

Study of QGP and Its Properties Using Correlation and Fluctuation Phenomena in Ultra-Relativistic High Energy Collision

Abstract

Quantum Chromodynamics (QCD) predicts that, under extreme conditions of temperature and density, hadronic matter undergoes a phase transition into a deconfined state of quarks and gluons, known as the Quark-Gluon Plasma (QGP). This state is believed to have existed naturally in the early universe a few microseconds after the Big Bang. Relativistic heavy-ion collisions provide a unique opportunity to recreate and study the QGP in laboratory conditions. Studying the properties of QGP is important for understanding the evolution of the early universe and the behavior of matter at fundamental levels.

In this thesis, a comprehensive study of complex dynamics of multiparticle production in high energy hadronic and heavy-ion collisions is performed using correlation and fluctuation observables. The analysis is based on both experimental data, primarily from nuclear emulsion detector, and Monte Carlo simulation data generated using EPOS3 and UrQMD models.

The introductory chapter provides an overview of heavy-ion collisions, highlighting the motivation for studying QGP, the evolution of the collision system through different stages, fundamental kinematic variables and some of the relevant experimental observables generally used to study QGP. The chapter also includes an extensive review of previous studies on forward-backward correlations, fractal characteristics in heavy-ion collisions and chaotic behavior in multiparticle production.

Chapter 2 elaborates the experimental techniques of nuclear emulsion detectors and Monte Carlo simulation basics of two MC models, EPOS3 and UrQMD used in this study.

The third chapter presents a detailed study of forward-backward (FB) correlations in small collision systems at different LHC energies (pp collisions at $\sqrt{s} = 0.9, 2.76, 7$ and 13 TeV and collisions at $\sqrt{s} = 5.02$ TeV). Using EPOS3 generated datasets, the dependence of FB multiplicity and momentum correlation coefficients on the gap between FB windows (η), collision energy, window width ($\delta\eta$) and minimum transverse momentum (p) is extensively analyzed. It is observed that the overall trends of these dependences are in agreement with the available experimental results from ALICE and ATLAS. Therefore, we conclude that the hybrid Monte Carlo model, EPOS3 remains consistent in explaining the LHC data in terms of FB multiplicity and momentum correlations qualitatively. Furthermore, for the first time, the $\delta\eta$ -weighted average of FB multiplicity and momentum correlation coefficients as a function of collision energy are investigated. We observe that $\delta\eta$ -weighted average of both FB correlation strengths increases with center-of-mass energy and interestingly, exhibit a saturation tendency

approximately beyond 7 TeV. Our multiplicity-dependent summed- p_T correlation study reveals that FB momentum correlation strength depends on the total number of charged particle produced in a pseudorapidity bin. To mitigate volume fluctuation effects, we also explore a strongly intensive observable Σ and study its dependence on multiplicity bin width and window separation for both pp and pPb events. The observed independence of Σ variable with respect to multiplicity bin width indicates that Σ is insensitive to dynamical fluctuations of the system.

In Chapter 4, we explore the fractal characteristics of heavy-ion collisions at high energy to identify possible sources of multiparticle production using Visibility Graph (VG) technique. The power of scale freeness of VG (PSVG) and related observables are studied using nuclear emulsion data of ^{16}O -AgBr interactions at 60 A GeV and their centrality dependence is also examined. We observe a clear centrality-dependent trend in fractal nature of pion fluctuations, with the Power of Scale-freeness decreasing toward more central event. Furthermore, transverse momentum threshold (p_{Tmin}) dependence of fractal behavior is analyzed for EPOS3 simulated pp events at $\sqrt{s} = 7$ TeV. We find that PSVG values increase with the transverse momentum threshold, indicating that as the transition from soft processes to hard processes occurs, particle production becomes more complex in nature.

In chapter 5, we investigate the chaotic nature of multiparticle production in ^{16}O -AgBr interactions at 60 A GeV by exploring erraticity moments. The presence of chaos in multiparticle production is confirmed and UrQMD model fails to explain our experimental findings. We explore the dependence of erraticity on target excitation and conclude that chaotic behavior is suppressed as the target excitation increases. We further extend our erraticity analysis from SPS energy to LHC energies and observe that EPOS3 generated pp ($\sqrt{s} = 13$ TeV) and pPb ($\sqrt{s_{NN}} = 5.02$ TeV) events exhibit chaos in multiparticle production and indicate a system-size dependence of the observed behavior. Interestingly, we observe that the degree of chaotic behavior in event-to-event fluctuations reduces as the energy increases from the SPS to the LHC scale.

Finally, Chapter 6 summarizes the major findings of the thesis and outlines possible future directions.

Through the study of correlations, fluctuations, fractality and chaoticity in various collision systems, this thesis contributes substantially in understanding of the complex dynamics governing high energy nuclear collisions.

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