QGP parameter extraction via a global analysis of event-by-event flow coefficient distributions

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A primary goal of heavy-ion physics is the measurement of the fundamental properties of the quark-gluon plasma (QGP), notably its transport coefficients, such as the specific shear viscosity η/s. Since these properties are not directly measurable, one relies on a comparison of the data to computational models of the time-evolution of the collision to connect measured observables to the properties of the transient QGP state. The computational model parameters are tuned such that simulated observables optimally match experimental data.

Most studies to date are severely limited by computation time: they typically 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.

We propose 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, we have run event-by-event simulations over wide ranges of several crucial parameters, e.g. the shear viscosity and hydrodynamic thermalization time. We calibrate 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-comparison yields new constraints on fundamental QGP properties and clarifies the essential features of a physically accurate model. The method is general and easily extensible to future studies.