CHAPTER I

INTRODUCTION

The primary focus in heavy-ion collision experiments is the detection of a possible QCD phase transition in dense baryonic matter. Specifically, the transition between a phase, known also as the QGP, which is also characterized by chiral symmetry restoration, and the confined phase of nuclear matter where chiral symmetry is spontaneously broken. We aim to study this transition in the context of a rapidly expanding fireball of hot and dense nuclear matter created during heavy-ion collision experiments. In such a scenario the rapid phase separation will lead to enhanced fluctuations and clustering of the baryon number, related to an increment of the baryon number susceptibilities.

In recent studies of heavy-ion collisions have highlighted the utility of light nuclei cumulants as sensitive observables for probing the QCD phase structure, particularly in the search for a critical point and phase transition signals. Theoretical investigations employing transport models, such as the Ultra-relativistic Quantum Molecular Dynamics (UrQMD) (Bleicher et al., 1999) framework with a density-dependent equation of state incorporating a first-order phase transition, have demonstrated substantial deviations from Gaussian fluctuation patterns in the cumulants of baryon number and light nuclei yields. These deviations are attributed to enhanced coordinate-space correlations and clustering effects in the vicinity of a phase boundary (Bumnedpan, Steinheimer, Reichert, et al., 2025) Complementary experimental measurements from the STAR collaboration at RHIC, particularly within the Beam Energy Scan program, have reported non-monotonic behavior in higher-order proton cumulants as a function of collision energy, consistent with theoretical expectations of critical phenomena. Collectively, these findings underscore the potential of light nuclei cumulants as robust signatures of critical behavior and phase transitions in strongly interacting matter.

The present work uses the Ultra-relativistic Quantum Molecular Dynamics (UrQMD) transport model together with the coalescence model to study potential enhancements of light nuclear cluster production, due to enhanced fluctuations, at a QCD first-order phase transition. The formation of clusters in UrQMD is based on the coalescence model, a phenomenological model of light nuclei formation based on the Wigner wave function formalism, where sufficiently close momenta and positions of protons and neutrons, after the chemical freeze-out, lead to light nuclei formation. Besides protons (p), the light nuclei of interest include deuteron (d), triton (t), helium-3 (^3He), and helium-4 (^4He). We will calculate their yields both within a spatial central volume and in momentum space by applying typical experimental cuts in rapidity and transverse momentum. We study the time evolution of the respective multiplicity for various energies and their maximum enhancement as a function of beam energy to search for potential enhancements as a consequence of a phase transition at low- to intermediate energies. Additionally, we will investigate the proton number variance and skewness which is also sensitive to a phase transition.