STUDY OF EVENT ACTIVITIES IN HIGH-MULTIPLICITY PROTON + PROTON COLLISIONS USING PYTHIA8

M.Sc. Thesis

by

Debasish Sahoo

DISCIPLINE OF PHYSICS

INDIAN INSTITUTE OF TECHNOLOGY INDORE

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STUDY OF EVENT ACTIVITIES IN HIGH-MULTIPLICITY PROTON + PROTON COLLISIONS USING PYTHIA8

A THESIS

Submitted in partial fulfillment of the requirements for the award of the degree

of

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by

Debasish Sahoo (1703151003)

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INDIAN INSTITUTE OF TECHNOLOGY INDORE

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Dedicated

to

My Family

INDIAN INSTITUTE OF TECHNOLOGY INDORE

CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **"STUDY OF EVENT ACTIVITIES IN HIGH MULTIPLICITY PROTON + PROTON COLLISIONS USING PYTHIA8"** in the partial fulfillment of the requirements for the award of the degree of **MASTER OF SCIENCE** and submitted in the **DISCIPLINE OF PHYSICS, Indian Institute of Technology Indore**, is an authentic record of my own work carried out during the time period from JULY 2018 of joining the M.Sc. program to JUNE 2019 of M.Sc. Thesis submission under the supervision of Dr. Raghunath Sahoo, Associate 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 other institute.

Debasish Sahoo

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

M.Sc. Thesis Supervisor

(Dr. Raghunath Sahoo)

Debasish Sahoo has successfully given his M.Sc. Oral Examination held on ___________________

M.Sc. Thesis Supervisor Date:	Convener, DPGC Date:
PSPC Member 1. Date:	PSPC Member 2. Date:

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"There are some people in life that make you laugh a little louder, smile a little bigger and live just a little bit better"....FRIENDS. I would like to thank all my friends for their support and encouragement and making the stay at IIT Indore a memorable one. I would also like to thank Suman bhai, Bhaswar bhai, Golam bhai, Ritu didi and all labmates for their continuous support.

Abstract

Heavy-ion collisions provide a unique opportunity for the laboratory tests for understanding the evolution of our Universe. The nuclear matter experiences several stages of evolution, starting from the production of partons to the final state particles like hadrons. In order to collect the evidences about these stages of matter we need to examine some of the signals predicted in the evolution of the early universe. Heavy quarks and their bound states like J/ψ plays an important role in describing the properties of matter at high energy density since they are produced at the early stages of collisions. This thesis comprises the study from the quark level to the formation of hadrons. In this work we have shown the production of charm quarks and its correlation with the production of heavy flavour (J/ψ) and open heavy flavour (D meson) particles in high multiplicity $p+p$ collision using the pQCD inspired model PYTHIA8. In order to have the information about screening effect due the presence of medium, we have done a study regarding the suppression of yields in case of high multiplicity p+p collisions. We have explained another important method called two particle azimuthal correlation, to explain the properties of the strongly interacting nuclear matter produced in ultra-relativistic heavy ion collisions. In this current work we have presented the measurements of two particle azimuthal correlation with neutral pion (π^0), neutral kaon (k^0) and proton as trigger particles having the highest transverse momentum (p_T) and associated charged hadrons having transverse momentum (p_T) > 0.5 GeV/c in an event. This has been done on the basis of the difference in azimuthal angle ($\Delta\phi$) and pseudorapidity ($\Delta\eta$) at midrapidity in p+p collisions at $\sqrt{s} = 13$ TeV using a widely accepted theoretical model - PYTHIA8. Measurements based on the multiplicity dependent study can also explain the particle production as well as hadronization mechanisms at different multiplicities. We have used the two particle angular correlation function in order to

extract the flow coefficients, which explains the collectivity of the matter formed and the effect of multi-partonic interactions in case of collectivity is briefly discussed.

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List of abbreviations

QGP	Quark Gluon Plasma
QCD	Quantum Chromodynamics
MPI	Multi − partonic Interactions
ISR	Initial State Radiation
FSR	Final State Radiation

Chapter 1

Introduction

The physical Universe comprises of energy in various forms like electromagnetic radiation and matter. Matter includes fundamental fermions like quarks, leptons, and their antiparticles. Gauge bosons responsible for different fundamental interactions. Higgs boson is responsible for mass generation. When we move our eyes around us, everything visible to us consists of these smallest units called as fundamental particles. These fundamental particles are controlled by four basic forces provided by nature. These forces are known as Strong force, Weak force, Electromagnetic force and Gravitational force. The standard model of particle physics explains the relation between these particles and the four fundamental forces. For few millionths of a second, just after the Big Bang Nucleosynthesis (BBN), the Universe was filled with an extremely hot, dense soup consisting of all kind of particles moving at the speed of light. This hot mixture was majorly filled with quarks and gluons, which are the fundamental constituents of matter, called as the Quark-Gluon-Plasma (QGP). It is envisaged that heavy-ion collisions at GeV and TeV energies could produce a QGP in the Laboratory. This can give a platform to study a deconfined matter in a volume larger than the hadronic volume. It has been found that the usual temperature for such a state of matter is 10^{15} times the core of the Sun temperature, whereas the energy density is few GeV/fm^3. Compared to the normal nuclear density of 0.17 GeV/fm^3, this is very high and thus this corresponds to nuclear matter at extreme conditions.

1.1 QCD phase diagram

Quantum Chromodynamics (QCD) is the theory of strong interaction. Its elementary building blocks, the quarks and gluons cannot be observed directly, as they are confined within hadronic bound states as constituents. Due to the asymptotic freedom property of QCD, the interactions between the quarks and the gluons are weak at short distances and become stronger as the distance increases. Lattice QCD predicts the formation of a partonic state at high temperature and baryon chemical potentials (μ_B). High temperature and low-μ_B corresponds to an early Universe scenario, whereas low temperature and high-μ_B represents neutron star like astrophysical objects. The diagram containing the hadronic phase and the QGP phase with temperature (T) and net baryon density (μ_B) as the control parameter is known as the QCD phase diagram. Temperatures of the order of $T_c \approx 10^{12}$ K, (were present

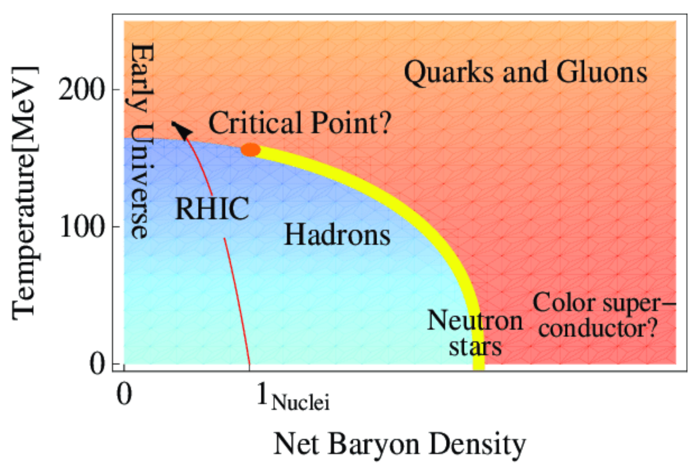

Figure 1.1: QCD phase Diagram [1]

in the early universe evolution) can create the environment for the phase transition

[2]. Baryon densities exceeding the critical value ($\approx 10^{15} g/cm^3$) [2] are present in the interior of compact, dense stellar objects like neutron stars. These are the two cases in which the strongly interacting matter may turn into the Quark-gluon plasma. The QGP phase can also be produced in relativistic heavy-ion collisions in which the center of mass energy ($\sqrt{s}$) acts as a parameter to control the energy density and temperature of the system. The Relativistic Heavy-Ion Collider (RHIC) and the Large Hadron Collider (LHC) operate at high energies in which the deconfined state is achieved. We can also have another state in which quarks and gluons form color cooper pairs at high baryon density and low temperature. This phase is known to be the color superconducting phase. Fig.1.1 represents the QCD phase diagram. At low temperature and high-μ_B hadronic phase is separated from QGP phase through a first 1st order phase transition line. This line ends with a possible critical point (CP), after which the phase transition is a cross-over. This happens at RHIC and LHC energies.

1.2 Heavy-Ion collisions

It is a huge challenge to understand the processes, which led to the creation of the physical world around us. In the Big Bang theory, a singularity in time created our universe, after that its evolution to baryonic matter can be determined by physical processes that took place at different time scales. One of the ways for studying the properties of the nuclear matter (similar to those of the early universe evolution) in the laboratory is through the high-energy heavy-ion collisions. These collisions provide a unique possibility to create and investigate the hadronic matter at high temperatures and high densities in the laboratory.Two nuclei colliding at relativistic energies gives us information about the particle production mechanism and helps to recreate the droplets of matter that has filled the early universe. The first heavy-ion collisions experiment was performed in the 1970s and 80s with fixed target nuclei at the Alternating Gradient Synchrotron (AGS) in Brookhaven and the Super

Proton Synchrotron (SPS) in CERN with the center of mass energies of 33 GeV and 400 GeV respectively. Most of the recent experiments are performed at the RHIC in Brookhaven National laboratory and the ALICE detector at the Large Hadron Collider (LHC) at CERN, where the energy has reached ≈ 13 TeV.

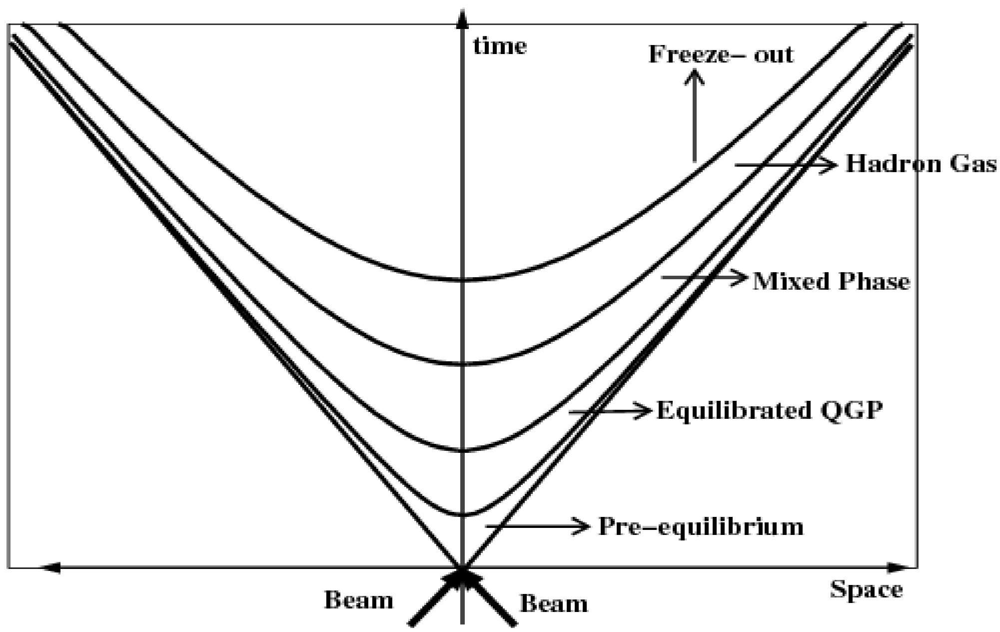

Figure 1.2: Space time evolution of Heavy-ion collisions [3]

These powerful accelerators make head-on collisions between massive ions or nuclei at an energy of the order of some trillion electronvolts (TeV). Fig.1.2 represents the space-time evolution of the heavy-ion collision. When the two Lorentz contracted nuclei collided, momentum and energy transfer occurs among the partons. The energy density is maximum just at the moment of collision and the system is far from equilibrium. This stage is known as the pre-equilibrium stage. It results in the liberation of numerous partons with high transverse momentum (p_T) traveling with a velocity of light and the matter starts expanding. So there is a possibility of multiple scattering between the partons. The hard scattering of the partons leads to the thermalization of the collision fireball. The system starts to expand

and the quarks and gluons become deconfined. This is known as the QGP state. This plasma state gradually expands and cools down. When the temperature of the system reaches the critical temperature, the phase transitions occur and the quarks and gluons forming hadrons. This is known as a mixed phase. The process of hadron formation is called as hadronization. This state of matter is called hadronization. The hadronic matter gradually proceeds towards equilibrium and all the chemical composition of hadrons get fixed, when the inelastic scatterings cease. It is known as the chemical freeze-out stage. We are left with the hadronic gas that continues to cool down until the interaction rates become insufficient to preserve thermal equilibrium in the expanding medium. Gradually the elastic scatterings also stop and the hadrons stream out to reach the detector. This stage is known as the thermal freezeout (or kinetic freeze-out).

1.3 Kinematic variables

In High energy physics, all the particles are treated relativistically. Einstein Special theory of relativity (STR) is applied. According to STR velocity of light (c) always remains constant in any inertial frame. This is known as the invariance of light. All the physical observables like position, momentum are treated as four vectors. It is always good to use Lorentz invariant variables or variables, which show shape invariance under Lorentz transformation.

Fig. 1.3 shows the collision of two Lorentz contracted nuclei approaching each other with velocities nearly equal to the velocity of light. The Z-axis is called as the beam axis. The XY plane is referred to as the transverse plane. where θ is the polar angle i.e the angle between the particle and the Z axis. Azimuthal angle ϕ is the angle measured from the x-axis in the transverse plane. Kinematic variables like rapidity (y), pseudorapidity (η) are discussed below.

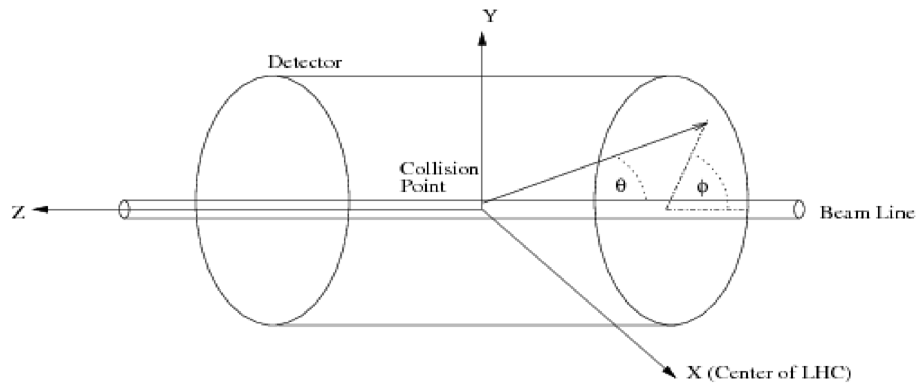

Figure 1.3: Coordinate System for a collider experiment [4]

1.3.0.1 Rapidity

Rapidity is a dimensionless quantity defined as the ratio of the forward light cone momentum (p_+) to the backward light cone momentum (p_-). It is given by the expression

$$y = \frac{1}{2} ln \left(\frac{E + p_z}{E - p_z} \right) = \frac{1}{2} ln \left(\frac{p_+}{p_-} \right) \tag{1.1}$$

Where E and p_z are the energy and z-component of the momentum of the particle, respectively. As the velocities are not additive, we use this variable in case of the heavy-ion collisions. It changes by an additive constant under successive Lorentz boosts [6]. In the case of a non-relativistic particle, the rapidity of the particle is equal to the velocity of the particle in units of c.

1.3.0.2 Pseudorapidity

For the estimation of y, one needs E and p_z, which in turn necessiates to know the particle identification (mass). In high-energy physics particle identification is a technology, which is specific to species of particles. The new variable called pseudo-rapidity defined as

$$\eta = -ln \left(tan \frac{\theta}{2} \right) \tag{1.2}$$

offers the advantage of just knowing θ for its estimation.

1.4 Signatures of QGP

In relativistic heavy-ion collision, the de-confined state of quarks and gluons evolves through different phases before going into the final hadrons. This medium exists only for a few microseconds. To find direct evidence for the existence of this deconfined medium within its small lifetime is quite impossible. There are certain probes, which are generated in the evolving process and can have the information about the deconfined medium. Few of the most promising probes for QGP formation are photon and dilepton production, J/ψ suppression, Strangeness enhancement, jet quenching, elliptic flow, and quarkonia production. Some of the probes which are useful for the current studies are discussed below.

1.4.1 J/ψ Suppression

We can treat QGP in analogous to an electromagnetic plasma. Color charge in the QGP is screened by the presence of colored quarks, gluons. This phenomenon is analogous to the Debye screening in electromagnetic plasma. J/ψ is a bound state of charm (c) and anticharm ($\bar{c}$). As these are heavy particles, they are produced in the early stages of the collision from hard scatterings. So if a J/ψ is produced inside the plasma, the potential between c and $\bar{c}$ will be screened by the presence of other quarks and gluons. This effect is known as Debye screening [7]. As a result of this effect, the production rate of J/ψ would decrease. So the suppression of J/ψ in the high energy heavy-ion collision can be a good probe for QGP. This also helps in the increase of open charm meson; like D^0, D^+, D_s etc.

1.4.2 Elliptic flow

Relativistic heavy-ion collisions produce very large numbers of subatomic particles in all possible directions. In this type of collisions, flow refers to how energy, momentum, and the number of these particles varies with direction. This is an important factor which is related to the initial geometry of the colliding systems. There is a collective motion of particles along the beam direction as well as the expansion of the matter in the transverse plane. Flow along the beam direction is given by the longitudinal expansion and in the transverse plane, it is given by the radial transverse flow and anisotropic transverse flow. The momentum distributions of particles in terms of azimuthal angle can be expressed in terms of a Fourier series and is given by

$$\frac{dN}{p_T dp_T d\phi dy} = \frac{dN}{2\pi p_T dp_T dy}\left[1 + \sum_{n=1}^{\infty} 2v_n cos(n(\phi - \psi))\right] \tag{1.3}$$

where ϕ is the azimuthal angle and ψ represents the reaction plane angle. In non central collisions reaction plane is consists of the beam axis and the impact parameter vector. v_n represents the Fourier coefficients. The v_1 is the directed flow, v_2 is

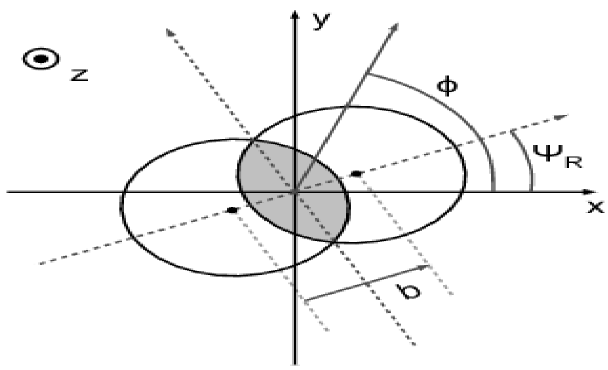

Figure 1.4: Collision mechanism explaining the reaction plane

the elliptic flow and v_3 is the triangular flow. These three quantities describe the magnitude of particle momentum anisotropy. In the case of noncentral collisions, the geometry is almond shape and elliptic flow (v_2) plays an important role. Flow signals represent the number of multiple interactions occurring between the constituents of the medium. More interaction leads to a larger magnitude of flow and the system gradually approaches thermalization. Hence the magnitude of the flow acts as a probe for medium formation. Elliptic flow is strong evidence for the existence of Quark-Gluon-Plasma and has been described as one of the most important observations at the Relativistic heavy-ion Collider (RHIC). Fig.1.4 represents the nucleus nucleus collision showing the reaction plane.

In order to have the information about the existence of QGP in the relativistic heavy-ion collision, we need a suitable probe. J/ψ production and suppression acts as a good probe, as these particles are formed in the early stages of the heavy-ion collision. To have a clear view of the medium properties, we have started off our analysis with the quark level to the particle production mechanism and then the interaction of the particle with the medium. We have analyzed the multiplicity dependence of charm (c) quark production and its conservation in terms of numbers of hadrons formed later such as J/ψ, D mesons etc. In the thesis, we also present the suppression of yields of J/ψ with respect to charged particle multiplicity. The detailed explanation of are given in chapter 3. To have a deeper understanding about the particle production and hadronization mechanism we can use two particle azimuthal correlation as an important tool. There is also an important role of jets in two particle azimuthal correlation as their production and the interactions of jet partons' with the medium gives an overall idea about the medium interacted particles. The surprising discovery of "ridge" in the heavy-ion collisions has opened gates to a vast area of research problems based on the collectivity of the medium. The ridge type structures in small systems (p+p) was first observed in high-multiplicity p+p collisions at $\sqrt{s}$=7 TeV from the analysis of two-particle angular correlations [5]. The ridge appears as a correlation of particles in azimuthal angle ($\Delta\phi$) across some ranges of pseudorapidity ($\Delta\eta$). To have the understanding of the underlying mechanism of particle production and information regarding the medium interacted particles, we have performed the two particle azimuthal correlation of some identified particles like neutral pion (π^0), neutral kaon (k^0) and proton (p). The detailed explanation of this procedure and analysis is given in chapter 4.

This thesis is organized as follows: In Chapter 1 we have given a brief introduction to the topic followed by the defination of the physics problem undertaken here. We briefly discuss the signatures of QGP. In Chapter 2 we have discussed the methodological tools and our motivation regarding the work. This includes the usage of PYTHIA8 and ROOT software. We have presented all analysis regarding the J/ψ and discussed its suppression of yields in Chapter 3. We have presented the detailed explanation regarding the two particle correlation mechanism discuss the flow effects in Chapter 4. At the end in Chapter 5 we summarize our work.

Chapter 2

Motivation & Methodological tools

Now-a-days the high-multiplicity $p+p$ collision at LHC energies are an intense topic in research to the scientific community. In the high-multiplicity $p+p$ collisions, many interesting results have been found [9], where a possible formation of a deconfined medium is under discussion. p+p collision act as a baseline to study the possible effects of QGP. The charged particle multiplicity measured in high-multiplicity $p+p$ collisions at $\sqrt{s}$= 7 TeV exceeds the charged particle multiplicity for peripheral $Cu + Cu$ collisions at $\sqrt{s_{NN}}$ = 200GeV [10]. Therefore, $p + p$ collisions at $\sqrt{s}$ = 13 TeV must be more interesting to look for heavy-ion-like phenomena in $p + p$ collisions. Due to the multipartonic interactions, partons form quark pairs($c\bar{c}$), by interaction among themselves and these quark pairs can change color through emitting gluons and bind into quarkonia pairs ($J/\psi, \psi$). To study whether the high-multiplicity $p+p$ collision exhibit the behavior of heavy-ion like phenomena or not we took one of the observable of heavy-ion collisions in high-multiplicity $p + p$ collisions. Here, the observable is Debye screening. Using PYTHIA8 we tried to study the J/ψ suppression from the basic principle, starting from the formation of heavy quark to its binding into quarkonia state through QCD medium. As these heavy quarks are formed in the early stage of the collision, they pass through all the evolution of the nuclear matter, which helps in finding the existence of QGP.

In order to have the idea about the particle production mechanism, hadronization, and the effects of the interaction of the particle with the medium, the azimuthal correlation among the particles act as an important method. The discovery of a near-side ridge in high-multiplicity pp [5] collisions has increased the interest in two-particle angular correlations in small collision systems. Before hadronization, the jets interact with the medium which results in the energy loss of jet partons inside the medium. These jets can act as a probe to QGP. In order to have the information regarding the medium effect on the particles, this medium interacted particles hold the first preference.

2.1 Experimental Tools

To perform our analysis, we need some methodological tools. Our analysis involves few steps such as :(i) generation of the data (event generation) (ii) Storing the data in trees (Ntuples) (iii) Reading of the data according to our use and analyzing the data for specific physics purpose followed by it. In order to perform the analysis, we have used PYTHIA8.235 for the event generation and ROOT5.34 for the analysis of the generated data.

2.1.1 PYTHIA8

PYTHIA is a program for the generation of high energy physics events in elementary particle collisions written in C++ [11]. The model we are using is a pQCD inspired event generator used for generation of the realistic data, which is comprising of a coherent set of physics models for the evolution from a few-body hard process to a complex multihadronic final state. This version is the successor of PYTHIA 6 which contains a library of processes such as hard processes, and models for initial and final-state parton showers, multiple parton-parton interactions, beam remnants, string fragmentation, and particle decays. MPI is one of the most important ingredients that has been included in Pythia. The generation of data involves three phases, such as

• Initialization, where the tasks to be performed are specified.

• Generation of individual events (the “event loop”).

• Access the properties of particles in individual events(“the particle loop”)

• Finishing, where final statistics are made available

This model has an important ingredient, MPI(Multi partonic interactions) in which the partons interact among each other multiple times via gluon fragmentation to from other partons. This model consists of various processes. Few of the processes are highlighted below:

2.1.1.1 Hard Process

The current PYTHIA contains around 300 different hard processes. These may be classified in many different ways, such as according to the number of final-state objects: we speak of ‘$2 \to 1$’ processes, ‘$2 \to 2$’ ones, ‘$2 \to 3$’ ones [12].

This aspect is very relevant from a programming point of view, the more particles in the final state, the more complicated the phase space and therefore the whole generation procedure. So PYTHIA is optimized for $2 \to 1$ and $2 \to 2$ processes. We can also differentiate the processes into Hard QCD and Soft QCD processes. The Hard QCD group contains the processes for QCD jet production above some minimum p_T threshold. The Soft QCD processes include all the elastic, inelastic, and diffractive part of the total cross section.

2.1.1.2 Multi partonic interactions

Multi partonic interactions(MPI) is defined as a large number of interactions occur in parallel in a single $p + p$ events. Due to the large no of interactions, the parton densities rescaled after each interaction taking into account the nature of the precede interaction. In the standard QCD $2 \to 2$ process, the possibility of multiple interactions producing prompt photons, charmonia, and bottomonia, is also observed.

2.1.1.3 Hadronization

Hadronization is the process of formation of hadrons out of the quarks and gluons. Color reconnection is the final step before the hadronization occurs, in which there is a certain probability for the partons of two sub scattering to have their colors inter-arranged in a way that reduces the total string length. In this model, this process is based on the Lund string model in which outgoing partons are connected to each other due to self-interaction to form strong color field lines otherwise referred to as strings, which are due to the high tension in the gluon field between them. These strings fragment into hadrons when moving apart due to the tension, which increases with the separation.

We can have all the information regarding the particle using the event record listed in PYTHIA8. This contains the particles' history information such as its mother and daughter indices, color flow of the process, component of the momentum four vectors, and their status codes explaining how the new particle, why it has been added to the event record. We have generated all our data using this program. Another important tool used to analyze the data is ROOT, explained below in detail.

2.1.2 ROOT

The ROOT Data Analysis Framework is written in the C++ programming language [13]. It is an open source project coordinated by the European Organisation for Nuclear Research, CERN in Geneva. ROOT is very flexible and provides both a programming interface to use in its own applications and a graphical user interface for interactive data analysis. It was developed in the context of the NA49 experiment at CERN. NA49 has generated an impressive amount of data, around 10 Terabytes per run. This huge amount of data gave an ideal environment to develop and test the next generation data analysis. It is an object-oriented framework that mostly solves data analysis in the high energy physics. This framework contains several c++ libraries to store the data and read the data. In our case, we can store the huge amount of data in histograms as well as in trees (Ntuples) according to our needs. It uses CINT as its C++ interpreter. It gives an interactive environment to read our data from the trees and perform fits in order to have the results of the analysis. We can plot our data using the TGraph class and histogram class (TH class). In the present analysis, we use the root 5.34 version.

Chapter 3

Event activity of charmonium in p+p collsion

Heavy quarks are predominantly produced in the early stage of a collision via parton hard scatterings due to the large mass scale. So heavy quarks like charm ($m_c \approx$1.3 GeV/c^2) and bottom ($m_b \approx 4.5$ GeV/c^2) quarks are useful tools for studying the early collision dynamics. When a quark and anti-quark form a bound state with each other they create a composite particle called as meson. A particle formed by a bound state of a quark and its anti-quark is known as quarkonium. In the starting of the November revolution with the discovery of charm quark J/ψ discovery was announced in 1974 independently by two groups: one led by Samuel Ting at Brookhaven National Laboratory (BNL) in New York and the second lead by Burton Richter at Standford Linear Accelerator Center (SLAC) in California. J/ψ ($c\bar{c}$) meson is known as charmonium which consists of a heavy quark(c) and its own antiquark ($\bar{c}$). It is an electrically neutral charmonium particle with mass 3.1 GeV, spin 1, orbital angular momentum 0 and odd charge conjunction and parity [14]. The production mechanism of heavy quarkonium states (eg. J/ψ) is very complex and is not fully understood. Different models put their explanation, how a heavy resonance state can be produced in hard processes. Some models like color singlet model, nonrelativistic QCD approach and the color evaporation model tried to explain the production mechanism [15]. In the color singlet model, the assumption is made that the $Q\bar{Q}$ pair which evolves into quarkonium are in the color singlet state having the same spin and angular momentum quantum numbers as the quarkonium. In the color evaporation model (CEM) it is assumed that every produced $Q\bar{Q}$ pair evolves into a quarkonium if it has an invariant mass that is less than the threshold for producing a pair of open-flavor heavy mesons.

According to Matsui and Satz [16], it can be stated that the J/ψ yield would be suppressed in the deconfined medium due to the Debye screening of the attractive color force which binds the c and $\bar{c}$ quarks together. Suppression study of the yield of J/ψ in high-multiplicity p + p collision is particularly an interesting signature of QGP formation because it probes the state of matter in the earliest stages of the collision since c & $\bar{c}$ pairs can only be produced at that time. As the J/ψ is a tightly bound state which can not be easily broken by interactions with the hadronic medium and therefore it carries its original message through the different stages of the reacting medium. In the present work, we have studied the multiplicity dependence of charm quark in the initial stages and its correlation with the heavy flavor mesons like J/ψ and open heavy flavor mesons $(D^+, D^-, D^0, etc.)$ produced in the final state. Open heavy flavor mesons are the combination of light quark/antiquark with a heavy quark/antiquark.

3.0.1 J/ψ Suppression & Debye Screening

One of the signatures of QGP is the suppression of J/ψ which consists of heavy quark (c) and its antiquark ($\bar{c}$). As these quarks are produced in the earliest time of the collision in hard scatterings, it can probe the QGP formation. Due to the tightly bound state, J/ψ mesons are not easy to break. In the QGP the suppression of J/ψ can be of two types.

1.**Anomalous Suppression** - $c\bar{c}$ became unbound due to the screening effect called as Debye screening in the plasma and combine with the light quarks to hadronize.

2.**Normal suppression-** The produced J/ψ particles may interact with hadrons and these J/ψ-hadron interactions may lead to the breakup of the J/ψ particles. These two effects are responsible for the suppression of J/ψ in the QGP and subsequent stages. We are taking the screening observable in QGP in analogous to the electromagnetic plasma. electromagnetic plasma is a state of matter in which the electric field is screened by the presence of other mobile charges. Due to the presence of color charge in the QGP, there is a color field which is also subjected to screening. The basic mechanism of the deconfinement of dense matter is the screening of the quark color charge. If the screening radius λ_D less than the binding radius,i.e the hadron radius the confining force cannot hold the quarks together and dissociation occurs. In the current study, we put an analogy between this by taking one of the observable of Debye screening i.e the Debye length and calculating it for both the potential. **Calculating for electromagnetic plasma :**

Let's put a point charge q into a plasma in which we take with $n_e = n_i$ everywhere in the unperturbed state (before q is introduced). We must ensure that the plasma must be neutral in the unperturbed state. When the charge is introduced, it attracts electrons toward itself and repels ions. We assume that the electrostatic potential $\phi(r)$ having spherical symmetry which is the function of r only. The Electron density is given by

$$n_e(r) = n_0 + n_1(r) \tag{3.1}$$

where n_0 is the ion density. The distribution function for the electrons is modified because the electron energy is affected by the electrostatic potential. The Boltzmann factor $e^{-E/KT}$ becomes

$$exp\left[-\frac{\frac{1}{2}(mv^2) - e\phi}{KT}\right] = exp\left(-\frac{mv^2}{2KT}\right) exp\left(\frac{e\phi}{KT}\right) \tag{3.2}$$

So the electron density can be given by

$$n_e(r) = n_0 exp\left(\frac{e\phi}{KT}\right) \tag{3.3}$$

Now writing the Poission equation and expanding the exponential term to the first order we get

$$\frac{1}{r^2}\frac{\partial}{\partial r}r^2\left(\frac{\partial \phi}{\partial r}\right) = \frac{e^2 n_0}{\epsilon_0 KT}\phi \tag{3.4}$$

We compared the dimension of the above equation and the right-hand side having the dimension of the inverse of length squared. So we called it as Debye length which is given by

$$\lambda = \sqrt{\frac{\epsilon_0 KT}{e^2 n_0}} \tag{3.5}$$

On solving the equation(3.4) we get the solution of the potential of the form

$$\phi(r) = \frac{q}{4\pi\epsilon_0 r}e^{-r/\lambda} \tag{3.6}$$

In the QGP the string tension is zero, so the only type of interaction between c & $\bar{c}$ is Coulombic type. If we place a J/ψ inside the QGP the color charge of c will be screened by quarks, antiquarks and the gluons in the plasma. The effect of Debye screening will modify the long-range Coulombic type interaction to short range Yukawa type interaction with the range given by the Debye screening length λ_D. The short range Yukawa potential is given by

$$V(r) = \frac{q}{4\pi}\frac{e^{-r/\lambda_D}}{r} \tag{3.7}$$

Here we are taking the abelian case in which the screened potential V(r) arises due to three contributions:

1. the potential $V_0(r)$ due the quark c placed at the origin r = 0,
2. the potential $V_q(r)$ due to the quarks of the plasma,
3. the potential $V_{\bar{q}}(r)$ due to the antiquarks of the plasma.

Taking this potential we solved the Poission equation and get the Yukawa type of potential. So the debye length in the abelian case is given by

$$\lambda_D(Abelian) = \sqrt{\frac{6}{g_q q^2}\frac{1}{T}} \tag{3.8}$$

Where $g_q = 6N_f$ the degeneracy of quark gas. The Debye screening length λ_D is inversely proportional to the temperature. At high temperatures, the range of the attractive interaction becomes so small as to make it impossible for the $c\bar{c}$ pair to form a bound state. When this happens, the $c\bar{c}$ system dissociates into a separate c and $\bar{c}$ in the plasma. The c and $\bar{c}$ subsequently hadronize by combining with light quarks or light antiquarks to form open charm mesons. The Hamiltonian for a $q\bar{q}$ system in the quark-gluon plasma is given by

$$H = \frac{p^2}{2\mu} - \frac{\alpha_{eff} e^{-r/\lambda_D}}{r} \tag{3.9}$$

Where α_{eff}= electromagnetic interaction coupling and μ is the reduced mass of the system. So the energy of the system can be written as

$$E(r) = \frac{1}{2\mu r^2} - \frac{\alpha_{eff} e^{-r/\lambda_D}}{r} \tag{3.10}$$

We have used here the uncertainty relation $< p^2 >\approx \frac{1}{r^2}$. Now a bound state is possible if the energy E(r) has a minimum with respect to r. So the condition for extremum is given by

$$\frac{\partial E}{\partial r} = -\frac{1}{\mu r^3} - \alpha_{eff} \left[\frac{-1}{r^2} exp\left(\frac{-r}{\lambda_D}\right) + \frac{1}{r} exp\left(\frac{-r}{\lambda_D}\right) \frac{-1}{\lambda_D} \right] \tag{3.11}$$

or

$$\frac{1}{\mu r^3} = \alpha_{eff} exp\left(\frac{-r}{\lambda_D}\right) \left[\frac{1}{r^2} + \frac{1}{r\lambda_D} \right] \tag{3.12}$$

or

$$\frac{1}{\mu\alpha_{eff}} exp\left(\frac{r}{\lambda_D}\right) = r\left(1 + \frac{r}{\lambda_D}\right) \tag{3.13}$$

So we can write

$$f(x) = x(1+x)e^{-x} = \frac{1}{\alpha_{eff}\mu\lambda_D} \tag{3.14}$$

Where x=r/λ_D. We can obtain the radius of the $q\bar{q}$ system by setting the screening length λ_D to infinite in equation (3.13), we get;

$$r = \frac{1}{\mu\alpha_{eff}} \tag{3.15}$$

Equation(3.14) has the solution only if $(\mu\alpha_{eff}\lambda_D) \leq 0.84$ [16]. From this we can say that the $q\bar{q}$ system will not be bound if $1.19r > \lambda_D$. So by comparing the radius "r" with the screening length we can find that the system remains bound in QGP or not.

3.1 Methodology

For the present study, we have generated 100 million events in $p+p$ collision at $\sqrt{s}$=13 TeV and the whole analysis has been done using ROOT. One of the major improvements in PYTHIA8 with respect to PYTHIA6 is the implementation of MPI scenario, where c and b quarks can be produced via $2 \rightarrow 2$ hard sub-processes [17]. Here in our analysis, we consider all the hard-QCD processes to be switched on for the generation of c quarks and quarkonia as well as open heavy flavor. We have used 4C tuned PYTHIA8 in $p+p$ collision at $\sqrt{s} = 13$ TeV and decay-off all the channels of charmonia as well as all open heavy-flavour mesons (eg. D^{+}, D^{0}, D^{-} *etc.*). The data generated using Pythia are analyzed by ROOT (5.36) having $C++$ interface.

We have stored the data of charm quark in the initial stages and study its correlation with the production of final stage particles like J/ψ, D^{0}, D^{+}, D^{-}, etc. During generating the events for charm, D-mesons, and charmonia, we have specifically calibrated the charm conservation by looking into the numbers of charm quarks at the initial state with the charm-content particle at the final state. This is the most important setting to look into physics, which we want to address. These settings have been dedicatedly done by looking into the event listing of PYTHIA8. For some processes, the momentum of the particle has been shifted by it taking a recoil in the dipole picture of parton showers[11]. As we are studying only the correlation of initial particle formed with the final ones we are preventing the production of copies of the particles. One of the important tool is the use of PYTHIA8 in terms of event listing method.

3.1.1 Results

We have stated the analysis with the first step as transverse momenta spectra of charm, D-meson and J/ψ as the feasibility study, although the used tuning of PYTHIA8 is well describing the charm production. The p_T spectras of J/ψ, D-meson and charm quarks are shown in the Fig.3.1.1

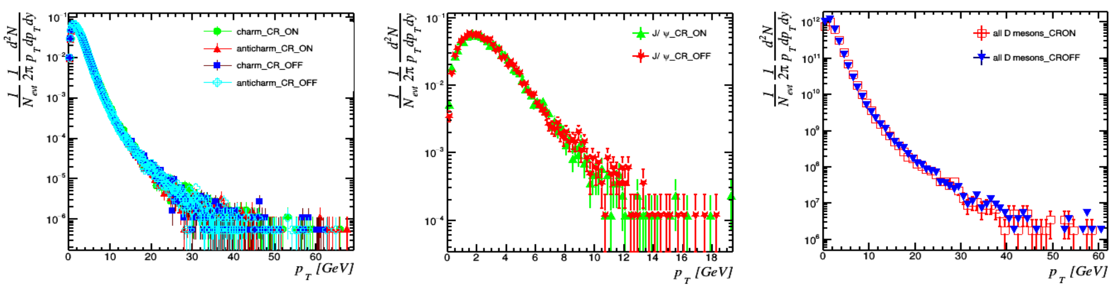

Figure 3.1: (Color Online)(Left) p_{T} spectra of c & $\bar{c}$ (Middle) p_{T} spectra of J/ψ, (Right) p_T spectra of all D group meson

In the second step of the analysis, we have tried to investigate the production of charm, D-meson and J/ψ per event as a function of multiplicity. The results are shown in Fig. 3.2. From the figure, it can be clearly seen that the charm quark production is more at low multiplicity and with decreasing trend saturated towards high-multiplicity, although the opposite trend has been observed for inclusive D-meson and J/ψ cases. To investigate more deeply into it and to have an idea of how much charm-quarks are going to J/ψ or D-meson, we have performed the ratio of D-meson to charm and J/ψ to charm and it is shown in the Fig. 3.3.

From Fig. 3.2 it is clearly visible that the production of the charm quark is not quite affected by the color reconnection process, while From Fig. 3.2 the production of D-mesons is quite more as compared to J/ψ when there is no color reconnection. From this analysis, we can say that the initial state particles are less affected by the color reconnection process as compare to the final state particles.

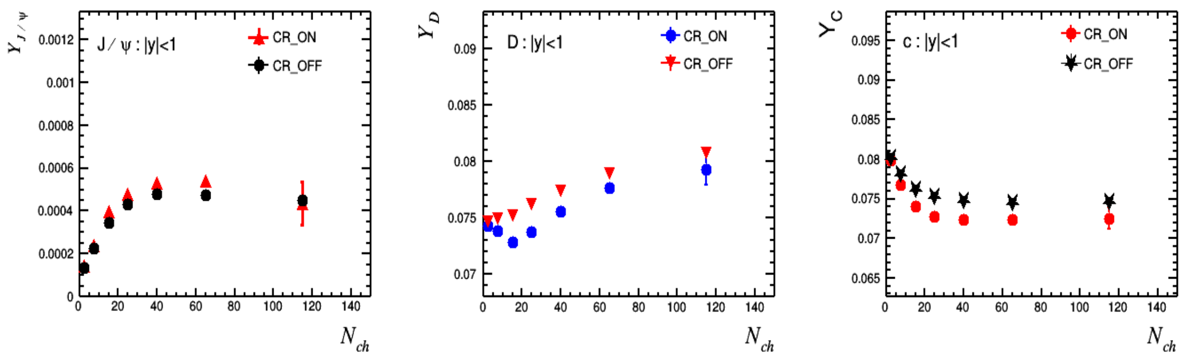

Figure 3.2: (Color Online)(Left) yield of J/ψ vs. N_{ch}. (Middle) yield of all D group meson vs. N_{ch} (Right) Yield of charm vs. N_{ch}

We can conclude the color reconnection process as a final state process as it affects more to the final state particles, and the effect of this process is more on open heavy flavor meson as compared to charmonia.

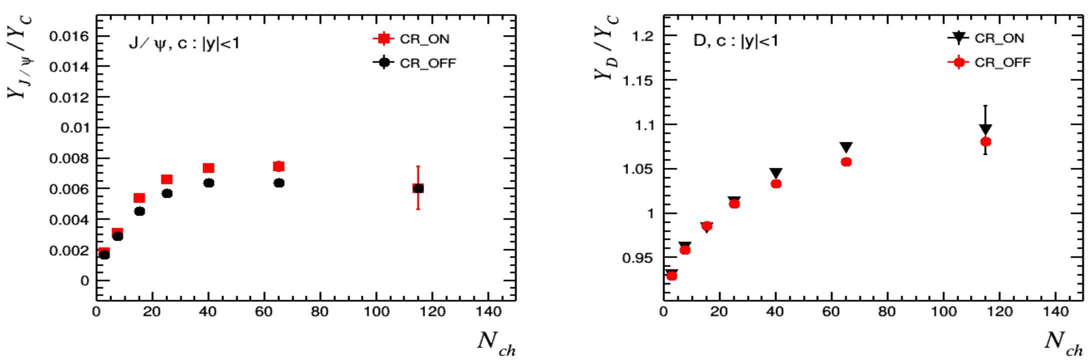

Figure 3.3: (Color Online)(Left) yield ratio of of J/ψ vs. $_{ch}$ (Right) Yield ratio of D meson to charm vs. N_{ch}.

From Fig. 3.3, it can be seen that the yield of D-meson to charm-quark is increasing with multiplicity and towards the higher multiplicity, it is getting saturated. But, the interesting result is coming from the ratio of J/ψ to charm-quark. In the absence of any kind of screening effect, the ratio is expected to increase monotonically with multiplicity, but we found that the ratio is falling towards higher multiplicity, hinting for possible Debye kind of screening due to the formation of QCD medium. The charm-quark produced at the initial state suffer some kind of screening effect from the QCD medium at high-multiplicity, therefore instead of producing charmonia at the final state, it produces D-meson. This mechanism leads to enhancement of D-mesons with the suppression of J/ψ.

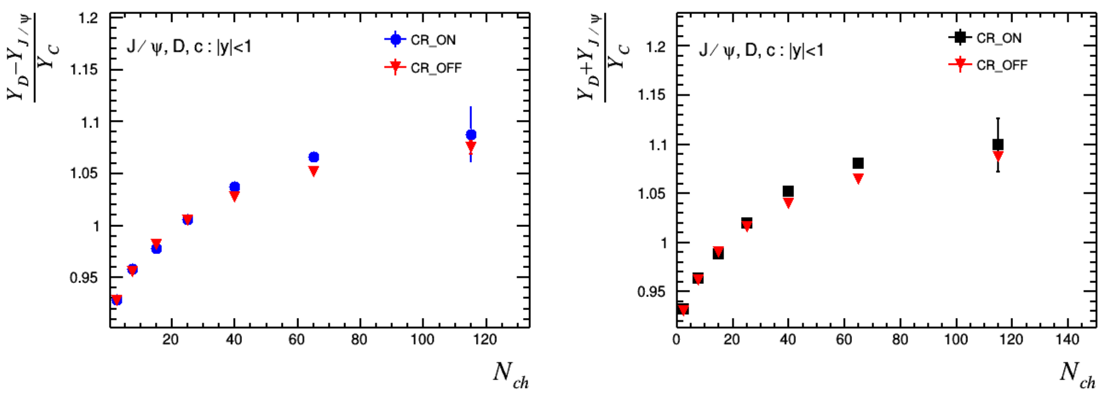

Figure 3.4: (Color Online)(Left) yield ratio of subtraction of J/ψ & all D meson to charm vs. N_{ch}. (Right) ratio of yield of subtraction and addition of J/ψ & D-mesons vs. N_{ch}

Thereafter, we have done the study of relative excess and compensation of J/ψ so that we can have a qualitative idea about the suppressions. As we have assumed, all the charm quark should go to either J/ψ or D-meson, the ratio $(Y_D + Y_{J/\psi})/Y_c$ will give us the uncertainty for qualifying J/ψ suppression. We are getting uncertainties around 7% to 8% which is due to some resonance effects and also the formation of the charmed baryons. With the inclusion of discount as uncertainty, we are getting around 3% suppressions. The J/ψ suppression($(Y_D - Y_{J/\psi})/Y_c$) and composition ($(Y_D + Y_{J/\psi})/Y_c$) to it (taken as uncertainty) are shown in the Fig. 3.4.

Chapter 4

Two particle Azimuthal Correlation

In order to have the knowledge of all of the stages during the evolution of the heavy-ion collisions with time " Two-particle correlation" method acts as an essential tool. Multiparticle correlation in heavy-ion collision at different energies has been studied in order to extract the information about the underlying mechanism of particle production [18]. The discovery of a near-side ridge in high-multiplicity pp and p–Pb collisions has increased the interest in two-particle angular correlations in small collision systems and has opened new areas of research in the small systems [19].

4.1 Why to measure two particle correlation ?

Two particle angular correlations are used to study jet fragmentation, particle in medium interaction. Ideally, fully reconstructed particles explain the particle in medium interactions pretty well. We can also have a reconstructed jet which tells about the jet medium interactions and explains the hadronization mechanism as well. It is difficult to reconstruct jets. First, the detector has finite coverage and limited particle detection capabilities due to which all particles can't be recorded in the detectors. As in high-multiplicity p+p collisions, a large number of final state particles are produced, making it even harder to distinguish which ones are from a jet, which are from the medium, and which are from the interaction between the jet and the medium. Due to such difficulties high p_T particles are substituted for jet as they are the leading fragment of the jet. If the jet interacts with the medium it loses some amount of energy. These jets are mostly generated near the surface of the medium. So, they provide little information as they interacted less with the medium. But these jets are mostly preferred for this analysis because due to momentum conservation the recoiled jet has to pass maximum length through the medium. So we can get the information about the particle production, fragmentation, hadronization and effects due to interaction with the medium.

Two-particle azimuthal correlation is a statistical method where the properties of pairs of particles from each event are studied. This correlation function measures the azimuthal distribution of trigger particle in association with the associated particles in one event in terms of the difference in azimuthal angle ($\Delta\phi$) and pseudorapidity ($\Delta\eta$) [20]. This kind of study is also interesting in high-multiplicity pp collisions at LHC which represent an enhancement of particle pair production at relative azimuth ($\Delta\phi \approx 0$) and particle in medium interaction resulting in the parton energy loss. The two particle correlation function i.e the associated yield per trigger particle is given by;

$$Y(\Delta\phi, \Delta\eta) = \frac{1}{N_{trig}} \frac{d^2 N^{assoc}}{d\Delta\eta d\Delta\phi} = B(0,0)\frac{S(\Delta\phi, \Delta\eta)}{B(\Delta\phi, \Delta\eta)} \tag{4.1}$$

Where N_{trig} represents the number of trigger particles. The associated yield per trigger particle is defined as the number of associated particles with respect to the difference in azimuthal angle $\Delta\phi = \phi_{trig} - \phi_{assoc.}$ and pseudo-rapidity $\Delta\eta = \eta_{trig} - \eta_{assoc}$, relative to the number of trigger particles [21]. Here S($\Delta\phi, \Delta\eta$) represents the same event correlation function that is the per trigger particle yield associated with charged hadrons in the same event normalized by the no of trigger particles.

The expression for same event correlation function given by

$$S(\Delta\phi, \Delta\eta) = \frac{1}{N_{trig}} \frac{d^2 N_{same}^{assoc}}{d\Delta\eta d\Delta\phi} \tag{4.2}$$

Where N_{same}^{assoc} represents the pair of particles from the same event. B$(\Delta\eta, \Delta\phi)$ represents the background distribution function or mixed event distribution function i.e the associated yield per trigger particle in a mixed event. Here the trigger particle is taken from one event and the associated particles are from other events. This function is normalized by a constant factor of α. The expression for background distribution function is given by

$$B(\Delta\eta, \Delta\phi) = \alpha \frac{d^2 N^{mixed}}{d\Delta\eta d\Delta\phi} \tag{4.3}$$

Where N^{mixed} represents the pair of particles from the mixed event. The factor α or B(0,0) is chosen to normalize the background distribution such that it is unity for pairs where both particles go into approximately in the same direction (i.e. $\Delta\phi \approx 0, \Delta\eta \approx 0$). The correlation distributions are unique and show peaks around $\Delta\phi \approx 0$ indicating the production of particles from the same jet and $\Delta\phi \approx \pi$ indicating the production of particles from back to back jets. In order to have knowledge about the collectivity of the medium, we have to study the angular correlation function in terms of Fourier series. The angular azimuthal distribution is represented as;

$$\frac{1}{N_{trig}} \frac{dN_{pair}}{d\Delta\phi} = \frac{N_{pair}}{2\pi} \left[1 + \sum_{n=1}^{\infty} 2 v_n cos(n\Delta\phi) \right] \tag{4.4}$$

Where N_{pair} represents the number of pairs of particles. v_n represents are the Fourier coefficients. Where v_1 is the directed flow; v_2 is the elliptic flow; v_3 is the triangular flow. They describe magnitudes of particle momentum anisotropy. The elliptic flow of a particle can also be calculated by using the following formula given by [22]

$$v_2 = \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \tag{4.5}$$

Where p_x and p_y represent the components of momentum of particles in the X and Y direction of the transverse plane. It measures the correlations of particle emission with respect to the reaction plane. So in terms of azimuthal angle (ϕ) [22], v_2 is given by

$$v_2(\phi) = cos2(\phi - \psi_{RP}) \tag{4.6}$$

where ψ_{RP} is the reaction plane angle i.e the azimuthal angle in the reaction plane.

4.1.1 Event generation & Methodology

For the current study, p + p collision at LHC energies has been chosen as the system. This analysis involves the generation of 1 million of events using p+p collision at $\sqrt{s}$=13 TeV and the whole analysis is done using ROOT software [13] having a C++ interface. We have simulated inelastic, a nondiffractive component of the total cross section for all hard QCD processes by using the flag " HardQCD:all=on". This analysis is performed using the 4C tuned PYTHIA8 (Tune:pp = 5). We have allowed for a large number of interactions to occur in parallel in a single event by using the flag (PartonLevel:MPI=on). We have included the MPI-based scheme of color reconnection (" ColourReconnection: reconnect = on") in which the color flow of two systems can be fused, by the addition of the partons of lower-p_T system with the strings of higher-p_T system to give the smallest total string length. In order to avoid the divergences in the QCD processes at lower limit we have used a transverse momentum cut (p_T = 0.5 GeV/c) using the PYTHIA8 switch (PhaseSpace:pHatMinDiverge=0.5). All trigger and associated particles are chosen under the pseudorapidity range of $|\eta| < 1$ and the whole analysis is done within midrapidity $|y| < 1$. The trigger particles are chosen in such a way that they have the highest p_T in the event and all the associated particles are charged hadrons having $p_T > 0.5$ GeV/c.

4.1.2 Results & Analysis

We have started our analysis in obtaining the p_T spectras for π^0, k^0 and proton and the charged particle multiplicity shown in the fig.4.1. The distribution of the correlation function in the same event as well as in the mixed event. We have formed pairs

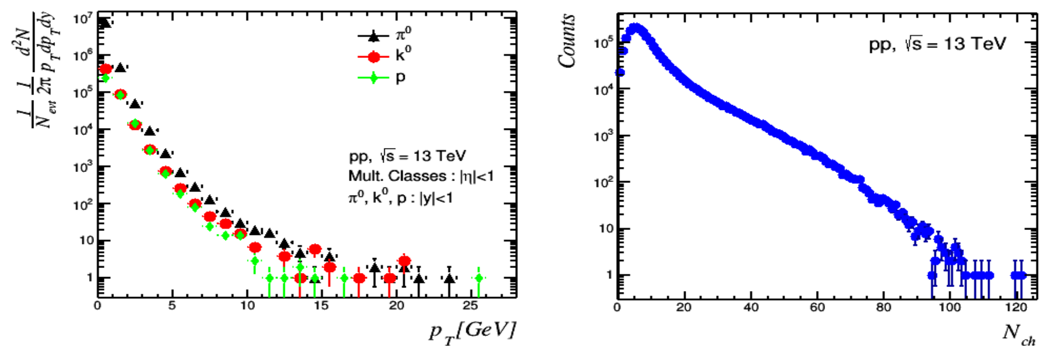

Figure 4.1: (Color Online)(Left) Transverse meomentum spectra of π^0,k^0, p (Right) The charged particle multiplicity distribution for pp collision at $\sqrt{s}$ = 13 TeV

by associating the trigger particle with the associated particles (charged-hadrons) in each event. In the same event or signal correlation function, the trigger particle and the associated charged hadrons are from the same event and in case of mixed event analysis, the associated particles are chosen from different events.

The particle pairs are obtained in terms of the difference in azimuthal angle (i.e $\Delta\phi = \phi_{trig} - \phi_{assoc}$) and pseudorapidity (i.e $\Delta\eta = \eta_{trig} - \eta_{assoc}$) of trigger and associated charged hadrons. In order to rectify the raw correlation distribution (same event distribution), we need to apply the mixed event analysis here. This correction is applied by dividing bin-by-bin the correlation distribution of the same event distributions by mixed event distributions. The ratio of these two distributions is scaled by a factor B (0,0) such that the distribution of mixed event is unity at $\Delta\phi = \Delta\eta = 0$. This particular normalization in hadron-hadron correlation is adopted since at $\Delta\eta = \Delta\phi = 0$, the trigger particle and associated particles experience same detector effects. The ratio of these two distributions is known as the corrected correlation distribution scaled by the total number of trigger particles. Fig. 4.2 represents the correlation distribution for π^0, k^0, p. From Fig.4.2 we can clearly see that there is a sharp peak arises around $\Delta\phi \approx 0$ indicating the formation of particles from the same parent parton. In the near side, there are some

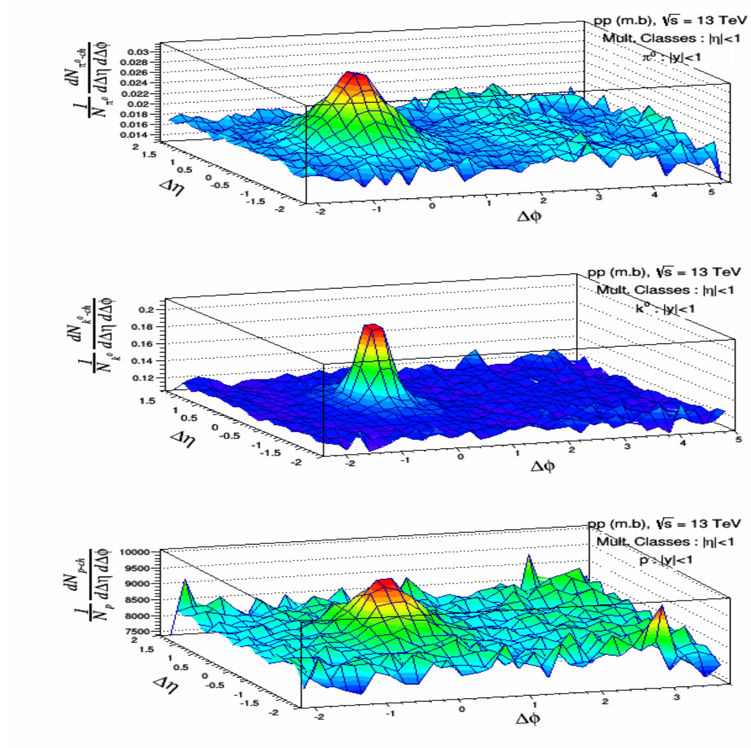

Figure 4.2: (Color Online) Correlation Distribution for pion (π^0) (Top), kaon (k^0) (middle), proton (Bottom)

typical structures elongated in some $\Delta\eta$ range visible, called as ridges (in heavy-ion collision), which are the indication towards the collectivity of the medium.

To have a clear view of the production of particles we have studied the correlation distribution in different charge particle multiplicities. We have divided charged-particle multiplicity to six different classes. Those are given as: $0 \leq N_{ch} < 5$, $5 \leq N_{ch} < 10$, $10 \leq N_{ch} < 20$, $20 \leq N_{ch} < 30$, $30 \leq N_{ch} < 50$, $50 \leq N_{ch} < 120$ respectively.

As the near side structures are indications for flow, we are observing some extended structures in some ranges of pseudorapidity ($|\eta| < 1$) hinting towards some flow kind of behavior as in heavy-ion collision. As we proceed towards high-multiplicity from low-multiplicity due to the increase in the number of multi-partonic

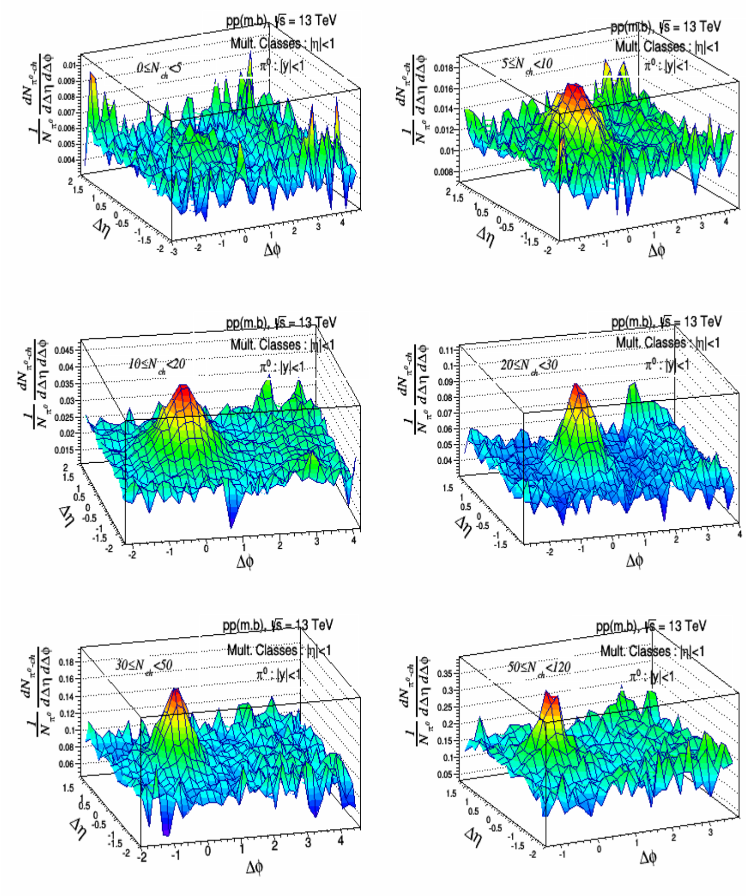

Figure 4.3: (Color Online) Correlation Distribution for pion (π^0) in different multiplicity classes

interactions we can see that the near side peak gradually increases. This explains that more no of the particles are formed from the same jet rather than the recoiled jet.

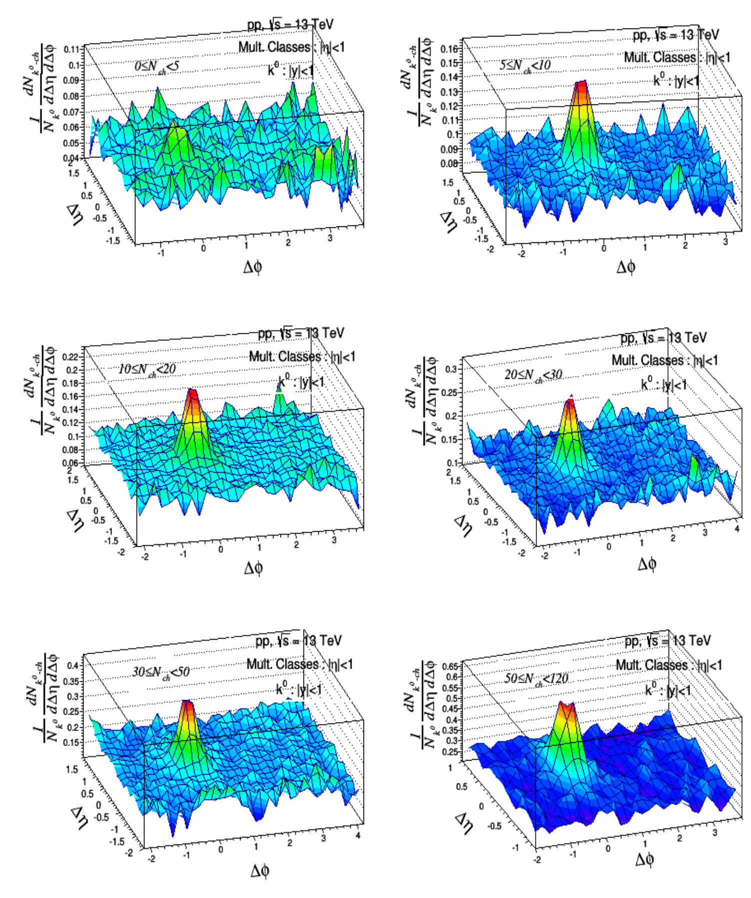

Figure 4.4: (Color Online) Correlation Distribution for kaon (k^0) in different multiplicity classes

Fig. 4.3, 4.4, 4.5 represent the correlation distributions in different charge particle multiplicity classes for π^0, k^0 and p respectively. The final correlation distribution or the 1D-Correlation distribution is obtained by integrating the 3D-Correlation distributions over $\Delta\eta$. The one-dimensional distribution obtained is given by :

$$C(\Delta\eta, \Delta\phi) = \frac{1}{N_{trig}} \frac{dN^{assoc}}{d\Delta\phi} \tag{4.7}$$

In case of π^0, the unique pattern of this distribution tells that the peak around $\Delta\phi \approx 0$, a strong correlation on the near side which indicates that the particles were produced from same parent parton. As a consequence of momentum,

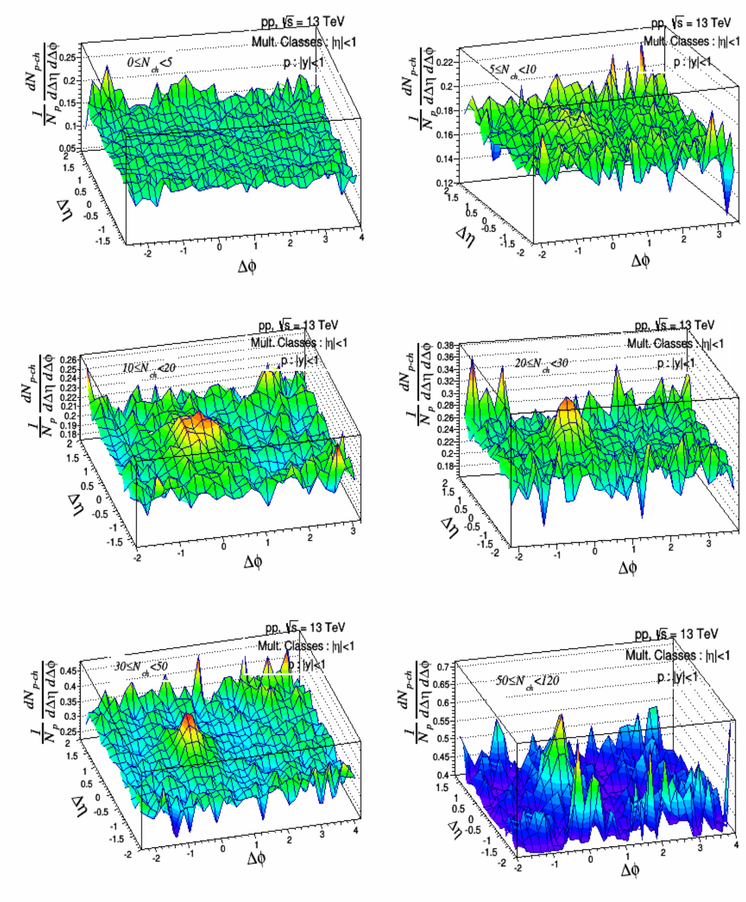

Figure 4.5: (Color Online) Correlation Distribution for proton in different multiplicity classes

energy conservation, recoiled parton too fragments to produce particles resulting in the production of away side the peak around ($\Delta\phi \approx \pi$). The other entries in the histogram reflect the complexity of the underlying events in the strong interactions, where many other particles are produced from the fragmentation of other partons. In case of kaon and proton, we can see that there is suppression of peak on the away side representing the particles formed from the recoiled jet which traversed more path in the medium due to which the jet partons interacted with the medium resulting in energy loss of the partons. Fig. 4.6 represents the 1D-Correlation distribution for minimum bias, low and high charged particle multiplicity classes.

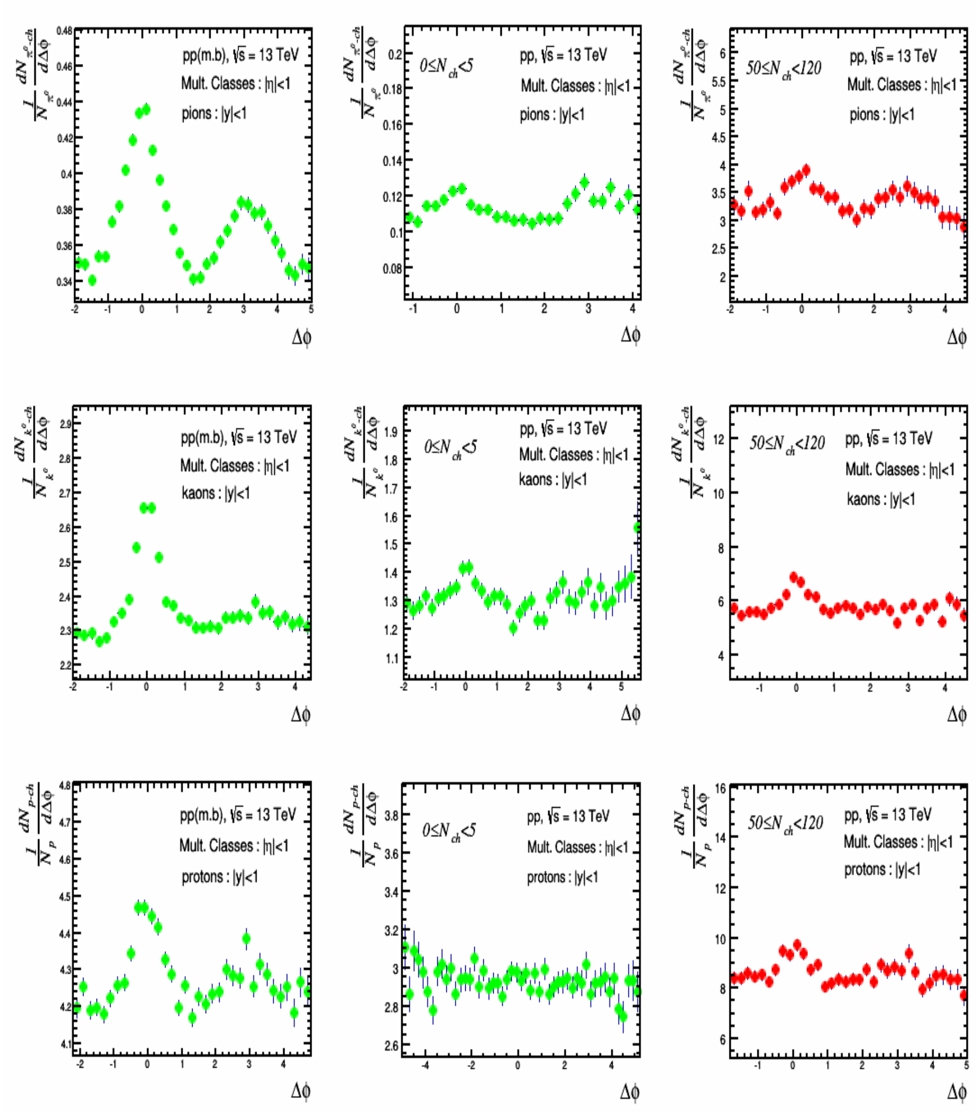

Figure 4.6: Column (I): 1D Correlation distributions Minimum Bias, Column (II): 1D Correlation distributions low-multiplicity ($0 \leq N_{ch} < 5$), Column (III): 1D Correlation distributions high-multiplicity ($50 \leq N_{ch} < 120$) for π^0, k^0, p

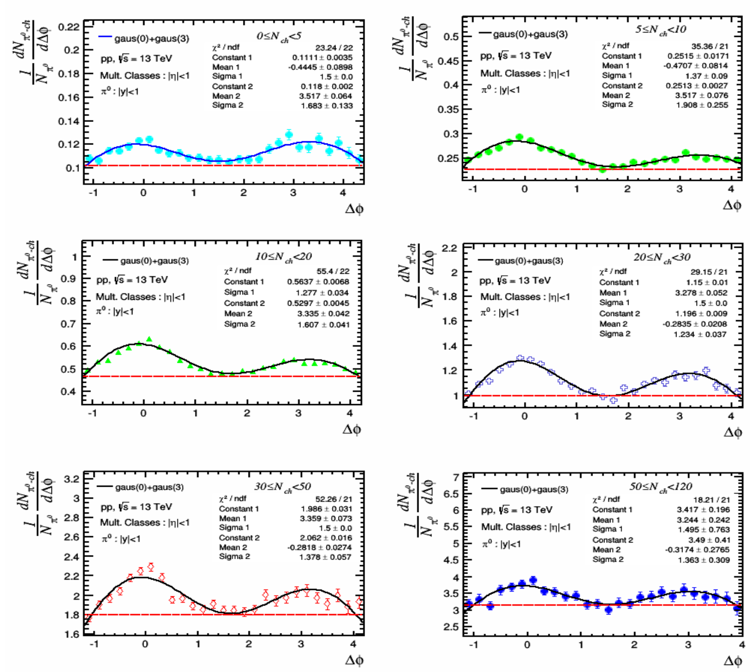

Figure 4.7: (Color Online) Correlation Distribution of π^0 in different multiplicity classes fitted with double gaussian function

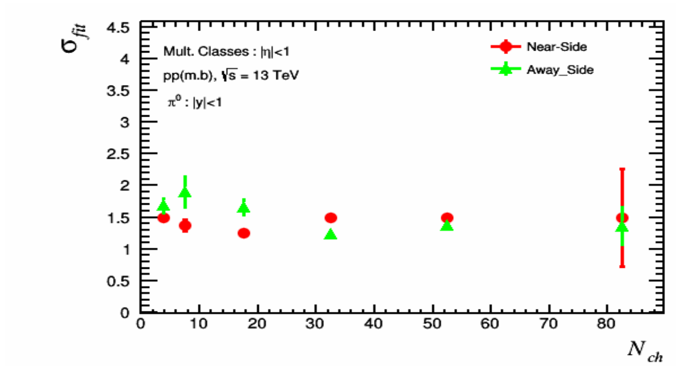

Figure 4.8: (Color Online) σ_{fit} vs. N_{ch} for π^0

In order to quantify the near-side peak shape, the peak is fitted with a sum of two Gaussians functions. Fig. 4.7 represents the 1D-Correlation distributions for π^0 fitted with the double Gaussian function in order to extract the peak widths in near and away side region. Fig. 4.8 represents the multiplicity dependence peak widths for six different charge particle multiplicity classes.

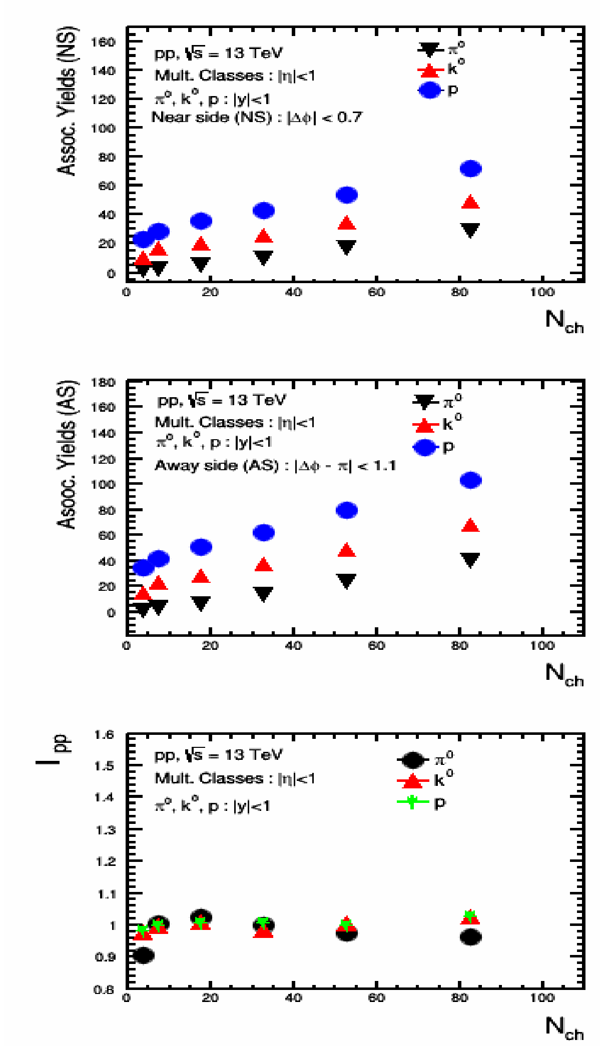

Figure 4.9: (Color Online) Row (I): Near Side yields vs. N_{ch}, Row (II): Away Side yields vs. N_{ch}, Row (III): I_{pp} vs. N_{ch}

From Fig. 4.8 we can see that in the near side the peak width is more than the away side in low-multiplicity classes and then the width of away side is more in comparison to near side as we proceed towards the high-multiplicity classes.

The associated yields on the near and away side are obtained by integrating the 1-D correlation distribution in a certain range. The near side yield is obtained by integrating over a region where $|\Delta\phi| < 0.7$ and the away side is over $|\Delta\phi - \pi| < 1.1$. Fig. 4.9 represents the near and away side yields of pion (π^0), kaons (k^0) and proton. We can observe that the per-trigger near and away-side pair yields as a function of charged particle multiplicity gradually increases with multiplicity, both followed the same trend. We can also see, from Fig. 4.3, 4.4, 4.5 that the yields in the near side is higher for proton and then for kaon and pion. It is quite reflecting the same type of observations through Fig.4.9. In the high-multiplicity region the increase in yields can be explained by a large number of multi partonic interactions, leads to fragmentation of many partons. After $N_{ch} > 20$ the growth in near side yield as compared to away side is significantly observed. The modification in the per trigger yield is calculated by a factor known as I_{pp} is given by:

$$I_{pp} = \frac{(Y_{NS}/Y_{AS})_i}{(Y_{NS}/Y_{AS})_{mb}} \tag{4.8}$$

We can see from Fig.4.9 that in the low-multiplicity region the ratio increases up to $N_{ch} \approx 20$ and then gradually decreases. In the case of π^0, we observed that the away side yield is more as compared to the near side region. In the case of proton and kaon, the ratio of yields is almost equal in the high-multiplicity classes. In the low-multiplicity classes, it gradually increases upto certain N_{ch} and saturating around unity.

In order to have information about the collectivity of the medium the 1D-Correlation distributions for different charge particle multiplicity classes are fitted with equation 4.4. The function is fitted in order to extract the flow parameter value (v_2) in different charged particle multiplicity classes.

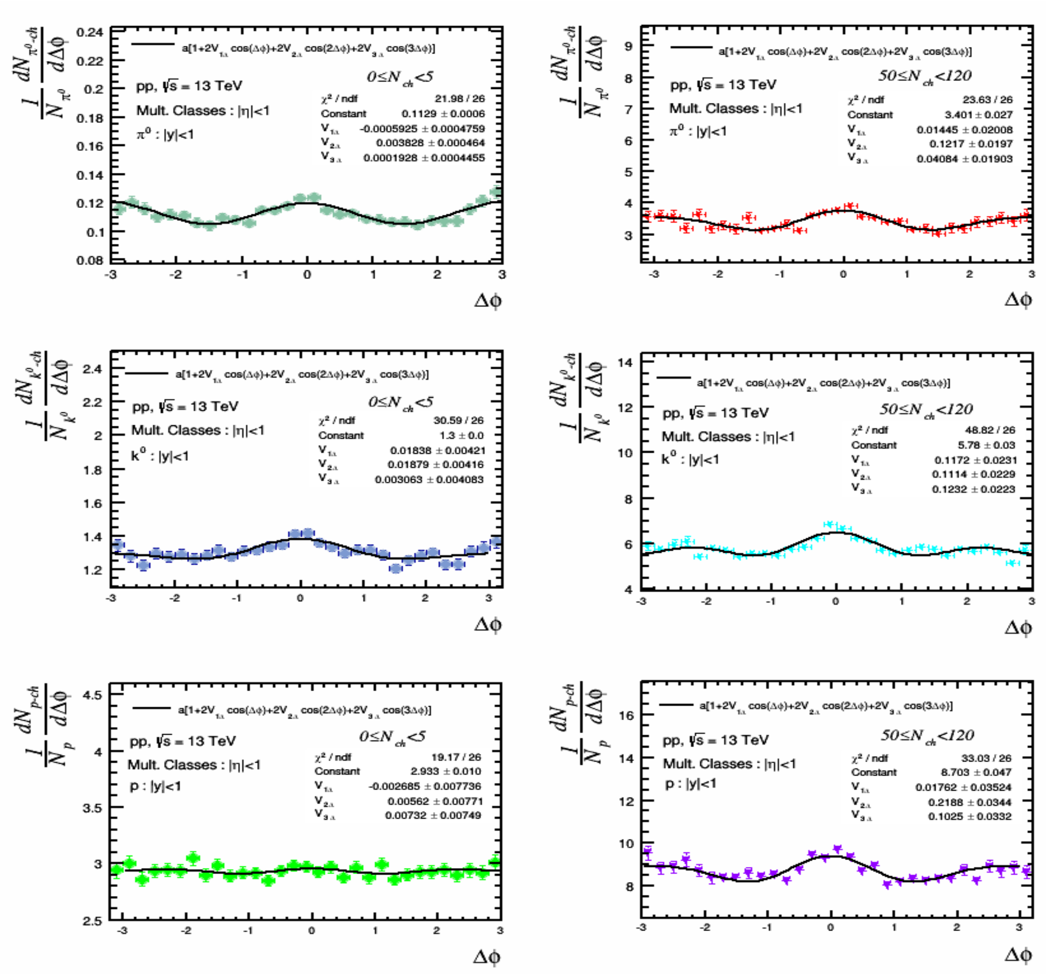

Figure 4.10: (Color Online) Row (I) Near Side yields vs. N_{ch}, Row (II) Away Side yields vs. N_{ch}, Row (III) I_{pp} vs. N_{ch}

Fig. 4.11 represents the value of v_2 vs. N_{ch} for different charge particle multiplicity classes for π^0, k^0, p. We can also observe from Fig. 4.11, the value of v_2 gradually increasing from lower multiplicity classes and getting saturated towards high-multiplicity. This is because, as we move towards higher multiplicity region the number of multi partonic interaction also increases. Due to this phenomena large no of particle produced and hence they move collectively in the medium. As a result, flow increases as shown in Fig. 4.11. We can also distinguish the mass dependency of the particles on v_2 from Fig. 4.11. The mass of the proton is high in comparison

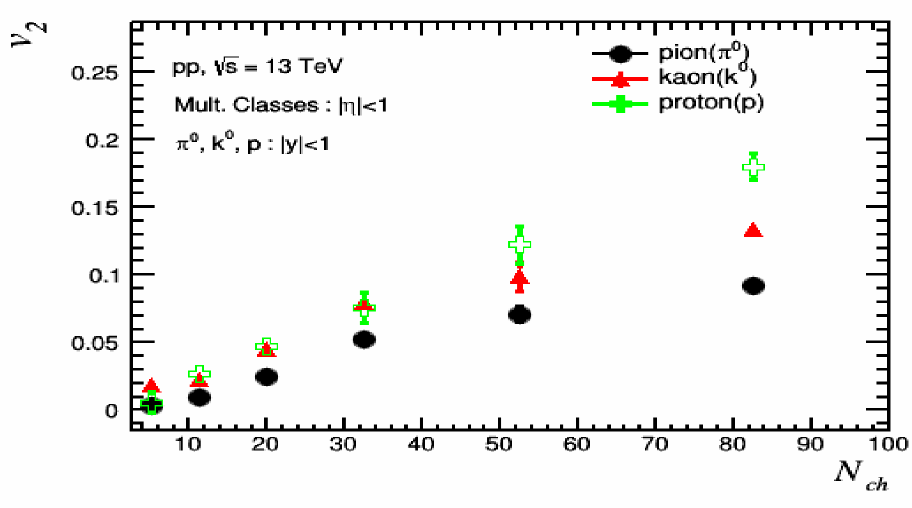

Figure 4.11: (Color Online) v_2 vs. N_{ch} for π^0, k^0, p

to the other two particles under study, it has higher flow like effect compared to other. The Fig.4.12 represents the elliptic flow of π^0, k^0& p calculated from the two

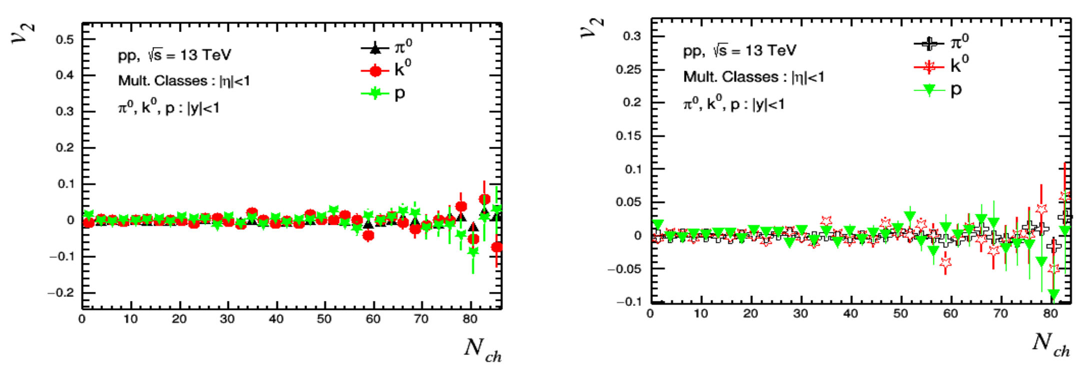

Figure 4.12: (Color Online) v_2 vs. N_{ch} for π^0, k^0, p calculated from equation 4.5(Left) 4.6 (Right)

methods (Equ. 4.5&4.6) mentioned in the above section. The same dataset has been used for the other methods as well. As there is no QGP like medium incorporated with PYTHIA one shouldn't expect any flow like effect. The values represented in Fig. 4.12 are calculated from basic principle of hydrodynamics, therefore as expected v_2 should be zero, because PYTHIA does not incorporate formation of QGP.

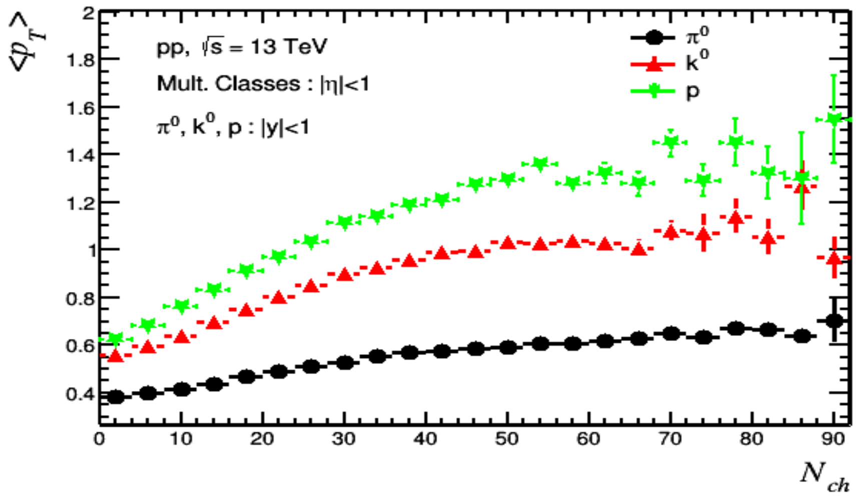

Figure 4.13: (Color Online) (Left) v_2 vs. N_{ch} from equation (4.5) (Right)v_2 vs. N_{ch} from equation (4.6) for π^0, k^0, p

To have detailed information about the flow nature observed in Fig. 4.11, we have analyzed the behavior of mean transverse momentum ($< p_T >$) with respect to the charged particle multiplicity. We have obtained that, as we proceed from low-multiplicity to high-multiplicity, the $< p_T >$ gradually increases upto certain N_{ch} and then gets saturated towards the high-multiplicity region. A similar kind of behavior is observed in the case of flow parameter (v_2) as we have shown in Fig. 4.11. Due to the incohorent superposition of large number of MPIs, the mean transverse momentum saturated towards the high-multiplicity region and is reflected in v_2 as well. So we can say that the flow parameter we got from the two particle correlation method is due to the multi partonic interactions and not due to any kind of QGP like system.

Chapter 5

Summary and Conclusions

we have studied some signatures of QGP, In order to get some evidence for the existence of QGP like matter in particle colliding mechanism. As in the case of high multiplicity p+p collision, there is a possibility of formation of nuclear matter at high energy density, we have analyzed some of the probes to QGP. In Chapter 2 we have studied the production of c quark and relate its production to final state hadrons like J/ψ, D mesons. We also observed the ratio of yield of J/ψ to charm is following an increasing trend in the low multiplicity region. When we proceed towards the high multiplicity there is some suppression of yields hinting towards the screening effect. This suppression yields of J/ψ and the properties of medium interacted J/ψ can be studied in detail by the particle correlation method. We obtained the correlation distributions for π^0, k^0& p and hence observed the underlying mechanism of their production. We have extracted the near and away side yields of the correlation distributions showing the effect of the multi partonic interactions. To have the information about the collectivity of the medium, Elliptic flow parameter (v_2) has been calculated using three different methods. Since there is no QGP like matter formed inside PYTHIA, we are getting the value of flow parameter only by the two particle correlation method. Due to the multi partonic interactions, the particles move collectively and hence the flow is measured. We compare the effect of mean transverse momentum with the flow parameter and hence observed that the flow parameter (v_2) shows the same trend as the $< p_T >$.

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