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Do lattice data constrain the vector interaction strength of QCD?

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Abstract

We investigate how repulsive interactions of deconfined quarks as well as confined hadrons can be constrained in a straight forward way by model comparisons of baryon number susceptibilities with lattice QCD results. Our results clearly point to a strong vector repulsion in the hadronic phase and near-zero repulsion in the deconfined phase.

The Combined EoS

The total grand canonical potential of our model includes contributions from the hadrons (Ω_{had}) the deconfined quarks (Ω_q), as well as contributions from mean fields interacting with the hadrons and quarks (V) and the Polyakov loop potential (U).

$$\Omega_{tot} = \Omega_{had} + \Omega_q + V + U \tag{1}$$

In the hadronic phase we use the parity doublet model for the baryon octet and add all hadronic resonances, with masses up to 2.2 GeV. To describe the transition from the confined hadronic phase to a deconfined quark phase we include explicitly the contributions of the quarks and gluons in the thermodynamic potential, as discussed in detail in [1]. This generates a smooth cross-over chiral and deconfinement transition at small chemical potential and high temperatures. The quarks and gluons are incorporated in a similar way as described in so-called Polyakov loop extended quark models [2, 3, 4, 5, 6]. In our implementation we add the thermal contribution of the quarks to the thermodynamic potential Ω_{tot}:

$$\Omega_q = -T \sum_{i \in Q} \frac{\gamma_i}{(2\pi)^3} \int d^3k \ln\left(1 + \Phi \exp\frac{E_i^* - \mu_i^*}{T}\right) \tag{2}$$

where we sum over all three quark flavors. γ_i is the corresponding degeneracy factor, Φ is the Polyakov loop.
To suppress hadrons when deconfinement is realized we adopt an ansatz introduced in [7] and used in [8], where we introduced an excluded volume for the hadrons (and not the quarks), which very effectively removes the hadrons once the free quarks give a significant contribution to the pressure.

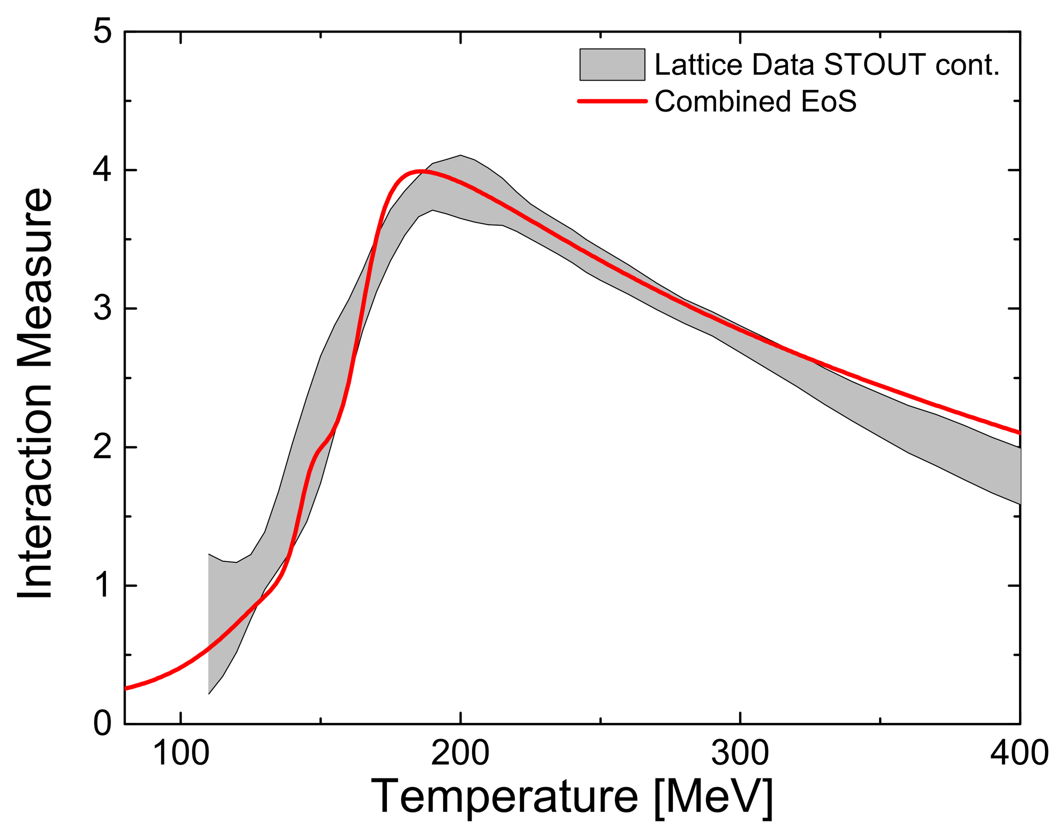

Figure: Interaction measure, $(\epsilon - 3p)/T^4$, for our combines equation of state (red solid line) compared to continuum extrapolated lattice QCD results [9] (grey band).

Susceptibilities

The thermodynamics of QCD at small values of μ_B/T can be obtained by a Taylor expansion of lattice results at $\mu_B = 0$, in terms of the chemical potential [10]. The pressure $p = -\Omega$ is expressed with the coefficients c_n^B, which can be related to the baryon number susceptibilities χ_n^B:

$$\chi_n^B/T^2 = n! c_n^B(T) = \frac{\partial^n (p(T,\mu_B)/T^4)}{\partial(\mu_B/T)^n} \tag{3}$$

As $p(T,\mu_B)$ also depends on the value of the vector field $\omega(T,\mu_B)$ explicitly, one can easily see that the susceptibilities depend on the derivatives of this field $\partial^n\omega(T,\mu_B)/(\partial\mu_B)^n \neq 0$. It is now interesting to investigate how large these contributions are and if one can use them to constrain $\omega(T,\mu_B)$ and subsequently g_V.

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Results

We have shown that lattice results for the baryon number susceptibilities can be used, even to lowest order, to constrain the repulsive vector interaction strength of quarks in the deconfined phase. We confirm [11] that only a nearly vanishing strength is supported by lattice QCD data. Even a small vector coupling would lead to a systematic deviation of the baryon number susceptibilities, i.e. a maximum as function of temperature at $\mu_B = 0$. Such a behavior is not observed, even when susceptibilities are calculated to very high temperatures on the lattice [12] and in perturbative QCD [13].
Concerning the repulsive hadronic interaction we find that, due to the large mass of the baryonic hadrons, the lowest order susceptibilities show only a very weak dependence and are not useful to constrain the hadronic repulsive interactions.

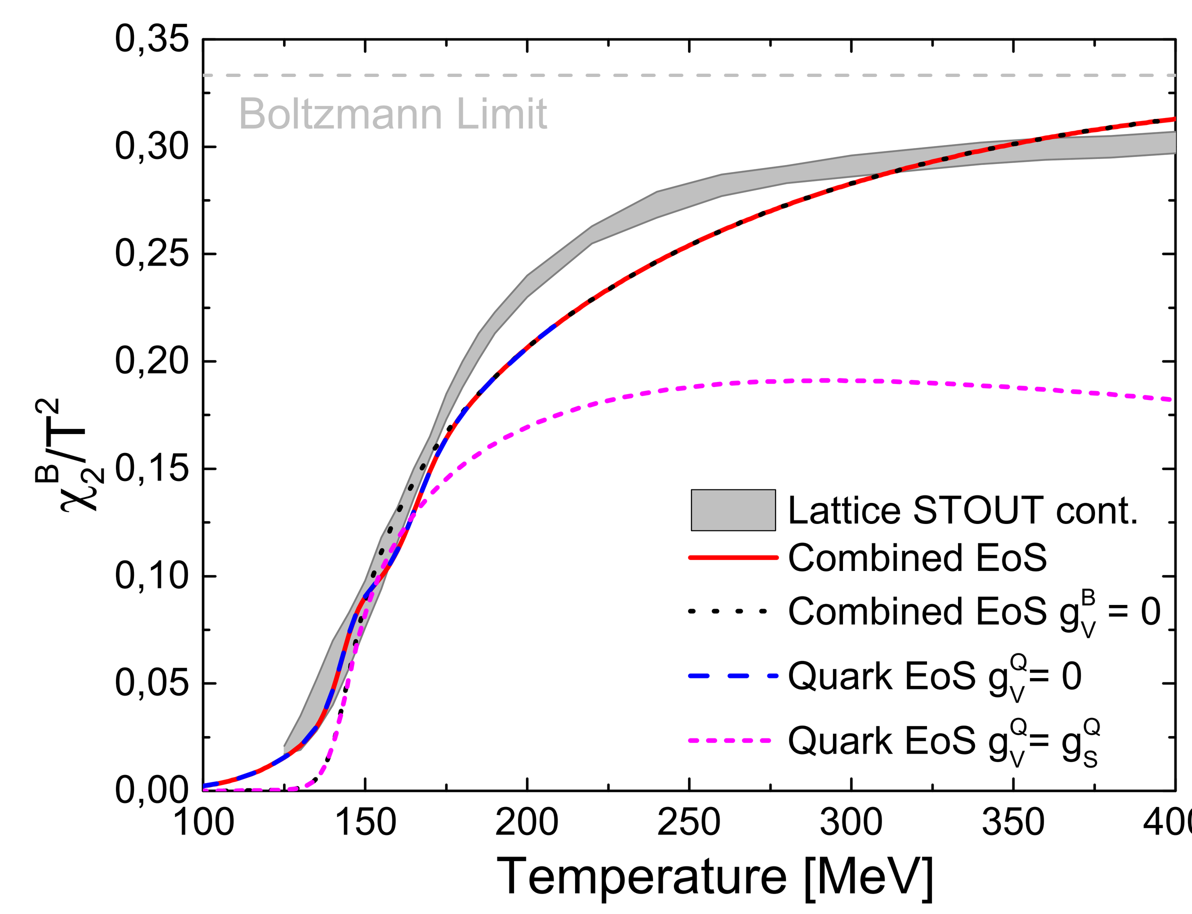

Figure: Second order baryon number susceptibility from our combined equation of state (red solid line) compared to continuum extrapolated lattice QCD results [14] (grey band). We also show the combined EoS with zero hadron vector interaction strength (black dashed line), and the quark part of the EoS with finite vector coupling (magenta short dashed line).

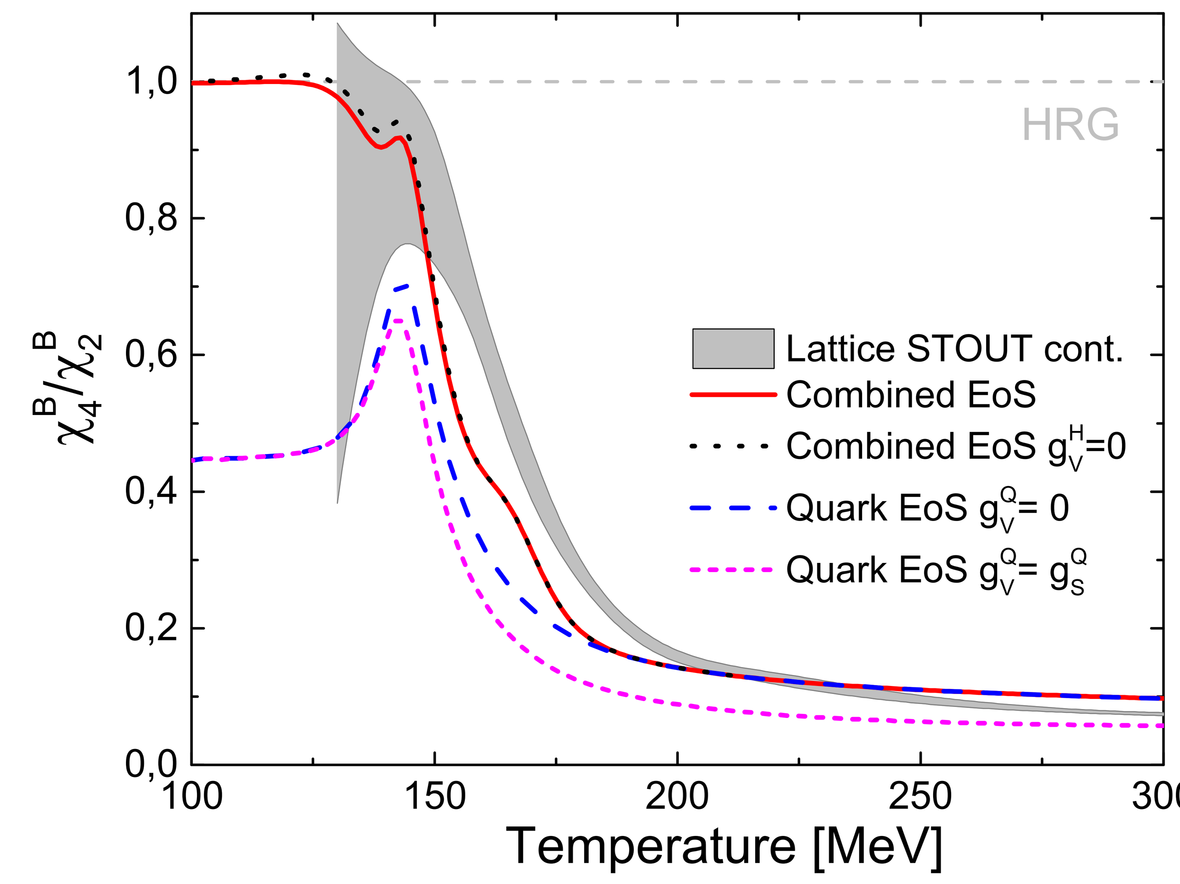

Figure: Forth order baryon number susceptibility from our combined equation of state (red solid line) compared to continuum extrapolated lattice QCD results [?] (grey band). We also show the combined EoS with zero hadron vector interaction strength (black dashed line), and the quark part of the EoS where quarks have a finite vector coupling (magenta short dashed line).

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