"Particle" states of Lattice QCD

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Introduction

Heavy ion collisions at RHIC and LHC suggest that the quark-gluon state formed is a strongly interacting one.

Hagedorn had suggested that a strongly interacting system can be equivalently described as a system of non-interacting entities with corresponding masses.

Thus, we seek "particle" massive states, which could equivalently describe the results of lattice calculations for the equation of state of QCD matter [1].

Lattice calculations

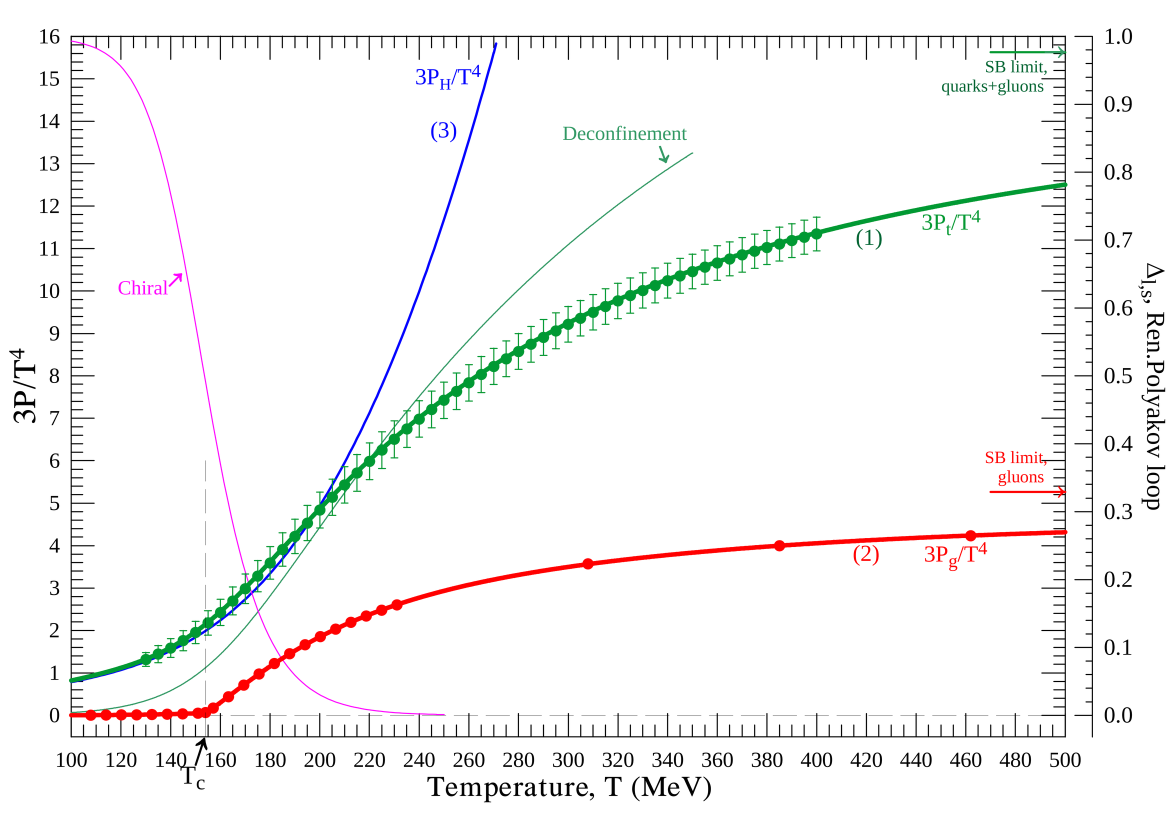

Figure 1: Normalised Pressure, P, as function of temperature T. Lattice calculations with (2+1) flavour QCD [2]: line 1 and SU(3) gauge field [3]: line 2. Hadron Resonance Gas (HRG) is line 3. Also shown are the corresponding non-interacting (SB) limits and lattice estimation of the order parameters of the chiral transition and deconfinement (corresponding to the far right vertical axis).

The number of states at the SB limit:

Gluons, due to spin (s) and colour (c):

$$g_G = g_s g_c = 2 \cdot 8 = 16 \qquad (1)$$

Quarks, due to spin (s), colour (c), flavour (f) and the presence of quarks and anti-quarks (an):

$$g_Q = g_s g_c g_f g_{an} = 2 \cdot 3 \cdot 3 \cdot 2 = 36 \qquad (2)$$

Total system:

$$g_T = g_G + g_Q = 16 + 36 = 52 \qquad (3)$$

Method

We seek the total number of states g_t and average mass $\langle m \rangle$ in the pressure:

$$P_f(T; g_t, \langle m \rangle) = \frac{T^2}{2\pi^2} g_t \langle m \rangle^2 K_2\left(\frac{\langle m \rangle}{T}\right) , \qquad (4)$$

so that P_f best fits a fragment of the Lattice pressure P_L around T. We work in the Boltzmann approximation, in the absence of knowledge whether the particles of our system are fermions, bosons or a mixture of both. We minimize the quantity

$$\chi^2 = \sum_{i=1}^{N} \frac{1}{\sigma(T)^2} \left[P_L(T_i) - P_f(T_i; g_t, \langle m \rangle) \right]^2 , \qquad (5)$$

$N = 101$, T_i equally distributed in the interval $(T - \Delta T, T + \Delta T)$ ($\Delta T = 5$ MeV), $\sigma(T) = T^4$.

"Toy Model": a system with 2 particle species with number of states $g_1 = 10$ and $g_2 = 20$ and masses $m_1 = 150$ MeV and $m_2 = 300$ MeV.

$$g_t \underset{T\to 0}{\longrightarrow} g_1 \; , \; \langle m \rangle \underset{T\to 0}{\longrightarrow} m_1 \qquad (6)$$

$$g_t \underset{T\to\infty}{\longrightarrow} g_1 + g_2 \; , \; \langle m \rangle \underset{T\to\infty}{\longrightarrow} m_{rms} = \sqrt{\frac{g_1 m_1^2 + g_2 m_2^2}{g_1 + g_2}} \qquad (7)$$

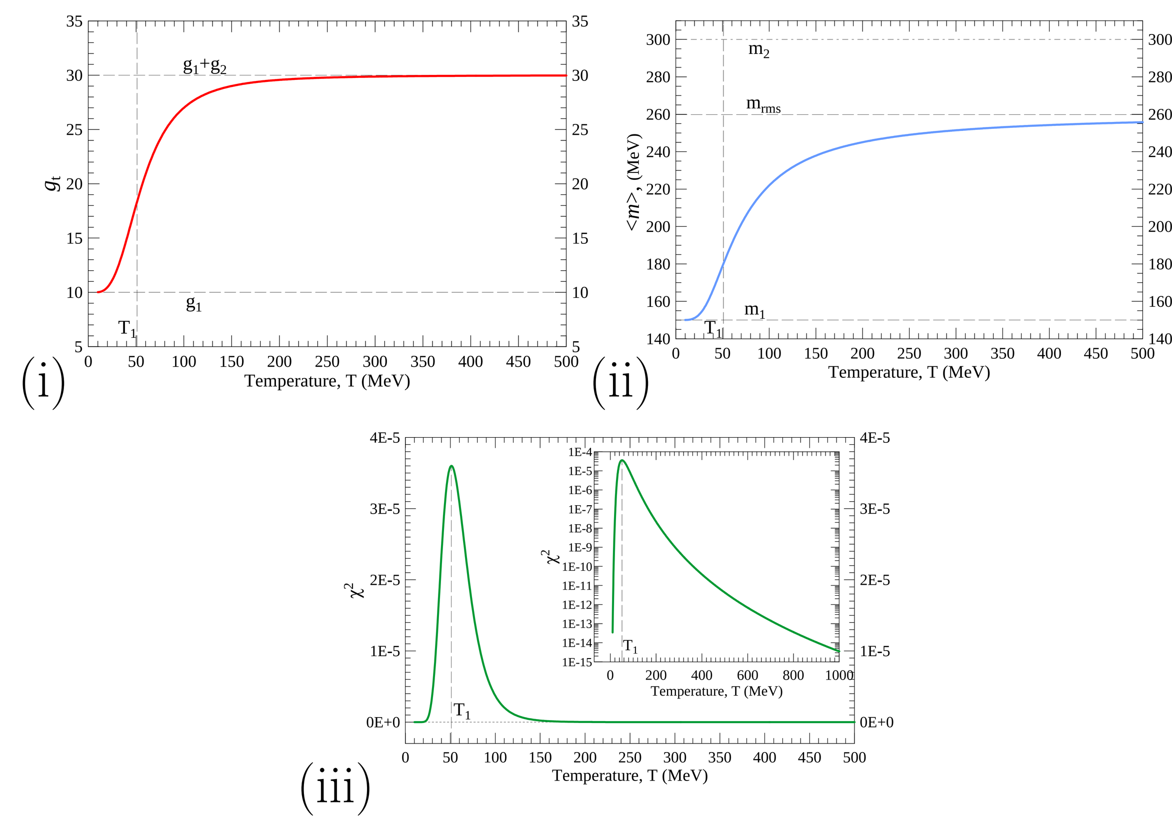

Figure 2: "Toy Model": (i) g_t as function of temperature. (ii) $\langle m \rangle$ as function of temperature. (iii) χ^2 as function of temperature. T_1 is the transition temperature between best descriptions with different sets of values of g_t and $\langle m \rangle$.

Results

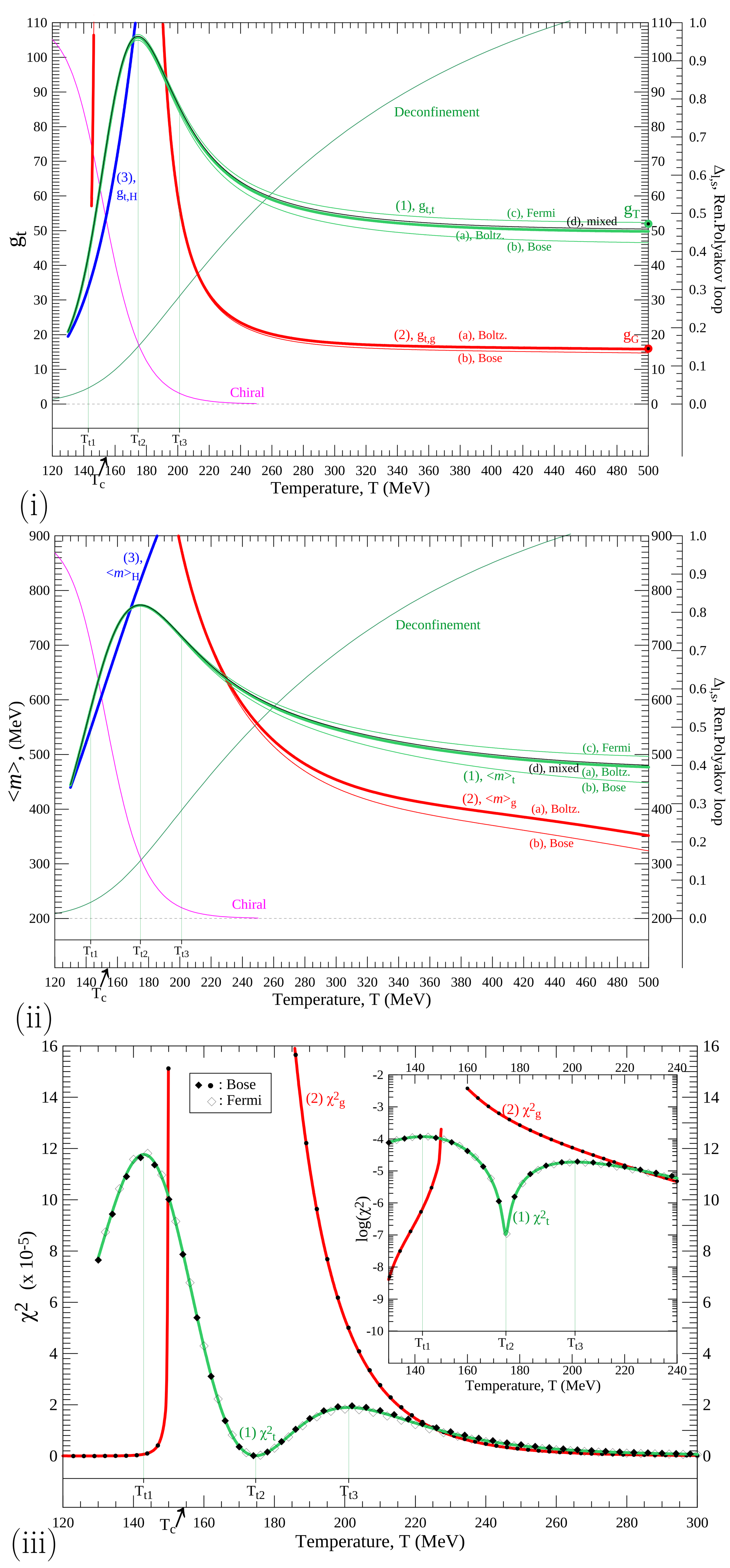

Figure 3: The number of states g_t, (i), average mass $\langle m \rangle$, (ii) and the value of χ^2, (iii), as function of temperature. Curves (1) correspond to the total system, curves (2) to a pure gluonic system, and curves (3) to HRG. Thick lines (a) are calculated with the Boltzmann approximation, lines (b) with Bose statistics, lines (c) with Fermi statistics and thin black line (d) to a system composed of $\frac{16}{52}$ bosons and of $\frac{36}{52}$ fermions. In (i) the solid coloured circles correspond to $g_G = 16$ and $g_T = 52$. The shown characteristic temperatures $T_{t1...t3}$ correspond to the local extremal points of χ^2 in (iii) (look Table 1). $T_c = 154$ MeV, is the critical temperature. Also shown in (i) and (ii) are the lattice estimation of the order parameters of the chiral transition and deconfinement.

Minimum values of $\chi^2 \to$ extremal values of g_t, $\langle m \rangle$

Maximum values of $\chi^2 \to$ transition between different best fitted g_t, $\langle m \rangle$

T (MeV)	Label	System	Extremal of χ^2	Extremal of g_t, $\langle m \rangle$
142.9	T_{t1}	total	max	-
174.7	T_{t2}	total	min	max
201.1	T_{t3}	total	max	-

Table 1: Location of the extremal points of χ^2 for the total system and their connection with the fitted parameters of Figure 3(i) and 3(ii). The maxima of χ^2 depend on the choice of the errors σ, while the minimum remains unchanged. In this calculation we have used $\sigma = T^4$.

Conclusions

- We have developed an effective description of the Lattice QCD pressure at zero baryon chemical potential with two parameters, the degeneracy factor g_t and the average particle mass $\langle m \rangle$. The description is carried out for the inclusive three flavour system, as well as, the gauge field sector.
- The calculated parameters of the total system have as their low temperature limit the corresponding parameters of the Hadron Resonance Gas.
- The number of states of the total and the gluon sector converge, above $T \simeq 230$ MeV, close to the number of states of an ideal Quark-Gluon Phase, indicating the existence of colour states at these temperatures. However, the corresponding high average masses suggest that the entities are strongly interacting.
- g_t and $\langle m \rangle$, corresponding to a pure gluon sector, are found to be in extreme increase with temperature just below the critical temperature, T_c and in extreme decrease just above T_c. The emerging picture is as if the gauge field occupies the whole system as a unique entity. This system, around T_c, cannot be described as a group of "particles" with specific mass and states, since the interaction is such that the whole system behaves as a single "particle" with divergent mass and number of states.
- The described changes of the total and gluon sector are taking place within the temperature range of the chiral transition.
- ***Look for detailed treatment in [1].***

References

[1] A. S. Kapoyannis and A. D. Panagiotou, *Particle states of Lattice QCD*, arXiv:1705.00291 [hep-ph].

[2] A. Bazavov et. al., (HotQCD Collaboration), *The equation of state in (2+1)-flavor QCD*, Phys. Rev. D **90** (2014) 094503; arXiv:1407.6387 [hep-lat].

[3] Sz. Borsányi, G. Endrődi, Z. Fodor, S. D. Katz and K. K. Szabó, *Precision SU(3) lattice thermodynamics for a large temperature range*, JHEP **1207** (2012) 056; arXiv:1204.6184 [hep-lat].

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