Chapter 59
Update on BEST Collaboration and Status of Lattice QCD

Claudia Ratti

Abstract The Beam Energy Scan Topical (BEST) Collaboration was formed to support the Relativistic Heavy Ion Collider (RHIC) experimental program in search for the QCD critical point. I will report on the status of the BEST collaboration, mainly focusing on the lattice QCD effort but also touching on the other main topics.

59.1 Introduction and Structure of the Collaboration

There are many open questions on the QCD phase diagram that can be answered by studying finite density QCD. The most pressing one is whether the deconfinement phase transition, an analytical crossover at chemical potential $\mu_B = 0$ [1], can turn into first order as the chemical potential is increased. Other relevant questions are the location of the transition line and the nature of the QCD phases at large densities. The only way to produce the high density phase of matter in the laboratory is to bring more net-baryon number in the mid-rapidity region, by systematically decreasing the collision energy so that some of the primordial baryons are left in the collision area. The RHIC facility at BNL is devoted to this purpose: the second Beam Energy Scan (BESII) is scheduled for 2019–2021. The foreseen runs will take place both in the collider and fixed target modes, so that higher values of the baryonic chemical potential can be reached. After RHIC, other facilities will study dense QCD matter: NICA, CBM and JPARC will pursue the study of critical point, onset of deconfinement and dense hadronic matter at least till 2025. For reviews on these topics see [2–4].

Fundamental theory and phenomenology need to provide adequate support to such a rich experimental program. The main purpose and goal of the project pursued by the Beam Energy Scan Topical (BEST) collaboration is to develop a dynamical framework which allows for a quantitative description of the heavy ion reaction for collision energies relevant to the RHIC BES. This framework will then enable a

C. Ratti (✉)
Department of Physics, University of Houston, Houston, TX 77204, USA
e-mail: cratti@uh.edu

D. Elia et al. (eds.), *The XVIII International Conference on Strangeness in Quark Matter (SQM 2019)*, Springer Proceedings in Physics 250,
https://doi.org/10.1007/978-3-030-53448-6_59

quantitative assessment of the data from the BES in order to either claim discovery or rule out the presence of a critical point and the onset of chiral restoration in the region of the QCD phase diagram accessible by the RHIC beam energy scan. In this contribution I will review the current status of the BEST collaboration, mainly focusing on the lattice QCD effort but also touching on other relevant topics.

To achieve the proposed goal, several elements need to be developed and eventually merged into the final framework. Following essentially the time evolution of the heavy ion collision, from initial conditions to hydrodynamic and transport evolution to the final analysis of the data, these are:

– **Initial conditions**: Calculate and model the initial distribution of all conserved charges as well as of axial charges.
– **Hydrodynamic evolution**: Development of (3+1)-D viscous relativistic (anomalous-magneto) hydrodynamics with transport coefficients for all charges which includes hydro fluctuations and coupling to a fluctuating critical field.
– **Equation of state and transport coefficients**: Carry out lattice QCD calculations of the EoS at large densities, needed for the hydrodynamic evolution, and determine some of the needed transport coefficients. Extend the EoS to regions beyond the reach of lattice calculations by careful modeling and matching to lattice results.
– **Transport evolution**: Development of a transport model which matches onto the hydrodynamic phase and is able to propagate fluctuations and anomalous currents.
– **Data analysis**: Develop and apply a data analysis framework which will enable a comparison of all observables, to constrain the model parameters.

The left panel of Fig. 59.1 shows a schematics of the above steps and how they are linked together. The right panel shows the twelve Universities and two national laboratories that belong to BEST.

Fig. 59.1 Left: The various components of the BEST program and how they are linked together. Right: BEST collaboration institutes

59.2 Lattice QCD and Equation of State with 3D-Ising Critical Point

The lattice effort in the BEST collaboration is conducted completely independently by the group at Brookhaven National Laboratory and the University of Houston group, using two different lattice discretizations and two different methodologies. The goals until now were to obtain the QCD transition temperature at finite μ_B, extract the equation of state up to power six in μ_B/T, to use as an input in hydro simulations and as a baseline in the EoS with critical point, and calculate fluctuations at finite μ_B.

The Wuppertal Budapest Houston [5] and the HotQCD [6] collaboration have published results for the QCD transition temperature at finite μ_B. The most recent value for the chiral transition temperature from the HotQCD is $T_c = 156.5 \pm 1.5$ MeV, obtained from chiral observables. Both collaborations found that the curvature of the phase diagram at $\mu_B = 0$ is extremely small (see Fig. 59.2 left).

After the publication of the QCD Equation of State at $\mu_B = 0$ [7–11], both collaborations proceeded to extend them to finite density. This is difficult due to the sign problem. One of the methods to circumvent the sign problem is to expand the thermodynamic observables as a Taylor series in powers of μ_B/T. The Taylor coefficients can be calculated in two ways, either by direct simulations (method chosen by the HotQCD collaboration), or simulations at imaginary chemical potentials (choice of the WBH collaboration). Besides, a finite μ_B chemical potential implies a choice for the strangeness and electric charge chemical potentials, μ_S and μ_Q respectively. The two possibilities that were considered are $\mu_S = \mu_Q = 0$ or $\mu_S(T, \mu_B)$ and $\mu_Q(T, \mu_B)$ such that the average strangeness density $\langle \rho_S \rangle = 0$ and the average electric charge density $\langle \rho_Q \rangle = 0.4 \langle \rho_B \rangle$. Both collaborations published results for the Taylor coefficients up to sixth order, in the case of $\mu_S = \mu_Q = 0$ [12, 13] and in the case of strangeness neutrality [13–15]. All results for the EoS are consistent between the two collaborations. More recently, a lattice-based Taylor expansion for the equation of state containing all conserved charges has been developed within the BEST collaboration [16, 17].

Fluctuations of conserved charges can be used to study criticality, as they are expected to diverge with powers of the correlation length near the critical point. Recent results by the HotQCD collaboration are showing the baryon number variance and the disconnected chiral susceptibility, extrapolated to finite μ_B along the crossover line. Both are expected to diverge at the critical point, but they do not show signs of criticality up to μ_B=250 MeV [18]. Both collaborations have expanded the higher order fluctuations as functions of μ_B/T, finding a behavior that is compatible with the experimental results [12, 19] (see Fig. 59.2 right). Both collaborations also have results for correlators between conserved charges [20, 21].

The lattice QCD Equation of state developed by the lattice effort of the BEST collaboration has been modified by introducing a critical point in the 3D Ising model universality class [22], in order to test its effects on thermodynamics and eventually dynamical observables. The hydrodynamics working group within BEST has already

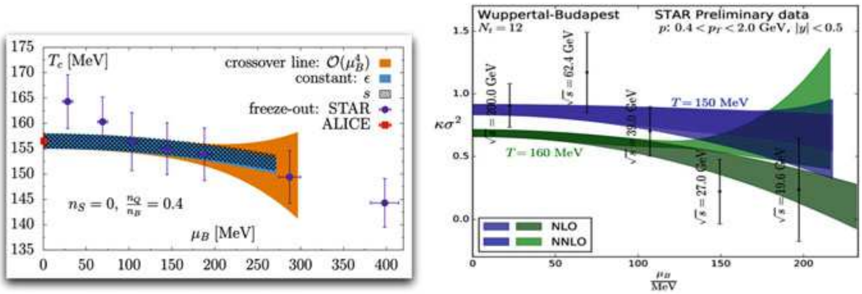

Fig. 59.2 Left: QCD transition line from [6]. Right: extrapolation of higher order fluctuations to finite μ_B [12]

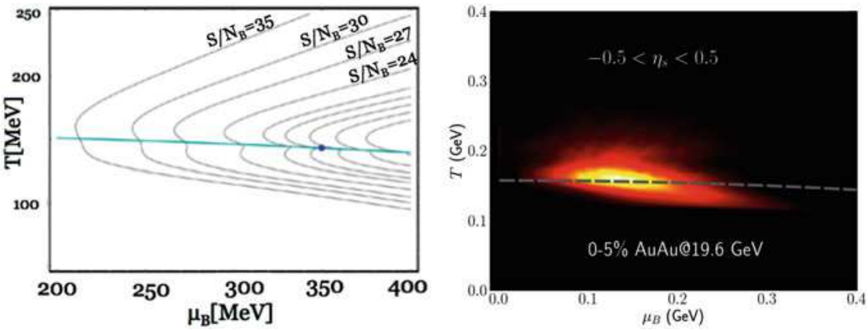

Fig. 59.3 Left: effect of the critical point on the isentropic trajectories in the QCD phase diagram [22]. Right: fireball trajectory of a central gold-gold collision at 19.6 GeV [25]

started testing it, and the predictions will be compared to the experimental data as they become available. The community also benefits from this achievement, since the code to generate the EoS is open source [23]. It was assumed that the lattice QCD Taylor expansion coefficients are the sum of a regular and a singular contributions. The latter are obtained by mapping the Ising model Equation of State onto the QCD one. The left panel of Fig. 59.3 shows the effect of the critical point on the isentropic trajectories in the QCD phase diagram.

59.3 Other Working Groups

Initial conditions for all three conserved charges have been developed, which take into account the fact that the nuclei at the lowest collision energies are not so Lorentz contracted and so there can be multiple scatterings between them [24–27]. The hydrodynamics simulations have been extended to include the propagation of net-baryon current including dissipative effects [28]. This has allowed the authors of [25] to extract the fireball trajectory of a central gold-gold collision at 19.6 GeV, shown in the right panel of Fig. 59.3.

One of the goals of BEST is to develop a quantitative understanding of fluctuations near the CP, which includes a modification of hydro to couple with a slow mode. This formalism has been developed [29–32]. In [29] it was shown that the dynamics of fluctuations (more precisely, the Wigner transform of the two-point correlation function of the fluctuations) and the influence of the fluctuations on the bulk hydrodynamic evolution can be studied together, self-consistently, by solving deterministic equations. This formalism is being implemented numerically within BEST [33, 34].

The chiral magnetic effect has been the goal of an active research program within the collaboration [35–38]. One of the goals is to model initial conditions not only for the conserved charges, but also for axial charges. In a series of papers [39–41] it has been demonstrated that glasma provides the appropriate methodology for addressing this question. Another goal is to develop anomalous magneto hydrodynamics [42–44]. A first step in this direction is the development of a code [45], which calculates electromagnetic fields from the spectators and participant nucleons in relativistic heavy-ion collisions. Finally, we want to quantify the experimental signal of the chiral magnetic effect. One first example is the prediction for CME-induced charge asymmetry of azimuthal correlations in 200 GeV Au+Au collisions, which happens to be in good agreement with the STAR H-correlation measurements [45].

I will finally touch on the topic of particlization and hadron dynamics. It was found out that the standard Cooper-Frye procedure is not suitable to study fluctuations because the Poisson sampling adds unphysical fluctuations and washes away correlations [46, 47]. A new micro-canonical sampling method has been proposed [48], which conserves all the charges as well as energy and momentum. This method has been tested in a toy model and it was shown that the obtained fluctuations are in agreement with the ones which were computed analytically, contrary to the Cooper-Frye ones.

For other important developments within the collaboration, which are not at the core of the BEST project but have important implications for the success of the BES program as a whole, see [49–58].

Acknowledgments This material is based upon work supported by the National Science Foundation under grant no. PHY-1654219 and by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, within the framework of the Beam Energy Scan Topical (BEST) Collaboration. The author acknowledges useful discussions with her colleagues and collaborators from BEST.

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