Transfer Request from Rutgers University to University of Illinois Urbana Champaign

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1 Goals

The primary goal of this project is to develop a new theoretical framework to study dynamical aspects of the phase transition in Quantum Chromodynamics (QCD) at finite baryon densities focusing on the conserved charges of baryon number and strangeness. To achieve this there are 3 major milestones that my group will accomplish (with a number of smaller milestones for each):

- Incorporate baryon number and strangeness conservation into relativistic hydrodynamics.
- Develop a new open-source software package (Initialized Conserved Charges In Nuclear Geometries- ICCING) that produces initial conditions for relativistic heavy ion collisions that initialize baryon number, strangeness, and electric charge.
- Investigate equilibrium properties at finite baryon densities (this includes the development of an equation of state with 3 conserved charges and new observables sensitive to the QCD phase transition).

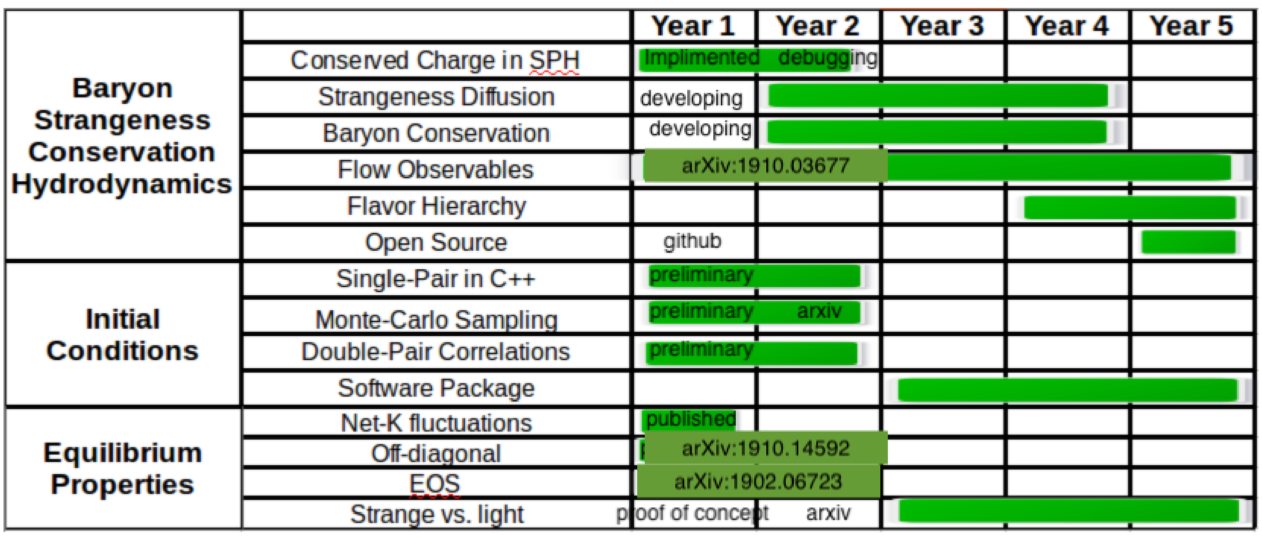

Figure 1: Timeline of project, current state at the beginning of Year 2.

An updated summary of the three major milestones and their objectives are listed in Fig. 1, which corresponds to roughly 4 years remaining on the project following my move from Rutgers University to University of Illinois at Urbana-Champaign. Since my yearly review in May 2019, my group has released preprints of the following papers to the arxiv [1–5] and the following proceedings as well [6,7]. The preprint numbers of recently released papers are shown in Fig. 1.

2 Remaining projects

Significant work still remains to be completed on the project and below I detail the major milestones that will be accomplished in the next four years.

2.1 BSQ Initial Conditions

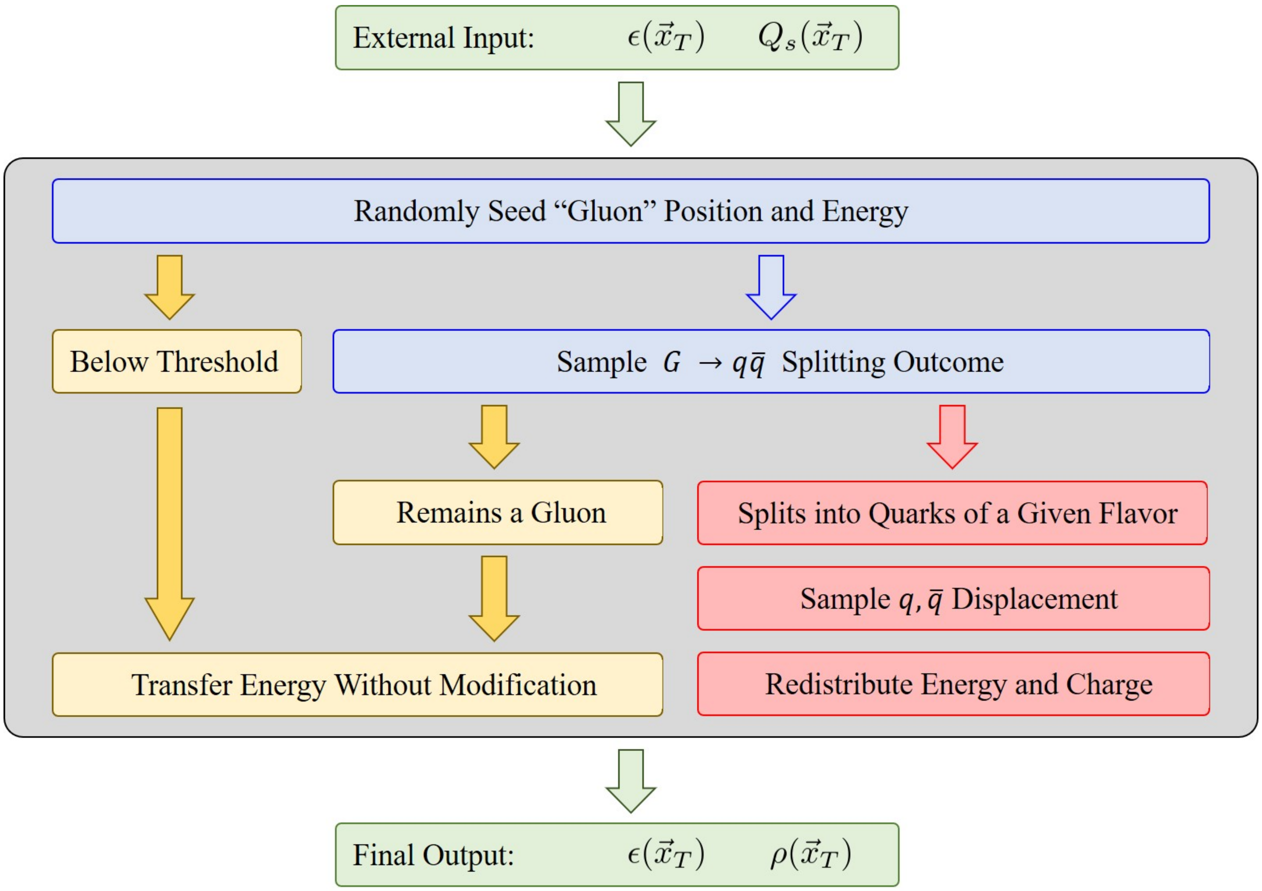

Figure 2: Flow chart of the subroutines within ICCING.

For a dynamical description of conserved charges, one must first have initial conditions that can initialize the baryon number (B), strangeness (S), and electric charge (Q) density distributions as well. Thus, we have created the new code called Initializing Conserved Charges in Nuclear Geometry (ICCING) and our first two papers should be released on the arxiv in the next couple of weeks. A flow chart of the code is shown in Fig. 2.

One of our most significant findings is that strange quarks are produced from the core of initial conditions and are sensitive to hot spot geometries. This leads to much more eccentric initial density distributions for strangeness, as shown in Fig. 3. However, a number of questions still remain in terms of the best method to quantify the initial state in order to correlate it to the final flow harmonics of strange hadrons (especially considering some hadrons also are baryons). Additionally, the current code is written in Mathematica and my Ph.D. student, Patrick Carzon, will spend the next year or two converting it into a user friendly version in C++ that can then be open-sourced.

Over the new four years my group will accomplish the following milestones:

- Convert the code over to C++ and make it open-source.

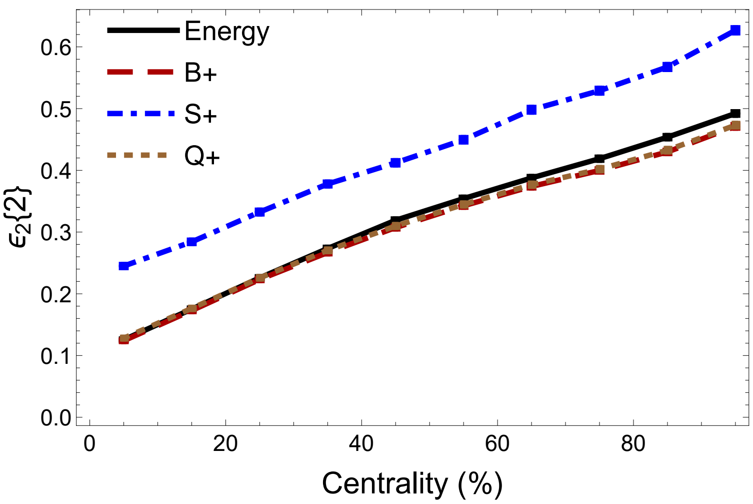

Figure 3: Positively charged BSQ densities eccentricities for LHC 5.02TeV PbPb collisions.

- Study the correct estimators that connect the initial state to final flow harmonics for BSQ conserved charges.
- Study the effect of charm quarks in the quark-gluon plasma (especially in small systems).
- Explore the effect of initializing conserved charges on the chiral magnetic effect.
- Incorporate double-pair correlations.
- Work towards initial conditions for the baryon dense regime.

2.2 BSQ in v-USPhydro

The next step of this project is to incorporate BSQ relativistic viscous hydrodynamics into v-USPhydro. As a first step towards this goal, my Ph.D. student, Travis Dore, has written a Bjorken flow model with all viscous terms at finite baryon density. This has allowed him to write the interpolation code needed for the 2D Equation of State (T and μ_B) that deals with the inversion problem (hydrodynamics runs with entropy and baryon density but the equation of state is written in terms of a grid in T and μ_B). His next steps are to expand this interpolation function to include the 3D phase diagram (T and μ_B, μ_S) and then finally the 3D phase diagram (T and μ_B, μ_S, μ_Q). Once the interpolation function is complete, it will then be integrated into the full 2+1 event-by-event hydrodynamic code.

In the meantime, we have used his current set up to study far-from-equilibrium dynamics. To do this we varied the initial conditions for the shear stress tensor and bulk pressure (essentially a measure of how far the initial conditions are from equilibrium) at a fixed baryon density and energy density. We find that the initial conditions dramatically change the path through the QCD phase diagram, as shown in Fig. 4.

Future milestones for the next four years consist of:

- Write up our results on far-from-equilibrium dynamics at the Beam Energy Scan.

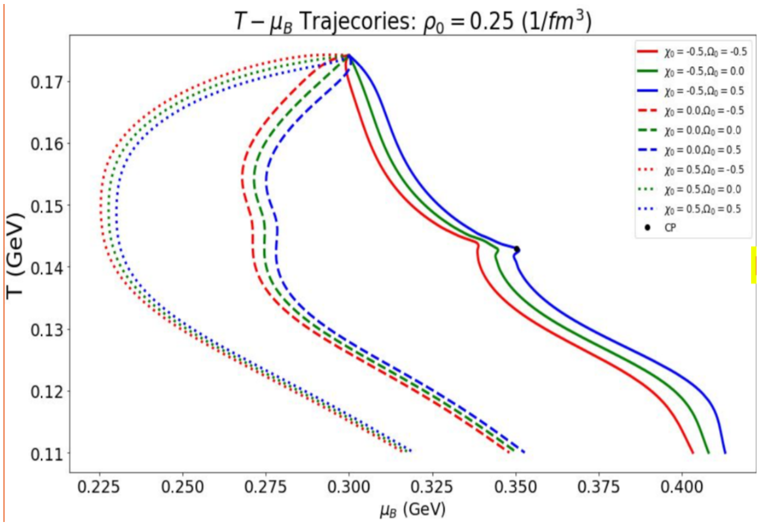

Figure 4: Shown is the passage through the T and μ_B QCD phase diagram using viscous hydrodynamic simulations (Bjorken flow) in the baryon dense regime and varying how far-from-equilibrium the initial conditions are.

- 4D interpolation function (and then couple to 2+1D hydrodynamics).
- BSQ diffusion transport coefficients incorporated into the 2+1D hydrodynamic code.
- Full simulations of ICCING initial conditions coupled to BSQ hydrodynamics.

2.3 Freeze-out

Since my progress report, we released our paper on BSQ correlations from Lattice QCD [5] and analyzed the best experimental measurements to be made in order to make direct comparisons to Lattice QCD. Additionally, we found that the flavor hierarchy still remains when one considers the BSQ correlations as well, as shown in Fig. 5.

A number of further goals remain, which include:

- Thermal fits comparison with two separate freeze-out temperatures with the most up-to-date PDG16+ list.
- Explore methods to extend the BSQ phase diagram to even larger baryon densities.

3 Personnel and Facilities

I was able to transfer my entire research group with me from Rutgers University to the University of Illinois and, thus, the amount of research time lost was minimal. I brought my postdoctoral fellow, Dr. Matthew Sievert (funded by start-up), and my two graduate students: Travis Dore and Patrick Carzon. Mr. Dore will be funded from the grant starting in Spring 2020. Additionally, I will be hiring a new postdoctoral fellow for the Fall 2020 funded by this project.

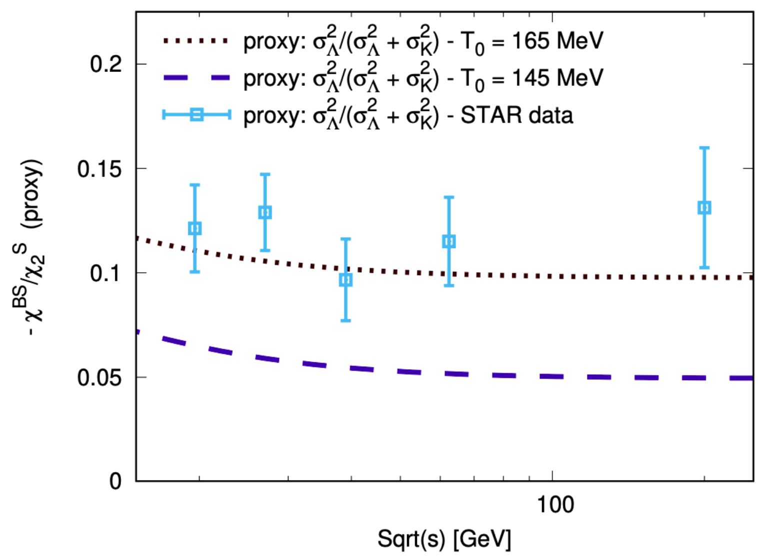

Figure 5: Proxies for the BS cross-correlators, $-\chi^{BS}/\chi_2^S$, compared to a hadron resonance gas that finds a preference for a higher freeze-out temperature for strangeness.

From my startup, I was able to purchase 18-TB of storage space (3 – 6-TB disks) and have access to five Xeon E5-2690 v3 compute nodes, providing a little over 1 million core hours/year. Thus, we have sufficient computational resources to complete this project.

4 Milestones 2019-2020

In my year 1 progress report, I said we plan on releasing the following papers in year 2. Below I note which papers we have already released and also which ones we expect to submit soon:

- Off-diagonal susceptibilities (preprint [5]).
- Baseline calculations of $v_2\{4\}/v_2\{2\}$ (preprint [4]).
- ICCING the initial gluon splitting into quark anti-quark paper sampling (to appear soon).
- Hydrodynamic evolution time and "cavitation" across the phase diagram (varying η/s and ζ/s) (to appear soon).
- Estimate for the transport coefficient $\eta T/w(T,\mu_B,\mu_S,\mu_Q)$ (late spring).

Below are goals (mentioned in the Year 1 progress report) that we are still working on for year 2 with remarks for the ones that are already completed:

- Derive the BSQ equation of motion within SPH, which will be aided by the visit of Prof. Gabriel Denicol in June 2019 and then begin coding them into v-USPhydro.

- Finish coupling the interpolation of the equation of state (first the one with finite μ_B and a critical point and then next the full BSQ equation of state) with the full 2+1 v-USPhydro code. Once this is completed we will be able to begin testing v-USPhydro with conserved charges (at this point the ideal scenario is already implemented, without diffusion effects) and possibly make predictions even in the absence of diffusion.
- [DONE] Implement a sampling of the energy distribution of gluons, such that different gluons can carry different amounts of energy in the initial condition.
- [DONE] Use this non-uniform distribution of gluon energies to implement a mass threshold for a given gluon to produce a particular flavor of quark, further coupling quark flavor to event geometry.
- [DONE] Implement a finite Gaussian width for charge distributions of the produced quarks, rather than using pointlike charges.
- [DONE] Refine the binning procedure to run operationally with the much smaller grids needed for accurate hydrodynamics, while counting the quanta on a coarser grid necessary to meet energy thresholds.

With our longer term goals still to remain for Year 3 and beyond:

- Calculate analytically the missing $g \to gg$ splitting channel, which is the same order in perturbation theory as the quark splitting channel $g \to q\bar{q}$, which we have included. This procedure will not generate conserved charges in the initial state, but it will make a comparable contribution to redistributing the energy. We will need to calculate this process analytically in the CGC formalism and incorporate it into our numerical sampling procedures. $\mathcal{O}$(1.5 - 2 years).
- Generalize the underlying analytical framework to include some form of pre-hydrodynamical evolution to a finite τ hypersurface. $\mathcal{O}$ (3+ years).
- Full BSQ initial conditions coupled to full BSQ hydrodynamics.
- Extend the initial conditions to include baryon stopping.

References

[1] J. Noronha-Hostler et al., (2019), 1905.13323.

[2] R. Katz et al., (2019), 1906.10768.

[3] R. Katz et al., (2019), 1907.03308.

[4] S. Rao, M. Sievert and J. Noronha-Hostler, (2019), 1910.03677.

[5] R. Bellwied et al., (2019), 1910.14592.

[6] J. Noronha-Hostler, 2019, 1911.01328.

[7] R. Katz et al., 2019, 1911.01396.