

On the theoretical side, we have a team focusing on the QCD phase structure and the spin polarization. We have made essential steps in studying both the spin and phase structure of QCD matter. In particular, we are the first group applying the newly developed non-equilibrium effective field theory to study the hydrodynamic fluctuations in the context of heavy-ion collisions experiments. In Ref. [2], we introduce a freeze-out procedure to convert the critical fluctuations in a droplet of quark-gluon plasma (QGP) that has, as it expanded and cooled, passed close to a posited critical point on the phase diagram into cumulants of hadron multiplicities that can subsequently be measured. In Ref. [3], we study this important mechanism for spin polarization generation that has not been systematically explored before and predict the signature of the SHE in those collisions using a (3+1) D viscous hydrodynamic model MUSIC with AMPT initial condition. We propose to use the second Fourier coefficients of the net spin polarization of Lambda hyperon as sensitive probes to search for the SHE (Fig. 2).

## References

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## 2 - 3 Exploring the Phase and Spin Structure of QCD Matter\*

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Exploration of the phase and spin structure of quantum chromodynamics (QCD) matter is one of the primary goals of the heavy-ion collision program. The intriguing hints observed in the first phase of the Beam energy scan (BES), in particular the deviations of certain measures of fluctuations from their non-critical baseline, deviations that vary non-monotonically as a function of  $\sqrt{s}$ , motivate the ongoing experimental efforts in its second, higher statistics, phase (BES II) to look for the conjectured QCD critical point. BES II data has been taken by the STAR collaboration over the course of 2019-2021 in AuAu collisions at a sequence of collision energies, which corresponds to a scan in  $\mu_B$ . The data is currently being analyzed and we look forward with considerable anticipation to learning much from these measurements. Furthermore, the recent observation of  $\Lambda$  hyperon polarization produced in heavy-ion collisions opens a new research front in understanding spin structure of hot and dense nuclear matter.

We have made essential steps in studying both spin and phase structure of QCD matter. In particular, we are the first group applying the newly developed non-equilibrium effective field theory to study the hydrodynamic fluctuations in the context of heavy-ion collisions experiments. The non-Gaussian fluctuations of baryon density are sensitive to the presence of the conjectured QCD critical point. Their observational consequences are crucial for the ongoing experimental search for this critical point through the beam energy scan program at Relativistic Heavy Ion Collider (RHIC). In the expanding fireball created in a heavy-ion collision, critical fluctuations would inescapably fall out of equilibrium and require a systematic description within a dynamical framework. In Ref. [1], we employ newly developed effective field theory (EFT) for fluctuating hydrodynamics to study the real-time critical non-Gaussian fluctuations of a conserved charge density. In particular, we derive the evolution equations for multi-point correlators of density fluctuations and obtain the closed-form solutions with arbitrary initial conditions that can readily be implemented in realistic simulations for heavy-ion collisions. We find that non-linear interactions among noise fields, which are missing in traditional stochastic hydrodynamics, could potentially contribute to the quartic (fourth-order) fluctuations in the scaling regime even at tree level in non-equilibrium situations.

In Ref. [2], we introduce a freeze-out procedure to convert the critical fluctuations in a droplet of quark-gluon plasma (QGP) that has, as it expanded and cooled, passed close to a posited critical point on the phase diagram into cumulants of hadron multiplicities that can subsequently be measured. The procedure connects the out-of-equilibrium critical fluctuations described in concert with the hydrodynamic evolution of the droplet of QGP by extended hydrodynamics, known as Hydro+, with the subsequent kinetic description in terms of observable hadrons. We introduce a critical scalar isoscalar field  $\sigma$  whose fluctuations cause correlations between observed hadrons due to the couplings of the  $\sigma$  field to the hadrons via their masses. We match the QGP fluctuations obtained by solving the Hydro+ equations describing the evolution of critical fluctuations before freeze-out to the correlations of the  $\sigma$  field. In turn, these are imprinted onto correlations and fluctuations in the multiplicity of hadrons, most importantly protons, after freeze-out via the generalization of the familiar half-century-old Cooper-Frye freeze-out prescription which we introduce. The proposed framework allows us to study the effects of critical slowing down and the consequent deviation of the observable predictions from equilibrium expectations quantitatively. We also quantify the suppression of cumulants due to conservation of baryon number. We demonstrate the procedure in practice by freezing out a Hydro+ simulation in an azimuthally symmetric and boost invariant background that includes radial flow discussed earlier.

Finally, we report the progress in studying the spin dynamics of QCD matter. In Ref. [3], we study this important mechanism for spin polarization generation that has not been systematically explored before and predict the signature of the Spin Hall effect (SHE) in those collisions using a (3+1) D viscous hydrodynamic model MUSIC with AMPT initial condition. We propose to use the second Fourier coefficients of the net spin polarization of Lambda hyperon as sensitive probes to search for the SHE. Those SHE observables show a qualitative difference in both the sign and beam energy dependence for the situations with and without the SHE. Future experimental observation of these distinct qualitative features would provide strong evidence for the existence of the SHE in the hot and dense QCD matter at trillions of degrees.

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