2.18 Interplay of Repulsive Interactions and Extra Strange Resonances

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Abstract

From simulations on lattice it is suggested that there exist missing states in the strange sector of the hadronic spectrum. Since those predictions mainly rely on the Hadron-Resonance Gas model assumption, it is important to check the influence of all the known possible implementation of such a model, in particular the effect of repulsive forces among hadrons. I explore the interplay between the inclusion of extra states predicted by the Quark Model, which I expect to be in line with possible future discoveries, and the corresponding repulsive forces parametrized trough the Excluded Volume. I find that the inclusion of Quark Model states improves the description of some observables, but in order to have an overall improvement for most of the available observables, repulsive interactions are needed. I check experimental measured yields and results from lattice simulations as well. I find that there is a better description of the data when including both effects, within a reasonable temperature range.

1. Introduction

In recent years the HIC program was very successful in providing results on strong interactions. Among these it is remarkable the success of the statistical hadronization model, which assumes that immediately after the collision the system thermalizes into a fireball from which hadrons are emitted. This result has been furtherly tested against hadron production [1], and with hydrodynamical simulations [2]. However it is worth to mention that other options exist, e.g., a microscopical description through transport models, from which it is possible to access directly the partonic nature of those interactions.

Lattice simulations provided excellent results, and in recent years it was possible to improve the accuracy and precision of those, in order to be able to analyze experimental data [3], and being able to do important step forward in the understanding of the QCD transition; this is extremely important because allows to directly connect the experiment with first principle calculations. From these, we know that the confinement transition is a crossover [4], i.e., does not allow to clearly asses when there is the passage between the two phases, but only to estimate a (pseudo-)critical temperature of about 150 MeV [5]. This has important consequences, e.g., the fact that the crossover acts differently for different constituent, hinting for a flavor hierarchy in the critical temperature [6].

Fluctuations of conserved charges have been proposed to be able to test these assumptions, and have been proven to be very sensitive observables from lattice simulations [6], and from experimental measurements [7,8].

One important tool used to overcome the inner differences between experimental measurements and lattice is the Hadron-Resonance Gas (HRG) model, which has proven to be successful in the description of particle yields [9], and shows a good agreement with lattice simulations [10] and experimental measurements for the fluctuations of conserved charges [11].

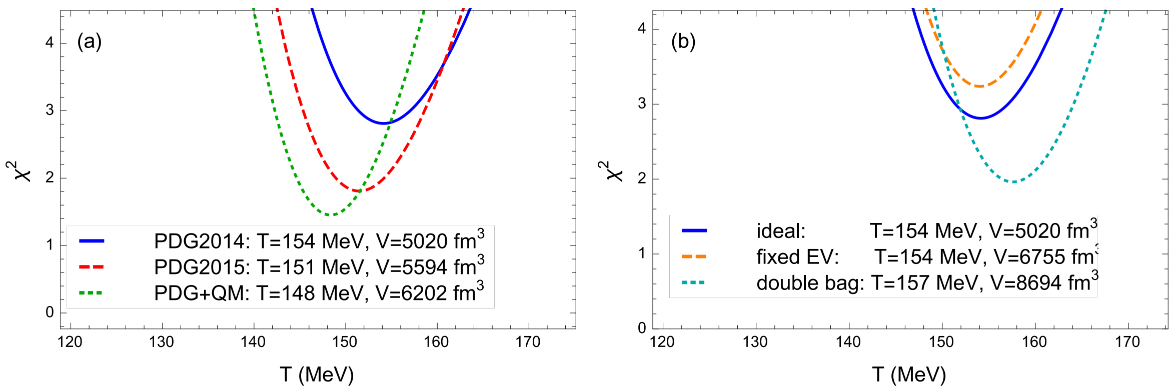

Figure 1: χ^2 profile with temperature from the fit to particle yields measured by the ALICE collaboration for PbPb collision at 2.76 TeV [14–16]. For every temperature the volume is minimized, but the baryon chemical potential is fixed to zero. On panel (a) is showed the effect of the inclusion of higher-mass states, while on panel (b) is showed the effect of EV effects.

2. **Quark Model**

From the discrepancy between lattice calculations and HRG predictions for a specific observable, it has been proposed that the actual measured hadronic spectrum is lacking in some states in the strange sector [12], and that Quark-Model (QM) predictions could fill the gap restoring the agreement between the two frameworks. However it is easy to check that the wild inclusion of all those states can ruin the agreement with other observables, due in particular to multi-strange baryons.

Indeed, this is connected with the uncertainty coming from the particle list used as an input in the HRG model, which relies essentially on the measured experimental states listed by the Particle Data Group [13].

In order to check the reliability of those states, I show in Fig. 1, panel (a), the χ^2 profile in temperature for the fit to particle yields from PbPb collisions at 2.76 TeV measured by the ALICE collaboration [14–16] (see [17] for more details), with χ^2 given by:

$$\chi^2 = \frac{1}{N_{\rm dof}} \sum_{h=1}^{N} \frac{(\langle N_h^{\rm exp} \rangle - \langle N_h \rangle)^2}{\sigma_h^2} . \tag{1}$$

It comes out that the updates from the PDG improve the description of the data (see also Table 1); extracting the informations on the branching ratios from the PDG 2015 and applying them to the QM states, the χ^2 is further decreased, leaving the freeze-out parameters almost unaffected.

By the way there are different options available for QM calculations with respect to the one employed here, which are essentially the most crude and most abundant.

A similar improvement can be achieved accounting for repulsive interactions (see Fig. 1 panel (b)), as will be explained in the following section.

Table 1: Freeze-out parameters, and corresponding χ^2 from the fit to particle yields measured by the ALICE collaboration for PbPb collision at 2.76 TeV [14–16] for different particle lists and EV parameterizations. In the last column is shown the χ^2 for observables calculated on the lattice for temperatures below 164 MeV; the parameters are the ones obtained from the fit to particle yields.

list	EV	χ^2_{yields}	T (MeV)	V (fm^3)	$\chi^2_{lattice}$
PDG2014	id	22.49/8 ≅ 2.81	154.19 ± 2.29	5047 ± 663	9.49
PDG2015	id	14.47/8 ≅ 1.8	151.53 ± 2.12	5620 ± 705	8.65
QM	id	11.62/8 ≅ 1.45	148.39 ± 1.18	6227 ± 722	15.905
PDG2014	fix	22.65/7 ≅ 3.23	154.11 ± 2.28	5934 ± 701	10.95
QM	fix	11.74/7 ≅ 1.67	148.33 ± 1.18	7131 ± 760	6.98
PDG2014	2b	11.77/6 ≅ 1.96	157.64 ± 2.46	5734 ± 620	14.07
QM	2b	13.47/6 ≅ 2.24	149.27 ± 1.8	7483 ± 704	1.705

3. **Repulsive Forces**

The inclusion of resonance formation mediates the attractive interactions among hadrons, neglecting the repulsive ones which however are present in the experimental scattering measurements. The last can be implemented within the HRG model with the so called Excluded Volume (EV) [18]; hadrons are considered as hard spheres, and are assumed to repel each other when their effective radii r_i overlap. In this picture hadrons posses an eigenvolume given by $v_i = \frac{16}{3}\pi r_i^3$, which must be subtracted to the total volume of the system. This implies a transcendental equation for the system pressure p with a shifted single particle chemical potential $\bar{\mu}_i = \mu_i - v_i p$. The others thermodynamical quantities are obtained from usual relations, e.g., the particle densities are:

$$n_i(T,\mu_B) \; = \; \frac{n_i^{\mathrm{id}}(T,\mu_i^*)}{1+\sum_j \; v_j \, n_j^{\mathrm{id}}(T,\mu_j^*)} \, , \tag{2}$$

where it is clear the double fold suppression, coming from the shifted chemical potential and the overall denominator.

It has been pointed out that the proper inclusion of repulsive forces is relevant for resonances like the σ and the κ [19, 20], and in general can influence other resonances.

Since data are not available for all the hadronic species present in our lists, I employ different parameterizations for the particle eigenvolumes: fixed for all species, directly proportional to the particle mass (as one could expect for radial excitations from QM calculations), and inversely proportional. The last case, even if may look counterintuitive, has been explored theoretically [21], and can derive from the assumption of diquarks as constituents building blocks together with quarks. It has been pointed out how this assumption can improve the description of particle yields [17], and of lattice simulations in the pure gauge sector [22].

It is worth to note that for a fixed radius the relative densities stay constant (see Eq.2), essentially leaving unaffected results based on particle yields. The situation is different when looking at higher order cumulants, as can be seen in Fig. 2.

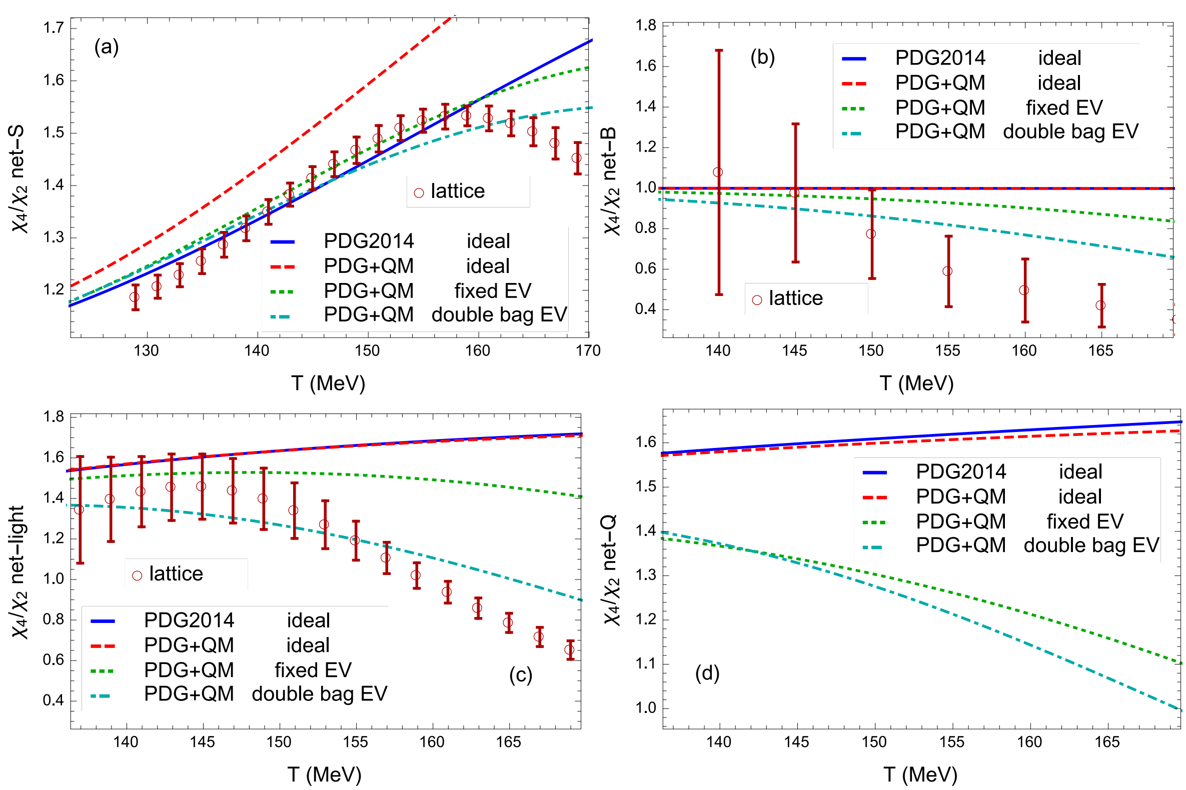

Figure 2: Comparison between lattice data [6, 24] and HRG calculations with different particle lists and particle eigenvolumes, for χ_4/χ_2 observables for different quantum numbers. Currently there are no lattice data available for net-electric charge.

4. **Comparison with Lattice**

In Table 1, I list the results from the fit to particle yields using the standard HRG (id), an EV with fixed radii (fix) and with radii proportional to the particle mass with proportionality constant dependent on the flavor (2b). The same EV parameters are applied for PDG2014, PDG2015 and QM lists. Here I also calculate the χ^2 for the different HRG options against the lattice data for pressure, interaction measure, χ_{11}^{us}, χ_{11}^{ud}, χ_2^s, $\mu_S/\mu_B|_{LO}$, $\chi_4/\chi_2|_{net-B}$, $\chi_4/\chi_2|_{net-S}$ and $\chi_4/\chi_2|_{net-light}$ for temperatures below 164 MeV [3, 23, 24], which should be a reasonable range of temperatures near the crossover. I show that with the inclusion of QM states and with a 2b EV with $r_p = 0.36$ fm and $r_\Lambda = 0.27$ fm (it is convenient to parametrize the r_i with the ground state hadrons in order to have an immediate comparison), I can systematically improve the description of both experimental and lattice data, with hints from both sectors for smaller strange hadrons with respect to the light ones with the same mass.

In Fig. 2, I show a comparison between lattice and HRG predictions for the χ_4/χ_2 for net-light, net-B and net-S quantum numbers; the improvement due to the EV could be understood in terms of the statistical suppression due to the finite sizes of resonances; in particular in the strange sector the EV suppression balances the effect of the inclusion of multi-strange baryons (leaving unaffected the results for the $\mu_S\mu_B|_{LO}$). There are no data for the net-electric charge, and here I show my prediction for this quantity.

It is worth to note at this point that the EV parameters employed are solely obtained from a fit to particle yields, which result in freeze-out parameters compatible with the id case.

5. **Conclusion**

In conclusion, I studied the balance between attractive and repulsive forces within the HRG framework. I find that the simultaneous inclusion of higher-mass states and EV interactions improves the description of a large set of observables both from experimental measurements and lattice simulations, hinting in particular to a flavor dependent size. This could depend on the QM calculations employed, and can be critical the inclusion of exotic resonances like the κ(800), which need still to be confirmed but which would have a large influence on observables related to strangeness.

A systematic study of all the different versions of the Quark Model against repulsive interactions is mandatory.

6. **Acknowledgments**

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