Quantifying the Properties of QCD Matter with Relativistic Heavy-Ion Collisions

for discussion at the Joint Town Meeting on QCD, Temple University, September 13-15 2015

Steffen A. Bass, Ulrich Heinz, Scott Pratt, Björn Schenke, Ron Soltz and Paul Sorensen

September 13, 2014

1 Overview

After becoming operational in 2000, the first years of RHIC's operation and analysis made a convincing case that the hot and dense QCD matter created at RHIC was strongly interacting and that its evolution could be described in hydrodynamic terms. By the time of the 2007 Long-Range Plan the field's goals were shifting from qualitatively characterizing the matter created in heavy-ion collisions to quantitatively extracting its properties and stating them with meaningful uncertainties. In Recommendation IV of the 2007 Long Range Plan [1], the goals of the field were summarized:

> *The major discoveries in the first five years at RHIC must be followed by a broad,* **quantitative** *study of the fundamental properties of the quark-gluon plasma. This can be accomplished through a 10-fold increase in collision rate, detector upgrades, and advances in theory. The RHIC II luminosity upgrade, using beam cooling, enables measurements using uniquely sensitive probes of the plasma such as energetic jets. and rare bound states of heavy quarks. The detector upgrades make important new types of measurements possible while extending significantly the physics reach of experiments.* **Achieving a quantitative understanding of the quark-gluon plasma also requires new investments in modeling of heavy-ion collisions, in analytic approaches, and in large-scale computing.**[1]

Since experimental observations are confined to the measurement of the momenta of the outgoing tracks of the collisions, detailed and careful modeling combined with a rigorous comparison with data is of paramount importance to achieve the following goals:

- Improve the accuracy with which the viscosity, including its temperature dependence, is determined.
- Determine the bulk viscosity of QCD matter, including its temperature dependence, which could be large near T_c
- Determine the equation of state of hot and dense QCD matter, including its dependence on baryon density, and search for a possible critical point
- Determine the jet energy loss transport coefficients and heavy quark transport coefficients, including their temperature dependence.

[1] Bold added for emphasis

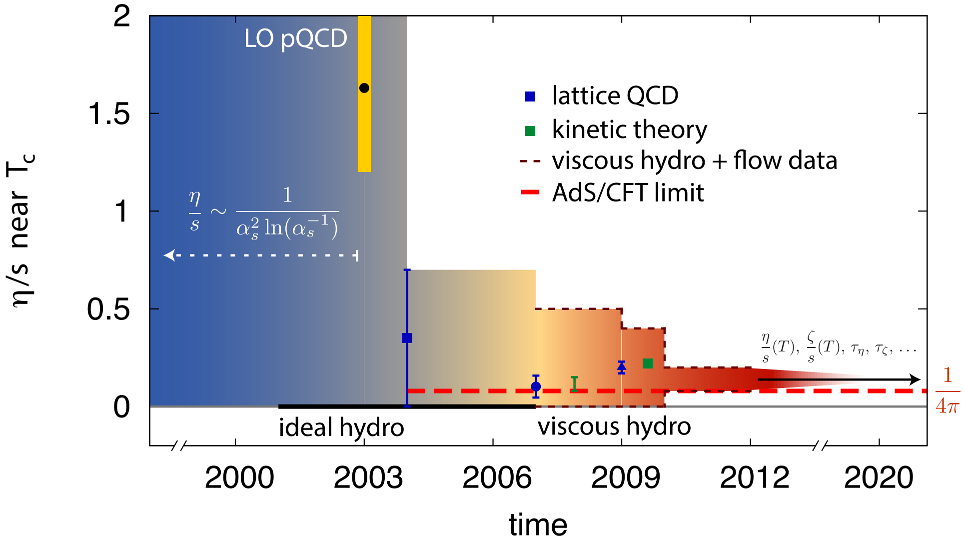

Figure 1: Evolution of the shear viscosity to entropy ratio [3].

- State the degree to which electromagnetic probes can help quantify properties of the collision

These goals are both ambitious and attainable, but success depends on investments in modeling, and in supporting more collaborative interactions between theory groups and experimental collaborations.

Since 2007 great strides have been made in transforming the field into a more quantitative science. First, the modeling of heavy ion collisions has dramatically improved. The evidence for a strongly interacting liquid has led to a consensus that much of the collisions history can be modeled with viscous relativistic hydrodynamics. Further, the final-state chemistry mostly agrees with hadronic chemical equilibrium – a few notable measured deviations from that equilibrium are understood in terms of hadronic final state interactions. Currently, great efforts are being made to understand the impact of fluctuating initial conditions and the role of saturation in seeding the hydrodynamic configuration. Figure 1 shows how the extracted shear viscosity to entropy ratio has converged with time. Additionally, new statistical tools [2] have enabled the simultaneous consideration of multiple model parameters and provide the means to rigorously state extracted properties with meaningful uncertainties. Even though the field has coalesced onto a standard theoretical framework for modeling these collisions, significant questions remain that need to be addressed in the next 5-10 years. Many of these questions cannot be well addressed by lattice calculations, and for those that are, it is important to determine whether the QCD matter created in the laboratory has the same properties of the equilibrated systems described in lattice calculations.

2 Advancing Modeling and Model/Data Comparison

During the last decade strategies have been developed expressly for comparing complex compute-intensive theoretical models to large heterogenous data sets. These strategies utilize a combination of state-of-the-art methodologies in the statistical sciences and high throughput computing technology that are just now becoming part of the scientific toolset in theoretical nuclear physics. They integrate Bayesian inference and model surrogate algorithms with the modeling environment to constrain the multi-parameter model space by comparison with the high-dimensional data from RHIC and LHC. These techniques enable comparison of a computational model to data with a feasible amount of

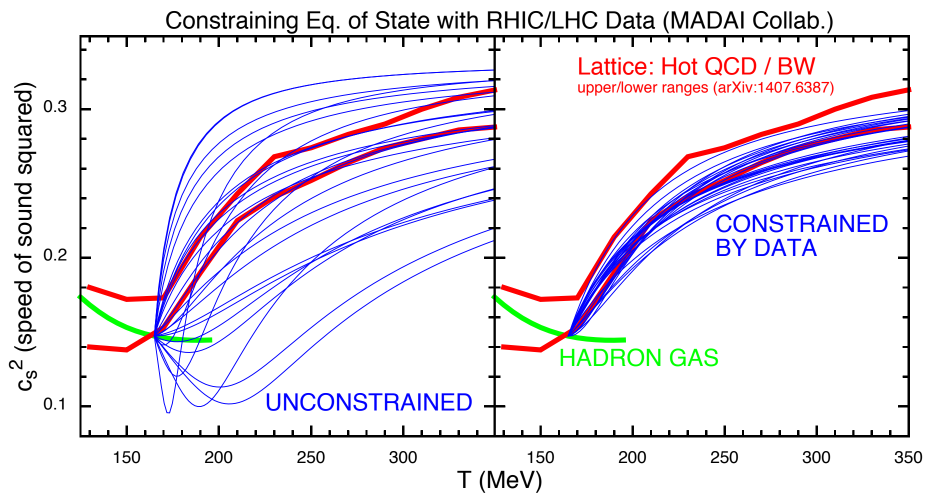

Figure 2: Samples of parameterized equations of state are shown in the left panel where the parameters are randomly chosen within fixed ranges, i.e. the prior distribution. After calculating likelihoods based on the comparison with experimental data from RHIC and the LHC, parameters were chosen weighted by the likelihood, the posterior distribution. A sampling of these equations of state are displayed in the right panel. Hadron gas curves are in green and the range of lattice calculations from [4] are in red. Assumed uncertainties were small, but at a level that should be attainable in the coming years.

resources. However, obtaining quantitative conclusions requires one to faithfully calculate what has been measured and to assign uncertainties for comparing experimental observables. This requires sustaining vigorous development of realistic computational models of heavy-ion collisions, and building close collaboration between the experimental and theoretical communities.

There is a growing consensus regarding the framework for modeling the bulk evolution of QCD matter produced in collisions at the highest RHIC energies or at the LHC, but several critical questions have yet to be settled, such as of how one should best model pre-equilibrium dynamics. In addition, modeling for lower energies requires significant theoretical investment due to the importance of non-zero baryon density, the dynamics of matter in the vicinity of the critical point, and due to the complex and poorly understood nature of the initial state. The modeling of rare and electromagnetic probes, and of jets, also requires significant theoretical progress. The milestones needed to be achieved to reliably conduct a quantitative extraction of QGP properties from a model to data comparison are:

- Achieve an understanding how to instantiate hydrodynamic runs for fluctuating initial conditions. Make a connection between sophisticated microscopic models of the pre-equilibrium evolution and hydrodynamic descriptions, and ultimately to the comparison of experimental data. Quantitatively state conclusions about the initial stage.
- Incorporate non-equilibrium chemistry and dynamics for the evolution of the system near T_c, including bulk viscosity.
- Develop and validate three-dimensional models to address lower beam energies where the non-zero baryon density and more complex initial conditions are required.
- Provide standard means to overlay calculations of jets, electromagnetic probes, and rare probes onto validated three-dimensional models of bulk evolution.
- Achieve a full three-dimensional dynamical treatment of fluctuations and identify and separate competing sources of fluctuations, such as those that might accompany a critical point

As an example of what may be achieved Fig. 2 shows how an initial distribution of parameterized equations of state are constrained by RHIC and LHC data in a 14-parameter model using the techniques of [2]. These calculations assume a 6% uncertainty for the model/data comparisons, which is somewhat over-optimistic for the current models, but should be attainable with improvements in models, better understandings of experimental details and more detailed studies of how missing physics might affect results. In principle, these methods can be extended to provide rigorous statements about all bulk properties, including those for finite-baryon density or for non-bulk phenomena such as jets, electromagnetic probes or rare probes. Statistical analyses like the one shown in Fig. 2 are resource intensive. They typically require one to execute models with sufficient statistics to compare with data at each of $\sim 10^3$ points in parameter space. Progress will require sustained investment and support of phenomenology, tools for collaboration between all parts of the community, and resources for large-scale computing.

References

[1] "The Frontiers of Nuclear Science, A Long Range Plan," R. Tribble et al., arXiv:0809.3137 [nucl-ex] (2008).

[2] J. Novak, K. Novak, S. Pratt, C. Coleman-Smith and R. Wolpert, Phys. Rev. C **89**, 034917 (2014).

[3] "Hydrodynamic Modeling of Heavy-Ion Collisions", C. Gale, S. Jeon and B. Schenke, Int. J. Mod. Phys. **A28**, 1340011 (2013).

[4] A. Bazavov *et al.* [HotQCD Collaboration], arXiv:1407.6387 [hep-lat].