Effect of rope hadronization on strangeness enhancement in proton+proton collisions at $\sqrt{s} = 13$ TeV using PYTHIA8

M.Sc. THESIS

by

Hitesh Arora

Roll No.(2103151008)

DEPARTMENT OF PHYSICS

INDIAN INSTITUTE OF TECHNOLOGY

INDORE - 453552, INDIA

June, 2023

Effect of rope hadronization on strangeness enhancement in proton+proton collisions at $\sqrt{s} = 13$ TeV using PYTHIA8

A THESIS

Submitted in partial fulfilment of the

requirements for the award of the degree

of

Master of Science

by

Hitesh Arora

DEPARTMENT OF PHYSICS

INDIAN INSTITUTE OF TECHNOLOGY INDORE

June, 2023

INDIAN INSTITUTE OF TECHNOLOGY INDORE

CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **Effect of rope hadronization on strangeness enhancement in proton+proton collisions at $\sqrt{s}$ = 13 TeV using PYTHIA8** in the partial fulfillment of the requirements for the award of the degree of **Master of Science** and submitted in the **Department of Physics, Indian Institute of Technology Indore**, is an authentic record of my own work carried out during the time period from July 2022 to June 2023 under the supervision of **Prof. Raghunath Sahoo, professor, Indian Institute of Technology Indore.**

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any institute.

Hitesh 23.5.23

Signature of the student with date

(Hitesh Arora)

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

Sahoo 23.05.23

Signature of the Supervisor of M.Sc. thesis (with date)

(Prof. Raghunath Sahoo)

Hitesh Arora has successfully given his M.Sc. Oral Examination held on **Date**

Sahoo 23/05/23

Signature of Supervisor of M.Sc. thesis

Date:

Convener, DPGC

Date: May 23, 2023

Signature of PSPC Member no. 1

Date: May 23, 2023

Signature of PSPC Member no. 2

Date: May 23, 2023

ACKNOWLEDGEMENTS

Foremost, I would like to express my sincere gratitude to my advisor Prof. Raghunath Sahoo for his continuous support during my M.Sc. project, patience, motivation, and immense knowledge. His guidance helped me in all the time of research, studying, and writing of this thesis.

Besides my advisor, I would like to thank my PSPC committee members: Dr. Manavendra Mahato and Dr. Alestin Mawrie for their support and encouragement. I am very grateful to the Physics Department of IIT Indore for providing me all the required facilities.

I am thankful to my fellow labmates of the Experimental High-Energy Physics group at IIT Indore. I can't express enough thanks to Bhagyarathi Sahoo who was of immense help during the project. He helped with everything, from all kinds of physics problems to technical problems in LaTeX and ROOT. I would also like to thank Kamaljeet Singh for his help and insightful comments. All the discussions I had with him helped me to stay motivated and work harder.

Hitesh Arora

Abstract

Traditionally, proton-proton (p-p) collisions were considered to be the baseline in measurement for heavy-ion collisions but from the recent observations of enhanced production of strange and multistrange hadrons in high multiplicity p-p collisions at $\sqrt{s}$ = 7 and 13 TeV as measured by the ALICE [2]experiment have generated a lot of interest in small systems as well. This hints for the possible formation of Quark Gluon Plasma (QGP) like medium even in the small systems as well.

The production of strange and multistrange hadrons in heavy ion collisions is considered as one of the signatures of QGP medium [11]. The strange valence quark is not present in the colliding nuclei and hence produced by hard partonic scattering processes. In this study, we have used a pQCD based model PYTHIA8 to study the strangeness enhancement for p-p collisions at $\sqrt{s}$ = 13 TeV. One of the hadronization mechanisms in PYTHIA8, based on string fragmentaion, is rope hadronization which within the mechanism of color reconnection, is quite successful in describing the strangeness enhancement [5]-[6]. So, the aim is to understand the effect of rope hadronization on strangeness enhancement in proton+proton collisions at $\sqrt{s}$ = 13 TeV using PYTHIA8.

Contents

1 Introduction **1**

1.1 Quantum Chromodynamics 3

1.2 QCD Phase Diagram 5

1.3 QGP and it's space-time evolution 6

1.4 Signatures of QGP 7

1.4.1 Strangeness enhancement 8

1.4.2 J/Ψ suppression 9

1.4.3 Collective flow 9

1.4.4 Photons and dileptons production 10

1.5 Relativistic Kinematics 11

1.5.1 Rapidity and pseudorapidity 11

1.5.2 Azimuthal and polar angles 12

1.5.3 Choice of Units 13

1.6 Thesis goals 14

2 Motivation and Analysis tools **15**

2.1 Motivation 15

2.2 PYTHIA8: Event Generator 16

2.3 CERN ROOT Framework 18

3 Results and discussion **19**

3.1 Tuning for the PYTHIA8 event generator 20

3.2 Yields of particles as a function of p_T 21

3.3 Effect of Rope hadronization on strangeness enhancement . . 23

4 Preliminary results for the heavy flavored particles **29**

4.1 Yields as a function of p_T 30

4.2 Ratios of particle yields 31

5 Summary **34**

List of Figures

1.1 Standard Model of elementary particles 3

1.2 Running of QCD coupling constant as a function of momentum transfer (Q) [3] 4

1.3 Schematic representation of the QCD phase diagram [4] . . . 5

1.4 Space-time evolution picture of the relativistic heavy-ion collision [14] 6

1.5 Strangeness Enhancement in pp, p-Pb and Pb-Pb systems using different models compared to ALICE data [2] 8

1.6 Anisotropy in non-central heavy-ion collision[10] 10

1.7 As angle increases from zero, pseudorapidity decreases from infinity [14] 12

1.8 Representation of detector geometry 13

3.1 Transverse momentum distribution of $\pi^{\pm}$ in p-p collisions at $\sqrt{s}$ = 13 TeV for $\mid y \mid< 0.5$ generated with PYTHIA8 generator with RH on 21

3.2 Transverse momentum distribution of $K^{+} + K^{-}$ in p-p collisions at $\sqrt{s}$ = 13 TeV for $\mid y \mid< 0.5$ generated with PYTHIA8 generator with RH on 22

3.3 Transverse momentum distribution of $\Lambda + \bar{\Lambda}$ in p-p collisions at $\sqrt{s}$ = 13 Tev for $\mid y \mid< 0.5$ generated with PYTHIA8 generator with RH on 22

3.4 Transverse momentum distribution of $\Xi^{+} + \Xi^{-}$ in p-p collisions at $\sqrt{s}$ = 13 TeV for $\mid y \mid< 0.5$ generated with PYTHIA8 generator with RH on 23

3.5 Comparision for RH on and RH off using $(\Lambda + \bar{\Lambda})/\pi^{\pm}$ ratio using PYTHIA8 24
3.6 Comparision for RH on and RH off using $(K^{\pm}/\pi^{\pm})$ ratio using PYTHIA8 25
3.7 Comparision for RH on and RH off using $((\Xi^{\pm}/\pi^{\pm}))$ ratio using PYTHIA8 26
3.8 Ratio for $\frac{\Lambda/\pi_{RHon}}{\Lambda/\pi_{RHoff}}$ in p-p collisions at $\sqrt{s}$ = 13 TeV using PYTHIA8 27
3.9 Ratio for $\frac{K/\pi_{RHon}}{K/\pi_{RHoff}}$ in p-p collisions at $\sqrt{s}$ = 13 TeV using PYTHIA8 27
3.10 Ratio for $\frac{\Xi/\pi_{RHon}}{\Xi/\pi_{RHoff}}$ in p-p collisions at $\sqrt{s}$ = 13 TeV using PYTHIA8 28

4.1 Transverse momentum distribution of D^0 in p-p collisions at $\sqrt{s}$ = 13 TeV for $|\ y\ |< 0.5$ generated with PYTHIA8 generator with RH on 30
4.2 Transverse momentum distribution of $D^{\pm}$ in p-p collisions at $\sqrt{s}$ = 13 TeV for $|\ y\ |< 0.5$ generated with PYTHIA8 generator with RH on 31
4.3 Transverse momentum distribution of $D_s^{\pm}$ in p-p collisions at $\sqrt{s}$ = 13 TeV for $|\ y\ |< 0.5$ generated with PYTHIA8 generator with RH on 31
4.4 Comparision for RH on and RH off using D_s^+/D^0 ratio using PYTHIA8 32
4.5 Ratio for $\frac{D_s^+/D^0_{RHon}}{D_s^+/D^0_{RHoff}}$ in p-p collisions at $\sqrt{s}$ = 13 TeV using PYTHIA8 33

List of Tables

3.1 The parameter values of the rope hadronization model . . . 20
3.2 Multiplicity classes 21

Chapter 1

Introduction

From time to time we humans have given many theories about the creation of the universe. The Big Bang is one of the prevailing scientific theories about the origin and evolution of the universe. It is believed that the universe began as a hot, dense and infinitely small point called a singularity which then rapidly expanded into an explosion known as the Big Bang. In the first few instants of time, between 10^{-35} sec and 10^{-32} sec, it underwent a period of exponential inflation. It has been estimated that this event occurred around 13.8 billion years ago [15].

After the Big Bang, the universe began to cool and expand and the matter began to form. The known matter in the universe is made up of nucleus surrounded by a cloud of leptons called electrons. The nucleus, is composed of protons and neutrons and we see that they are also composed of elementary particles called quarks and gluons. The Standard Model (SM), developed during the later half of the 20^{th} century, describe these fundamental particles 1.1 and their interactions with the three fundamental forces - electromagnetic, weak and strong nuclear forces (SM does not consider the gravitaional force). It is based on the idea that all matter is made up of fundamental particles, and that these particles interact through the exchange of other particles, called bosons.

The SM includes twelve fundamental particles: There are six quarks (up (u), down (d), strange (s), charm (c), bottom (b) (or beauty) and top (t)) and their anti-quarks. Six leptons (electron, muon, tau and their corresponding neutrinos), their anti leptons also occur like positrons and four force-carrying particles, or bosons (photons, $W^{+-}$and Z bosons, and gluons). These particles are classified into two groups based on their spin quantum number: fermions (quarks and leptons) and bosons (force-carrying particles).

The SM describes the interactions of these particles through the strong, weak, and electromagnetic forces. The strong force is responsible for holding the nucleus of an atom together, while the weak force is responsible for certain types of radioactive decay. The electromagnetic force is responsible for the interactions between charged particles, such as electrons and protons.

The Higgs boson, which was discovered in 2012 [7]-[1], is also a part of the Standard Model. It is a scalar boson responsible for giving the masses to quarks and leptons by interacting with them and itself.

Despite its success in explaining the behaviour of particles and their interactions, the standard model has some limitations. For example, it does not include gravity, and it cannot explain certain phenomena such as dark matter or the imbalance between matter and antimatter in the universe. Therefore, researchers continue to explore new theories and models that can expand our understanding of the universe beyond the standard model.

In the high energy physics, the properties of matter in the high-energy density state of the early universe are studied through the production of quark-gluon plasma (QGP). QGP is a state of matter in which quarks and gluons are not confined to form hadrons, such as protons and neutrons. The details about the QGP will be discussed later in this thesis.

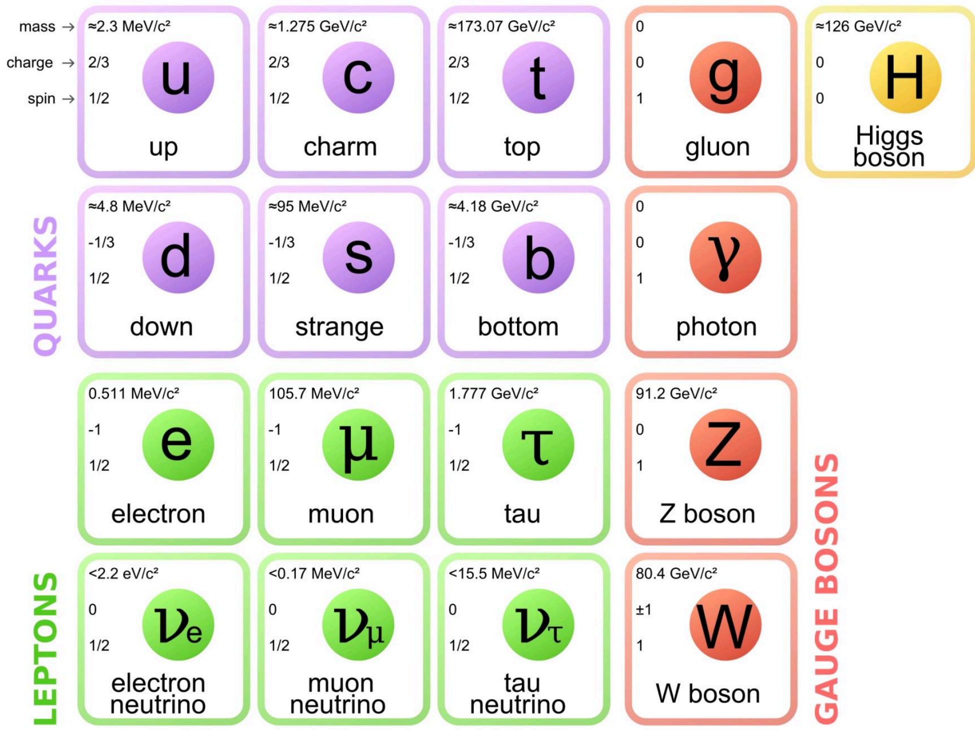


Figure 1.1: Standard Model of elementary particles

1.1 Quantum Chromodynamics

Quantum chromodynamics (QCD) is a branch of theoretical physics that seeks to understand the strong nuclear force. The strong interaction is mediated by the exchange of massless particles called gluons that act between quarks and antiquarks. Quarks come in six different "flavors": up, down, charm, strange, top, and bottom. Gluons themselves also carry a "color charge," which is analogous to electric charge in electromagnetism.

Unlike electromagnetic potential [18], the QCD potential between partons (quarks and gluons) can be defined by the following equation(1):

$$V = \frac{-4}{3}\frac{\alpha_s}{r} + kr \tag{1.1}$$

where α_s is the coupling strength of strong interaction, k is the string tension and r is the distance between two quarks.

For the larger values of r, $(r >> 1fm)$ the spring tension term of the equation will dominate the potential function. This describes the property of confinement, which requires the quarks and gluons to be confined in hadrons. For the smaller distances, ($r << 1fm$) the quarks exchange fewer gluons and net force becomes weaker and thus quarks are relativeley free. This property of quarks is known as "asymptotic freedom".

The properties of confinement and asymptotic freedom arise due to the fact that the gluons carry color charges, which give rise to the self-interactions due to which QCD coupling constant, α_s increases with increase in separation between the quarks or decrease in the momentum transferas shown in 1.2 .

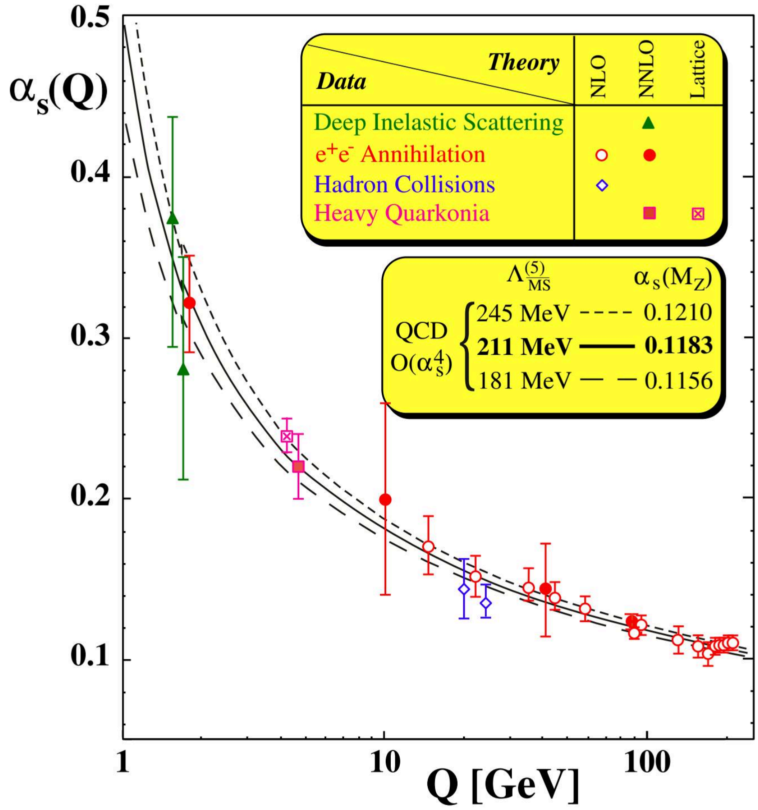


Figure 1.2: Running of QCD coupling constant as a function of momentum transfer (Q) [3]

1.2 QCD Phase Diagram

There are two ways to achieve the state of Quark Gluon Plasma (QGP). One of the ways is by heating the nuclei to ultra high tempeartures, as is done at Relativistic Heavy Ion Collider (RHIC) and Large Hadron Collider (LHC), or by compressing the nuclei so as to diffuse the boundaries, this experiment is expected to be carried out at the Facility for Antiproton and Ion Research (FAIR) at GSI, Germany, and the Nuclotron-based Ion Collider facility (NICA), Joint Institute for Nuclear Research (JINR), Russia.

In the QCD phase diagram 1.3 high temperature and low μ_B(baryon density) corresponds to an early Universe scenario, whereas low temperature and high baryon density corresponds to different astrophysical objects like neutron stars. At the low value of μ_B, there is a smooth crossover from the hadronic to the to the QGP phase. However, at higher μ_B, there exists a first order phase transition line which ends with a possible critical point after which the phase transition is a cross-over.

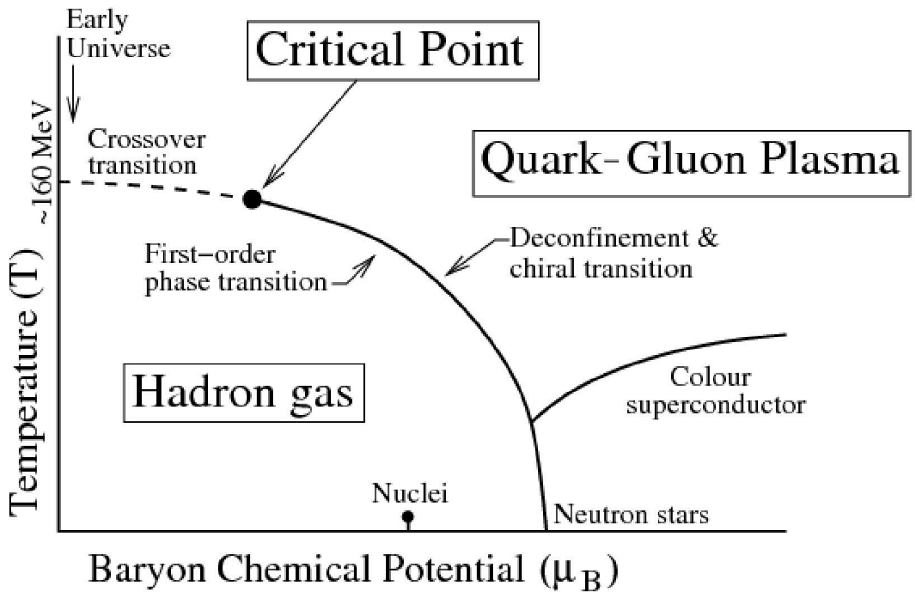


Figure 1.3: Schematic representation of the QCD phase diagram [4]

1.3 QGP and it's space-time evolution

Quark gluon plasma (QGP) is the thermalized state of partons (quarks and gluons), in which the partons are no longer bound into colour-neutral hadrons. The quark-gluon plasma resembles an ionised atomic gas with quarks and gluons corresponding to electrons and ions, and hadrons being the analogues of atoms. The QGP medium behaves like a superfluid with minimal viscosity. The expansion of QGP is described hydrodynamically. The strongly interacting deconfined state of quarks and gluons (QGP), was expected to have prevailed shortly after the Big-Bang. Exploration of the phase structure of such a strongly interacting matter of quarks and gluons has been one of the driving forces behind the high energy physics research.

The space-time evolution of the Quark-Gluon Plasma in Relativistic Heavy-Ion Collisions is shown in the 1.4.

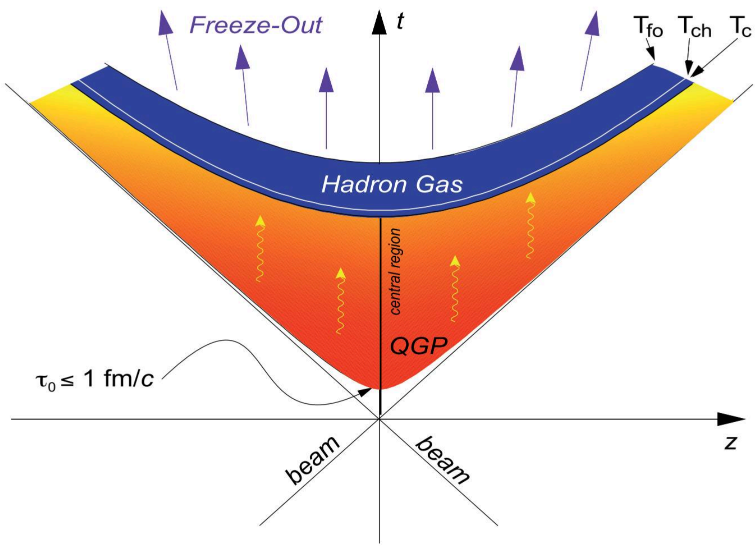


Figure 1.4: Space-time evolution picture of the relativistic heavy-ion collision [14]

The space-time evolution of QGP is characterised by several stages. After the collisions, a series of events leads to the formation of QGP which undergoes hadonization in the later stages. In the initial stage, i.e., the pre-equilibrium stage, two Lorentz contracted nuclei collide with each other and resulting in the liberation of a large fraction of partons and leads to the inelastic interactions among them. Now, the partons undergo multiple re-scatterings due to smaller mean free path compared to the system size. This leads the system to thermalization. After some time (duration of QGP, $\tau_{QGP} \approx 3 - 5fm/c$), energy density begins to drop below critical value ($\epsilon_c \approx 1GeV/fm^3$), required for the formation of QGP. Now, the system starts to cool down, and then hadronization starts. These hadrons formed interact inelastically and produce new particles. The stage when the inelastic collisions stop, is called the chemical freezeout. Even after chemical freezeout, hadrons still interact with each other through elastic collisions and can alter the momentum distribution of the system. Finally, when the mean free path of the hadrons formed becomes larger than the system size, they no longer interact with each other (known as kinetic freeze-out) and momentum distributions of the particles become fixed and then they are freely streamed into the detector.

1.4 Signatures of QGP

As, the time for which QGP is formed is very short ($\approx 10^{-23}sec$), so, it is not possible to probe its existence directly in the experiments. One of the ways is to develop some observables that can be measured in the experiments, and the existence of the QGP can be detected indirectly. Some of the signatures of the QGP are strangeness enhancement, photons and dileptons production, collective flow, quarkonium suppression, etc. These are discussed in brief in the following sections.

1.4.1 Strangeness enhancement

Strangeness enhancement is a well known signature of QGP. Usually, quarks and gluons are confined to hadrons (such as protons and neutrons), but in QGP medium, where the temperature and pressure are ultra high causes the quarks and gluons to become free and move around in deconfined state. As, a result, strange quarks (which are heavier than up and down quarks) become more abundant than they would be in a normal hadronic matter. As we know that the strange quarks are being produced via the strong interaction, and in QGP medium, there is an abundance of gluons, which are the carriers of the strong force, are significantly higher than in the hadronic matter.

So, the enhancement production of strange particles in final yield in heavy ion collisions, example, Pb-Pb collisions (Lead-Lead nuclei) in comparision to proton-proton(p-p) and p-Pb, collisions is considered as a probe to QGP. As there are no strange quarks present in the initial colliding nuclei but in the final yield we observe strange particles as the strange production is more favourable in parton-parton interactions in comparison to the hadronic interactions which proves the existence of QGP.

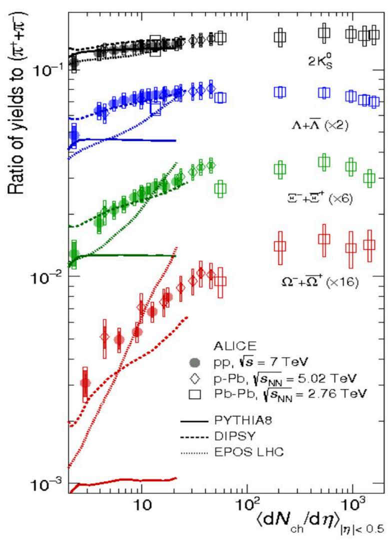


Figure 1.5: Strangeness Enhancement in pp, p-Pb and Pb-Pb systems using different models compared to ALICE data [2]

1.4.2 J/Ψ suppression

J/Ψ is a bound state of charm and anti-charm quark and it is formed in the initial hard scattering. In the QGP medium, due to the presence of various quarks and gluons, a charm quark may not come in vicinity of an anti-charm quark (or vice-versa) to form a bound state, this phenemenon is called color Debye screening. In pp collisions, it is believed that no medium is formed (QGP), so the charm and anti-charm can easily combine to form J/Ψ, whereas, in case of heavy-ion collisions, there is a possible formation of a thermalized medium (QGP) due to which Debye screening occurs and the production of J/Ψ is suppressed.

J/Ψ suppression was first proposed by Matsui and Satz in 1986 [8]. At very high temperatures the string tension between charm and anti-charm vanishes. Also, due to the Debye screening yields of open charms(D^0, $D^{\pm}$ etc) are enhanced since, the unbounded charm quarks can possibly combine with nearby light flavors [12]. It is also possible that a large number of charm and anti-charms are formed in the system if the collision energy is sufficiently high. This can possibly create a competition between suppression and regeneration/recombination and due to this reason the J/Ψ suppresion is less in LHC heavy-ion collisions in comparison with RHIC heavy-ion collisions [12].

1.4.3 Collective flow

The shape of the interaction or overlapping region depends on the impact parameter ($\vec{b}$) of the collision in heavy-ion collisions. As a result, in the central collisions where the impact parameter is close to zero, the collective flow has two components viz., longitudinal and transverse flow, due to the isotropic nature of the initial geometry. On the other hand, in non-central collisions, initial anisotropy in the spatial distribution leads to an additional component in the collective flow decomposition, i.e., transverse anisotropic flow.

The initial spatial anisotropy transforms into the momentum anisotropy due to the multiple rescatterings that occurred at the early stage, as depicted in 1.6. Moreover, these rescatterings will also drive the medium into thermal equilibrium, which will further expand collectively. This collectivity might reflect in the distributions of the produced particles. The Fourier expansion of the azimuthal distribution of the final state particles is given by the 1.2,

$$E\frac{d^3N}{d^3\mathbf{p}} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left[1 + \Sigma 2v_n cos(n(\phi - \Psi_{rp}))\right] \tag{1.2}$$

where, n= 1,2,3...., ϕ, Ψ_{rp} and v_n are azimuthal angle of the particle, reaction plane angle and n^{th} Fourier coff. of the azimuthal distribution, respectively. v_n can be written as,

$$v_n =< \cos(n(\phi - \Psi_{rp})) >$$

where, v_1, v_2 , v_3 , are known as directed flow, elliptic flow, triangular flow respectively and so on.

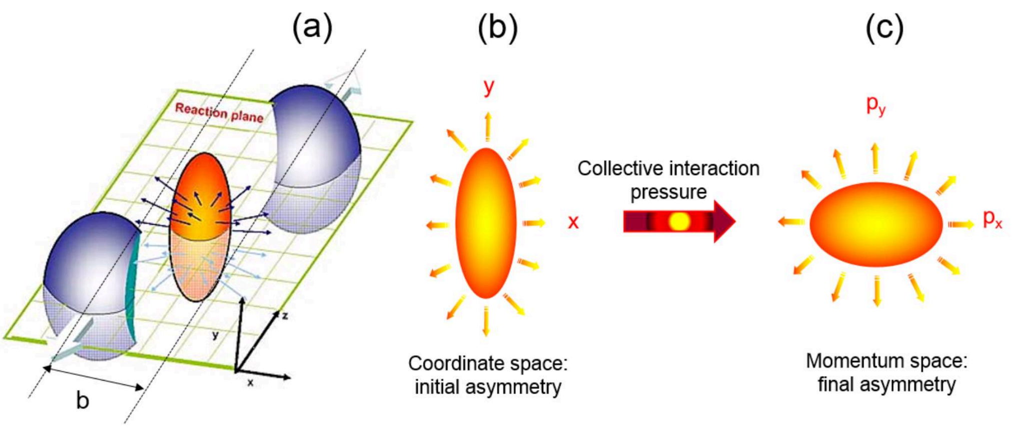


Figure 1.6: Anisotropy in non-central heavy-ion collision[10]

1.4.4 Photons and dileptons production

Photons and dileptons (i.e. $e^+e^-, \mu^+\mu^-$) are produced in almost every phase of the relativistic heavy ion-collisions. Since these are electromagnetic radiations, they don't interact strongly which makes them a perfect probe to investigate the produced strongly interacting medium. Indeed, even at the highest of the temperatures in heavy-ion collisions, the mean free path of these probes is way bigger than the size of the system which implies they would emerge out without interacting with the medium conveying the information about the medium where they are produced.

1.5 Relativistic Kinematics

In the high energy physics study, we deal with the relativistic particles, ($v \approx c$), as a result the Einstein's Special Theory of Relativity is of utmost importance in describing the particle kinematics. STR is based upon the following two main assumptions:

- The speed of light in a vacuum is always constant, regardless of the motion of the observer or the source of the light.
- The laws of physics are the same for all observers in uniform motion relative to one another.

1.5.1 Rapidity and pseudorapidity

In the relativistic domain, velocity is not an additive quantity (it is not linear in successive Lorentz transformation). As, a result it is not useful to study velocity in relativistic domain and hence a new quantity rapidity is being introduced. It is a dimensionless quantity and mathematically, it is expressed as:

$$y = \frac{1}{2} ln \frac{E + p_z c}{E - p_z c} \tag{1.3}$$

where, E and p_z are the energy and z- component of the particle's momentum. One can show rapidity to be an additive quntity i,e.$y^{''} = y + y^{'}$. Thus, it changes by an additive constant under successive Lorentz boosts. Rapidity is a Lorentz-invariant quantity, it is same in all reference frames. Rapidity spectra has a shape invariance under Lorentz transformation. It is a useful quantity to describe the relative velocities of particles in high-energy collisions, where the traditional concept of velocity breaks down. Now, mathematically pseudorapidity is defined as:

$$\eta = -\ln(\tan((\theta)/2)) \tag{1.4}$$

where θ, is the angle between the particle's momentum vector and the beam axis. Pseudorapidity is also a Lorentz-invariant quantity, and it is used to describe the distribution of particles in the detector. The advantage of pseudorapidity over rapidity is that it is easier to measure experimentally, since it only depends on the angles of the particles and not on their energies. For relativistic particles it can be proved that rapidity is approximately equals to pseudorapidity(y$\approx \eta$).

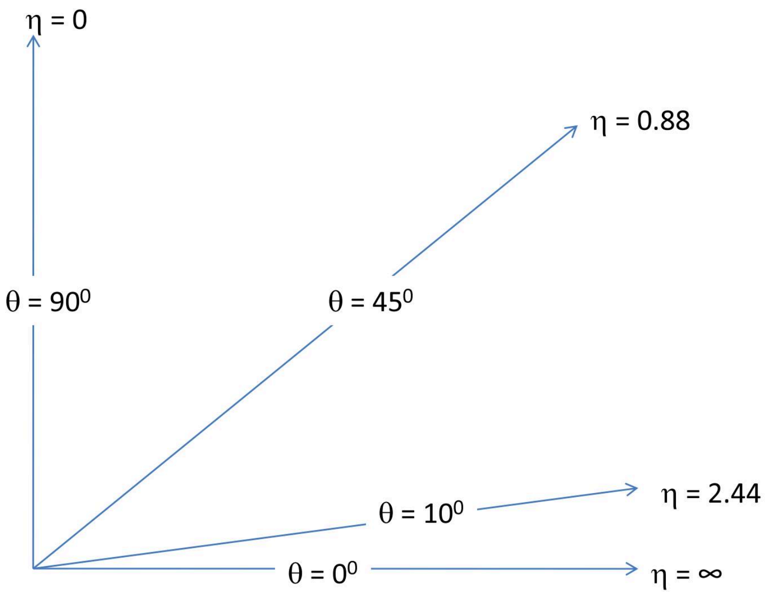


Figure 1.7: As angle increases from zero, pseudorapidity decreases from infinity [14]

1.5.2 Azimuthal and polar angles

In the $(\eta - \phi)$ coordinate system, the azimuthal angle ϕ is defined as:

$$\phi = tan^{-1}\left(\frac{p_y}{p_z}\right) \tag{1.5}$$

The polar angle θ describes the particle trajectory angle w.r.t the beam direction (z-axis). It is defined as the:

$$\theta = cos^{-1}\left(\frac{p_z}{p}\right) = tan^{-1}\left(\frac{p_t}{p_z}\right) \tag{1.6}$$

Figure, 1.8 shows a pictorial representation of detector geometry with z- axis taken as the beam axis, the polar angle θ and the azimuthal angle ϕ with the impact parameter b in the reaction plane.

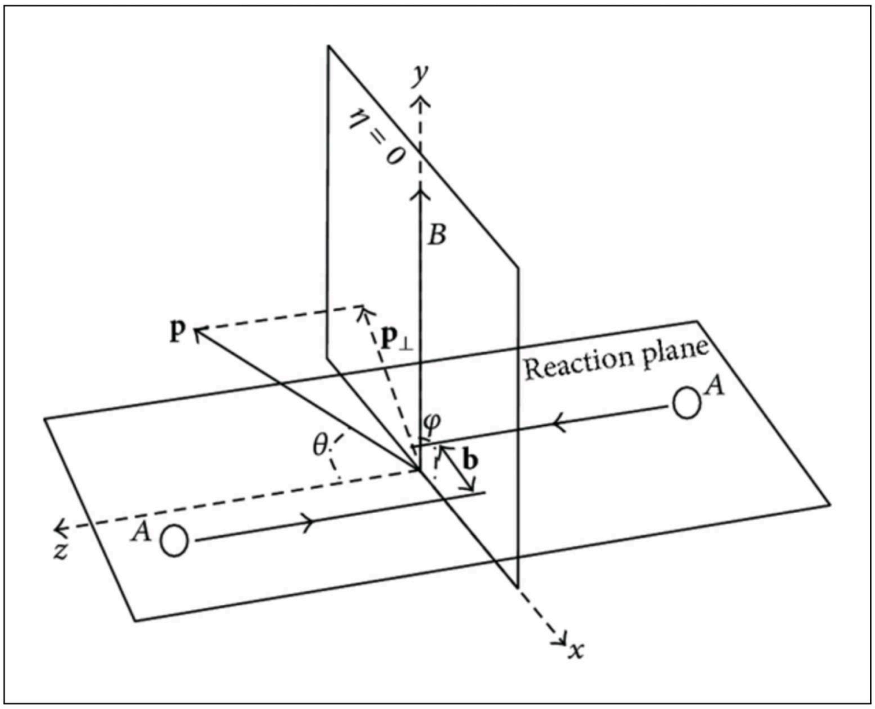


Figure 1.8: Representation of detector geometry

1.5.3 Choice of Units

During the study of high energy physics there are some constant terms which occur continuously in the calculation part which makes it tedious to handle. These constants are speed of light (c), reduced Planck's constant ($\hbar$) and Boltzmann's constant (k). Thus, in order to simplify things, we introduce a new system of unit called the natural units. It is very popularly being used in the high energy physics. In natural units: $\hbar$ = c = 1.

For natural units, the relativistic energy formula:

$$E^2 = p^2c^2 + m^2c^4 \tag{1.7}$$

reduces to the simple formula:

$$E^2 = p^2 + m^2 \tag{1.8}$$

In particles physics, the unit of energy is GeV($1GeV = 10^9 eV$). This helps us to express mass (m) and momentum (mc) in GeV, length and time in GeV^{-1}.

1.6 Thesis goals

High multiplicity p-p collisions at LHC energies are gaining a research spotlight in the high energy scientific community nowadays. Many results pertaining to high multiplicity p-p collision indicate towards a possible formation of a deconfined medium. One such indication is the strangeness enhancement. One way of studying the strangeness enhancement is by taking the ratio of the particle yields for the strange to non-strange hadrons. For example, if we plot the yield ratio for the lambda to pions (Λ/π) produced in a heavy ion collisions then we can study the strangeness enhancement.

Now, we have used the PYTHIA8 model for studying the strangeness enhancement in small systems. Although, PYTHIA8 is a non-thermal model and it does not consider the thermalization of the system, it does not define any temperature to the system but still there are processes included in PYTHIA8 (like, Multi Parton Interactions (MPI) and Color Reconnections (CR)), which can be used to mimic collectivity and thermalization-like behaviour.

In this work, the aim is to understand the effect of rope hadronization on strangeness enhancement in p-p collisions for light flavored particles and then to extend the research to get some results for the heavy flavored particles also (i.e., the D mesons).

Chapter 2

Motivation and Analysis tools

2.1 Motivation

The study of the high-energy particle collisions is an important area of research in modern physics. These collisions allow us to probe the fundamental nature of matter and the interactions between its constituent particles. In particular, the study of the production and behavior of strange hadrons (particles that contain one or more strange quarks) provides important insights into the underlying mechanisms of particle production and the properties of the quark-gluon plasma (QGP), a state of matter that is believed to have existed in the early universe.

One of the key questions in this field is how the QGP is formed and what factors influence its properties. One possibility is that the QGP is created when high-energy protons collide with each other, generating a "rope" of gluons and quarks that undergo a process known as hadronization. The properties of this rope and the hadronization process may have a significant impact on the properties of the resulting QGP.

Recently, the possible formation of a deconfined medium at high multiplicity pp collisions has gained an immense spotlight and an area of intense research for the scientific community. Therefore, studying the effect of rope hadronization on strangeness enhancement in proton-proton (p-p) collisions at LHC energies is an important and interesting research topic. By investigating the production and behavior of strange hadrons in these collisions, we can gain a better understanding of the role of rope hadronization in the formation and properties of the QGP. This information may have important implications for our understanding of the early universe, as well as for the development of new technologies and applications based on high-energy particle physics.

We have investigated this topic by generating events using a Monte Carlo event generator which does not incorporate the formation of QGP medium in its model, viz., PYTHIA8. The generated data is then analysed using ROOT framework. The details about the PYTHIA8 event generator and rope hadronization is discussed in the next section.

2.2 PYTHIA8: Event Generator

PYTHIA8 is an event generator software that is being used to mimic the high energy collisions between particles, where the effects of the strong nuclear force, governed by QCD, are of utmost importance. Basically it is written in C++. It is based on some physics models that describe the evolution from a few body hard process to a multihadronic state. There are various physics processes incorporated in PYTHIA8, some of them related to my work are discussed below:

- Hard and Soft QCD processes: Soft processes contains elastic, diffractive and minimum bias events, together covering the total cross section.

Hard processes are the normal $2 \rightarrow 2$ ones, including charm and bottom production (plus an incomplete implementation of $2 \rightarrow 3$ processes). They are contained as a subset of the soft processes via the Multi Parton Interactions (MPI) mechanism.

- Multi Parton Interactions (MPI): MPI is an important aspect of hadron-hadron collisions, and are simulated in Monte Carlo event generators such as PYTHIA8. In PYTHIA8, MPI are simulated using the framework of the Lund string model, where the incoming partons are described as strings of color flux tubes, which can interact and fragment into hadrons. MPI refers to a large number of interactions occurring amongst the partons. One major difference between PYTHIA8 and PYTHIA6 is that MPI is impact parameter dependent for the former whereas it is independent of the impact parameter for the latter. MPI are used for describing underlying events such as production of gluons, light quarks and production of heavy flavour particles such as J/Ψ, open heavy flavour particles, etc.

• Color Reconnection (CR): In PYTHIA8, each quark is considered a color tube. Color Reconnection is a technique of hadronization in PYTHIA8 in which these color tubes are connected through a color string.

These color tubes are connected in such a way that their total string length is as short as possible. This ensures for a stable configuration. CR applies for both soft and hard QCD processes. PYTHIA8 has three different CR models:

1 : CR-0 - This is the default mode, where there is no modification of the color flow between partons in the final state.

2 : CR-1 - In this color flow is reconnected between distant partons in the final state. This may lead to the change in distribution of the final state particles and can affect the observables such as transverse momentum.

3 : CR-2 - This model is based on gluon motion, in which partons are moved from one location to another to shorten the total string length.

• Rope Hadronization (RH): The rope hadronization mechanism in PYTHIA8 is a model for describing the hadronization process that takes place after the partonic interactions in a hadron-hadron collision.

In this model, the overlapping colored strings forms a color rope which hadronize with a high string tension. The overlap region is having very high energy density than its surroundings and hence as a consequence of it, a pressure gradient is developed which pushes the strings in the overlap region outwards. Now, the pushing of the strings in the transverse direction (also known as the string shoving) can mimic the flowlike patterns as observed in the high energy collisions. The breakup of the strings with the high string tension results in the production of more strange quarks and diquarks, which consequently produces more baryons and strange hadrons. This mechanism was firstly implemented in the DIPSY event generator [6].

2.3 CERN ROOT Framework

CERN Object-Oriented ROOT, is a software framework developed by CERN, for the analysis of energy physics data. It is mainly used by experimental high energy physicists to analyse the data collected from RHIC and LHC. The root framework is written mainly in C++ language and it can also be integrated with python for those who are more familiar with it. Root includes many packages as well as standard libraries, making it easier for the user to extract physics from the data.
Overall, the ROOT framework is an essential tool for physicists working in particle physics research, as it enables them to efficiently process and analyse large amounts of data from particle colliders such as the Large Hadron Collider (LHC) at CERN.

Chapter 3

Results and discussion

We have done the whole analysis using the PYTHIA8 event generator. It has been done to understand the mechanism of strange particle production under the rope hadronization process for the high multiplicity p-p collisions. Firstly, we have plotted the yields of the strange and multi strange hadrons, $\frac{1}{Nevt}\frac{d^2N}{dydp_T}$, with respect to, p_T (transverse momentum) or known as the p_T spectra. The following strange and multi strange hadrons have been been chosen for the analysis:

- Λ (lambda) particle with the rest mass of 1115.683±0.006 MeV/c^2 and having quark content of: uds

- K$^{\pm}$, (kaon) particle with the rest mass of 493.677±0.016 MeV/c^2 and quark content of K^+: u$\bar{s}$

- $\Xi^{\pm}$, (cascade) particle with the rest mass of 321.71±0.07 MeV/c^2 and Ξ^-, having quark content of: dss

The transverse momentum (p_T) distribution for the pions is also being plotted (with RH on). By taking the ratio of the strange particle with respect to the pions, strangeness enhancement plots can be obtained.

3.1 Tuning for the PYTHIA8 event generator

The analysis is done by generating 2.5 million inelastic non-diffractive events with soft QCD processes for proton-proton (p-p) collisions at $\sqrt{s} = 13\ TeV$ within the mechanism of rope hadronization and without it. The parameter values of the rope hadronization model [9] used with the color reconnection mechanism have been shown in the table 3.1:

Rope Hadronization	Values
Ropewalk:RopeHadronization	On
Ropewalk:doShoving	On
Ropewalk:r0	0.5
Ropewalk:m0	0.2
Ropewalk:beta	1.0
Ropewalk:tInit	1.0
Ropewalk:deltat	0.05
Ropewalk:tShove	10.0

Table 3.1: The parameter values of the rope hadronization model

In this analysis we have used the Monash 2013 tune of PYTHIA [17] based on larger and recent set of LHC data has been used to generate events for p-p collisions. The MPI are on ("PartonLevel:MPI = on"), throughout the whole generation of the events with the QCD- based color reconnections. The tunings of the rope hadronization are similar to one provided in PYTHIA8 (version 8.235) with the shoving mechanism.

The process of the hadronization is studied within the mechanism of formation of color ropes and the results are also shown for the mechanism where the rope hadronization is excluded.

The explanation of these physics processes can be found in detail in the reference [16].

3.2 Yields of particles as a function of p_T

The yield of the particles was obtained for the mid-rapidity region ($|\ y\ | < 0.5$) for the given multiplicity class of the Nch values 3.2:

Multiplicity Class	N_{ch}
Mul-1	5-10
Mul-2	10-15
Mul-3	15-20
Mul-4	20-30
Mul-5	30-40
Mul-6	40-150

Table 3.2: Multiplicity classes

The p_T spectras of the pion particle (and its anti particle), kaon (and its anti particle), lambda (and its anti particle) and for the cascade(and its anti particle) (with the mechanism of rope hadronization) have been shown below:

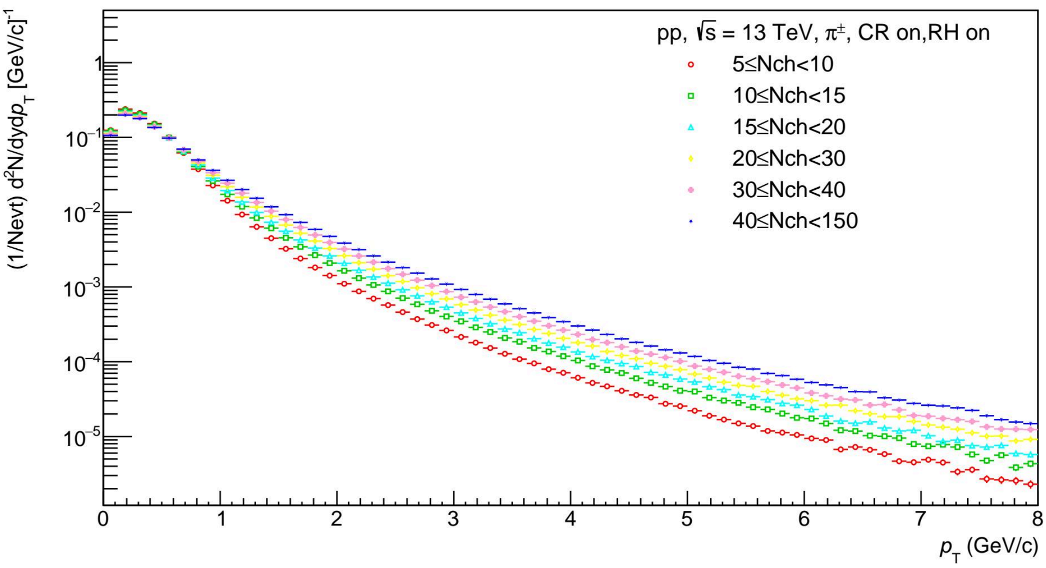


Figure 3.1: Transverse momentum distribution of $\pi^{\pm}$ in p-p collisions at $\sqrt{s}$ = 13 TeV for $|\ y\ | < 0.5$ generated with PYTHIA8 generator with RH on

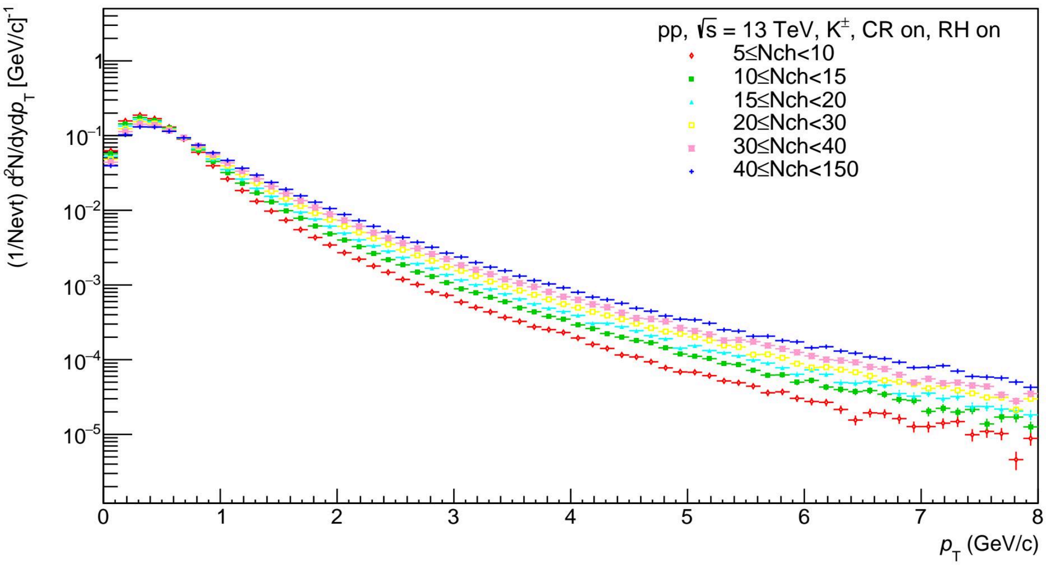


Figure 3.2: Transverse momentum distribution of $K^+ + K^-$ in p-p collisions at $\sqrt{s}$ = 13 TeV for $\mid y \mid< 0.5$ generated with PYTHIA8 generator with RH on

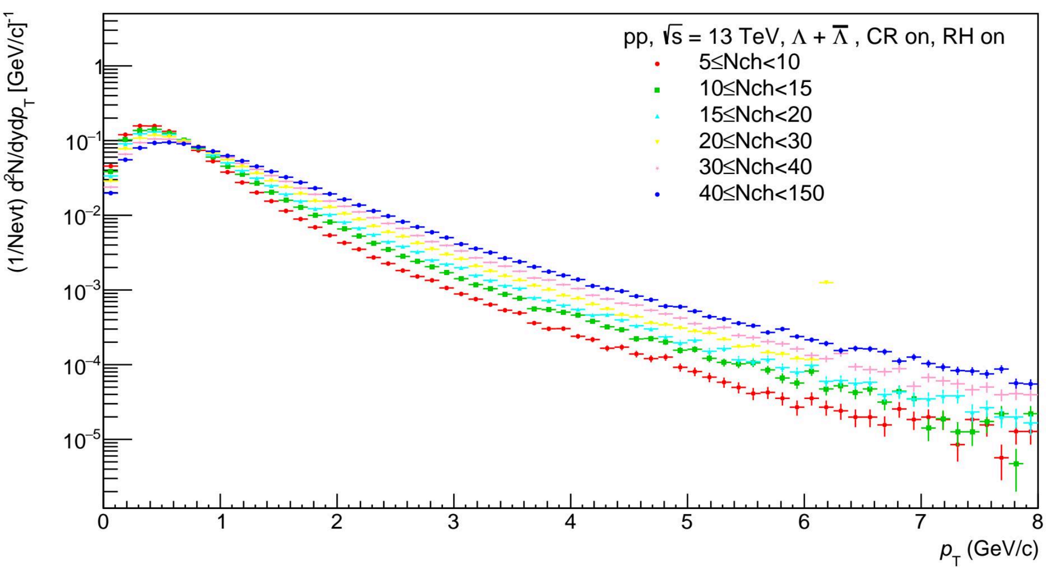


Figure 3.3: Transverse momentum distribution of $\Lambda + \bar{\Lambda}$ in p-p collisions at $\sqrt{s}$ = 13 Tev for $\mid y \mid< 0.5$ generated with PYTHIA8 generator with RH on

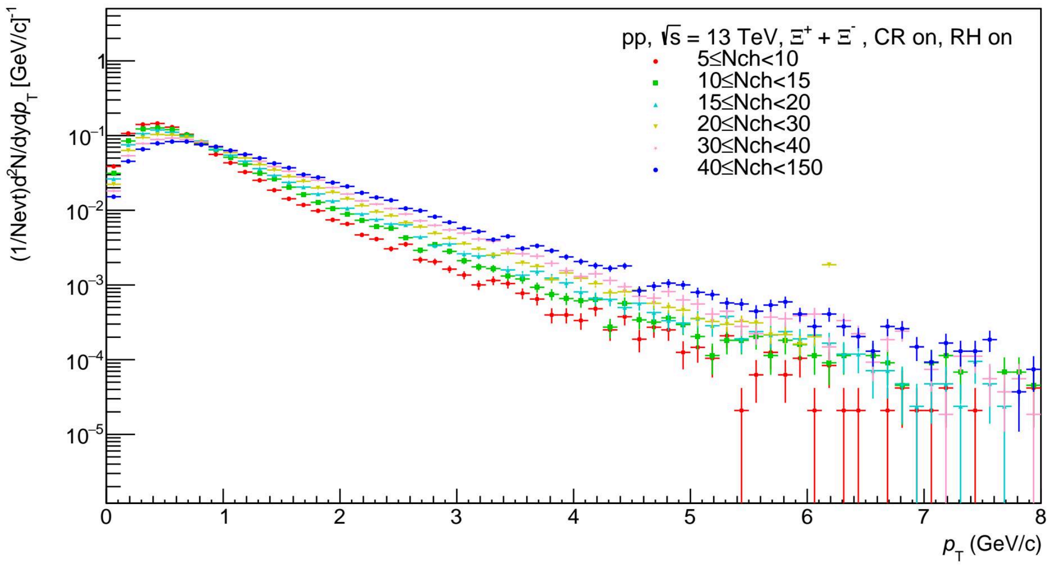
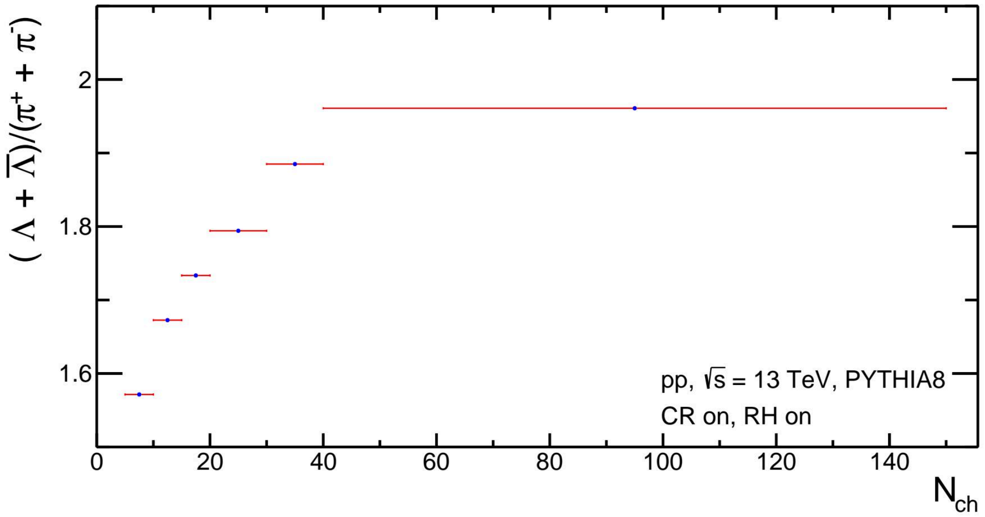


Figure 3.4: Transverse momentum distribution of $\Xi^+ + \Xi^-$ in p-p collisions at $\sqrt{s}$ = 13 TeV for $\mid y \mid < 0.5$ generated with PYTHIA8 generator with RH on

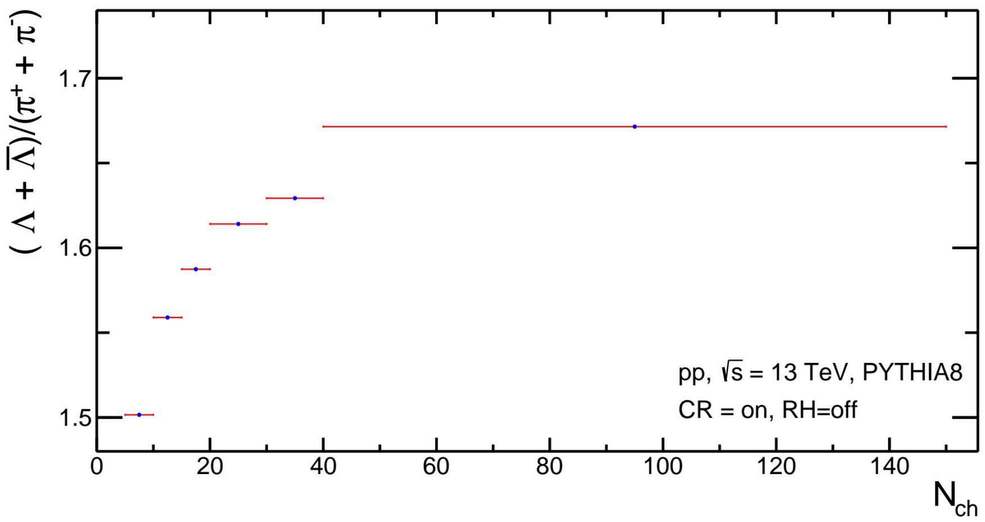
3.3 Effect of Rope hadronization on strangeness enhancement

Strangeness enhancement is considered as one of the signatures of the QGP. QGP is the thermalized state of partons(quarks and gluons) which shows the collective behaviour. Although, in PYTHIA8, we don't talk about the temperature of the system but there is a possible explanation of the QGP through the non thermal model PYTHIA8 as well. In PYTHIA8 we have the processes of the MPI and Color Reconnections. In PYTHIA8, CR along with the MPI could mimic the thermalisation effect [13], and the absence of either of them in the simulation process is picked up by the decrease in effective temperature. CR being a hadronization process, it increases the number of particles in the system and along with MPI, it helps the system to thermalize.

In figure, 3.5a and 3.5b, the ratio of the strange particle(Λ) to non strange particle(π), is plotted for both the rope hadronization process on and off. For the CR-on and MPI-on, we get the strangeness enhancement trend and after the inclusion of the rope hadronization framework, the particle ratio is increased and this is what expected also. It is because the rope hadronization favours the strange particle production and in numerator we are having the strange particles.



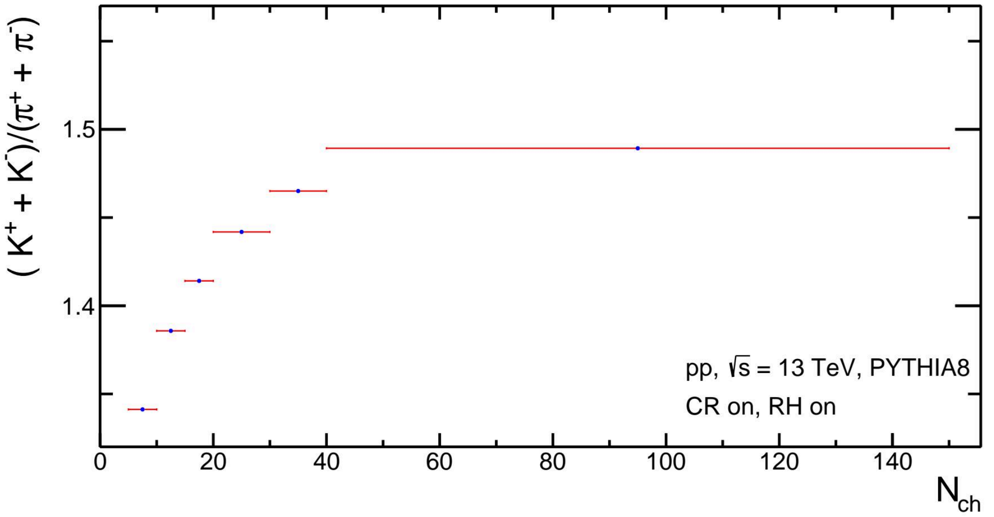
(a) Strangeness enhancement plot for $(\Lambda + \bar{\Lambda})/\pi^{\pm}$ ratio using PYTHIA8 for p-p collision at $\sqrt{s}$ = 13 TeV with CR on and RH on



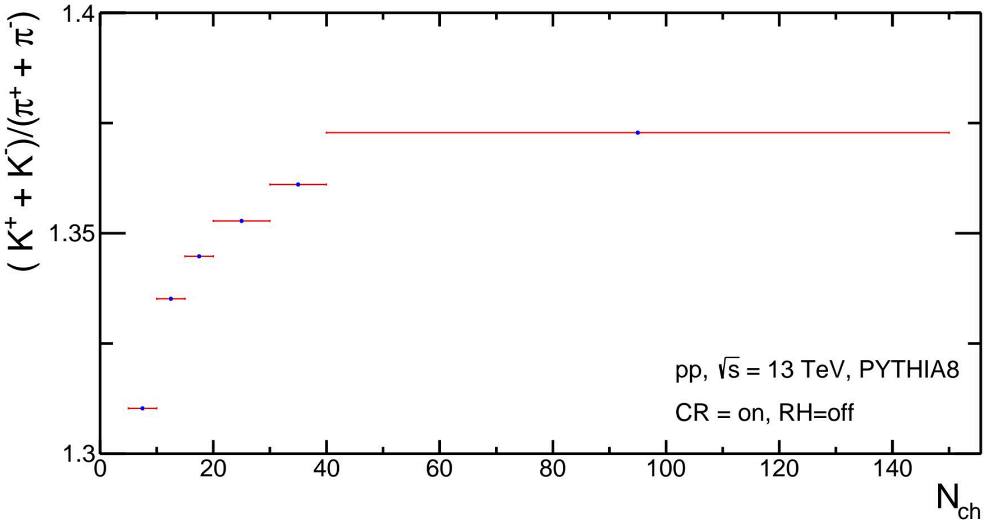
(b) Strangeness enhancement plot for $(\Lambda + \bar{\Lambda})/\pi^{\pm}$ ratio using PYTHIA8 for p-p collision at $\sqrt{s}$ = 13 TeV with CR on and RH off

Figure 3.5: Comparision for RH on and RH off using $(\Lambda + \bar{\Lambda})/\pi^{\pm}$ ratio using PYTHIA8

Figure, 3.6a , 3.6b , 3.7a and 3.7b shows the similar trends which are being expected also.

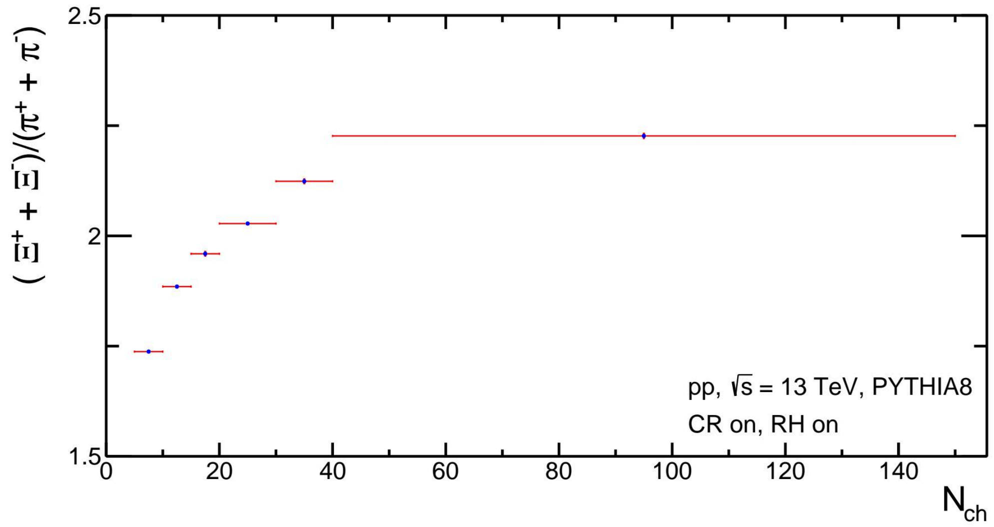


(a) Strangeness enhancement plot for $(K^{\pm}/\pi^{\pm})$ ratio using PYTHIA8 for p-p collision at $\sqrt{s} = 13$ TeV with CR on and RH on

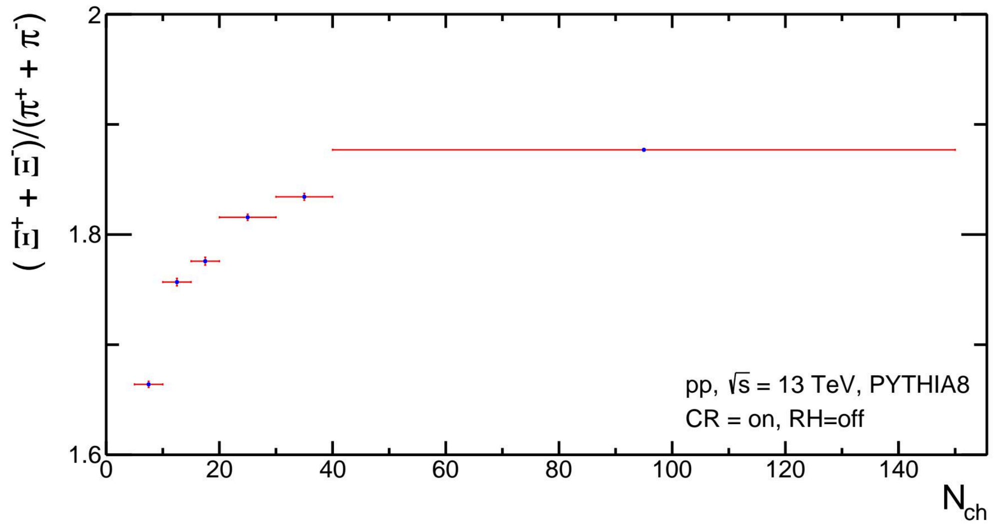


(b) Strangeness enhancement plot for $(K^{\pm}/\pi^{\pm})$ ratio using PYTHIA8 for p-p collision at $\sqrt{s}$= 13TeV with CR on and RH off

Figure 3.6: Comparision for RH on and RH off using $(K^{\pm}/\pi^{\pm})$ ratio using PYTHIA8



(a) Strangeness enhancement plot for $(\Xi^{\pm}/\pi^{\pm})$ ratio using PYTHIA8 for p-p collision at $\sqrt{s} = 13$ TeV with CR on and RH on



(b) Strangeness enhancement plot for $(\Xi^{\pm}/\pi^{\pm})$ ratio using PYTHIA8 for p-p collision at $\sqrt{s} = 13$ TeV with CR on and RH off

Figure 3.7: Comparision for RH on and RH off using $((\Xi^{\pm}/\pi^{\pm}))$ ratio using PYTHIA8

Now, we have taken the ratios for the RH on and RH off mechanisms to show the effect of rope hadronization on strangeness enhancement.

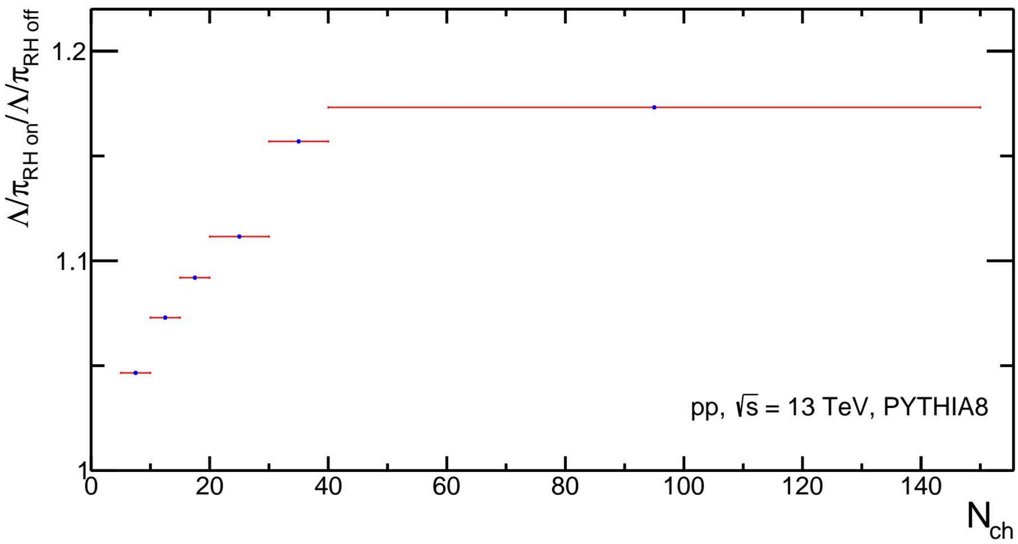


Figure 3.8: Ratio for $\frac{\Lambda/\pi_{RHon}}{\Lambda/\pi_{RHoff}}$ in p-p collisions at $\sqrt{s}$ = 13 TeV using PYTHIA8

In figure, 3.8, the ratio is plotted for the RH on and RH off (for Λ/π ratio). It is observed that with increase in multiplicity the ratio is increasing which shows that the RH on mechanism favours the strange particle production as compared to RH off.

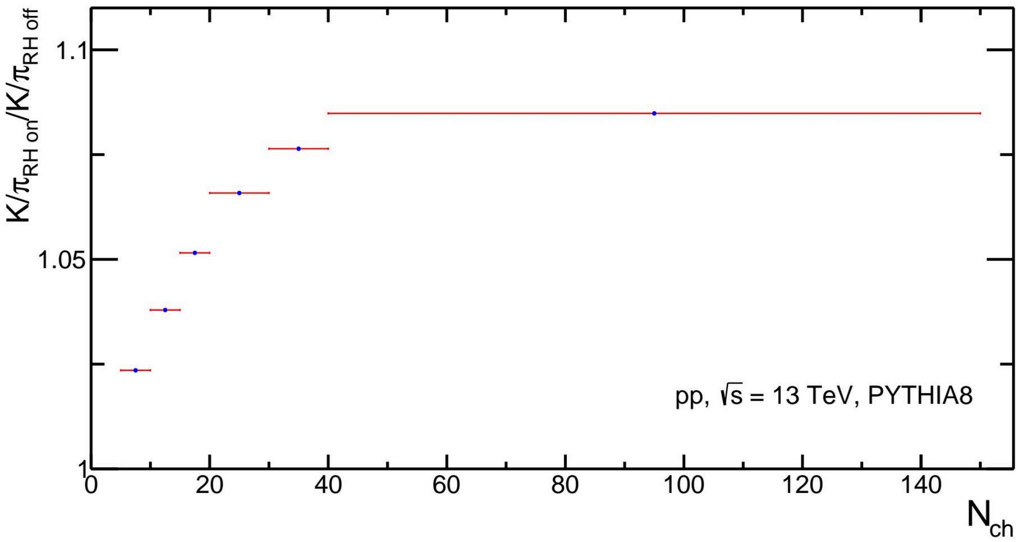


Figure 3.9: Ratio for $\frac{K/\pi_{RHon}}{K/\pi_{RHoff}}$ in p-p collisions at $\sqrt{s}$ = 13 TeV using PYTHIA8

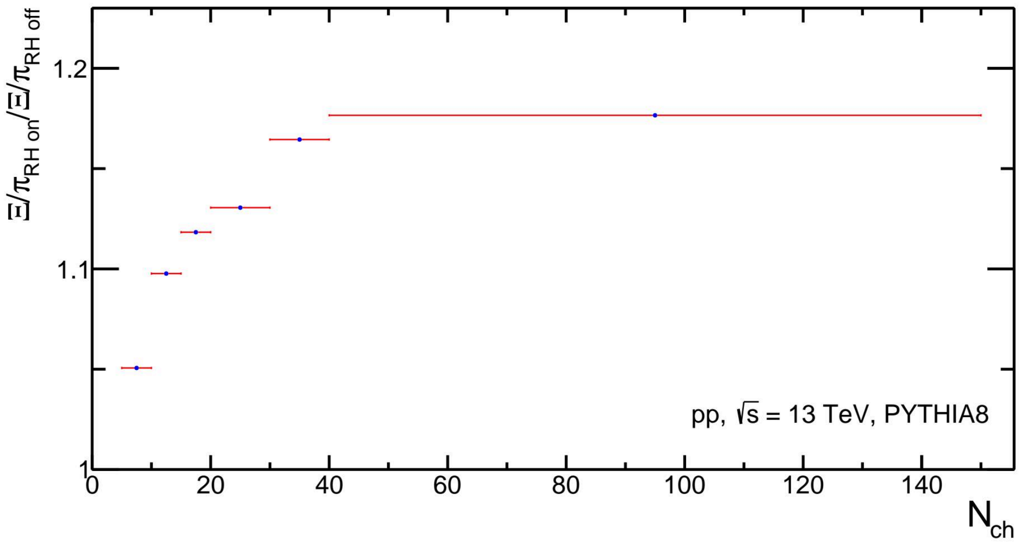


Figure 3.10: Ratio for $\frac{\Xi/\pi_{RHon}}{\Xi/\pi_{RHoff}}$ in p-p collisions at $\sqrt{s}$ = 13 TeV using PYTHIA8

Similar observations have been found for K/π ratio (3.9) and Ξ/π ratio (3.10).

Chapter 4

Preliminary results for the heavy flavored particles

Till now, we have shown the results regarding the light flavored particles. Now, some of the results are shown if we do the similar analysis for the heavy flavored particles with charm quark. The mass of the charm quark is about 1.18-1.34 GeV/c^2 which is higher than the masses of up and down quarks.

For this study we have chosen the following particles:

- $D_s^{\pm}$, quark content of D_s^+ (c$\bar{s}$) and mass is around 1968.34 $\pm$ 0.07 MeV/c^2

- D^0 ,quark content (c$\bar{u}$) and mass is around 1864.83 $\pm$ 0.05 MeV/c^2

- $D^{\pm}$, quark content of D^+ (c$\bar{d}$) and mass is around 1869.65 $\pm$ 0.05 MeV/c^2

The physics idea will be the same by taking the ratio of the strange D mesons to the non strange D meson and then to study if PYTHIA8 can explain the strangeness enhancement trend and then to study the effect of rope hadronization.

4.1 Yields as a function of p_T

For the generation of events, we have used the hard scattering processes (HardQCD:all=on) as it favours the production of heavy flavored particles. To avoid the divergences of QCD processes in the limit $p_T \to 0$, a transverse momentum cut is taken (PhaseSpace:pTHatMinDiverge = 0.5). Also, for the production of charm quarks, we have used Charmonium:all flag (Charmonium:all = on) in the simulation.

The tuning for the RH is similar as in the table 3.1 (with MPI on).

Here, we have generated 15 million events for p-p collisions at $\sqrt{s} =$ 13 TeV using PYTHIA8.

Transverse momentum distribution of D^0, $D^{\pm}$ and $D_s^{\pm}$ have been shown:

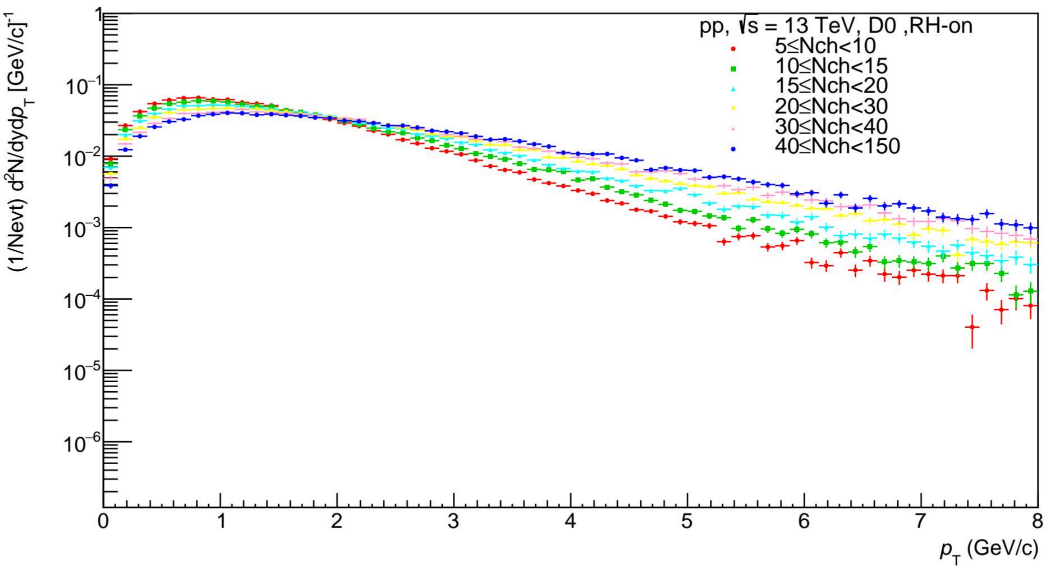


Figure 4.1: Transverse momentum distribution of D^0 in p-p collisions at $\sqrt{s}$ = 13 TeV for $\mid y \mid < 0.5$ generated with PYTHIA8 generator with RH on

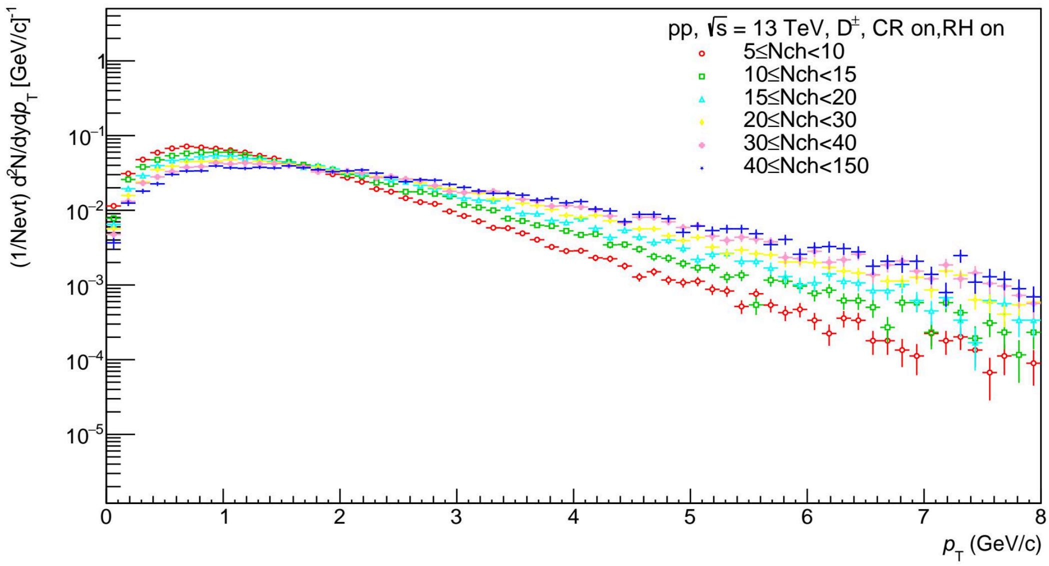


Figure 4.2: Transverse momentum distribution of $D^{\pm}$ in p-p collisions at $\sqrt{s} = 13$ TeV for $| y |< 0.5$ generated with PYTHIA8 generator with RH on

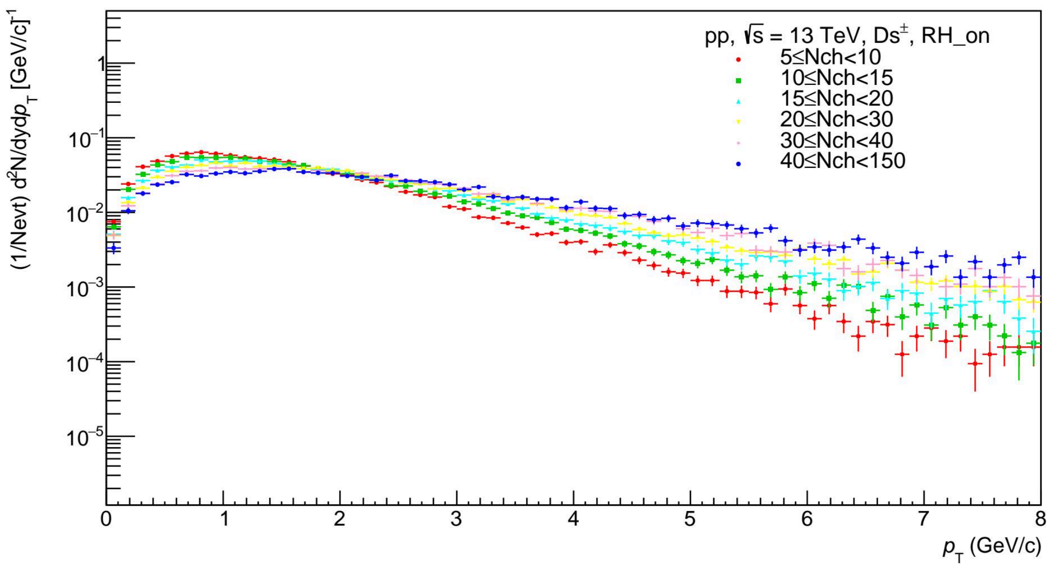


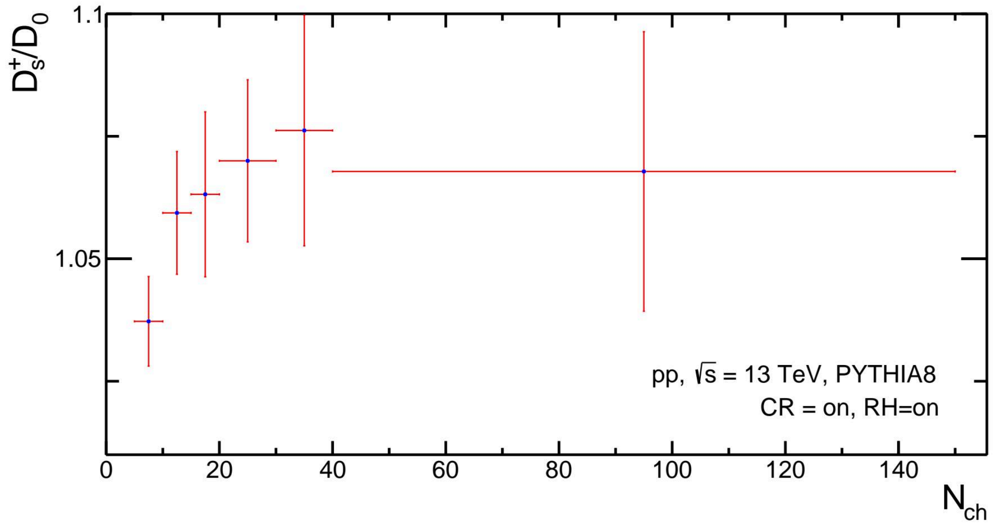
Figure 4.3: Transverse momentum distribution of $D_s^{\pm}$ in p-p collisions at $\sqrt{s} = 13$ TeV for $| y |< 0.5$ generated with PYTHIA8 generator with RH on

4.2 Ratios of particle yields

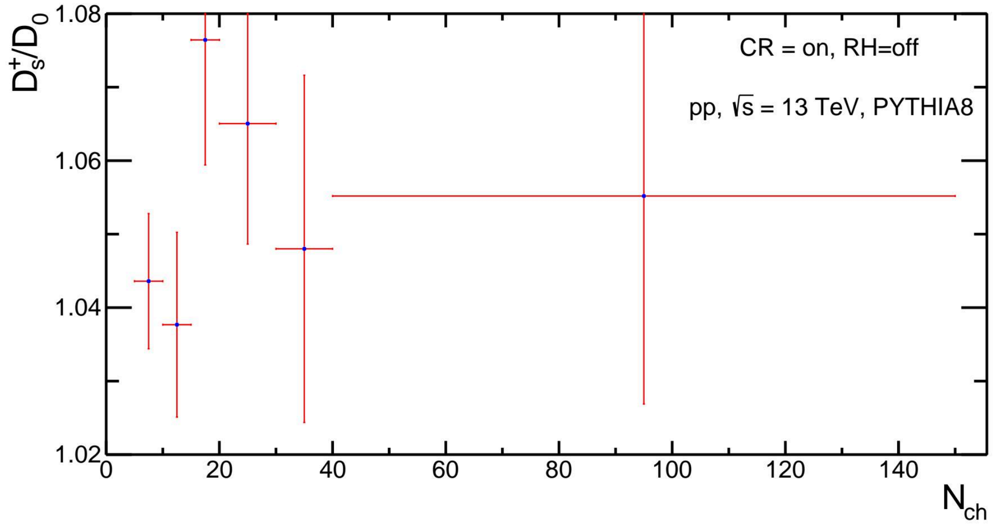
From figure 4.4a and 4.4b, it is clear that RH with the CR-on (MPI-on) is able to explain the strangeness enhancement trend. But without the

RH mechanism the plot becomes scattered. Although the error bar is quite large, this must be because of the reason of less statistics.

Similarly, we can plot the other ratios of strange and non strange particles (eg. D_s^+/D^+ etc).



(a) Particle ratio for D_s^+/D^0 using PYTHIA8 for p-p collision at $\sqrt{s} = 13$ TeV with CR on and RH on



(b) Particle ratio for D_s^+/D^0 using PYTHIA8 for p-p collision at $\sqrt{s} = 13$ TeV with CR on and RH off

Figure 4.4: Comparision for RH on and RH off using D_s^+/D^0 ratio using PYTHIA8

Now, we have taken the ratios for RH on and RH off mechanisms to show the effect of rope hadronization on strangeness enhancement. With the increase in multiplicity the ratio tends to increase which shows that the RH mechanism favours the strange particle production.

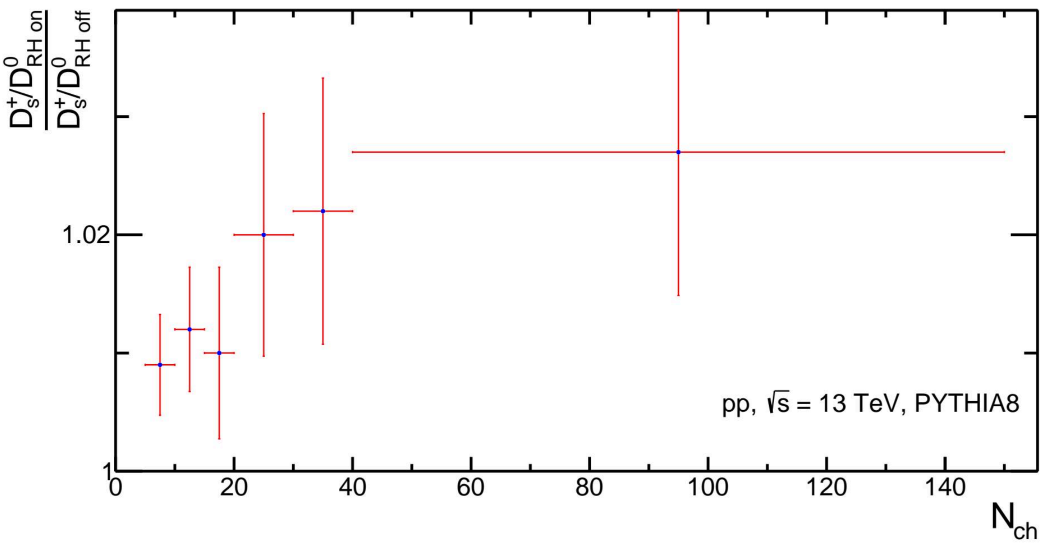


Figure 4.5: Ratio for $\frac{D_s^+/D^0_{RHon}}{D_s^+/D^0_{RHoff}}$ in p-p collisions at $\sqrt{s}$ = 13 TeV using PYTHIA8

Chapter 5

Summary

In this whole thesis, we have studied the basics of the QCD, QCD phase diagram, Quark Gluon Plasma (QGP), its signatures and some basics of the relativistic kinematics. After, the discussion of the aforementioned topics, we have discussed about the motivation of the work and the analysis tools used in this particular work, i.e., PYTHIA8 (event generator) and CERN ROOT framework.

In the results and discussion section, we have carried out the whole analysis using the PYTHIA8 model and have generated the events for proton-proton (p-p) collisions at $\sqrt{s} = 13$ TeV.

We have obtained the transverse momentum distribution for, π, K, Λ and Ξ particles with the rope hadronization process on (and CR on). Then, we have taken the particle ratios (strange to non-strange particles) to study the effect of rope hadronization on the strangeness enhancement. We have obtained that the rope hadronization mechanism enhances the production of strange and multistrange hadrons.

Also, we have extended the research for heavy flavored particles, with charm quark. So, we have obtained their p_T spectra, for $D^0, D_s^{\pm}$ and $D^{\pm}$ particles. We have seen that the ratio for D_s^+/D^0 shows the strangeness enhancement trend with increase in multiplicity within the framework of rope hadronization and there is no clear dependence of strangeness enhancement when RH is off.

Bibliography

[1] Georges Aad, Tatevik Abajyan, B Abbott, J Abdallah, S Abdel Khalek, Ahmed Ali Abdelalim, R Aben, B Abi, M Abolins, OS AbouZeid, et al. Observation of a new particle in the search for the standard model higgs boson with the atlas detector at the lhc. *Physics Letters B*, 716(1):1–29, 2012.

[2] Jaroslav Adam et al. Enhanced production of multi-strange hadrons in high-multiplicity proton-proton collisions. *Nature Phys.*, 13:535–539, 2017.

[3] S. Bethke. s 2002. *Nuclear Physics B - Proceedings Supplements*, 121:74–81, 2003.

[4] Rajeev S. Bhalerao. Relativistic heavy-ion collisions. pages 219–239, 2014. Comments: Updated version of the lectures given at the First Asia-Europe-Pacific School of High-Energy Physics, Fukuoka, Japan, 14-27 October 2012. Published as a CERN Yellow Report (CERN-2014-001) and KEK report (KEK-Proceedings-2013-8), K. Kawagoe and M. Mulders (eds.), 2014, p. 219.

[5] Christian Bierlich. Microscopic collectivity: The ridge and strangeness enhancement from string–string interactions. *Nucl. Phys. A*, 982:499–502, 2019.

[6] Christian Bierlich, Gösta Gustafson, Leif Lönnblad, and Andrey Tarasov. Effects of overlapping strings in pp collisions, 2015.

[7] Serguei Chatrchyan, Vardan Khachatryan, Albert M Sirunyan, Armen Tumasyan, Wolfgang Adam, Ernest Aguilo, Thomas Bergauer,

M Dragicevic, J Erö, C Fabjan, et al. Observation of a new boson at a mass of 125 gev with the cms experiment at the lhc. *Physics Letters B*, 716(1):30–61, 2012.

[8] T. Matsui and H. Satz. J/ suppression by quark-gluon plasma formation. *Physics Letters B*, 178(4):416–422, 1986.

[9] Ranjit Nayak, Subhadip Pal, and Sadhana Dash. Effect of rope hadronization on strangeness enhancement in mml:math xmlns:mml="http://www.w3.org/1998/math/MathML" display="inline"mml:mrowmml:mip/mml:mimml:mtext-/mml:mtextmml:mip/mml:mi/mml:mrow/mml:math collisions at LHC energies. *Physical Review D*, 100(7), 2019.

[10] Roman Pasechnik and Michal Šumbera. Phenomenological review on quark–gluon plasma: Concepts vs. observations. *Universe*, 3(1):7, 2017.

[11] Johann Rafelski and Berndt Müller. Strangeness production in the quark-gluon plasma. *Phys. Rev. Lett.*, 56:2334–2334, 1986.

[12] RaghunathSahoo. Possible formation of qgp-droplets in proton- proton collisions at the cern large hadron collider. *AAPPS Bulletin*, 29(4):16–20.

[13] Bhagyarathi Sahoo, Suman Deb, and Raghunath Sahoo. Multiplicity, transverse momentum and pseudorapidity dependence of open-heavy flavored hadron production in proton+ proton collisions at \sqrt {s} $= 13tev.arXivpreprintarXiv : 2208.10901, 2022.$

[14] Raghunath Sahoo. Relativistic kinematics, 2016.

[15] Raghunath Sahoo and Tapan K. Nayak. Possible early universe signals in proton collisions at the large hadron collider. *Current Science*, 121(11):1403, 2021.

[16] Torbjörn Sjöstrand, Stefan Ask, Jesper R. Christiansen, Richard Corke, Nishita Desai, Philip Ilten, Stephen Mrenna, Stefan Prestel, Christine O.

Rasmussen, and Peter Z. Skands. An introduction to PYTHIA 8.2. *Computer Physics Communications*, 191:159–177, 2015.

[17] P. Skands, S. Carrazza, and J. Rojo. Tuning PYTHIA 8.1: the monash 2013 tune. *The European Physical Journal C*, 74(8), 2014.

[18] CY WONG. Introduction to High-Energy Heavy-Ion Collisions, 1994.