

# Annual report

Jonah Bernhard

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## 1 Primary project

My primary project is called *QGP parameter extraction via a global analysis of event-by-event flow coefficient distributions*. I am conducting a systematic model-to-data comparison in order to quantify the fundamental properties of the quark-gluon plasma (QGP). The measurement of these properties is a primary goal of heavy-ion physics.

Heavy-ion collisions produce a hot, dense phase of strongly-interacting matter known as the quark-gluon plasma (QGP) which quickly ( $\sim 10^{-23}$  s) expands and freezes into discrete particles. The QGP cannot be observed directly—only final-state particles are detectable—so computer models are used to indirectly characterize the medium. A successful model must simulate the time-evolution of the collision and connect measured observables to the properties of the transient QGP state.

The computational model takes a set of input parameters, including physical properties of the QGP. Parameters are constrained by calibrating the model to data, i.e. tuning model parameters such that simulated observables optimally match experimental data.

Modern models use a “hybrid” approach with relativistic fluid dynamics for the early hot and dense phase followed by non-equilibrium transport for the later dilute gas phase. Hybrid models have provided approximate descriptions of a variety of observables, but are computationally expensive and therefore difficult to test systematically. Most studies to date rely on averaged quantities such as the average elliptic flow coefficient  $\langle v_2 \rangle$  for a given centrality bin—disregarding the effects of event-by-event fluctuations—and use ad hoc methods for optimizing model parameters. Often, each parameter is varied independently, while best-fit values are chosen via qualitative comparisons to single observables. This neglects correlations among parameters and leads to nebulous results lacking quantitative uncertainty.

I am developing a systematic model-to-data comparison method for extracting QGP properties. First, a set of salient model parameters is chosen for calibration—physical properties such as transport coefficients are of primary interest. An event-by-event model is then evaluated at many points in parameter space; this is made possible by recent advances in high-throughput computing. Finally, a statistical surrogate algorithm is used to interpolate the parameter space and determine the values which optimally reproduce experimental data. This provides rigorous constraints including quantitative uncertainty and sheds light on the relative importance of each parameter.

The methodology is applied to a modern hybrid model with MC-Glauber and MC-KLN initial conditions, viscous 2+1D hydrodynamics, and the hadron cascade UrQMD. By leveraging the power of the Open Science Grid, I have run event-by-event simulations over wide ranges of several crucial parameters, e.g. the shear viscosity  $\eta/s$  and hydrodynamic thermalization time. I am in the process

of calibrating the model to experimental event-by-event flow distributions measured by the ATLAS experiment; these distributions are sensitive to initial-state fluctuations and therefore constitute a more comprehensive probe of the QGP than event-averaged flow.

This massive-scale model-to-data comparison will yield new constraints on fundamental QGP properties and clarify the essential features of a physically accurate model.

The current goal of this project is to develop and validate the model-to-data comparison framework. This is a significant undertaking, requiring the creation of a new system for deploying computational models on the Open Science Grid and analyzing the results. This phase is nearing completion, with publishable results anticipated this summer. Further, the method is general and easily extensible to future studies. I plan to repeat the analysis with more advanced computational models.

## 2 Other projects

While most research effort is devoted to the above project, other ventures are in progress. We are collaborating with the Nagoya University group to develop a new 3+1D viscous hydrodynamics model and hypersurface sampler.

The 3+1D hydro model will be one of the few full-3D models in the field, enabling state of the art simulations and benefiting numerous projects in the Duke group. While the bulk of the software development is taking place at Nagoya, I am acting as a liaison and assisting in testing the model.

All hybrid models require a hypersurface sampler, which produces an ensemble of particles after hydro evolution is complete. Many samplers are in use today, but most are inefficient and lack documentation and proper testing. I am developing a new, fast sampler for use with the 3+1D hydro model. It will include rigorous validation and be flexible enough for any research group to use. The goal is not only to create a new piece of software, but to standardize this critical component of heavy-ion collision models across the field.

The hydrodynamics model and hypersurface sampler will eventually be used in my model-to-data comparison framework.