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Nuclear Physics A 967 (2017) 67–73

NUCLEAR PHYSICS A

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Determination of Quark-Gluon-Plasma Parameters from a Global Bayesian Analysis

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Abstract

The quality of data taken at RHIC and LHC as well as the success and sophistication of computational models for the description of ultra-relativistic heavy-ion collisions have advanced to a level that allows for the quantitative extraction of the transport properties of the Quark-Gluon-Plasma. However, the complexity of this task as well as the computational effort associated with it can only be overcome by developing novel methodologies: in this paper we outline such an analysis based on Bayesian Statistics and systematically compare an event-by-event heavy-ion collision model to data from the Large Hadron Collider. We simultaneously probe multiple model parameters including fundamental quark-gluon plasma properties such as the temperature-dependence of the specific shear viscosity η/s, calibrate the model to optimally reproduce experimental data, and extract quantitative constraints for all parameters simultaneously. The method is universal and easily extensible to other data and collision models.

Keywords: Quark-Gluon-Plasma, model-to-data comparison, Bayesian analysis

1. Introduction

Relativistic heavy-ion collisions produce a hot, dense phase of strongly-interacting matter commonly known as the quark-gluon plasma (QGP), which rapidly expands and freezes into hadrons [1, 2, 3, 4, 5, 6, 7]. Since the QGP is not directly observable – only final-state hadrons are detected – present research seeks to quantify the fundamental properties of the QGP, such as its transport coefficients and the nature of the initial state, through comparisons of experimental measurements to computational model calculations.

Computational models must take a set of input parameters including the physical properties of interest, simulate the full time-evolution of heavy-ion collisions, and produce outputs analogous to experimental measurements. The true values of the physical properties are then extracted by calibrating the input parameters so that the model output optimally reproduces the experimental data. This generic recipe is called "model-to-data comparison". Challenges faced by this type of analysis are the amount of computational effort required to scan the parameter space of the model and correlations among the input parameters which may affect multiple observables, so that they cannot be constrained independently.

This article introduces the use of a Bayesian model-to-data analysis for the extraction of QGP properties such as the temperature-dependence of its specific shear viscosity. It is designed to serve as an example of

http://dx.doi.org/10.1016/j.nuclphysa.2017.05.052
0375-9474/

many different possible applications. Due to space constraints, only a broad sketch of the analysis can be given – for a rigorous description we refer the reader to [8, 9].

2. Bayesian Model to Data Comparison

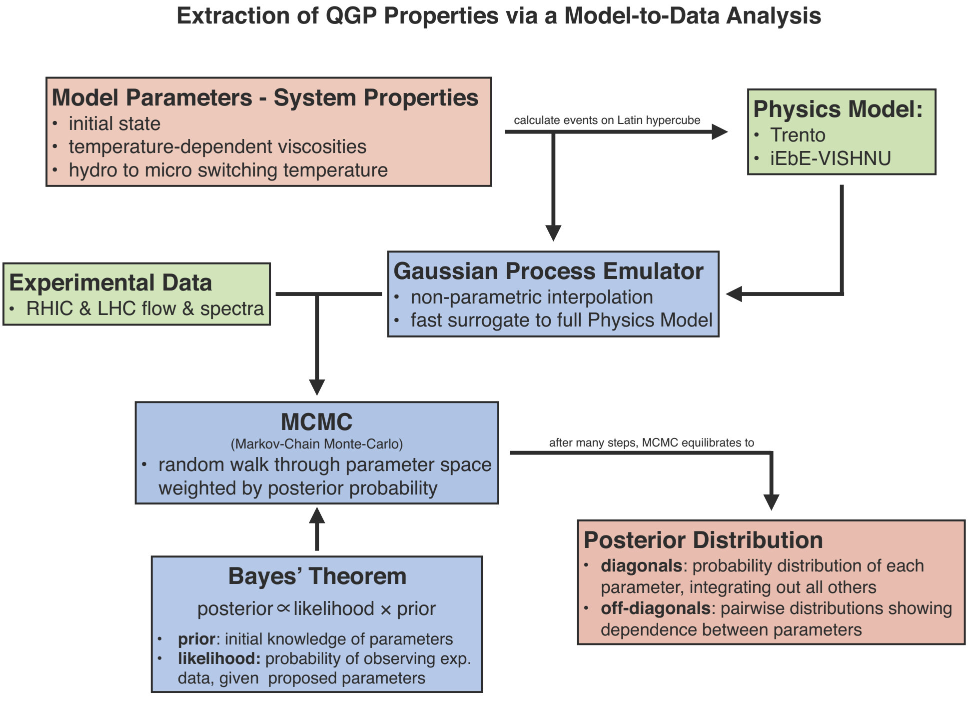

Fig. 1. Schematic overview of a Bayesian Model-to-Data analysis.

Figure 1 provides a schematic overview of the of the different components of a Baysian model-to-data comparison. Starting point is a computational physics model with a set of model parameters encoding the physics that one wishes to extract from the data. Here, we use a full event-by-event heavy-ion collision model, VISHNU, based on relativistic viscous fluid dynamics with a microscopic hadronic afterburner [10, 11, 12]. The model has 12 input parameters that encode the initial condition, temperature dependent shear- and bulk viscosities and a couple of additional quantities, such as the thermalization time of the QGP and the transition temperature from the hydrodynamic evolution to the microscopic evolution. We calibrate to multiplicity and flow data from the Large Hadron Collider (LHC) – for the sake of simplicity we focus here on data taken by ALICE at 2.76 and 5.02 TeV beam energy respectively [13, 14].

In principle the model can be evaluated on a fine grid of points in its 12-dimensional parameter space. One can then utilize algorithms such as Markov Chain Monte Carlo (MCMC) to rigorously explore the complex high-dimensional parameter space. However, performing the MCMC analysis requires a very large number of model evaluations in parameter space – often thousands or millions, depending on the problem at hand. Heavy-ion collision models may run for several hours, so a direct MCMC approach may require in excess of 10^{14} CPU hours and is thus intractable. The situation is exacerbated when studying event-by-event fluctuations as opposed to average quantities: while event-averaged models save computation time by