High-Throughput Validation of Nuclear Matter Equations of State via the 4D-TExS Computational Framework

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Mapping the Quantum Chromodynamics (QCD) phase diagram behavior for the quark-gluon plasma state of matter and finding its critical point is still challenging in high-energy physics. Lattice QCD calculations at zero baryonic chemical potential have revealed a crossover transition from hadronic matter to a deconfined quark-gluon plasma state of matter. However, at finite chemical potential, the fermion sign problem is still present. Results from the Beam Energy Scan (BES) program at the Relativistic Heavy Ion Collider (RHIC) search for signatures of a first-order phase transition and a critical point at finite baryon chemical potential, providing constraints on the QCD Equation of State (EoS) and insights into the behavior of quark matter. A large variety of phenomenological EoS constructions exist, as different models introduce parameters and approximations, producing many candidates with varying physical validity. However, the validation of these models is often computationally expensive, time-consuming, and unstable, primarily due to the numerical differentiation of thermodynamic quantities which can present a non-physical behavior near to a possible critical point. This work integrates the *4D-TExS Model* framework with the *Utilities to Execute Pipelines* (UTEP) workflow, which enables the automated generation of EoS and a validation process. The workflow employs numerical differentiation to classify outputs as physically valid or invalid efficiently by conditions such as causality

Figure 1. Utilities to Execute Pipelines flowchart, 4D-TExS Model

$(0 < c_s{}^2 < 1)$ and stability (positive values for the pressure, entropy, and baryon density, the second-order baryon susceptibility χ_2^B, and the heat capacity $(T)\frac{\partial S}{\partial T}_{n_B}$). Building upon this automated framework, we propose the development of a neural network capable of recognizing pressure-based patterns and predicting EoS validity without requiring explicit derivative computations. This integration of computational physics and machine learning aims to reduce computational cost, improve numerical stability, and accelerate the exploration of the QCD phase diagram through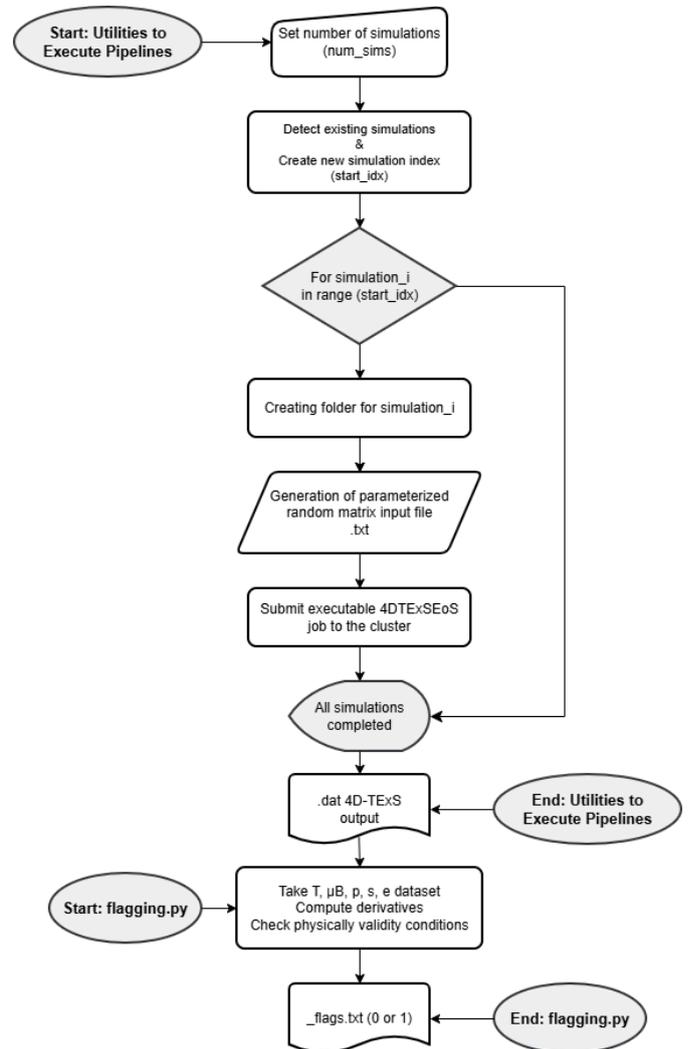 automated validation and intelligent model classification.