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Sign-Posting the Phase Diagram of Quantum Chromo Dynamics

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ABSTRACT *The good agreement between lattice predictions and data for the shape of the distribution of event-by-event fluctuations of the baryon number is discussed. Such comparisons can give fine probes of thermalization, and can be used to provide a direct determination of the cross-over temperature TCU of QCD. The logic of these comparisons and the systematic involved are discussed.*

The same methods can be used to further explore the phase diagram.

The study of heavy-ion collisions has provided a variety of complex and interesting puzzles. A coherent picture has emerged: that high-energy collision of heavy ions produces a fireball, and that this fireball approaches thermal equilibrium, with well-defined temperature (T) and chemical potentials (μ), sometime before hadrons freeze out of it. It also appears that a hydrodynamic description of the evolution of the fireball may be possible; and although the initial conditions and the equation of state cannot yet be pinned down, it seems that it may be possible to constrain the values of the transport coefficients until now the relation between any of these phenomena and predictions of quantum chromo dynamics (QCD) remained obscure. That has now changed.

The development is an offshoot of old ideas about event-to-event fluctuations It was known for some time that if one measures the net value of a conserved quantity in an event, and studies how it fluctuates from one event to another, then the histogram is approximately Gaussian A net conserved quantity is easier to understand in a heavy-ion collision than many of the classic observables.

If one measured such a quantity in the whole fireball, then that would exactly equal the amount in the initial state. However, because of the limited angular acceptance of a detector, one usually studies a small fraction of the whole fireball. If the fireball is thermal zed and one study only a small part of it, then it should be possible to describe this observed volume in terms of the grand canonical ensemble. One simple outcome of such reasoning is that measurements of net values of conserved quantities will fluctuate, and the shape of the fluctuations will be Gaussian if the observed volume is large enough and the system is not near a phase transition. In fact, it is possible to predict what the finite volume corrections to the shape should be, in terms of the grand canonical potential of QCD. Since methods have recently been developed to extract predictions for this quantity from QCD, a quantitative comparison of data with prediction now becomes possible.

The study of fluctuations is a very fine probe for thermalization. The material inside the fireball must be highly non-ideal for it to the realize However, as it expands and cools, it eventually reaches a stage where its constituents freeze out: they stop interacting and begin to free-stream towards the detector. So, the spectrum of particles received at the detector must behave as an ideal gas. This reasoning also explains the perfect Planck spectrum of the microwave background remnant of the hot stages of the early Universe (where again the photons cannot be considered free before the last scattering surface). However, a perfectly thermal source also contains fluctuations, and the study of the ensemble of such fluctuations is a finer test of thermalization. Cosmology, restricted as it is to a single Universe, cannot perform the test that the repeatable experiment of heavy-ion collisions can.

In fact, such a comparison of data and predictions of fluctuations is now available the good agreement between lattice predictions and experimental data are shown in The temperature and chemical potentials shown in the scales on top refer to those deduced from the relative yields of different hedonic species. Also shown in this is the expectation for fluctuations in an ideal hadrons gas; the data and the QCD predictions are in good agreement with this. Such an agreement is a fine test of thermalization, as we have argued above.

It may be recalled that particle yields in pp collisions, where thermal behavior cannot be expected, are sometimes fitted by a thermal model. If the model is incorrect, then one should not expect QCD predictions to agree with measurements of event-to-event fluctuations of conserved quantities in pp collisions. A test of this kind would be a very useful addition to the literature. Recently, it has been found that high multiplicity events in pp collisions at the LHC are qualitatively similar to heavy-ion collisions.

So a study of fluctuations binned in multiplicity would be of considerable interest. This agreement was used quantitatively to determine the QCD cross-over temperature, TCU (at vanishing chemical potential), directly from experimental data because the lattice QCD computations have an undetermined scale factor. This scale is fixed by equating one of the many lattice QCD predictions to experimental data: usually to some single hadrons property. The QCD cross-over temperature is then an output (which was used in demonstrating thermalization). However, the good agreement between data and prediction also allows us to overturn this method and use it to extract the scale (this is shown in the remaining panels of figure 1). The result is

TCU = 175+1

-7 Me V.

The errors are statistical only the agreement with previous indirect determinations of this scale of QCD thermodynamics is a vindication of our understanding of all aspects of non-perturbative QCD through lattice computations. Other ways of using this agreement were discussed earlier.

The result is sufficiently important that it will be re-examined in future. There are several systematic uncertainties which will have to be studied and their effects quantified.

Among these are systematic effects in the theoretical prediction: the computations are performed at finite lattice spacing and extrapolation to the continuum will have to be done, the quark masses have to be chosen to be physical while keeping the lattice volumes large. There have been attempts to quantify some of these uncertainties. On the experimental side, the main uncertainty comes from the fact that neutrons escape detection and therefore a better understanding of is spin fluctuations is needed.

One also needs to understand better the relation between the freeze-out of hadrons yields and that of chemical fluctuations. Some extensions of this method are clear, and here is an incomplete list. The good agreement of the predictions and data can also be turned around to deduce the freeze-out conditions for the fluctuations. Understanding these conditions through hydrodynamics would be an important step towards understanding the approach to thermal behavior.

The shape of the distribution of fluctuations has been examined till now using the four lowest cumulates of the distributions. It is well known that the means of distributions tend to Gaussian faster than the tails. Studying the tails of the distribution, perhaps through higher cumulates, can be a good way to study the non-equilibrium physics which precedes the realization. The study of other conserved quantities is another avenue to explore. Recall that thermal models contain a factor called the strangeness saturation constant, which quantifies the observation that the strange flavor lies below its thermal expectation value. The study of strangeness fluctuations would therefore give more information about the non-equilibrium physics of strangeness production in the fireball.

The method described here will be used extensively to probe the part of the phase diagram accessible to the RHIC as it performs the beam energy scan. Agreements between predictions and experiments will hone our understanding of the QCD which underpins the phenomenology of heavy-ion collisions. However, with this tool it is the disagreement of QCD thermodynamics and experiment which will be interesting.

That is because a disagreement will signal a departure from thermal equilibrium. Equilibrium in large parts of the phase diagram and disequilibrium in a small part is interesting, because it implies that Thermalization times are large in this part of the phase diagram, implying the presence of a critical point. The predicted critical point is the ultimate goal of this search.

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