Research Statement

The new state of matter created in the extreme condition of density and temperature in heavy nuclei collisions gives us opportunity to study the QCD phase transition and underlying properties that believed to be present in the early universe. My primary interest is to study the **QCD phase transition** dynamics by creating a deconfined state of matter known as Quark-Gluon Plasma(QGP) at different conditions using various heavy-ion collision models. Various simulation models have been developed over the years following different theoretical concepts e.g. transport models(**AMPT**), hydrodynamic models(**VISH2+1**), hybrid models. We study numerous properties related to the space-time dynamics of high energy heavy-ion collisions in the early stage, in the pre-equilibrium stage and also in the later stages of hadronic scatterings. This includes **vorticity, velocity and temperature fluctuations, power spectrum analysis, anisotropic flows** etc.

As the system retains a large angular momentum after the collision, which causes a nonzero rotational motion in the fluid. This is one of the major reasons for getting overall vorticity in the system that polarizes the spin of the produced particle along its direction due to spin-vorticity coupling. We studied the vorticity structures in the initial parton phase and the final hadronic phase with varying initial conditions and discussed its effect on the shear viscosity. One of the reasons why lower collision energies are studied experimentally is to include a finite baryon chemical potential. **Hadron resonance gas models** have been used to model the quark-gluon plasma at finite baryon chemical potentials. We are interested to see whether these models can account for the vorticity patterns obtained from the hybrid transport models. We use shear viscosity to make a connection between these two models. The results are obtained for different initial conditions and we found respectable change in the vorticity patterns for varied conditions e.g. collision energy($\sqrt{s}$), system size etc. We have discussed how these changes in the vorticity patterns can possibly be dependent on the interplay between viscous stress and angular momentum of the system. Our results indicate that viscosity plays a more significant role at higher chemical potential and lower collision energies. **Reference: Int. J. Mod. Phys. E** Vol. 29, No. 01, 2050001 (2020)

The existence of vorticity suggests the presence of anisotropic flow components which indicates a deviation from laminar like flow. We study the fluctuations in the flow in terms of turbulence spectra and find that there are significant departures from isotropic turbulence in the initial and the pre-equilibrium stages of the collision. The plasma created in these collisions has a very high Reynolds number, creating an imbalance in the inertial and viscous forces in the plasma. This makes the fluctuations sustainable and the **Kolmogorov spectra** can be obtained in such cases. Since a strong momentum anisotropy exists between the transverse and the longitudinal plane, we study the energy density spectrum in these two planes by slicing the sphere into different planes. The geometrical anisotropy is reflected in the anisotropic turbulence generated in the rotating plasma and we find that the scaling exponent is different in the two planes which shows the imbalance in the forces over all the planes. Like flow velocity fluctuations, we also observe the temperature fluctuations in the early stages of the collision. We calculated the power spectrum of the temperature fluctuation. The spectrum deviates from the Gaussian spectra expected for an isotropic turbulence. All these seem to indicate that the large scale momentum anisotropy persists in the smaller length scales for the relativistic heavy-ion collisions. **Reference:** `https://arxiv.org/abs/2108.01847`

To quantify the anisotropy in the temperature fluctuations, we use the formalism of **non-extensive Tsallis statistical mechanics** which is a generalization of Boltzmann-Gibbs(BG) thermodynamic approach to non-equilibrium systems. Temperature fluctuations can help us understand various thermodynamic properties of a system. The non-extensive statistics has been used extensively to calculate **the entropic index(q)** by fitting the p_T spectra of finally produced hadrons. We use this statistics to find the entropic index from the **temperature fluctuations in the partonic stages** of the relativistic heavy-ion collisions. We found similarities with the previously obtained entropic index form the hadron spectra at various initial conditions. We find that the temperature and the entropic index have a linear relationship during the partonic stages of the heavy ion collision similar to the observation from the hadronic spectra. We have shown the change in q with a change in centrality and $\sqrt{s}$, and all the results agree with the recent analysis of transverse momentum data using Tsallis statistics for the hadronic stage. We also talked about how the entropic index can be used as a parameter to study the equillibration process. Thus, our current work indicates that a non-extensive formalism can be used in conjunction with a transport model to study the partonic stages of relativistic heavy-ion collisions. **Reference: Mod. Phys. Lett. A** Vol. 36, No. 22, 2150152 (2021)

In our recent work, we have done a detailed analysis of the performance of various **Machine Learning(ML)** models on the predictions of several initial state geometry parameters. As QGP is formed only for a fraction of a second, we only get spectra of finally produced hadrons. Any kind of external probing is not possible to obtain the initial state geometry parameters. In order to extract the thermal and transport properties of the QGP, one needs to rely on Monte-Carlo event-by-event model simulations, which back trace the experimental measurements to the early time dynamics of the relativistic heavy-ion collisions. In recent time, Machine Learning (ML) models gained popularity to do this job. We demonstrate high prediction accuracy of three important properties that determine the initial geometry of the heavy-ion collision (HIC) experiments by using supervised Machine Learning (ML) methods. These properties are the the impact parameter(b), the eccentricity(ϵ_2), and the participant eccentricity(ϵ_{part}). Though ML techniques have been used previously to determine the impact parameter of these collisions, we study multiple ML algorithms, their **error spectrum, and sampling methods** using exhaustive parameter scans to determine a combination of efficient algorithm and tuned training set that gives multi-fold improvement in accuracy for all three different heavy-ion collision models. The three models chosen are a transport model, a hydrodynamic model and a hybrid model. The motivation of using three different heavy-ion collision models was to show that even if the model is trained using a transport model, it gives accurate results for a hydrodynamic model as well as a hybrid model provided that the spectra of all the simulation models reproduce the correct experimental spectra. We show that the accuracy of the impact parameter prediction depends on the centrality of the collision. With the standard application of ML training methods, prediction accuracy is considerably low for central collisions. After using various popular **sampling techniques**, e.g., **SMOTER**, **ADASYN**, to rebalance the training data, a custom sampling method is built, giving different weights to different centrality classes. Our method increases this accuracy by multiple folds. **Reference: Phys. Rev. C** 00, 004900 (2022)

Early Universe Cosmology

In my M.Sc. project, we modeled massive particle diffusion in the vicinity of a static cosmic string as a two-dimensional random walk problem in the cosmic string space-time. We find that the particles start clustering around the cosmic string. This means that we get density fluctuations around a stationary cosmic string which depend on the deficit angle of the space around the cosmic string. **Reference:** JCAP03(2018)022

In our recent work, we have studied the decay of baryon inhomogeneities in an expanding universe generated at the electroweak scale. We used the diffusion equation in the Friedmann-

Lemaitre-Robertson-Walker metric and calculate the interaction cross-section of the quarks with the neutrinos, the electrons and the muons and obtain the diffusion coefficients. We find that the expansion of the universe causes the inhomogeneities to decay at a faster rate. **Reference:** Eur. Phys. J. C 81, 816 (2021)

In our ongoing project, we are focusing on fluctuation analysis to look for possible signatures of QGP. We are analyzing fractal structures for non-statistical fluctuations in terms of scaled factorial moments analysis, Multifractal method and Takagi method for smaller to larger HIC systems. We are also making an detailed analysis of Scaled charge varience and net charge variance per entropy.

As the ML based modelshighly dependent on the fitting of simulated data with the experimental data, I want to do a comprehensive study how the different experimental factors(e.g. noise) can hamper the model accuracy.

There are several project ideas based on Machine learning and deep learning that I want to carry out in future. Some of them are i) Train ML models such that it can separate out the nuclear deformation contribution on the elliptic flow and its fluctuation. ii) Train ML models to detect signatures of QGP by studying the Strangeness Enhancement and Charmonium suppression for different initial conditions by just using the spectra.

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