OO Collision at LHC energies

A
Report
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by

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Contents

Abstract

In this study, I investigate event-by-event fluctuations of the mean transverse momentum ($\langle p_T \rangle$) and the two-particle correlator, defined as

$$\langle \Delta p_{T,i} \Delta p_{T,j} \rangle,$$

in oxygen–oxygen (O–O) collisions at a center-of-mass energy of $\sqrt{s} = 7$ TeV. The analysis utilizes the PYTHIA8 Monte Carlo event generator and focuses on charged particles within the pseudorapidity range $|\eta| \leq 0.8$ for the central detector, and

$$(2.8 \leq \eta \leq 5.1) \quad \text{or} \quad (-3.7 \leq \eta \leq -1.7)$$

for the forward multiplicity region.

Three distinct nuclear geometry configurations are considered for the initial state: the Harmonic Oscillator (HO), Woods–Saxon (WS), and alpha-cluster (AS) models. The observables are examined as functions of the final-state charged particle multiplicity in the central barrel region.

Acknowledgment

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Chapter 1

Introduction

1.1 Background

A key goal in the field of high-energy nuclear physics is to explore the properties of strongly interacting matter when subjected to extreme conditions. According to Quantum Chromodynamics (QCD), when the temperature and energy density reach sufficiently high levels, ordinary hadronic matter undergoes a transition into a deconfined phase composed of quarks and gluons—commonly referred to as the *Quark-Gluon Plasma* (QGP). This unique state of matter is believed to have existed for a brief moment shortly after the Big Bang.

1.2 Probing the QGP with Event-by-Event Fluctuations

To investigate the microscopic properties of the Quark-Gluon Plasma (QGP), physicists rely on final-state observables that carry imprints of the early stages of heavy-ion collisions. Among these observables, fluctuations in the mean transverse momentum ($\langle p_T \rangle$) on an event-by-event basis provide valuable insights into the system's dynamical behavior.

Such fluctuations are sensitive to correlations among particles emerging from the medium and can reflect contributions from various physical processes including jet production, collective flow, and thermalization. By comparing fluctuations in different collision systems and at various centralities or multiplicities, one can better understand the role of initial conditions and the medium's response.

1.3 Multiplicity and Centrality in Small Systems

While QGP signatures are well-established in large collision systems like Pb–Pb, recent studies have shown that similar collective phenomena may appear even in small systems such as p–Pb and pp collisions at high multiplicities [2]. This has motivated further exploration into intermediate systems like O–O collisions, which offer a unique testing ground to investigate the onset of QGP-like behavior.

Multiplicity, typically measured by counting charged particles in a defined pseudorapidity region, serves as a proxy for the collision's centrality or the degree of overlap between colliding nuclei. Correlating event-by-event p_T fluctuations with multiplicity thus enables a more differential study of the underlying physics.

1.4 Initial-State Geometry Models

Understanding the impact of initial nuclear configurations on final-state observables is essential for accurate modeling. To this end, various geometrical models of the oxygen nucleus are considered in this study:

- **Harmonic Oscillator (HO) Model:** A simplified model that assumes nucleons are distributed according to a Gaussian-like potential.
- **Woods–Saxon (WS) Distribution:** A commonly used realistic density profile that captures the diffuse edge of the nucleus.
- **Alpha-Cluster (AS) Structure:** A model inspired by the idea that light nuclei may exhibit cluster-like substructures, such as four-alpha configurations in O–16[7].

Comparing results obtained using these models allows for the investigation of how initial-state geometry affects the magnitude and trend of p_T fluctuations and correlations.

1.5 Experimental Signatures of QGP

A variety of observables are used to infer the formation and properties of the QGP:

- **Quarkonium Suppression:** Bound states like J/ψ and Υ are suppressed in the presence of a QGP due to Debye screening .
- **Jet Quenching:** High-energy partons lose energy while traversing the medium, leading to suppressed or modified jet structures .
- **Electromagnetic Probes:** Photons and dileptons do not interact strongly and thus escape the medium carrying undistorted information about its properties .
- **Strangeness Enhancement:** An increased production of strange hadrons relative to pp collisions is considered a signature of deconfined matter .

These observables are studied using detectors such as ALICE, CMS, and ATLAS at the LHC.

1.6 Collective Effects in Small Systems

Unexpectedly, several QGP-like features have been observed in high-multiplicity proton–proton (pp) and proton–nucleus (p–A) collisions [3]. Notable examples include:

- Ridge-like long-range angular correlations.
- Azimuthal anisotropy (flow-like behavior).
- Strangeness enhancement.

These phenomena have raised questions about the possible formation of QGP droplets in small systems or the existence of alternative collective mechanisms such as multi-parton interactions or initial-state effects.

1.7 Oxygen–Oxygen Collisions as a Test System

To probe the transition between small and large systems, intermediate systems such as oxygen–oxygen (O–O) collisions are under investigation. These offer a controllable environment with moderate system size, allowing studies of:

- System-size dependence of collective phenomena.
- The onset of QGP-like behavior.
- Validation of scaling laws in QCD matter.

O–O collisions serve as a bridge between pp/p–Pb and Pb–Pb collisions, potentially helping to identify the minimum conditions necessary for QGP formation.

Chapter 2

Theoretical Framework

2.1 Event-by-Event Fluctuations

Event-by-event fluctuations serve as an important tool to study the properties of the matter created in heavy-ion collisions. Unlike single-particle observables, fluctuation measurements reflect collective behavior and correlations within and between events.

2.1.1 Correlations and Fluctuations

Correlations refer to relationships between particles within a single event, often in position or momentum space. Examples include angular correlations (used to study azimuthal anisotropies, or "flow"), two-particle transverse momentum correlations, and Hanbury-Brown–Twiss (HBT) correlations which estimate the spatial extent of the emission source [6].

Fluctuations, in contrast, measure variations between different events. These often arise from underlying correlations and provide insights into the dynamics and state of the system. Some observables even analyze correlations between fluctuation measures themselves.

2.1.2 Statistical Framework

The matter created in ultra-relativistic heavy-ion collisions is believed to reach a state near thermal equilibrium . Due to experimental limitations (e.g., limited pseudorapidity coverage), only a subsystem is typically measured. As such, the grand-canonical ensemble is often used to describe these measurements. This allows exchange of energy and conserved charges—baryon number (B), electric charge (Q), and strangeness (S)—with the surrounding system via associated chemical potentials (μ_B, μ_Q, μ_S) .

For rare particles or cases involving strict conservation within the observed region, the canonical ensemble may be more appropriate.

2.1.3 Significance of Fluctuations

Fluctuation measurements can be sensitive to QCD phase transitions, especially in the search for a possible critical point associated with a first-order phase transition line . Near such transitions, fluctuations of conserved charges and temperature are expected to be enhanced.

Moreover, fluctuations help probe the effective degrees of freedom—whether the system behaves like a collection of nucleons or involves partonic (quark-gluon) dynamics .

2.1.4 Sources of Fluctuations

Fluctuations can be separated into two components:

- **Trivial Fluctuations:** Arising from finite particle statistics and experimental limitations. These do not carry physical information and must be subtracted or corrected for.
- **Dynamical Fluctuations:** Contain information about the system's thermodynamics and phase structure. These are the focus of interest in QGP studies.

Additionally, event-to-event fluctuations in the system volume—primarily due to variations in the collision impact parameter—can obscure physical signals. For this reason, volume-independent observables are often used.

2.2 Some Fundamental Statistics

2.2.1 Mean Transverse Momentum

The mean transverse momentum $\langle p_T \rangle$ in an individual event is defined as [6]:

$$\langle p_T \rangle = \frac{1}{N_{\mathrm{ch}}} \sum_{i=1}^{N_{\mathrm{ch}}} p_{T,i} \tag{2.1}$$

where N_{ch} is the number of charged particles in the event, and $p_{T,i}$ is the transverse momentum of the i^{th} particle.

2.2.2 Two-Particle Correlator

To study dynamical fluctuations in p_T, a two-particle correlator is used:

$$\langle \Delta p_T \Delta p_T \rangle = \left\langle \frac{1}{N_{\mathrm{ch}}(N_{\mathrm{ch}}-1)} \sum_{i \neq j} (p_{T,i} - \langle p_T \rangle)(p_{T,j} - \langle p_T \rangle) \right\rangle_{\mathrm{ev}} \tag{2.2}$$

This measure quantifies correlated fluctuations beyond statistical expectations and is sensitive to physical mechanisms such as jet fragmentation, collective flow, or thermalization.

2.2.3 Reformulation Using Moments

To facilitate computational efficiency, the correlators can be reformulated in terms of raw moments defined for each event:

$$Q_1 = \sum_{i=1}^{N_{\mathrm{ch}}} p_{T,i} \tag{2.3}$$

$$Q_2 = \sum_{i=1}^{N_{\mathrm{ch}}} p_{T,i}^2 \tag{2.4}$$

$$Q_3 = \sum_{i=1}^{N_{\mathrm{ch}}} p_{T,i}^3 \tag{2.5}$$

Using these, we can write the mean transverse momentum across events as:

$$\langle\langle p_T \rangle\rangle = \left\langle \frac{Q_1}{N_{\text{ch}}} \right\rangle_{\text{ev}} \tag{2.6}$$

The two-particle correlator becomes:

$$\langle \Delta p_T \Delta p_T \rangle = \left\langle \frac{Q_1^2 - Q_2}{N_{\text{ch}}(N_{\text{ch}} - 1)} \right\rangle_{\text{ev}} - \left\langle \left(\frac{Q_1}{N_{\text{ch}}} \right)^2 \right\rangle_{\text{ev}} \tag{2.7}$$

2.2.4 Fluctuation

To facilitate meaningful comparisons across different systems or centralities, we define the following normalized and intensive measures:

Normalized Fluctuation Measure

$$\frac{\sqrt{\langle \Delta p_T \Delta p_T \rangle}}{\langle\langle p_T \rangle\rangle} \tag{2.8}$$

This dimensionless ratio helps quantify the relative strength of p_T fluctuations.

Chapter 3

Analysis

3.1 Meam Transverse momentum Calculation

This study investigates two-particle correlations in mean transverse momentum ($\langle p_T \rangle$) across different class intervals, which are defined based on event activity such as charged-particle multiplicity. By examining how momentum correlations vary across these intervals, we aim to gain insights into the underlying particle production dynamics and possible collective behavior in the system .

3.1.1 Event Classification

The dataset is divided into multiple classes of 0-10%, 10-20% and so on, based on charged-particle multiplicity (N_{ch}), measured within a specific pseudorapidity window (e.g., $|\eta| < 0.8$). Each class represents a different level of event activity, ranging from peripheral (low multiplicity) to central (high multiplicity) events. This classification allows for a differential study of correlation behavior as a function of central barrel multiplicity in that class.

3.1.2 Mean p_T Correlation Function

For each event class, we calculate the event-wise mean transverse momentum as:

$$\langle p_T \rangle = \frac{1}{N} \sum_{i=1}^{N} p_{T,i}$$

To investigate the correlation between transverse momenta of pairs of particles, we compute the two-particle correlation using the method of moments:

$$\langle \Delta p_T \Delta p_T \rangle = \left\langle \frac{Q_1^2 - Q_2}{N_{\text{ch}}(N_{\text{ch}} - 1)} \right\rangle_{\text{ev}} - \left\langle \left(\frac{Q_1}{N_{\text{ch}}} \right)^2 \right\rangle_{\text{ev}} \tag{3.1}$$

where $p_{T,i}$ and $p_{T,j}$ are the transverse momenta of two particles in the same event, and $\langle p_T \rangle$ is the average transverse momentum in that event. This observable reflects dynamical correlations beyond statistical fluctuations. A positive value indicates that particles with higher p_T tend to be correlated, whereas a negative value would imply anticorrelation.

3.2 Multiplicity Regions in the ALICE Experiment:

In high-energy collision experiments, multiplicity denotes the number of charged particles produced during an event. In the ALICE detector at the LHC, multiplicity is classified according to the pseudorapidity (η) range of the detected particles:

- **Central Multiplicity:** Refers to the count of charged particles detected in the central region of the ALICE detector, defined by the pseudorapidity interval $|\eta| < 0.8$. This region is covered by the central barrel detectors, which include tracking systems like the Inner Tracking System (ITS) and the Time Projection Chamber (TPC) [1].

- **Forward Multiplicity:** Charged particle multiplicity is also measured in forward regions using dedicated detectors. ALICE utilizes the V0 system for this purpose, consisting of:

  - **V0A:** Located on one side of the interaction point, covering $2.8 < \eta < 5.1$
  - **V0C:** Positioned on the opposite side, covering $-3.7 < \eta < -1.7$

  These forward detectors are used to assess event activity without overlapping with the central detector measurements.

Chapter 4

Methodology

This study analyzes simulated collisions of O–O nuclei at LHC energies of $\sqrt{s} = 7\,\text{TeV}$, using the event generator **PYTHIA**. The analysis focuses on the calculation of mean transverse momentum ($\langle p_{\text{T}} \rangle$) fluctuations and two-particle correlations for different nuclear models and their comparison.

To carry out this investigation, the following tools and techniques were employed:

4.1 ROOT Framework:

ROOT is an object-oriented computer program and library developed by CERN. It is a powerful data analysis framework widely used in high-energy physics and other scientific disciplines. ROOT offers a comprehensive set of tools for data storage, manipulation, statistical analysis, and visualization. One of its notable features is the `PyROOT` interface, which allows users to access ROOT's full functionality from within Python, combining the performance of C++ with the flexibility of Python[5].

Key Tools Used in This Analysis

- **THnSparse:** This is a memory-efficient multi-dimensional histogram class used to store sparse data. In this analysis, `THnSparse` is employed to study correlations between multiple event variables in high-dimensional space without the computational cost of dense binning. It is particularly useful when the data is sparse in some regions but dense in others.

- **TProfile:** This class provides a way to represent the mean value of one variable as a function of another. In this study, `TProfile` is utilized to analyze the mean transverse momentum ($\langle p_T \rangle$) as a function of multiplicity or other event observables, enabling a compact representation of statistical fluctuations and trends with associated error bars.

4.2 PYTHIA8:

PYTHIA is a widely-used Monte Carlo event generator designed for the simulation of high-energy particle collisions, such as those occurring at the LHC or future colliders like the EIC. It provides a detailed framework for modeling the physics of parton showers, hadronization, multiple interactions, and particle decays. PYTHIA is an essential tool for theorists and experimentalists aiming to interpret experimental data or test new physics scenarios through simulated events[4].

4.2.1 Key Features

- **Comprehensive Physics Modeling:** Simulates a wide range of physics processes, including QCD and electroweak interactions, initial- and final-state radiation, and hadronization via the Lund string model.

- **User Configurability:** Offers an extensive set of parameters that allow users to control beam setup, particle types, energies, and process selections.

- **Modularity:** Easily integrates with other simulation and detector frameworks such as GEANT4, Delphes, and ROOT.

- **Standardized Output:** Generates event records in widely accepted formats (HEPMC, ROOT) that are compatible with downstream analysis tools.

- **Broad Applicability:** Supports proton-proton, electron-proton, and heavy-ion collisions, making it suitable for both collider and fixed-target experiments.

4.3 Dataset

In this study, all datasets were generated using the `PYTHIA` event generator . The simulations focused on proton-proton (pp), oxygen-proton (Op), and oxygen-oxygen (OO) collisions at a center-of-mass energy of $\sqrt{s} = 7$ TeV. These synthetic datasets form the basis for analyzing mean transverse momentum ($\langle p_T \rangle$) fluctuations and two-particle angular correlations across different collision systems.

- **Collision Systems:**
  - Proton–Proton (pp): Both beams set to `Beams:idA = 2212`, `Beams:idB = 2212`.
  - Oxygen–Proton (Op): `Beams:idA = 1000080160` (Oxygen-16 nucleus), `Beams:idB = 2212`.
  - Oxygen–Oxygen (OO): `Beams:idA = Beams:idB = 1000080160`.

- **Event Generation:** Each system was simulated with appropriate physics settings in PYTHIA. 20 milloin for O-O and 50 million for O-p events were generated for each configuration to ensure meaningful statistical analysis.

- **Data Output:** Events were saved in a ROOT files in the form of histograms, retaining complete final-state particle information such as transverse momentum, meanpt, foeward multiplicity. These datasets were then analyzed using ROOT-based scripts.

This synthetic dataset serves as the backbone for the entire analysis presented in this study.

Chapter 5

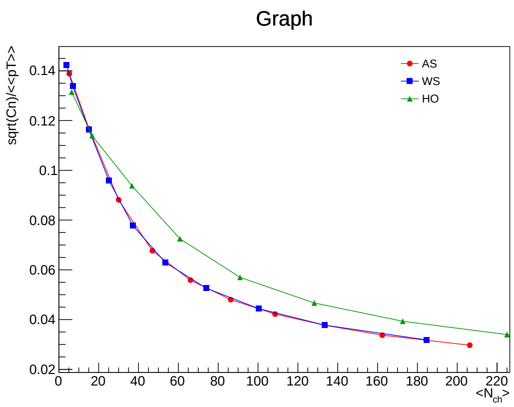
Result

I analyzed Oxygen nuclei using three different nuclear models: Woods-Saxon (WS), Alpha-Cluster (AC), and Harmonic Oscillator (HO). The simulations were performed with 20 million events for the WS and AC models, and 6 million events for the HO model.

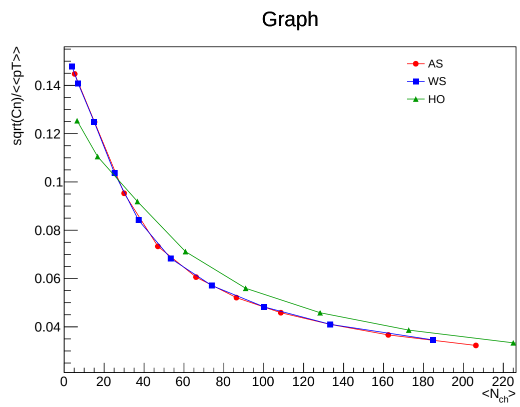
The results show that the **mean transverse momentum** ($\langle p_T \rangle$) distributions for the Woods-Saxon (WS) and Alpha-Cluster (AC) models are nearly overlapping in the low multiplicity region, with WS showing slightly higher values than AC at high multiplicity. This indicates consistent behavior between these two more realistic nuclear descriptions. In contrast, the Harmonic Oscillator (HO) model exhibits a noticeably different $\langle p_T \rangle$, suggesting its limitations in accurately representing medium-sized nuclei such as Oxygen.

A similar trend is observed in the **two-particle correlation** measurements. At **high multiplicity**, the HO model shows **weaker correlations** compared to WS and AC, while at **low multiplicity**, the HO model exhibits **stronger correlations**. This disparity likely stems from the oversimplified nature of the HO potential, which does not account for surface diffuseness or clustering effects, making it less suitable for modeling medium-mass nuclei.

Due to the smaller dataset for the HO model and the limited statistics for identified particles, I was unable to extract reliable results for them. Increasing statistics in future studies will be essential for more conclusive comparisons, particularly for identified particle spectra.



((a)) Relative dynamical fluctuations for all charged particles



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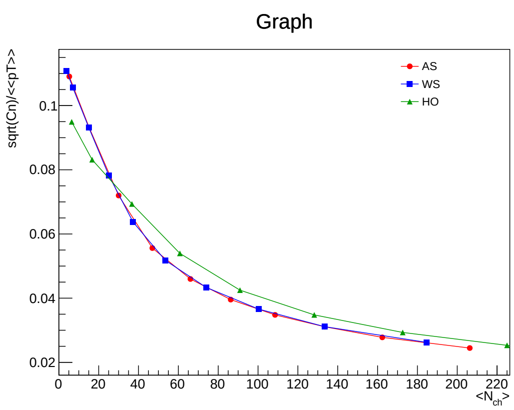
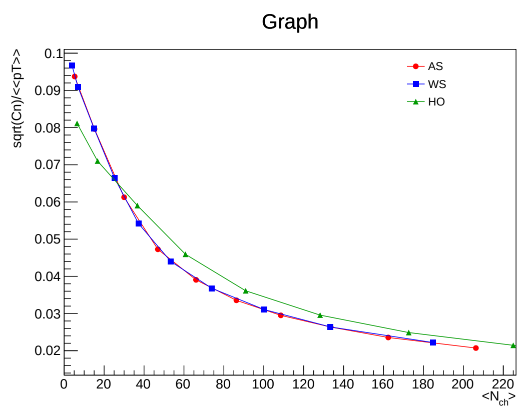


((c)) Relative dynamical fluctuations for kaons



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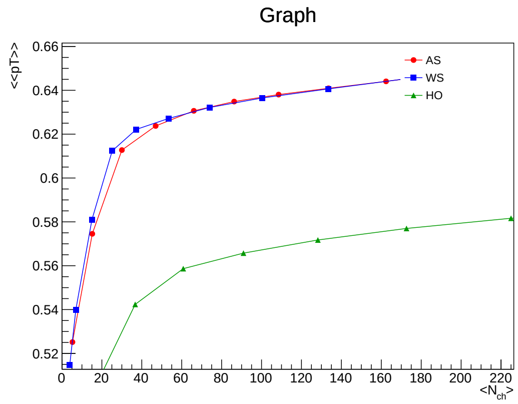
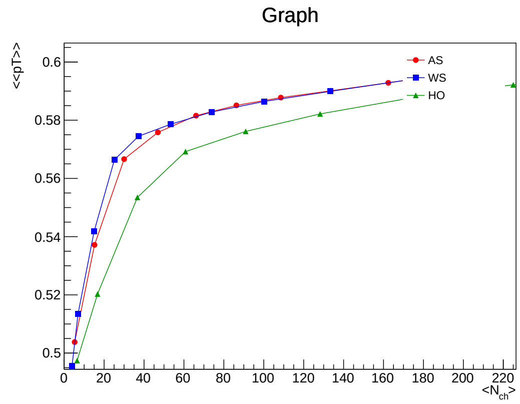


((a)) mean p_T fluctuations for all charged particles



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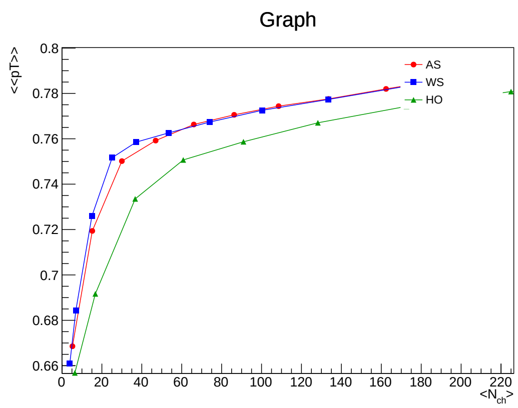
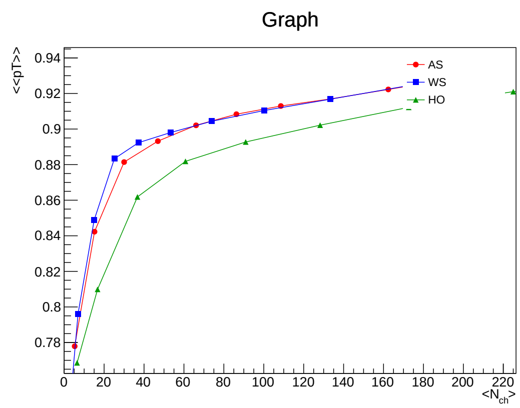
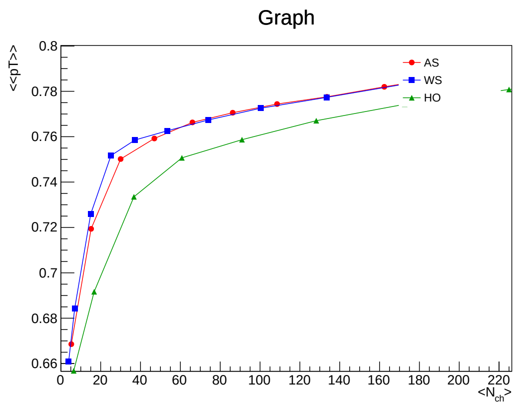


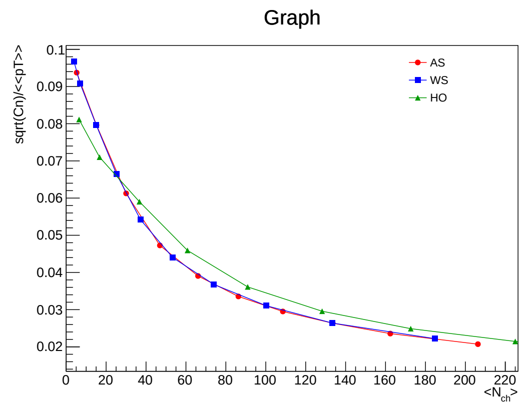
((c)) Mean p_T fluctuations for kaons



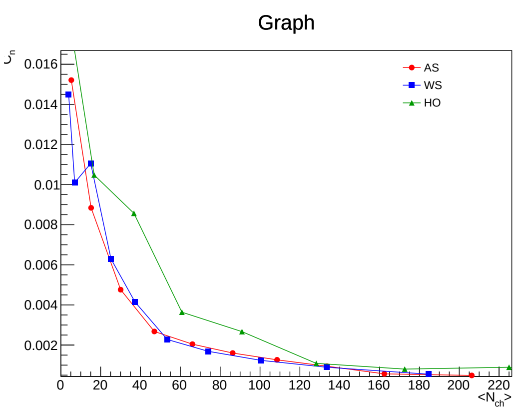
((d)) Mean p_T fluctuations for kaons



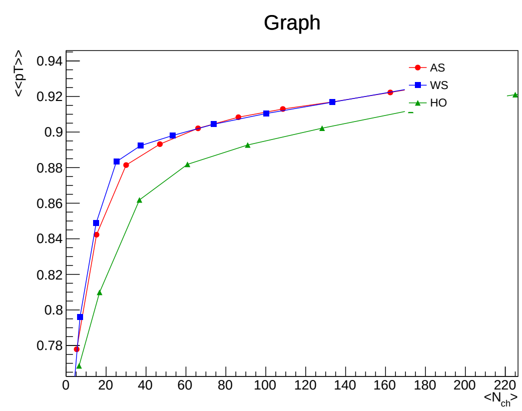
((a)) Mean P_T for kaons



((b)) Relative dynamical fluctuations for protons



((c)) Dynamical fluctuations for protons



((d)) Mean P_T for protons

Chapter 6

Conclusion and future work

The event-by-event fluctuations of the mean transverse momentum ($\langle p_T \rangle$) and the two-particle correlator $\langle \Delta p_{T,i} \Delta p_{T,j} \rangle$ have been investigated in oxygen–oxygen (O–O) collisions at $\sqrt{s} = 7TeV$ using three different initial nuclear geometry configurations: the Harmonic Oscillator (HO), Woods–Saxon (WS), and alpha-cluster (AS) models. The results show a clear dependence of both observables on the final-state multiplicity, reflecting the role of initial-state geometry and system size in influencing collective dynamics.
As an extension of this study, a similar event-by-event fluctuation analysis is being carried out for oxygen–proton (O–p) collisions. This investigation aims to explore the impact of asymmetric collision systems on transverse momentum correlations and to provide further insight into the role of initial geometry in small systems.

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