

Quark-hadron duality at finite temperature : Local Correlators in the hadron resonance gas

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XIIIth Quark Confinement and the Hadron
Spectrum
Maynooth University, Dublin (Ireland)
31 July to 6 August 2018

Works with Eugenio Megias and Lorenzo Salcedo

Issues

Outline

- The Hadron Spectrum at zero temperature
- Quarks and gluons at finite temperature
- Quark Hadron duality at finite temperature
- Entropy shifts
- Anatomy of Hadron Resonance Gas
- Conclusions
- References

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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.Supp. 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

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

QCD Thermodynamics

- The partition function of QCD

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

- Spectrum of QCD Thermodynamics

Hadron Resonance Gas Model

- In the **confined phase**: Colour singlet states (hadrons + ⋯ ???)
Low temperature partonic expansion [EM, E. Ruiz Arriola, L.L. Salcedo, Acta Phys. Pol. B45 '14]:

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

- 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”?

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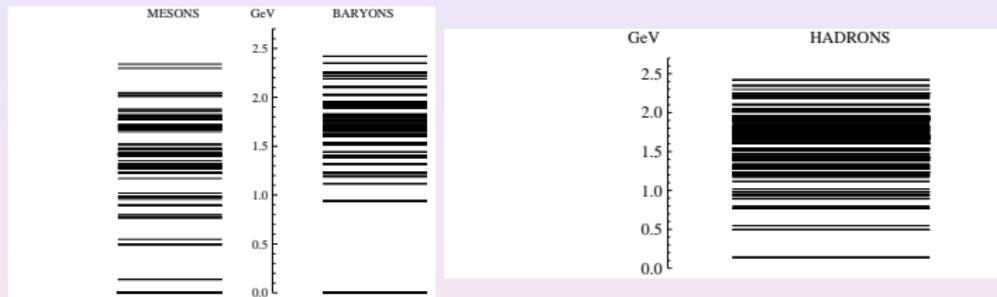
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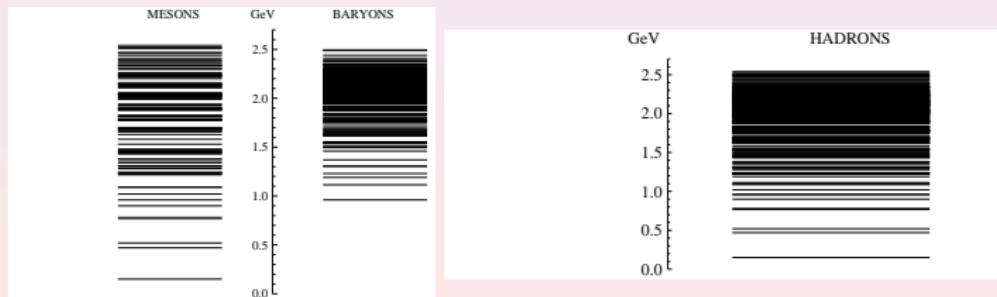
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Hadron Spectrum (u,d,s)

- Particle Data Group (PDG) compilation 2016



- Relativized Quark Model (RQM), Isgur, Godfrey, Capstick 1985



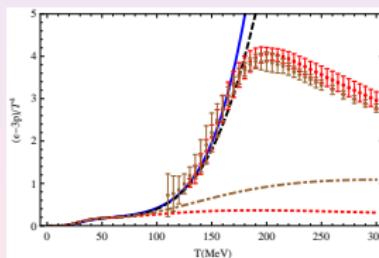
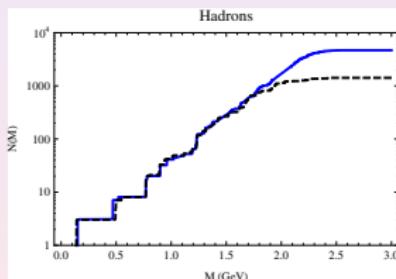
Cumulative number of states

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

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

- Which states count?

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



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

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

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

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Entropy Shift and Polyakov loop

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

$$E_n \rightarrow E_n^+ \Delta_n^+ m_+ \dots .$$

Δ_n remains finite in the limit $m \rightarrow \infty$.

- In the static gauge $\partial_0 A_0 = 0$ the **Polyakov loop** operator reads

$$\text{tr } \Omega(\vec{r}) = \text{tr } e^{iA_0(\vec{r})/T} .$$

- Ratio of partition functions Free energy shift $\equiv \Delta F$

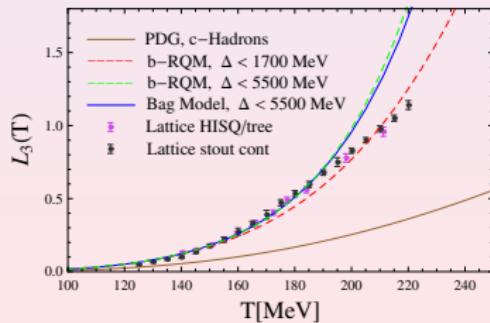
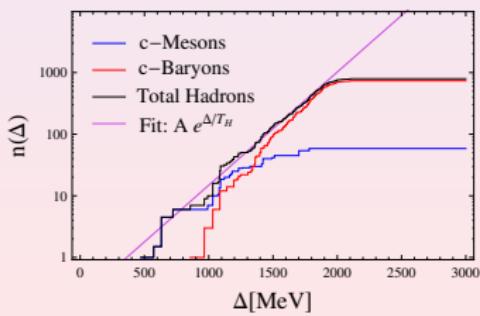
$$L \equiv \langle \text{tr } \Omega(0) \rangle = \frac{Z}{Z_0} = e^{-\Delta F/T} = \frac{\sum_n e^{-\Delta_n/T}}{1 + \dots}$$

Polyakov loop and Hadron Resonance Gas model

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

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

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)]:

$$L_+ e^{c/T} \cdot L_-$$

- The ambiguity can be removed by computing the entropy shift

$$L_+ \langle \text{tr}_\Omega(0) \rangle_T = e^{-\Delta F(T)/T} \quad \Delta S(T) = -\frac{\partial}{\partial T} \Delta F(T).$$

- Third principle of thermodynamics for degenerate states

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

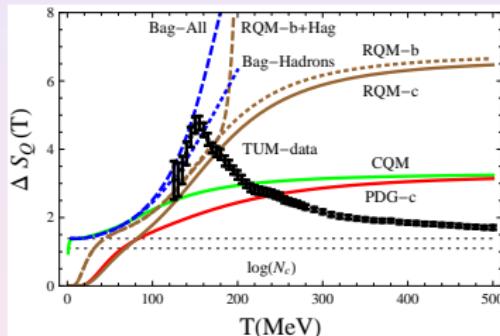
- Renormalization Group Equation:

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

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 $[Qqqg]$).

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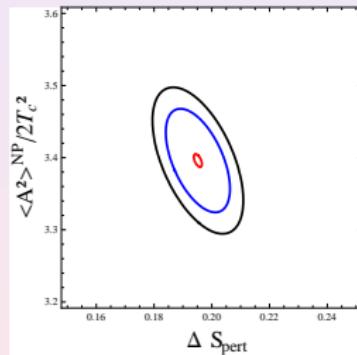
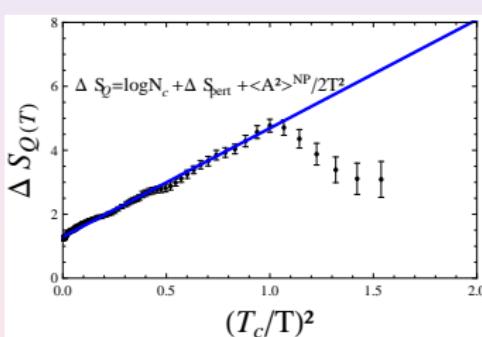
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Power corrections above T_c

- Polyakov loop at high temperatures:

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

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



- 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.

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Fluctuations of Conserved Charges

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

$Q \equiv$ Electric charge, $B \equiv$ Baryon number, $S \equiv$ Strangeness.

- In the hot vacuum (no chemical potential):

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

- **Fluctuations Susceptibilities:**

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

At high temperature

$$\left\{ \begin{array}{l} \chi_{BB}(T) \propto \langle B^2 \rangle_T \rightarrow 1/N_c \\ \chi_{QQ}(T) \propto \langle Q^2 \rangle_T \rightarrow \sum_{i=1}^{N_f} q_i^2 \\ \chi_{SS}(T) \propto \langle S^2 \rangle_T \rightarrow 1 \end{array} \right.$$

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:

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

by differentiation

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

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

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

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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 i th-hadron corresponding to symmetry a .

- Averaged number of hadrons of type i is

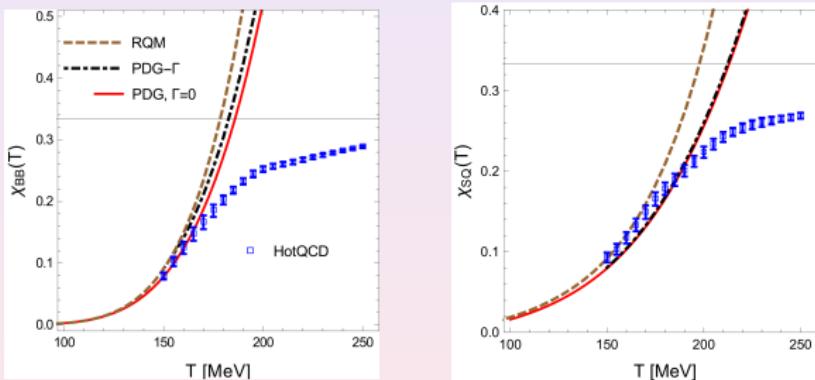
$$\langle N_i \rangle_T = V \int \frac{d^3 k}{(2\pi)^3} \frac{g_i}{e^{E_{k,i}/T} - \xi_i},$$

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)]

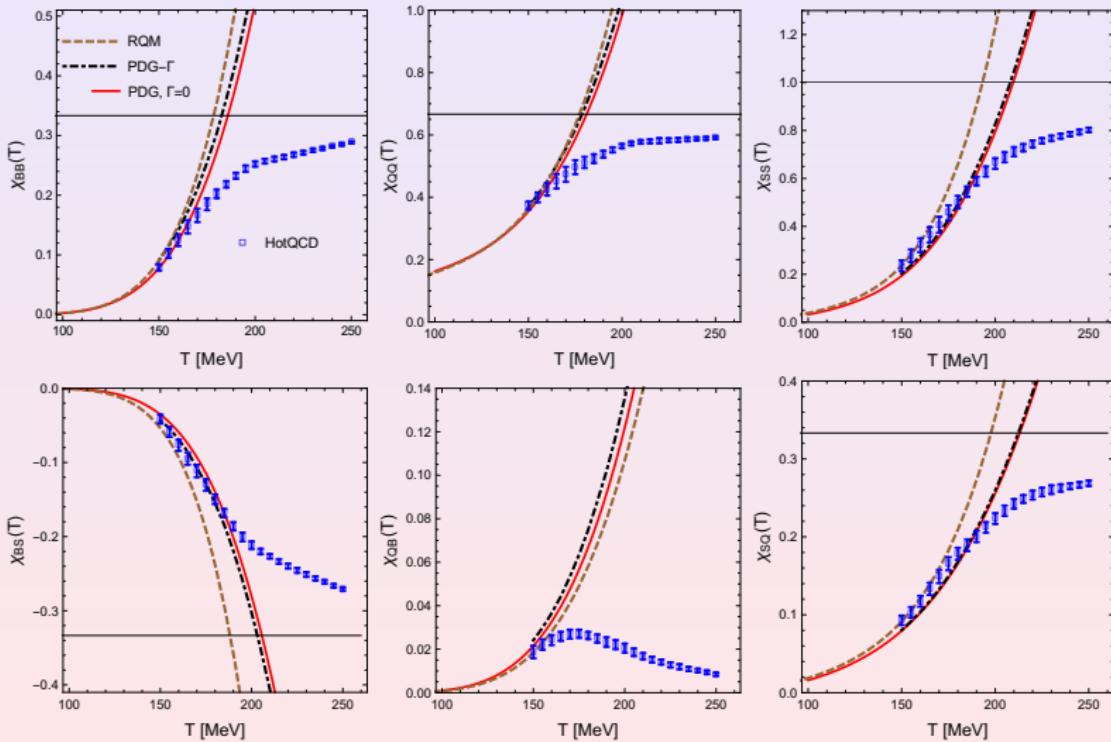


Fluctuations as a diagnostic tool to study missing states.

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



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Current correlators of free particles of spin 1/2

- Lagrangian density for Dirac fermions

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

where m is the mass and $\not{D} = \gamma^\mu D_\mu$.

- Partition function of the system

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

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

- Vector currents

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

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

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

Current correlators of free particles of spin 1/2

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

$$S_{1/2}(x) = - \int \frac{d^4 k}{(2\pi)^4} \frac{i k + m}{k^2 + m^2} e^{-ikx}.$$

- 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:

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

where

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

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

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

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

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

- Conservation of the current

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

- Behavior at small distances

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

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

- Correlator at finite temperature. Using Poisson's formula

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

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

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

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

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

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

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

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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

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

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,

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

and L are differential operators

$$\begin{aligned} L_1 &= 1 - \frac{1}{m^2} \partial_\alpha \partial_\alpha^2, & L_\mu &= \frac{1}{m} \left(\partial_\mu - \partial_\mu^2 \right), \\ L_{\mu\nu} &= \delta_{\mu\nu} \left(1 + \frac{1}{m^2} \partial_\alpha \partial_\alpha^2 \right) - \frac{1}{m^2} \left(\partial_\mu \partial_\nu + \partial_\nu \partial_\mu \right). \end{aligned}$$

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Current correlators in the HRG model

- Within the HRG model the correlator writes

$$C_{\mu\nu}^{ab}(x) \equiv \langle j_\mu^a(x) j_\nu^b(0) \rangle = \sum_i \frac{1}{2} q_i^a q_i^b C_{\mu\nu}^{J_i}(x), \quad q_i^a \in \{Q_i, B_i, S_i\}.$$

- 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: $C_{00}^J(r) \underset{r \rightarrow 0}{\sim} \frac{m^2}{r^4} \frac{1}{(mr)^{4J}}$.
- After summation over hadrons of higher and higher spin

$$C_{00}^{HRG}(r) = \sum_J C_{00}^J(r) \underset{r \rightarrow r_H^+}{\longrightarrow} \infty$$

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

Current correlators in the HRG model

- An equivalent expression:

$$C_{\mu\nu}^{ab}(x) \equiv \langle j_\mu^a(x) j_\nu^b(0) \rangle =$$

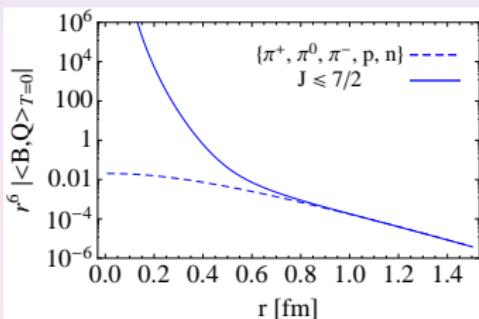
$$\sum_{M \in \text{Mesons}} \frac{1}{2} (2J_M + 1) q_M^a q_M^b C_{\mu\nu}^{J_M}(x) + \sum_{B \in \text{Baryons} > 0} (2J_B + 1) q_B^a q_B^b C_{\mu\nu}^{J_B}(x)$$

- 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

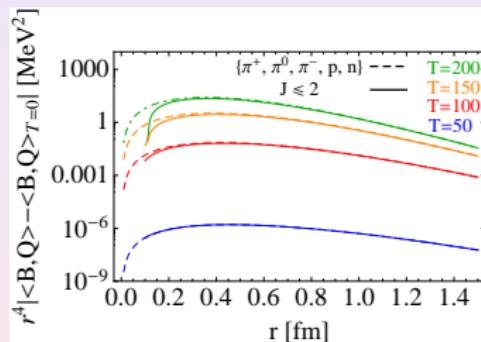
$$\chi_{ab}(T) = \int d^3x C_{00}^{ab}(0, \vec{x}).$$

Correlations in the confined phase of QCD

Static C_{00} correlator at $T = 0$



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

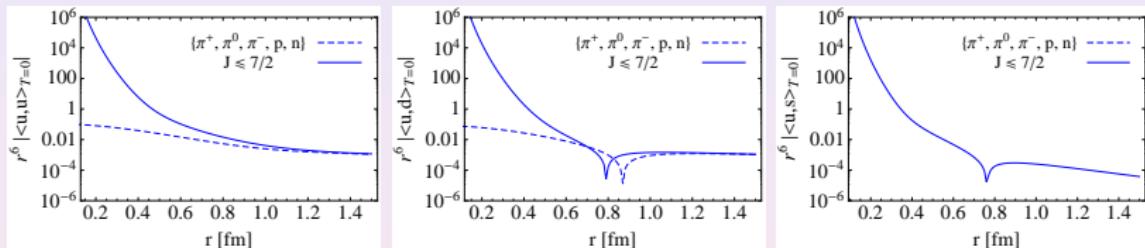


- Analogy: “correlators at $T=0$ ” \Leftrightarrow “susceptibilities $T \neq 0$ ”

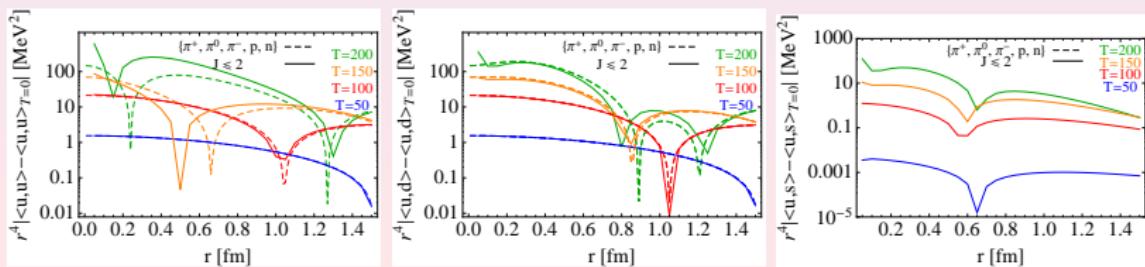
$$C_{00}^{ab}(0, \vec{x}) \underset{r \rightarrow \infty}{\sim} e^{-Mr} \quad \text{and} \quad \chi_{ab}(T) \underset{T \rightarrow 0}{\sim} e^{-M/T}$$

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 $T \lesssim 0.8T_c$.
- Close T_c many hadrons are needed to saturate the sum rule \Rightarrow 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 Qqg).
- 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!