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A machine learning study on spinodal clumping in heavy ion collisions

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Possible observables of baryon number clustering due to the instabilities occurring at a first order QCD phase transition are discussed. The dynamical formation of baryon clusters at a QCD phase transition can be described by numerical fluid dynamics, augmented with a gradient term and an equation of state with a mechanically unstable region. It is shown that the dynamical description of this phase transition, in nuclear collisions, will lead to the formation of dense baryon clusters at the phase boundary. State-of-the-art machine learning methods find that the coordinate space clumping leaves characteristic imprints on the spatial net density distribution in almost every event. On the other hand the momentum distributions do not show any clear event-by-event features. It is shown that the 'third order' cumulant, the skewness, shows a peak at the beam energy where the system, created in the heavy ion collision, reaches the deconfinement phase transition.

INTRODUCTION

The QCD phase structure is still an unsolved mystery of high energy nuclear physics. Several heavy-ion experiments are currently performed or in preparation at RHIC, SPS-CERN, GSI, FAIR, NICA and JPARC-HI, with the goal to experimentally verify the structure of the QCD interaction. Effects from the non-equilibrium features and critical phenomena are one possible venue for this experimental verification. Recently it was suggested that a new approach based on modern machine-learning methods can be useful as neural networks are powerful tools for extracting information from complex datasets [1]. In this work we present results where this method was used to identify special phase space features of a 'first order' phase transition, features that appear through instabilities in domains away from phase equilibrium, which are expected to occur in nuclear collisions.

THE SETUP

A framework that is capable of correctly reproducing the underlying physics of the conjectured spinodal decomposition is relativistic fluid dynamics augmented with a gradient term to ensure the proper dispersion relation as expected for spinodal decomposition [2]. In addition, we implement an equation of state that is mechanically unstable in the phase-coexistence region at large densities. This model was introduced in previous works [2–5] and can be used to describe nuclear collisions at various incident beam energies. In our calculations the spinodal instabilities that occur during the evolution are seeded by the fluctuations present in the initial state, generated with the UrQMD model [6–8].

We will focus on two equations of state that differ only with respect to the instabilities associated with the phase transition. They are identical outside of the spinodal region of the phase diagram, but within the phase coexistence region they differ significantly [4]. The spinodal equation of state has a mechanically unstable region with a negative square of the isothermal speed of sound $c_s^2 < 0$ while the stable partner equation of state is obtained by means of a Maxwell construction. In the following events calculated with these equations of state will be referred to as either 'Spinodal' or 'Maxwell' events respectively.

RESULTS

First we test a convolutional neural networks (CNN) performance for detecting the baryon clumping in coordinate space as expected from the spinodal equation of state (for more details on the network structure and how it works we refer to [9]). About 20 000 Pb+Pb collision events are generated at a beam energy of $E_{\mathrm{lab}} = 3.5\,A$ GeV, for each equation of state. The time evolution of the system is stopped at the point in time where the density fluctuations are strongest, at $t = 3$ fm/c. From each event an 'image' is then generated, containing information on the net baryon density distribution in the transverse spatial $X - Y$ plane for $Z = 0$. This image is used as input for the CNN and the output of this network is a binary classification on whether an input is from a spinodal or from a Maxwell event.

Figure 1 shows the resulting accuracy and loss during the training stage for the training dataset and for an independent validation set. A rather good accuracy of 95% is reached. In addition figure 1 shows the distribution of probabilities that the network assigns to the images to belong to either class. These indicate that the network is usually very 'certain' about its decision.

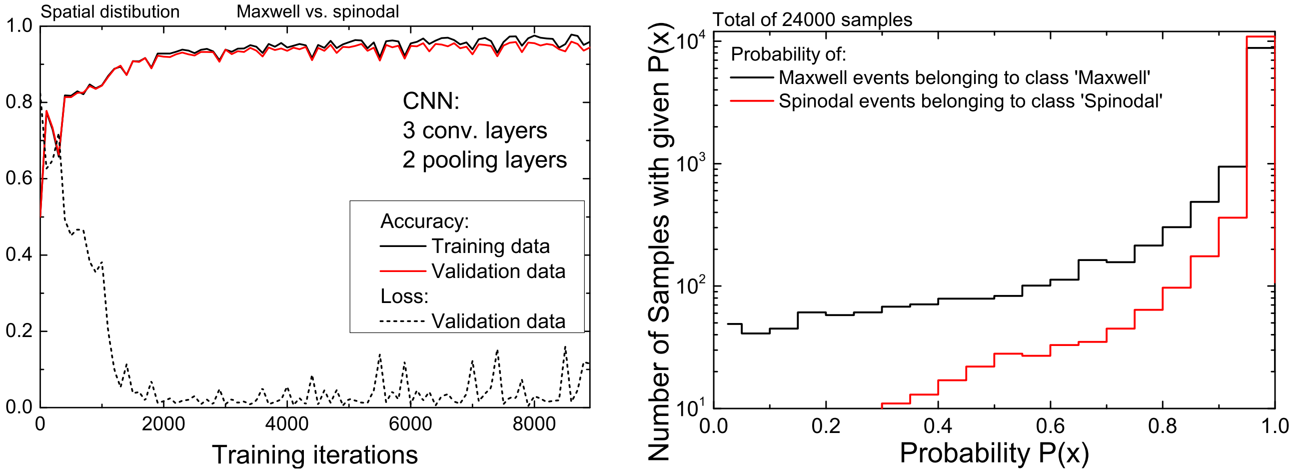

FIG. 1. Left: Training and validation accuracy as well as training loss for the CNN employed to distinguish spinodal from Maxwell events, using the coordinate space density distributions. Right: The number of training samples of each class that where assigned a given probability to belong to the corresponding class. The probabilities where assigned by the CNN through the supervised training. Generally a very high probability to be in the correct class is assigned by the network, with the probabilities of the spinodal events to be identified correctly being slightly higher.

To understand what the network considers to be relevant for the classifications, we show in figure 2 two examples of the normalized input density distributions for each class. We chose those examples which were assigned, by the network, the highest probabilities to be in either class, i.e. these images can be considered the most 'Spinodal' and most 'Maxwell' like events according to the CNN.

Next, the baryon distributions in momentum space were investigated. Here the connection of the final momentum space distributions to the baryon clumping during the early compression phase evolution is less obvious. To obtain the 'final' information on the momenta of all particles we run the fluid dynamical simulation until a later time. Baryons are then produced on an isoenergy density hyper-surface, that is below the coexistence energy density at $e \approx 600$ MeV/fm^3, by sampling the Cooper-Frye equation [10]. We compare results obtained with a varying number of test particles in the Cooper-Frye procedure. In this way, we take into account different scenarios of hadron production, i.e. global conservation as well as exact local conservation.

Two different network types are trained on the final momentum space distributions, a CNN as well as a Point Cloud Network (PCN). The PCN is able to process particle vector information as input. Again the details of these networks can be found in [9]. Figure 3 shows the result of the training. Only a rather low accuracy of uo to 54 % can be achieved for the momentum space from the PCN. This indicates that in momentum space the two classes of events show a strong overlap and can not be distinguished clearly on an event-by-event basis.

Using 'conventional' statistical methods to distinguish spinodal events from Maxwell events we find an interesting behaviour of the third order net-baryon number cumulant, the skewness, when the system undergoes the spinodal separation. These cumulants are defined by $K_1 = M = \langle N \rangle$, $K_2 = \sigma^2 = \left\langle (\delta N)^2 \right\rangle$, $K_3 = S\sigma^3 = \left\langle (\delta N)^3 \right\rangle$, where $\delta N = N - \langle N \rangle$ and N is the number of particles in a given experimental acceptance window. The brackets denote an event average. The beam energy dependence of these observables has been published recently by the STAR collaboration [12].

The energy dependence of the skewness is presented in Fig. 3 where a clear enhancement is seen at the beam energy with the strongest clustering ($E_{\mathrm{lab}} = 3.5$ A GeV). However, we also show the recent preliminary results of the HADES collaboration as a band at a lower beam energy. This shows that within the current systematic uncertainties it will be difficult to make any definite statements on the existence of a phase transition [1].

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[1] Note that one should keep in mind that the HADES results where taken in a slightly smaller acceptance and are for protons and not baryons. The comparison was done to point out the large systematic uncertainties in the current data.

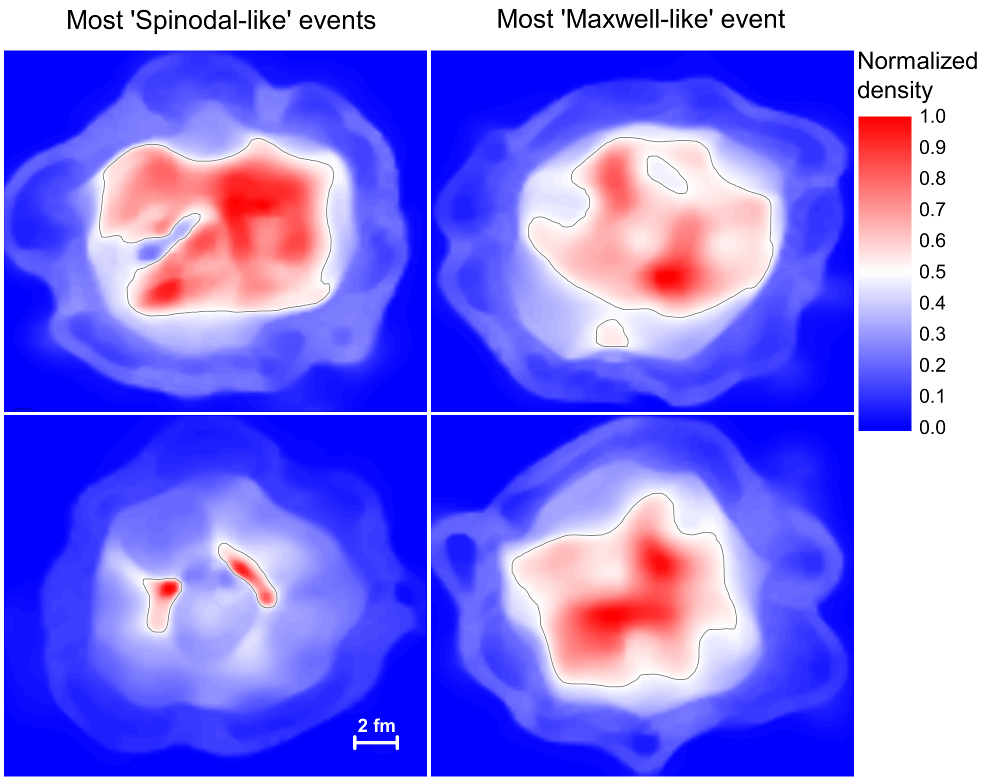

FIG. 2. Normalized density distributions in the transverse plane (for Z=0 fm) for several nuclear collisions. Shown are for each class the two events which where assigned, by the network, the highest probability to be in either class, spinodal or maxwell. One can clearly see systematic differences. While the Maxwell events are more smooth, the spinodal events show clear signs of domain formation. This indicates, that the clustering is indeed the relevant feature that is identified by the network.

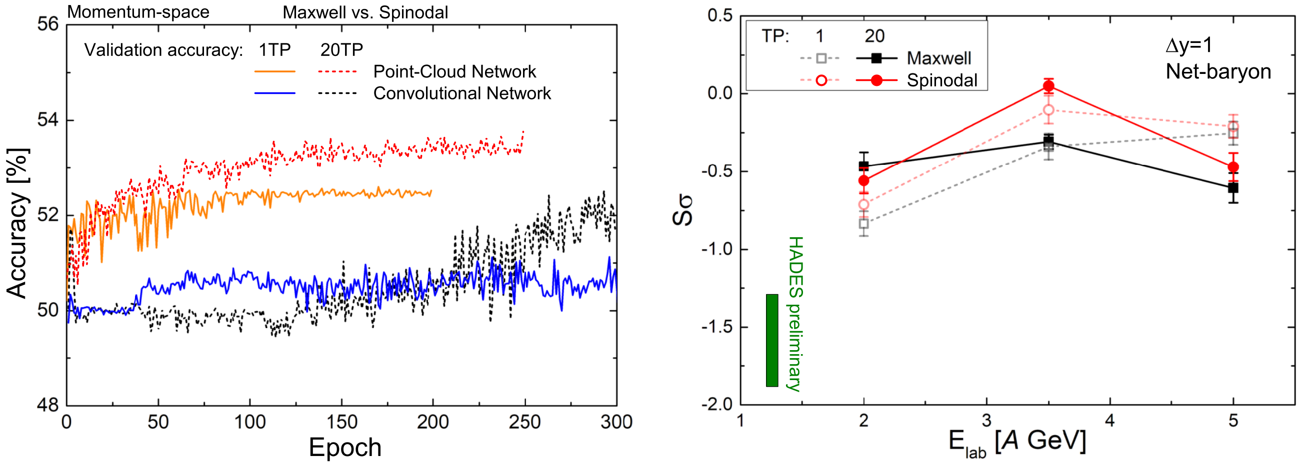

FIG. 3. Left: Validation accuracy for the CNN and the PCN, comparing the spinodal equation of state and the Maxwell construction for `TP=1` and `TP=20` in momentum space. The PCN shows a better performance than the CNN, but both network structures display only a very low validation accuracy just above 50%. Right: The normalized skewness of the net baryon number distribution in the rapidity window of $-0.5 < y < 0.5$ for several incident beam energies (in the lab frame). Results for `TP=1` and `TP=20` are compared. A peak is found for the beam energy that produces the largest effect of the spinodal decomposition. Preliminary results of the HADES collaboration are shown as green band. Within such uncertainty no conclusions can be drawn [11].

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