

$$\langle T_{0k} \rangle_{\boldsymbol{\xi}} = \frac{1}{L_0} \lim_{V\to\infty} \frac{1}{V} \frac{\partial}{\partial \xi_k} \ln Z(L_0, \boldsymbol{\xi})$$

can be imposed on the lattice to fix Z_T

$$Z_T(g_0^2) = -\frac{\Delta f}{\Delta \xi_k} \frac{1}{\langle T_{0k}^{[1]} \rangle_{\boldsymbol{\xi}}}$$



where the derivative in the shift is discretized by the symmetric finite difference

$$\frac{\Delta f}{\Delta \xi_k} = \frac{1}{2aV} \ln \left[\frac{Z(L_0, \boldsymbol{\xi} - a\hat{k}/L_0)}{Z(L_0, \boldsymbol{\xi} + a\hat{k}/L_0)} \right]$$

- Within statistical errors, the non-perturbative determination starts to deviate significantly from the one-loop result [Caracciolo et al. 88, 90]

$$Z_T(g_0^2) = 1 + 0.27076\, g_0^2$$

already at $g_0^2 \sim 0.25$

The triplet renormalization constant z_T

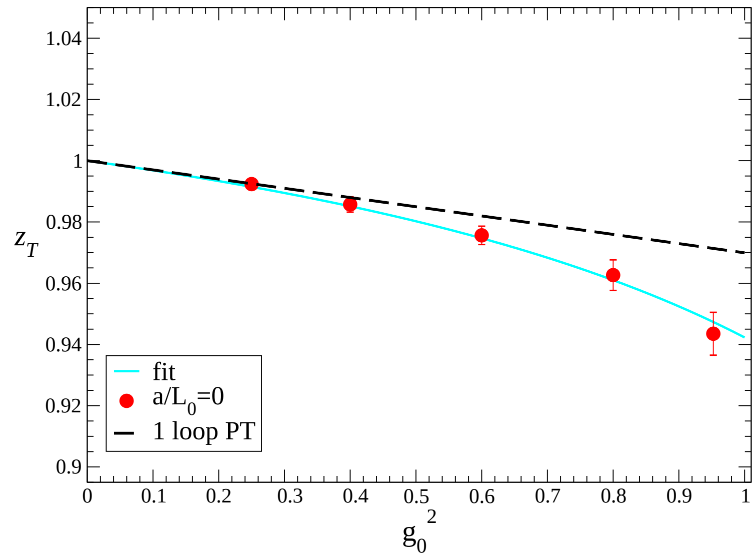
- The continuum relation

$$\langle T_{0k}\rangle_{\boldsymbol{\xi}} = \frac{\xi_k}{1-\xi_k^2}\left\{\langle T_{00}\rangle_{\boldsymbol{\xi}} - \langle T_{kk}\rangle_{\boldsymbol{\xi}}\right\}$$

is enforced on the lattice to determine z_T

$$z_T(g_0^2) = \frac{1-\xi_k^2}{\xi_k}\,\frac{\langle T^{[1]}_{0k}\rangle_{\boldsymbol{\xi}}}{\langle T^{[3]}_{00}\rangle_{\boldsymbol{\xi}} - \langle T^{[3]}_{kk}\rangle_{\boldsymbol{\xi}}}$$

with the condition $\frac{L\,\xi_k}{L_0(1+\xi_k^2)} = q \in \mathbb{Z}$



- The results for $z_T(g_0^2)$ are well represented by

$$z_T(g_0^2) = \frac{1-0.5090\,g_0^2}{1-0.4789\,g_0^2}$$

where the error grows linearly from 0.15% to 0.75% in the interval $0 \leq g_0^2 \leq 1$

The triplet renormalization constant z_T

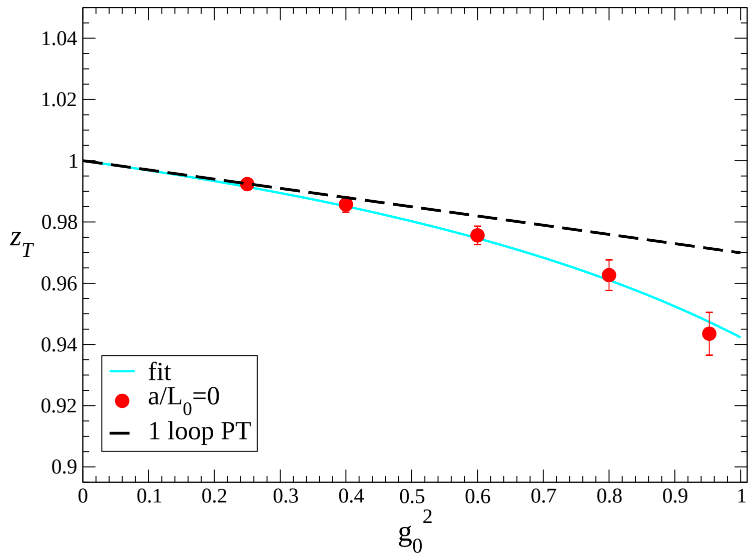
- The continuum relation

$$\langle T_{0k}\rangle_{\boldsymbol{\xi}} = \frac{\xi_k}{1-\xi_k^2}\left\{\langle T_{00}\rangle_{\boldsymbol{\xi}} - \langle T_{kk}\rangle_{\boldsymbol{\xi}}\right\}$$

is enforced on the lattice to determine z_T

$$z_T(g_0^2) = \frac{1-\xi_k^2}{\xi_k}\,\frac{\langle T_{0k}^{[1]}\rangle_{\boldsymbol{\xi}}}{\langle T_{00}^{[3]}\rangle_{\boldsymbol{\xi}} - \langle T_{kk}^{[3]}\rangle_{\boldsymbol{\xi}}}$$

with the condition $\frac{L\,\xi_k}{L_0(1+\xi_k^2)} = q \in \mathbb{Z}$



- Within statistical errors, the non-perturbative determination starts to deviate significantly from the one-loop result [Caracciolo et al. 88, 90]

$$z_T(g_0^2) = 1 - 0.03008\; g_0^2$$

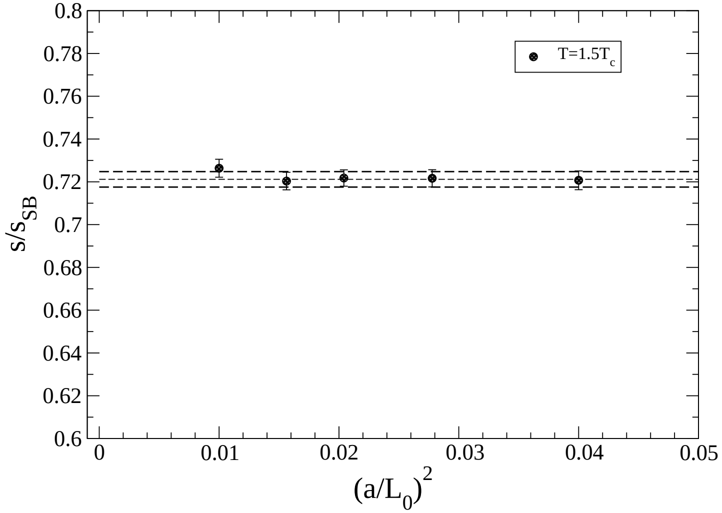
already at $g_0^2 \sim 0.4$

Entropy density in the continuum

- Entropy density obtained by extrapolating

$$\frac{s}{s_{\rm SB}} = -\frac{45}{32\pi^2}\frac{(1+\xi^2)}{\xi_k}\frac{Z_T\,\langle T^{[1]}_{0k}\rangle_{\boldsymbol{\xi}}}{T^4}$$

to the continuum limit

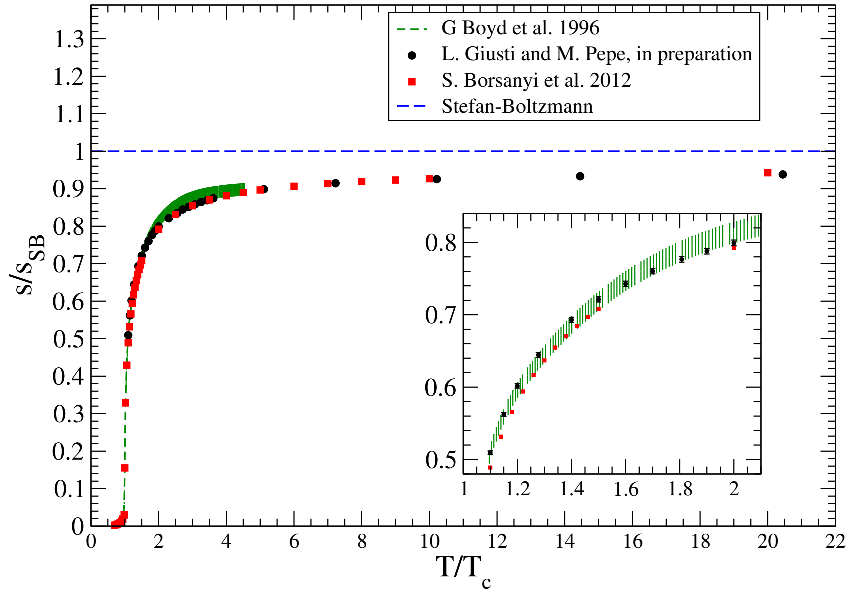


Entropy density in the continuum

- Entropy density obtained by extrapolating

$$\frac{s}{s_{\rm SB}} = -\frac{45}{32\pi^2}\frac{(1+\xi^2)}{\xi_k}\frac{Z_T\,\langle T^{[1]}_{0k}\rangle_{\boldsymbol{\xi}}}{T^4}$$

  to the continuum limit



- Precision of $\sim 0.5\%$ for all points

- Results for $T \leq 4\,T_c$ agree with [Boyd et al 96, Meyer 09]

- For $T \geq 2\,T_c$ agree with [Borsanyi et al 13] within errors. We observe a discrepancy of many (4 to 8) statistical sigmas with these data, however, for $T \leq 2\,T_c$

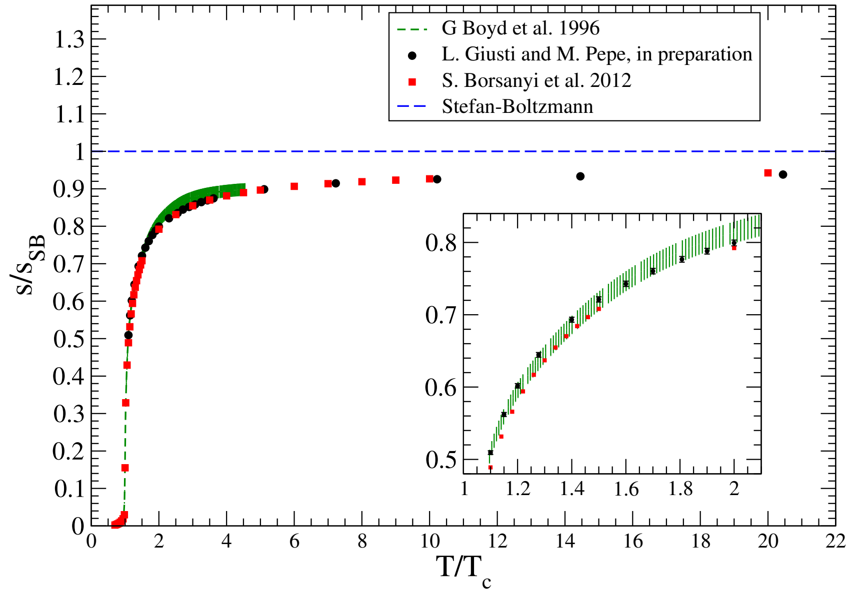
- The computation at temperatures up to $T \sim 200\,T_c$ is completed. The analysis of the data is in progress

Entropy density in the continuum

- Entropy density obtained by extrapolating

$$\frac{s}{s_{\mathrm{SB}}} = -\frac{45}{32\pi^2}\,\frac{(1+\xi^2)}{\xi_k}\,\frac{Z_T\,\langle T_{0k}^{[1]}\rangle_{\boldsymbol{\xi}}}{T^4}$$

to the continuum limit



- Precision of $\sim 0.5\%$ for all points

- The computation at temperatures up to $T \sim 200\,T_c$ is completed. The analysis of the data is in progress

- At $T \sim 20\,T_c$ the entropy still differs from the Stefan-Boltzmann value by roughly 5%

- When matching with perturbation theory, the series has oscillating coeffs. At $T \sim 20\,T_c$, the $O(g^6)$ is roughly 40% of total correction with respect to SB

Conclusions and outlook (I)

- Lorentz invariance implies a great degree of redundancy in defining a relativistic thermal theory in the Euclidean path-integral formalism

- In the thermodynamic limit, the orientation of the compact periodic direction with respect to the coordinate axes can be chosen at will and only its length is relevant

$$f\left(L_0\sqrt{1+\boldsymbol{\xi}^2}\right) = -\lim_{V\to\infty}\frac{1}{L_0 V}\ln Z(L_0,\boldsymbol{\xi})$$

- The redundancy in the description implies that the total energy and momentum distributions in the canonical ensemble are related

- For a finite-size system, the lengths of the box dimensions break this invariance. Being a soft breaking, however, interesting exact Ward Identities survive

- As in the standard case, if the lightest screening mass $M \neq 0$, leading finite-size corrections are exponentially small in (ML)

Conclusions and outlook (II)

- When the theory is regularized on a lattice, the overall orientation of the periodic directions with respect to the lattice coordinate system affects renormalized observables at the level of lattice artifacts

- As the cutoff is removed, the artifacts are suppressed by a power of the spacing

- The flexibility in the lattice formulation added by the introduction of a triplet $\boldsymbol{\xi}$ of (renormalized) parameters has interesting consequences:

  $*$ WIs to renormalize non-perturbatively $T_{\mu\nu}$

  $*$ Simpler ways to compute thermodynamic potentials

$$s = -\frac{Z_T L_0 (1+\boldsymbol{\xi}^2)^{3/2}}{\xi_k} \langle T_{0k} \rangle_{V_{\rm sbc}}$$

  $*$ ...

- In the Yang–Mills theory we defined non-perturbatively $T_{\mu\nu}$, and we computed the entropy density over several orders of magnitude in T. Discretization and statistical errors are at the level of a few per mille in both cases