Characterizing hadronic phase in relativistic hadronic and heavy-ion collisions and study of muon puzzle in cosmic ray events with GRAPES−3 experiment

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Introduction

The primary goal of ultra-relativistic heavy-ion collisions is to study the creation and characterize quark-gluon plasma (QGP) in the laboratory. QGP is a deconfined state where quarks and gluons are freed from their usual confinement within hadrons and move freely within a volume larger than the hadrons that can be realized at high energy density and temperature. Several signatures at the forefront of experimental and theoretical investigations indicate the formation and properties of QGP. Studies have observed strong collective flow patterns in particle distributions, which indicate the QGP's hydrodynamic behavior and rapid expansion and cooling phases. Additionally, strangeness enhancement, jet quenching, and suppression of quarkonia states serve as indirect probes into the dynamics and thermalization processes within the QGP medium. Contrary to heavy ion collisions, in proton-proton (pp) collisions, one does not expect a QGP medium due to their smaller system size and lower energy densities than heavy ion collisions. However, recent observations at the LHC have challenged this concept. High-multiplicity pp collisions have shown fascinating characteristics generally associated with heavy ion collisions, such as the emergence of ridge-like structures in two-particle correlations and enhanced production of strange particles.

Apart from this, the data produced by the secondary particles of cosmic rays in the Earth's atmosphere gives us beneficial information that complements the collider experiment like the LHC. Ground-based detectors collect extensive information regarding the secondary particles produced, which enriches our understanding of these ultra-high energetic particles in a natural environment. This synergy between the collider and cosmic ray physics motivates us to take a broad approach to study the Universe's most energetic phenomenon at the highest energy level. Once we combine collider and cosmic ray physics, one can gather knowledge on particles and the fundamental forces that govern them, which will eventually enhance our understanding of high-energy particle and astroparticle physics.

Objectives and Results

In the following bullet points, we highlight the key objectives and essential results, offering a comprehensive glimpse of the work achieved in the thesis.

1. In this analysis [1], we used a multiphase transport (AMPT) model with string melting mode to investigate how nuclear deformation and hadron cascade time affect the particle production and elliptic flow in Xe+Xe collisions at $\sqrt{s_{\rm NN}} = 5.44$ TeV. In this study, we vary the hadron cascade time ($\tau_{\rm HC}$) to investigate the particle ratios as a function of transverse momenta ($p_{\rm T}$) spectra for various final state particles. Also, the effect of hadron cascade time on elliptic flow (v_2) was investigated by varying the cascade time between 5 and 25 fm/c. The $p_{\rm T}$-differential charged particle elliptic flow is higher for $\tau_{\rm HC} = 25$ fm/c compared to 5 fm/c showing an additional anisotropy from multiple scatterings in the hadronic phase. We compare our findings with the experimental ALICE results for both (20-30)% and (50-60)% centrality classes and observe that our results qualitatively explain the experimental observations [2]. We did not observe scal-

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ing behavior with the number of constituent quarks ($n_{\rm q}$) on elliptic flow, which suggests that quark-participant scaling violation is an initial state effect, whereas it is not influenced by hadronic rescattering.

2. In this analysis [3], we have used the non-extensive Tsallis statistics to estimate the thermodynamic observables of a magnetized hadron gas. The various thermodynamic observables such as energy density (ϵ), magnetization (M), entropy density (s), pressure (P), and square speed of sound ($c_{\rm s}^2$). A positive magnetization is observed for all the q values when under both weak ($eB = m_\pi^2$) and a strong magnetic field ($eB = 15m_\pi^2$) for both near and away from equilibrium. However, for $eB = m_\pi^2$ and away from equilibrium ($q = 1.15$), it behaves like a diamagnetic. A diamagnetic to paramagnetic transition in non-central heavy-ion collisions was identified as collision energy increases from RHIC to LHC. We also examined the squared speed of sound (c_s^2) of the hadron gas in a magnetic field. We observed that increasing magnetic field strength c_s^2 value decreases for both near and away from the equilibrium scenario, suggesting increased interactions within the system.

3. The charged-particle transverse momentum ($p_{\rm T}$) spectra measured by the ALICE collaboration for pp collisions at $\sqrt{s} = 7$ and 13 TeV is studied utilizing a thermodynamically consistent form of Tsallis non-extensive statistics [4]. The $p_{\rm T}$ spectra were fitted with the Tsallis distribution function and analyzed based on final state charged-particle multiplicity for various particles such as $\pi^{\pm}$, $K^{\pm}$, $p + \bar{p}$, ϕ, $\Lambda + \bar{\Lambda}$, $\Xi + \bar{\Xi}$, and $\Omega + \bar{\Omega}$. This work offers an alternative to the single freeze-out scenario by incorporating a finite chemical potential during the kinetic freeze-out stage. The transverse momentum spectra of various particles were analyzed using the Tsallis distribution function, showing good agreement with experimental data. We find a finite chemical potential at the kinetic freeze-out temperature. The temperature for all the particle species studied seems to be the same when one considers a finite chemical potential at the kinetic freeze-out, hence concluding that there may be evidence of thermal equilibrium at the kinetic freeze-out.

4. We investigate the decades-old problem called the muon puzzle in cosmic ray physics. The discrepancy between the observed and expected muon multiplicity in the cosmic ray air showers is known as the muon puzzle. Current theoretical models consistently predict fewer muons than experiments detect, especially at higher energies. Our study involves extensive air shower simulations using the CORSIKA program and data from the GRAPES-3 experiment. By analyzing the muon multiplicity, energy spectrum, and zenith angle distributions, this work aims to elucidate the discrepancies between theoretical predictions and observational data. Exploring potential explanations for the muon puzzle could enhance our understanding of the mechanisms behind muon production in cosmic ray showers. The research emphasizes the importance of refining theoretical models and improving our understanding of cosmic ray interactions through detailed comparisons between simulation results and experimental observations.

Acknowledgments

I greatly acknowledge the guidance of my thesis supervisors, Prof. Raghunath Sahoo and Dr. Pravata Kumar Mohanty. I thank the DST-INSPIRE program of Govt. of India for providing the fellowship throughout my Ph.D. tenure.

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