Thermodynamic Characterizations of Exotic and Missing States

Eugenio Megías[1],
W. Broniowski[2], E. Ruiz Arriola[3] and L.L. Salcedo[3]
[1]**Department of Theoretical Physics, University of the Basque Country UPV/EHU, Bilbao, Spain.**
[2]**H. Niewodniczański Institute of Nuclear Physics, Cracow, Poland.**
[3]**Department of Atomic, Molecular and Nuclear Physics, University of Granada, Spain.**
[1]Supported by the University of the Basque Country UPV/EHU as a Visiting Professor.

Excited QCD 2018
13 March, 2018, Kopaonik, Serbia.

Based on: E. Megías et al. PRD74 (2006) 065005, 114014; PRL109 (2012) 151601; PRD89 (2014) 076006; PRD94 (2016) 096010; arXiv:1711.09837.

Issues

1. Introduction
   - QCD Thermodynamics
   - Hadron Spectrum
2. Entropy Shift and Missing States
   - Entropy Shift below T_c
   - Entropy Shift above T_c
3. Fluctuations of Conserved Charges in a Thermal Medium
   - Fluctuations of Conserved Charges
   - Fluctuations in the HRG model
4. Correlations in a Thermal Medium
   - Free particles of spin $1/2$
   - Free particles of any spin
   - Correlations in the HRG model

Issues

Issues

1. Introduction
   - QCD Thermodynamics
   - Hadron Spectrum
2. Entropy Shift and Missing States
   - Entropy Shift below T_c
   - Entropy Shift above T_c
3. Fluctuations of Conserved Charges in a Thermal Medium
   - Fluctuations of Conserved Charges
   - Fluctuations in the HRG model
4. Correlations in a Thermal Medium
   - Free particles of spin $1/2$
   - Free particles of any spin
   - Correlations in the HRG model

Issues

References

- **QCD at finite T:** Phys.Lett. B563 (2003) 173-178; Phys.Rev. D69 (2004). 116003.
- **Polyakov-Nambu–Jona-Lasinio:** hep-ph/0410053; AIP Conf.Proc. 756 (2005) 436-438; Phys.Rev. D74 (2006) 065005; Rom.Rep.Phys. 58 (2006) 081-086; PoS JHW2005 (2006) 025; AIP Conf.Proc. 892 (2007) 444-447; Eur.Phys.J. A31 (2007).
- **Dim-2 Condensates:** JHEP 0601 (2006) 073; Phys.Rev. D75 (2007) 105019; Nucl.Phys.Proc.Suppl. 186 (2009) 256-259; Phys.Rev. D81 (2010) 096009.
- **Hadron Resonance Gas for Polyakov loop:** Phys.Rev.Lett. 109 (2012) 151601; Nucl. Phys. Proc. Suppl. 234 (2013) 313-316; Acta Phys. Polon. B 45, 2407 (2014).
- **Polyakov loop Spectroscopy:** Phys.Rev. D89 (2014) 076006; Nucl. Part. Phys. Proc. 258-259 (2015) 109.
- **Heavy Quark Physics:** Nucl. Part. Phys. Proc. 270-272 (2016) 170-174; Phys.Rev. D94 (2016) 096010.
- **Fluctuations:** 1612.07091; 1711.09837.

Issues

QCD Thermodynamics

- The partition function of QCD

$$Z_{QCD} = \mathrm{Tr}\, e^{-H_{\mathrm{QCD}}/T} = \sum_n e^{-E_n/T} \,, \qquad H_{\mathrm{QCD}}\psi_n = E_n \psi_n \,,$$

- Spectrum of QCD ⟶ Thermodynamics

  Hadron Resonance Gas Model

- In the confined phase: Colour singlet states (hadrons + $\cdots$???)

  ⟶ Low temperature partonic expansion **[EM, E. Ruiz Arriola, L.L. Salcedo, Acta Phys. Pol. B45 '14]**:

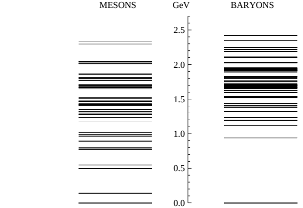
$$Z = \underbrace{Z_0}_{\text{Vacuum}} \cdot \underbrace{Z_{q\bar{q}}}_{\text{Mesons}} \cdot \underbrace{Z_{qqq} \cdot Z_{\bar{q}\bar{q}\bar{q}}}_{\text{Baryons}} \cdot \underbrace{Z_{q\bar{q}g}}_{\text{Hybrids}} \cdot \underbrace{Z_{q\bar{q}q\bar{q}}}_{\text{Tetraquarks}} \cdots$$

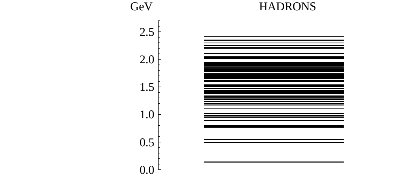
- In the deconfined phase: quarks and gluons ⟶ quark-gluon plasma.
- Phase transition is a crossover ⟶ Do we see quark-gluon substructure BELOW the "*phase transition*"?

Issues

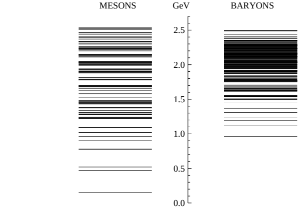
Hadron Spectrum (u,d,s)

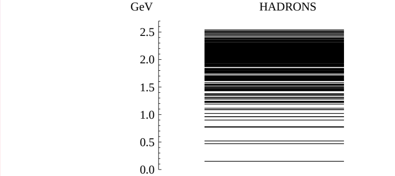
- Particle Data Group (PDG) compilation 2016





- Relativized Quark Model (RQM), Isgur, Godgrey, Capstik 1985





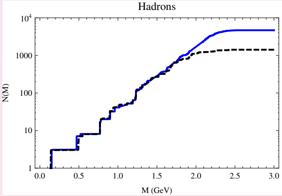
Cumulative number of states

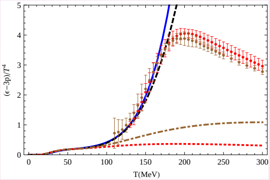
- Cumulative number $\equiv$ number of bound states below M.

$$N(M) = \sum_n \Theta(M - M_n) \,,$$

- Which states count?

$$N(M) = N_{q\bar{q}}(M) + N_{qqq}(M) + \cdots \,,$$





$$N_{q\bar{q}} \sim M^6 \,, \qquad N_{qqq} \sim M^{12} \,, \qquad N_{q\bar{q}q\bar{q}} \sim M^{18} \quad \text{and} \quad N_{\text{hadrons}} \sim e^{M/T_H}$$

$$Z = \text{Tr}\, e^{-H/T} \underset{T \to T_H^-}{\longrightarrow} \infty \,, \qquad T_H \sim 150\,\text{MeV} \equiv \text{Hagedorn temperature}$$

- Non-interacting Hadron-Resonance Gas works for $T \lesssim 0.8 T_c$.

Issues

Entropy Shift and Polyakov loop

- Physical situation: Add to the QCD thermal vacuum one extra heavy charge belonging to representation **R**.
- Charge is screened by dynamical constituents to form color neutral states: $[Q\bar{q}], [Qqq], [Q\bar{q}g], [Q\bar{q}q\bar{q}], [Q\bar{q}qqq], \cdots$
- Energy of the states changes under the presence of the charge

$$E_n \to E_n^{\mathbf{R}} \to \Delta_n^{\mathbf{R}} + m_{\mathbf{R}} + \cdots .$$

  $\Delta_n^{\mathbf{R}}$ remains finite in the limit $m_{\mathbf{R}} \to \infty$.
- In the static gauge $\partial_0 A_0 = 0$ the Polyakov loop operator reads

$$\mathrm{tr}_{\mathbf{R}}\, \Omega(\vec{r}) = \mathrm{tr}_{\mathbf{R}}\, e^{iA_0(\vec{r})/T} .$$

- Ratio of partition functions ⟶ Free energy shift $\equiv \Delta F_{\mathbf{R}}$

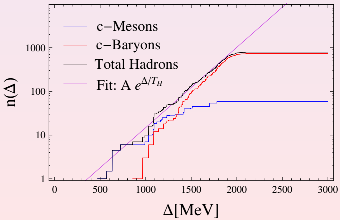
$$L_{\mathbf{R}} \equiv \langle \mathrm{tr}_{\mathbf{R}}\, \Omega(0) \rangle = \frac{Z_{\mathbf{R}}}{Z_0} = e^{-\Delta F_{\mathbf{R}}/T} = \frac{\frac{1}{2}\sum_n e^{-\Delta_n^{\mathbf{R}}/T}}{1 + \dots}$$

Polyakov loop and Hadron Resonance Gas model

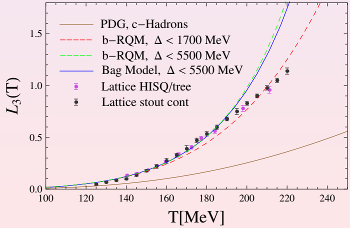
- Counting states ➞ Mesons and Baryons with 1 heavy quark ($\mathbf{R}=\mathbf{3}$) ➞ HRG model for the Polyakov loop in the fund. rep.
  [EM, E.Ruiz Arriola, L.L.Salcedo, PRL 109 (2012)]

$$n(\Delta) = \sum_n \Theta(\Delta - \Delta_n) \sim e^{\Delta/T_{H,L}} \quad \rightarrow \quad L_3(T) = \frac{1}{2}\int d\Delta \frac{\partial n(\Delta)}{\partial \Delta} e^{-\Delta/T}$$

Hadron spectrum with one c-quark, and Polyakov loop: $\Delta_n = M_n - m_Q$



➞



Entropy Shift and Missing States

[EM, E.Ruiz Arriola, L.L.Salcedo, PRD94 (2016)]

- Polyakov loop renormalization ambiguity **[S.Gupta, K.Hübner, O.Kaczmarek, PRD77 (2008)]**:

$$L_{\mathbf{R}} = e^{c/T} \cdot L'_{\mathbf{R}} \,.$$

- The ambiguity can be removed by computing the entropy shift

$$L_{\mathbf{R}} = \langle \mathrm{tr}_{\mathbf{R}} \Omega(0) \rangle_T = e^{-\Delta F_{\mathbf{R}}(T)/T} \quad \longrightarrow \quad \Delta S_{\mathbf{R}}(T) = -\frac{\partial}{\partial T} \Delta F_{\mathbf{R}}(T) \,.$$

- Third principle of thermodynamics for degenerate states

$$\Delta S_Q(0) = \log(2N_f) \,, \qquad \Delta S_Q(\infty) = \log N_c \,.$$

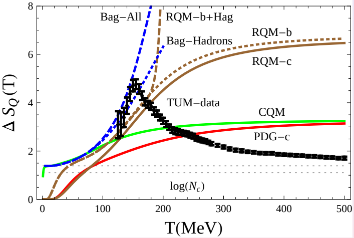
- Renormalization Group Equation:

$$0 = \mu \frac{d\Delta S_Q}{d\mu} = \beta(g) \frac{\partial \Delta S_Q}{\partial g} - \sum_q m_q (1 + \gamma_q) \frac{\partial \Delta S_Q}{\partial m_q} - T \frac{\partial \Delta S_Q}{\partial T} \,.$$

Entropy Shift and Missing States

Lattice data for the Entropy Shift $(N_c = 3, N_f = 2+1)$

[A.Bazavov et al., PRD93 (2016) 114502].



- Entropy shift as a function of the temperature:
  - ➞ PDG not enough to describe lattice data.
  - ➞ Relativistic Quark Model (Mesons + Baryons) **[S.Godfrey, N.Isgur, PRD32 '85].**
  - ➞ MIT Bag Model **[A. Chodos et al., PRD9 '74]** including All = ($[Q\bar{q}]$, $[Qqq]$, $[Q\bar{q}g]$ and $[Qqqg]$).

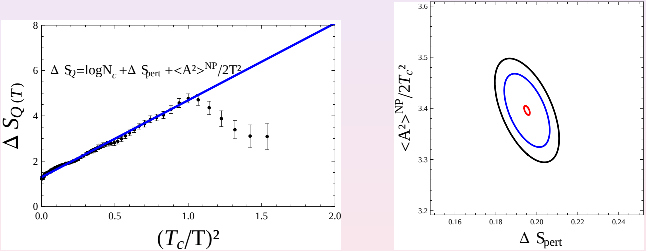
Issues

Power corrections above T_c

- Polyakov loop at high temperatures:

$$\langle \mathrm{tr}(e^{igA_0/T}) \rangle \sim N_c e^{-g^2 \langle \mathrm{tr} A_0^2 \rangle / 2N_c T^2} + \dots$$

- $\rightarrow \Delta S_Q(T) = \log(N_c) + \Delta S_{\mathrm{pert}}(T) + \langle A^2 \rangle^{\mathrm{NP}} / 2T^2$



- *Left panel*: Lattice data **[A.Bazavov et al, PRD93 '16].** The straight line is the fit using the dim-2 condensate.
- *Right panel*: Correlation plot between the dim-2 condensate and the perturbative entropy.

Issues

Fluctuations of Conserved Charges

- Conserved charges → $[Q_a, H] = 0.$
- In the *uds* sector the only conserved charges are:

$$Q \equiv \text{Electric charge}, \quad B \equiv \text{Baryon number}, \quad S \equiv \text{Strangeness}.$$

- In the hot vacuum (no chemical potential):

$$\langle Q \rangle_T = 0\,, \qquad \langle B \rangle_T = 0\,, \qquad \langle S \rangle_T = 0\,.$$

- Fluctuations → Susceptibilities:

$$\chi_{ab}(T) \equiv \frac{1}{VT^3} \langle \Delta Q_a \Delta Q_b \rangle_T\,, \qquad \Delta Q_a = Q_a - \langle Q_a \rangle_T\,.$$

At high temperature →
$$\begin{cases} \chi_{BB}(T) \propto \langle B^2 \rangle_T \to 1/N_c \\ \chi_{QQ}(T) \propto \langle Q^2 \rangle_T \to \sum_{i=1}^{N_f} q_i^2 \\ \chi_{SS}(T) \propto \langle S^2 \rangle_T \to 1 \end{cases} .$$

Fluctuations of Conserved Charges

[M.Asakawa, M.Kitazawa, Prog. Part. Nucl. Phys. 90 (2016)].

- Fluctuations of conserved charges can be computed from the grand-canonical partition function:

$$Z = \mathrm{Tr} \exp\left[- \left(H - \sum_a \mu_a Q_a \right) / T \right] , \qquad \Omega = -T \log Z ,$$

by differentiation

$$-\frac{\partial \Omega}{\partial \mu_a}\bigg|_{\mu_a = 0} = \langle Q_a \rangle_T , \quad -T \frac{\partial^2 \Omega}{\partial \mu_a \partial \mu_b}\bigg|_{\mu_a = 0 = \mu_b} = \langle \Delta Q_a \Delta Q_b \rangle_T \equiv V T^3 \chi_{ab}(T)$$

- $Q_a \in \{Q, B, S\}$, or, in the quark-flavor basis, $Q_a \in \{u, d, s\}$ where

$$B = \frac{1}{3}(u + d + s) , \quad Q = \frac{1}{3}(2u - d - s) , \quad S = -s .$$

Issues

1. Introduction
   - QCD Thermodynamics
   - Hadron Spectrum
2. Entropy Shift and Missing States
   - Entropy Shift below T_c
   - Entropy Shift above T_c
3. Fluctuations of Conserved Charges in a Thermal Medium
   - Fluctuations of Conserved Charges
   - Fluctuations in the HRG model
4. Correlations in a Thermal Medium
   - Free particles of spin $1/2$
   - Free particles of any spin
   - Correlations in the HRG model

Fluctuations in the HRG model

- Fluctuations in the HRG model:

$$Q_a = \sum_{i \in \text{Hadrons}} q_a^i N_i \,, \quad \chi_{ab}(T) = \sum_{i,j \in \text{Hadrons}} q_a^i q_b^j \langle \Delta N_i \Delta N_j \rangle_T \,, \quad a, b \in \{Q, B, S\}$$

where $q_a^i \in \{Q_i, B_i, S_i\} \equiv$ charge of the ith-hadron corresponding to symmetry a.

- Averaged number of hadrons of type i is

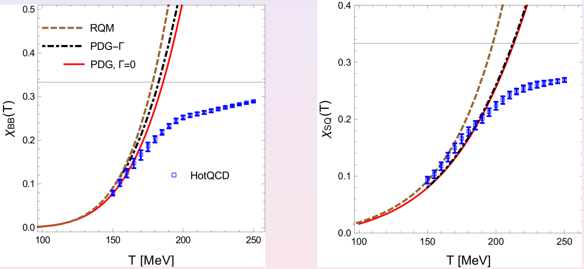
$$\langle N_i \rangle_T = V \int \frac{d^3k}{(2\pi)^3} \frac{g_i}{e^{E_{k,i}/T} - \xi_i} \,,$$

with $E_{k,i} = \sqrt{k^2 + M_i^2}$, and $\xi = \pm 1$ for bosons/fermions.

Fluctuations and Missing States

- Fluctuations of Conserved Charges ➞ Good description of lattice data for $T \lesssim 160$ MeV.

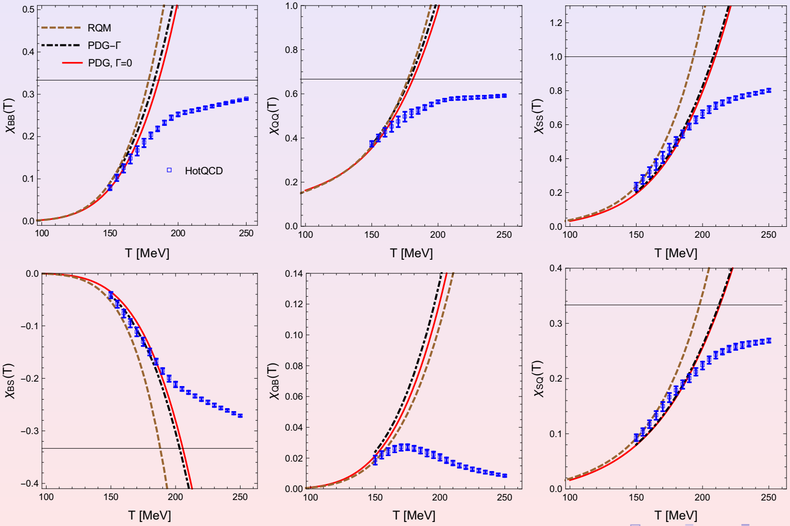
Lattice data of Fluctuations [A.Bazavov et al., PRD86 (2012)]



➞ *Fluctuations as a diagnostic tool to study missing states*.
Example: RQM seems to have too many baryonic states, but not too many charged states.

[E.Ruiz Arriola, W.Broniowski, EM, L.L.Salcedo, 1612.07091].

Fluctuations in the HRG model



Issues

Current correlators of free particles of spin $1/2$

- Lagrangian density for Dirac fermions

$$\mathcal{L}(x) = \overline{\Psi}(x)(\not{D} + m)\Psi(x)$$

  where m is the mass and $\not{D} = \gamma^\mu D_\mu$.
- Partition function of the system

$$Z = \int \mathcal{D}\Psi(x)\mathcal{D}\overline{\Psi}(x)e^{-\int_0^\beta dx_0 \int d^3x \mathcal{L}(x)}$$

- Fermions are antiperiodic: $\Psi(x_0 + \beta, \vec{x}) = -\Psi(x_0, \vec{x})$ with $\beta = 1/T$ the inverse of temperature.
- Vector currents

$$j^\mu(x) = \overline{\Psi}(x)\gamma^\mu\Psi(x) \,.$$

- Zero components are the conserved charges: $\rho(x) \equiv j^0(x)$.
- Retarded correlator

$$C^{\mu\nu}_{1/2}(x) \equiv \langle j^\mu(x) j^\nu(0)\rangle$$

Current correlators of free particles of spin 1/2

- Propagator of fermions of spin $1/2$ in position space

$$S_{1/2}(x) = -\int \frac{d^4k}{(2\pi)^4} \frac{i\not{k} + m}{k^2 + m^2} e^{-ikx} \,.$$

- The correlator writes

$$\langle j^\mu(x) j^\nu(0) \rangle = \langle S_{1/2}(x) \gamma^\mu S_{1/2}(-x) \gamma^\nu \rangle$$

- Correlator at zero temperature:

$$\langle j^\mu(x) j^\nu(0) \rangle = 4 \left[2(\partial^\mu \Delta(x))(\partial^\nu \Delta(x)) - ((\partial_\alpha \Delta(x))^2 + m^2 \Delta(x)^2) \eta^{\mu\nu} \right]$$

where

$$\Delta(x) = \int \frac{d^4k}{(2\pi)^4} \frac{e^{-ik_\mu x^\mu}}{k^2 + m^2} = \frac{m}{4\pi^2} \frac{K_1(m|x|)}{|x|} \,, \qquad |x| = \sqrt{x_0^2 + \vec{x}^2} \,.$$

$K_1 \equiv$ Bessel function of the second kind.

Free particles of spin $1/2$: $T = 0$

- Explicit result for the correlator at $T = 0$:

$$\langle j^\mu(x) j^\nu(0)\rangle = \frac{4m^4}{(4\pi^2)^2}\left[\left(\frac{K_2(m|x|)}{|x|^2}\right)^2 \left[2x^\mu x^\nu - \eta^{\mu\nu}x^2\right] - \left(\frac{K_1(m|x|)}{|x|}\right)^2 \eta^{\mu\nu}\right]$$

- Conservation of the current

$$\partial_\mu \langle j^\mu(x) j^\nu(0)\rangle = 0 \,.$$

- Behavior at small distances

$$\langle j^0(\vec{x}) j^0(0)\rangle \simeq -\frac{1}{\pi^4 r^6} + \frac{m^2}{4\pi^4 r^4} + \mathcal{O}(r^{-2}) \,, \qquad \text{with} \quad r = |\vec{x}| \,.$$

Free particles of spin 1/2: $T \neq 0$

- Correlator at finite temperature. Using Poisson's formula

$$\int \frac{dk_0}{2\pi} F(k_0, \vec{k}) \to i \sum_{n=-\infty}^{\infty} \xi^n \int \frac{dk_4}{2\pi} F(ik_4, \vec{k}) e^{ink_4/T} ,$$

where $\xi = \pm 1$ for bosons (fermions).

- $n \equiv$ number of thermal loops:
  $n = 0 \to\ T = 0$ contribution, $\quad n \neq 0 \to$ finite T corrections.
- Correlator at finite temperature:

$$\langle j^\mu(x) j^\nu(0)\rangle_T = 4\left[2(\partial^\mu \Delta_T(x))(\partial^\nu \Delta_T(x)) - ((\partial_\alpha \Delta_T(x))^2 + m^2 \Delta_T(x)^2)\eta^{\mu\nu}\right]$$

$$\Delta_T(x) = \frac{m}{4\pi^2} \sum_{n=-\infty}^{+\infty} \xi^n \frac{K_1(m|x|)}{|x|} , \qquad |x| = \sqrt{\left(x_0 - \frac{n}{T}\right)^2 + \vec{x}^2} .$$

- At small distances $\to$ finite T correction starting at $\mathcal{O}(r^{-2})$

$$\langle j^0(\vec{x}) j^0(0)\rangle_T - \langle j^0(\vec{x}) j^0(0)\rangle_{T=0} = \frac{1}{r^2} \frac{m^2 T}{\pi^2} \left(m K_1\left(\frac{m}{T}\right) + 2T K_2\left(\frac{m}{T}\right)\right) + \cdots$$

Issues

Current correlators of free particles of any spin

- By using the formalism of **[V.Bargmann, E.Wigner, Proc. Nat. Acad. Sci 34 (1948)]**, in Euclidean space

$$C^J_{\mu\nu}(x) \equiv \langle j_\mu(x) j_\nu(0)\rangle = (2m)^2 \frac{(-1)^n}{n^2} \left(a_n L_1^{n-1} L_{\mu\nu} + a_{n-1} L_1^{n-2} L_\mu L_\nu \right) \Delta^2(x)$$

for $J \geq 1/2$, where $a_n = 2^{1-n}\binom{n+2}{3}$, $(a_0 = 0)$, $n = 2J$, where J is the spin,

$$C^0_{\mu\nu}(x) = m^2 L_\mu L_\nu \Delta^2(x)\,,$$

and L are differential operators

$$L_1 = 1 - \frac{1}{m^2}\overset{1}{\partial}_\alpha \overset{2}{\partial}_\alpha\,, \qquad L_\mu = \frac{1}{m}\left(\overset{1}{\partial}_\mu - \overset{2}{\partial}_\mu\right)\,,$$

$$L_{\mu\nu} = \delta_{\mu\nu}\left(1 + \frac{1}{m^2}\overset{1}{\partial}_\alpha \overset{2}{\partial}_\alpha\right) - \frac{1}{m^2}\left(\overset{1}{\partial}_\mu \overset{2}{\partial}_\nu + \overset{1}{\partial}_\nu \overset{2}{\partial}_\mu\right)\,.$$

Issues

1. Introduction
   - QCD Thermodynamics
   - Hadron Spectrum
2. Entropy Shift and Missing States
   - Entropy Shift below T_c
   - Entropy Shift above T_c
3. Fluctuations of Conserved Charges in a Thermal Medium
   - Fluctuations of Conserved Charges
   - Fluctuations in the HRG model
4. Correlations in a Thermal Medium
   - Free particles of spin 1/2
   - Free particles of any spin
   - Correlations in the HRG model

Current correlators in the HRG model

- Within the HRG model the correlator writes

$$C^{ab}_{\mu\nu}(x) \equiv \langle j^a_\mu(x) j^b_\nu(0)\rangle = \sum_i \frac{1}{2} q^a_i q^b_i C^{J_i}_{\mu\nu}(x) \,, \quad q^a_i \in \{Q_i, B_i, S_i\} \,.$$

- i stands for any hadron, distinguishing between spin J_i, isospin and particle-antiparticle.
- Lowest lying states in the meson and hadron spectrum corresponding to pions and protons/neutrons:

$$i \in \{\pi^+, \pi^0, \pi^-, p\uparrow, p\downarrow, \bar{p}\uparrow, \bar{p}\downarrow, n\uparrow, n\downarrow, \bar{n}\uparrow, \bar{n}\downarrow\}.$$

- Small distance behavior: $C^J_{00}(r) \underset{r\to 0}{\sim} \frac{m^2}{r^4}\frac{1}{(mr)^{4J}}$.
- After summation over hadrons of higher and higher spin

$$C^{HRG}_{00}(r) = \sum_J C^J_{00}(r) \underset{r\to r_H^+}{\longrightarrow} \infty$$

$r_H \equiv$ Hagedorn distance $\longleftrightarrow$ Analogous to T_H at finite T.

Current correlators in the HRG model

- An equivalent expression:

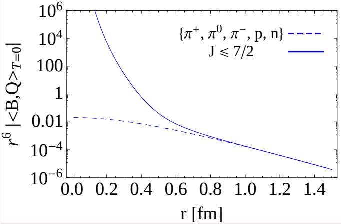
$$C^{ab}_{\mu\nu}(x) \equiv \langle j^a_\mu(x) j^b_\nu(0)\rangle = \sum_{M\in\text{Mesons}} \frac{1}{2}(2J_M+1) q^a_M q^b_M C^{J_M}_{\mu\nu}(x) + \sum_{B\in\text{Baryons}>0} (2J_B+1) q^a_B q^b_B C^{J_B}_{\mu\nu}(x)$$

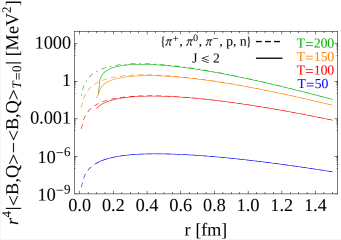
- M and B run now over the spin multiplets of mesons and baryons, each of them with degeneracy $(2J_M+1)$ and $(2J_B+1)$.
- Lowest lying states: $M \in \{\pi^+, \pi^-, \pi^0\}$ and $B \in \{p, n\}$.
- These correlators (in the static limit $x^0 = 0$) fulfill

$$\chi_{ab}(T) = \int d^3x\, C^{ab}_{00}(0, \vec{x})\,.$$

Correlations in the confined phase of QCD

Static C_{00} correlator at $T = 0$ **Static C_{00} correlator at $T \neq 0$**



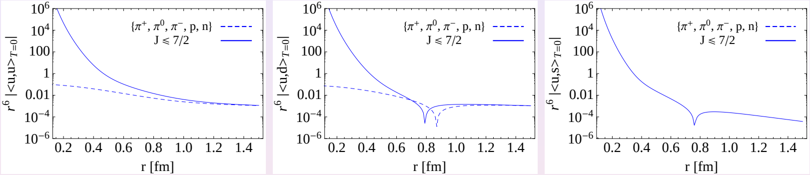


- Analogy: "correlators at T=0" ⇔ "susceptibilities $T \neq 0$'

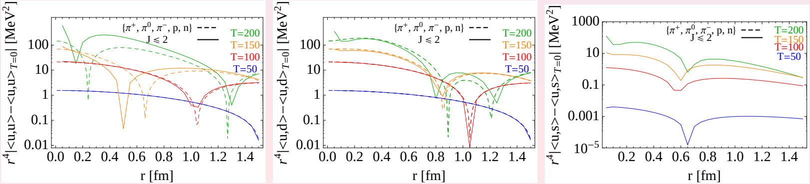
$$C_{00}^{ab}(0, \vec{x}) \underset{r \to \infty}{\sim} e^{-Mr} \quad \text{and} \quad \chi_{ab}(T) \underset{T \to 0}{\sim} e^{-M/T}$$

Correlations in the confined phase of QCD

- Correlations $T = 0$



- Correlations $T \neq 0$



Conclusions

- At low temperatures hadrons can be considered as a complete basis of states in terms of a Hadron Resonance Gas (HRG) model. The HRG works at $T \lesssim 0.8 T_c$.
- Close T_c many hadrons are needed to saturate the sum rule $\Longrightarrow$ What states are needed when approaching T_c from below?
- Polyakov loop and Entropy shift due to a heavy quark suggests that there are in the QCD spectrum: i) conventional missing states ($Q\bar{q}$ and Qqq), and ii) hybrid states ($Q\bar{q}g$ and $Qqqg$).
- This establishes a *new tool* for Polyakov loop spectroscopy of the QCD spectrum including exotic states.
- Fluctuations of conserved charges in the confined phase of QCD allow to study missing states in three different sectors:

  i) electric charge, ii) baryon number, and iii) strangeness.
- We have obtained results for the correlations of conserved charges at zero and finite temperature ➞ Confronting these with future results on the lattice will help in the study of missing states!!!

Thank You!