

**Event shape and Multiplicity dependence of
 ϕ meson production in Proton+Proton
collisions with ALICE at the LHC and
Characterization of Heavy-ion collisions
using Relativistic Kinetic Theory**

Ph.D. Thesis

By

SUSHANTA TRIPATHY



DISCIPLINE OF PHYSICS

INDIAN INSTITUTE OF TECHNOLOGY INDORE

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A THESIS

*Submitted in partial fulfilment of the
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By

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INDIAN INSTITUTE OF TECHNOLOGY INDORE

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Administrative Officer

CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled "EVENT SHAPE AND MULTIPLICITY DEPENDENCE OF ϕ MESON PRODUCTION IN PROTON+PROTON COLLISIONS WITH ALICE AT THE LHC AND CHARACTERIZATION OF HEAVY-ION COLLISIONS USING RELATIVISTIC KINETIC THEORY" in the partial fulfilment of the requirements for the award of **DOCTOR OF PHILOSOPHY** 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 2015 to August 2019 under the supervision of Prof. Raghunath Sahoo, Associate Professor, Discipline of Physics, Indian Institute of Technology Indore, M.P., India.

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.

[Signature of Sushanta Tripathy]
(SUSHANTA TRIPATHY)

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

[Signature of Prof. Raghunath Sahoo]
(Prof. RAGHUNATH SAHOO)

Mr. **SUSHANTA TRIPATHY** has successfully given his Ph.D. Oral Examination held on 18/10/19.....

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*Dedicated to my family, teachers and to the
researchers of basic sciences...*

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(Sushanta Tripathy)

ABSTRACT

From the ancient times, exploration of the unknown has been the intrinsic nature of Mankind, which is also one of the core principles of fundamental research in basic sciences. To explore the nature of the Universe, an engineering marvel, “Large Hadron Collider (LHC)” was built at CERN, Geneva. One of the main goals of the LHC is to study the matter at high temperature and density where quantum chromodynamics (QCD) predicts the existence of quark-gluon plasma (QGP) in ultra-relativistic heavy-ion collisions. In central heavy-ion collisions, nucleons in the overlap regions (participants) undergo multiple collisions. These central events produce a large number of particles. Even though many of the observed particles are just the result of the fragmentations of pieces of the two nuclei which release some of the bound nucleons, at high incident energies considerable amount of particle creation occurs. While the particles created are mostly pions, the production of relatively heavy particles than pions and heavy flavor (strange and charm) quark matter also takes place. However, historically the pp collisions were considered as a baseline for the formation of QGP in heavy-ion collisions due to their significantly smaller system size compared to heavy-ion collisions. In pp collisions, it was expected that the final state particles are only the result of the fragmentations of pieces of the two protons. Recent multiplicity dependent measurements of identified particle production from the experiments at the LHC have revealed surprising discovery of QGP-like behavior, such as strangeness enhancement, flow-like pattern and double ridge structure in high multiplicity proton+proton (pp) collisions, which raise concerns whether pp collisions can be used as a proper benchmark for comparison with heavy-ion results to understand the formation of a medium with high temperature/energy density. These behaviours have important consequences in understanding the data from heavy-ion collisions at the LHC energies as one should consider the contribution of QGP-like effects in small systems. They open new directions for theoretical and experimental studies of small collision systems. While hydrodynamic calculations describe data qualitatively, other approaches

suggest that these can be initial state effects. To understand the recent measurements, it is important to perform double differential studies of pp collisions with event shape observables and charged-particle multiplicity. Event shape observables like transverse sphericity, allow the possibility to separate the high and low number of MPI events to isolate the behavior of particles inside jets (hard processes) and pertaining to the soft processes. This result can help to understand more on the jet production, identified particle ratios (baryon to meson and strange to non-strange), double ridge structure and the steep rise of mean transverse-momenta of charged particles in small systems compared to large systems. A comprehensive differential study using event shapes would reveal interesting features, which could be exploited to improve models as well.

Study of resonances containing strange quarks as a function of charged-particle multiplicity, would provide important contribution to the origin of QGP-like effects in pp collisions. Resonances are usually referred as the particles, which have higher mass than the corresponding ground state particle(s) with similar quark content. As hadronic resonances decay strongly, they have very short lifetime, $\tau \sim \text{few fm}/c$. Before decaying, these particles can only travel upto few femto-meters, which is about the diameter of proton. The width (Γ) and lifetime (τ) of the resonances are related by the Heisenberg's uncertainty relation, i.e. $\Gamma\tau = \hbar$. As the broad resonance states decay very shortly after their production, it can only be measured by reconstruction of their decay daughters in a detector. The typical lifetime of experimentally measured hadronic resonances ranges from 1.1 fm/c to 46 fm/c. Hadronic resonances are produced in the bulk of the expanding medium in heavy-ion collisions and they can decay while still traversing in the medium. The decay daughters may interact with other particles in the medium, which would result in suppression of resonances while their reconstruction, as the invariant mass of the daughters may not match that of the parent particle. This process is known as re-scattering. In other way, resonances can be regenerated as a consequence of pseudo-elastic collisions in the hadronic phase of the medium, which would result

in enhancement of resonances. Resonances, with relatively higher life-time, might not go through any of the above mentioned processes. It may also happen that the re-scattering and re-generation processes compensate each other. Thus, the interplay of these processes makes the study of resonances in heavy-ion collisions more fascinating. Also resonances like, $K^*(892)^0$ and $\phi(1020)$ contain strange (or anti-strange) quarks, they can be used for a systematic study of the particle species dependence of the partonic energy loss in the medium. Also, recent results from LHC suggest that ϕ behaves like a particle with net strangeness of 1 or 2 in small systems. These observations open new directions for theoretical and experimental studies of pp collisions. So far, none of the models explain the recently discovered behaviors satisfactorily.

The major objectives of the thesis are to understand the processes discussed above with the double differential (Event shape and Multiplicity) study of ϕ meson production with ALICE at the LHC. Also, we phenomenologically attempt to formulate a model to characterize the heavy-ion collisions using relativistic kinetic theory in the form of Boltzmann Transport equation using relaxation time approximation.

The organization of the thesis is as follows:

- **Chapter 1** gives a general and brief introduction on standard model and Quantum chromodynamics (QCD). Then the Quark gluon plasma (QGP) and its indirect signatures are briefly discussed. Then, the role of hadronic resonances as a probe of hadronic phase of the system formed in heavy-ion collisions is discussed. In addition, the unique and peculiar property of ϕ meson in strangeness sector is discussed in the context of recent results from the LHC. We also briefly introduce event generators like AMPT and PYTHIA8 along with their usage in LHC era. Finally, short notes on Tsallis non-extensive statistics and Boltzmann Transport equation is presented in this chapter, making a stage for their use in subsequent chapters.
- **Chapter 2** gives an overview of the ALICE experiment, with a de-

tailed description of central barrel detectors which are used for the data analysis of ϕ meson production in this thesis. In addition, we provide short notes on all other detectors in ALICE experiments. Also, we discuss about the ALICE online and trigger system, offline computing and reconstruction system based on the GRID framework briefly.

- **Chapter 3** is devoted the detailed methodology of invariant mass reconstruction of ϕ meson production in minimum bias pp collisions with ALICE at the LHC is discussed and the results are compared with different collision energies.
- In **chapter 4**, we have presented the double differential study of ϕ meson production pp collisions as a function of event shape and charged particle multiplicity with ALICE at the LHC. We have also shown the identified particle production in pp collisions as a function of transverse sphericity and charged-particle multiplicity using PYTHIA8 event generator.
- In **chapter 5**, we phenomenologically attempt to formulate a model to characterize the heavy-ion collisions using relativistic kinetic theory in the form of Boltzmann Transport equation using relaxation time approximation. We have also studied the transport properties using Tsallis non-extensive statistics with the help of relativistic Boltzmann Transport equation. Also, we have given predictions of the elliptic flow (v_2) of produced particles in Xe + Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV using A Multi-Phase Transport model (AMPT) with string melting version.
- Finally, the conclusions drawn from the current studies have been presented in **chapter 6**.

PUBLICATIONS

List of Publications:

(Publications with [*] are included in this thesis.)

1. [*] **“Energy dependence of $\phi(1020)$ production at mid-rapidity in pp collisions with ALICE at the LHC”**
S. Tripathy (for the ALICE collaboration)
Nucl. Phys. A 982, 180 (2019)
Best Poster Plenary Flash talk at Quark Matter-2018, Venice, Italy.
2. [*] **“Evidence of rescattering effect in Pb-Pb collisions at the LHC through production of $K^*(892)^0$ and $\phi(1020)$ mesons”**
S. Acharya,...,S. Tripathy *et al.* [ALICE Collaboration]
arXiv:1910.14419 [nucl-ex]
3. [*] **“ K^{*0} and ϕ production in pp and Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV”**
B. Mohanty, A. K. Dash, R. Singh, S. Tripathy, C. Jena (paper committee)
<https://alice-publications.web.cern.ch/node/4518>
4. [*] **“Measurement of ϕ Mesons at Mid-Rapidity in pp Collisions at $\sqrt{s} = 5.02$ TeV as a function of Transverse Sphericity and Charged-particle Multiplicity”**
S. Tripathy, R. Sahoo and A. Ortiz Velasquez
<https://alice-notes.web.cern.ch/node/888>
5. [*] **“Measurement of ϕ Mesons at Mid-Rapidity in pp Collisions at $\sqrt{s} = 5.02$ TeV as a function of charged particle multiplicity”**
S. Tripathy, A. Khuntia and R. Sahoo
<https://alice-notes.web.cern.ch/node/756>
6. [*] **“Inelastic Normalization Factors for pp collisions at $\sqrt{s} = 5.02, 8,$ and 13 TeV”**

S. Tripathy, A. Khuntia, R. Sahoo and A. G. Knospe

<https://alice-notes.web.cern.ch/node/665>

7. [*] **“Measurement of ϕ Mesons at Mid-Rapidity in Minimum-Bias pp Collisions at $\sqrt{s} = 5.02$ TeV and Nuclear modification factor for ϕ Mesons in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV”**

S. Tripathy, A. Khuntia, R. Sahoo and A. G. Knospe

<https://alice-notes.web.cern.ch/node/545>

8. [*] **“Predictions for azimuthal anisotropy in Xe+Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV using a multiphase transport model”**

S. Tripathy, S. De, M. Younus and R. Sahoo.

Phys. Rev. C **98**, 064904 (2018).

9. [*] **“Dissipative Properties and Isothermal Compressibility of Hot and Dense Hadron Gas using Non-extensive Statistics”**

S. K. Tiwari, S. Tripathy, R. Sahoo and N. Kakati.

Eur. Phys. J. C **78**, 938 (2018).

10. [*] **“Elliptic flow in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV at the LHC using Boltzmann transport equation with non-extensive statistics”**

S. Tripathy, S. K. Tiwari, M. Younus and R. Sahoo.

Eur. Phys. J. A **54**, 38 (2018).

11. [*] **“Transverse Momentum Spectra and Nuclear Modification Factor using Boltzmann Transport Equation with Flow in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV”**

S. Tripathy, A. Khuntia, S. K. Tiwari and R. Sahoo.

Eur. Phys. J. A **53**, 99 (2017).

12. [*] **“Nuclear Modification Factor Using Tsallis Non-extensive Statistics”**

S. Tripathy, T. Bhattacharyya, P. Garg, P. Kumar, R. Sahoo and J. Cleymans.

Eur. Phys. J. A **52**, 289 (2016).

13. [*] **Event Shape Engineering and Multiplicity dependent Study of Identified Particle Production in proton+proton Collisions at $\sqrt{s}=13$ TeV using PYTHIA**

A. Khuntia, S. Tripathy, A. Bisht, R. Sahoo.

arXiv:1811.04213 [hep-ph].

14. [*] **“Elliptic flow of hadrons via quark coalescence mechanism using Boltzmann transport equation for Pb+Pb collision at $\sqrt{s_{NN}}=2.76$ TeV”**

M. Younus, S. Tripathy, S. K. Tiwari and R. Sahoo.

arXiv:1803.01578 [hep-ph]

15. **“ $K^*(892)^0$ and $\phi(1020)$ production at midrapidity in pp collisions at $\sqrt{s}=8$ TeV”**

S. Acharya,...,S. Tripathy *et al.* [ALICE Collaboration]

arXiv:1910.14410 [nucl-ex].

16. **“Measurement of ϕ Mesons at Mid-Rapidity in Minimum-Bias pp Collisions at $\sqrt{s}=8$ TeV”**

S. Tripathy, A. Khuntia, R. Sahoo and A. G. Knospe

<https://alice-notes.web.cern.ch/node/672>

17. **“Measurement of K^*0 at Mid-Rapidity in Minimum-Bias pp Collisions at $\sqrt{s}=8$ TeV”**

A. Khuntia, A. N. Mishra, S. Tripathy, R. Sahoo and A. G. Knospe

<https://alice-notes.web.cern.ch/node/563>

18. **“Role of Event Multiplicity on Hadronic phase Lifetime and QCD Phase boundary in Ultra-relativistic Collisions at the RHIC and LHC”**

D. Sahu, S. Tripathy, G. S. Pradhan, R. Sahoo

arXiv:1909.05788 [hep-ph], Phys. Rev. C (in press).

19. **“Identified particle production in Xe+Xe collisions at $\sqrt{s_{\text{NN}}} = 5.44$ TeV using a multiphase transport model”**
R. Rath, S. Tripathy, R. Sahoo, S. De and M. Younus,
Phys. Rev. C **99**, 064903 (2019).

20. **“Violation of Wiedemann-Franz Law for a Hot Hadronic Matter created at NICA, FAIR and RHIC Energies using Non-extensive Statistics”**
R. Rath, S. Tripathy, B. Chatterjee, R. Sahoo, S. K. Tiwari and A. Nath,
Eur. Phys. J. A **55**, 125 (2019).

21. **“Multiplicity Dependence of Non-extensive Parameters for Strange and Multi-Strange Particles in Proton-Proton Collisions at $\sqrt{s} = 7$ TeV at the LHC”**
A. Khuntia, S. Tripathy, R. Sahoo and J. Cleymans.
Eur. Phys. J. A **53**, 103 (2017).

22. **“Indication of a Differential Freeze-out in Proton-Proton and Heavy-Ion Collisions at RHIC and LHC energies”**
D. Thakur, S. Tripathy, P. Garg, R. Sahoo and J. Cleymans.
Adv. High Energy Phys. **2016**, 4149352 (2016).

23. **“Event shape and Multiplicity dependence of Freeze-out Scenario and System Thermodynamics in Proton+Proton Collisions at $\sqrt{s} = 13$ TeV”**
S. Tripathy, A. Bisht, R. Sahoo, A. Khuntia and M. P. S,
arXiv:1905.07418 [hep-ph].

24. **“Event-shape and Multiplicity dependence of Chemical freeze-out Parameters in Proton+Proton Collisions at $\sqrt{s} = 13$ TeV using PYTHIA8”**
R. Rath, A. Khuntia, S. Tripathy and R. Sahoo,
arXiv:1906.04047 [hep-ph].

25. **“Measurements of inclusive jet spectra in pp and central Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV”**
S. Acharya,...,S. Tripathy *et al.* [ALICE Collaboration].
arXiv:1909.09718 [nucl-ex].
26. **“Studies of J/ψ production at forward rapidity in Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV”**
S. Acharya,...,S. Tripathy *et al.* [ALICE Collaboration].
arXiv:1909.03158 [nucl-ex].
27. **“Global polarization of Λ and $\bar{\Lambda}$ hyperons in Pb-Pb collisions at the LHC,”**
S. Acharya,...,S. Tripathy *et al.* [ALICE Collaboration].
arXiv:1909.01281 [nucl-ex].
28. **“Multiplicity dependence of (multi-)strange hadron production in proton-proton collisions at $\sqrt{s} = 13$ TeV”**
S. Acharya,...,S. Tripathy *et al.* [ALICE Collaboration].
arXiv:1908.01861 [nucl-ex]
29. **“ ${}^3_{\Lambda}\text{H}$ and ${}^3_{\Lambda}\bar{\text{H}}$ lifetime measurement in Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV via two-body decay”**
S. Acharya,...,S. Tripathy *et al.* [ALICE Collaboration].
arXiv:1907.06906 [nucl-ex]
30. **“Measurement of $\Upsilon(1S)$ elliptic flow at forward rapidity in Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV”**
S. Acharya,...,S. Tripathy *et al.* [ALICE Collaboration].
arXiv:1907.03169 [nucl-ex]
31. **“Measurement of prompt D^0 , D^+ , D^{*+} , and D_s^+ production in p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV”**
S. Acharya,...,S. Tripathy *et al.* [ALICE Collaboration].
arXiv:1906.03425 [nucl-ex]
32. **“Multiplicity dependence of light (anti-)nuclei production in p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV”**

- S. Acharya,...,S. Tripathy *et al.* [ALICE Collaboration].
arXiv:1906.03136 [nucl-ex]
33. **“Measurement of the inclusive isolated photon production cross section in pp collisions at $\sqrt{s} = 7$ TeV”**
S. Acharya,...,S. Tripathy *et al.* [ALICE Collaboration].
arXiv:1906.01371 [nucl-ex]
34. **“Scattering studies with low-energy kaon-proton femtoscopy in proton-proton collisions at the LHC”**
S. Acharya,...,S. Tripathy *et al.* [ALICE Collaboration].
arXiv:1905.13470 [nucl-ex]
35. **“Inclusive J/ψ production at mid-rapidity in pp collisions at $\sqrt{s} = 5.02$ TeV”**
S. Acharya,...,S. Tripathy *et al.* [ALICE Collaboration].
arXiv:1905.07211 [nucl-ex]
36. **“Study of the Λ - Λ interaction with femtoscopy correlations in pp and p-Pb collisions at the LHC”**
S. Acharya,...,S. Tripathy *et al.* [ALICE Collaboration].
arXiv:1905.07209 [nucl-ex]
37. **“Charged-particle production as a function of multiplicity and transverse sphericity in pp collisions at $\sqrt{s} = 5.02$ and 13 TeV”**
S. Acharya,...,S. Tripathy *et al.* [ALICE Collaboration].
arXiv:1905.07208 [nucl-ex]
38. **“Production of muons from heavy-flavour hadron decays in pp collisions at $\sqrt{s} = 5.02$ TeV”**
S. Acharya,...,S. Tripathy *et al.* [ALICE Collaboration].
arXiv:1905.07207 [nucl-ex]
39. **“Measurement of charged jet cross section in pp collisions at $\sqrt{s} = 5.02$ TeV”**

- S. Acharya,...,S. Tripathy *et al.* [ALICE Collaboration].
arXiv:1905.02536 [nucl-ex]
40. **“Exploration of jet substructure using iterative declustering in pp and Pb-Pb collisions at LHC energies”**
S. Acharya,...,S. Tripathy *et al.* [ALICE Collaboration].
arXiv:1905.02512 [nucl-ex]
41. **“Measurement of the production of charm jets tagged with D^0 mesons in pp collisions at $\sqrt{s}=7$ TeV”**
S. Acharya,...,S. Tripathy *et al.* [ALICE Collaboration].
arXiv:1905.02510 [nucl-ex]
42. **“Measurement of jet radial profiles in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV”**
S. Acharya,...,S. Tripathy *et al.* [ALICE Collaboration].
arXiv:1904.13118 [nucl-ex]
Phys. Lett. B **796**, 204 (2019)
43. **“First observation of an attractive interaction between a proton and a multi-strange baryon”**
S. Acharya,...,S. Tripathy *et al.* [ALICE Collaboration].
arXiv:1904.12198 [nucl-ex]
44. **“Coherent J/ψ photoproduction at forward rapidity in ultra-peripheral Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV”**
S. Acharya,...,S. Tripathy *et al.* [ALICE Collaboration].
arXiv:1904.06272 [nucl-ex]
45. **“One-dimensional charged kaon femtoscopy in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV”**
S. Acharya,...,S. Tripathy *et al.* [ALICE Collaboration].
arXiv:1903.12310 [nucl-ex]
46. **“Measurement of $p\bar{\Lambda} \oplus \bar{p}\Lambda$ and $\Lambda\bar{\Lambda}$ interactions with femtoscopic correlations in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV**

and $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$ ”

S. Acharya,...,S. Tripathy *et al.* [ALICE Collaboration].

arXiv:1903.06149 [nucl-ex]

47. **“Investigations of anisotropic flow using multi-particle azimuthal correlations in pp, p-Pb, Xe-Xe, and Pb-Pb collisions at the LHC”**

S. Acharya,...,S. Tripathy *et al.* [ALICE Collaboration].

arXiv:1903.01790 [nucl-ex]

48. **“Multiplicity dependence of (anti-)deuteron production in pp collisions at $\sqrt{s} = 7 \text{ TeV}$ ”**

S. Acharya,...,S. Tripathy *et al.* [ALICE Collaboration].

arXiv:1902.09290 [nucl-ex]

Phys. Lett. B **794**, 50 (2019)

49. **“Calibration of the photon spectrometer PHOS of the ALICE experiment”**

S. Acharya,...,S. Tripathy *et al.* [ALICE Collaboration].

arXiv:1902.06145 [physics.ins-det]

JINST **14**, no. 05, P05025 (2019)

50. **“Measurement of D^0 , D^+ , D^{*+} and D_s^+ production in pp collisions at $\sqrt{s} = 5.02 \text{ TeV}$ with ALICE”**

S. Acharya,...,S. Tripathy *et al.* [ALICE Collaboration].

arXiv:1901.07979 [nucl-ex]

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Chapter 1

Introduction

“Let noble thoughts come to us from every direction of the Universe.”

– Rig Veda, 1-89-i

The objective of high-energy nuclear and particle physics is to understand the basic structure and laws in nature, from the largest dimensions of the universe (like galaxy, stars etc.) to all the way down to the smallest dimensions of micro-organisms. Today, the field of ultra-relativistic heavy-ion collisions is one of the flourishing research areas on experimental as well as theoretical side. Study of heavy-ion collisions help us to probe the matter formed in extreme conditions such as high temperature and high energy density. Quantum Chromo-Dynamics (QCD), which describe the strong interactions, predicts that the nuclear matter at such extreme conditions undergoes a phase transition to a deconfined state of quarks and gluons, which is termed as Quark Gluon Plasma (QGP). The study of ultra-relativistic heavy-ion collisions already has a history of around 35 years with experiments from AGS at BNL, SPS at CERN, Relativistic Heavy ion Collider (RHIC) at BNL to current Large Hadron Collider (LHC) at CERN where the center of mass collision energy reaches upto 13 TeV. In this chapter, to introduce the physics motivation behind the ALICE experiment, the QCD theory is briefly presented and few relevant measurements from ALICE is shown. As classification is the first and foremost stage in the development of any science, we begin with classification of elementary particles which is known as *Standard Model*. It is followed briefly by discussions on Quantum Chromodynamics (QCD). The third section would give

an insight on Quark Gluon Plasma (QGP) and ultra-relativistic heavy-ion collisions with its thermodynamics and QCD phase transition. Also, we discuss the “Little Bang” at the LHC in one of the section followed by the signatures of the QGP from experiments in another section. A section is dedicated to the study of resonances production as probe for the evolution stages of the medium along with the speciality of ϕ meson. The last section briefly discusses about the motivation of the thesis.

1.1 Standard Model

Since the discovery of electron by J. J. Thompson in 1897, many theories and experiments resulted in remarkable insights and heroic triumphs into the fundamental structure of matter. In the next few decades, many new particles were proposed theoretically and discovered experimentally. Till 1961, there were no classification of huge number of particles. In early 1970’s, Gell-Mann for the first time introduced the Eight-fold way to classify the hadrons based on the electric charge and net strangeness content following Mendeleev’s way of classification of elements, which resulted in periodic table of elements. However, the quark model has superseded the Eight-fold way, when Gell-Mann and Zweig independently proposed that all the hadrons are in fact composed of quarks [2]. The Standard model is a theory, proposed by Glashow, Salam and Wienberg in 1970, which is successful in explaining experimental results of elementary particles with high precision [3–5]. In a more general way, the Standard model is a quantum field theory based on the gauge symmetry $SU(3)_C \times SU(2)_L \times U(1)_Y$. The elementary particles are characterized by quantum numbers such as the spin (S), electric charge (Q), baryon (B) and lepton (L) numbers etc. The schematic representation of the standard model is depicted in Fig. 1.1.

According to the standard model, the elementary particles which constitute all the visible matter in the Universe, are classified into quarks, leptons, gauge bosons and Higgs boson. There are six flavors of quarks namely up (u), down (d), strange (s), charm (c), bottom (b) and top (t). The first

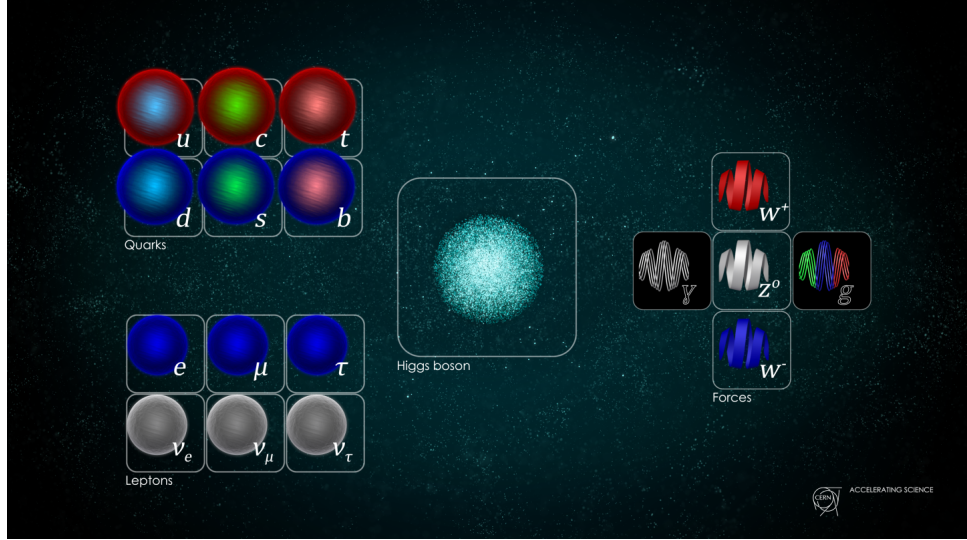


Figure 1.1: The representation of standard model. Figure has been taken from [1].

generation of quarks consist of lightest and the most stable particles and the second and third generation consist of heavier and less stable particles. As of quarks, there are 6 types of leptons namely electron (e), electron-neutrino (ν_e), muons (μ), muon-neutrino (ν_μ), tau (τ) and tau-neutrino (ν_τ). Quark and leptons are spin-1/2 particles and they follow Fermi-Dirac statistics and Pauli's exclusion principle. Thus, they are known as fermions. Quarks combine together to form hadrons. A hadron consisting quark-antiquark pair is called as meson while three quarks combining to form hadron is called as baryon. Due to Pauli's exclusion principle, all the three quarks inside a baryon cannot be identical. Thus, a new quantum number, color charge was introduced. Each quark carry a color charge (red, blue or green) along with a fractional electric charge. The gauge bosons are the carriers of the fundamental forces at work in the Universe. The fundamental forces are the strong force, the weak force, the electromagnetic force and the gravitational force. Electromagnetic and gravitational forces have infinite range while strong and weak forces have short range and are effective only at sub-atomic levels. The strong force is mediated by the exchange of gluons (g), the weak force is mediated by the exchange of $W^\pm$ and Z bosons and the electromagnetic force is carried by the photon

(γ). Gluons also carry the color charge and have got self-interaction. After the discovery of Higgs boson at the Large Hadron Collider (LHC), CERN, Geneva, which is responsible for generation of mass in elementary particles, the Standard Model in its prescribed form stands complete. However, the postulated carrier for the gravitational force, Graviton is yet to be discovered. The quantum field theory (QFT) which governs the electromagnetic interaction is known as Quantum electrodynamics (QED) and the unified weak and electromagnetic force is governed by Electroweak (EW) theory. Quantum Chromodynamics (QCD) governs the strong interaction, which will be briefly discussed in next section.

1.2 Quantum Chromodynamics (QCD)

QCD is responsible for the confinement of quarks inside hadrons and nucleons inside nuclei. In QCD, the color charge allows a SU(3) symmetry and it is conserved in all strong interactions. To obtain a perfect color symmetry, the color singlet state of a gluon is not allowed and there are only eight types of gluons. The QED coupling of fermions and photons is similar to the gluon interaction with quarks in QCD. Gluon can interact with each other, unlike photons, which allows more complex QCD processes. The QCD effective potential between partons is given as,

$$V_{QCD}(r) = -\frac{4}{3} \frac{\alpha_S}{r} + kr. \quad (1.1)$$

Here, α_S is the strong coupling constant, also called as running coupling constant as it explicitly depends on the scale of momentum transfer. k is the color string tension constant which equals to $0.85 \text{ GeV } fm^{-1}$ [6] and r is the distance between interacting partons. QCD has two characteristic features called confinement and asymptotic freedom, which are discussed below.

1.2.1 Confinement

The QCD potential indicates that the quarks exhibit the property of color confinement, which means a quark cannot be found in isolation. The first term of Eq. 1.1 is similar to Coulomb potential, arises from single gluon exchange and dominates at small r . As the distance between the two color charges increases, the linear term dominates. Thus nearly infinite energy is required to get free quarks. When the separation between two quarks increases, the color field lines are attracted to form a string due to the gluon self-coupling. At a large distance, the potential energy becomes high enough to create quark-antiquark pair instead of producing two free quarks. Thus, the quarks are always confined inside hadrons [6].

1.2.2 Asymptotic Freedom

Asymptotic freedom is one of the unique features of QCD, which states that the strength of interaction between quarks and gluons become smaller when distance between them become shorter or the energy density gets higher. The Nobel Prize in Physics 2004 was awarded jointly to David J. Gross, H. David Politzer and Frank Wilczek “for the discovery of asymptotic freedom in the theory of the strong interaction” [7]. This can be understood in following way.

The coupling constant (α_S) in Eq. 1.1 is not really a constant but a function of four momentum transfer. This property is called running coupling in QCD. It is an outcome of vacuum polarization of gluon or quark pairs. Similar to a molecule can be polarized by an electric charge in a dielectric medium, the quark-antiquark pair created and annihilated in the vacuum can be polarized by the color charge. In QCD, the quark polarization screens the color charge which is pretty much similar to electric charge screening in QED. However, the gluon self-interaction smear the color charge of quarks and create an anti-screening effect. The running

coupling constant as a function of momentum transfer (Q^2) is given as,

$$\alpha_S(Q^2) = \frac{12\pi}{(11n - 2n_f)\ln(Q^2/\Lambda_{QCD}^2)}. \quad (1.2)$$

Here, n_f is the number of quark flavours and Λ_{QCD} is the non-perturbative QCD scale parameter. Above $\Lambda_{QCD} \simeq 200$ MeV, the perturbative QCD is applicable. When, we go low in values of Q , $\alpha_S(Q^2)$ grows and perturbation theory breaks down around the scale comparable to the masses of light hadrons, i.e. around $1 \text{ GeV}/c^2$. However, if $11n$ becomes higher than $2n_f$ then anti-screening will dominate and the strong coupling constant will decrease with an increase of momentum transfer. At very short distances, in high momentum transfer, the value of $\alpha_S(Q^2)$ becomes small, the coupling becomes weak. When Q^2 tends to ∞ , the coupling strength becomes almost negligible and eventually quarks and gluons behave as free particles inside the QCD vacuum. This property is called as “asymptotic freedom” [9]. As the coupling becomes small, in this case perturbative QCD is applicable. Fig. 1.2 shows the value of $\alpha_S(Q^2)$ estimated by different systems.

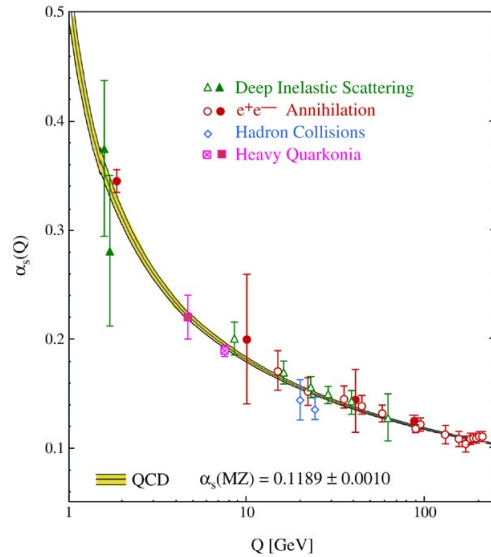


Figure 1.2: α_S as a function of momentum transfer (Q) [8].

1.3 The Quark-Gluon Plasma and QCD phase transition

QCD calculations and thermodynamic considerations suggest that strongly interacting matter can exist in different phases, based on the temperature and the density of the system. A phase transition characterised by a specific critical temperature and baryo-chemical potential brings a system of deconfined quarks and gluons (QGP) into a confined state where partons are confined inside hadrons. This QCD phase transition can be investigated in laboratory by reproducing the similar temperature, pressure and energy density conditions that lead to the QGP formation with the help of ultra-relativistic heavy-ion collisions. In heavy-ion (A-A) collisions, large number of nucleon-nucleon collisions takes place in a very small spatial region which provides enough energy density to allow the transition to the QGP state. If the collision energy is sufficient for the QCD phase transition to deconfined matter, then the initial state is made up of strongly interacting quarks and gluons which later hadronise, when the system cools down below the critical temperature. This evolution of the system (fireball) after heavy-ion collisions is believed to reproduce the evolution stages of the early Universe after the electro-weak phase transition from the partonic deconfined matter to confined hadrons nearly $1\mu\text{s}$ after the Big bang. Due to this, heavy-ion collisions are often referred as “Little Bang”.

1.3.1 Thermodynamics of QCD

As summarised by the phase diagram of QCD in Fig. 1.3, strongly interacting matter can exist in different phases characterized by temperatures and densities. The baryon chemical potential (μ_B) is defined as the energy needed to increase one unity of the total number of baryons and anti-baryons (N_B) in a system, $\mu_B = \frac{\partial E}{\partial N_B}$. It is introduced due to the fact that at relativistic energies the particle (baryon) number in a system may not be conserved due to particle annihilation and creation processes at the mi-

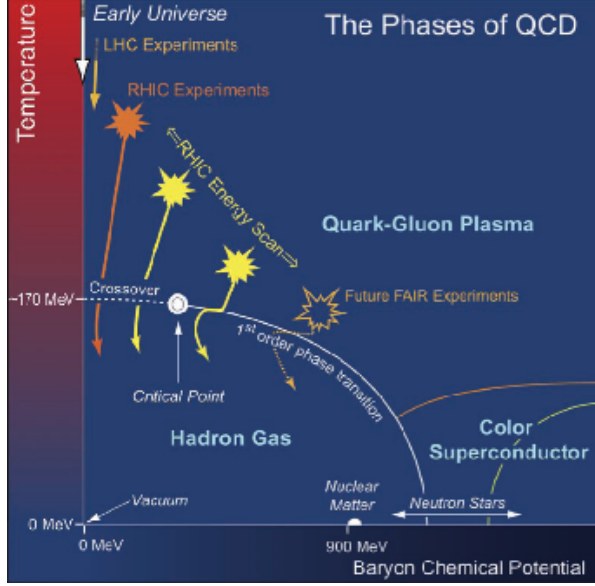


Figure 1.3: Sketch of QCD phase diagram with boundaries for various states of QCD matter [11].

croscopic level. Low baryon chemical potential ($\mu_B \sim m_p \sim 1 \text{ GeV}$) in the diagram correspond to the nuclear matter in its ordinary state. By moving towards higher temperature or higher chemical potential, one can reach a hadronic phase (HG). The pressure of HG as a function of temperature can be expressed by the Stefan-Boltzmann law:

$$P_{HG} = g \frac{\pi^2}{90} T^4. \quad (1.3)$$

Here, g is the degeneration factor that accounts system degrees of freedom (for pion gas, $g = 3$). QGP is predicted to be reached by further increasing the temperature and the energy density, so that the partons interact without being confined into hadrons. The degrees of freedom in QGP increases to include bosonic ($2 \text{ spin} \times 8 \text{ colour states for gluons}$) and fermionic ($3 \text{ colors} \times N_f \text{ flavours} \times 2 \text{ spin states}$) degrees of freedom. Now, the pressure is given as,

$$P_{HG} = g \frac{\pi^2}{90} T^4 - B. \quad (1.4)$$

Here, B is the bag constant [9] and $B^{-1/4} \simeq 0.2 \text{ GeV}$. It acts as an external pressure and is equivalent to some sort of latent heat defined as the difference in energy density per unit volume between the two phases of the

QCD matter.

It is believed that, the matter produced in Big Bang in the early Universe evolved from very high temperature to hadronisation featuring only a small quark–antiquark excess of nearly 10^{-9} which is $\mu_B \sim 0$. In heavy ion-collisions at the LHC, the nuclear matter is heated and compressed enough in the collision to undergo the transition to QGP, at low baryon chemical potential ($\mu_B \sim 0$). Neutron star could represent a case of very high baryonic density induced by the gravitational collapse of a star, for very low temperatures. However, for extreme values of chemical potential (μ_B), the nuclear matter would be in conditions of quark–colour superconductivity. The order of any phase transition is governed by how fast the free energy of the system varies in a neighbourhood of the transition/critical temperature. A first order transition occurs when the first derivative of the free energy is discontinuous and it is accompanied by a discontinuous variation of entropy and the presence of latent heat. Second order transition occurs when the second derivative of the free energy is discontinuous. If a phase transition occurs without any discontinuity of free energy of the system, it is called a “crossover”. Critical points are temperatures in which the process becomes from first order to second order transition. Two states of matters can coexist at the critical point. The QCD phase transition is expected to be of the first order until the critical end point is reached.

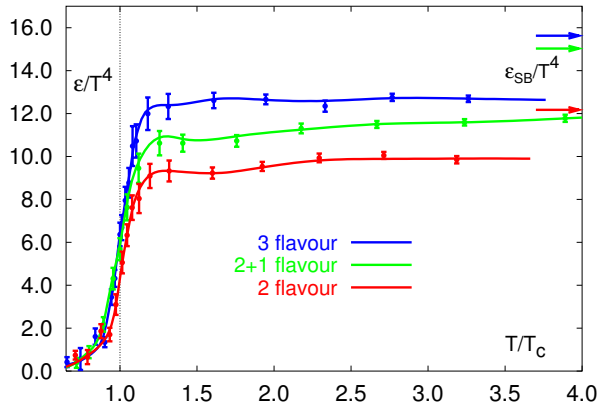


Figure 1.4: Lattice QCD predictions of ϵ/T^4 as a function of temperature normalized by the critical temperature (T_c) and the horizontal arrows show the Stefan-Boltzmann limit [12].

The lattice QCD predicts a transition from a hadronic phase to QGP at a temperature of about 154-170 MeV [12, 13]. Fig. 1.4 show the energy density of the system as a function of its temperature from lattice calculation with $\mu_B = 0$ and for 2 and 3 light (u and d) quarks considered, or with 2 lights and 1 heavier (strange quark). The “2+1” case would be the closest to the physically realized quark mass spectrum. The steep trend of this ratio reflects the increase of the degrees of freedom of the system when in the deconfined phase.

1.3.2 Chiral symmetry and the QCD vacuum

The phase transition can be characterized at the microscopic level by changes in the symmetry of the system, besides looking at macroscopic or thermodynamic approach. An “order parameter” is required to quantify the order of phase transition and to identify a broken symmetry in a phase transition.

Let us begin with Dirac equation for the u and d quarks represented by the q_i spinor [14]:

$$(i\gamma^\mu\partial_\mu - m_i)q_i = 0. \quad (1.5)$$

The isospin currents can be expressed as:

$$\partial_\mu(\bar{u}\gamma^\mu d) = i(m_u - m_d)\bar{u}d, \quad (1.6)$$

$$\partial_\mu(\bar{u}\gamma^\mu\gamma_5 d) = i(m_u + m_d)\bar{u}\gamma_5 d. \quad (1.7)$$

Here, m_u and m_d are the quark masses. The first isospin current is conserved, as the QCD Lagrangian is invariant with respect to the SU(2) group. Another global symmetry also holds in the limit of massless quarks, which can be represented by the following transformation:

$$q_i \rightarrow \exp(-i\alpha^i \frac{1}{2}\sigma^j\gamma_5)q_i, \quad (1.8)$$

where, σ^j are the Pauli matrices. In the above case the left-handed and right-handed components of the spinors can be decoupled as, $q_{R,L} = (1 + \gamma_5)q$. In the chiral limit when m_q is zero, the $q_{R,L}$ are conserved owing to $SU(2)_L \times SU(2)_R$ symmetry of the Lagrangian. This suggests that the left and right handed quarks should be separately conserved in QCD. As, this degeneration is not seen in the hadrons hierarchy and quarks are massive particles, the chiral symmetry has to be spontaneously broken. It can be shown that only the sum of left and right-handed quarks is a conserved quantum number related to the symmetry, not separately. A left-handed quark, propagating through the vacuum can be annihilated by its anti-quark. The coupled anti-right-handed quark of the QCD vacuum can then create its anti-quark with the same momentum of the first. Here, the QCD vacuum is considered to be unstable with respect to the formation of a tightly bound $q\bar{q}$ condensate. Due to the spontaneous chiral symmetry breaking, a large value for the QCD vacuum is reflected into a large constituent mass with respect to the intrinsic mass of the quarks. This happens due to the dynamical mass generation. For example, the intrinsic masses of the constituent quarks in a proton (uud) accounts for less than 6% of the proton mass. During the phase transition between the hadronic phase of the nuclear matter and the deconfined state, the chiral symmetry should be restored. With this the independent conservation on left and right handed quarks takes place. As quarks are deconfined now, the quark masses go back to the bare values which is few MeV for light quarks and around 150 MeV for strange quarks. This is usually referred to as “partial restoration of chiral symmetry”, as the masses do not go exactly to zero. Two order parameters are associated to this QCD phase transition: the Polyakov loop and the chiral condensate. The Polyakov loop is related to the free energy of quarks at large distances or the confinement while the chiral condensate refers to the chiral symmetry breaking or restoration. At the transition/critical temperature, the rapid decrease of the chiral condensate and the increase in the Polyakov loop takes place. This suggests the passage between the confined and deconfined phase is also accompanied

by a chiral transition. The temperature range for this to happen is 160-180 MeV, which is compatible to the temperature at which the interacting potential between quarks vanishes. [16, 17]

1.4 The “Little Bang” at the LHC

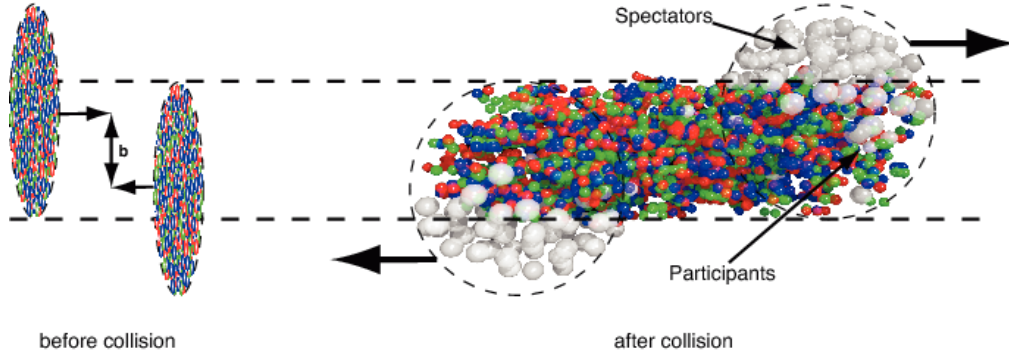


Figure 1.5: Schematic picture of ultra-relativistic heavy ion collisions [18].

At LHC, heavy nuclei are accelerated at ultra-relativistic energies, which appear as Lorentz contracted pancakes while travelling along the beam axis (Fig. 1.5). Their transverse dimension becomes larger than longitudinal dimension. Thus, their collision can be considered as the superposition of binary nucleon-nucleon collisions. The nucleons which participate in the collisions are defined “participants” (N_{part}) and those that do not interact are called “spectators” ($N_{spect} = 2A - N_{part}$, A being the mass number). The geometry of the heavy-ion collision is shown in next subsection.

1.4.1 Geometry of heavy-ion collision

Fig. 1.6 shows a schematic picture of transverse plane in collision of two symmetric heavy-ions. Generally, the beam axis is considered as z-axis. The impact parameter(b) is defined as the perpendicular distance between the centres of the two nuclei in the transverse plane and it quantifies the overlap region of the colliding nuclei. Central collisions are characterized

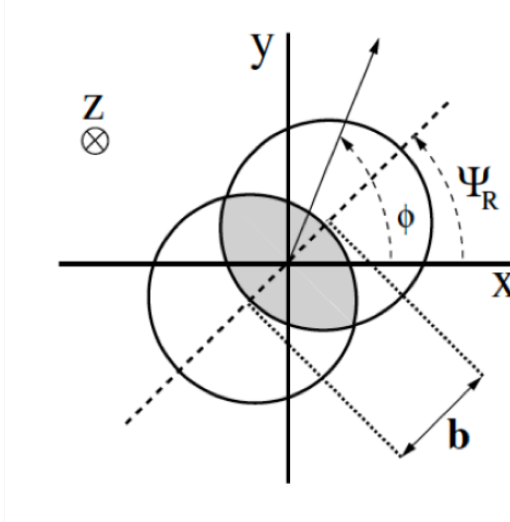


Figure 1.6: The transverse plane of ultra-relativistic heavy ion collisions [14].

by a small impact parameter, which suggests that the collision is almost head-on and most of the nucleons interact in the collision with each other. Thus, the central collisions would have maximum final state multiplicity. On the other hand, peripheral collision has large impact parameter and a few nucleons participate in the collision. Fig. 1.7 shows the correlation of the final state charged particle multiplicity with impact parameter and number of participants. Generally, centrality classes are defined in terms of percentiles of the nucleus-nucleus cross section. Centrality selection and finding the number of participants and spectators in heavy-ion collisions are quite crucial because they are needed to normalise the other measured observables prior to the comparison with other collision systems (relatively smaller systems like pp and p-Pb collisions). Centrality selection can be done in the following ways [14]: 1. From the correlation between centrality and the number of final state charged particles in the collision and, 2. from the measurement of the number of spectators in the collision. The first method relies on the choice of a geometrical model for the hadronic processes while the latter exploits the measurement of the energy of the spectator nucleons in the forward calorimeters/detectors. A similar method based on final state multiplicity is used for dividing the events in small collision systems like pp and p-Pb collisions. The detailed methods are

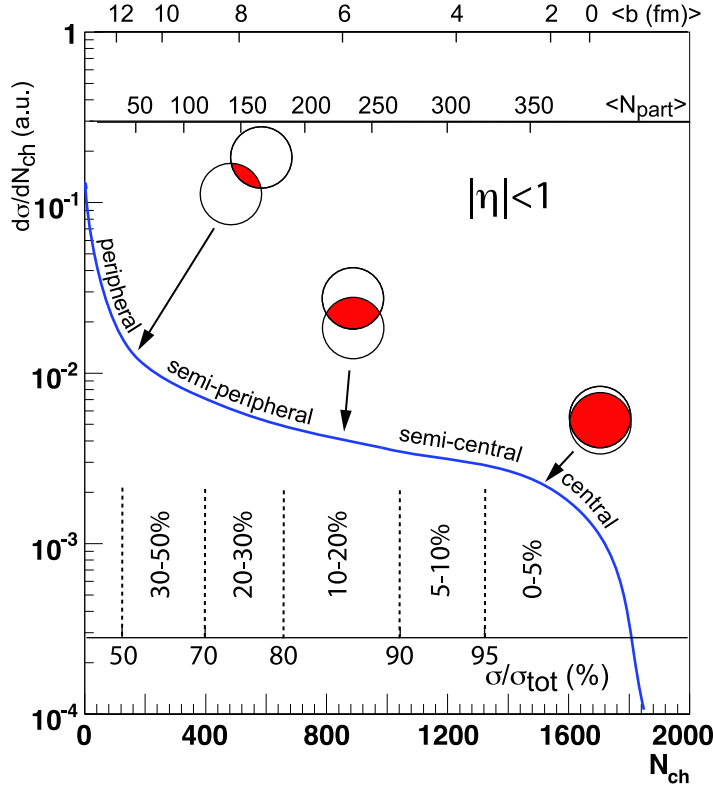


Figure 1.7: Cartoon showing the correlation of the final state charged particle multiplicity with impact parameter and number of participants [15].

discussed in the subsequent chapters. Event plane in heavy-ion collisions is defined by the event plane angle (Ψ_R) and the impact parameter (b) vector as depicted in Fig. 1.6. Thus, to determine the event plane of a collision, the impact parameter vector is required.

1.4.2 Space-time evolution

The schematic diagram of the space-time evolution of relativistic nucleus-nucleus collision with and without a deconfined state is shown in Fig. 1.8. Let us start at $z = 0$ and $t = 0$, a collision between two heavy-ions takes place. For a central heavy-ion collision, a very hot and dense matter is

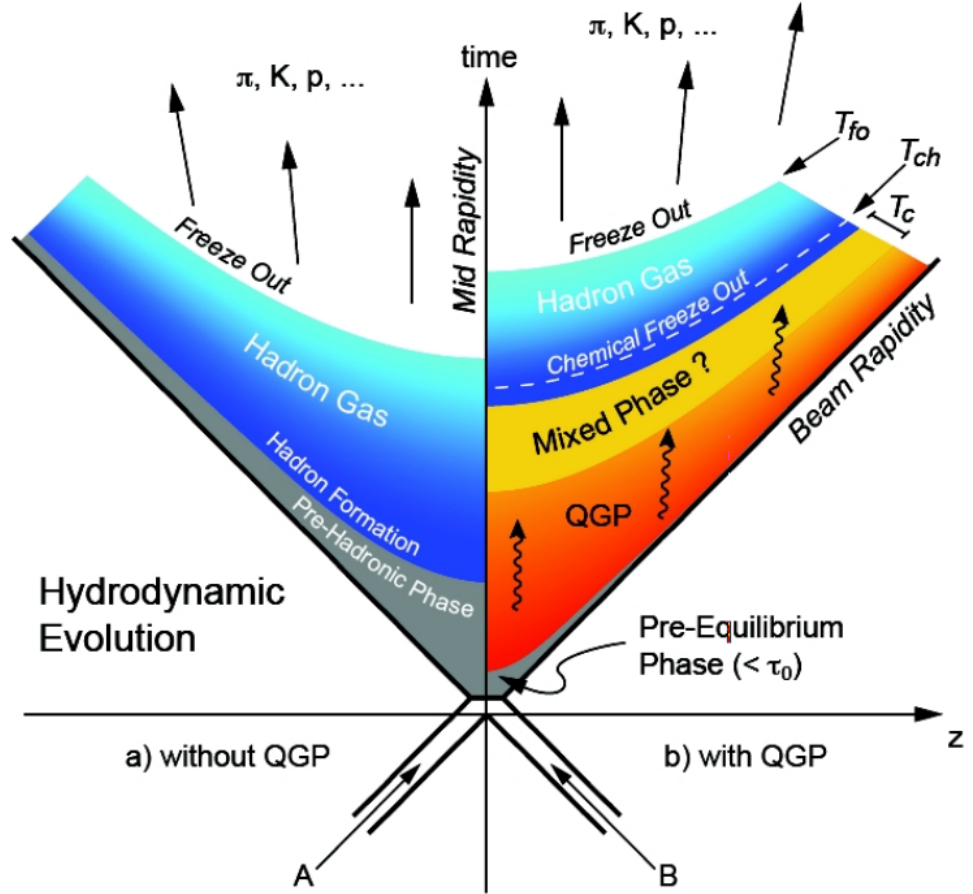


Figure 1.8: A schematic diagram of the space-time evolution of relativistic nucleus-nucleus collision [19].

expected to be produced, which is depicted in the right side of Fig. 1.8.

- **Pre-equilibrium stage:** The interaction among partons (quarks and gluons) gives rise to an abundant production of de-confined quarks and gluons at $t \leq 1 \text{ fm}/c$. Particles with very high momentum are mostly produced in this stage.
- **QGP evolution:** After the fireball reaches the critical energy density and temperature, a the local equilibrium is reached. Then, the fully deconfined state of partons form QGP. Lattice QCD calculations indicate that QGP is formed beyond a critical energy density of $1 \text{ GeV}/\text{fm}^3$ or beyond the critical temperature. The elastic and inelastic interactions between quarks and gluons in QGP lead to the thermalization phase. Due to the inelastic interactions, the flavor

composition of the partons of the system changes. Because of the high internal pressure and temperature, the system begins to expand rapidly. When the system cools down, QGP starts converting into a hadron gas. This is known as the mixed phase.

- **Hadron gas phase and Freeze-out:** There could be two possible mechanisms of hadronization from QGP, namely fragmentation and coalescence. Hadronization from fragmentation dominates at high energy which happens when a high- p_T parton fragments into lower p_T hadrons. Coalescence occurs through which lower momenta partons combine to form higher p_T hadrons. After hadronization, hadrons continue to interact with each other via elastic and inelastic interactions until they reach freeze-out. When the inelastic collisions cease the system reaches chemical freeze-out and the corresponding temperature is called as chemical freeze-out temperature (T_{ch}). This is the phase where the stable particle ratios get frozen. But, still the elastic collision takes place at this stage. When the mean free path gets high enough, the elastic collisions among the hadrons cease and the kinetic/thermal freeze-out is reached and the corresponding temperature is called as kinetic freeze-out temperature (T_{fo}). This is the phase where the transverse momentum spectral shape of a particle gets frozen. After the freeze-out, all the particles fly towards the detector.

However, another scenario of space-time evolution could also be possible when the matter produced in the heavy-ion or hadronic collisions do not meet the high temperature/energy density criteria. It is depicted in the left side of Fig. 1.8. In this case, the system is left with hadronic degrees of freedom only. Just after the collisions a pre-hadronic phase is created. Then the nucleons can recombine into new hadrons and the produced hadrons can be detected after the hadron gas phase freeze-out.

1.4.3 Kinematic variables in heavy-ion collisions

It is convenient to use the kinematic variables which are invariant or take simple form under the Lorentz transformation from one frame to another frame of reference. The kinematic variables which are frequently used in heavy-ion collisions are listed below and they are discussed briefly.

Natural units

In high-energy physics, all the physical quantities are usually expressed in natural units *i.e.* $\hbar = c = k_B = 1$. All the SI units are converted into natural units using the conversion, $\hbar c = 0.1975 \text{ GeV fm}$. Thus the length and time are expressed in terms of GeV^{-1} . The strong interaction lifetime of 10^{-23} sec. , which is of the order of 1 fermi, and proton mass being order of 1 GeV supports the central idea of using natural units in this length scale.

Center-of-mass energy

Center-of-mass energy is the square of sum of four momentum of the two incoming particles in a two body collision process. It is Lorentz invariant and it is expressed as:

$$s = (p_1 + p_2)^2 = (E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2 = (E_1 + E_2)^2, \quad (1.9)$$

s is the Mandelstam variable. Here, p_1 and p_2 are the four-momenta of the colliding particles and E_1 , E_2 , $\vec{p}_1$ and $\vec{p}_2$ are the energy and momentum of the particles. If the mass of two colliding particles are the same and in center of mass frame, $E_1 = E_2$ and $\vec{p}_1 = -\vec{p}_2$. Thus the center-of-mass energy becomes $\sqrt{s} = E_1 + E_2 = 2E$.

Rapidity

Rapidity is a kinematic variable which has advantage over velocity due to its additive property under a Lorentz boost. It is defined as:

$$y = \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right) = \frac{1}{2} \ln \left(\frac{1 + \beta}{1 - \beta} \right). \quad (1.10)$$

Here p_z is the longitudinal momentum and β is the longitudinal velocity along the z-axis. In the non-relativistic limits, rapidity is equivalent to velocity.

Pseudo-rapidity

At experiments like RHIC and LHC, the mass of the particles cannot be measured directly in an experiment, which makes impossible to measure energy (E) simultaneously with the momentum (p). Thus, pseudo-rapidity is preferred over rapidity which is given by:

$$\eta = \frac{1}{2} \ln \left(\frac{p + p_z}{p - p_z} \right) = -\ln(\tan \theta / 2). \quad (1.11)$$

Here, $\theta = \tan^{-1}(p/p_z)$ is the angle of a particle emitted to the beam axis. The pseudo-rapidity is a Lorentz invariant quantity. As, it only requires θ , it is convenient to use η in experiments as its use does not warrant particle identification. In relativistic limits, pseudo-rapidity is equivalent to rapidity.

Azimuthal angle

In relativistic heavy-ion collisions, the co-ordinate system is represented by (p_T, η, ϕ) . The azimuthal angle (ϕ) is defined as:

$$\phi = \tan^{-1} \left(\frac{p_y}{p_x} \right). \quad (1.12)$$

This is the angle between total momentum vector and one of the axis (x-axis) in the transverse (x-y) plane of the particle.

Invariant yield

The invariant yield is given by $E \frac{d^3N}{dp^3}$, is a Lorentz invariant quantity, where E and p are the energy and momentum of the particle, respectively. In terms of experimentally measurable quantities this could be expressed as

$$\begin{aligned} \frac{Ed^3\sigma}{dp^3} &= \frac{1}{m_T} \frac{d^3N}{dm_T d\phi dy} \\ &= \frac{1}{2\pi m_T} \frac{d^2N}{dm_T dy} \\ &= \frac{1}{2\pi p_T} \frac{d^2N}{dp_T dy}. \end{aligned} \tag{1.13}$$

As, it is expressed as a function of $p_T(m_T)$, it is usually called as the $p_T(m_T)$ -spectra of a particle. This in addition, encodes various dynamics of particle production, which include: temperature, radial flow, the domains of hard and soft physics in particle production. Most of the results in this thesis begin with the p_T -spectra.

1.5 Signatures of QGP and experimental probes

Due to very short lifetime of QGP (few fm/c), there is no direct observables for the detection of the QGP, unlike the ordinary electromagnetic plasma. If QGP medium is formed, it expands, cools down and hadronize to form final state hadrons. It is not possible to observe each stage separately in the experiment. Rather, we can measure the time integrated final state quantities like charged particle multiplicities, multiplicities of photons or leptons, particle transverse momentum spectra, energy, anisotropic flow etc. However, different processes during the time evolution of fireball resulting in final state observables preserve some information in time. Var-

ious signatures of QGP include Strangeness enhancement, anisotropic flow, J/ψ suppression, jet quenching etc., which are discussed below.

1.5.1 Strangeness Enhancement

The enhanced production of strange particle could signal to the formation of QGP, as the strange quarks are absent in the colliding matter [20]. To quantify the strangeness enhancement, one needs to compare the abundance of strangeness between QGP and hadronic phases as the strange particle production mechanism and production rates are different in a hadron gas as compared to QGP medium. The formation of $s\bar{s}$ pair in QGP from the channel $g\bar{g} \rightarrow s\bar{s}$ dominates over annihilation of light quarks, $q\bar{q} \rightarrow s\bar{s}$ channel due to higher gluon density. However in minimum bias pp collisions, where QGP medium formation is not expected, annihilation of light quarks to strange quark is the main channel for the production of strangeness. The enhancement factor (E) is defined as,

$$E = \frac{2}{\langle N_{part} \rangle} \left[\frac{\frac{dN^{AA}}{dy}|_{y=0}}{\frac{dN^{pp}}{dy}|_{y=0}} \right]. \quad (1.14)$$

Here $\langle N_{part} \rangle$ is the number of participants. $\frac{dN^{AA}}{dy}|_{y=0}$ and $\frac{dN^{pp}}{dy}|_{y=0}$ are the integrated yields in heavy-ion and pp collisions, respectively. Fig. 1.9 shows the yield of hyperons enhancement factor (E) as a function of centrality N_{part} [21–23]. The observed enhanced production of strange particle in Pb-Pb with respect to small collision systems indicate the formation of deconfined state of matter in LHC energies. It is also observed that the enhancement factor is higher for particles containing more number of strange quarks i.e. $E(\Lambda) < E(\Xi) < E(\Omega)$ [21–23]. Surprisingly, the measurements reported by ALICE in 2017 [2] provide one of the strongest evidences to validate that QGP-like conditions are also created in pp collisions, which is shown in Fig. 1.10. ALICE has observed enhanced production of strange particles in high-multiplicity pp collisions, which was historically considered to be one of the manifestations of QGP formation [24].

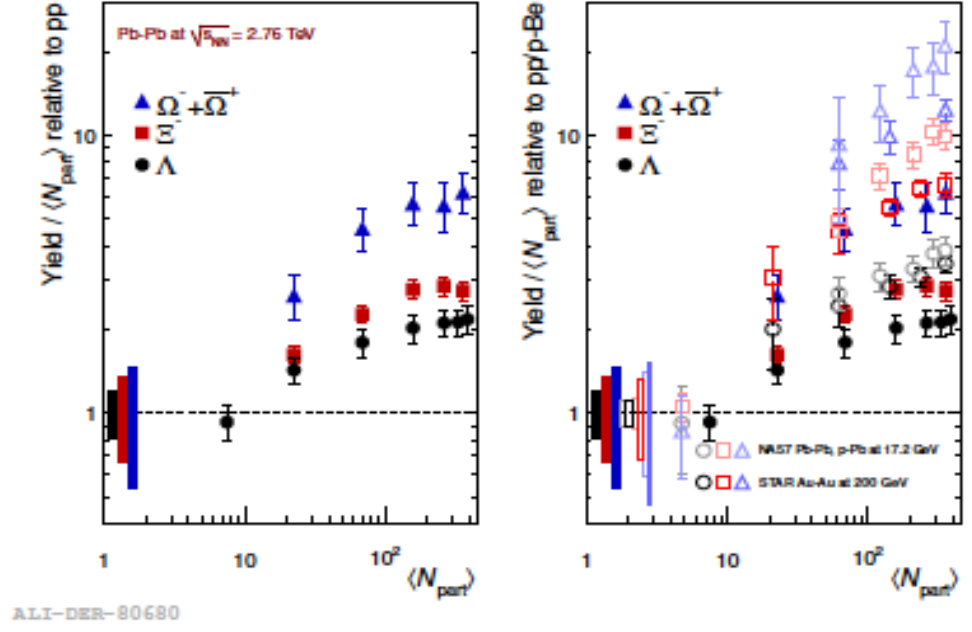


Figure 1.9: The yield of multi-strange hadrons in Pb-Pb relative to pp collisions measured in ALICE (left) and NA57, STAR (right) as function of $\langle N_{\text{part}} \rangle$ [21–23].

1.5.2 Anisotropic flow

Elliptic flow is an important observable to understand initial condition and the collective behavior of the system. The collective expansion of matter created in peripheral ultra-relativistic collisions results in spatial anisotropy of the initial density profile resulting in final state momentum anisotropy due to presence of pressure gradients. This phenomenon is called as anisotropic flow. This can be quantified using the azimuthal momentum anisotropy, which is defined as the fourier expansion in the azimuthal angle ϕ as [27, 28],

$$\frac{dN}{p_T dp_T d\phi dy} = \frac{dN}{2\pi p_T dp_T d\phi dy} \left[1 + 2 \sum_1^{\infty} v_n \cos[n(\phi - \psi_R)] \right], \quad (1.15)$$

where v_n 's are various order of flow harmonics, v_1 , v_2 and v_3 being the directed, elliptic and triangular flow, respectively. ψ_R is the event plane angle. The elliptic flow of charged particles presented in Fig. 1.11 shows that, the dense media produced at RHIC and LHC are of similar nature.

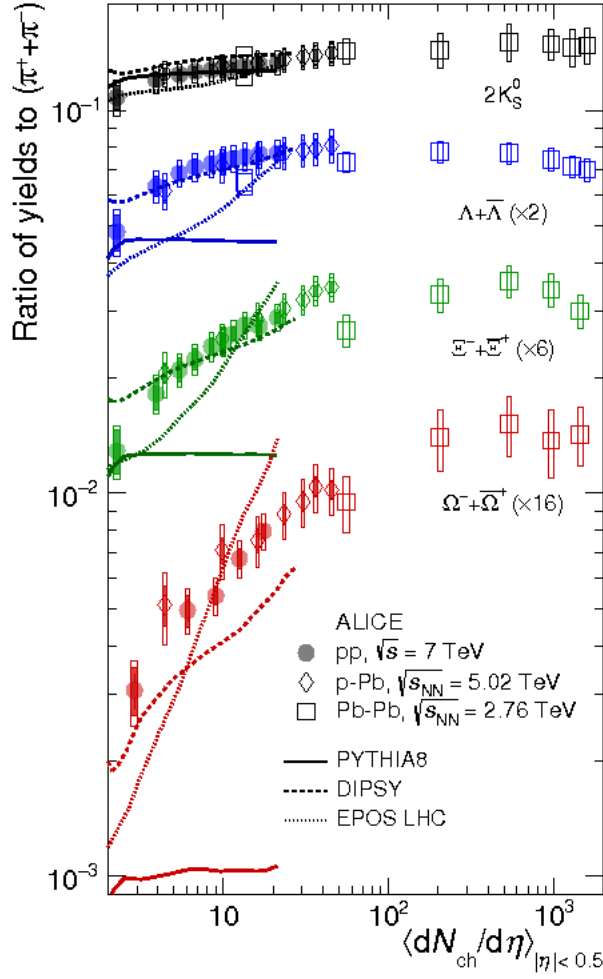


Figure 1.10: Enhanced strangeness production as a function of charged particle multiplicities for different collision systems [24].

The 30% higher value of v_2 at LHC is due to availability of larger phase space and larger re-scattering among partons. This also indicates an early thermalization of high- p_T partons compared to RHIC.

1.5.3 Jet quenching

The discovery of suppression in the production of high transverse momentum (p_T) mesons is one of the exciting results obtained at RHIC which is a hint of QGP medium formation. In relativistic heavy-ion collisions, partons with very high- p_T are produced which fly off to all possible directions

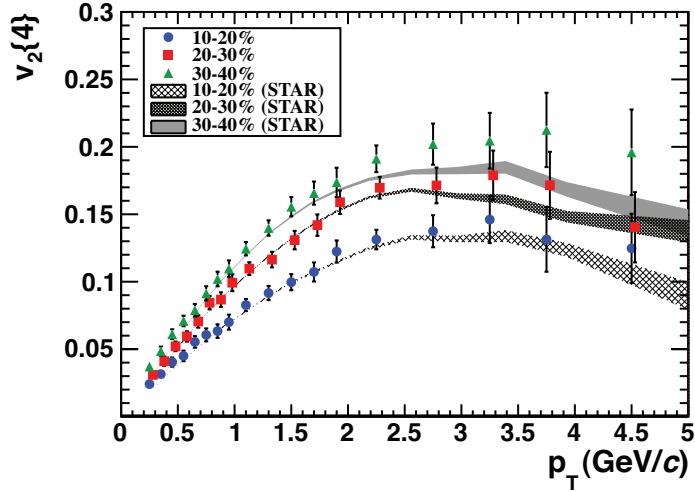


Figure 1.11: Elliptic flow of charged particles in Pb + Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV are compared to Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV, which are in shaded regions [26].

from the collision points and finally fragment into narrow cones of hadrons, called jets. These highly energetic shower of secondary partons are commonly referred as a jet. When these jets enter in the thermalized QGP medium, they interact with the particles in the medium and lose energies and eventually their momenta before hadronizing. Thus, the suppression is observed in nucleus-nucleus collisions compared to corresponding data from pp collisions scaled with the number of binary collisions [29, 30]. This phenomena is called as the jet quenching. The suppression of high- p_T particles are usually expressed in terms of the nuclear modification factor (R_{AA}),

$$R_{AA}(p_T) = \frac{1}{\langle T_{AA} \rangle} \times \left[\frac{(\frac{d^2N}{dp_T dy})_{AA}}{(\frac{d^2N}{dp_T dy})_{pp}} \right]. \quad (1.16)$$

R_{AA} is the ratio between the invariant yield in heavy-ion (A-A) collisions to that of pp collisions scaled with the average nuclear overlap function, $\langle T_{AA} \rangle = \langle N_{coll} \rangle / \sigma_{inel}$, where $\langle N_{coll} \rangle$ and σ_{inel} are number of binary collisions and inelastic pp cross section, respectively. $R_{AA} = 1$, suggests that the heavy-ion collisions are simply linear superposition of pp collisions and thus there is no QGP medium formation. However, any deviation from the unity value at high- p_T is an indication of quenching/enhancement in high-density medium. Fig. 1.12 shows the results of R_{AA} for charged hadrons

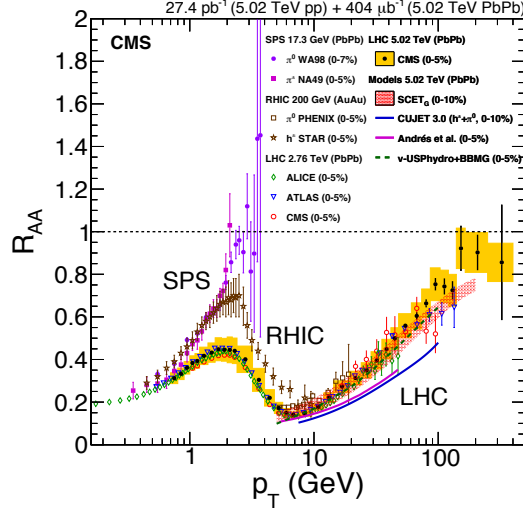


Figure 1.12: $R_{AA}(p_T)$ for charged hadrons ($h^\pm$) and neutral pions (π^0) in central heavy-ion collisions at SPS, RHIC and the LHC [26].

($h^\pm$) and neutral pions (π^0) in Au+Au and Pb+Pb collisions. The high- p_T suppression of hadrons in dense QGP medium could be seen in both RHIC and LHC energies.

1.5.4 J/ψ suppression

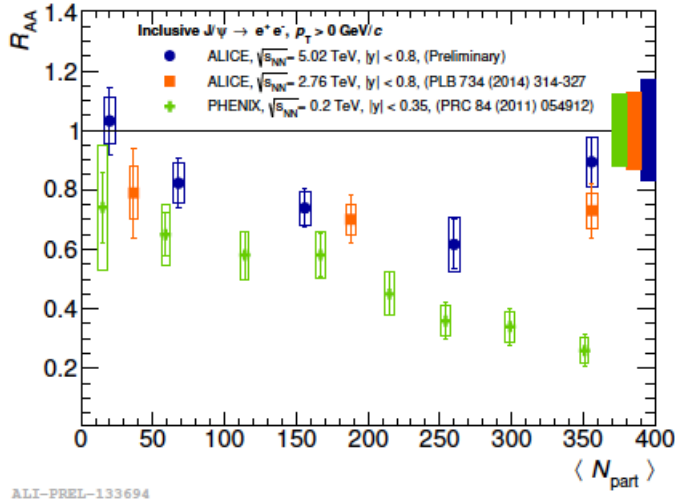


Figure 1.13: R_{AA} of J/ψ as function of centrality in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV.

The bound state of charm quark and its anti-quark, $c\bar{c}$ (J/ψ) is expected to be formed at the early stages of the hadronic and nuclear col-

lisions. Thus, the J/ψ becomes an excellent probe to study the early dynamics of the medium formed in heavy-ion collisions. Theoretical models suggest that the production of J/ψ in heavy-ion collisions is expected to be suppressed as compared to pp collisions [34]. The QGP screens the color charge of the quarks which reduces the J/ψ production. Significant J/ψ suppression is observed in heavy-ion collisions, whereas the disassociated charm quarks at the same time increases the open charm production ($D^0, D^\pm$). The J/ψ suppression is first observed in SPS [35] and then in RHIC [36, 37] energies, which confirms the QGP formation. Figure 1.13 shows the nuclear modification factor (R_{AA}) of J/ψ in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV as a function of centrality. The suppression in LHC energies is found to be less compared to RHIC and SPS energies [36]. This enhancement in the J/ψ yield at LHC is explained by the recombination/coalescence of charm quarks during the hadronization process.

1.5.5 Electromagnetic Probes

Photons and di-leptons are the electromagnetic probes, which helps get more information about the QGP properties [38–40]. As they do not have strong final state interactions, they act as ideal penetrating probe of strongly-interacting QCD matter [41]. In the heavy-ion collisions the photons and di-leptons can be produced in the initial hard scattering by the processes like: annihilation ($q\bar{q} \rightarrow \gamma g, q\bar{q} \rightarrow \gamma\gamma$), Bremsstrahlung ($qg \rightarrow gq^* \rightarrow q\gamma g$), fragmentation ($qg \rightarrow qg^* \rightarrow q\gamma X$), compton ($qg \rightarrow \gamma q$) and pair production ($q\bar{q} \rightarrow l\bar{l}$). Also, they can be radiated from the partons and hadrons in thermal equilibrium or via the decay of hadrons. Except the decay photons, others photons are called direct/prompt photons. The high- p_T photons which directly come from initial hard-scattering can be used for calculation of the momentum of the associated partons, which allows to study the parton energy loss in the medium. Hence they can be used as probes of gluon saturation. The thermal photons are emitted in

the dense matter and they carry the information on temperature of QGP.

Proton-Proton collisions are not usually expected to form a deconfined medium of partons and hence they are very useful in serving as a baseline measurement for nuclear collisions. After a brief discussions on the important signatures of QGP, we now focus on pp collisions at the LHC. Study of resonances containing strange quarks as a function of charged-particle multiplicity, would provide important contribution to explore the origin of QGP-like effects in pp collisions, which is discussed in the next section. To be specific, in this thesis we have looked into the production of ϕ mesons in pp collisions.

1.6 Resonance production in pp collisions

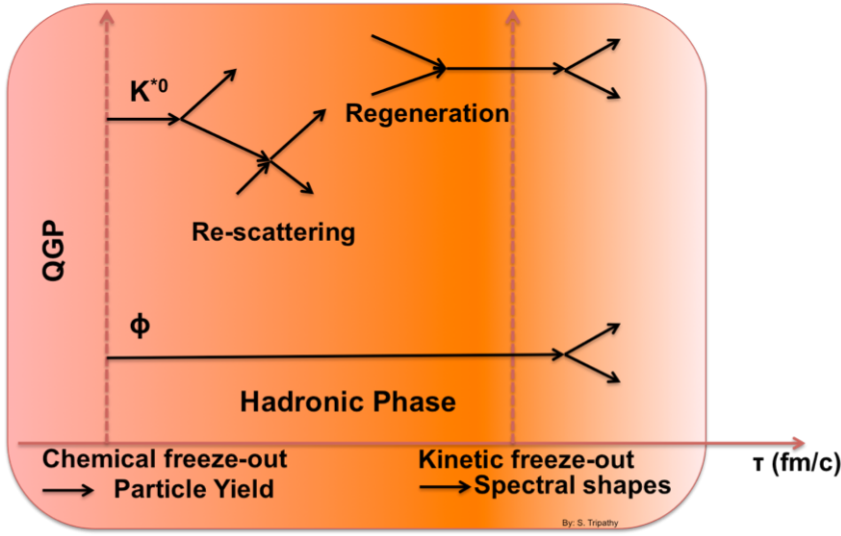


Figure 1.14: Depiction of re-scattering and regeneration processes in hadronic phase in heavy-ion collisions. [42]

Resonances are usually referred as the particles, which have higher mass than the corresponding ground state particle(s) with similar quark content. As hadronic resonances decay strongly, they have very short lifetime, $\tau \sim \text{few fm}/c$. Before decaying, these particles can only travel upto few femto-meters, which is about the diameter of proton. The width (Γ) and lifetime (τ) of the resonances are related by the Heisenberg's uncer-

tainty relation, i.e. $\Gamma\tau = \hbar$. As the broad resonance states decay very shortly after their production, it can only be measured by reconstruction of their decay daughters in a detector. The typical lifetime of experimentally measured hadronic resonances ranges from 1.1 fm/c to 46 fm/c. Hadronic resonances are produced in the bulk of the expanding medium in heavy-ion collisions and they can decay while still traversing in the medium. The decay daughters may interact with other particles in the medium, which would result in suppression of resonances while their reconstruction, as the invariant mass of the daughters may not match that of the parent particle. This process is known as re-scattering. In other way, resonances can be regenerated as a consequence of pseudo-elastic collisions in the hadronic phase of the medium, which would result in enhancement of resonances. Resonances, with relatively higher life-time, might not go through any of the above mentioned processes. It may also happen that the re-scattering and re-generation processes compensate each other. Thus, the interplay of these processes makes the study of resonances in heavy-ion collisions (Fig. 1.14) more fascinating. Also resonances like, $K^*(892)^0$ and $\phi(1020)$ contain strange (or anti-strange) quarks, they can be used for a systematic study of the particle species dependence of the partonic energy loss in the medium. Also, recent results from LHC [25] suggest that ϕ behaves like a particle with net strangeness of 1 or 2 in small systems. These observations open new directions for theoretical and experimental studies of pp collisions.

1.7 Thesis motivation

The major objectives of the thesis are to understand the processes discussed above with the double differential (Event shape and Multiplicity, discussed in subsequent chapters) study of ϕ meson production with ALICE at the LHC. Also, we phenomenologically attempt to formulate a model to characterize the heavy-ion collisions using relativistic kinetic theory in the form of Boltzmann Transport equation using relaxation time approximation. The

objectives of the thesis are briefly discussed below.

1.7.1 ϕ meson production in minimum bias pp collisions

In this thesis, the first measurements of ϕ meson in pp collisions at $\sqrt{s} = 5.02$ TeV with ALICE at the LHC is shown. The results include the invariant mass plots, peak fits, fitting parameters and the corrected p_T -spectra with reconstruction efficiencies.

1.7.2 Event shape and multiplicity dependence of ϕ meson production in pp collisions

The first measurements of ϕ meson in pp collisions at $\sqrt{s} = 5.02$ TeV as a function of charged particle multiplicity and transverse sphericity is shown. The results include the invariant mass plots, peak fits, fitting parameters and the corrected p_T spectra with reconstruction efficiencies.

We have also made an extensive study of various observables taking sphericity and event multiplicity in pp collisions at $\sqrt{s} = 13$ TeV using the pQCD inspired PYTHIA 8 model. The aim of the present study is to understand the high-multiplicity pp events at the highest LHC energy in view of a possible formation of QGP-droplets in pp collisions. In view of QGP-like behaviors observed in the LHC pp collisions and the fact that pp no longer serves as a baseline to understand a possible nuclear medium formation in heavy-ion collisions at the LHC energies, it is crucial to understand the mechanism of particle production in these high-multiplicity events. Through these simulation studies, we invoke the explicit inclusion of Multi-Partonic Interactions (MPI) and Color Reconnection (CR) effects responsible for particle production in pp collisions and then through transverse sphericity and multiplicity dependent analysis we try to understand various aspects of identified particle production in LHC pp collisions.

1.7.3 Azimuthal anisotropy in Xe-Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV using a multiphase transport model

Xe-Xe collision may provide us with a partonic system whose size is approximately in between those produced by pp and Pb-Pb collisions. The experimental results on anisotropic flow in Xe-Xe and Pb-Pb collisions should provide us with an opportunity to study system size dependence of v_2 at the approximately same collision energies. In the present work, we have used A Multi-Phase Transport (AMPT) model to calculate charged particles' v_2 for Xe-Xe collisions at $\sqrt{s_{NN}}=5.44$ TeV at mid-rapidity region $|\eta| < 0.8$ in $0 < p_T < 2.7$ GeV/c.

1.7.4 Nuclear Modification Factor and azimuthal anisotropy using non-extensive statistics

We have used Boltzmann transport equation in relaxation time approximation with non-extensive Tsallis statistics for the first time to estimate nuclear modification factor and elliptic flow for the identified hadrons in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV.

1.7.5 Transport properties of Hot and Dense Hadron Gas using Non-extensive Statistics

We have studied the transport coefficients using the relativistic non-extensive Boltzmann transport equation (NBTE), where we employ the relaxation time approximation for the collision integral. Here, we have extended the approach using Tsallis non-extensive statistics as q -equilibrium distribution function (q being the non-extensive parameter) and calculated shear and bulk viscosity to the entropy density ratios. We have also calculated isothermal compressibility and squared speed of sound using Tsallis statistics at finite baryon chemical potential for different q .

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Chapter 2

A Large Ion Collider Experiment at the LHC

“We shall not cease from exploration. And the end of all our exploring will be to arrive where we started and know the place for the first time”.

— *T. S. Eliot*

From the ancient times, exploration of the unknown has been the intrinsic nature of Mankind, which is also one of the core principles of fundamental research in basic sciences. To explore the nature of the Universe, an engineering marvel, “Large Hadron Collider (LHC)” was built at CERN, Geneva. Currently, the LHC is the most powerful and the largest particle accelerator in the world. One of the major experiments at the LHC, A Large Ion Collider Experiment (ALICE), has been taking data of hadronic and nuclear collisions from the commence of the LHC run on 23 November 2009. ALICE has been optimised to study the high-multiplicity environment of nucleon-nucleon and heavy-ion collisions. It has got excellent tracking and particle identification performance.

This chapter discusses the overview of the LHC and its major experiments. A brief description of the experimental setup in ALICE along with the primary focus to the particle identification technique is also discussed in this chapter. A short description on the ALICE online and trigger system is also given. The last part of the chapter is dedicated to the offline computing and reconstruction system based on the GRID framework.

2.1 Overview of Large Hadron Collider

The LHC is installed in a 27 km long underground tunnel across Switzerland and France border at a depth of about 50-150 m. It is a double-ring-superconducting hadron accelerator and collider which hosted the LEP machine and it completes the CERN accelerator complex together with the Proton Synchrotron (PS) and Super Proton Synchrotron (SPS) rings, among the others shown in Fig. 2.1. Along the circumference of the LHC, four main experiments are located in the four interaction points. ATLAS and CMS are multi-purpose detectors built to discover Higgs Boson and hints of physics beyond standard model. LHCb is dedicated to flavor physics, which focuses on CP violation studies using B meson decay channels. On the contrary, ALICE is dedicated to explore the dynamics of the infant Universe through the Quark Gluon Plasma in heavy-ion collisions. ALICE also explores QGP-like scenario in pp collisions.

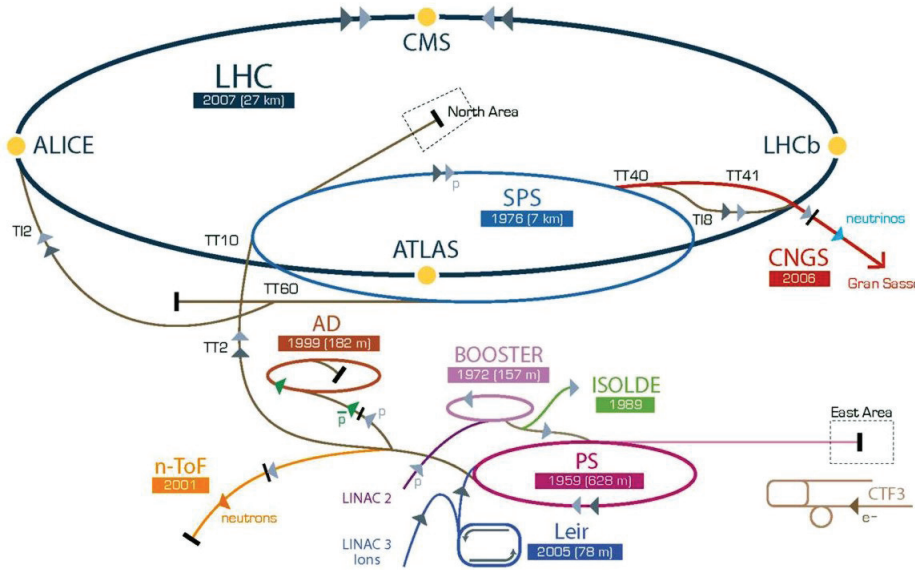


Figure 2.1: CERN accelerator complex showing the four main LHC experiments (ALICE, ATLAS, CMS and LHCb) around the LHC ring, the PS (Proton Synchrotron) and SPS (Super Proton Synchrotron) rings at Switzerland-France border [1].

Each machine in the accelerator complex boosts the energy of a beam of particles, prior to injecting in the next machine in the sequence. Starting from a simple bottle of hydrogen gas as proton source, an electric field is

used to strip the hydrogen atoms of their electrons. The first accelerator in the chain, LINAC 2, accelerates the protons to an energy of 50 MeV. Then the protons are injected to the PS Booster (PSB), which accelerates the protons to 1.4 GeV. Then the beam is injected to PS, which pushes the beam to 25 GeV, followed by the SPS. SPS accelerates protons to 450 GeV. The beam is finally transferred to the LHC both in a clockwise and anticlockwise direction, where they are accelerated for 20 minutes to 6.5 TeV. The beams are circulated for many hours inside the LHC beam pipes under normal operating conditions. Along with accelerating protons, the CERN accelerator complex can also accelerate lead ions.

Besides energy, another important accelerator parameter is the instantaneous luminosity (L). It is a proportionality factor between the event rate R and the interaction cross section (σ_{int}):

$$R = L\sigma_{int} \quad (2.1)$$

The instantaneous luminosity can be determined with the help of colliding beam parameters.

$$L = \frac{N^2 n f \gamma}{4\pi\epsilon\beta^*} F, \quad (2.2)$$

where N and n are the number of particles per bunch and number of bunches in a beam, respectively. ϵ is the normalized transverse beam emittance, f is the revolution frequency, γ is the relativistic gamma factor. The β^* and F respectively are the amplitude functions at the interaction point (IP) and the geometrical reduction factor that accounts for the crossing angle the IP.

The LHC was initially designed to provide collisions of proton-proton (pp) at the energy $\sqrt{s} = 14$ TeV and Pb-Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV. However due to the technical incident of quenching of a magnet in 2008 [2], in the first phase of LHC Run from 2009 to 2013 (Run 1), it run at nearly half of the design energy, thus providing pp collisions at $\sqrt{s} = 7$ and 8 TeV

and Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV. Special short periods of pp collisions at lower energies of 0.9 and 2.76 TeV and p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV were also provided by the LHC. In the Run 2 from 2015 to 2018, LHC has provided pp collisions at $\sqrt{s} = 5.02$ and 13 TeV, p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV and Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. Special one day run of Xe-Xe collisions was also provided by the LHC at $\sqrt{s_{\text{NN}}} = 5.44$ TeV. Currently, LHC is undergoing a major upgrade in the long shut-down period of 2019-2020 to fulfil the main physics goal of increasing the luminosity in Run 3.

2.2 The ALICE detector

ALICE is a 26m long, 16m wide and 16m high detector which weighs around 10,000 tonnes [3], situated in a vast cavern 56m below the ground in the territory of Serres in France border. ALICE is optimized to study heavy-ion and nucleon-nucleon collisions at ultra-relativistic energies provided by the LHC. The heavy-ion collisions provide experimental conditions to produce Quark Gluon Plasma (QGP), which is believed to have existed up to a few millionths of a second after the Big Bang before quarks and gluons were bound together to form protons and neutrons. One of the major goals of ALICE is to recreate this primordial state of matter in the laboratory and understand its time evolution, which will allow to shed light on questions about how matter is organized and the mechanisms that confine quarks and gluons. The main features of the ALICE detector are its excellent capability of particle identification by the help of specific energy loss, time of flight, transition and Cherenkov radiation, electromagnetic calorimetry and muon spectrometry.

ALICE consists of 19 detector subsystems (Fig. 2.2) that can be categorized into three groups namely central barrel detectors, muon spectrometer and forward detectors. ALICE has wide pseudorapidity coverage, which is shown in Fig. 2.3 with each detector acceptance. The acceptance in pseudorapidity, azimuth, the position and the main purposes of these

detectors are listed in Table 2.1. The detailed description of these detectors are discussed in the following sections.

THE ALICE DETECTOR

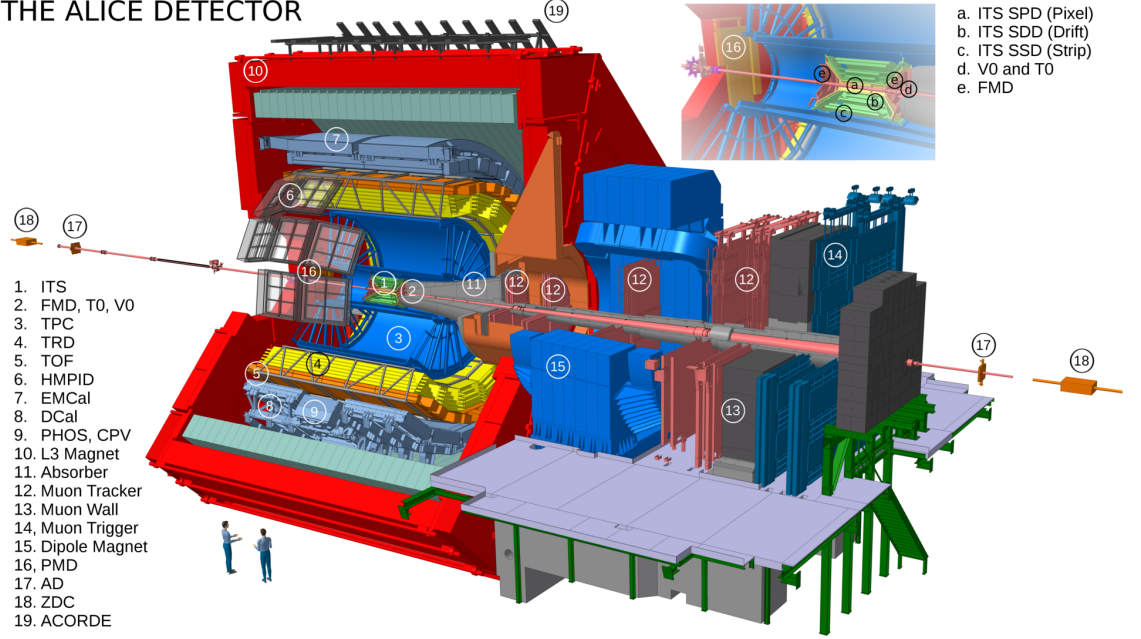


Figure 2.2: Schematic layout of ALICE detector [4].

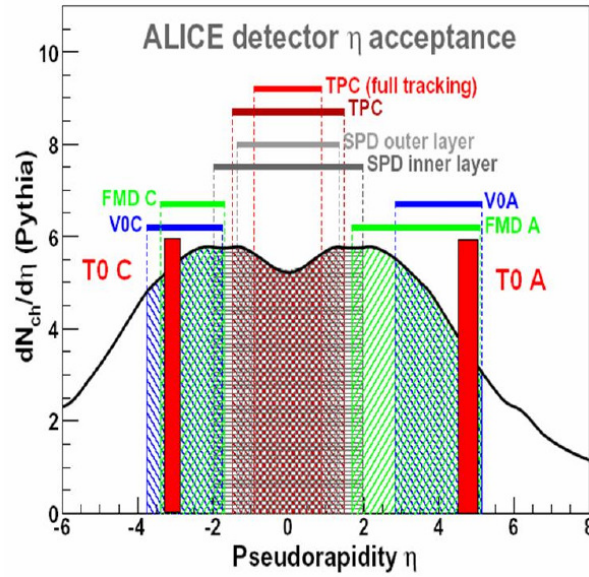


Figure 2.3: Pseudo-rapidity coverage of ALICE sub-detectors [5]

Table 2.1: Summary of sub-detector systems in ALICE [6].

Detector	Acceptance (η)	Acceptance (ϕ)	Position	Purpose
SPD	± 2.0	full	$r = 3.9$ cm	tracking, vertex
	± 1.4	full	$r = 7.6$ cm	tracking, vertex
SDD	± 0.9	full	$r = 15.0$ cm	tracking, PID
	± 0.9	full	$r = 23.9$ cm	tracking, PID
SSD	± 1.0	full	$r = 38$ cm	tracking, PID
	± 1.0	full	$r = 43$ cm	tracking, PID
TPC	± 0.9	full	$85 < r/\text{cm} < 247$	tracking, PID
TRD	± 0.8	full	$290 < r/\text{cm} < 368$	tracking, $e^\pm$ id
TOF	± 0.9	full	$370 < r/\text{cm} < 399$	PID
PHOS	± 0.12	$220^0 - 320^0$	$460 < r/\text{cm} < 478$	photons
EMCal	± 0.7	$80^0 - 187^0$	$430 < r/\text{cm} < 455$	photons and jets
HMPID	± 0.6	$1^0 - 59^0$	$r = 490$ cm	PID
ACORDE	± 1.3	$30^0 - 150^0$	$r = 850$ cm	cosmics
PMD	$2.3 - 3.9$	full	$z = 367$ cm	photons
FMD	$3.6 - 5.0$	full	$z = 320$ cm	charged particles
	$1.7 - 3.7$	full	$z = 80$ cm	charged particles
	$(-3.4) - (-1.7)$	full	$z = -70$ cm	charged particles
V0	$2.8 - 5.1$	full	$z = 329$ cm	charged particles
	$(-3.7) - (-1.7)$	full	$z = -88$ cm	charged particles
T0	$4.6 - 4.9$	full	$z = 370$ cm	time, vertex
	$(-3.3) - (-3.0)$	full	$z = -70$ cm	time, vertex
ZDC	> 8.8	full	$z = \pm 113$ m	forward neutrons
	$6.5 - 7.5$	$\phi < 10^0$	$z = \pm 113$ m	forward protons
	$4.8 - 5.7$	$2\phi < 32^0$	$z = 7.3$ m	photons
MCH	$(-4.0) - (-2.5)$	full	$-14.2 < z/m < -5.4$	muon tracking
MTR	$(-4.0) - (-2.5)$	full	$-17.1 < z/m < -16.1$	muon trigger

2.3 Central Barrel detectors

The central barrel is embedded in a large solenoidal magnet (L3 magnet, taken from LEP experiment), which provides 0.5 T magnetic field and it covers pseudo-rapidity interval of $-0.9 < \eta < 0.9$ (polar angle 45^0 to 135^0) and full azimuth. Central barrel comprises of Inner Tracking System (ITS) [7], Time Projection Chamber (TPC) [8], Transition Radiation Detector (TRD) [9], Time of Flight (TOF) [10] detector, Cherenkov counter (HMPID) [11], Photon Spectrometer (PHOS) [12], Electro-magnetic calorimeter (EMCAL) [13] and the ALICE Cosmic Ray Detector (ACORDE) [14]. The central detectors are mainly used for tracking, vertex reconstruction, particle identification and measurement of track momentum. The details of the central barrel detectors are discussed in the following sub-sections. Special emphasis is given to ITS, TPC and TOF detectors, as the ALICE data analyses in the thesis use these detectors extensively.

2.3.1 Inner Tracking System (ITS)

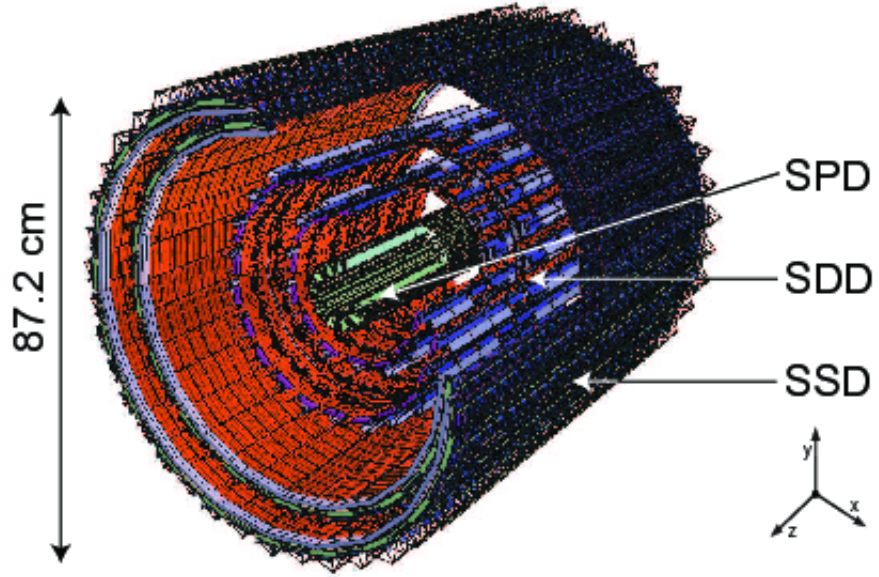


Figure 2.4: Schematic layout of Inner Tracking System (ITS) [7]

The ITS comprises of six cylindrical layers of silicon detectors, which encircles the interaction point and covers full azimuth. The geometric layout is shown in Fig. 2.4. The main purpose of ITS is the precise determination of primary and secondary vertices. In addition, it is essential to reach a high two-track resolution and momentum resolution of the tracks along with the track impact parameter (the distance of closest approach to the primary vertex).

Silicon Pixel Detector (SPD), the innermost detector in the ITS, plays an important role in the determination of primary and secondary vertices. It can operate at high radiation levels and at very high track densities about 50 tracks/cm^3 . The main components of SPD are the hybrid silicon pixels in the form of a two dimensional matrix of reverse-biased silicon detector diodes. The diodes are connected through a conductive solder bump to contacts on a read out chips which correspond to the input of readout cells. The SPD contains 107 cells and 1200 readout pixel chips. Each pixel chip of SPD also provides a Fast-OR digital pulse whenever a pixel or a group of them detects a particle signal above the threshold, which makes

SPD capable of generating a prompt trigger.

Silicon Drift Detector (SDD) are the intermediate layers (3rd and 4th) of the ITS. These layers are assembled with ladders and modules in order to ensure full angular coverage. SDD provides very high precision position information with position resolution of $35\ \mu m$. It also provides the information of the energy loss (dE/dx), which can be used for particle identification.

Silicon Strip Detector (SSD), the outermost layers in the ITS, is crucial in matching the tracks in ITS and TPC. It comprises of 698 modules and each module consists of a 1536 strip double sided silicon sensor connected through a aluminium kapton micro-cables to the front end electronics. It provides a two dimensional measurement of the track position along with the dE/dx information.

2.3.2 Time Projection Chamber (TPC)

The TPC is the main tracking detector among the central barrel detectors, which is optimised to measure the momentum of charged particles with good two-track separation. The schematic layout of TPC is shown in Fig. 2.5. TPC covers the pseudo-rapidity range $|\eta| < 0.9$ and full azimuthal angle. TPC is cylindrical in shape with an inner radius of 80 cm and an outer radius of 250 cm. It occupies an active volume of $88\ m^3$ covering length of 500 cm along the beam axis. During the data taking from the summer 2008 (cosmics) until the end of 2010, the TPC was filled with Ne : CO₂ : N₂ gas in the proportion of 90 : 10 : 5. Afterwards N₂ was removed from the gas mixture. A cylindrical conducting electrode is placed at the centre to maintain a uniform axial electrostatic field of 400 V/cm.

The working principle of TPC is the following, which is also shown schematically in Fig. 2.6. When a charged particle traverses through the gas volume, it excites and ionizes gas atoms along its track. As a consequence, the charged particle loses an amount of energy per unit track length (dE/dx) which is different for each particle type. The free electrons drift

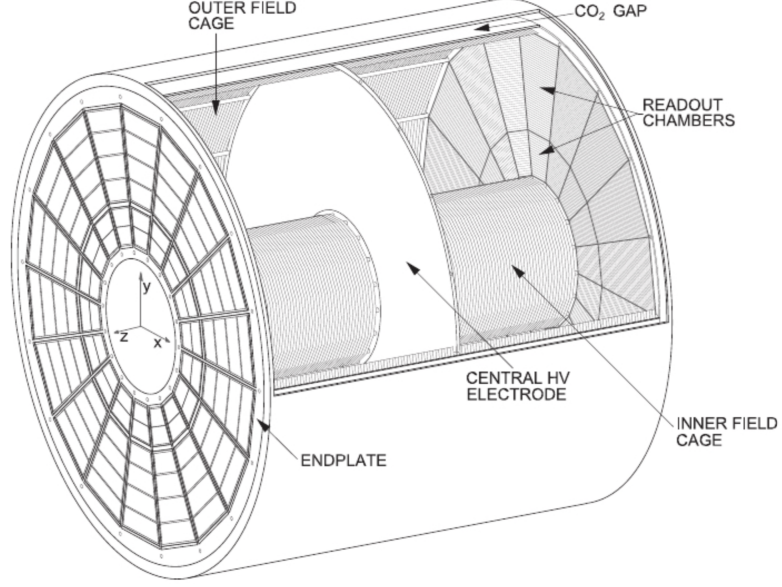


Figure 2.5: Schematic layout of Time Projection Chamber (TPC) [8, 15]

towards the endplates of the cylinder under the influence of the electric field and the ions drift towards the high voltage cathode placed at the centre of the TPC. The magnetic field is oriented parallel to the electric field such that the drifting electrons are not influenced by it. At the end of drift path of the electrons, they are amplified by an avalanche process around the anode wires. For the readout of the signal the Multi-Wire Proportional Chambers (MWPCs) at the end plates are used. There are two endplates and each endplate has 36 readout chambers arranged in 18 sectors. Each sector contains an Outer Readout Chamber (OROC) and an Inner Readout Chamber (IROC).

From 3D space points, the tracks are reconstructed in TPC and the transverse momentum (p_T) can be obtained from the curvature of the track. TPC can reconstruct a primary track of momentum (p) from 100 MeV/c up to 100 GeV/c. The Fig. 2.7 shows the tracks reconstructed inside TPC in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV during 2015. Apart from track reconstruction, TPC is crucial for particle identification. The particle identification in the TPC is performed by the simultaneous measurement of the charge, momentum and specific energy loss of each particle that traverses through the chamber.

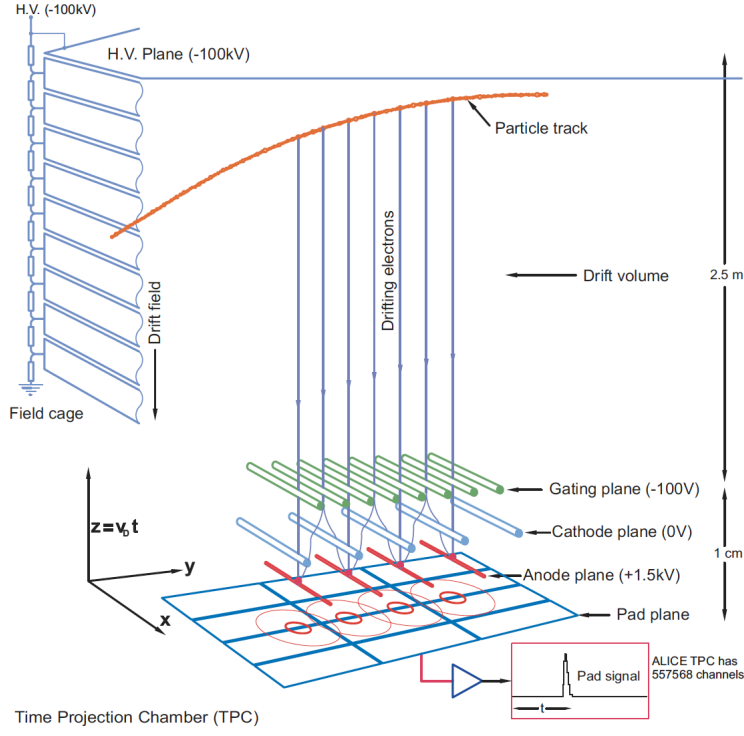


Figure 2.6: The schematic illustration of the working principle and the read-out chambers of the TPC [16].

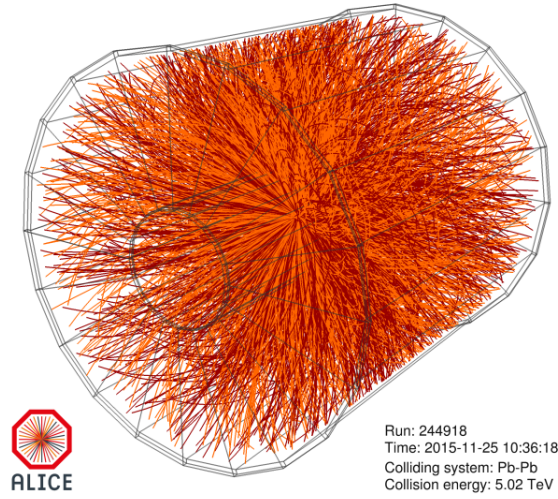


Figure 2.7: Event display of the tracks reconstructed inside TPC in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV during 2015 [18].

Bethe-Bloch formula describes the energy loss in TPC which is param-

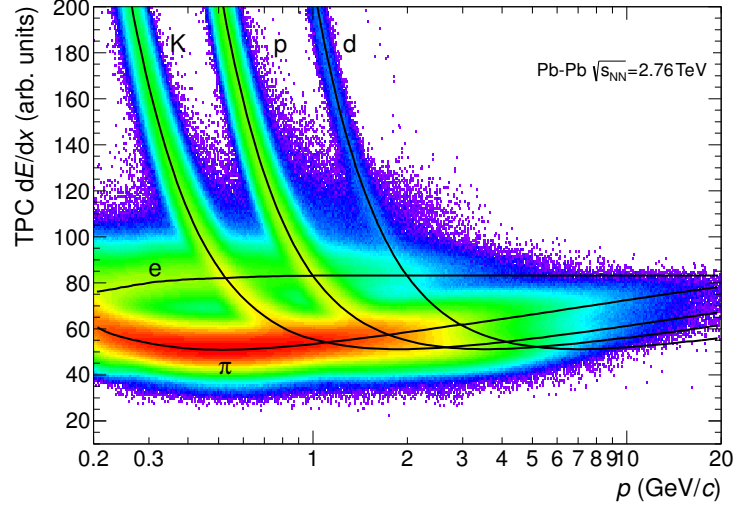


Figure 2.8: Specific energy loss (dE/dx) of the tracks as a function of momentum using TPC in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [21]

eterized by a function originally proposed by ALEPH collaboration [19, 20].

$$f(\beta\gamma) = \frac{P_1}{\beta^{P_4}} \left(P_1 - \beta^{P_4} - \ln \left(P_3 + \frac{1}{(\beta\gamma)^{P_5}} \right) \right). \quad (2.3)$$

Here β is the particle velocity and γ is the Lorentz factor. The parameters P_1 to P_5 are the fit parameters extracted for each data taking period [16]. In the low-velocity region, the energy loss decreases and at a relativistic limit the ionization value becomes minimum. At this region, the particles are called minimum ionization particles (MIP). Fig. 2.8 shows specific energy loss (dE/dx) of the tracks as a function of momentum using TPC in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [21]. The solid line represents the expectations from Bethe-Bloch formula. At low momentum, the particles can be identified on a track-by-track basis. On the other hand, at higher momentum particles can be separated on a statistical basis via multi-Gaussian fits to the difference between the dE/dx measured and dE/dx parameterized by Eq. 2.3. Another important approach to identify particles is via $n\sigma$ cut, where σ is the resolution. $n\sigma$ is defined in the

following way.

$$n\sigma = \frac{dE/dx_{measured} - dE/dx_{expected}}{\sigma_{TPC}^{PID}} \quad (2.4)$$

Here, $dE/dx_{measured}$ is the energy loss of the tracks measured in TPC, $dE/dx_{expected}$ is the expected energy loss of the tracks using a parameterization of modified Bethe Bloch function and σ_{TPC}^{PID} is the PID resolution of the TPC.

The analyses done in the thesis uses the $N\sigma$ method extensively.

2.3.3 Transition Radiation Detector (TRD)

The TRD is located in the radial position $2.9 < r < 3.7$ m from the interaction point. It covers full azimuthal angle and pseudo-rapidity region, $-0.84 < |\eta| < 0.84$. It is comprised of six layers of radiators followed by a drift chamber.

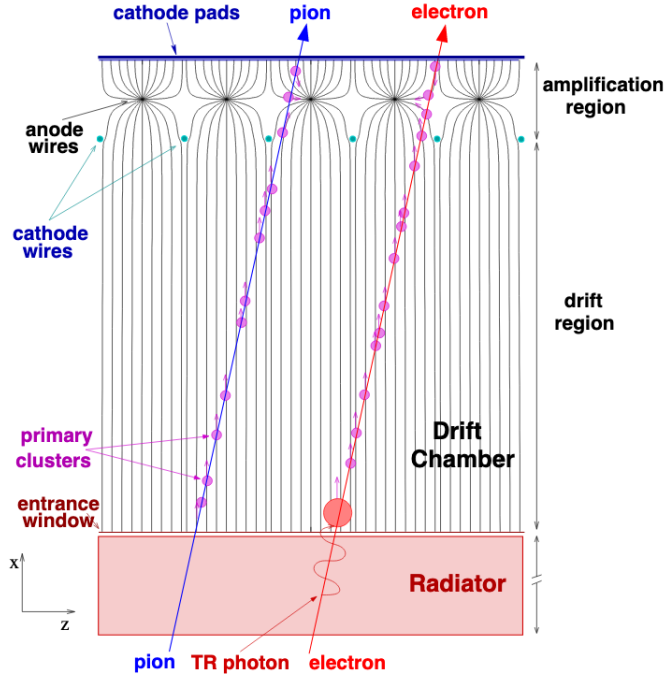


Figure 2.9: Schematic cross-sectional view of a module and working principle of TRD [17]

The TRD is dedicated for the electron identification for $p_T > 1$

GeV/c, where the TPC cannot identify the electrons via the dE/dx measurements. When the charged particles pass the interface of two media of different dielectric constant, transition radiation is emitted, with photons in the KeV range. The electrons above threshold momentum radiate differently with respect to pions. So the TRD can extend the pion rejection capability of the TPC up to very high momenta. The electron identification is essential for the study of electron spectra and study of light and heavy vector meson resonances via their leptonic decay channel. Fig. 2.9 shows the schematic cross-sectional view of a module and working principle of TRD [17].

2.3.4 Time Of Flight (TOF) detector

The TOF detector is a gaseous cylindrical detector comprises of Multi-gap Resistive Plate Chamber (MRPC). It is placed around the TRD at a radial distance of 2.70-3.99 m covering polar angles 45^0 to 135^0 within $|\eta| < 0.9$. The main purpose of TOF is to identify particles in the intermediate momentum region, where TPC cannot discriminate the hadrons by dE/dx measurement. When a charged particle passes through the detector, it ionizes the gas and the high electric field amplifies the ionization through electron avalanche, which are stopped due to the resistive plates. TOF detector has an ability to detect particles with 99.9% efficiency and a time resolution about 85 ps for Pb–Pb and 120 ps in pp collisions. The charged particles can be identified by the $n\sigma$ cut, which is defined by,

$$n\sigma = \frac{t_{measured} - t_{expected}}{\sigma_{TOF}^{PID}} \quad (2.5)$$

Here, $t_{measured}$ is the flight time of the particle measured by an algorithm of TOF and T0 detector, $t_{expected}$ is the flight time computed during the central tracking procedure and σ_{TOF}^{PID} is the PID resolution of the TOF detector.

2.3.5 High Momentum Particle Identification Detector (HMPID)

The HMPID is based on proximity-focusing Ring Imaging Cherenkov (RICH) counters with a radiator liquid C_6F_{14} (perfluorohexane). The major goal of HMPID is to extend track-by-track charged hadron identification at high- p_T in ALICE, which is beyond the momentum interval achievable by ionization energy loss in ITS and TPC and time of flight measurements in TOF. When a charged particle passes through the detector the electromagnetic radiation is emitted in a cone and the Cherenkov photons emitted by a fast charged particle traversing the radiator, are detected by a photon counter consists of 10 m^2 of active CsI photo-cathode area.

2.3.6 Photon Spectrometer (PHOS)

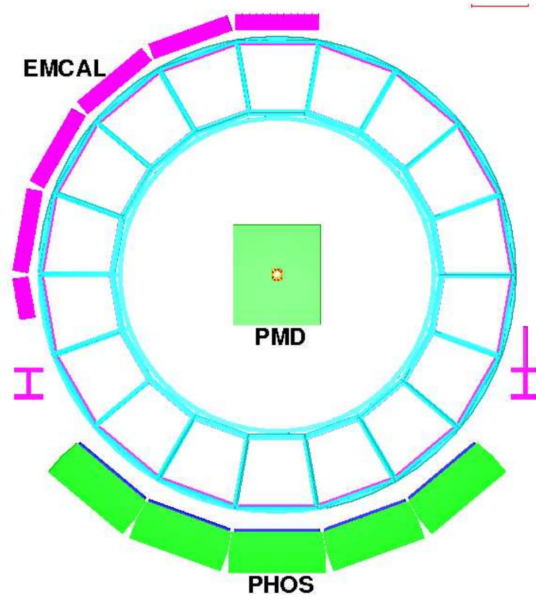


Figure 2.10: ALICE setup with PHOS, EMCAL and PMD [22]

PHOS is a high resolution electro-magnetic calorimeter and the major physics goals are to study the properties of the initial phase of the collision, study probes for de-confinement like jet quenching and validating the pQCD results. These studies are performed via the measurements of

direct and thermal photons, neutral pions and η mesons. It is located at a radial distance of 4.6 m with pseudo-rapidity acceptance of $|\eta| < 0.12$ and azimuthal acceptance of 220° - 320° . It has 5 modules with 3584 tungsten crystals (PbWO_4) in each module. The position of PHOS in ALICE is shown in Fig. 2.10. The Charged Particle Veto (CPV), a set of MWPCs, is placed in front of PHOS to reject charged particles.

2.3.7 Electro Magnetic Calorimeter (EMCAL)

The major goals of EMCAL are to enhance the measurement of jets and high- p_T photons and electron identification. It is located opposite to the PHOS with radial distance of 4.5 m from the beam line. It's a coverage of azimuthal angle between 80° to 187° and pseudo-rapidity range of $|\eta| < 0.7$. The acceptance of EMCAL is larger than PHOS but it has lower granularity and resolution. EMCAL produces an electromagnetic shower when the electrons and photons enter to the EMCAL. They deposit their energy in the EMCAL towers, which is reconstructed using cluster finding algorithms. It provides the measurement of transverse energy in the region from 100 MeV to 100 GeV. For hard jets, photons and electrons, EMCAL provides a fast and efficient trigger. The position of EMCAL in ALICE is shown in Fig. 2.10.

2.3.8 ALICE Cosmic Ray Detector (ACORDE)

As the name suggests, the ACORDE [23] provides a trigger for the cosmic rays. It is located at a radial distance of 8.5 m over the azimuthal angle -60° to 60° and pseudo-rapidity range of $|\eta| < 1.3$. It consists of an array of 60 plastic scintillators placed on the top of L3 magnet. It acts as a crucial detector as it provides a fast L0 trigger signal during the calibration and alignment of some ALICE tracking detectors.

2.4 Muon Spectrometer

The Forward Muon Spectrometer has been designed to identify heavy flavour vector mesons as well as the ϕ -meson at forward rapidity, through their leptonic decay to muon pairs. The different states of quarkonia exhibit invariant mass peaks very close to each other, which require a good mass resolution of the detector. The simultaneous measurement of all the quarkonia species allows a direct comparison of their production rate. The muon spectrometer is located exterior to the central barrel and covers the pseudorapidity region $-4.0 < |\eta| < -2.5$ and full azimuth. A 3.5 *m* long carbon conic-shaped absorber has been placed in front of the spectrometer to screen the detector from most of the primary and secondary particles produced in the interaction point. The cut-off of muon pairs $p_T > 4$ GeV/*c* is due to the fact that muons have to pass through the front absorber made of carbon, concrete and steel. The muons are measured by five tracking stations with two planes each made up of very highly granular cathode strip tracking stations. To reconstruct the momenta of muons, a dipole magnet is placed outside the L3 magnet. An iron wall of 1.2 *m* acts as a further muon filter after which two trigger stations are located. Finally an inner beam shield protects the muon spectrometer from secondaries produced at large rapidity.

2.5 Forward Detectors

The forward detectors comprises of VZERO (V0) detector [24], TZERO (T0) detector [24], Zero Degree Calorimeter (ZDC) [29], Photon Multiplicity Detector (PMD) [26] and Forward Multiplicity Detector (FMD) [24]. The brief description of these detectors are discussed below. A special emphasis on V0 detector is given as V0 is used as trigger and multiplicity estimator in the ALICE data analyses in the thesis.

2.5.1 VZERO (V0) detector

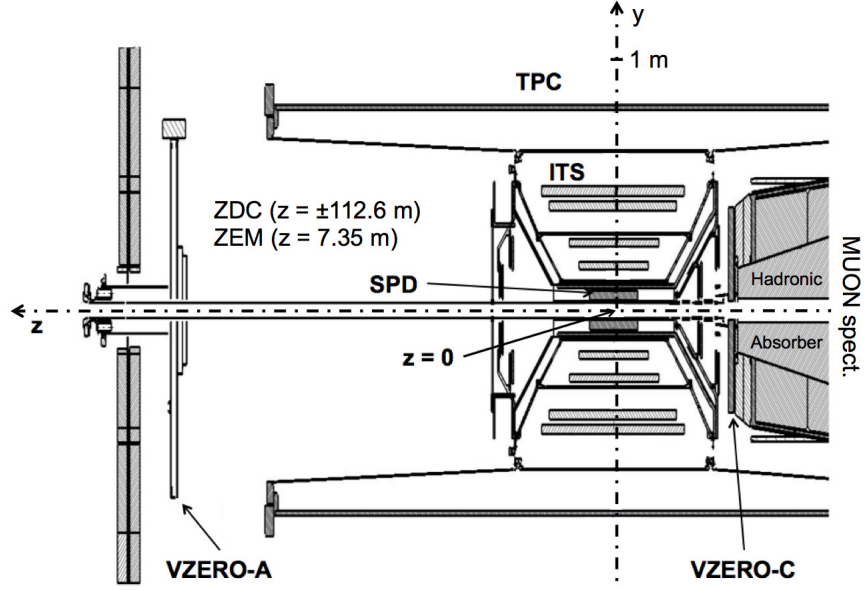


Figure 2.11: Position of the two VZERO arrays within the general layout of the ALICE [27].

V0 detectors are the plastic scintillators located both sides of the interaction point. The one in forward direction is called as VZERO-A (V0-A) and the one in backward direction is called as VZERO-C (V0-C). Both of them cover full azimuth while the pseudo-rapidity coverage for V0-A is $2.8 < |\eta| < 5.1$ and is $-3.7 < |\eta| < -1.7$ for V0-C. The detectors are segmented in 4 rings and each ring is divided into 8 sectors, which is segmented in 32 counters. Position of the two V0 arrays within the general layout of the ALICE is shown in Fig. 2.11.

V0 detector has several functions. It is used as minimum bias trigger for central barrel detectors. The particles originating from initial collisions and from secondary interactions in the vacuum chamber elements, provide the trigger information for central barrel detectors. The dependence between the number of registered particles on the V0 arrays and the number of primary emitted particles is monotonic. Thus, the V0 serves as an indicator of the centrality of the collision via the multiplicity recorded in the event. Cuts on the total charge and the number of fired counters can be applied to achieve rough centrality triggers [31].

There are three such triggers namely, the multiplicity, semi-central and central triggers.

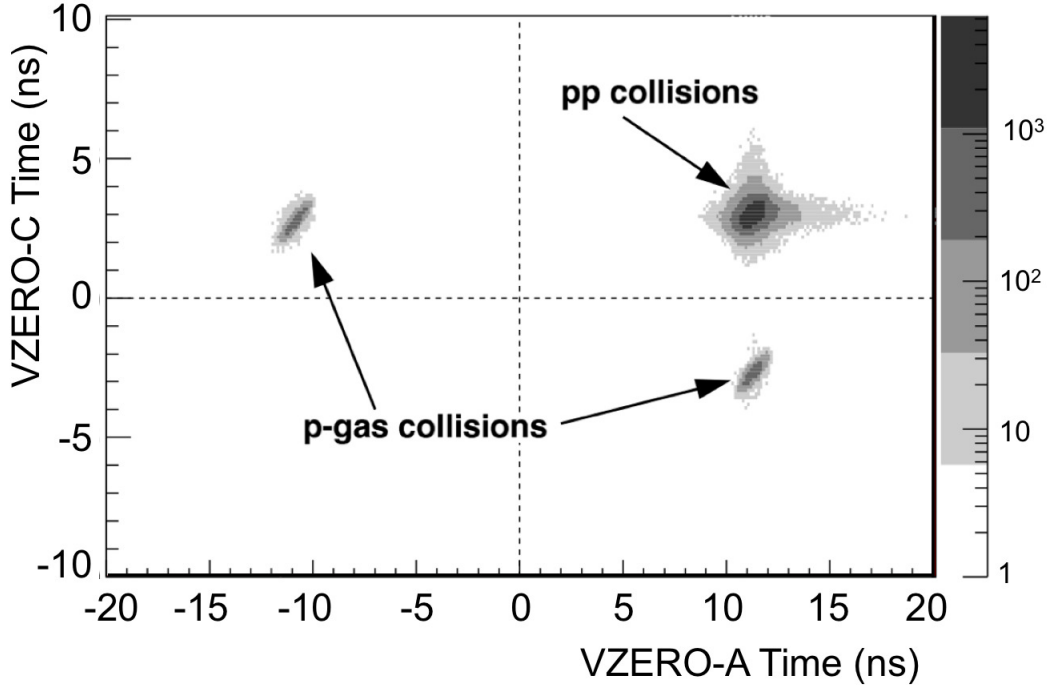


Figure 2.12: Timing criteria to discriminate beam-beam and beam-gas events using the average time response correlation of V0 detectors [27].

The interaction of proton and residual gas in the vacuum chamber can generate tracks in the detectors and these false events can be eliminated by using the Minimum Bias p-Gas trigger (PG). The timing criteria is used to discriminate beam-beam and beam-gas events using the average time response correlation of V0 detectors, which is shown in Fig. 2.12. The large part of the false muon trigger can also be rejected by using the V0-C. The V0 detector takes part in luminosity measurement in pp collisions with a precision of 10%. V0 detector also provides an early wake-up signal for the TRD, prior to the level 0 trigger.

2.5.2 TZERO (T0) detector

T0 detector comprises of two arrays of Cherenkov counters, called as T0-A and T0-C. T0-A detector is located opposite to the Muon spectrometer, at a distance of 3.75 m from the interaction point. It covers the range

of $4.61 < |\eta| < 5.92$. T0-C is located on the opposite side of T0-A at a distance of 7.27 m from the interaction point with pseudo-rapidity coverage $-3.28 < |\eta| < -2.97$. T0 has high time resolution which can measure the collision time with a precision of 25 ps . This collision time is used as a reference time for Time of Flight detector. The T0 can also send a pre-trigger to the TRD and can also generate minimum bias and multiplicity triggers.

2.5.3 Zero Degree Calorimeter (ZDC)

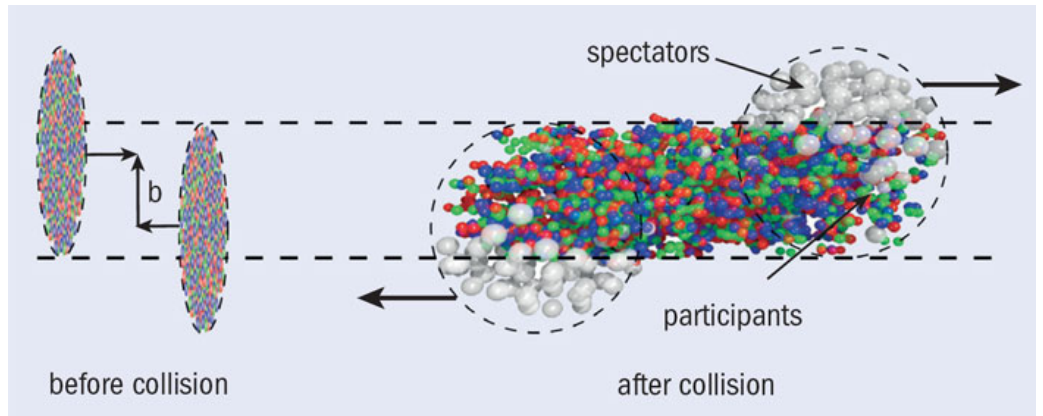


Figure 2.13: Left: Two heavy ions before collision, Right: Spectators and participants after collision [28].

In the heavy-ion collisions the nucleons which are involved in the collisions are called participants and the nucleons which fly along the beam line without participating in the collisions are called spectators. Participants and spectators in heavy-ion collisions are shown in Fig. 2.13. ZDCs are the detectors, which measure the energy of spectator nucleon to determine the overlap region of the colliding nuclei. The ZDCs are located on either sides of the interaction point at a distance of 116 m . It is placed along the beam pipe at 0° relative to the LHC. Thus, it is called as Zero Degree Calorimeter. The positions of ZDCs are depicted in Fig. 2.14. The hadronic ZDC consists of two type of detectors namely, neutron detector (ZN) and the proton detector (ZP). Typically, the colliding beams are deflected via two separation dipoles at a certain distance from the interaction

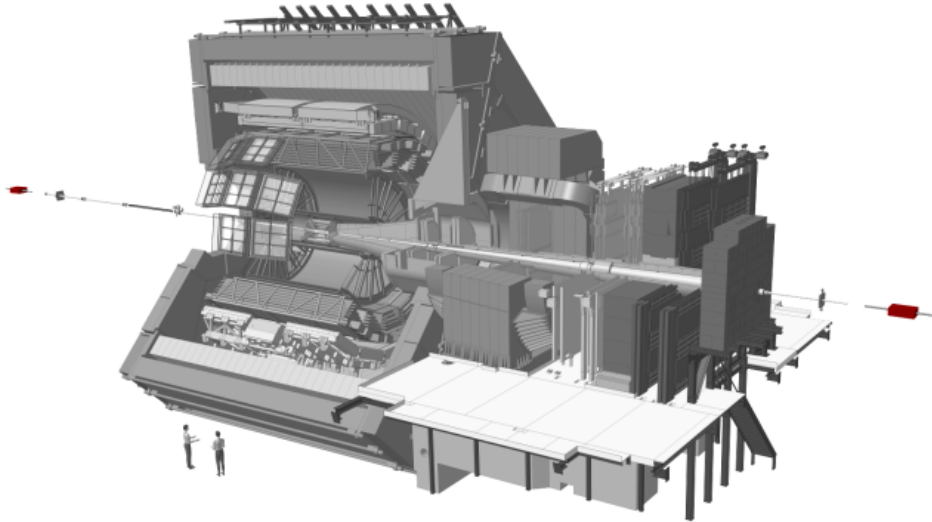


Figure 2.14: Position of the two ZDCs (highlighted in red) within the general layout of the ALICE [29].

point (IP). These magnets will also deflect the spectator protons as they are charged particles. This also separates them from the spectator neutrons, which fly away at 0° . Thus, the calorimeter ZN and ZP are placed in different positions: ZN is positioned between the two beams to intercept the spectator neutrons while ZP is placed external to the outgoing beam, to collect the spectator protons [30]. The ZDCs are made up matrix of quartz fibres and of heavy metal plates. The heavy metal plates for neutrons are made of tungsten and for protons they are made up of brass. The material of the metal plate is called passive material. When neutrons and protons traverse through the passive material, a shower of particles is created. When particle with high enough energy, crosses the fibre it produces the light via Cherenkov effect. The generated light in the fibre is converted to electric signals via photomultipliers. The amplitude of electric signal is proportional to the energy of incoming neutrons and protons, which allows to estimate the size of the overlap region of the two colliding nuclei.

2.5.4 Photon Multiplicity Detector (PMD)

The main physics goal of PMD is to measure the multiplicity of photons produced in pp and Pb-Pb collisions in the forward rapidity. It is also used

for the determination of the reaction plane.

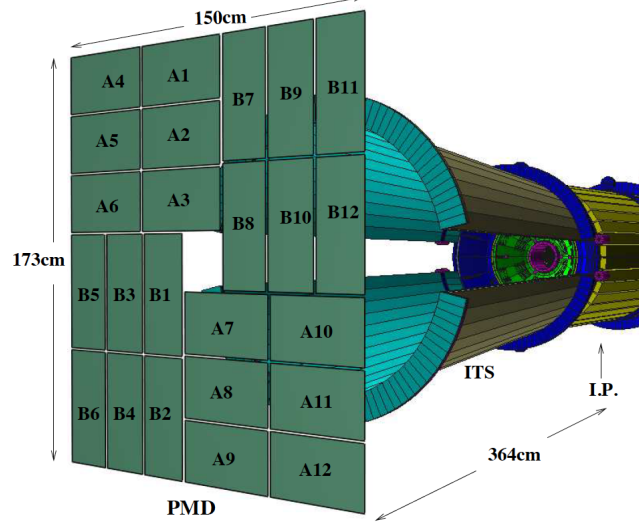


Figure 2.15: The position of PMD in ALICE [17].

The PMD is located in the forward region of ALICE at 3.67 m from the interaction point. It covers pseudo-rapidity range $2.3 < |\eta| < 3.9$ and full azimuth. The position of PMD in ALICE shown in Fig. 2.15. The PMD is a pre-shower detector, where lead converter is sandwiched between two planes of gaseous proportional counters. The thickness of converter and the granularity of the gaseous proportional chambers are optimized for high particle density. The PMD has 40 modules in two planes (CPV and pre-shower), which consists of 184320 honeycomb structured gas cells. The charged particle veto (CPV) plane in the PMD registers charged particle hits, whereas photons do not leave any signature in CPV. Photons passing through the converter produce electromagnetic shower in the pre-shower plane, which leads to a large signal spread over many cells. The signal from a charged particle is confined to a single cell in PMD, which along with the CPV information, is used to reject the charged-particle tracks. It measures the multiplicity and spatial distribution of photons in an event-by-event basis.

2.5.5 Forward Multiplicity Detector (FMD)

The FMD is located at forward and backward rapidities $-3.4 < |\eta| < -1.7$ and $1.7 < |\eta| < 5.0$ with full azimuthal coverage. It is used to determine the multiplicity of the charged particles and also used to determine the reaction plane. Common phase space of FMD and PMD allows to study charged-neutral particle fluctuations and correlations. It is placed away from the interaction point opposite to the muon spectrometer, which is to extend the charged particle multiplicity coverage.

2.6 Online and Trigger

The data taking activities in ALICE are controlled by the central online systems. The Detector Control System (DCS) allows to operate the detector hardware from a central interface. The Data AcQuisition (DAQ) system is responsible for defining the configuration of the detectors during data taking. It is interfaced with the Trigger (TRG) and High-Level Trigger (HLT) systems. All the operations of the central systems (DAQ, TRG and HLT) are coordinated by the Experiment Control System (ECS). The detectors can operate individually which is known as standalone mode. Standalone mode is used to perform commissioning, calibration and debugging activities. During the physics data taking, the detectors are grouped in partitions which can operate concurrently with a given set of trigger inputs.

2.6.1 Central Trigger Processor (CTP)

The ALICE trigger system comprises of Central Trigger Processor (CTP) and a High Level Trigger (HLT) [32, 33]. For each detector, the CTP consists of 24 Local Trigger Units (LTU). The first level trigger is called the L0 and the second level is called L1. L0 is delivered after $1.2 \mu s$ and L1 is delivered after $6.5 \mu s$. The final trigger, L2, is delivered after $100 \mu s$.

After the L2 trigger the event is stored and the output of the CTP goes to the LTUs of each detectors. Then the output is transferred to the front end electronics of the detector via Low Voltage Differential Signalling (LVDS) cables and optical fibres.

2.6.2 High Level Trigger (HLT)

To select interesting events, HLT permits a firmware and software via filtering mechanism. HLT receives the raw data via Detector Data Links (DDL). Then it extracts hits and clusters and performs the basic calibration. Then the event is reconstructed for each detector individually and the selection of event is performed with the reconstructed physics observables. HLT also performs data compression.

2.6.3 Data Acquisition (DAQ)

The DAQ system handles the data flow from the electronics of the detector to the permanent storage. The Local Data Concentrators (LDCs) read out the events from the optical DDLs. The LDC assembles the data into the sub-events and they are shipped to Global Data Collectors (GDCs). The GDCs records the events to Transient Data Storage (TDS). Then it is migrated to the tape (PDS) in the storage.

2.7 Offline and Computing

The offline project is dedicated to the development of the framework of data processing.

2.7.1 ALICE Grid and ALIEN

To handle and process huge amount of data distributed among computing resources, the concept of ALICE Grid was introduced. In ALICE Grid, the

data processing is distributed to several computing centres located world-wide. The distributed computing infrastructure, which is used in the LHC experimental program, is managed under Worldwide LHC Computing Grid (WLCG) project. The ALICE grid uses Models of networked analysis at regional centres (MONARC) model, which is classified into different stages and tiers. All real data originate from CERN, which is called Tier-0. Tier-1, which are large regional computing centres, share with CERN for the role of a safe storage of the data. Tier-2 are the smaller centres which are logically clustered around Tier-1. The main function for Tier-2 is to perform Monte-Carlo simulations and user analysis tasks. ALICE Offline project also develops ALIce Environment (ALIEN), which allows ALICE users to have transparent access to grid computing and storage resources.

2.7.2 AliRoot Framework

ALICE uses ROOT framework [34], which is a scientific software framework. ROOT is primarily C++ based while other languages such as R and Python are also integrated to ROOT. It includes all the functionality required for big data processing, statistical analysis and storage of physics analysis. In addition to the package for physics analysis, the software for the simulation of events and detector is required. To fulfil all requirements AliRoot [35] framework was developed, which is based on ROOT. AliRoot also uses different Monte-Carlo softwares like GEANT3 [36], GEANT4 [37], and FLUKA [38] to simulate the interaction of particles with detector material. For simulation of events for pp and heavy-ion collisions, different event generators are used.

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Chapter 3

Measurement of ϕ meson in minimum bias pp collisions

“Science is a way of thinking much more than it is a body of knowledge”.

– Carl Sagan

Resonances are usually referred as the particles, which have higher mass than the corresponding ground state particle(s) with similar quark content. As hadronic resonances decay strongly, they have very short lifetime, $\tau \sim \text{few fm}/c$. Before decaying, these particles can only travel upto few femto-meters, which is about the diameter of the proton. The width (Γ) and lifetime (τ) of the resonances are related by the Heisenberg’s uncertainty relation, i.e. $\Gamma\tau = \hbar$. As the broad resonance states decay very shortly after their production, it can only be measured by reconstruction of their decay daughters in a detector. The typical lifetime of experimentally measured hadronic resonances ranges from 1.1 fm/c to 46 fm/c. Hadronic resonances are produced in the bulk of the expanding medium in the heavy-ion collisions and they can decay while still traversing in the medium. The decay daughters may interact with other particles in the medium, which would result in suppression of resonances while their reconstruction, as the invariant mass of the daughters may not match that of the parent particle. This process is known as re-scattering. In other way, resonances can be regenerated as a consequence of pseudo-elastic collisions in the hadronic phase of the medium, which would result in enhancement of resonances. Resonances, with relatively higher life-time, might not go through any of

the above mentioned processes. It may also happen that the re-scattering and re-generation processes compensate each other. Thus, the interplay of these processes makes the study of resonances in heavy-ion collisions (Fig. 3.1) more fascinating. Also resonances like, $K^*(892)^0$ and $\phi(1020)$ contain strange (or anti-strange) quarks, they can be used for a systematic study of the particle species dependence of the partonic energy loss in the medium.

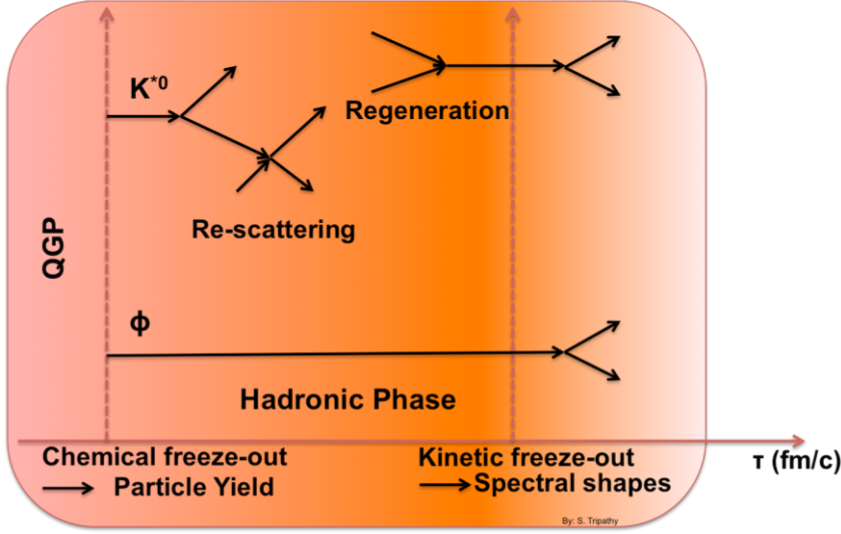


Figure 3.1: Depiction of re-scattering and regeneration processes in hadronic phase in heavy-ion collisions. [1]

Measurements reported by ALICE in 2017 [2] provide one of the strongest evidences to validate that QGP-like conditions are also created in pp collisions. ALICE has observed enhanced production of strange particles in high-multiplicity pp collisions, which was historically considered to be one of the manifestations of QGP formation [2]. Also, recent results from LHC [13] suggest that ϕ behaves like a particle with net strangeness of 1 or 2 in small systems. These observations open new directions for theoretical and experimental studies of pp collisions. So far, none of the models explain the recently discovered behaviors satisfactorily. Study of resonances containing strange quarks as a function of charged-particle multiplicity, would provide important contribution to the origin of QGP-like effects in pp collisions. A new observable for the LHC era, transverse sphericity is

also an important observable which can isolate events on the basis of its geometrical shape. A double differential study of resonance production using multiplicity and sphericity would give more insight into the particle production in high multiplicity pp collisions. The measurement of resonances in minimum bias pp collisions also set the baseline to which heavy-ion collisions are compared as well as contribute to the understanding of particle production mechanisms through comparison with different model predictions.

This chapter describes the detailed methodology and results for measurement of ϕ meson production in minimum bias pp collisions at different collision energies. The results will be mainly focused on ϕ meson production in minimum bias pp collisions at $\sqrt{s} = 5.02$ TeV and the final results will be compared with other collision energies. The next chapter will be dedicated to discuss the results from multiplicity and sphericity dependence ϕ meson production in pp collisions at $\sqrt{s} = 5.02$ and 13 TeV.

3.1 Introduction

The existence of ϕ -meson was first postulated by Prof. J. J. Sakurai in 1962, which is a resonance state between K^0 and $\bar{K}^0$ [4]. Later it was discovered in a 20-inch hydrogen bubble chamber at the Alternative Gradient Synchrotron (AGS) in Brookhaven National Laboratory (BNL), USA in the same year [5]. It was naively expected that the most energetic decay channel of ϕ would be decaying into 3 pions. However, it was instead observed from experiments that the ϕ decays to kaons more frequently [6]. Later in the years between 1963 to 1966, Susumu Okubo, George Zweig and Jugoro Iizuka, independently proposed a rule to account for the observed suppression of the 3 pion decay [7–9]. This rule is known as OZI rule, a consequence of quantum chromodynamics (QCD), which states that strongly occurring process will be suppressed if its Feynman diagram can be separated into two disconnected diagrams via only the removal of the internal gluon lines. This is shown in Fig. 3.2 in terms of Feynman diagrams.

This rule also explains the unusually long lifetime of J/ψ -meson. In this thesis, the hadronic decay channel to 2 kaons is used for the reconstruction of ϕ . The basic analysis flow is shown in Fig. 3.3.

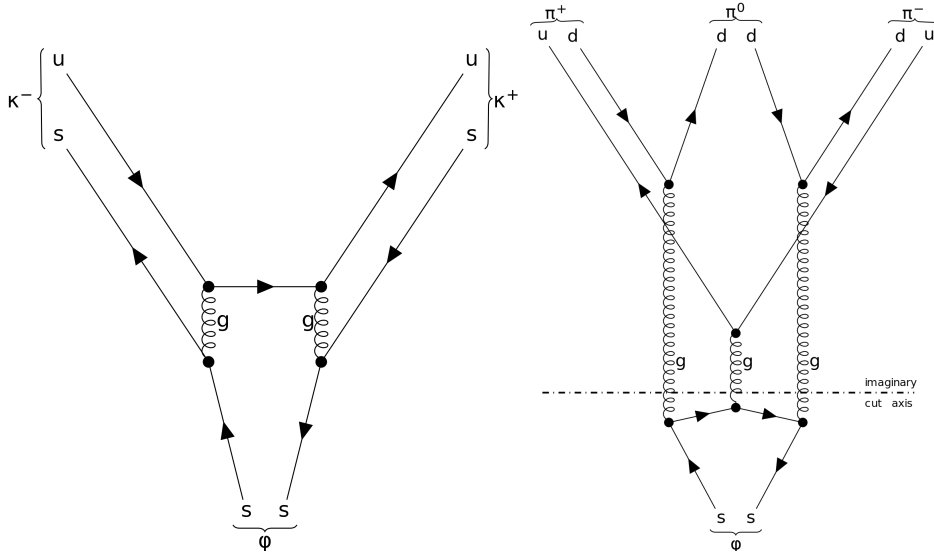


Figure 3.2: Depiction of preferred decay channel of ϕ as per the OZI rule [6, 10]. The left diagram is more preferred while the right one is significantly suppressed.

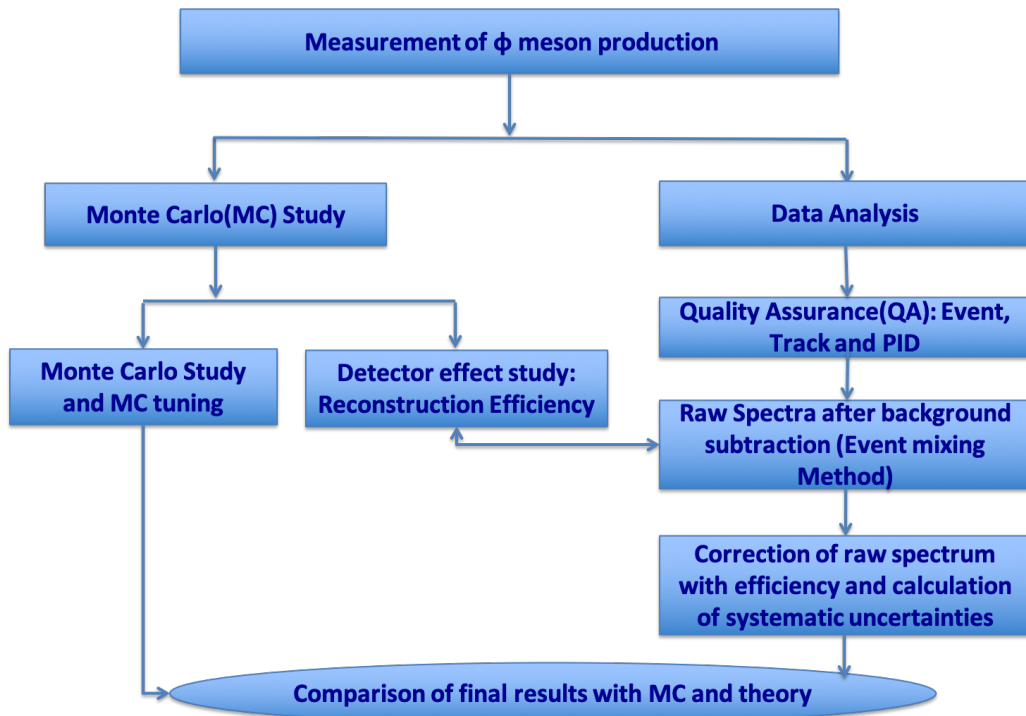


Figure 3.3: Data analysis flow chart.

3.2 Dataset and Event selection

The production of ϕ meson is measured at mid-rapidity ($|y| < 0.5$) in minimum-bias pp collisions at $\sqrt{s} = 5.02$ TeV using ALICE detector [11]. For pp minimum-bias collision at $\sqrt{s} = 5.02$ TeV, the data were collected during Run 2 operation at the LHC. The data were collected with a minimum bias trigger (trigger is an electronic system which makes a decision whether the collision data are worth to save or not), which requires a hit in both VZERO detectors (kINT7), in coincidence with the arrival of proton bunches from both directions. The detailed method of event selection in VZERO detectors is discussed in Sec. 2.5.1. The physics selection framework is widely used within ALICE to select events satisfying certain trigger criteria and reject beam-gas. The physics selection framework is also used to reject pileup events. The physics selection is performed in two steps: (1) selection of events with relevant trigger classes fired, (2) rejection of background, pileup events and poor quality events. The input to the trigger system is taken from triggering detectors and the output from the trigger system is sent to readout detectors which detect and save the collisions. In this analysis, decays of ϕ mesons to charged kaons are reconstructed. The yield of ϕ mesons is extracted from K^+K^- invariant-mass distributions as a function of transverse momentum (p_T). Then, the integrated yield and mean- p_T of ϕ mesons are obtained.

The following event-selection cuts were used for the analysis.

1. kINT7 trigger (requires a hit in both VZERO detectors)
2. Standard Physics Selection
3. IsIncompleteDAQ check is used to reject events for the cases which the event building does not work
4. Pileup Rejection using `AliAnalysisUtils::IsPileUpEvent()`
5. SPD Clusters vs. Tracklets Check

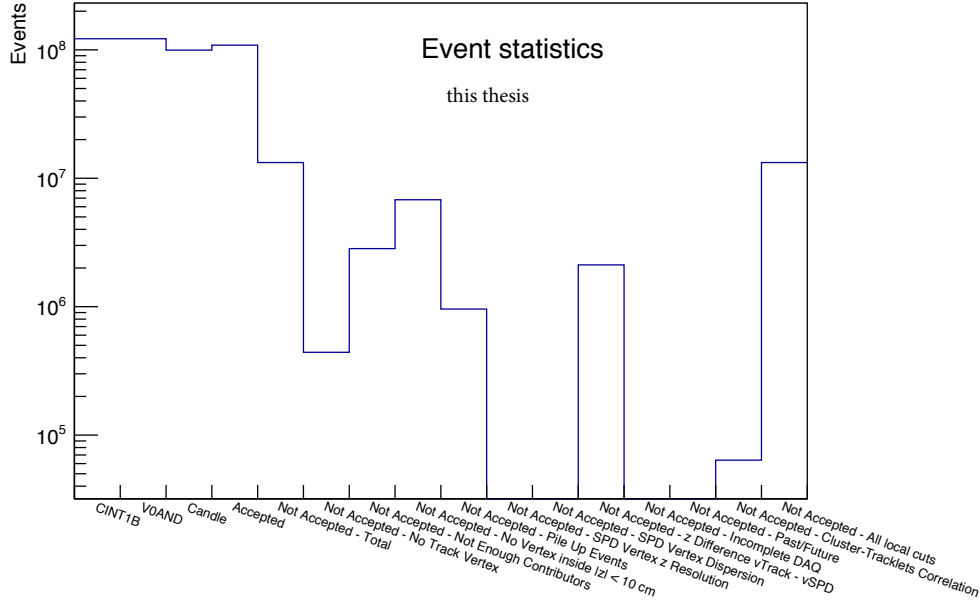


Figure 3.4: Event statistics after implementing event-selection cuts. The fourth bin shows the total number of accepted events for this analysis [11].

using `AliAnalysisUtils::IsSPDClusterVsTrackletBG()` with default parameters

6. Event has a track or SPD primary vertex identified
7. SPD vertex z resolution < 0.25 cm
8. SPD vertex dispersion < 0.04
9. z -position difference between track and SPD vertex < 0.5 cm
10. Vertex z position: $|v_z| < 10$ cm

After implementation of the above cuts, the total number of accepted events are around $\simeq 105$ M which is shown in the fourth bin of Fig. 3.4. The last bin shows the total number of events which are not accepted due to different event cuts listed above.

3.3 Track Selection and Particle Identification

3.3.1 Track Cuts

The ϕ mesons were identified by reconstructing their decays to charged kaons ($\phi \rightarrow K^- K^+$), which has a branching ratio of 0.492 ± 0.005 [33].

Charged tracks are selected for analysis by applying following cuts:

1. minimum number of crossed rows in TPC: $N_{cr,TPC} \geq 70$
2. minimum ratio of number of crossed rows to number of findable clusters in TPC: $R_{TPC} \geq 0.8$
3. maximum χ^2 per cluster in TPC: $\chi^2_{TPC} < 4$
4. reject kink daughters
5. require ITS refits
6. require TPC refits
7. minimum number of clusters in SPD: 1
`(AliESDtrackCuts::SetClusterRequirementITS(kSPD, kAny))`
8. DCA_{xy} p_T formula: $DCA_{xy} < 0.0105 + 0.035p_T^{-1.1}$ (a 7- σ cut)
9. maximum χ^2 in TPC-Constrained Global: $\chi^2_{CGI} < 36$
10. $DCA_z < 2$ cm
11. `AliESDtrackCuts::SetDCAToVertex2D(kFALSE)`
12. `AliESDtrackCuts::SetRequireSigmaToVertex(kFALSE)`
13. maximum χ^2 per cluster in ITS: $\chi^2_{ITS} < 36$
14. $p_{T,track} > 0.15$ GeV/c
15. $|\eta_{track}| < 0.8$

16. For a pair of tracks to be considered as a ϕ candidate, its rapidity was required to be within the range $|y_{\text{pair}}| < 0.5$.

All of these cuts except the last three are included in the function

```
AliESDtrackCuts::GetStandardITSTPCTrackCuts2011(kTRUE,
1),
```

which implements the standard ITS/TPC track cuts from 2011.

3.3.2 Particle IDentification (PID) cuts

The kaons are identified through their energy loss in the TPC and their time of flight in the TOF. As described in the Sections. 2.3.2 and 2.3.4, we have followed the $n\sigma$ method for the analyses described in the thesis. Although the detailed method is described in the previous chapter, for the sake of completeness we mention the definition of $n\sigma$ method for TPC and TOF here as well. $n\sigma_{TPC}$ is defined in the following manner.

$$n\sigma_{TPC} = \frac{dE/dx_{\text{measured}} - dE/dx_{\text{expected}}}{\sigma_{TPC}^{PID}}. \quad (3.1)$$

Here, dE/dx_{measured} is the energy loss of the tracks measured in TPC, dE/dx_{expected} is the expected energy loss of the tracks using a parameterization of modified Bethe Bloch function and σ_{TPC}^{PID} is the PID resolution of the TPC. Also, the charged particles can be identified by the $n\sigma_{TOF}$ cut, which is defined by,

$$n\sigma_{TOF} = \frac{t_{\text{measured}} - t_{\text{expected}}}{\sigma_{TOF}^{PID}}. \quad (3.2)$$

Here, t_{measured} is the flight time of the particle measured by an algorithm of TOF and T0 detector, t_{expected} is the flight time computed during the central tracking procedure and σ_{TOF}^{PID} is the PID resolution of the TOF detector.

Several independent iterations of the analysis are performed, with each iteration using a different set of PID cuts. “TOF veto” means that

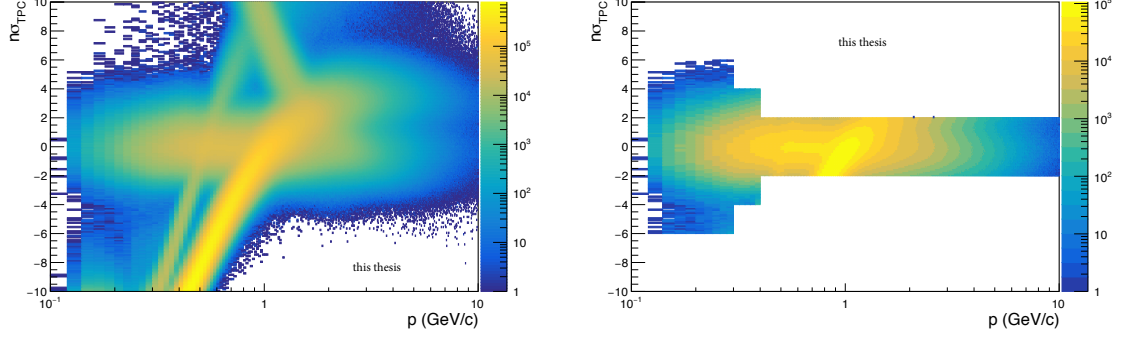


Figure 3.5: $n\sigma_{tpc}$ vs. p for different PID cut schemes. **Left Panel:** no PID cuts applied. **Right Panel:** default PID cuts (the `tpc2stofv3s` scheme) applied [11].

the TOF cut is applied only for cases where the track matches a hit in the TOF; for tracks without matches, no TOF cut is applied. The veto cut on TOF bears a special significance due to the fact that one does not have to consider the TPC-TOF matching efficiency while using the veto cut.

- $n\sigma_{tpc} < 2$ with a TOF veto of $n\sigma_{tof} < 3$ (shorthand: `tpc2stofv3s`)
- $n\sigma_{tpc} < 2$ (shorthand: `tpc2s`)
- $n\sigma_{tpc} < 1.5$ with a TOF veto of $n\sigma_{tof} < 3$ (shorthand: `tpc15stofv3s`)
- $n\sigma_{tpc} < 2.5$ with a TOF veto of $n\sigma_{tof} < 3$ (shorthand: `tpc25stofv3s`)
- $n\sigma_{tpc} < 2$ with a TOF veto of $n\sigma_{tof} < 4$ (shorthand: `tpc2stofv4s`)

The analysis is also rerun with different track quality cuts (always using the `tpc2stofv3s` PID cut set). The following cut sets are also used (all other cuts are the same as in the list of track-quality cuts above):

- $N_{cr,TPC} \geq 100$ (shorthand: `ncr100`)
- $N_{cr,TPC} \geq 80$ (shorthand: `ncr80`)
- $R_{TPC} \geq 0.9$ (shorthand: `rtpc9`)
- $\chi^2_{track} < 2.3$ (shorthand: `x2track23`)
- $\chi^2_{track} < 3.5$ (shorthand: `x2track35`)

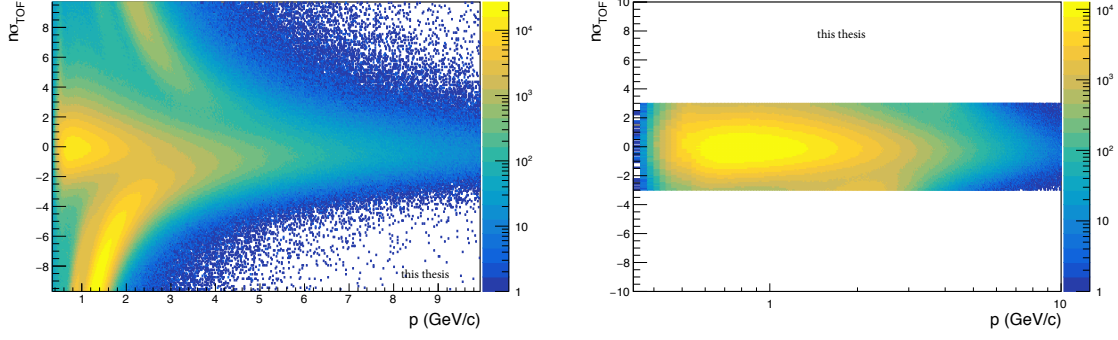


Figure 3.6: $n\sigma_{tof}$ vs. p for two different PID cut schemes. **Left Panel:** no PID cuts applied. **Right Panel:** default PID cuts (the `tpc2stofv3s` scheme) applied (with the aforementioned wider cuts at low momentum) [11].

- DCA_{xy} p_T formula: $DCA_{xy} < 0.006 + 0.020p_T^{-1.01}$ (a $4\text{-}\sigma$ cut, [shorthand: dcaxy4s](#))
- $|DCA_z| < 0.2$ cm ([shorthand: dcaz02](#))
- $|DCA_z| < 1$ cm ([shorthand: dcaz1](#))

Variations in ϕ meson yields, masses, widths, etc. due to the different kaon-identification and track-quality cuts were incorporated into the systematic uncertainties as described in Section 3.7.

3.4 Signal Extraction

Table 3.1 gives a list of the p_T bins analyzed. To extract the yields of ϕ mesons in each p_T bin, the following procedure is used. The invariant-mass distribution of unlike-charge kaon pairs from the same event is computed. When possible, this unlike-charge distribution is fitted directly with a 2^{nd} order polynomial plus a peak. In addition, the combinatorial background is estimated and subtracted from the unlike-charge distribution. The background-subtracted unlike-charge distribution is fitted with a combined fit function: a residual background polynomial plus a peak. These steps are described in more detail in the following sections.

Table 3.1: List of p_T bins analyzed (units of GeV/c).

bin	minimum	maximum	bin	minimum	maximum
0	0.4	0.6	12	2.4	2.7
1	0.6	0.7	13	2.7	3.0
2	0.7	0.8	14	3.0	3.5
3	0.8	0.9	15	3.5	4.0
4	0.9	1	16	4.0	4.5
5	1	1.1	17	4.5	5.0
6	1.1	1.2	18	5.0	6.0
7	1.2	1.4	19	6.0	7.0
8	1.4	1.6	20	7.0	9.0
9	1.6	1.8	21	9.0	12.0
10	1.8	2.1	22	12.0	16.0
11	2.1	2.4	23	16.0	20.0

3.4.1 Combinatorial Background

The method in which the unlike-charge distribution is fitted directly is denoted `ulfit`. Two methods are used to estimate the combinatorial background. See Section 3.4.3 for an example plot.

1. Event Mixing: Invariant-mass distributions are calculated for pairs of oppositely charged kaons from different events. Each event analyzed is mixed with ~ 5 other events; for pairs of events, the difference in vertex- z is required to be less than 1 cm, while the difference in the multiplicity is required to be less than 5 (shorthand: `event_mix`).

The mixed event background is normalized so that it has the same integral as the unlike-charge distribution in a given normalization region.

Normalization Region 1: $0.995 < m < 1.005$ GeV/c² (shorthand: `mix1`)

Normalization Region 2: $1.04 < m < 1.06$ GeV/c² (shorthand: `mix2`)

Normalization Region 3: $1.05 < m < 1.08$ GeV/c² (shorthand: `mix3`)

Therefore, for the mixed-event combinatorial background, there are three different background-subtracted invariant-mass distributions, each of which is fitted independently.

2. Like Charge: Invariant-mass distributions are calculated using pairs of kaons with the same charge from the same event. In each invariant-mass bin, the value of the like-charge background is $2\sqrt{n_{--}n_{++}}$, where n_{--} (n_{++}) is the number of K^-K^- (K^+K^+) pairs in the bin. (shorthand: [like_sign](#))

3.4.2 Residual Background

After subtraction of the combinatorial background, a residual background may still be present in the vicinity of the ϕ peak. When the unlike-charge distribution is fitted directly, the peak sits on top of a smooth background that can be parameterized by a polynomial. In this case, the background will be called “residual” in the following discussion, even though this might not be the right name for it. (This is just to avoid repeating the same discussion, since the procedure is exactly the same.) Five different fit regions are used (units of GeV/c) :

Fit Region 0: $0.995 < m < 1.06$ GeV/c² (shorthand: [fr0](#))

Fit Region 1: $0.995 < m < 1.07$ GeV/c² (shorthand: [fr1](#))

Fit Region 2: $0.99 < m < 1.09$ GeV/c² (shorthand: [fr2](#))

Fit Region 3: $0.995 < m < 1.09$ GeV/c² (shorthand: [fr3](#))

Fit Region 4: $0.99 < m < 1.06$ GeV/c² (shorthand: [fr4](#))

Linear ([shorthand: pol1](#)), quadratic ([shorthand: pol2](#)), and cubic ([shorthand: pol3](#)) fits were performed to parameterize the residual background. Variations in ϕ meson yields are due to variations in the residual background fit function and the boundaries of the fit region are incorporated into the systematic uncertainties (see Section [3.7](#)). Note that the

fits described in the section are only used as an estimate of the residual background: these fits are used as a starting point for the fits described in the next section (combined fits of residual background plus peak, during which the residual background fit parameters are allowed to vary).

3.4.3 ϕ Peak Fits

After the residual background has been fit, the invariant-mass distributions are fitted using a combined function: the residual background plus a peak. Initially, the residual background parameters are fixed to the values from the fits described in Section 3.4.2. However, in the final step of the fit procedure, the residual background parameters are allowed to vary freely along with the peak fit parameters.

A Voigtian fit function [39] (shorthand: `voigtG`), which is a convolution of a Breit-Wigner peak to describe the ideal signal and a Gaussian to account for detector resolution, is used to fit the ϕ peaks. The purpose of using the Breit-Wigner fit function along with its derivation to describe the signal, is shown in the appendix section 3.13. The functional form of Voigtian function is the following:

$$\frac{dN}{dm_{KK}} = \frac{A\Gamma}{(2\pi)^{3/2}\sigma} \int_{-\infty}^{\infty} \exp\left[-\frac{(m_{KK} - m')^2}{2\sigma^2}\right] \frac{1}{(m' - M)^2 + \Gamma^2/4} dm'. \quad (3.3)$$

Here, A is the normalization of the function (from 0 to ∞), M is a fit parameter that gives the mass of the resonance, Γ is a fit parameter that gives the width of the resonance. Also, σ is the Gaussian width (p_T -dependent, generally between 1.3 and 2 MeV/c). The Voigtian function is implemented using ROOT's `TMath::Voigt` function:

$$A \cdot \text{TMath::Voigt}(m - M, \Gamma, \sigma). \quad (3.4)$$

Here, the width parameter is fixed to the vacuum value

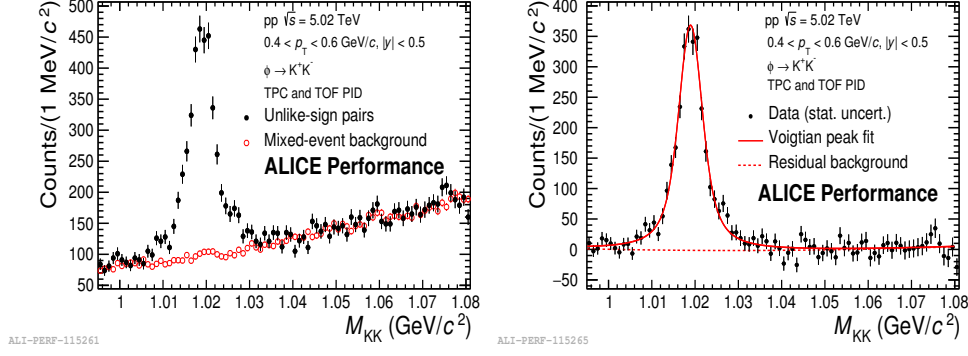


Figure 3.7: Representative plot of Invariant-mass distribution for `tpc2stov3s` combination in one of the measured p_T bins. Left: The black solid marker shows the invariant-mass distribution of unlike-charge kaon pairs. Red open marker shows the normalized event-mixing background. Right: The red line shows Voigtian peak fit to the unlike signals after the combinatorial background subtraction. The dotted line shows the residual background [11].

4.26 MeV/c [33] and the resolution is allowed to vary freely. The fitting procedure will be varied in later stage.

Left plot of Fig. 3.7 shows a representative plot of the unlike-charge signal and the event-mixing combinatorial background for a measured p_T bin while the right plot of Fig. 3.7 shows the event-mixing background-subtracted signals with residual background and peak fit. Similar procedure is followed for all measured p_T bins as shown in Table 3.1. The ϕ mass as a function of p_T is shown in Figure 3.8 and it is found to be consistent with PDG value. The black solid marker shows the value of mass and σ parameter from real data and the red open marker shows from simulation. They seem to be fairly consistent with each other. The mass parameter seem to be consistent with the PDG mass of ϕ meson (red dotted line). σ is found to be ranging from 1-3 MeV/ c^2 .

3.4.4 ϕ Yield

The yield is extracted by integrating the invariant-mass histogram over the region $I_{\min} < m < I_{\max}$ and subtracting the integral of the residual background portion of the fit function (divided by the bin width) over

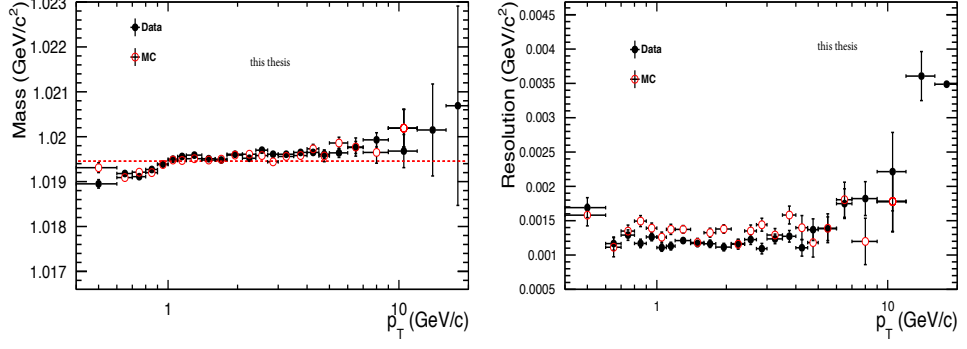


Figure 3.8: Mass (Left) and σ (Right) parameter obtained from signal fit as a function of p_T . The red dotted line in the left plot shows the expected mass from PDG [33]. The mass parameter from data and MC are found to be consistent with the PDG value. The σ parameter is consistent for data and MC within the statistical uncertainties [11].

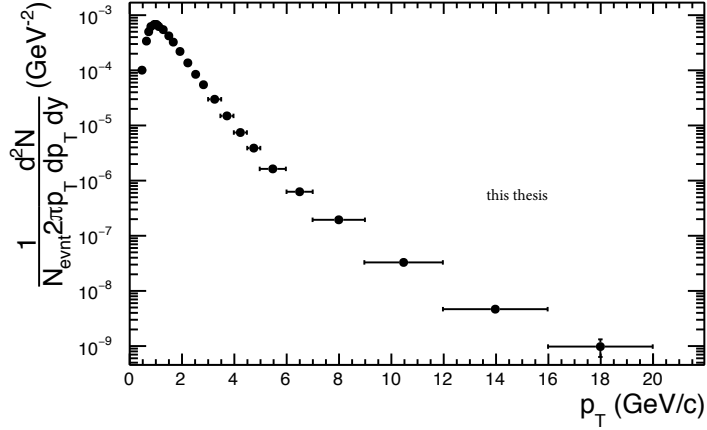


Figure 3.9: Raw Yield as a function of p_T [11]. The errors reported are statistical only.

that same interval. The yields for the regions $2M(K^\pm) < m < I_{\min}$ and $m > I_{\max}$ are extracted from the peak fit and added to the yield calculated from the histogram. It is assumed that the statistical uncertainties of the yields in the tail regions are fully correlated with each other and with the statistical uncertainty of the yield calculated from the histogram. Here, $I_{\min} = 1.01$ GeV/c and $I_{\max} = 1.03$ GeV/c. The raw yield normalized to the total number of analysed events as a function of p_T is shown in Figure 3.9.

3.5 Simulations

After obtaining the raw p_T -spectra, one has to correct it with detector efficiency and its acceptance. A simulated data set is analyzed in order to extract the ϕ reconstruction efficiency $\times$ acceptance (this calculation is described in Section 3.6.1) and estimate the ϕ mass resolution (which is used as an input parameter for Voigtian fits of real ϕ peaks).

Particle production and decays are simulated using PYTHIA (the Monash 2013 tune of PYTHIA 8 for LHC16h8a and the Perugia 2011 tune of PYTHIA 6 for LHC16h8b), while particle interactions with the ALICE detector are simulated using GEANT3 [13]. As mentioned in Section 2.7.2, GEANT3 is used to simulate the interaction of particles with detector material. The simulated data set consists of 34 million events in the the LHC16h8a production and 17 million events in the LHC16h8b production. The same event selection and track quality cuts are used for the real and simulated data. In the context of this section and Section 4.2.6, the particles produced by the event generator (without any detector effects) are referred to as the “generated” particles. These particles are the input for the GEANT3 detector simulation and the track and signal reconstruction algorithms. The tracks which are identified by the reconstruction algorithms and which pass the track selection and PID cuts are referred to as “reconstructed” tracks.

3.5.1 Invariant-Mass Histograms

Histograms of the invariant mass of reconstructed ϕ mesons are fitted using the function described in Section 3.4.3. The resolution of these peaks is extracted using the `voigtG` fit, which was also used to fit the real data. The fit region for these histograms is $1.01 < m < 1.03$ GeV/c.

3.6 Correction and Normalization of Spectra

3.6.1 Reconstruction Efficiency $\times$ Acceptance

The reconstruction efficiency $\times$ acceptance, denoted as ϵ_{rec} , is calculated using the same simulated data described in Section 3.5. In each transverse momentum bin, ϵ_{rec} is the ratio of two quantities

Denominator: Generated ϕ : the number of generated ϕ mesons with $|y_{\text{gen}}| < 0.5$ that decayed to two charged kaons

Numerator: Reconstructed ϕ : the number of ϕ mesons with $|y_{\text{rec}}| < 0.5$ for which both kaon decay daughters were reconstructed

Here, “ y ” is the rapidity of kaon pairs. The correction ϵ_{rec} for different PID, event and track selection cuts are shown in Figure 3.10. It has a strong dependence on transverse momentum at low p_{T} .

The uncertainty in ϵ_{rec} is calculated using the Bayesian approach [20]. The standard deviation in an efficiency $\varepsilon = k/n$, where the numerator k is a subset of the denominator n , is

$$\sigma_{\varepsilon} = \sqrt{\frac{k+1}{n+2} \left(\frac{k+2}{n+3} - \frac{k+1}{n+2} \right)}. \quad (3.5)$$

The fractional statistical uncertainty in ϵ_{rec} is added in quadrature with the statistical uncertainty in the uncorrected ϕ yield to give the total statistical uncertainty of the corrected ϕ yield.

Different ϵ_{rec} are expected for different combinations due to different set of track/event cuts, which is shown in Figure 3.10. The difference should also be reflected in the real data and Figure 3.15 confirms that there is no large deviation in the corrected spectra compared to the default for all the combinations.

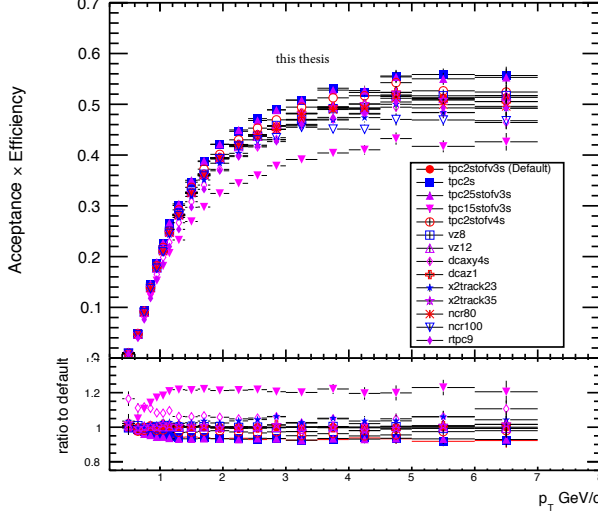


Figure 3.10: **Upper plot:** ϕ meson reconstruction efficiency (ϵ_{rec}) as a function of p_T for different PID, event and track selection cuts. **Bottom plot:** ratio of the ϵ_{rec} values in the upper plot to default [11].

3.6.2 Signal-Loss Correction

The signal loss correction factor is calculated to account for the loss of ϕ mesons incurred by selecting events that satisfy only kINT7 trigger, rather than all inelastic events. This is a p_T -dependent correction factor which is peaked at low p_T , indicating that events that fail the kINT7 selection have softer ϕ p_T -spectrum than the average inelastic event. This correction is the ratio of the p_T -spectrum in inelastic events to the p_T -spectrum in kINT7 events. The correction factor is calculated using the two different simulation productions, LHC16h8a (PYTHIA 8, Monash 2013 tune) and LHC16h8b (PYTHIA 6, Perugia 2011 tune), which is shown in figure 3.11. The PYTHIA 8 correction is used as the default. A systematic uncertainty is assigned to the p_T -spectrum due to the signal loss correction factor. Let ϵ_{SL8} be the PYTHIA 8 correction and ϵ_{SL6} be the PYTHIA 6 correction. The systematic uncertainty is the greater of $|\epsilon_{SL8} - \epsilon_{SL6}|$ and $\frac{1}{2}(\epsilon_{SL8} - 1)$.

3.6.3 Inelastic Normalization Factor

In order to normalize to the number of inelastic pp collisions, the inelastic normalization factor (f_{norm}) is calculated. This is needed to convert a parti-

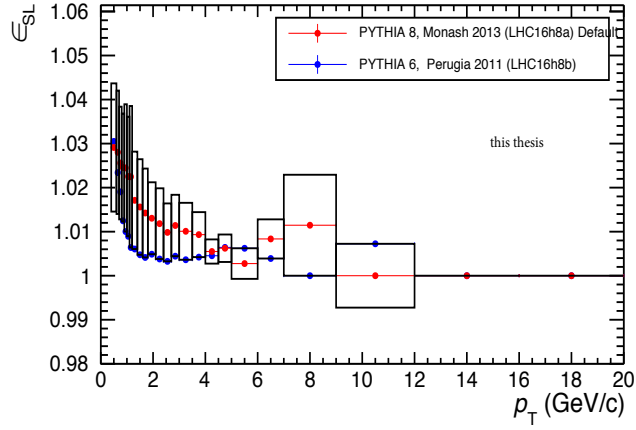


Figure 3.11: Signal loss correction factor as a function of p_T . The boxes show the systematic uncertainties for each p_T bin. The statistical uncertainties are not shown [11].

cle yield normalized to the number of triggered events to a yield normalized to the number of inelastic events. As there is no measurement done by ALICE, the normalized value for this energy is calculated through the method of interpolation which is described in the appendix section 3.14. The value of inelastic normalization factor is found out to be 0.7574 ± 0.0190 for $\sqrt{s} = 5.02$ TeV.

3.6.4 Normalization

The ϕ meson spectra are normalized as follows. The normalized, uncorrected yield in a given p_T bin (of width dp_T) is

$$\frac{d^2N_{\text{raw}}}{dp_T dy} = \frac{(\text{raw counts})}{N_{\text{evt}} \cdot BR \cdot dp_T dy} \times f_{\text{norm}} \times f_{\text{vtx}}, \quad (3.6)$$

where N_{evt} is the number of events analyzed, BR is the branching ratio ($BR = 0.492 \pm 0.005$), and $dy = 1$. The factor f_{vtx} is also needed in the normalization. It is a ratio with:

Denominator: the number of triggered events (after application of the `IsIncompleteDAQ` cut and the pileup cuts)

Numerator: the subset of the events in the denominator for which a good vertex was found (*i.e.*, it passes the vertex quality cuts, but without the cut on the z -position of the vertex)

The vertex normalization for this analysis is found to be 0.958. This is the ratio of number of events, so it doesn't have associated systematic uncertainty.

The corrected ϕ meson spectra are calculated as follows:

$$\frac{d^2N}{dp_T dy} = \frac{d^2N_{\text{raw}}}{dp_T dy} \cdot \frac{\epsilon_{SL}}{\epsilon_{\text{rec}}} \quad (3.7)$$

3.6.5 Transverse Momentum Spectrum

Figure 3.12 shows the efficiency corrected and normalized p_T spectrum. The boxes show the systematic uncertainties in each p_T bin which is calculated in Section 3.7.

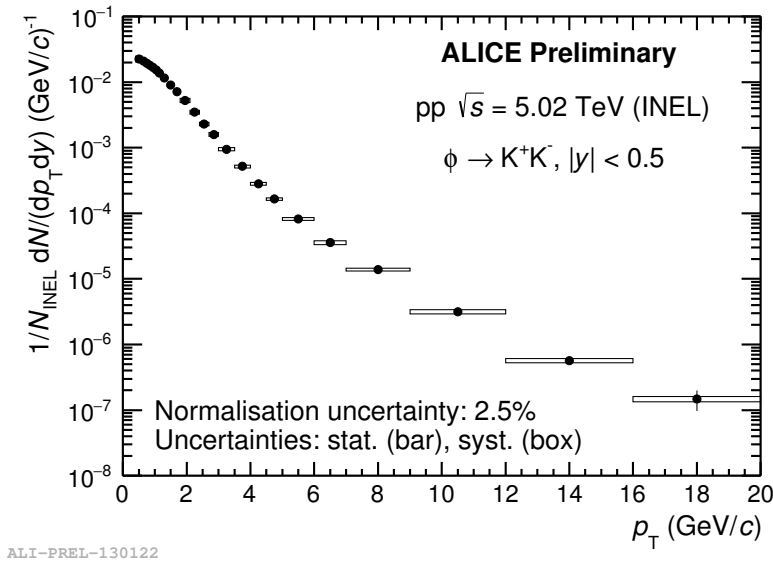


Figure 3.12: Efficiency corrected and normalized ϕ spectrum. The bars and boxes show the statistical and systematic uncertainties in each p_T bin [11].

3.7 Systematic Uncertainties of the Spectrum

3.7.1 Introduction

In general, the analysis is performed many times, using every possible permutation of analysis parameters (PID cuts, combinatorial background, etc.) described in Section 3.4. This means that there are multiple measurements of the yield for each transverse momentum bin. Broadly, the uncertainties are calculated in 2 different groups.

1. Grouped Uncertainties
 - (a) Signal Extraction
 - (b) Background Subtraction method
 - (c) Track Selection Cuts
2. Other sources of Uncertainties
 - (a) Material Budget
 - (b) Hadronic interaction cross-section
 - (c) Signal Loss uncertainty
 - (d) Inelastic Normalization
 - (e) Branching Ratio

This procedure is illustrated explicitly for the ϕ yield in the following section.

3.7.2 Calculation

For each transverse-momentum bin, there are several measurements of the yield and its statistical uncertainty. The uncertainties are grouped in the following way:

1. Signal Extraction:

Event Mixing Normalization regions: 3 choices: mixed event (*event_mix*) (with three different normalization regions: *mix1*, *mix2*, or *mix3*)

Fit Region: 5 choices (*fr0*, *fr1*, *fr2*, *fr3*, *fr4*)

Residual Background Fit: 3 choices: linear (*pol1*), quadratic (*pol2*), or cubic (*pol3*)

Peak Fit: 1 choice: *voigtG*

For each background subtraction method and track selection cut, the above signal extraction variations are calculated. For these set of variations the mean value is calculated. The standard deviation from the set of measurements is the signal extraction systematic uncertainty. Then the mean statistical uncertainty is obtained. After this step, the mean value is the yield and mean statistical uncertainty is the statistical error for the particular set of background subtraction method and track selection cut. This procedure is repeated for each track selection cut and background subtraction method. Figure 3.13 shows an example of different variations for signal extraction grouping procedure.

2. Background Subtraction:

3 choices: no background subtraction (*ulfit*), like-charge (*like_sign*), or mixed event (*event_mix*)

For a particular track selection cut, the mean values from the previous grouping are used. Now, for each track selection cut, background subtraction techniques are varied. So, there will be three measurements for each set. The standard deviation from each set is taken as the background subtraction systematic uncertainty. The mean value is the yield and mean statistical uncertainty is the statistical error for the particular set of track

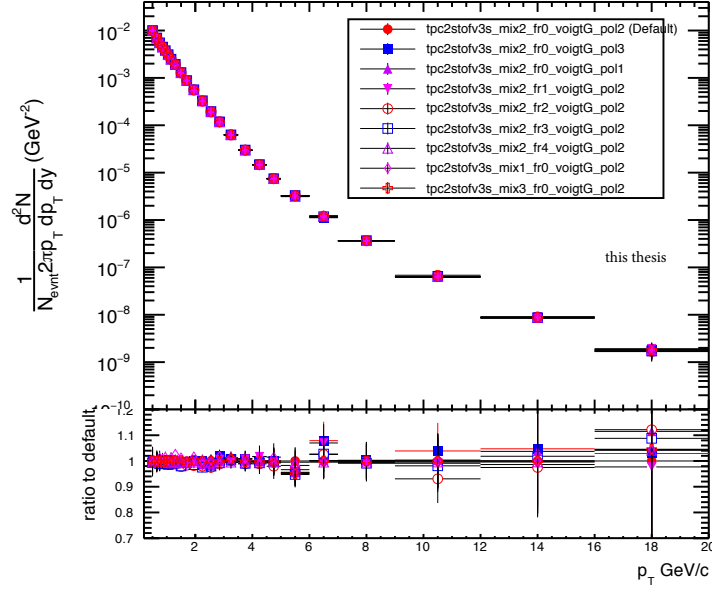


Figure 3.13: **Upper plot:** Yield from `tpc2stofv3s` after varying different signal extraction techniques, **Lower plot:** Ratio to default combination [11].

selection cut, and PID strategy. Figure 3.14 show the example of different variations for background subtraction grouping procedure.

3. Track Selection Cuts:

PID Cuts: 5 choices: $2\sigma_{\text{TPC}}$ with $3\sigma_{\text{TOF}}$ veto (`tpc2stofv3s`), $1.5\sigma_{\text{TPC}}$ with $3\sigma_{\text{TOF}}$ veto (`tpc15stofv3s`), $2.5\sigma_{\text{TPC}}$ with $3\sigma_{\text{TOF}}$ veto (`tpc25stofv3s`), $2\sigma_{\text{TPC}}$ (`tpc2s`), or $2\sigma_{\text{TPC}}$ with $4\sigma_{\text{TOF}}$ veto (`tpc2stofv4s`)

Event/Track Selection Cuts: 10 choices (calculated with `tpc2stofv3s` PID cuts only): event $|v_z| < 8$ cm (`vz8`), event $|v_z| < 12$ cm (`vz12`), $N_{\text{cr,TPC}} \geq 100$ (`ncr100`), $N_{\text{cr,TPC}} \geq 80$ (`ncr80`), $R_{\text{TPC}} \geq 0.9$ (`rtpc9`), $\text{DCA}_{xy} < 4\sigma$ (`dcaxy4s`), $\text{DCA}_z < 1$ cm (`dcaz1`), $\chi^2_{\text{track}} < 2.3$ (shorthand: `x2track23`), $\chi^2_{\text{track}} < 3.5$ (shorthand: `x2track35`)

There will be five TPC/TOF cuts and nine quality cuts variation in this step. The standard deviation from these set of measurements is taken as track selection systematic uncertainty. The

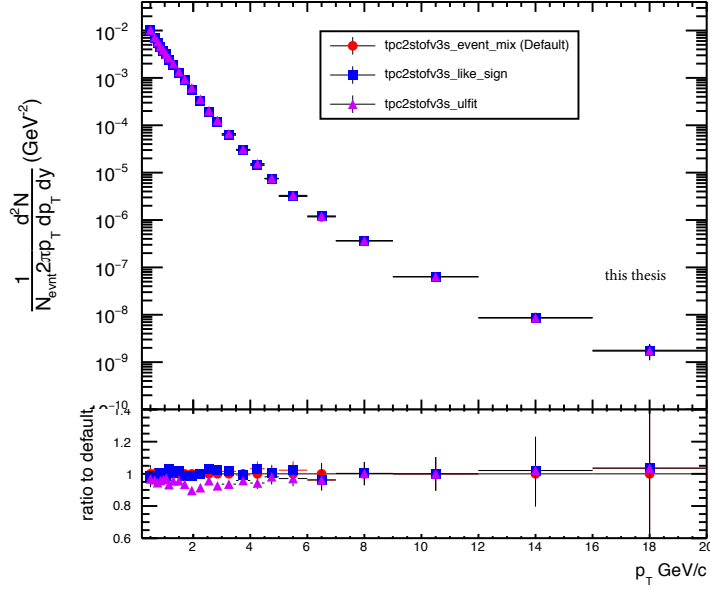


Figure 3.14: **Upper plot:** Yield of `tpc2stofv3s` after varying different background subtraction techniques, **Lower plot:** Ratio to default combination [11].

mean value is the yield and mean statistical uncertainty is the final statistical error. Figure 3.15 shows the yield from different PID cuts, event-selection cuts and track quality cuts. It is found that for the `tpc2s` combination, the `like sign` and `ulfit` are outliers for the range $1.4 < p_T < 2.8$ GeV/c. So, only the event-mixing background subtraction are considered in the range $1.4 < p_T < 2.8$ GeV/c.

4. **Material Budget:** The material budget systematic uncertainty is estimated by using the p_T dependent material budget uncertainty of single kaons. Then the daughters are assigned an uncertainty corresponding to that p_T bin. The systematic uncertainty due to uncertainties in the ALICE material budget is taken from the analysis of the ϕ mesons in p-Pb collisions [36, 37]. It is p_T -dependent and reaches a maximum value of a few percent.
5. **Hadronic Interaction Cross-section:** The systematic uncertainty due to uncertainties in the ALICE hadronic interaction cross-section is taken from the analysis of the ϕ mesons in p-Pb collisions [36, 37].

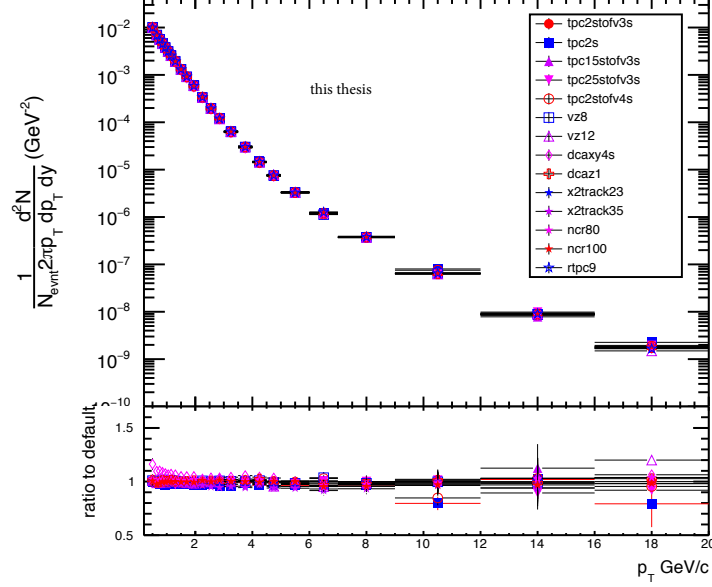


Figure 3.15: **Upper plot:** Yield from different track cuts, **Lower plot:** Ratio of all track cuts to default [11].

It is p_T -dependent and reaches a maximum value of a few percent.

6. **Signal Loss Uncertainty:** The systematic uncertainty due to the signal-loss correction factor is described in Section 3.6.2. It is p_T -dependent and reaches a maximum value of 1.5% at low p_T .
7. **Inelastic Normalization:** The systematic uncertainty due to the uncertainty in the factor f_{norm} (used to normalize to the number of inelastic pp collisions) has a value of 2.5%.
8. **Branching Ratio:** The systematic uncertainty due to the uncertainty in the branching ratio is 1% and independent of p_T .
9. **Tracking Uncertainty:**

The tracking uncertainty, due to the uncertainty in ITS-TPC matching, is derived for the ϕ as follows. The one-particle uncertainty is inherited from the analysis of unidentified charged hadron production in the same collision system [43]. The two-particle (ϕ) uncertainty is derived from the one-particle uncertainty through weighting. A PYTHIA simulation (the LHC16h8a production) is used to find the p_T distributions of the ϕ decay daughters as functions of the ϕ trans-

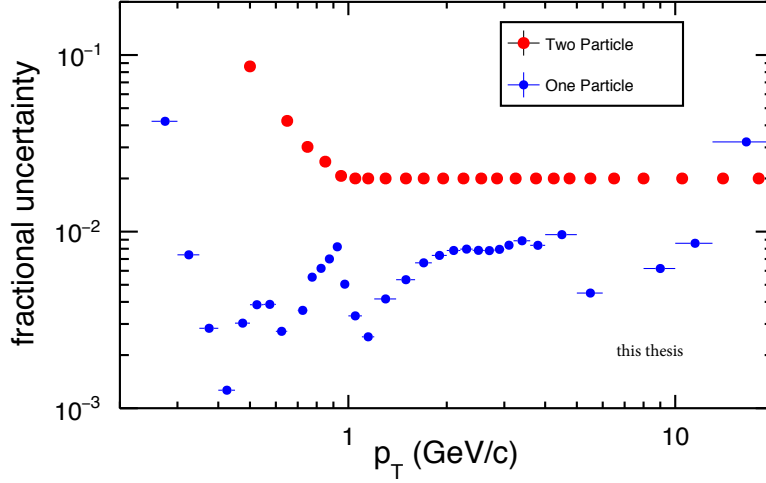


Figure 3.16: Tracking (ITS-TPC Matching) efficiency uncertainty for single particles and for the ϕ (a two-particle decay). The two particle uncertainty is considered 2% when the single particle uncertainty is below 1% [11].

verse momentum. These decay-daughter distributions are then used to obtain the weighted average of the tracking uncertainty for each ϕ transverse-momentum bin. The calculation is also weighted so that the simulated ϕ p_T -spectrum has a realistic shape.

Let $w(p_{T\phi})$ be the ratio between the measured and generated ϕ p_T -spectra. Let $u(p_T)$ be the one-particle tracking uncertainty. Let p_{T1} and p_{T2} be the transverse momenta of the first and second decay daughters of each simulated ϕ meson. Let $N(p_{T\phi}, p_{T1}, p_{T2})$ be the number of ϕ with $p_{T\phi}$ that decay to kaons with p_{T1} and p_{T2} . The two-particle tracking uncertainty is the ratio of two histograms (a weighted average):

Numerator: the sum, for all generated ϕ mesons, of

$$N(p_{T\phi}, p_{T1}, p_{T2})w(p_{T\phi})[u(p_{T1}) + u(p_{T2})]$$

Denominator: the sum, for all generated ϕ mesons, of

$$N(p_{T\phi}, p_{T1}, p_{T2})w(p_{T\phi})$$

The calculation assumes that the tracking-efficiency uncertainties of the two decay daughters are fully correlated.

10. **Total Systematic uncertainty:** The total systematic uncertainty

is the sum in quadrature of the uncertainties from the sources listed above.

3.7.3 Fractional Uncertainties

Figure 3.17 shows the fractional uncertainties from all the sources as a function of p_T .

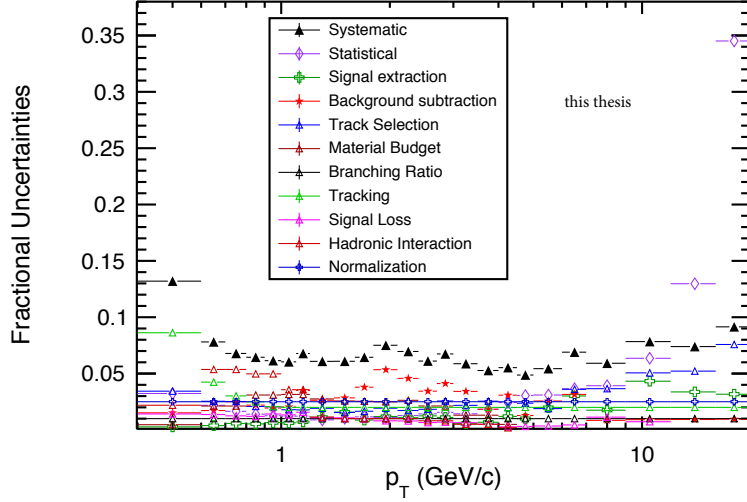


Figure 3.17: Fractional uncertainties from all the sources [11].

3.7.4 Consistency Checks

This analysis has been run many times with many different variations of analysis parameters. However, it is necessary to ensure that the systematic uncertainties are not simply accounting for statistical fluctuations. As described in [40], the condition for consistency is *not* in agreement within the statistical uncertainties: since the default and alternate measurements use (mostly) overlapping data sets, agreement within the statistical uncertainties is not sufficient. Instead, agreement within the difference in quadrature of the statistical uncertainties is required. If two measurements are found to be consistent within the quadrature difference of their statistical uncertainties, then it is not necessary to account for the differences between them in the systematic uncertainties.

As an example, consider the alternate measurement using the track selection method of extracting the ϕ yield. Figure 3.18 shows a consistency check for this measurement. The distribution is Δ/σ_{cc} , where Δ is the difference between the default measurement (`tpc2stofv3s`) and all the other measurements, and σ_{cc} is the difference in quadrature of the statistical uncertainties of these measurements. In general, if two measurements are consistent, Δ should lie within a few multiples of σ_{cc} of zero. It is expected that the distribution of Δ/σ_{cc} would have a mean near zero, a standard deviation near one. Figure 3.18 shows the distribution of Δ/σ_{cc} for all p_T bins for variation of different track selection techniques. Here, the mean is shifted from zero and the standard deviation is greater than one. Therefore, it appears that the measurements are not consistent with the default measurement; it is necessary to account for the differences between these measurements in the systematic uncertainties.

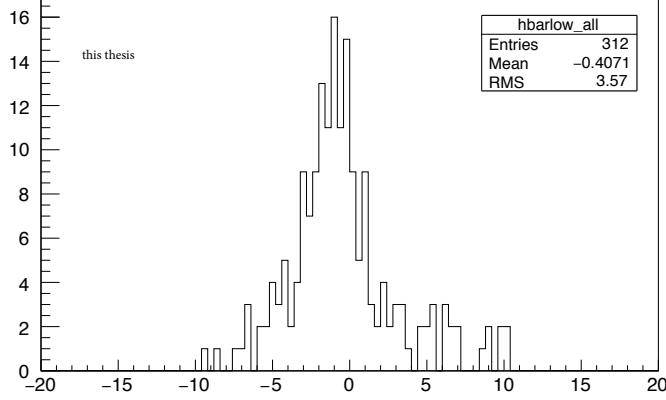


Figure 3.18: Consistency checks for variations in track selection techniques [11].

Figure 3.19 shows the distributions of Δ/σ_{cc} for the various alternate analysis parameters. For the shown figures, there appear to be potential inconsistencies between the default and alternate measurements: the distribution is not centered at zero or is much wider than ideal. Since these alternate measurements do not pass the consistency check, it is necessary

to account for these differences in the systematic uncertainties.

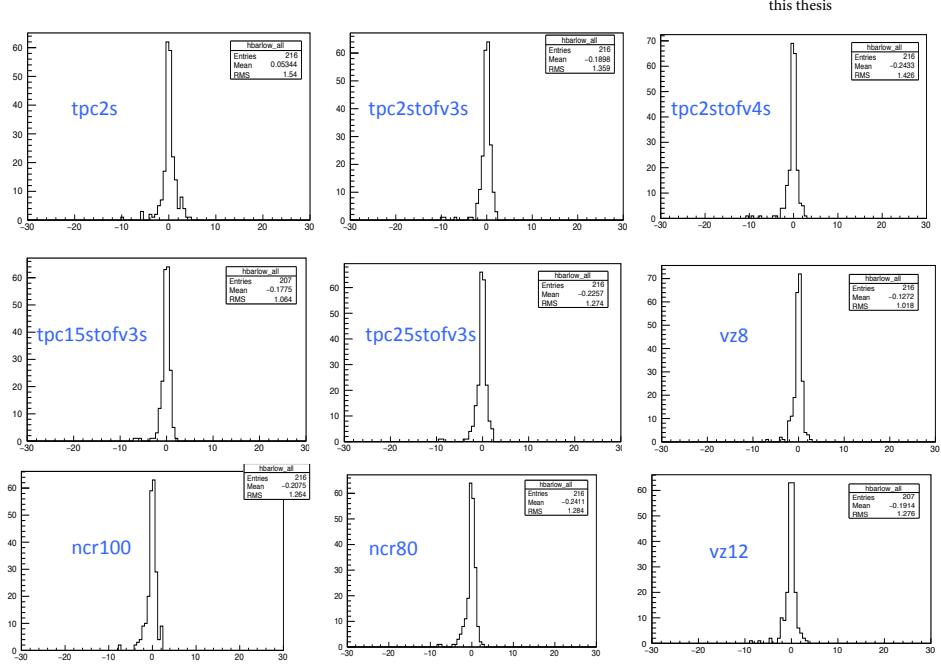


Figure 3.19: Consistency checks for variations in signal extraction techniques [11].

3.8 Fits of the Spectrum

This section describes the procedure used to fit the ϕ -meson p_T -spectrum and the quantities (dN/dy and $\langle p_T \rangle$) derived from the fits of the spectrum.

3.8.1 Procedure

The normalized, corrected ϕ meson spectrum is fitted with several different functions ($f_0(p_T)$), which are listed below. One of the best fit is considered as default fit while the others are used for systematic uncertainties. All the functions are normalized such that the scale parameter A in the functions gives their integral.

1. **An exponential function in m_T**

$$f_0(p_T) = p_T \times A \times (e^{-m_T/T}) \times \frac{e^{M/T}}{T^2 + TM}. \quad (3.8)$$

Here, M is the mass of the ϕ meson, $m_T = \sqrt{M^2 + p_T^2}$. For this fit function, the histogram is only fit over the range $0.4 < p_T < 1$ GeV/c, giving a better fit in the low- p_T region.

2. **An exponential function in p_T**

$$f_0(p_T) = p_T \times A \times (e^{-p_T/T}) \times \frac{e^{M/T}}{T^2 + TM}. \quad (3.9)$$

Here, M is the mass of the ϕ meson. For this fit function, the histogram is only fit over the range $0.4 < p_T < 1$ GeV/c.

3. **A Boltzmann distribution:**

$$f_0(p_T) = p_T \times A \times m_T \times (e^{-m_T/T}) \times \frac{e^{M/T}}{2T^3 + 2T^2M + TM^2}. \quad (3.10)$$

As with the closely related m_T exponential and the fit is only performed over the range $0.4 < p_T < 1$ GeV/c.

4. **Lévy-Tsallis function:** The histogram is fit over the range the range $0.4 < p_T < 2$ GeV/c using a Lévy-Tsallis function [38, 39]. This is used as the **default function**:

$$f_0(p_T) = p_T \times \frac{A(n-1)(n-2)}{nT[nT + M(n-2)]} \left[1 + \frac{m_T - M}{nT} \right]^{-n}, \quad (3.11)$$

The Lévy-Tsallis function fit is also done for different p_T ranges such as: $0.4 < p_T < 1.5$ GeV/c, $0.4 < p_T < 2.5$ GeV/c and $0.4 < p_T < 3$ GeV/c and they are included for the calculation of systematic uncertainty in integrated yield and mean transverse momentum.

Table 3.2: χ^2/ndf and Fitting parameters for fits

Functions	Fit range	χ^2/ndf	A	n	T (GeV)
Levy-Tsallis	0.4-2	0.107	0.0329 ± 0.003	3.697 ± 1.049	0.230 ± 0.043
Levy-Tsallis	0.4-1.5	0.085	0.038 ± 0.014	2.895 ± 1.263	0.201 ± 0.064
Levy-Tsallis	0.4-20	0.513	0.029 ± 0.001	7.644 ± 0.173	0.311 ± 0.007
m_T -exp	0.4-1	0.264	0.0236 ± 0.001	—	0.280 ± 0.037
p_T -exp	0.4-2	0.116	0.0120 ± 0.0004	—	0.519 ± 0.015
Boltzmann	0.4-1	0.261	0.0321 ± 0.003	—	0.280 ± 0.037
Bose-Einstein	0.4-1	0.253	0.1730 ± 0.0244	—	0.283 ± 0.039

5. **Bose-Einstein distribution:** The histogram is fit over the range $0.4 < p_T < 1$ GeV/c using a Bose-Einstein distribution:

$$f_0(p_T) = p_T \times A \times \frac{1}{e^{m_T/T} - 1} \times (e^{M/T} - 1). \quad (3.12)$$

6. **Power-law function:** The histogram is fit for $2 < p_T < 20$ GeV/c with a power-law function:

$$f_0(p_T) = p_T \times A \times (1 + p_T/T)^{-n}. \quad (3.13)$$

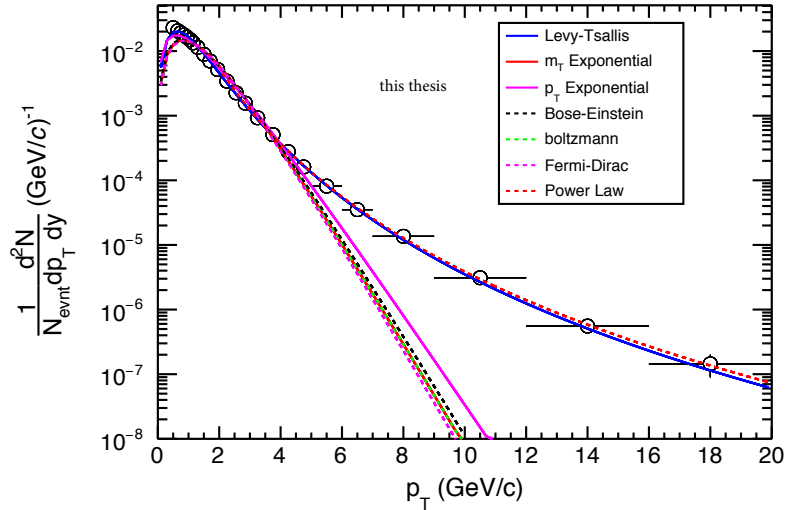


Figure 3.20: Corrected ϕ spectrum (open circle) with fits over the range $0 < p_T < 20$ GeV/c [11].

Figure 3.20 shows the fitting of listed functions. Each fit is performed twice. First, each spectrum is fit with the statistical and systematic uncertainty for each point added in quadrature; collectively, this set of fits will

be denoted $f(p_T)$. Second, each spectrum is fit using only its statistical uncertainties; collectively, this set of fits will be denoted $f'(p_T)$. The set f is the primary set of fits and will be used to extract dN/dy and $\langle p_T \rangle$. The set f' is used in the calculation of the statistical uncertainties of those quantities, as explained in subsequent sections.

3.8.2 Total dN/dy

dN/dy is calculated by integrating the histogram (which spans the range $0.4 < p_T < 20$ GeV/c) and using the spectrum fit $f(p_T)$ described in Section 3.8.1 to extrapolate the yield to the low and high- p_T regions outside the measured range. The central value is calculated using Lévy-Tsallis function which spans the range $0.4 < p_T < 2$ GeV/c and the function is extrapolated to 0 GeV/c. The extrapolated region accounts for 16.6% of dN/dy .

It is very crucial and non-trivial to obtain the statistical and systematic uncertainty in the dN/dy as a fitting function does not contain an uncertainty and one has to carefully obtain the uncertainty in extrapolated region. The statistical and systematic uncertainties are evaluated using the following method.

Low and high- p_T extrapolation histograms with narrow bins (0.05 GeV/c wide) are generated using the spectrum fit f' . The statistical uncertainties of the bin contents of these histograms are determined using ROOT's `TF1::IntegralError()` function. A large number (1000) of alternate histograms is randomly generated by shifting the points in the measured and extrapolation histograms. A random factor k is generated from a Gaussian with mean 0 and $\sigma = 1$. Each of the measured bins is shifted independently (*i.e.*, a different k factor is generated for each bin). All of the bins in the low- p_T extrapolation histogram are shifted coherently using the same k factor, and similarly for the high- p_T extrapolation histogram. For each iteration, the three alternate (random) histograms are integrated and the total dN/dy is stored. The mean (μ_{alt}) and standard

deviation (σ_{alt}) of the set of 1000 alternate values are found. The statistical uncertainty in the default value of dN/dy is

$$\sigma(dN/dy) = (dN/dy) \times \frac{\sigma_{\text{alt}}}{\mu_{\text{alt}}}. \quad (3.14)$$

The systematic uncertainties in dN/dy due to uncertainties in the p_T -spectrum are calculated using an extreme fit method. As an example, the calculation of the material budget uncertainty will be described. Four extreme histograms (extreme low, extreme high, extreme soft, and extreme hard) are generated by shifting the points of the p_T -spectrum down or up by their material budget uncertainties. These shifted spectra are fitted and alternate dN/dy values are calculated. These values are compared to the default value and the maximum difference is taken as the systematic uncertainty. The same procedure is repeated separately for all other uncertainties in Section 3.7.

The systematic uncertainty due to the choice of spectrum fit function (to find the yield in the extrapolation region) is calculated by comparing dN/dy measured using the other fit scenarios (described in Section 3.8.1) with Lévy-Tsallis function fit as a central value. Also, the Lévy-Tsallis function fit is varied for different p_T ranges. The maximum difference due to different fits are considered as the systematic uncertainty due to extrapolation, which is 1.9%.

All of the systematic uncertainties considered are added in quadrature, giving the total systematic uncertainty in dN/dy . The value of dN/dy for ϕ mesons in minimum-bias pp collisions at $\sqrt{s} = 5.02$ TeV is measured to be $0.030123 \pm 0.0002(\text{stat.}) \pm 0.0025(\text{sys.})$.

3.8.3 Mean Transverse Momentum

In general, the mean transverse momentum, $\langle p_T \rangle$ over a p_T range $A < p_T < B$ is

$$\langle p_T \rangle|_A^B = \frac{\int_A^B p_T \times f(p_T) dp_T}{\int_A^B f(p_T) dp_T}. \quad (3.15)$$

Here, $f(p_T)$ is the distribution function (the best fit function to the p_T -spectra). The $\langle p_T \rangle$ is calculated using only the spectrum fits (the “fit method”, **iqF**), using equation 3.15 with $A = 0$ and $B = 20$ GeV/c.

The statistical uncertainty of $\langle p_T \rangle$ is calculated using a procedure similar to the calculation for dN/dy . The measured and extrapolated histograms are shifted randomly (based on their statistical uncertainties) to generate 1000 alternate histograms. The values of $\langle p_T \rangle$ for these alternate histograms are recorded and the mean and standard deviation of the alternate set are found. The statistical uncertainty in the default value of $\langle p_T \rangle$ is

$$\sigma(\langle p_T \rangle) = (\langle p_T \rangle) \times \frac{\sigma_{\text{alt}}}{\mu_{\text{alt}}}. \quad (3.16)$$

The procedure used to evaluate the systematic uncertainties of $\langle p_T \rangle$ is essentially the same as the procedure described in Section 3.8.2. The systematic uncertainty due to extrapolation is 1.5%. All of the systematic uncertainties considered are added in quadrature, giving the total systematic uncertainty in $\langle p_T \rangle$.

The value of $\langle p_T \rangle$ for ϕ mesons in pp collisions at $\sqrt{s} = 5.02$ TeV is measured to be 1.1257 ± 0.0047 (stat.) ± 0.0370 (sys.) GeV/c.

3.9 Comparison with other measurements

Figure 3.21 shows the comparison of ϕ spectrum at $\sqrt{s} = 5.02$ TeV with other collisions energies. From the plot, it can be concluded that the bulk

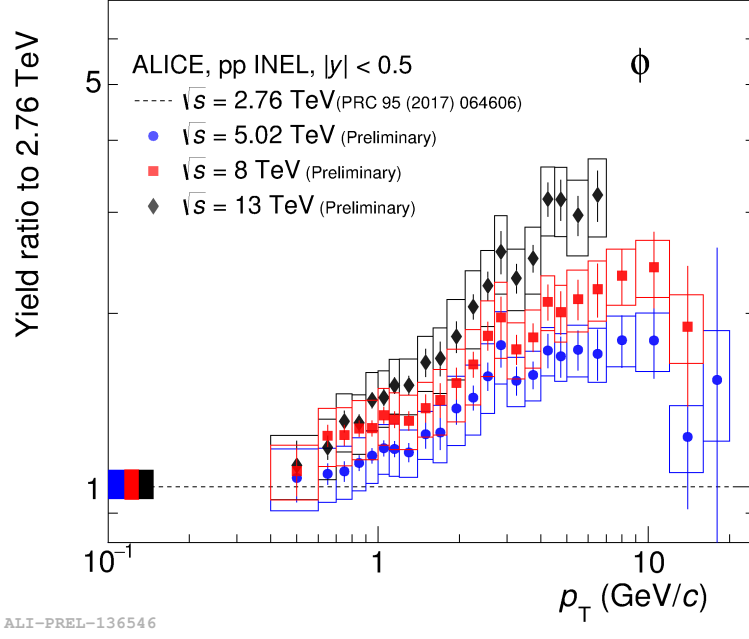


Figure 3.21: Comparison of ϕ spectrum $\sqrt{s} = 5.02$ TeV with other collisions energies at the LHC [11].

production (which is governed by the low- p_T particles) is independent of collision energy. Also, the p_T -spectra gets harder with increasing in collision energy. In Table 3.3, the dN/dy and $\langle p_T \rangle$ of ϕ is compared with other energies. As expected, the dN/dy and $\langle p_T \rangle$ increases with increasing collision energy, which is also evident from Fig. 3.21.

Table 3.3: ALICE measurements of the ϕ meson at various energies.

$\sqrt{s}$ [TeV]	dN/dy	$\langle p_T \rangle$ [GeV/c]	Ref.
0.9	$0.021 \pm 0.004 \pm 0.003$	$1.00 \pm 0.14 \pm 0.20$	[42]
2.76	$0.0260 \pm 0.0004 \pm 0.003$	$1.04 \pm 0.01 \pm 0.09$	[24]
5.02	$0.030123 \pm 0.0002 \pm 0.0025$	$1.1257 \pm 0.0047 \pm 0.0370$	this work
7	$0.0320 \pm 0.0004^{+0.004}_{-0.0035}$	$1.070 \pm 0.005 \pm 0.03$	[39]
13	$0.0374 \pm 0.0004 \pm 0.0024 \pm 0.0016$	$1.234 \pm 0.009 \pm 0.032$	[30]

3.10 Particle ratios

Fig. 3.22 shows the ratio of ϕ/K is plotted as a function collision energy in minimum bias pp collisions. In Fig. 3.23 the ratio of ϕ/K is plotted as a function of center-of-mass energy per nucleon pairs for different collision

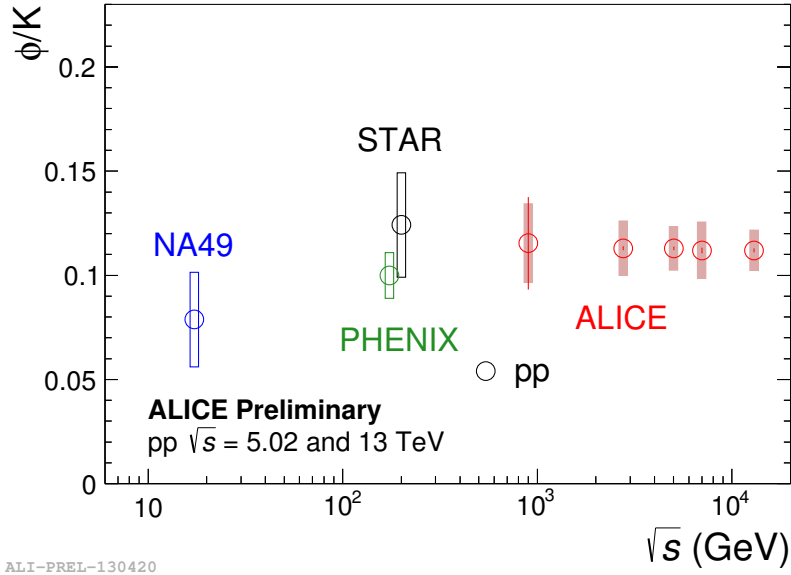


Figure 3.22: Particle ratio ϕ/K presented for pp collisions as a function of the collision energy. The values reported are $2\phi/(K^- + K^+)$ for the ALICE pp measurement at 5.02 and 13 TeV. Bars (when present) represent statistical uncertainties. Boxes represent the total systematic uncertainties or the total uncertainties for cases when separate statistical uncertainties were not reported. The RHIC points at 200 GeV have been shifted horizontally for visibility. [11]

systems. The ϕ/K ratio is found to be independent of the collision energy and of the colliding system. The behaviours of these ratios in pp collisions agree with the predictions [46, 47] of a thermal model in the grand-canonical limit.

3.11 Nuclear modification factor (R_{pPb}) for p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV

After obtaining the ϕ meson spectrum in pp collisions, the R_{pPb} is calculated with the published result for ϕ in p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV [37], using the following formula.

$$R_{\text{pPb}}(p_{\text{T}}) = \frac{d^2 N_{\text{pPb}}/dydp_{\text{T}}}{N_{\text{coll}} \times d^2 N_{\text{pp}}/dydp_{\text{T}}}. \quad (3.17)$$

Here, N_{coll} is the number of the binary collisions for p-Pb collisions which needs to be scaled for pp collisions. The value of N_{coll} for minimum bias

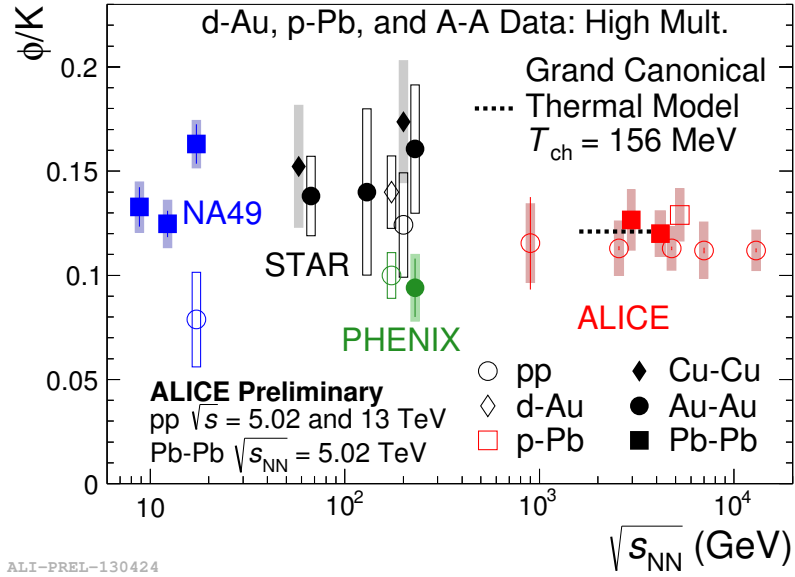


Figure 3.23: Particle ratio ϕ/K presented for pp, high-multiplicity p-Pb, central d-Au, and central A-A collisions as a function of the collision energy [28, 31–34, 36–42, 42–45]. The values reported are $2\phi/(K^- + K^+)$ for the ALICE pp measurement at 5.02 and 13 TeV and Pb-Pb measurement at 5.02 TeV (0-10%). Bars (when present) represent statistical uncertainties. Boxes represent the total systematic uncertainties or the total uncertainties for cases when separate statistical uncertainties were not reported. Some points at RHIC and LHC energies have been shifted horizontally for visibility. The value given by a grand-canonical thermal model with a chemical freeze-out temperature of 156 MeV is also shown. [11]

p-Pb collisions is 6.87 ± 0.5 . Figure 3.24 shows the R_{pPb} for minimum bias p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV using the measured pp reference and comparison with the published R_{pPb} for charged particles. It is observed that the nuclear modification factor in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV is similar for charged particles and ϕ meson.

3.12 Summary

In this chapter, the first measurements of ϕ meson in pp collisions at $\sqrt{s} = 5.02$ TeV is shown. The results include the invariant mass plots, peak fits, fitting parameters and the corrected p_T -spectra with reconstruction efficiencies. The efficiency-corrected p_T -spectrum is compared with the results from other energies and it has been observed that the bulk production in minimum-bias pp collisions remains independent of collision

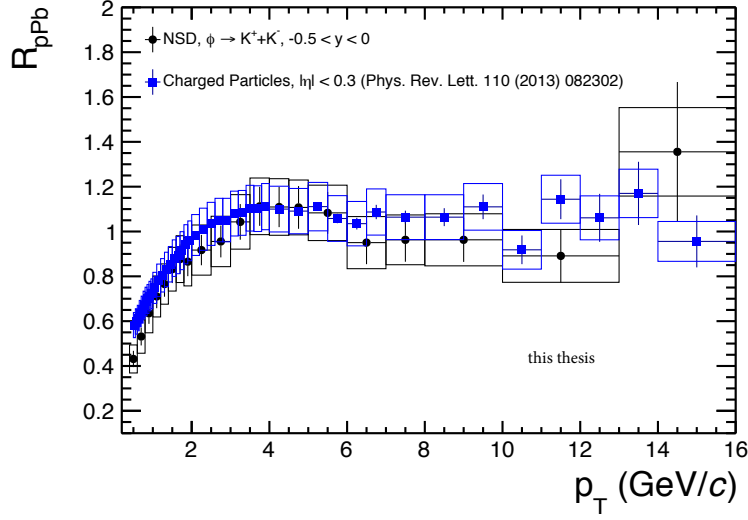


Figure 3.24: R_{pPb} for p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV using the measured pp reference and comparison with the published R_{pPb} for charged particles [11].

energy. It is also observed that the p_T -spectra gets harder with increasing collision energy. The integrated yield and mean transverse momentum are also calculated and compared with other energies. The ratio of the integrated yield of ϕ to charged kaons are shown, which remains independent of collision energy and colliding systems. Also, the nuclear modification factor for ϕ mesons in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV is shown and they are compared with that of the charged particles.

3.13 Appendix-1: Fermis's Golden Rule and Breit-Wigner distribution

Transition rate of an unstable state to a continuum of other states can be given by Fermi's Golden rule [48],

$$\Gamma = \frac{2\pi}{\hbar} |V_{fi}|^2 \frac{dN}{dE_f}, \quad (3.18)$$

where, V_{fi} is the matrix element of the Hamiltonian coupling of the initial and final states and dN/dE_f is the density of the final states. Crudely, the number of particles remaining at time 't' is governed by the decay law,

$$\frac{dN}{dt} = -\Gamma N \quad (3.19)$$

$$\implies N(t) = N_0 e^{-\Gamma t}. \quad (3.20)$$

One can calculate a particle's proper lifetime ' τ ' using the probability that decay between 't' to 't+ δt ',

$$p(t)\delta t = -\frac{1}{N_0} \frac{dN}{dt} \delta t = \Gamma e^{-\Gamma t} \delta t \quad (3.21)$$

$$\tau = \langle t \rangle = \frac{\int_0^t t p(t) dt}{\int_0^t p(t) dt} = \frac{\int_0^t t \Gamma e^{-\Gamma t} dt}{\int_0^t \Gamma e^{-\Gamma t} dt} = \frac{1}{\Gamma} \quad (3.22)$$

One should remember that if the particles are travelling relativistically, the decay clocks will be dilated in time. So, the average number remaining after some distance 'x' will be,

$$N = N_0 e^{-x/L_0}, \quad (3.23)$$

where, $L_0 = \beta\gamma c\tau$ and β is the velocity, γ is the Lorentz boost factor and c is the speed of light. The time-energy uncertainty relation is given by,

$$\Delta E \Delta t \simeq \hbar \quad (3.24)$$

$$\implies \Delta E = \frac{\hbar}{\tau} = \hbar\Gamma \quad (3.25)$$

Assuming $\hbar = 1$ in natural units, $\Delta E = \Gamma$. This suggests that if we take a set of identical unstable particles and measure the mass of each, we are expected to get a range of values with width of order Γ .

One can make the smearing of the energy more precise. If we require that the probability of finding the particle decays with rate Γ , the amplitude is given by

$$a(t) = e^{(-i(E-E_0)t - \Gamma/2t)} \quad (3.26)$$

After fourier transformation to the energy domain, the probability density function is given as,

$$p(E) \propto \frac{1}{(E - E_0)^2 + (\Gamma/2)^2}, \quad (3.27)$$

where, E_0 is the rest mass of the particle and Γ is the full width half maximum (FWHM) often called as width of the particle. Consider the following process, where initial particles collide to form an unstable intermediate particle, which then decays to the final state.

$$A + B \rightarrow O \rightarrow C + D \quad (3.28)$$

Assuming the width of the intermediate particle is not too large ($\Gamma \leq E$), the cross-section for the process is given by the famous **Breit-Wigner** formula,

$$\sigma = \frac{\pi}{k^2} \frac{\Gamma_i \Gamma_f}{(E - E_0)^2 + \frac{\Gamma^2}{4}}, \quad (3.29)$$

where, Γ_i and Γ_f are the partial width of the resonance decay to the initial and final state, respectively. Γ is the full width of resonance. E is the centre-of-mass energy of the system and E_0 is the characteristic rest mass energy of the resonance. k is the wave-number of the incoming projectile in the centre-of-mass frame.

More formally, one can obtain the Breit-Wigner distribution in the context of the partial wave expansion in 3D scattering theory. When a partial wave experiences a phase shift of δ_l at energy E near mass M , we have a resonant scattering. For a l^{th} partial wave, the amplitude is given as,

$$a_l = e^{i\delta_l} \sin \delta_l = \frac{1}{(\cot \delta_l - i)} \quad (3.30)$$

Expanding the partial wave amplitude about the resonance energy yields,

$$\cot \delta_l(E) \simeq -\frac{E - E_0}{\Gamma/2} \quad (3.31)$$

Now, the scattering cross-section is by Breit-Wigner formula,

$$\sigma = \frac{\pi(2l+1)}{k^2} \frac{\Gamma^2}{(E - E_0)^2 + \frac{\Gamma^2}{4}}. \quad (3.32)$$

One should remember that in this context, the Breit-Wigner formula is clearly an approximation valid only near resonant peak.

3.14 Appendix-2: Inelastic Normalization

Factors for pp collisions at

$$\sqrt{s} = 5.02, 8, \text{ and } 13 \text{ TeV}$$

3.14.1 Introduction

In order to normalize the yield to the number of inelastic pp collisions, an inelastic normalization factor (f_{norm}) is calculated. This is needed to convert a particle yield normalized to the number of triggered events to a yield normalized to the number of inelastic events. The inelastic normalization factor is the ratio of the V0 visible cross section to the inelastic cross section. As no measurement of the inelastic cross section has been performed by ALICE for pp collisions at $\sqrt{s} = 5.02, 8$ and 13 TeV, we have adopted values obtained from fits to measured data from other energies and/or other experiments. The following sections discuss the V0 visible cross sections, the inelastic cross sections, and the inelastic normalization factors derived from them.

3.14.2 V0 Visible Cross Sections

In ALICE, the luminosity determination is based on the visible cross sections measured in van der Meer (vdM) scans [49, 50]. The visible cross section σ_{V0} seen by a given detector (or set of detectors) with a given trigger condition is a fraction of the total inelastic interaction cross section σ_{inel} : $\sigma_{\text{V0}} = \epsilon \sigma_{\text{inel}}$, where ϵ is the fraction of inelastic events that satisfy the trigger condition. ALICE has measured the σ_{V0AND} values for $\sqrt{s} = 5.02, 8$, and 13 TeV for the determination of luminosity [50–52], which corresponds to INT7 trigger. The values with their statistical and systematic uncertainties are listed below.

1. σ_{V0AND} for pp collisions at $\sqrt{s} = 5.02$ TeV is $51.2 \text{ mb} \pm 2.3\%$
2. σ_{V0AND} for pp collisions at $\sqrt{s} = 8$ TeV is $55.8 \text{ mb} \pm 2.6\%$

3. σ_{V0AND} for pp collisions at $\sqrt{s} = 13$ TeV is $57.8 \text{ mb} \pm 2.2\%$

Here, the statistical uncertainties are negligible with respect to the systematic ones. The systematic uncertainty includes the uncertainty due to stability and consistency. The uncertainty due to stability and consistency is assigned after comparing the trigger rates for all run numbers for corresponding collision energy [50–52]. For pp collisions at $\sqrt{s} = 13$ TeV, the comparison of trigger rates are performed for all run numbers in LHC15f period [52].

3.14.3 Inelastic Cross Sections

So far, ALICE has not measured the inelastic cross sections for pp collisions at $\sqrt{s} = 5.02$, 8, and 13 TeV. Therefore, we have adopted values taken from [53], which performs a fit using measured values from several experiments, including ALICE, ATLAS, CMS, TOTEM, and others. The resulting values of the inelastic cross sections for all three energies are listed below.

1. σ_{inel} for pp collisions at $\sqrt{s} = 5.02$ TeV is $(67.6 \pm 0.6) \text{ mb}$
2. σ_{inel} for pp collisions at $\sqrt{s} = 8$ TeV is $(72.3 \pm 0.5) \text{ mb}$
3. σ_{inel} for pp collisions at $\sqrt{s} = 13$ TeV is $(77.6 \pm 1.0) \text{ mb}$

The experimental data were fitted using functions of the form $\sigma(s) = A + B \ln^n s$. The central value is extracted from the $\ln^2 s$ fit ($n = 2$). The uncertainties are estimated from the difference between the central values and the results from the $\ln s$ and $\ln^n s$ fits ($n = 1$ and n free, respectively).

3.14.4 Inelastic Normalization Factors

Inelastic normalization factor (f_{norm}) is the ratio between the V0 visible cross section (σ_{V0AND}) and the inelastic cross section (σ_{inel}) for each energy.

The uncertainties of the numerator and denominator cross sections are uncorrelated. The values for f_{norm} are listed below.

1. f_{norm} for pp collisions at $\sqrt{s} = 5.02$ TeV is 0.7574 ± 0.0190 (2.51%)
2. f_{norm} for pp collisions at $\sqrt{s} = 8$ TeV is 0.7718 ± 0.02075 (2.69%)
3. f_{norm} for pp collisions at $\sqrt{s} = 13$ TeV is 0.7448 ± 0.0190 (2.55%)

The quoted f_{norm} value for pp collisions at $\sqrt{s} = 13$ TeV is valid only for LHC15f period. The proper normalization for other periods need more refined studies.

Now the total number of inelastic events (N_{inel}) can be calculated as,

$$N_{\text{inel}} = N_{\text{V0AND}} \times \frac{\sigma_{\text{inel}}}{\sigma_{\text{V0AND}}} = \frac{N_{\text{V0AND}}}{f_{\text{norm}}} \quad (3.33)$$

where, N_{V0AND} is the total number of events from V0AND.

As the raw p_T spectrum is normalized with N_{V0AND} , we need to normalize with the total number of inelastic events (N_{inel}). Thus, f_{norm} has to be multiplied to the p_T spectrum in order to normalize with N_{inel} .

3.15 Appendix-3: Barlow/Consistency Checks

The most common way of finding systematic uncertainties (e.g., in a particle yield) is to perform the analysis many times to get many measurements. Each measurements has to be performed with one or more analysis parameters changed (e.g. a fitting range, the form of a fitting function, PID cuts etc.). The measurements are all obtained from the same data set so they are not statistically independent. One measurement (or possibly an average of all) is identified as the “default” measurement (the central value). The “alternate” measurements are used to calculate the systematic uncertainties by finding the differences between them and the default measurement. However, an alternate measurement which is statistically consistent with the default measurement should not be used in calculating a systematic uncertainty. As the alternate and default measurements are not statistically independent, the question of whether they are consistent within their statistical uncertainties does not have a trivial answer. As one cannot just check to see if their uncertainties overlap, following method has been used by ALICE and it is our attempt to implement the advice given by Barlow in Ref. [40]. Due to this reason, such checks are often called as “Barlow checks”.

Based on the Ref. [40], the difference between the alternate and default measurements is compared to the difference in quadrature of the uncertainties of those measurements. Let D be the default measurement and σ_D be its statistical uncertainty. Let A be the alternate measurement and σ_A be its statistical uncertainty. The difference between the two measurements is given by $\Delta \simeq A - D$. The difference in quadrature of the uncertainties is given by,

$$\sigma_{cc} \simeq \sqrt{|\sigma_A^2 - \sigma_D^2|} \quad (3.34)$$

It would be possible to simply check if $\Delta < \sigma_{cc}$ and exclude such cases from the systematic uncertainties. But, there can be statistical fluctuations

for which $\Delta > \sigma_{cc}$. We therefore follow a more complicated procedure explained below. The distribution of the ratio Δ/σ_{cc} is obtained, where each entry is for a different p_T bin and centrality/multiplicity/spherocity bin. This is done separately for each alternate analysis parameter. If the variations between the default and alternate measurements are purely statistical, the distribution of Δ/σ_{cc} should be almost a Gaussian with a mean of 0 and $\sigma=1$. Large deviations from the ideal behavior indicate that the variations between the default and alternate measurements are not purely statistical and they should be included in the systematic uncertainties.

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Chapter 4

Event shape and multiplicity dependence of ϕ meson production in pp collisions

“Success is a science; if you have the conditions, you get the result”.

— *Oscar Wilde*

4.1 Introduction

QGP, a deconfined state of quarks and gluons, is believed to be produced in heavy-ion collisions at RHIC and LHC. Recent multiplicity dependent measurements of identified particle production from the experiments at the LHC have revealed QGP-like behavior, such as strangeness enhancement [1] and double ridge structure [2] in high multiplicity proton+proton (pp) collisions, which raise concerns whether pp collisions can be used as a proper benchmark for comparison with heavy-ion results to understand the formation of a medium with high temperature/energy density. These behaviours have important consequences in understanding the data from heavy-ion collisions at the LHC energies as one should consider the contribution of QGP-like effects in small systems. They open new directions for theoretical and experimental studies of small collision systems. While hydrodynamic calculations [3, 4] describe data qualitatively, other approaches suggest that these can be initial state effects [5, 6]. To understand the recent measurements, it is important to perform double differential studies of

pp collisions with event shape observables and charged-particle multiplicity. Event shape observables like transverse sphericity, allow the possibility to separate the high and low number of MPI events to isolate the behavior of particles inside jets (hard processes) and pertaining to the soft processes [7–9]. This result can help to understand more on the jet production, identified particle ratios (baryon to meson and strange to non-strange), double ridge structure and the steep rise of mean transverse-momenta of charged particles in small systems compared to large systems [10]. A comprehensive differential study using event shapes would reveal interesting features, which could be exploited to improve models as well.

This chapter describes a double differential study of sphericity and multiplicity dependence measurement of ϕ meson production at the LHC. It is divided into three sections. The first section describes the production of ϕ mesons in pp collisions at $\sqrt{s} = 5.02$ TeV as a function of the multiplicity (V0M) using the ALICE detectors. This study is essential as it will be helpful in understanding the ϕ production in high multiplicity environment. The second section describes the identified particle production in pp collisions as a function of transverse sphericity and charged-particle multiplicity using PYTHIA8 [11] event generator, which would help to understand the effects of event shape and multiplicity on identified light-flavored particle production in one of the popular event generators in the current LHC era. The last section describes the production of ϕ mesons in pp collisions at $\sqrt{s} = 5.02$ TeV as a function of the transverse sphericity and charged-particle multiplicity (V0M) using the ALICE detector. Most of the analysis techniques along with the calculation of systematic uncertainties are similar to the inelastic analysis at $\sqrt{s} = 5.02$ TeV, which was already discussed in the previous chapter. Thus, here they are briefly introduced.

4.2 Multiplicity dependence of ϕ production in pp collisions at $\sqrt{s} = 5.02$ TeV with ALICE

4.2.1 Event Selection

The data set used in this analysis is the same as mentioned in the previous chapter. The analysis uses the Resonance Package available in ALIROOT software. For this analysis, the following event-selection cuts were used:

1. `kINT7` trigger (requires a hit in both VZERO detectors)
2. Standard Physics Selection
3. `IsIncompleteDAQ` check
4. Pileup rejection using `AliESDEvent::IsPileUpFromSPDInMultBins()`
5. SPD clusters vs. tracklets check with standard parameters
6. SPD vertex z resolution < 0.25 cm
7. SPD vertex dispersion < 0.04
8. z -position difference between track and SPD vertex ($|v_z \text{ (diff)}| < 0.5$ cm)
9. vertex z position: $|v_z| < 10$ cm

Figure 4.1 shows the event statistics after implementing all the above event-selection cuts for the multiplicity dependent analysis. The fourth bin shows the total number of accepted minimum bias events for this analysis, which is around 85 M events out of around 100 M events. The multiplicity classes analysed along with the corresponding $\langle dN_{\text{ch}}/d\eta \rangle$ are shown in Table 4.1.

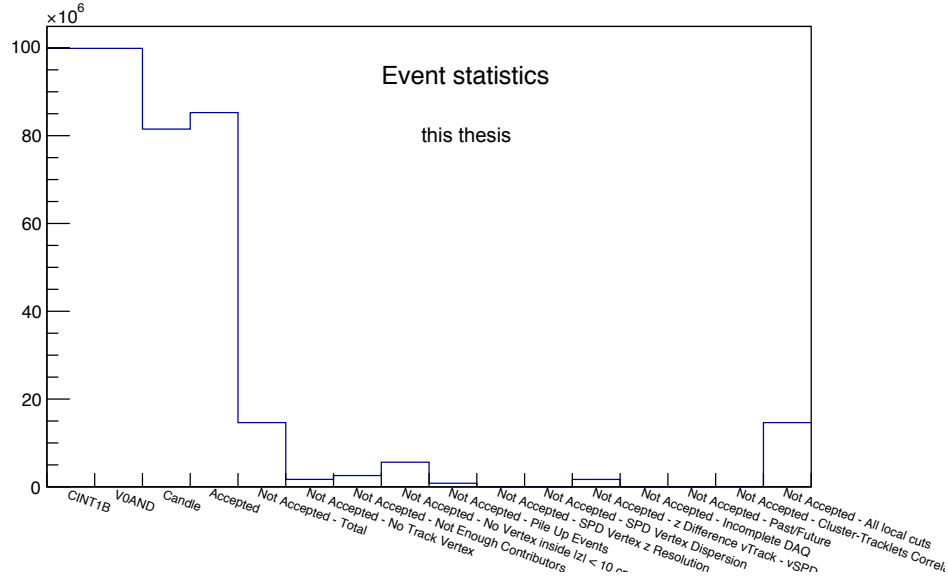


Figure 4.1: Event statistics after implementing event-selection cuts for multiplicity analysis. The fourth bin shows the total number of accepted events (0-100)% V0M multiplicity class [26].

Table 4.1: List of multiplicity classes analyzed with their $\langle dN_{\text{ch}}/d\eta \rangle$ values [28].

percentile (%)	$\langle dN_{\text{ch}}/d\eta \rangle$	Nomenclature
0-1	18.92 ± 0.16	I
1-5	14.86 ± 0.12	II
0-5	15.67 ± 0.13	I+II
5-10	12.23 ± 0.10	III
10-15	10.57 ± 0.09	IV
15-20	9.36 ± 0.08	V
20-30	7.97 ± 0.07	VI
30-40	6.53 ± 0.06	VII
40-50	5.40 ± 0.05	VIII
50-70	4.13 ± 0.04	IX
70-100	2.67 ± 0.03	X

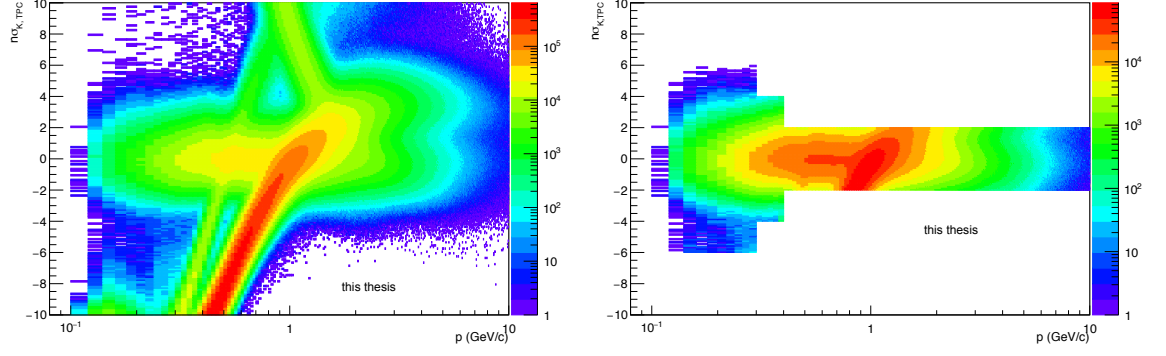


Figure 4.2: (Color Online) $n\sigma_{tpc}$ vs. p for different PID cut schemes. **Left Panel:** no PID cuts applied. **Right Panel:** default PID cuts (the tpc2stofv3s scheme) applied [26].

4.2.2 Track Selection and Particle Identification

Track selection cuts

The ϕ mesons were identified by reconstructing their decays to charged kaons, which has a branching ratio of 0.492 ± 0.005 [33]. The selection criteria for kaon tracks are similar to the inelastic analysis which was listed in the previous chapter.

Particle IDentification (PID) cuts

The kaons are identified through their energy loss in the TPC and their time of flight in the TOF. Several independent iterations of the analysis are performed, with each iteration using a different set of PID cuts. “TOF veto” means that the TOF cut is applied only for cases where the track matches a hit in the TOF; for tracks without matches, no TOF cut is applied.

- $n\sigma_{tpc} < 2$ with a TOF veto of $n\sigma_{tof} < 3$ (shorthand: tpc2stofv3s)
- $n\sigma_{tpc} < 1.5$ with a TOF veto of $n\sigma_{tof} < 3$ (shorthand: tpc15stofv3s)
- $n\sigma_{tpc} < 2.5$ with a TOF veto of $n\sigma_{tof} < 3$ (shorthand: tpc25stofv3s)
- $n\sigma_{tpc} < 2$ with a TOF veto of $n\sigma_{tof} < 4$ (shorthand: tpc2stofv4s)

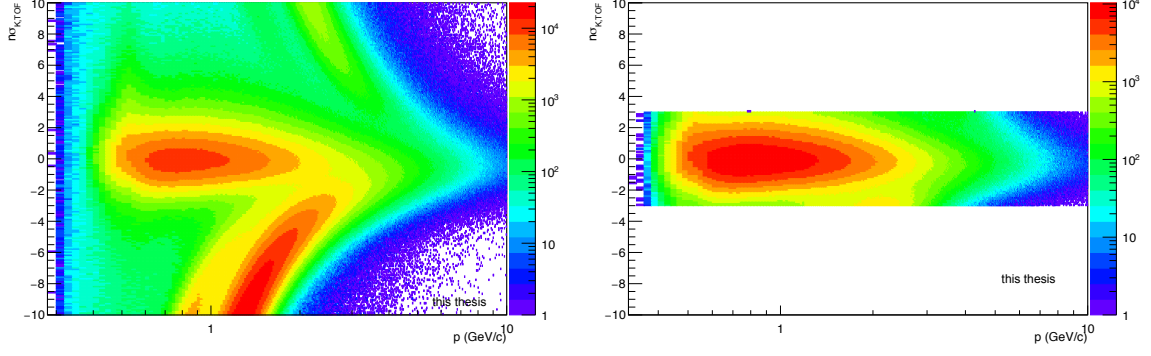


Figure 4.3: (Color Online) $n\sigma_{tof}$ vs. p for two different PID cut schemes. **Left Panel:** no PID cuts applied. **Right Panel:** default PID cuts (the `tpc2stofv3s` scheme) applied. (with the aforementioned wider cuts at low momentum) [26].

For $p(K^\pm) < 0.3$ GeV/c, a cut of $|n\sigma_{tpc}| < 6$ is applied, while for $0.3 < p(K^\pm) < 0.4$ GeV/c, a cut of $|n\sigma_{tpc}| < 4$ is used. Figures 4.2 and 4.3 illustrate the TPC and TOF cuts used. The analysis is also rerun with different track quality cuts (always using the `tpc2tof v3` PID cut set). Variations in ϕ meson yields, masses, widths, etc. due to the different kaon-identification and track-quality cuts were incorporated into the systematic uncertainties as described in Section 4.2.7.

4.2.3 Signal Extraction

Table 4.2 gives a list of the p_T bins analyzed. To extract the yields of ϕ mesons in each p_T bin, the following procedure is used. The invariant-mass distribution of unlike-charge kaon pairs from the same event is computed. In addition, the combinatorial background is estimated and subtracted from the unlike-charge distribution. The background-subtracted unlike-charge distribution is fitted with a combined fit function: a residual background polynomial plus a peak. The peak is fitted with a Voigtian function and the residual background is fitted with 2^{nd} order polynomial. The description of combinatorial background, residual background and the peak fits are discussed in the previous chapter. Left figure of Figure 4.4 shows the representative plot of unlike-charge signal and the event-mixing combinatorial background for $0.5 < p_T < 0.7$ GeV/c in V0M multiplicity class VII. Right

Table 4.2: List of p_T bins analyzed (units of GeV/c).

bin	minimum	maximum	bin	minimum	maximum
0	0.5	0.7	8	2.2	2.6
1	0.7	0.9	9	2.6	3.0
2	0.9	1.2	10	3.0	3.5
3	1.2	1.4	11	3.5	4.0
4	1.4	1.6	12	4.0	5.0
5	1.6	1.8	13	5.0	8.0
6	1.8	2.0	14	8.0	12.0
7	2.0	2.2	15	—	—

figure of Figure 4.4 shows the event-mixing background-subtracted signals with residual background. Similar procedure is followed for all measured p_T bins as listed in Table 4.2.

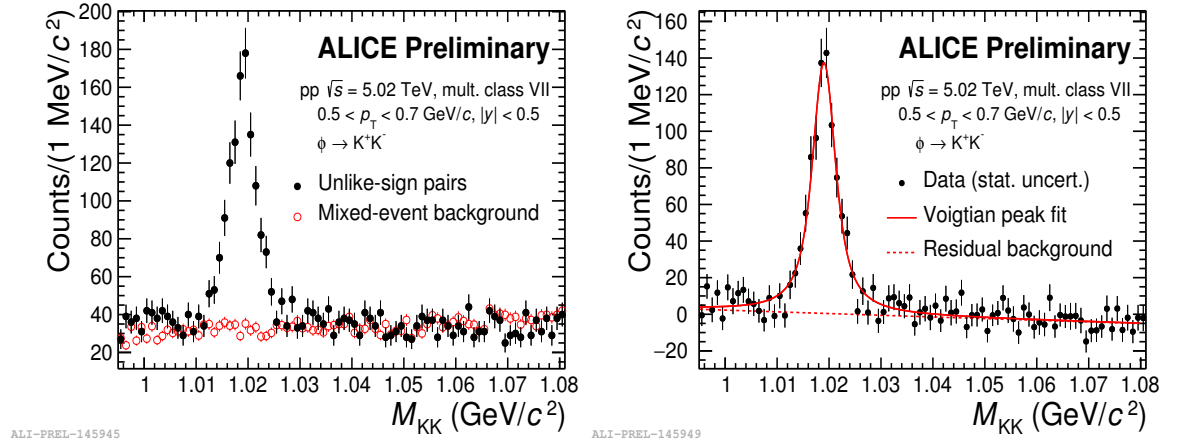


Figure 4.4: (Color Online) Left Figure: Representative invariant-mass distribution for $0.5 < p_T < 0.7$ GeV/c in V0M multiplicity class VII. The black marker shows the invariant-mass distribution of unlike-charge kaon pairs. Red markers show the normalized event-mixing background. Right Figure: Invariant-mass distribution after event-mixing background subtraction. The residual background is fitted with 2^{nd} order polynomial which is shown in dotted red line. Solid red line shows the fitting of signal + residual background [26].

4.2.4 ϕ raw Yield

The yield is extracted by integrating the invariant-mass histogram over the region $I_{min} < m < I_{max}$ and subtracting the integral of the residual background portion of the fit function (divided by the bin width) over

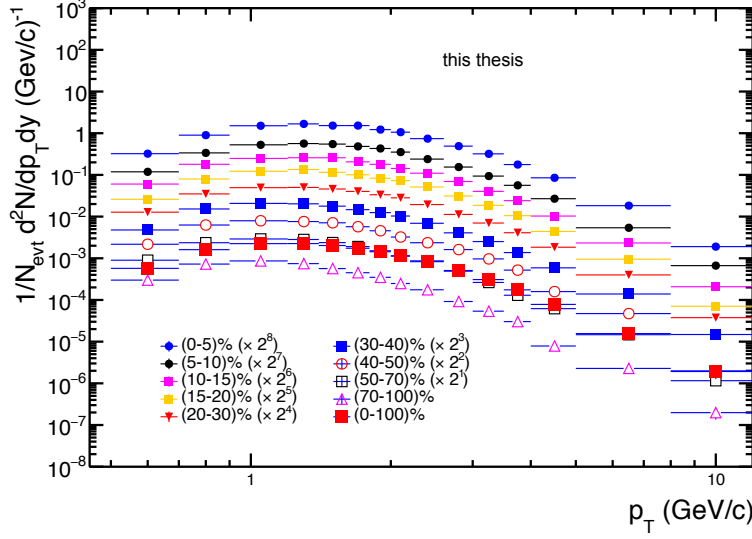


Figure 4.5: (Color Online) Raw Yield as a function of p_T for different multiplicity classes. For distinct visualization, the spectrum in different multiplicity classes are scaled with a proportionality factor, which is mentioned in the bracket of the legends [26].

that same interval. The yields for the regions $2M(K^\pm) < m < I_{min}$ and $m > I_{max}$ are extracted from the peak fit and added to the yield calculated from the histogram. It is assumed that the statistical uncertainties of the yields in the tail regions are fully correlated with each other and with the statistical uncertainty of the yield calculated from the histogram. Here, $I_{min} = 1.01 \text{ GeV}/c^2$ and $I_{max} = 1.03 \text{ GeV}/c^2$. The raw yield as a function of p_T for different multiplicity classes are shown in Figure 4.5. The errors reported in Figure 4.5 are statistical only. As these are raw counts, one has to correct them with detector efficiency and acceptance along with other normalization parameters, which are discussed in following sub-sections. Although, some of these procedures are similar as in previous chapter, for the sake of completeness they are repeated in this chapter as well.

4.2.5 Simulations

A simulated data set is analyzed in order to extract the ϕ reconstruction efficiency $\times$ acceptance (this calculation is described in Section 4.2.6) and estimate the ϕ mass resolution (which is used as an input parameter for

Voigtian fits of real ϕ peaks). The simulated data set consists of 95 million events in the the LHC16k5a and LHC16k5b production. Particle production and decays are simulated using PYTHIA (the Monash 2013 tune of PYTHIA 8 for LHC16k5a and the Perugia 2011 tune of PYTHIA 6 for LHC16k5b), while particle interactions with the ALICE detector are simulated using GEANT3. The same event selection and track quality cuts are used for the real and simulated data.

In the context of this section and Section 4.2.6, the particles produced by the event generator (without any detector effects) are referred to as the “generated” particles. These particles are the input for the GEANT3 detector simulation and, the track and signal reconstruction algorithms. The tracks which are identified by the reconstruction algorithms *and* which pass the track selection and PID cuts are referred to as “reconstructed” tracks. Histograms of the invariant mass of reconstructed ϕ mesons are fitted using the function described in Section 3.4.3. The resolutions of these peaks are extracted using the `voigtG` fit, which was also used to fit the real data. The fit region for these histograms is $1.01 < m < 1.03 \text{ GeV}/c^2$ (shorthand: `fr1`).

4.2.6 Correction and Normalization of Spectra

Reconstruction Efficiency $\times$ Acceptance

The reconstruction efficiency $\times$ acceptance, denoted as $A \times \epsilon$, is calculated using the same simulated data described in Section 4.2.5. In each transverse-momentum bin, $A \times \epsilon$ is the ratio of the following two quantities:

Denominator: Generated ϕ : the number of generated ϕ mesons with $|y_{\text{gen}}| < 0.5$ that decayed to two charged kaons

Numerator: Reconstructed ϕ : the number of ϕ mesons with $|y_{\text{rec}}| < 0.5$ for which both kaon decay daughters were reconstructed

The correction $A \times \epsilon$ for different PID, event and track selection cuts are shown in Figure 4.6. It has a strong dependence on transverse momentum at low p_T .

The uncertainty in $A \times \epsilon$ is calculated using a Bayesian approach [35]. The standard deviation in an efficiency $\epsilon = k/n$, where the numerator k is a subset of the denominator n , is

$$\sigma_\epsilon = \sqrt{\frac{k+1}{n+2} \left(\frac{k+2}{n+3} - \frac{k+1}{n+2} \right)}. \quad (4.1)$$

The fractional statistical uncertainty in $A \times \epsilon$ is added in quadrature with the statistical uncertainty in the uncorrected ϕ yield to give the total statistical uncertainty of the corrected ϕ yield.

Figure 4.6 shows the ϕ meson reconstruction efficiency ($A \times \epsilon$) as a function of p_T for different multiplicity classes in `tpc2stofv3s` combination and their ratio of the $A \times \epsilon$ values in the top plot to the (0-100)% multiplicity class. No multiplicity dependence of $A \times \epsilon$ is observed in all p_T bins. Thus the $A \times \epsilon$ of (0-100)% is used for all other multiplicity classes.

Signal-Loss Correction

The signal loss correction factor (ϵ_{SL}) is calculated to account for the loss of ϕ mesons incurred by selecting events that satisfy only kINT7 trigger, rather than all INEL>0 events. This is a p_T -dependent correction factor which peaks at low p_T . This correction is the ratio of the p_T spectrum in true INEL>0 events to the p_T spectrum with standard event selections. The correction factor is calculated using the two different simulation productions, LHC16k5a (PYTHIA 8, Monash 2013 tune) and LHC16k5b (PYTHIA 6, Perugia 2011 tune), which is shown in figure 4.7 for 0-100% multiplicity class. The PYTHIA 8 correction is used as the default. A systematic uncertainty is assigned to the p_T spectrum. Let ϵ_{SL8} be the PYTHIA 8 correction and ϵ_{SL6} be the PYTHIA 6 correction. The systematic uncertainty is the greater of $|\epsilon_{SL8} - \epsilon_{SL6}|$ and $\frac{1}{2}(\epsilon_{SL8} - 1)$.

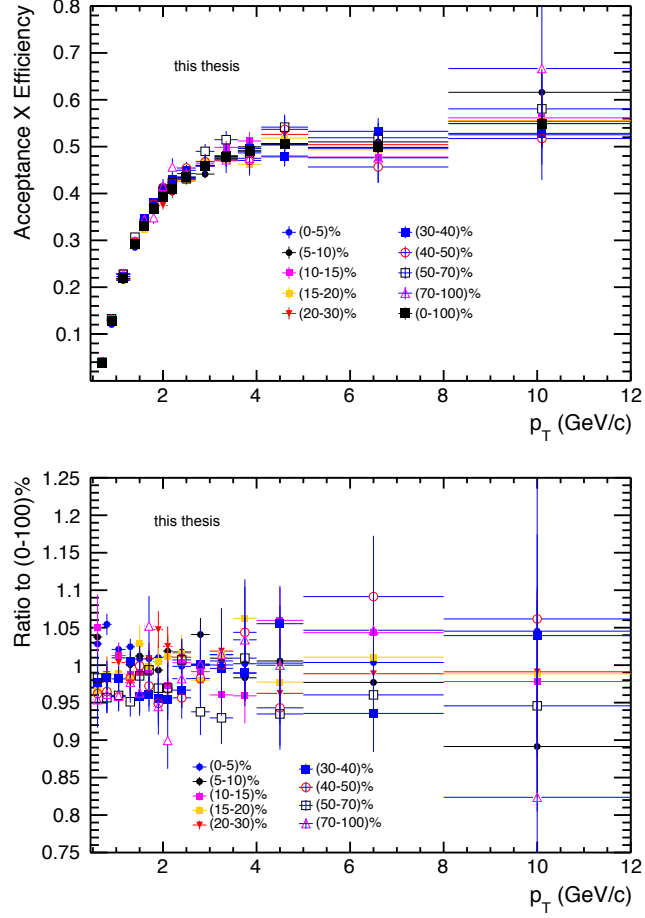


Figure 4.6: (Color Online) **Top plot:** ϕ meson reconstruction efficiency ($A \times \epsilon$) as a function of p_T for different multiplicity classes in `tpc2stofv3s` combination. **Bottom plot:** ratio of the $A \times \epsilon$ values in the top plot to the (0-100)% multiplicity class [26].

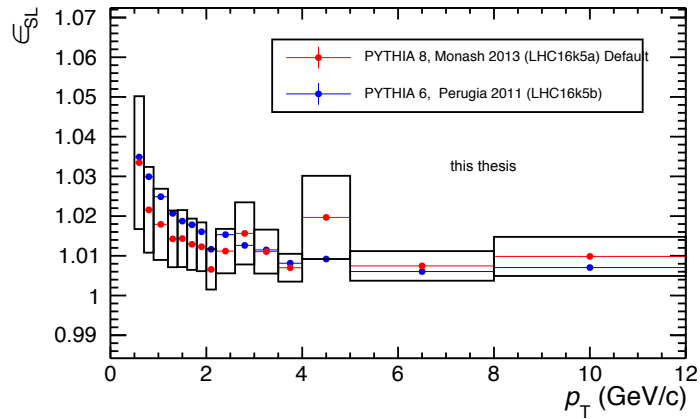


Figure 4.7: Signal loss correction factor as a function of p_T for (0-100)% V0M multiplicity class. The boxes show the systematic uncertainties for each p_T bin [26].

Table 4.3: List of multiplicity classes analyzed with their f_{norm} factor

Percentile (%)	f_{norm}
0-5	0.998452
5-10	0.994840
10-15	0.990076
15-20	0.984323
20-30	0.971406
30-40	0.947951
40-50	0.917386
50-70	0.852545
70-100	0.516628

Normalization

The ϕ meson spectra are normalized as follows. The normalized and the corrected ϕ meson spectra for a given multiplicity class is calculated as follows:

$$\frac{d^2N}{dp_T dy} = \frac{(\text{raw counts})}{N_{\text{evt}} \cdot BR \cdot dp_T dy} \times f_{\text{norm}} \times \frac{\epsilon_{\text{SL}}}{A \times \epsilon}, \quad (4.2)$$

where N_{evt} is the number of events analyzed for a given multiplicity class, BR is the branching ratio ($BR = 0.492 \pm 0.005$), and $dy = 1$. The f_{norm} factor is applied to normalize to the true number of INEL>0 events in the given multiplicity class. This is the ratio between number of events with standard event selections to the number of events in true INEL>0 sample. The values of the f_{norm} factor are given in Table 4.3. As it is the ratio of events, there is no uncertainty associated with this factor.

Transverse Momentum Spectrum

Figure 4.8 shows the efficiency corrected and normalized p_T spectra for different multiplicity classes and their ratios to the (0-100)% multiplicity class. The boxes show the systematic error in each p_T bin which is calculated in Section 4.2.7. Figure 4.8 shows that the corrected p_T spectra depends on charged particle multiplicity. The ratio of p_T spectra in different multiplicity classes to the minimum bias spectrum shows that p_T

spectra (yield) increases with increasing charged particle multiplicity.

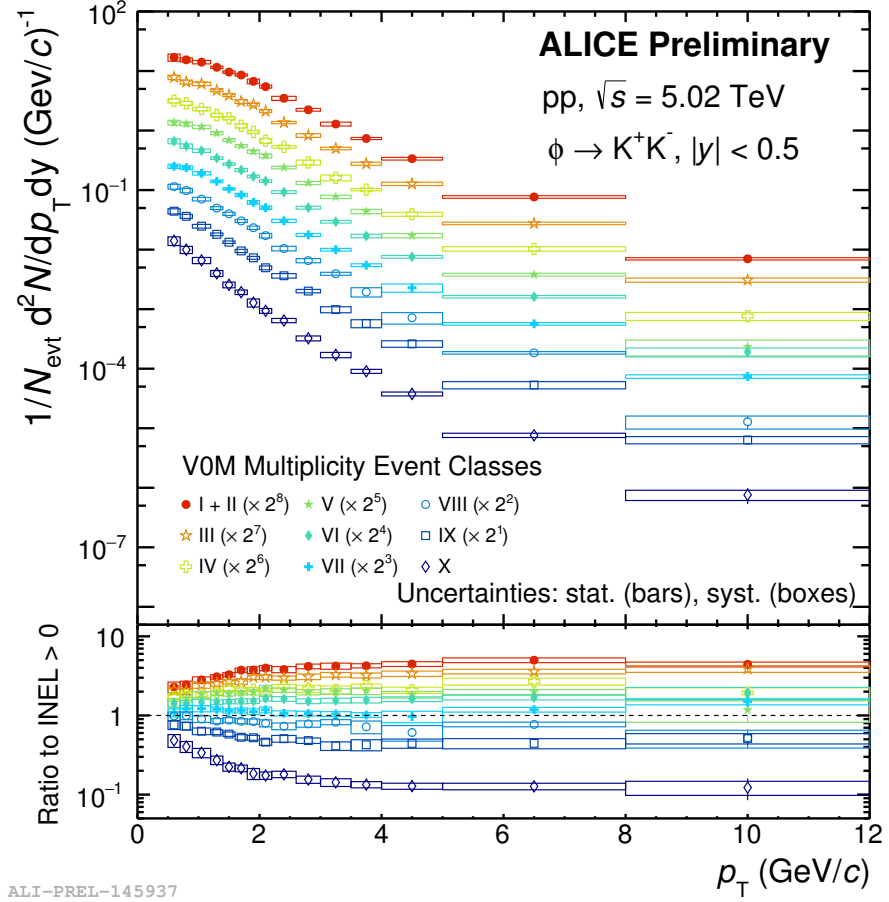


Figure 4.8: (Color Online) Efficiency corrected and normalized ϕ spectra for different multiplicity classes and their ratios to the (0-100)% multiplicity class. The boxes show the systematic error in each p_T bin [26].

4.2.7 Systematic Uncertainties of the Spectrum

Introduction

In general, the analysis is performed many times, using every possible permutation of analysis parameters (PID cuts, combinatorial background, etc.) described in Section 4.2.3. This means that there are multiple measurements of the yield for each transverse momentum bin. Broadly, the uncertainties are calculated in two different groups.

1. Grouped Uncertainties

(a) Signal Extraction

(b) Background Subtraction method

(c) Track Selection Cuts

2. Other sources

(a) Material Budget

(b) Hadronic interaction cross-section

(c) Signal Loss uncertainty

(d) Normalization

(e) Branching Ratio

3. Total Systematic Uncertainty

This procedure is illustrated explicitly for the ϕ yield in the following section. These procedures are performed for different multiplicity classes separately.

Calculation

For each transverse-momentum bin, there are several measurements of the yield and its statistical uncertainty. In general, the yield is calculated for every possible permutation of the analysis parameters (PID cuts, combinatorial background, etc.) described in Section 4.2.3. The uncertainties are grouped in the following way:

1. **Signal Extraction:**

Event Mixing Normalization regions: Three choices: mixed event (*event_mix*) (with three different normalization regions: $0.995 < m < 1.005$ (shorthand: `mix1`), [Normalization Region 2:] $1.04 < m < 1.06$ (shorthand: `mix2`), [Normalization Region 3:] $1.05 < m < 1.08$ (shorthand: `mix3`))

Fit Region: Five choices (`fr0`, `fr1`, `fr2`, `fr3`, `fr4`)

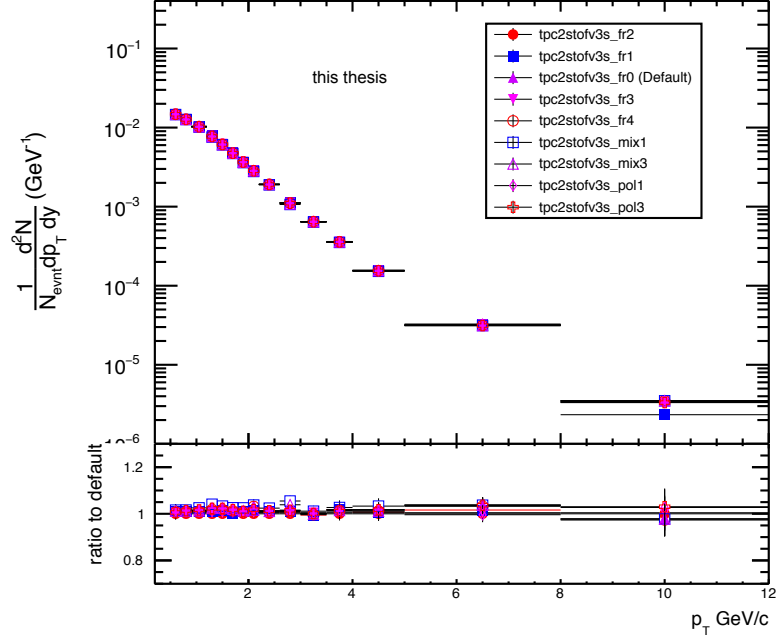


Figure 4.9: (Color Online) **Upper plot:** Yield from `tpc2stofv3s` after varying different signal extraction techniques, **Lower plot:** Ratio to default combination [26].

Residual Background Fit: Three choices: linear (`pol1`), quadratic (`pol2`), or cubic (`pol3`)

Peak Fit: One choice: `voigtG`

For each background subtraction method and track selection cut, the above signal extraction variations are calculated. For these set of variations the mean value is calculated. The standard deviation from the set of measurements is the signal extraction systematic uncertainty. Then the mean statistical uncertainty is obtained. After this step, the mean value is the yield and mean statistical uncertainty is the statistical error for the particular set of background subtraction method and track selection cut. This procedure is repeated for each track selection cut and background subtraction method. Figure 4.9 show the example of different variations for signal extraction grouping procedure.

2. Background Subtraction:

3 choices: no background subtraction (`ulfit`), like-charge

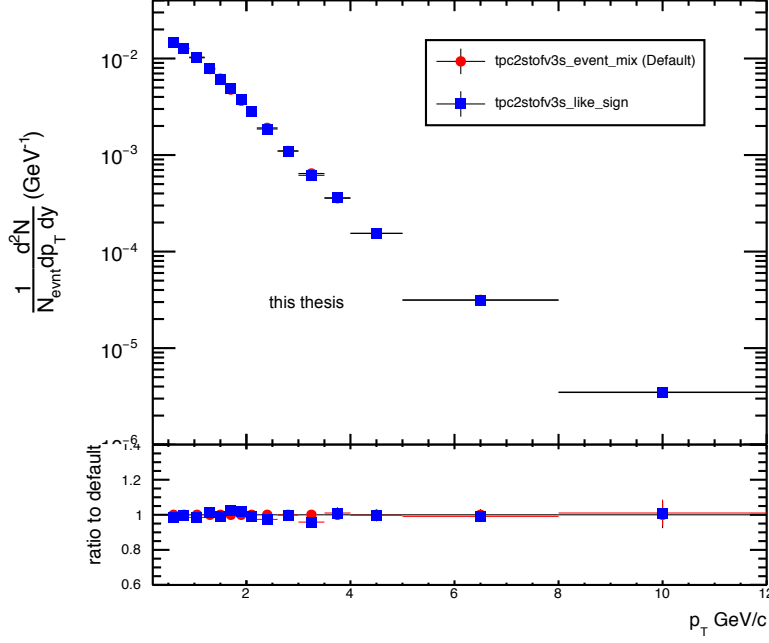


Figure 4.10: (Color Online) **Upper plot:** Yield of `tpc2stofv3s` after varying different background subtraction techniques, **Lower plot:** Ratio to default combination [26].

(`like_sign`), or mixed event (`event_mix`)

For a particular track selection cut, the mean values from the previous grouping are used. Now, for each track selection cut, background subtraction techniques are varied. So, there will be three measurements for each set. The standard deviation from each set is taken as the background subtraction systematic uncertainty. The mean value is the yield and mean statistical uncertainty is the statistical error for the particular set of track selection cut, and PID strategy. Figure 4.10 shows the example of different variations for background subtraction grouping procedure.

3. Track Selection Cuts:

PID Cuts: Four choices: $2\sigma_{TPC}$ with $3\sigma_{TOF}$ veto (`tpc2stofv3s`), $1.5\sigma_{TPC}$ with $3\sigma_{TOF}$ veto (`tpc15stofv3s`), $2.5\sigma_{TPC}$ with $3\sigma_{TOF}$ veto (`tpc25stofv3s`), or $2\sigma_{TPC}$ with $4\sigma_{TOF}$ veto (`tpc2stofv4s`)

Event/Track Selection Cuts: Eight choices (calculated with

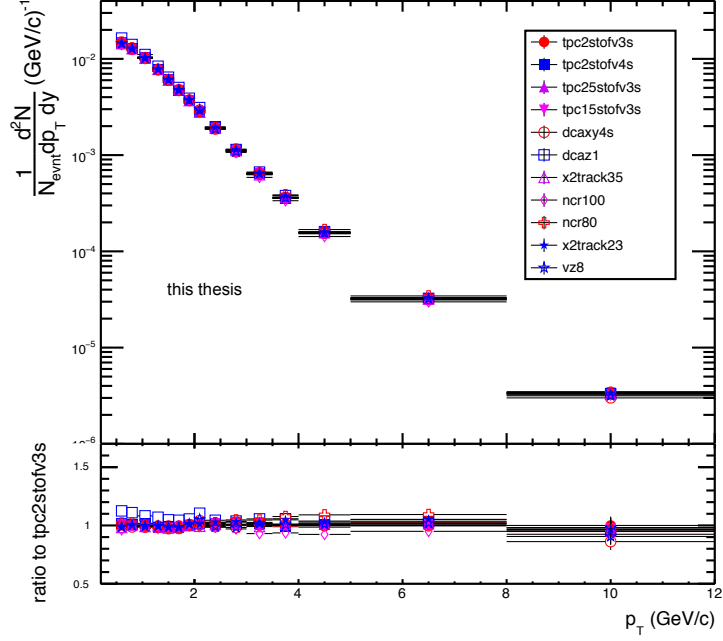


Figure 4.11: (Color Online) **Upper plot:** Yield from different track cuts, **Lower plot:** Ratio of all track cuts to tpc2stofv3s [26]

tpc2stofv3s PID cuts only): event $|v_z| < 8$ cm (vz8), $N_{cr,TPC} \geq 100$ (ncr100), $N_{cr,TPC} \geq 80$ (ncr80), $R_{TPC} \geq 0.9$ (rtpc9), $DCA_{xy} < 4\sigma$ (dcaxy4s), $DCA_z < 1$ cm (dcaz1), $\chi^2_{track} < 2.3$ (shorthand: x2track23), $\chi^2_{track} < 3.5$ (shorthand: x2track35)

There are four TPC/TOF cuts and eight quality cuts variations in this step. The standard deviation from these set of measurements is taken as track selection systematic uncertainty. The mean value is the yield and mean statistical uncertainty is the final statistical error. Figure 4.11 shows the yield from different PID cuts, event-selection cuts and track quality cuts.

4. **Hadronic Interaction Cross-section:** The systematic uncertainty due to uncertainties in the ALICE hadronic interaction cross-section is taken from the analysis of the ϕ mesons in p-Pb collisions [36, 37]. It is p_T -dependent and reaches a maximum value of a few percent.
5. **Signal Loss Uncertainty:** The systematic uncertainty due to the signal-loss correction factor is described in Section 4.2.6.

6. **Branching Ratio:** The systematic uncertainty due to the uncertainty in the branching ratio is 1% and independent of p_T .
7. **Tracking Uncertainty:** The tracking uncertainty, due to the uncertainty in ITS-TPC matching, is taken from the inelastic analysis as shown in the previous chapter. The values of tracking uncertainty as a function of p_T is shown in Fig. 3.16 of the previous chapter.
8. **Total Systematic uncertainty:** The total systematic uncertainty is the sum in quadrature of the uncertainties from the sources listed above. The consistency checks (mentioned in the previous chapter) is also performed for each multiplicity classes.

Fractional Uncertainties

Figure 4.12 shows the fractional uncertainties from all the sources as a function of p_T for different multiplicity classes. A smoothing procedure was applied to smoothen the systematic uncertainties [24].

4.2.8 Fits of the Spectrum

This section describes the procedure used to fit the ϕ -meson p_T spectrum and the quantities derived from fits of the spectrum.

Procedure

The normalized, corrected ϕ meson spectrum is fit with several different functions ($f_0(p_T)$), which always include a multiplicative pre-factor of p_T .

1. **Lévy-Tsallis function (Default function):** The histogram is fit over the range $0.5 < p_T < 3.3$ GeV/c using a Lévy-Tsallis function [38, 39]. This is used as the **default function**:

$$f_0(p_T) = p_T \times \frac{A(n-1)(n-2)}{nT[nT + M(n-2)]} \left[1 + \frac{m_T - M}{nT} \right]^{-n}, \quad (4.3)$$

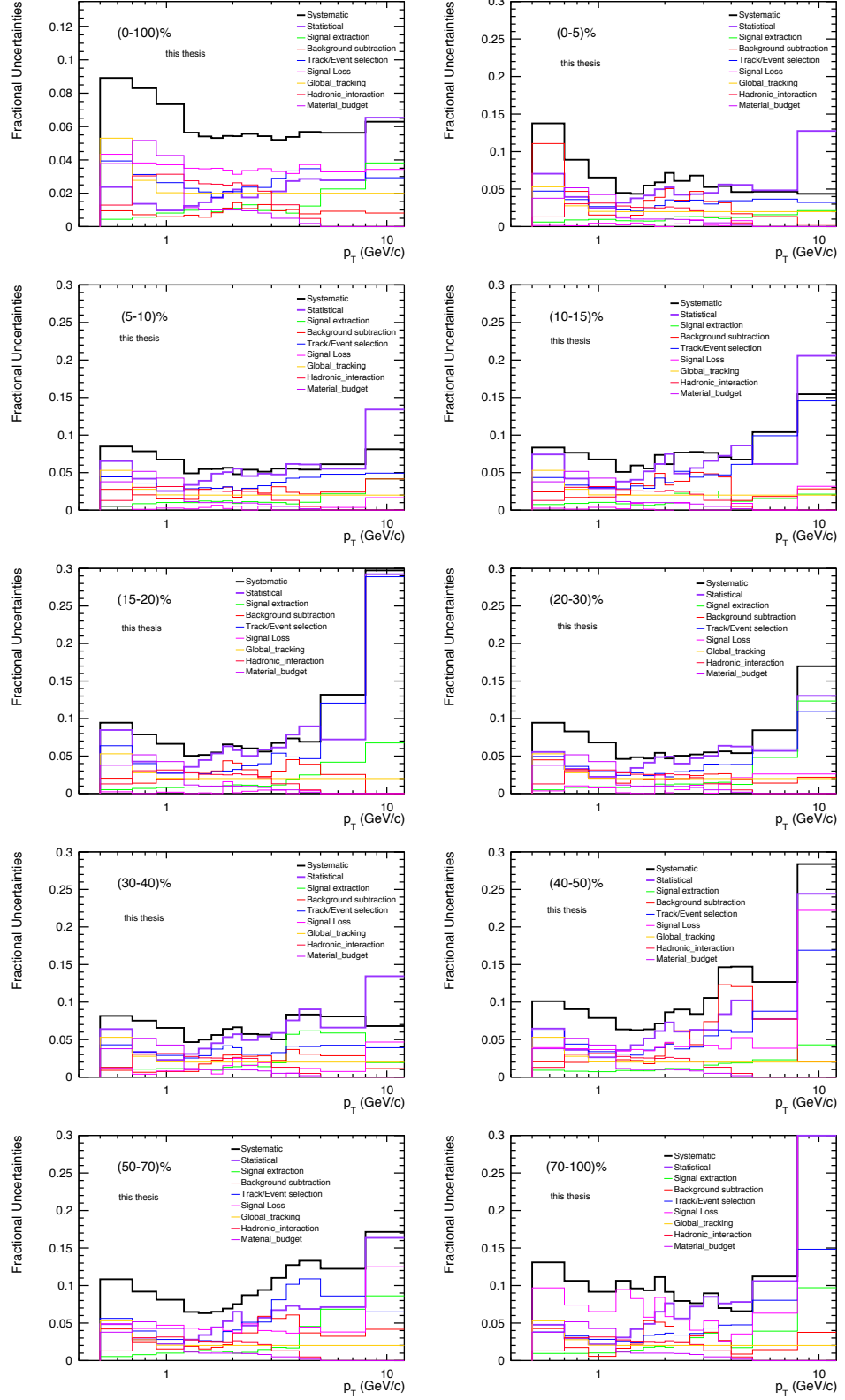


Figure 4.12: (Color Online) Fractional uncertainties from all the sources as a function of p_T for different multiplicity classes [26].

The Lévy-Tsallis function fit is also done for different p_T ranges such as: $0.5 < p_T < 3.3$ GeV/c, $0.5 < p_T < 3.5$ GeV/c and $0.5 < p_T <$

3.7 GeV/c and they are included for the calculation of systematic uncertainty in integrated yield and mean transverse momentum.

2. An exponential function in p_T :

$$f_0(p_T) = p_T \times A \times (e^{-p_T/T}) \times \frac{e^{M/T}}{T^2 + TM}. \quad (4.4)$$

Here, M is the mass of the ϕ meson and the function is normalized so that the scale parameter A gives its integral. For this fit function, the histogram is only fit over the range $0.5 < p_T < 2.0$ GeV/c. This is included as a systematic uncertainty.

3. A Boltzmann distribution:

$$f_0(p_T) = p_T \times A \times m_T \times (e^{-m_T/T}) \times \frac{e^{M/T}}{2T^3 + 2T^2M + TM^2}. \quad (4.5)$$

As with the closely related m_T -exponential, this function is normalized so that the scale parameter A gives its integral and the fit is only performed over the range $0.5 < p_T < 1.5$ GeV/c. This is included as a systematic uncertainty.

4. An exponential function in m_T :

$$f_0(p_T) = p_T \times A \times (e^{-m_T/T}) \times \frac{e^{M/T}}{T^2 + TM}. \quad (4.6)$$

Here, M is the mass of the ϕ meson, $m_T = \sqrt{M^2 + p_T^2}$ and the function is normalized so that the scale parameter A gives its integral. For this fit function, the histogram is only fit over the range $0.5 < p_T < 1.5$ GeV/c, giving a better fit in the low- p_T region. This is included as a systematic uncertainty.

5. Bose-Einstein: The histogram is fit over the range $0.5 < p_T < 1.5$ GeV/c using a Bose-Einstein distribution:

$$f_0(p_T) = p_T \times A \times \frac{1}{e^{m_T/T} - 1} \times (e^{M/T} - 1), \quad (4.7)$$

Table 4.4: Fitting parameters for fits for (0-100)% multiplicity class.

Fit Functions	Fit range	A	n	T (GeV)
Levy-Tsallis	0.5-3.3	0.0400 ± 0.0014	6.807 ± 1.041	0.2990 ± 0.0234
Levy-Tsallis	0.5-3.7	0.0400 ± 0.0014	6.807 ± 1.041	0.2990 ± 0.0234
Levy-Tsallis	0.5-12.0	0.039 ± 0.001	7.569 ± 0.281	0.3120 ± 0.0101
m_T exponential	0.5-1.5	0.036 ± 0.001	—	0.356 ± 0.019
p_T exponential	0.5-2.0	0.0170 ± 0.0006	—	0.5130 ± 0.0164
Boltzmann	0.5-1.5	0.053 ± 0.002	—	0.356 ± 0.019
Bose-Einstein	0.5-1.5	0.192 ± 0.016	—	0.3630 ± 0.0202

The function is normalized so that when the pre-factor of p_T is removed, each has a value of A at $p_T = 0$. These fittings are included as systematic uncertainty.

6. Power-law function: The histogram is fit for $3.0 < p_T < 12.0$ GeV/c with a power-law function:

$$f_0(p_T) = p_T \times A \times (1 + p_T/T)^{-n}. \quad (4.8)$$

Figure 4.13 shows the fitting of listed functions to one of the multiplicity classes (0-100)% as an example. Each fit is performed twice. First, each spectrum is fit with the statistical and systematic uncertainty for each point added in quadrature; collectively, these set of fits will be denoted as $f(p_T)$. Second, each spectrum is fit using only its statistical uncertainties; collectively, this set of fits will be denoted $f'(p_T)$. The set f is the primary set of fits and will be used to extract dN/dy and $\langle p_T \rangle$. The set f' is used in the calculation of the statistical uncertainties of those quantities, as explained in subsequent sections.

Total dN/dy

dN/dy is calculated by integrating the histogram (which spans the range $0.5 < p_T < 12$ GeV/c) and using the spectrum fit $f(p_T)$ described in Section 4.2.8 to extrapolate the yield to the low and high- p_T regions outside the measured range. The central value is calculated using Lévy-Tsallis function which spans the range $0.5 < p_T < 3.3$ GeV/c and the function is

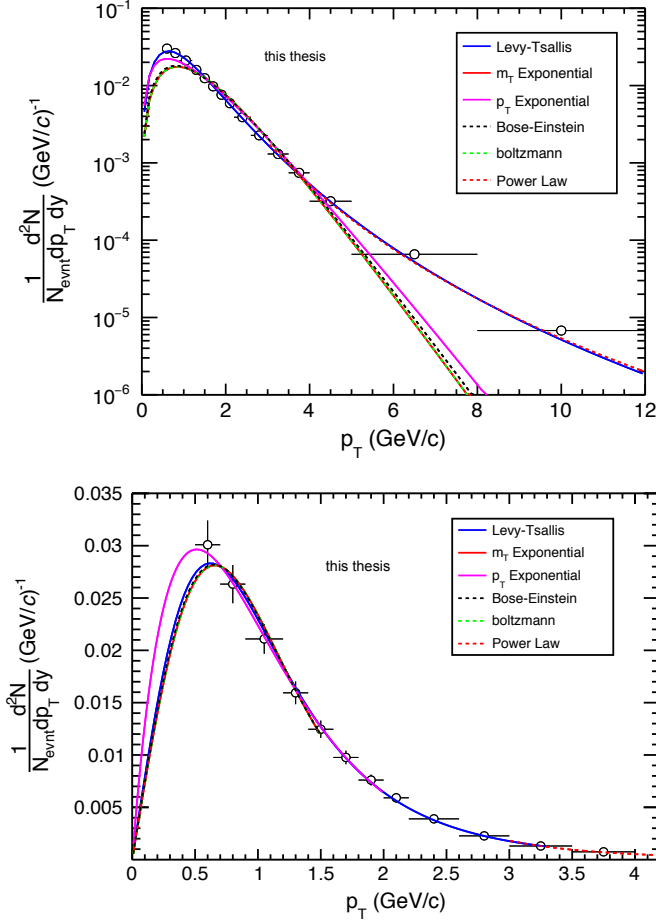


Figure 4.13: (Color Online) **Upper Plot:** Corrected ϕ spectrum with fits over the range $0 < p_T < 12$ GeV/c for (0-100)% multiplicity class, **Lower Plot:** Corrected ϕ spectrum with default fitting ranges for (0-100)% multiplicity class [26].

extrapolated to 0 GeV/c. The extrapolated region accounts for 24.7% of dN/dy in (0-100)% multiplicity class.

The following methods are used to calculate the statistical uncertainties. Low- and high- p_T extrapolation histograms with narrow bins (0.05 GeV/c wide) are generated using the spectrum fit f' . The statistical uncertainties of the bin contents of these histograms are determined using ROOT's `TF1::IntegralError()` function. A large number (1000) of alternate histograms are randomly generated by shifting the points in the measured and extrapolation histograms. A random factor k is generated from a Gaussian with mean 0 and $\sigma = 1$. Each of the measured bins is shifted independently (*i.e.*, a different k factor is generated for each bin). All of the bins in the low- p_T extrapolation histogram are shifted coherently

using the same k factor, and similarly for the high- p_T extrapolation histogram. For each iteration, the three alternate (random) histograms are integrated and the total dN/dy is stored. The mean (μ_{alt}) and standard deviation (σ_{alt}) of the set of 1000 alternate values are found. The statistical uncertainty in the default value of dN/dy is

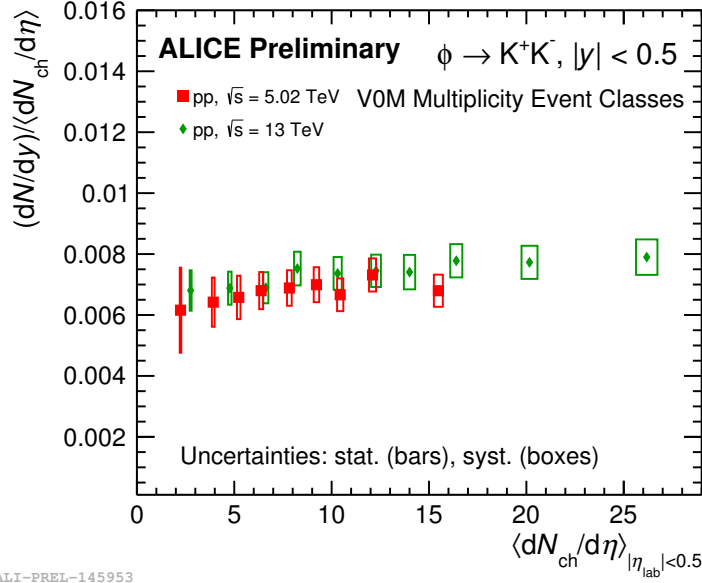
$$\sigma(dN/dy) = (dN/dy) \times \frac{\sigma_{\text{alt}}}{\mu_{\text{alt}}}. \quad (4.9)$$

The **systematic uncertainties** in dN/dy due to the uncertainties in the p_T spectrum are calculated using an extreme fit method. As an example, the calculation of the material budget uncertainty will be described. Four extreme histograms (extreme low, extreme high, extreme soft, and extreme hard) are generated by shifting the points of the p_T spectrum down or up by their material budget uncertainties. These shifted spectra are fit and alternate dN/dy values are calculated. These values are compared to the default value and the maximum difference is taken as the systematic uncertainty. The same procedure is repeated separately for all other uncertainties in Section 4.2.7.

The systematic uncertainty due to the choice of spectrum fit function (to find the yield in the extrapolation region) is calculated by comparing dN/dy measured using the other fit scenarios (described in Section 4.2.8) with Lévy-Tsallis function fit as a central value. Also, the Lévy-Tsallis function fit is also varied for different p_T ranges. The maximum difference due to different fits are considered as the systematic uncertainty due to extrapolation, which ranges from 15% to 40% of the total systematic uncertainty.

All of the systematic uncertainties considered are added in quadrature, giving the total systematic uncertainty in dN/dy . The value of dN/dy for ϕ mesons in pp collisions at $\sqrt{s} = 5.02$ TeV for different multiplicity classes are shown in Table 4.5.

Fig 4.14 shows the integrated yield as a function of charged particle multiplicity. It is observed that the the Integrated yield normalized to



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Figure 4.14: Integrated yield normalized to charged particle multiplicity as a function of charged particle multiplicity compared with $\sqrt{s} = 13$ TeV. The boxes show the systematic uncertainty and the bars are the statistical uncertainties [26].

charged particle multiplicity is independent of charged particle multiplicity and this is independent of collision energies. This indicates that the ϕ production at the LHC energies is driven by the final state multiplicity.

Mean Transverse Momentum

In general, the mean transverse momentum of the function f over the range $A < p_T < B$ is

$$\langle p_T \rangle_A^B = \frac{\int_A^B p_T \times f(p_T) dp_T}{\int_A^B f(p_T) dp_T}. \quad (4.10)$$

The $\langle p_T \rangle$ is calculated using only the spectrum fits (the “fit method”, $\mathbf{iqF}$), using equation 4.10 with $A = 0$ and $B = 12$ GeV/c. The default function to calculate $\langle p_T \rangle$ is Lévy-Tsallis function.

The **statistical uncertainty** of $\langle p_T \rangle$ is calculated using a procedure similar to the calculation for dN/dy . The measured and extrapolated his-

tograms are shifted randomly (based on their statistical uncertainties) to generate 1000 alternate histograms. The values of $\langle p_T \rangle$ for these alternate histograms are recorded and the mean and standard deviation of the alternate set are found. The statistical uncertainty in the default value of $\langle p_T \rangle$ is

$$\sigma(\langle p_T \rangle) = (\langle p_T \rangle) \times \frac{\sigma_{\text{alt}}}{\mu_{\text{alt}}}. \quad (4.11)$$

The procedure used to evaluate the **systematic uncertainties** of $\langle p_T \rangle$ is essentially the same as the procedure described in Section 4.2.8. The systematic uncertainty due to extrapolation has been calculated and it has been added to the total systematic uncertainty.

All of the systematic uncertainties considered are added in quadrature, giving the total systematic uncertainty in $\langle p_T \rangle$. The value of $\langle p_T \rangle$ for ϕ mesons in pp collisions at $\sqrt{s} = 5.02$ TeV for different multiplicity classes are shown in Table 4.5. Fig 4.15 shows the $\langle p_T \rangle$ as a function of charged particle multiplicity. It is observed that the $\langle p_T \rangle$ for ϕ is independent of collision energy within the uncertainties.

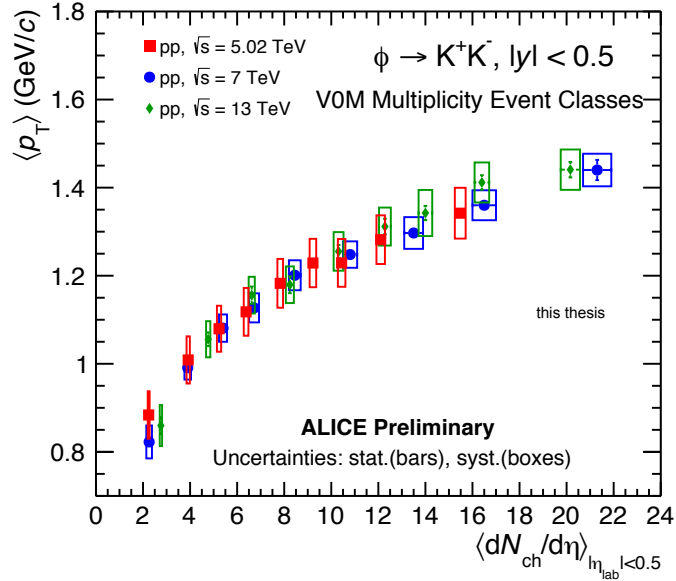


Figure 4.15: $\langle p_T \rangle$ as a function of charged particle multiplicity compared with $\sqrt{s} = 7$ and 13 TeV. The boxes show the systematic uncertainty and the bars are the statistical uncertainties [26].

Table 4.5: dN/dy and $\langle p_T \rangle$ of ϕ mesons in different multiplicity classes. The first uncertainty is statistical and the second is systematic uncertainty.

Multiplicity (%)	dN/dy	$\langle p_T \rangle$ (GeV/c)
0-5	$0.1052 \pm 0.0014 \pm 0.0081$	$1.3540 \pm 0.0103 \pm 0.0580$
5-10	$0.0884 \pm 0.0013 \pm 0.0065$	$1.2940 \pm 0.0112 \pm 0.0560$
10-15	$0.0695 \pm 0.0011 \pm 0.0055$	$1.2390 \pm 0.0119 \pm 0.0560$
15-20	$0.0643 \pm 0.0011 \pm 0.0052$	$1.2360 \pm 0.0123 \pm 0.0550$
20-30	$0.0537 \pm 0.0007 \pm 0.0045$	$1.1950 \pm 0.0092 \pm 0.0560$
30-40	$0.0430 \pm 0.0006 \pm 0.0038$	$1.1310 \pm 0.0100 \pm 0.0550$
40-50	$0.0337 \pm 0.0006 \pm 0.0036$	$1.0720 \pm 0.0113 \pm 0.0570$
50-70	$0.0239 \pm 0.0004 \pm 0.0037$	$1.0050 \pm 0.0090 \pm 0.0560$
70-100	$0.0167 \pm 0.0003 \pm 0.0031$	$0.8550 \pm 0.0093 \pm 0.0550$
0-100	$0.0341 \pm 0.0002 \pm 0.0033$	$1.1470 \pm 0.0044 \pm 0.0570$

4.3 Event shape and Multiplicity dependence of identified particle production in pp collisions with PYTHIA8

4.3.1 Event Generation and Analysis Methodology

PYTHIA is an event generator used to simulate ultra-relativistic collision events at high energies among the particles like $e^\pm$, p , and $\bar{p}$. It is incorporated with many models and theory relevant in physics like hard and soft interactions, parton distributions, initial- and final-state parton showers, multipartonic interactions, fragmentation, color reconnection and decay [11].

In our present study, we have used PYTHIA 8.235, an advanced version of PYTHIA 6 which includes the multi-partonic interaction (MPI) scenario as one of the key improvements. In PYTHIA, MPI scenario is crucial to explain the underlying events, multiplicity distributions and flow-like patterns in terms of color reconnection. The detailed explanation of the physics processes in PYTHIA 8.235 can be found in Ref. [11]. We have implemented the inelastic, non-diffractive component of the total cross-

section for all soft QCD processes (SoftQCD: all = on). This analysis is carried out with 250 million events at $\sqrt{s} = 13$ TeV with Monash 2013 Tune (Tune:14) [14] and MPI based scheme of color reconnection (ColorReconnection:mode(0)). For the generated events we let all the resonances to decay except the ones used in our study (HadronLevel:Decay = on). The event selection criteria throughout the analysis is such that only those events were chosen which have at-least 5 tracks (charged particles). Charged particle multiplicities (N_{ch}) have been chosen in the acceptance of V0 detector in ALICE at the LHC with pseudo-rapidity coverage of V0A ($2.8 < \eta < 5.1$) and V0C ($-3.7 < \eta < -1.7$) [21]. These events are categorized in ten V0 multiplicity (V0M) bins and we define V0M-I as the top 10 percent of events and V0M-X as the lowest 10 percent of events. The number of charged particle multiplicities in each event in different V0M classes are listed in Table 4.6. The minimum bias events are those events where no selection on charged particle multiplicity is applied. To disentangle the jetty and isotropic events from the average-shaped events, we have applied sphericity (defined in next section) cuts on generated events. In this analysis the sphericity distributions are selected in the pseudo-rapidity range of $|\eta| < 0.8$ with a minimum constraint of 5 charged particles with $p_T > 0.15$ GeV/ c . The jetty events are those having $0 \leq S_0 < 0.29$ with lowest 20 percent and the isotropic events are those having $0.64 < S_0 \leq 1$ with highest 20 percent of the total events [21].

Table 4.6: V0M multiplicity classes and the corresponding charged particle multiplicities

V0M class	I	II	III	IV	V	VI	VII	VIII	IX	X
N_{ch}	50-140	42-49	36-41	31-35	27-30	23-26	19-22	15-18	10-14	0-9

4.3.2 Transverse spherocity, Multi-partonic interactions and Charged particle multiplicity

Transverse spherocity for an event is defined for a unit vector $\hat{n}(n_T, 0)$ which minimizes the following ratio [7, 8, 17]:

$$S_0 = \frac{\pi^2}{4} \left(\frac{\sum_i \vec{p}_{T_i} \times \hat{n}}{\sum_i p_{T_i}} \right)^2. \quad (4.12)$$

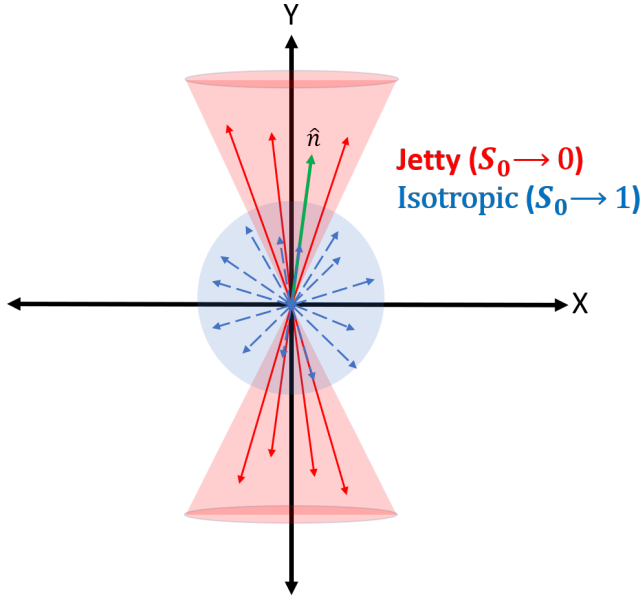


Figure 4.16: Depiction of jetty and isotropic events in the transverse plane [18].

By restricting it to transverse plane, spherocity becomes infrared and collinear safe [19]. By construction, the extreme limits of spherocity are related to specific configurations of events in transverse plane. The limit of spherocity is in between 0 to 1. Spherocity becoming 0 would mean that the events are pencil-like (back-to-back structure) while 1 would mean the events are isotropic. The pencil-like events are hard events while the isotropic events are the result of soft processes. Figure 4.16 depicts the jetty and isotropic events in the transverse plane.

Left (Right) panel of fig. 4.17 shows the correlation between the spherocity (nMPI) with charged particle multiplicity. A clear charged particle multiplicity dependence of spherocity and nMPI distributions is observed.

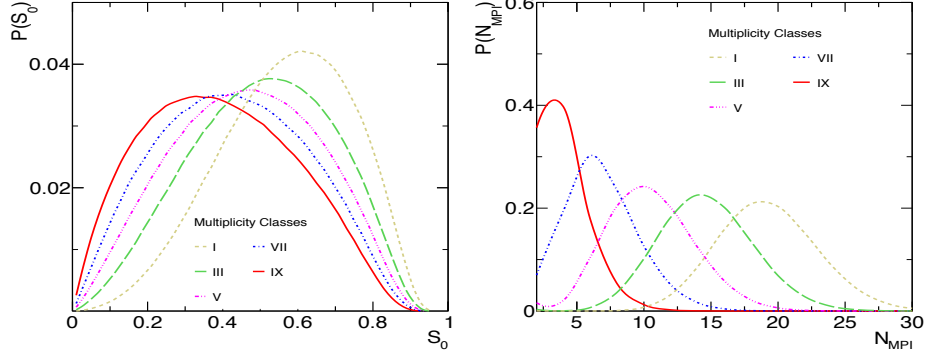


Figure 4.17: (Color Online) Sphericity (Left panel) and nMPI (Right Panel) distributions for different charged particle multiplicity in pp collisions at $\sqrt{s} = 13$ TeV. Different line styles and colors are for different multiplicity classes [18].

As we move from low to high multiplicity events, the peak of the sphericity distribution shifts towards right. This indicates that the high multiplicity pp collisions are dominated by isotropic events while the low multiplicity events are dominated by the jetty ones. The nMPI distributions suggest that large number of multi-partonic interactions occur for high multiplicity pp collisions. From fig. 4.17 one observes that the width of the nMPI distribution increases from lower to higher multiplicity classes making it squat, whereas the height goes down. For all multiplicity classes the distribution seems to be positively skewed. For a given class of multiplicity, as nMPI follows a distribution and towards high-multiplicity it shows a saturation behaviour [8], event multiplicity and nMPI can't be used uniquely to classify events in pp collisions. We observe larger number of average nMPIs for isotropic events than the jetty events. It is evident from event shape analysis that sphericity along with the charged particle multiplicity (which is correlated with nMPI) should be preferred for a better selectivity of events. We use the sphericity distribution shown in fig. 4.17 to make a clear distinction between isotropic and jetty events. Further combining sphericity with event multiplicity, we study various observables as discussed in the following section to understand the dynamics of particle production in pp collisions at $\sqrt{s} = 13$ TeV.

4.3.3 Results and Discussion

As discussed in the previous section, we use sphericity as a tool to distinguish the isotropic and jetty events for each multiplicity class. We study the p_T -spectra, integrated yield, mean transverse momentum for $(\pi^+ + \pi^-)$, $(K^+ + K^-)$, K^{*0} , $(p + \bar{p})$, ϕ , $(\Lambda + \bar{\Lambda})$ as a function of sphericity and charged particle multiplicity. We also study the p_T -differential and p_T -integrated particle ratios to $(\pi^+ + \pi^-)$ and $(K^+ + K^-)$ and $(p + \bar{p})$ to ϕ ratio as a function of sphericity for high multiplicity pp collisions. From here onwards, $(\pi^+ + \pi^-)$, $(K^+ + K^-)$, $(p + \bar{p})$ and $(\Lambda + \bar{\Lambda})$ are denoted as pion (π), kaon (K), proton (p) and Λ , respectively.

p_T -spectra

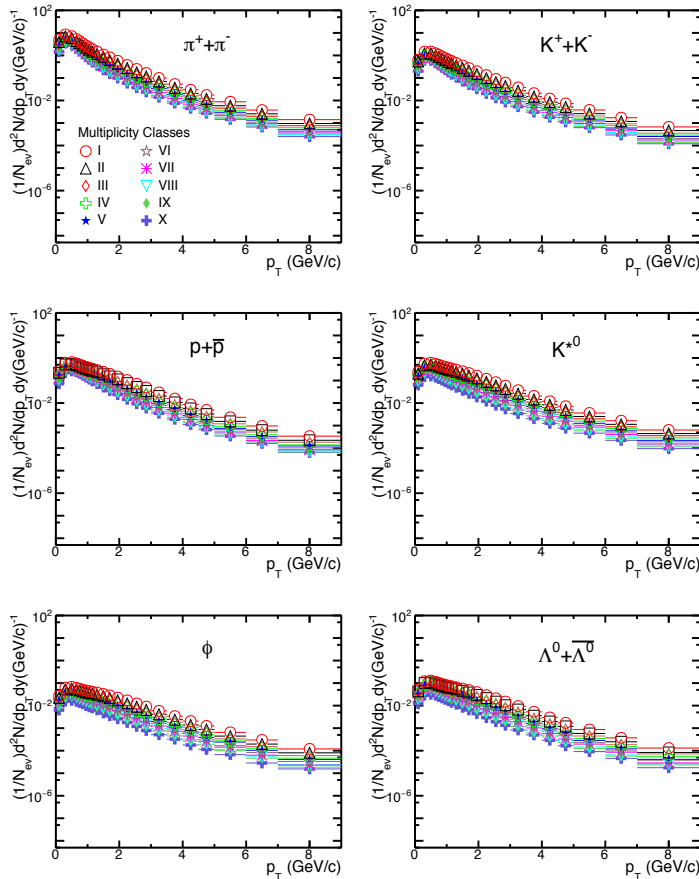


Figure 4.18: (Color online) p_T -spectra for light-flavor hadrons like pion, kaon, K^{*0} , proton, ϕ , and Λ at mid-rapidity ($|\eta| < 0.5$) as a function of charged particle multiplicity for pp collisions at $\sqrt{s} = 13$ TeV. Different markers and colors correspond to different multiplicity classes [18].

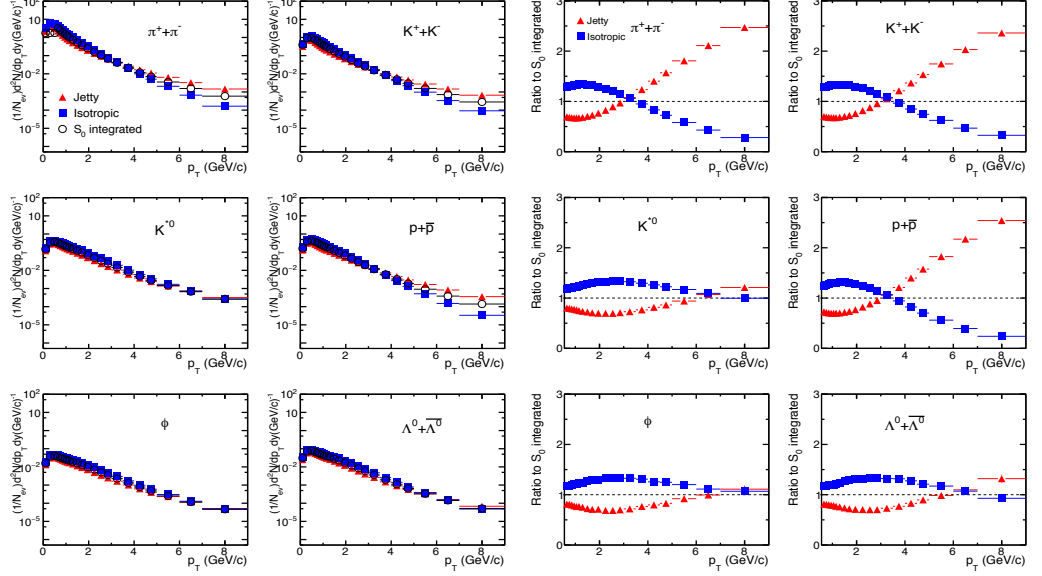


Figure 4.19: (Color online) Left Panel: p_T -spectra for pion, kaon, K^{*0} , proton, ϕ , and Λ for minimum bias pp collisions as a function of sphericity. The blue squares are for isotropic events and red triangles are for jetty events and open circles are for S_0 integrated events. Right Panel: Ratio of p_T -spectra for isotropic and jetty events to the sphericity integrated events [18].

Figure 4.18 shows the p_T -spectra for pion, kaon, K^{*0} , proton, ϕ and Λ at mid-rapidity ($|\eta| < 0.5$) for different multiplicity classes in pp collisions at $\sqrt{s} = 13$ TeV. We observe a clear multiplicity dependence of the spectral shapes. As we move from low to high charged particle multiplicity, we observe hardening of p_T -spectra while the bulk production is similar for all the multiplicity classes. This trend is similar to that in experimental data from ALICE [20] for multiplicity dependence study in pp collisions at $\sqrt{s} = 7$ TeV.

Left panel of Fig. 4.19 shows the sphericity dependence of p_T -spectra of identified particles for minimum bias pp collisions. The right panel shows the ratio of p_T -spectra for isotropic and jetty events to the sphericity integrated events. We observe the crossing of the ratios for pions, kaons and protons at around 3 GeV/c while for other particles we do not observe the crossing of ratios till 6 GeV/c. This suggests that for minimum bias pp collisions, the production of pions, kaons and protons at low p_T are dominated by isotropic events while after 3 GeV/c, the production is dominated

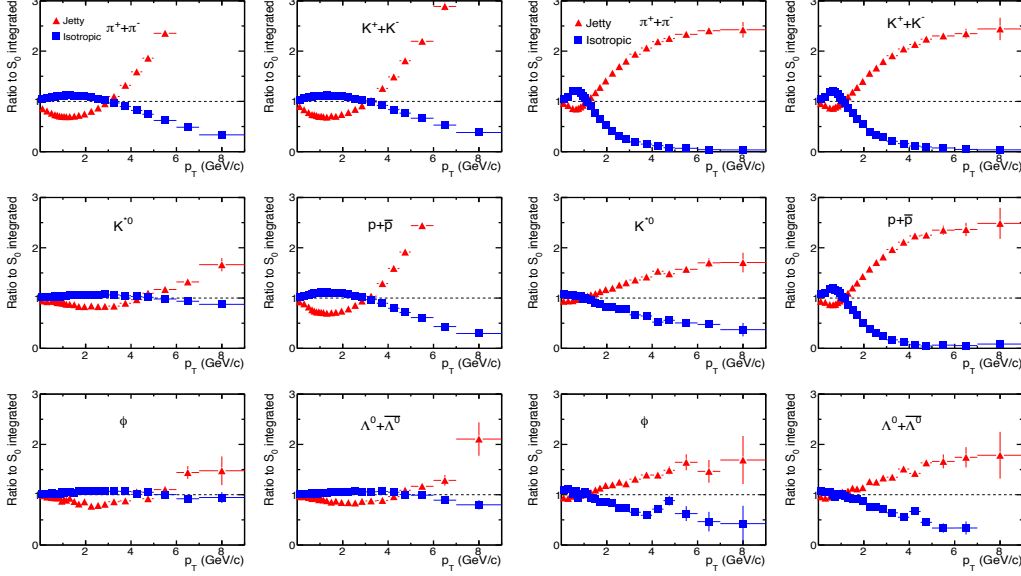


Figure 4.20: (Color online) Ratio of p_T -spectra for isotropic and jetty events to the sphericity integrated events for V0M-I (left) and V0M-X (right) multiplicity class. The blue squares are for isotropic events and red triangles are for jetty events [18].

by jetty events. For resonances (K^{*0} and ϕ) and Λ , the production is dominated by isotropic events till 5 GeV/c, which indicate different production mechanisms for resonances and heavier particles compared to pions, kaons and protons.

Figure 4.20 shows the ratio of p_T -spectra for isotropic and jetty events to the sphericity integrated events for V0M-I (left) and V0M-X (right) multiplicity classes. To see the effect of multiplicity on the crossing point of jetty and isotropic events, we have taken the lowest (V0M-X) and the highest (V0M-I) multiplicity classes for a comparison. For stable particles like, π , K and p , the crossing point moves towards high- p_T , while going from low (~ 1 GeV/c) to high multiplicity classes (~ 3 GeV/c). This indicates that particle production in high-multiplicity collisions are dominated by isotropic events whereas in low multiplicity it is dominated by jetty events. The preliminary results from ALICE [21] shows a mass dependence of the crossing points for high multiplicity pp collisions which could be attributed to flow-like behavior. Although the color reconnection in PYTHIA mimics a flow-like behavior [22], we do not observe mass dependence of crossing points with the default color reconnection setting. Similar to the results

from minimum bias pp collisions, we observe crossing points for resonances and Λ at higher- p_T (around 6 GeV/c) for V0M-I class. However, we observe the crossing point for low multiplicity pp collisions (V0M-X class) is similar for all particles, i.e. around 1 GeV/c.

Integrated yields (dN/dy)

Figure 4.21 shows the dN/dy of pions, kaons, K^{*0} , protons, ϕ , and Λ at mid-rapidity ($|\eta| < 0.5$) as a function of charged particle multiplicity for isotropic, jetty and spherocity integrated events for pp collisions at $\sqrt{s} = 13$ TeV. Pion being the lightest particle, the integrated yield is the maximum compared to other particles. The mass and charged particle multiplicity dependence of integrated yield for spherocity integrated events is similar to the experimental data from ALICE [20] for multiplicity dependence study in pp collisions at $\sqrt{s} = 7$ TeV. As it appears, in low-multiplicity classes, the effect of spherocity is minimal, whereas towards higher-multiplicity classes, it starts playing a role in making a separation of jetty to isotropic events for all identified particles. The contribution to integrated yield is always dominated by the isotropic events but we observe significant contributions from jetty events as well. As we have observed in the left panel of fig. 4.17, the contribution to dN/dy from jetty events decreases with charged particle multiplicity. The right panel of fig. 4.21 shows the spherocity integrated-scaled yield as a function of minimum-bias-scaled charged particle multiplicity. Slowly towards higher multiplicity classes, a clear separation of jetty to isotropic events is observed. The separation however is the highest for the lightest meson, π .

Mean Transverse Momentum ($\langle p_T \rangle$)

The $\langle p_T \rangle$ of pions, kaons, K^{*0} , protons, ϕ , and Λ at mid-rapidity ($|\eta| < 0.5$) as a function of charged particle multiplicity for isotropic, jetty and spherocity integrated events are shown in fig. 4.22. For pions, kaons and protons we observe that the $\langle p_T \rangle$ is higher for jetty events compared to the

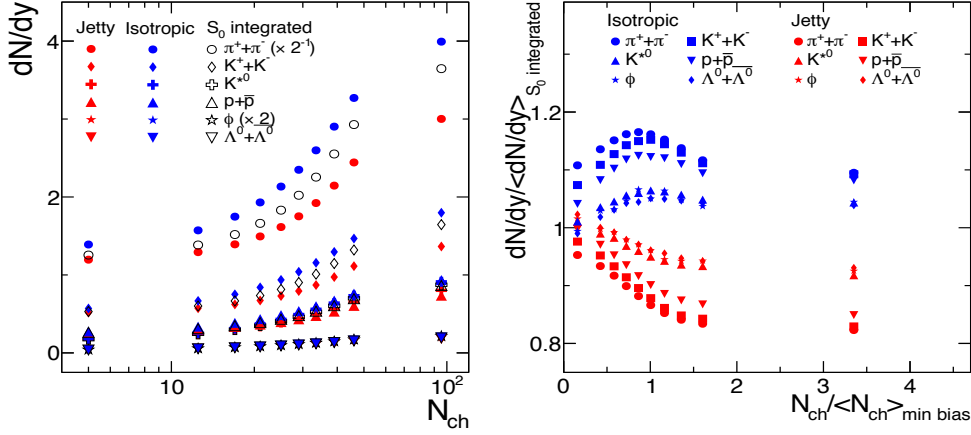


Figure 4.21: (Color online) Left: Integrated yield (dN/dy) of pions, kaons, K^{*0} , protons, ϕ , and Λ at mid-rapidity ($|\eta| < 0.5$) as a function of charged particle multiplicity for isotropic (blue squares), jetty (red triangles) and spherocity integrated (open circles) events. Right: The spherocity-integrated-scaled yield showing a separation of jetty and isotropic events towards high multiplicity classes in pp collisions [18].

isotropic events for all the multiplicity classes. This is one of the reasons that one should use spherocity as a selective parameter along with the charged particle multiplicity. However, we see significant differences in $\langle p_T \rangle$ for other particles at only low multiplicity classes but the $\langle p_T \rangle$ remains spherocity independent for high multiplicity pp collisions for resonances and Λ .

After studying these observables in details, let us now focus on the highest multiplicity class, which is of special importance to us, for understanding the spherocity dependent p_T -differential particle ratios.

Particle Ratios

Figure 4.23 shows the p_T -differential particle ratio to pions for high multiplicity pp collisions in isotropic, jetty and spherocity integrated events. The trend of particle ratios involving K^{*0} and ϕ for S_0 -integrated events are similar to that of experimental data in pp collisions at $\sqrt{s} = 13$ TeV [23]. The kaon to pion and proton to pion ratios seem to be independent of spherocity classes but we observe a clear spherocity dependence of K^{*0} , ϕ and Λ to pion ratio as a function of p_T . This effect could be due to

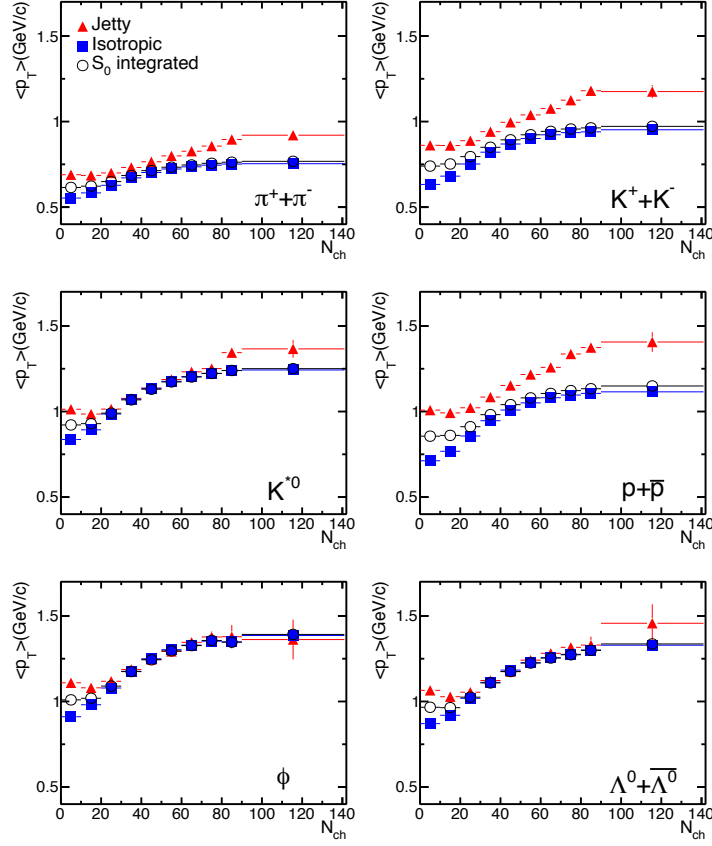


Figure 4.22: Mean transverse momentum ($\langle p_T \rangle$) of pions, kaons, K^{*0} , protons, ϕ , and Λ at mid-rapidity ($|\eta| < 0.5$) as a function of charged particle multiplicity for isotropic (blue squares), jetty (red triangles) and sphericity integrated (open circles) events [18].

color reconnection (CR), as lower mass strings are produced more which are less likely to have enough energy during fragmentation to create massive hadrons like resonances. At low- p_T , the dependence on sphericity is negligible for all identified particles. However, at high- p_T the ratios of K^{*0} , ϕ and Λ to pion are higher for isotropic events as compared to jetty events. Considering kaon to pion ratio as a measure of strangeness enhancement, although we see a p_T -dependent strangeness production, this seems to be independent of event sphericity. Further the proton to pion ratio, which is a measure of baryon to meson ratio, is independent of event sphericity. This ratio increases up to $p_T \sim 3-4$ GeV/c and then decreases towards higher- p_T making the high- p_T domain meson rich. This is similar to the experimental observations [28, 29]. For the ratios of K^{*0} , ϕ and Λ to pions, the sphericity integrated events show a p_T -independent behavior after

around 2 GeV/c, whereas for isotropic events these ratios show a sharp rise. These observations open up new domain of studies, which may shed light on particle production mechanisms taking event multiplicity, sphericity and p_T -differential particle ratios.

The p_T -differential particle ratios to kaons for high multiplicity pp collisions in isotropic, jetty and sphericity integrated events are shown in fig. 4.24. The proton to kaon ratio seems to be independent of sphericity classes up to $p_T \sim 9$ GeV/c. But we observe a clear sphericity dependence of K^{*0} , ϕ and Λ to kaon ratios as a function of p_T . At low- p_T , the K^{*0} , ϕ and Λ to kaon ratios are higher for jetty events and also lower for isotropic events compared to the sphericity-integrated events. However, at high p_T a complete opposite behavior is observed. And this behavior is similar to particle ratio with respect to pions.

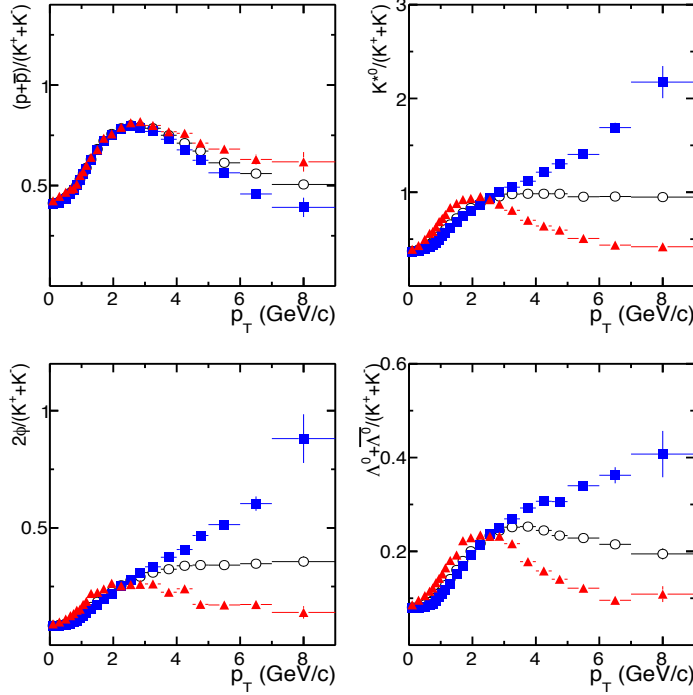


Figure 4.24: (Color Online) p_T -differential particle ratio to kaons for high multiplicity pp collisions in isotropic (blue squares), jetty (red triangles) and sphericity integrated (open circles) events [18].

Figure 4.25 shows the p_T -differential particle ratio of proton to ϕ for minimum bias (left panel) and high multiplicity (right panel) pp collisions in isotropic, jetty and sphericity integrated events. Assuming QGP-like

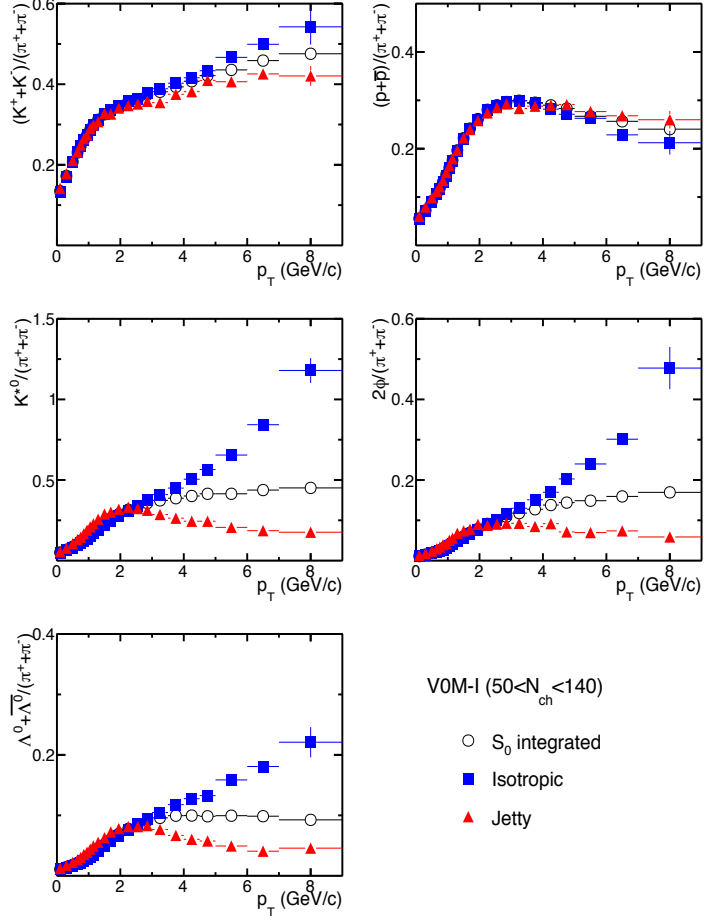


Figure 4.23: (Color Online) p_T -differential particle ratio to pions for high multiplicity pp collisions in isotropic (blue squares), jetty (red triangles) and sphericity integrated (open circles) events [18].

behavior is driven by hydrodynamics, one would expect similar shape of p_T spectra at low- p_T for proton and ϕ due to their similar masses [44]. A comparison of p/ϕ ratio in minimum bias and high multiplicity pp collisions shows a flatness at low- p_T in isotropic events for high-multiplicity pp collisions. This hints to the QGP-like behavior in high multiplicity pp collisions, which might be produced due to the CR in Pythia. It is worth noticing that at low- p_T the p/ϕ ratio for isotropic events are more flatter compared to the S_0 -integrated ones. This leads to an interesting finding that while comparing the experimental p/ϕ ratio from high multiplicity pp collisions to the heavy-ion data [45], one should separate jetty events from all the events.

To have a direct comparison to experimental measurements, let us

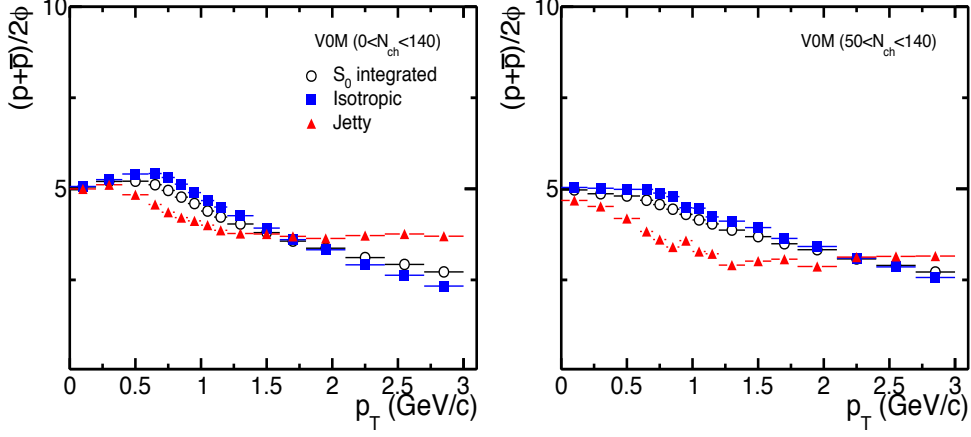


Figure 4.25: (Color Online) p_T -differential particle ratio of proton to ϕ for minimum bias (left panel) and high multiplicity (right panel) pp collisions in isotropic (blue squares), jetty (red triangles) and sphericity integrated (open circles) events [18].

now consider the p_T -integrated particle ratios with respect to pions and kaons as a function of sphericity classes and charged particle multiplicity. Left (Right) panel of fig. 4.26 shows p_T -integrated particle ratio to pions (kaons) for high multiplicity pp collisions in isotropic, jetty and sphericity integrated events. Although, we observe significant sphericity dependence of integrated yield of different particles (fig. 4.21), we do not observe any large dependence of p_T -integrated particle ratios to pions and kaons. This suggests that the relative increase in integrated yield for different particles as a function of sphericity are similar, while indicating that the domain of transverse momentum is very crucial for the nature of particle production. As expected, the ratios of particles with respect to lighter mass particle seem to increase with charged particle multiplicity. The slight increasing trend of K/π , K^{*0}/π and Λ/π suggests strangeness enhancement in high multiplicity pp collisions [1]. The trend of p_T -integrated particle ratios for ϕ to π and ϕ to K in S_0 -integrated events is similar to that of experimental data in pp collisions at $\sqrt{s} = 13$ TeV [30]. Due to possible re-scattering effects, the experimental data for K^{*0}/K decreases with charged particle multiplicity [30]. But we do not observe the same trend, which indicates that PYTHIA fails to explain the possible re-scattering effects. While comparing the upper and lower panel of fig. 4.26, one can observe that

although the sphericity dependence on the particle ratio is not high but the dependence seem to be opposite compared to integrated yield in fig. 4.21. For all the identified particle ratios to pions and kaons, the contribution from jetty events are higher compared to the isotropic ones. This leads to the conclusion that while studying the QGP-like behavior in pp collisions, one should separate the jetty events from the total events.

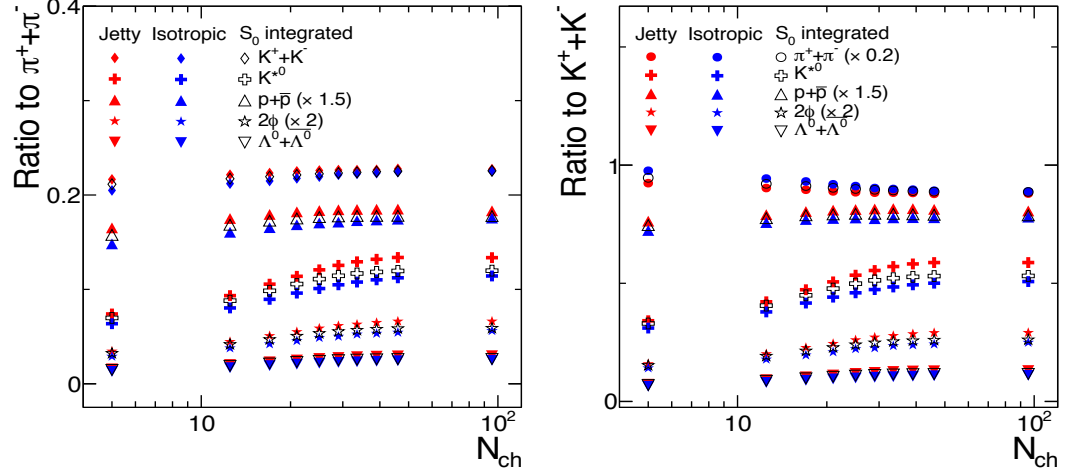


Figure 4.26: (Color Online) p_T -integrated particle ratio to pions (left panel) and kaons (right panel) for high multiplicity pp collisions in isotropic (blue squares), jetty (red triangles) and sphericity integrated (open circles) events [18].

As one can observe throughout the studies discussed here, the resonance particles, namely K^{*0} , ϕ behave differently for all the observables. This hints for further investigation related to the production mechanism of resonances both in pp and heavy-ion collisions.

The present studies in view of the high-multiplicity era of pp collisions at the LHC energies bear high-level of importance in view of a possible QGP-like medium formation in pp collisions, while giving enough differential information about particle production mechanism taking into account event multiplicity, event sphericity, the transverse momentum and multi-partonic interactions. Availability of experimental data in near future would help us having a better understanding of underlying physics behind the high-multiplicity pp collisions at the LHC energies. In addition, these studies should help in fine-tuning the pQCD based event generators, while

comparing similar findings in experimental data. Keeping this in mind, we try to understand the ϕ production as a function of transverse sphericity and charged-particle multiplicity in the next section.

4.4 Event shape dependence of ϕ production in pp collisions at $\sqrt{s} = 5.02$ TeV with ALICE

As discussed in the first section, we have ten charged-particle multiplicity classes. But to ensure we have decent statistics for sphericity dependent studies, here (0-10)%, (10-30)%, (30-60)% and (60-100)% V0M multiplicity classes are used.

4.5 Sphericity Selection

Figure 4.27 shows the event statistics after implementing all the above event-selection cuts for the sphericity dependent analysis. The fourth bin shows the total number of accepted events for this analysis, which is around 105 M events out of 120 M events.

Following cuts were used for sphericity calculation, which is similar to the analysis of charged particle production as a function of sphericity in pp collisions at $\sqrt{s} = 13$ TeV [31] and analysis of identified particle production as a function of sphericity in pp collisions at $\sqrt{s} = 13$ TeV [32]. For this analysis, the minimum number of required tracks for sphericity calculation are 3. The track cuts for the sphericity calculations are listed below.

1. minimum number of clusters in TPC: 50
2. maximum χ^2 per cluster in TPC: $\chi^2_{\text{TPC}} < 4$
3. reject kink daughters

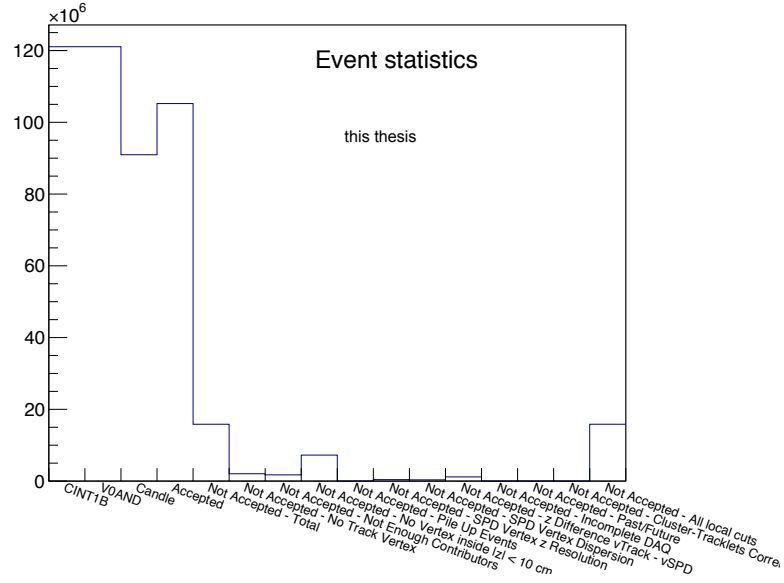


Figure 4.27: Event statistics after implementing event-selection cuts for the sphericity analysis. The fourth bin shows the total number of accepted events [27].

Table 4.7: Range for jetty and isotropic events in sphericity distribution in pp collisions at $\sqrt{s} = 5.02$ TeV

Multiplicity (V0M)	Isotropic	Jetty
(0-10)%	$0.73 \leq S_0 \leq 1$	$0 \leq S_0 \leq 0.43$
(10-30)%	$0.68 \leq S_0 \leq 1$	$0 \leq S_0 \leq 0.32$
(30-60)%	$0.62 \leq S_0 \leq 1$	$0 \leq S_0 \leq 0.24$
(60-100)%	$0.56 \leq S_0 \leq 1$	$0 \leq S_0 \leq 0.18$
(0-100)%	$0.64 \leq S_0 \leq 1$	$0 \leq S_0 \leq 0.25$

4. require ITS refits
5. require TPC refits
6. $|DCA_z| < 3.2$ cm
7. $|DCA_{xy}| < 2.4$ cm
8. `AliESDtrackCuts::SetDCAToVertex2D(kFALSE)`
9. $p_{T,track} > 0.15$ GeV/c
10. $|\eta_{track}| < 0.8$

The events which have lowest 20% sphericity events are called as jetty events, while the ones having highest 20% sphericity events are called as

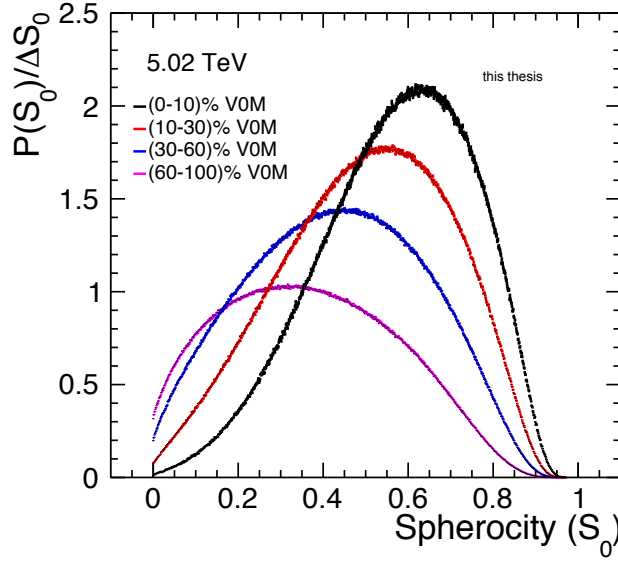


Figure 4.28: (Color Online) Spherocity distribution for different multiplicity classes in pp collisions at $\sqrt{s} = 5.02$ TeV [27].

isotropic events. The spherocity ranges for the jetty and isotropic events are shown in Table 4.7. Figure 4.28 shows spherocity distribution for different multiplicity classes in pp collisions at $\sqrt{s} = 5.02$ TeV. As expected, the lowest multiplicity class is dominated by the jetty events and the highest multiplicity class is dominated by the isotropic events, with isotropic events increasing with event multiplicity.

Figure 4.29 shows one of the representative invariant mass plots, where the event-mixing background-subtracted signals with residual background and peak fits in isotropic events for p_T bins ranging from $0.5 < p_T < 2.6$ GeV/c in pp collisions at $\sqrt{s} = 5.02$ TeV. Similar procedure has been followed for other spherocity and multiplicity classes.

Figure 4.30 shows the raw yield as a function of p_T for different spherocity classes for (0-100)% (upper left), (0-10)% (upper right), (10-30)% (middle left), (30-60)% (middle right), (60-100)% (lower) in pp collisions at $\sqrt{s} = 5.02$ TeV. The errors reported in the plots are statistical only. The behavior of the raw p_T spectra in spherocity integrated, isotropic and jetty events are similar to the one seen in the multiplicity dependent analysis. The comparison of the particle spectra in isotropic, jetty and spherocity

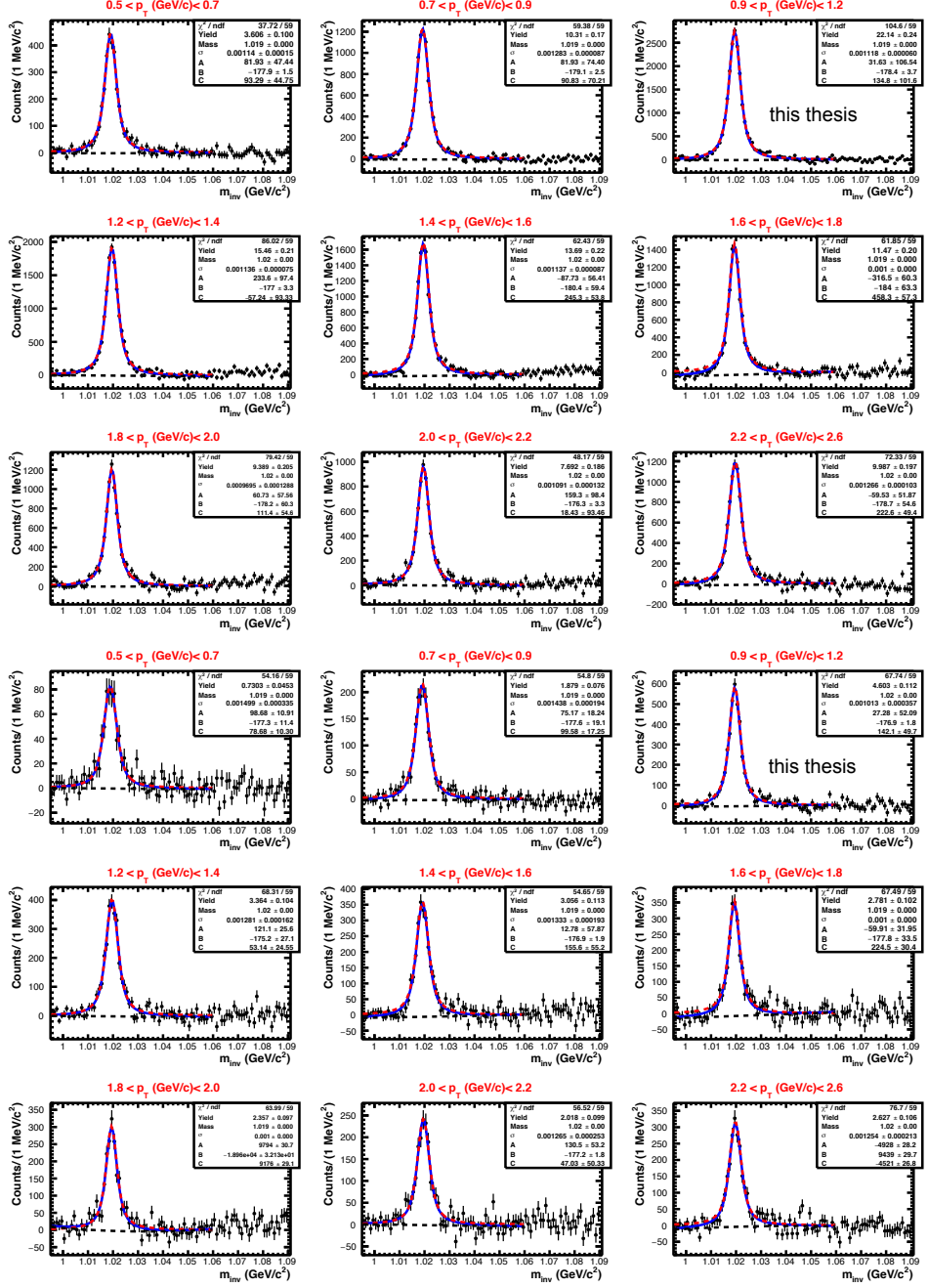


Figure 4.29: (Color Online) Invariant-mass distributions and fits for p_T bins ranging from $0.5 < p_T < 2.6$ GeV/c after event-mixing background subtraction for **isotropic** events for (0-100)% (upper 9 plots) and (0-10)% (lower 9 plots) multiplicity classes in pp collisions at $\sqrt{s} = 5.02$ TeV. The residual background is fitted with 2^{nd} order polynomial. Blue line shows the fitting of signal + residual background. Dotted red line shows the signal and dotted black line shows residual background separately [27].

integrated classes for different multiplicity classes shows that the crossing point of the ratios to sphericity integrated class for isotropic and jetty events depends on the multiplicity. These results can shed light to explore

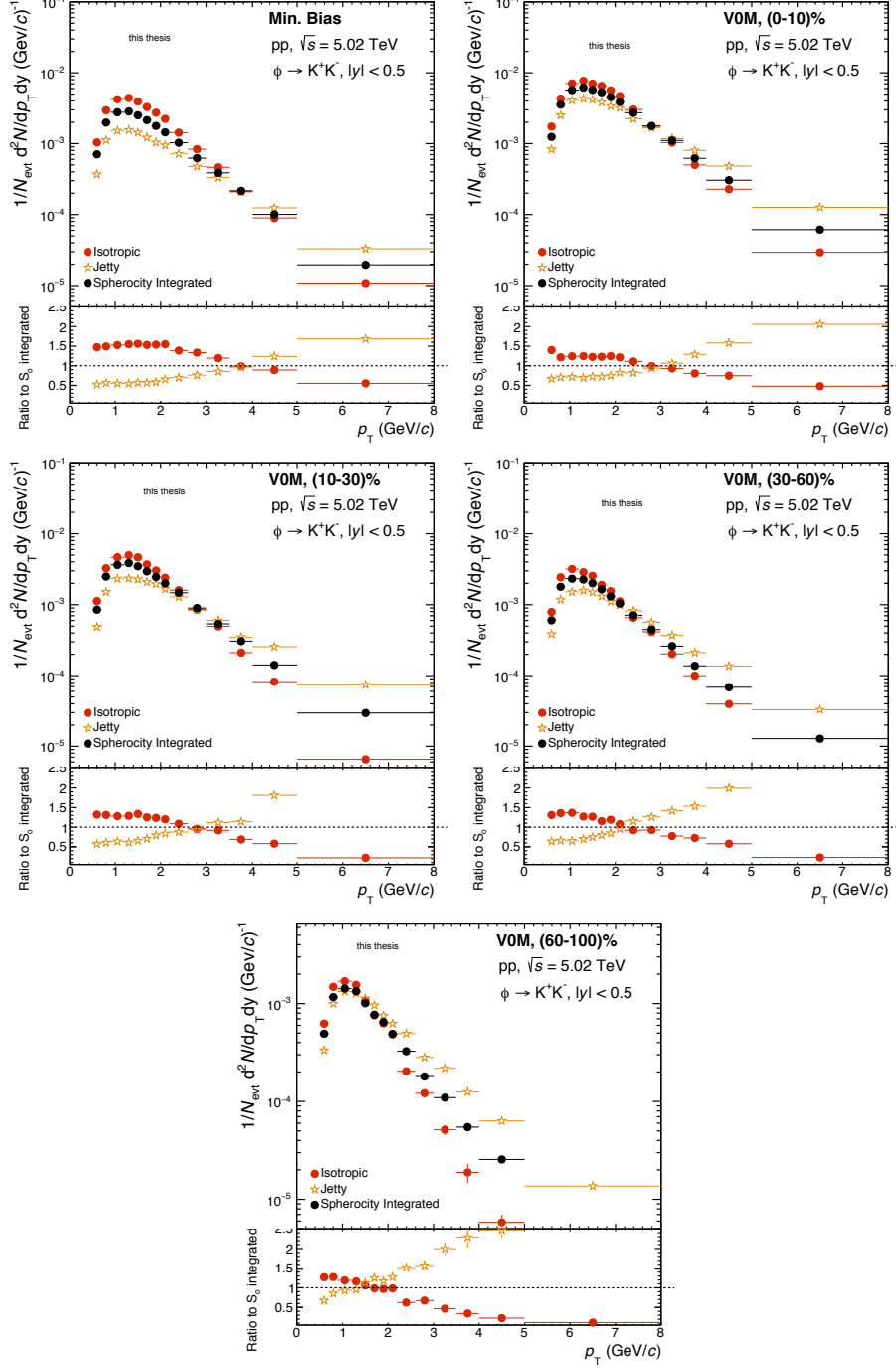


Figure 4.30: (Color Online) Raw Yield as a function of p_T for different sphericity classes for (0-100)% (upper left), (0-10)% (upper right), (10-30)% (middle left), (30-60)% (middle right), (60-100)% (lower) in pp collisions at $\sqrt{s} = 5.02$ TeV [27].

the QGP-like conditions in high-multiplicity pp collisions. However, for the final conclusion one should look into the corrected p_T spectra for different sphericity and multiplicity classes.

4.6 Summary

The first measurements of ϕ meson in pp collisions at $\sqrt{s} = 5.02$ TeV as a function of charged particle multiplicity and transverse sphericity is shown. The results include the invariant mass plots, peak fits, fitting parameters and the corrected p_T spectra with reconstruction efficiencies. The corrected p_T spectra depends on charged particle multiplicity. The ratio of p_T spectra in different multiplicity classes to the minimum bias spectrum shows that the yield increases with increasing charged particle multiplicity. The integrated yield and mean transverse momentum are also calculated and compared with other energies. It is observed that the integrated yield and mean transverse momentum are independent of collision energies and they are solely dependent on the charged-particle multiplicity.

We have made an extensive study of various observables taking sphericity and event multiplicity in pp collisions at $\sqrt{s} = 13$ TeV using the pQCD inspired PYTHIA 8 model. The aim of the present study is to understand the high-multiplicity pp events at the highest LHC energy in view of a possible formation of QGP-droplet in pp collisions. In view of QGP-like behaviors observed in the LHC pp collisions and the fact that pp no longer serves as a baseline to understand a possible nuclear medium formation in heavy-ion collisions at the LHC energies, it is crucial to understand the mechanism of particle production in these high-multiplicity events. Through these simulation studies, we invoke the explicit inclusion of MPI and CR effects responsible for particle production in pp collisions and then through transverse sphericity and multiplicity dependent analysis we try to understand various aspects of identified particle production in LHC pp collisions.

The behavior of the raw p_T spectra in sphericity integrated, isotropic and jetty events are similar to the one seen in the multiplicity dependent analysis. The comparison of the particle spectra in isotropic, jetty and sphericity integrated classes for different multiplicity classes show that the crossing point of the ratios to sphericity integrated class for isotropic and

jetty events depends on the multiplicity. These results can shed light to explore the QGP-like conditions in high-multiplicity pp collisions. However, for the final conclusion one should look into the corrected p_T spectra for different sphericity and multiplicity classes, which will be reported in future. The presented results of the last section, should serve as a outlook of the ongoing studies.

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Chapter 5

Characterization of Heavy-ion collisions using Relativistic Kinetic Theory

“Scientific knowledge is a body of statements of varying degrees of certainty – some most unsure, some nearly sure, none absolutely certain.”

– Dr. Richard P. Feynman

The main goal of ultra-relativistic heavy-ion collisions is to study the matter at high temperature and density where quantum chromodynamics predict the existence of the quark-gluon plasma (QGP) [1] under such extreme conditions. Relativistic Heavy Ion Collider (RHIC) and Large Hadron Collider (LHC) are the dedicated state-of-the-art experimental facilities to this end and are focused to understand the properties of QGP. In central heavy-ion collisions, nucleons in the overlap regions (participants) undergo multiple collisions. These high multiplicity events produce a large number of particles. Even though many of the observed particles are just the result of the fragmentations of pieces of the two nuclei which release some of the bound nucleons, at high incident energies considerable amount of particle creation occurs. While the particles created are mostly pions, the production of relatively heavy particles than pions and heavy flavor (strange and charm) quark matter also takes place. The complexity of a heavy-ion collision is not only apparent in the composition of the outgoing fragments, but it is also apparent in the kinematical structure of the event [2]. To understand better the outcome of a collision of two heavy

nuclei, it is worthwhile pursuing the simplest picture first. The motivations for investigating simple models in heavy-ion collisions comes from the history of models in particle physics. Specifically, in high energy particle collisions, Fermi [3], Landau [4], Pomeranchuk [5] and Hagedorn [6] proposed several equilibrium statistical concepts to explain the multiple formation of particles. The main idea in these pictures is that, owing to the strong interactions that exist between hadronic particles, the distribution of these particles maybe governed by statistical laws only rather than by any specific theory of the detailed dynamics of the process. Such a statistical description of transverse momentum (p_T) of final state particles produced in high-energy collisions has been proposed to follow a thermalized Boltzmann-Gibbs (BG) distribution. But, a finite degree of deviation from the equilibrium statistical description of p_T spectra has been observed by experiments at RHIC [7, 8] and Large Hadron Collider (LHC) [9–12].

Anisotropic flow as an observable of QGP, is caused by the initial asymmetries in the geometry of the system produced in any non-central collision, and plays an important role to understand the collective motion and bulk property of the QGP. The elliptic flow or azimuthal anisotropy (v_2), which is defined as the second-order Fourier component of the particle azimuthal distribution provides information about the equation of state, initial geometrical anisotropy and the transport properties of created QGP [13]. The anisotropic flow can be characterized by the coefficients (v_n), which are obtained from a Fourier expansion of the momentum distribution of the charged particles and is given by,

$$E \frac{d^3 N}{d^3 p} = \frac{d^2 N}{2\pi p_T dp_T dy} \left(1 + 2 \sum_{n=1}^{\infty} v_n \cos[n(\phi - \psi_n)] \right), \quad (5.1)$$

where ϕ is the azimuthal angle in the transverse momentum plane and ψ_n is the n^{th} harmonic event plane angle [14]. In the current work, elliptic flow is calculated with respect to the reaction plane by taking $\psi_n = 0$, which implies event plane coincides with the reaction plane. Taking $n = 2$ gives the second order harmonics in the expansion and its coefficient,

v_2 is calculated to provide the measure of the elliptic flow or azimuthal anisotropy. For a given rapidity window the v_2 is defined as:

$$v_2 = \langle \cos(2\phi) \rangle \quad (5.2)$$

For non-central collisions the v_2 should be a non-zero finite quantity. The elliptic flow has been intensively studied at RHIC and LHC for different systems like Au + Au, Cu + Cu and Pb + Pb at different center of mass energies from 7.7 GeV to 5.02 TeV. From many of the measurements from these previous experiments we have seen that v_2 has contributed significantly to the characterization of the system created in heavy-ion collisions as it is sensitive to the properties of the system at an early time of its evolution. Earlier RHIC experiments show that at low transverse momentum (p_T) region ($p_T < 2$ GeV/c), v_2 follows the mass ordering i.e. higher mass particles having lower v_2 values [15–22]. Another important feature of v_2 is the the number of constituent quark (NCQ) scaling, where v_2 and p_T of identified hadrons are divided by the number of constituent quarks (n_q): 3 for baryons and 2 for mesons, showing a scaling behavior in v_2 . This scaling interprets the dominance of the quark degrees of freedom at early stages of the collision. Recently LHC shows similar mass ordering of v_2 at low- p_T but it seems that v_2 does not follow the NCQ scaling at LHC energies [23, 24] for intermediate or high momentum. It would be very interesting to study these properties of v_2 in QGP medium with varying spatial configurations and densities etc. of partons, which can be achieved by relativistic collisions of different species of ions with a large variation of mass number at same centre of mass energy. In the first section of this chapter, we have discussed the v_2 of produced particles in Xe + Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV using A Multi-Phase Transport model (AMPT) with string melting version [25, 26].

The bulk properties of QGP are governed by light quarks and gluons. The heavy quarks act as probes for QGP properties due to the fact that they witness the entire plasma evolution as they are produced in the

initial hard scattering and endure until hadronization. Also, as their time scale of thermalization is longer than that of light quarks, they can retain the entire interaction history more effectively. Similarly, the energy loss of light quarks becomes important to study the flavor dependence of the energy loss in heavy-ion collisions. The energy loss is more for high- p_T heavy and light quark flavors [27–30] due to interaction with the medium. Finally they appear as constituents of hadrons. The propagation of energetic quarks through the medium has been treated as Brownian motion which is described by means of Fokker-Planck equation. In this equation, the interaction is encoded in drag and diffusion coefficients. Many theoretical efforts have been made using Fokker-Planck equation to reproduce the experimentally observed value of R_{AA} of heavy and light quarks [31–39]. Also, there have been studies to elucidate the dominant mode of energy loss [31] or the flavor dependence of energy loss [40, 41]. But, till date the issues are far from being settled [42]. The nuclear modification factor (R_{AA}) is a measure of the modification of particle production due to the medium effects. It can be represented as

$$R_{AA} = \frac{f_{fin}}{f_{in}}, \quad (5.3)$$

where f_{in} is the distribution of the highly energetic particles immediately after their formation and f_{fin} is the distribution of the particles after the interaction with the medium.

R_{AA} is defined as

$$R_{AA}(p_T) = \frac{(1/N_{AA}^{evt})d^2N_{AA}/dydp_T}{(\langle N_{coll} \rangle / \sigma_{NN}^{inel}) \times d^2\sigma_{pp}/dydp_T}, \quad (5.4)$$

where $d^2N_{AA}/dydp_T$ is the yield in A+A collisions, $\langle N_{coll} \rangle$ is the number of binary nucleon-nucleon collisions averaged over the impact parameter range of the corresponding centrality bin calculated by Glauber Monte-Carlo simulation [43]. σ_{NN}^{inel} is the inelastic cross section and $d^2\sigma_{pp}/dydp_T$ is the differential cross section for inelastic $p + p$ collisions. N_{AA}^{evt} is the number of events in A+A collisions. If, $R_{AA} = 1$, this indicates that A+A

collisions are mere superposition of scaled $p + p$ collisions. A deviation of R_{AA} from unity indicates a medium modification. It has been observed that high- p_T particle yields in Au+Au and Pb+Pb collisions at RHIC and LHC are suppressed as compared to $p + p$ collisions [44, 45], which suggests the formation of a dense medium. In the second section of this chapter, we represent the initial distribution of the energetic particles with the help of Tsallis power law distribution parameterized by the Tsallis q parameter and the Tsallis temperature T , remembering the fact that their genesis is due to very hard scatterings. We plug the initial distribution (f_{in}) in Boltzmann Transport Equation (BTE) and solve it with the help of Relaxation Time Approximation (RTA) of the collision term to find out the final distribution (f_{fin}). Then we proceed to calculate two of the above mentioned observables (R_{AA} and v_2) using the proposed formalism.

The space-time evolution of a system formed in heavy-ion collisions is governed by its dissipative properties such as shear viscosity (η), bulk viscosity (ζ) etc. The spatial anisotropy created in heavy-ion collisions gets converted to the momentum anisotropy of the produced particles due to the pressure gradient and the mutual interactions among the system quanta. The equilibration of momentum anisotropy is governed by the shear viscosity. The AdS/CFT calculation shows that there is a lower bound to the value of shear viscosity to entropy density ratio (η/s) for any fluid found in nature. The lower bound (known as the Kovtun-Son-Starinets (KSS) bound) has been set to the value of $1/4\pi$ in natural units [46, 47]. The elliptic flow measurements at Relativistic Heavy-Ion Collider (RHIC) experiment have found that the η/s is close to the KSS bound, which developed intense interest in this ratio of the strongly interacting matter described by quantum chromodynamics (QCD) [48, 49]. Also, a peak in Bulk viscosity to entropy density ratio (ζ/s) is expected near QCD critical temperature (T_c), where conformal symmetry breaking might be significant as expected by various effective models [50–52]. Other interesting thermodynamic properties are the isothermal compressibility (κ_T) and speed of sound (c_s), which are used to define the equation of state of the system

and quantify the softest point of the phase transition along with the location of the critical point [53]. Due to high multiplicities produced in high-energy collisions, the statistical models are more suitable to describe the particle production mechanism and to study the QCD thermodynamics. In addition, the matter produced in high energy collisions evolves rapidly in a non-homogeneous way. Hence, the spatial configuration of the matter becomes non-uniform and the global equilibrium is not established [54–57]. As a consequence of which some of the observables become non-extensive and develop a power-law tail in the spectra instead of exponential distributions. This also happens when there is local temperature fluctuation and long-range correlations in the produced system [58]. In these cases, the use of BG distribution is questionable [59–63]. Systems, where the usual ergodicity is violated, such as, the states in large systems involving long-range forces between particles and metastable states in small systems where the number of particles are relatively smaller, a generalized BG entropy has been introduced by C. Tsallis [64, 65]. Recently, a growing attention has been paid towards the possible non-extensive effects in thermodynamics and statistical mechanics [66, 67] as well as to explain the particle spectra in high-energy hadronic and heavy-ion collisions [68–73]. In the third section of this chapter, we discuss various dissipative properties such as shear and bulk viscosities using the relativistic non-extensive Boltzmann transport equation (NBTE), where we employ the RTA for the collision term. In NBTE, we assume that a non-equilibrium system, which dissipates energy and produces entropy, measured by the non-extensive parameter q , relaxes to a local q -equilibrium after a certain relaxation time τ . A similar approach has been employed in Ref. [74], where an extensive statistics is used in BTE to calculate the transport coefficients. Here, we extend the approach using Tsallis non-extensive statistics and calculate shear viscosity, bulk viscosity and their ratios over entropy density. First time, we quantify the isothermal compressibility for a hadronic matter using non-extensive statistics. We also calculate the squared speed of sound of hadron resonance gas at finite baryon chemical potential.

We explain the works performed for characterizing heavy-ion collisions using Boltzmann Transport Equation briefly. We try to be as informative as possible. However, for the detailed analysis, the reader is suggested to follow the Refs. [75–80]. The concise summary is listed in the fourth section of the chapter.

5.1 Azimuthal anisotropy in Xe+Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV using a multiphase transport model

Recently LHC has collided Xe^{129} nuclei at $\sqrt{s_{NN}} = 5.44$ TeV. Since the mass number of the Xe^{129} nuclei is roughly in the middle of proton and Pb^{208} nuclei, this can provide a unique opportunity to study the system-size dependence of elliptic flow at LHC energies. According to the recent hydrodynamical calculations [81], v_2 is found larger by 25% in $\text{Xe} + \text{Xe}$ than in $\text{Pb} + \text{Pb}$ collisions in 0-5% centrality class but it is smaller by 10% above 30% centrality classes. An earlier prediction from A Multi-Phase Transport (AMPT) model suggests that the NCQ scaling will hold when we consider much smaller system than $\text{Pb} + \text{Pb}$, which has shown that the number of constituent quarks (NCQ), n_q scaling holds for $\text{Si} + \text{Si}$ collisions at $\sqrt{s_{NN}} = 2.76$ TeV much better than that of $\text{Pb} + \text{Pb}$ collisions at the same energy [82]. Hence, It is also expected that NCQ scaling will also hold true for v_2 in $\text{Xe} + \text{Xe}$ collisions. As expected, this may also indicate the formation of partonic system in Xenon nuclei collisions similar to $\text{Au} + \text{Au}$ or $\text{Pb} + \text{Pb}$ collisions. Therefore the study of v_2 will be very interesting at LHC energies with colliding species of smaller system size. Here, we have studied the v_2 of produced particles in $\text{Xe} + \text{Xe}$ collisions at $\sqrt{s_{NN}} = 5.44$ TeV using A Multi-Phase Transport model (AMPT) with string melting version [25, 26].

5.1.1 A Multi-Phase Transport (AMPT) model

AMPT is a hybrid transport model which contains four components namely, initialization of collisions, parton transport after initialization, hadronization mechanism and hadron transport [83]. The initialization of the model follows HIJING model [84] and calculates the differential cross-section of the produced minijet particles in p+p collisions which is given by,

$$\begin{aligned} \frac{d\sigma}{dp_T^2 dy_1 dy_2} = & K \sum_{a,b} x_1 f_a(x_1, p_{T1}^2) x_2 f_2(x_2, p_{T2}^2) \\ & \times \frac{d\hat{\sigma}_{ab}}{d\hat{t}}, \end{aligned} \quad (5.5)$$

where σ is the cross-section of the produced particles and $\hat{t}$ is the momentum transfer during partonic interactions in p+p collisions. x_i 's are the momentum fraction of the mother protons which are carried by interacting partons and $f(x, p_T^2)$'s are the parton density functions (PDF). The produced partons calculated in p + p collisions are then converted into A + A and p + A collisions by incorporating parametrized shadowing function and nuclear overlap function using inbuilt Glauber model within HIJING. Similarly, initial low-momentum partons which are separated from high momenta partons by a momentum cut-off, are produced from parametrized coloured string fragmentation mechanisms. The produced particles are initiated into parton transport part, ZPC [85], which transport the quarks and gluons using Boltzmann transport equation. This is given by,

$$p^\mu \partial_\mu f(x, p, t) = C[f] \quad (5.6)$$

The leading order equation showing interactions among partons is approximately given by,

$$\frac{d\hat{\sigma}_{gg}}{d\hat{t}} \approx \frac{9\pi\alpha_s^2}{2(\hat{t} - \mu^2)^2}. \quad (5.7)$$

Here σ_{gg} is the gluon scattering cross-section, α_s is the strong coupling constant used in the above equation, and μ^2 is the cutoff used to avoid infrared divergences which can occur if the momentum transfer, $\hat{t}$, goes to

zero during scattering. In the String Melting version of AMPT (AMPT-SM), melting of coloured strings into low momentum partons also take place at the start of the ZPC and are calculated using Lund FRITIOF model of HIJING. This melting phenomenon depends upon spin and flavour of the excited strings. The resulting partons undergo multiple scatterings which take place when any two partons are within distance of minimum approach which is given by $d \leq \sqrt{\sigma/\pi}$, where σ is the scattering cross-section of the partons. In AMPT-SM, the transported partons are finally hadronized using coalescence mechanism [86], when two (or three) quarks sharing a close phase-space combine to form a meson (or a baryon). As of present, AMPT-SM uses three-momentum conservation and the invariant masses of the coalescing partons. The coalescence takes place using the following equation (for e.g. meson),

$$\frac{d^3 N}{d^3 p_M} = g_M \int d^3 x_1 d^3 x_2 d^3 p_1 d^3 p_2 f_q(\vec{x}_1, \vec{p}_1) f_{\bar{q}}(\vec{x}_2, \vec{p}_2) \delta^3(\vec{p}_M - \vec{p}_1 - \vec{p}_2) f_M(\vec{x}_1 - \vec{x}_2, \vec{p}_1 - \vec{p}_2). \quad (5.8)$$

Here g_M is the meson degeneracy factor, f_q 's are the quark distributions after the evolution, and f_M is the coalescing function commonly called Wigner functions [87].

The produced hadrons further undergo evolution in ART mechanism [88, 89] via meson-meson, meson-baryon and baryon-baryon interactions, before final spectra can be observed. There is another default version of AMPT known as AMPT-Def where instead of coalescing the partons, fragmentation mechanism using Lund fragmentation parameters a and b are used for hadronizing the transported partons. However, it is believed that particle flow and spectra at the mid- p_T regions are well explained by quark coalescence mechanism for hadronization [90–92]. We have used AMPT-SM mode for our calculations. We have used the AMPT version 2.26t7 (released: 28/10/2016) in our current work.

Before we start discussing about v_2 , it is important to have a look into the p_T spectra of the produced particles such as π , K , and p . Fig. 5.1

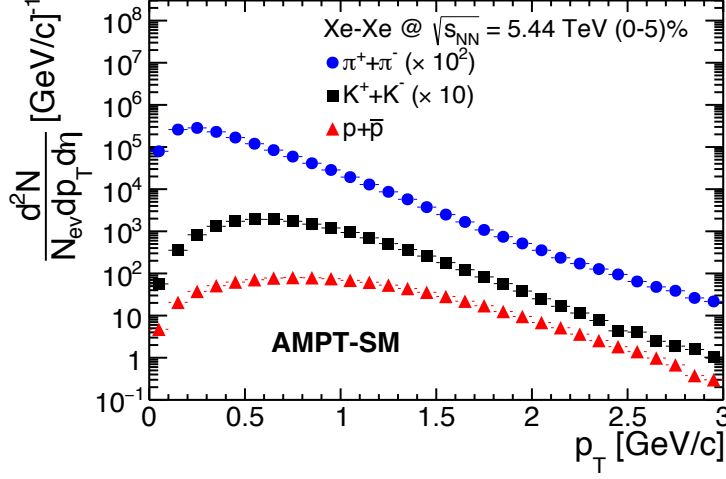


Figure 5.1: (Color online) p_T spectra of π , K and p for (0 - 5)% centrality in Xe+Xe collisions. Circles are for pions, squares stand for kaons and triangles represent protons. The vertical lines in data points show the statistical uncertainties [75].

shows p_T spectra of π , K , and p for (0-5)% centrality. The error bars in the data points are the statistical uncertainties. The spectra of pions and kaons are multiplied by different constant factors to get a clear view of each spectrum. This provides a very good baseline to study the p_T spectra of identified particles in experiment for Xe+Xe collisions.

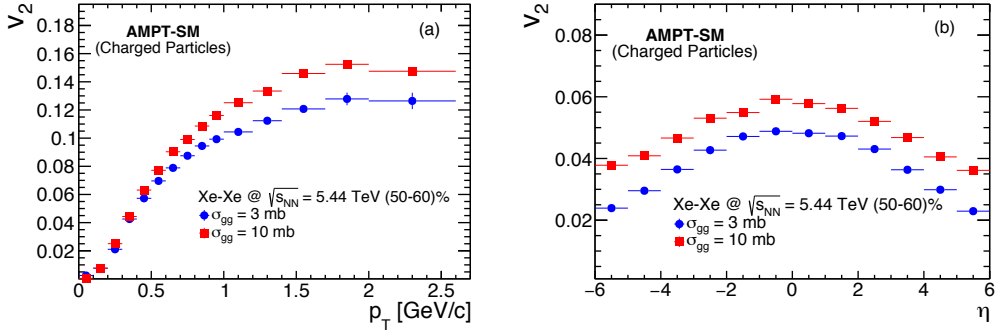


Figure 5.2: (Color online) Charged particles v_2 vs. transverse momentum, p_T (a), and pseudo-rapidity, η (b). Different symbols are for $\sigma_{gg}=3$ mb and 10 mb [75].

It is worthwhile to mention that earlier studies of particle v_2 in Pb+Pb collisions with AMPT showed greater match with experimental data when large partonic scattering cross-section ($\sigma_{gg} \approx 10$ mb) is taken [93]. In Fig. 5.2, we have shown azimuthal anisotropy or elliptic flow of charged particles, v_2 , as functions of transverse momentum, p_T , and rapidity, η for

two values of scattering cross-sections, $\sigma_{gg} = 3$ mb and 10 mb. As expected, results with 10 mb shows greater v_2 than 3 mb. In case of p_T as variable, the flow increases more with transverse momentum in 10 mb scenario than 3 mb. While, taking rapidity, η , as the variable, the difference in 10 mb and 3 mb results can be seen as a constant multiplication factor, particularly in the central rapidity region. In the present work we have fixed $\sigma_{gg} = 10$ mb as cross-section for our calculations and calculated charged particle v_2 . The Lund string fragmentation parameters a and b are kept fixed at their default values of 2.2 and 0.5/GeV², respectively. We will compare our results with the experimental data when it becomes available and further optimise the parameters.

5.1.2 Results and Discussions

We have calculated charged particles' elliptic flow or azimuthal anisotropy, v_2 for various centralities, namely, (0-5)%, (10-20)%, (20-30)%, (50-60)%, (60-70)% centrality classes. Results are presented for $0 < p_T < 2.7$ GeV/c in midrapidity region ($|\eta| < 0.8$). It is believed that Xe nucleus is moderately deformed. Earlier theoretical studies [81] on central collisions ($\approx$ (0-15)%) of Xe nuclei have shown that incorporating deformation parameters cause about 15% deviation in v_2 compared to non-deformed cases. Beyond 15% centrality, it is claimed that the deformity has no discernible effects on particle spectra or other observables. In the present work as the first approximation, we haven't used any deformation for Xenon nuclei. Most of the results are shown for the above mentioned centralities for Xe+Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV.

In Fig. 5.3, we have shown elliptic flow of charged particles for six different centralities. For the most central collision (0-5%), the calculated v_2 is minimum. The elliptic flow increases as the centrality is increased as evident from the next three centralities [(10-20)%, (20-30)% and (30-40)%] shown in the figure. However we see that the difference between (20-30)% and (30-40)% is small. In (50-60)% onwards, we have a decreasing

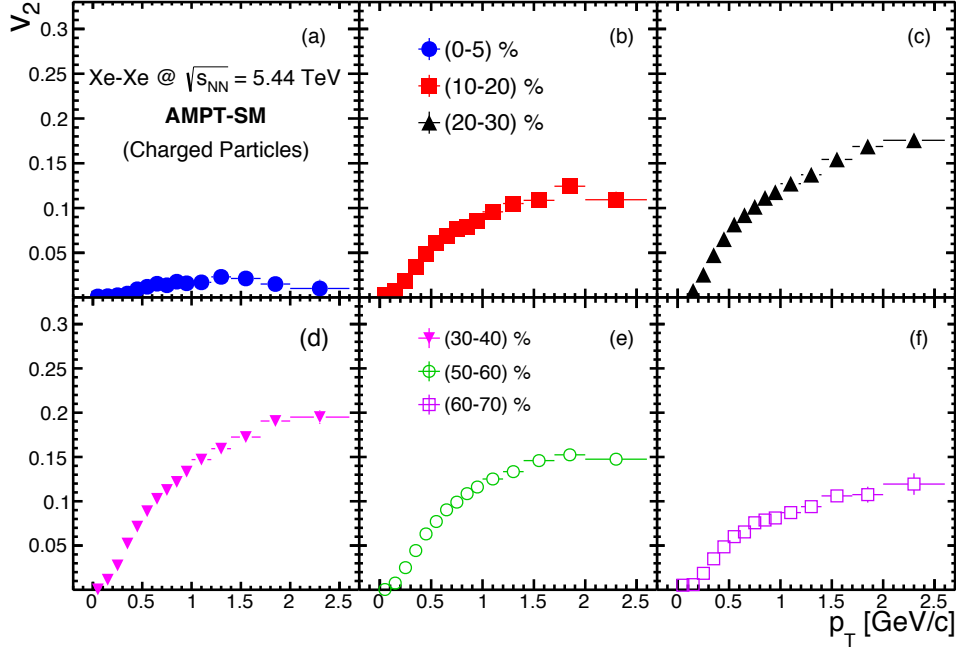


Figure 5.3: (Color online) Charged particles v_2 as a function of transverse momentum, p_T for different centrality classes. Different sections of the figure represent different centrality bins starting from (0-5)% (a) to (60-70)% (f) [75].

trend in the flow and smaller v_2 , which continues to decrease for more peripheral collisions. We feel that this might be due to formation of smaller system in peripheral collisions at which although we have more geometrical anisotropy, the medium density is very small and probability of formation of collective motion decreases.

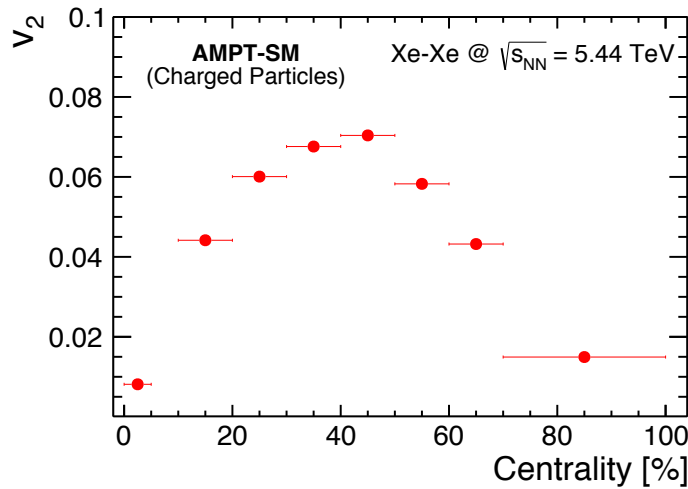


Figure 5.4: (Color online) Charged particles v_2 vs. centrality for $|\eta| < 0.8$ [75].

Fig. 5.4 shows transverse momentum integrated v_2 with the centrality in the p_T range mentioned above. As expected, a strong dependence of v_2 with centrality is observed. It is quite evident from this figure that v_2 increases from most central to mid-central collisions. Beyond that, as we move towards peripheral collisions the flow decreases rapidly. Similar behaviour of the charged particle elliptic flow has also been observed for Pb-Pb collisions at LHC energies [94]. Earlier calculations with hydrodynamical models give similar pictures of elliptic flow with centrality. However, our calculations underestimate the results of hydrodynamics roughly by (13-30)% [81]. The v_2 shows a very small value at most peripheral collisions in AMPT scenario. We feel that although the spatial anisotropy is largest for the peripheral collisions, the medium density is too small to provide any collective flow effects and the interactions among partons are less.

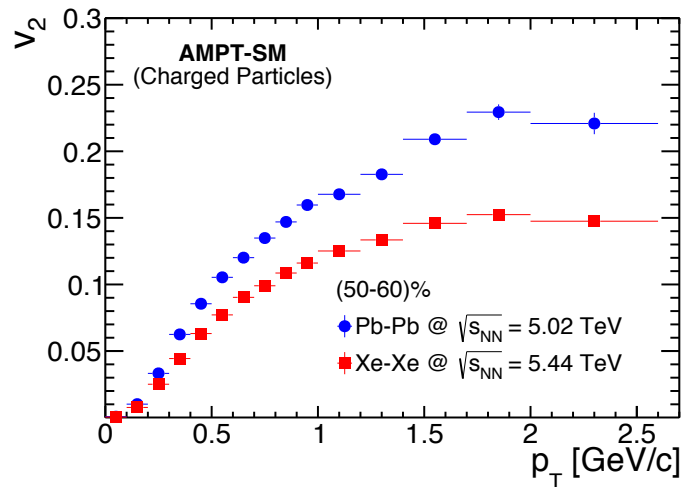


Figure 5.5: (Color online) Charged particles v_2 vs. transverse momentum, p_T for (50 - 60)% centrality of Pb+Pb and Xe+Xe collisions. Circles are for Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and squares are for Xe+Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV. The vertical lines in data points show the statistical uncertainties [75].

In Fig. 5.5, we have compared v_2 of charged particles in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with Xe+Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV at midrapidity ($|\eta| < 0.8$) using same configurations in the AMPT model. The available collision energies for these two different systems are close to each other and hence we may be able to discern various properties of

QGP which depend on system sizes. The dependence of elliptic flow on the system size is quite evident from the plot, as v_2 from Xe+Xe is always different from Pb+Pb collisions. For (50-60)% centrality, the anisotropic flow is more in Pb system than that of Xe. The difference increases toward higher p_T and around 30% higher v_2 is observed in Pb system. We would like to re-iterate that inclusion of intrinsic deformations for Xenon nuclei in the calculations may change many of the above features of observables and their comparative studies.

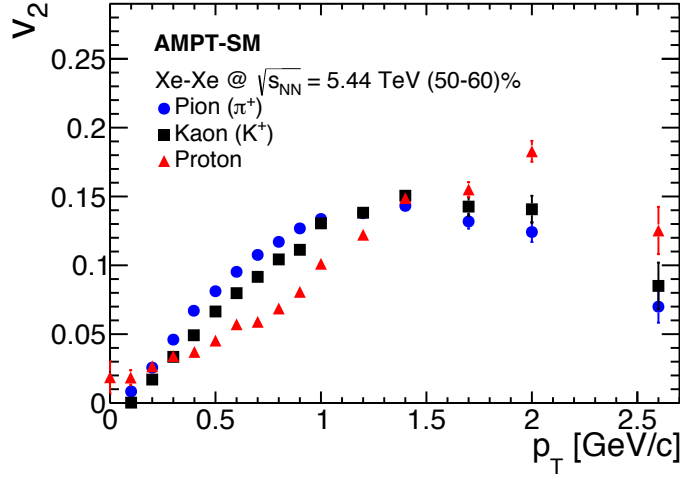


Figure 5.6: (Color online) v_2 vs. transverse momentum, p_T of π , K and p for (50 - 60)% centrality in Xe+Xe collisions. Circles are for pions, squares stand for kaons and triangles represent protons. The vertical lines in data points show the statistical uncertainties [75].

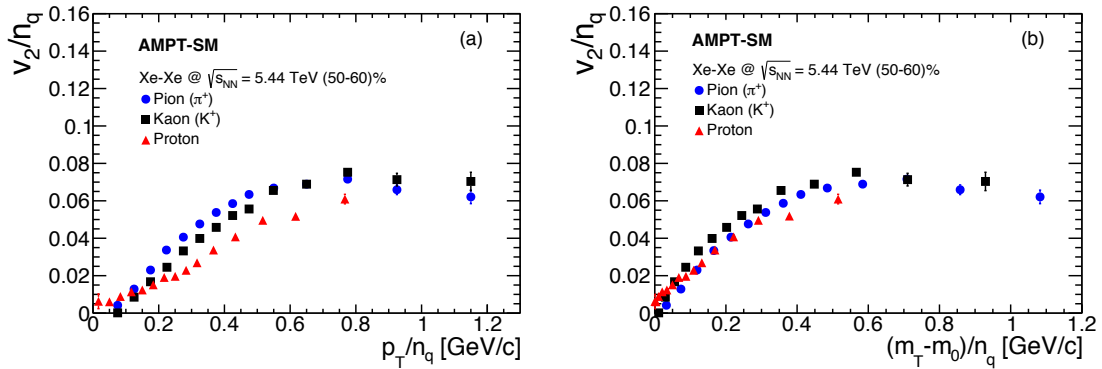


Figure 5.7: (Color online) (a): v_2/n_q as a function of p_T/n_q for π , K and p . (b): v_2/n_q as a function of $(m_T - m_0)/n_q$ for π , K and p . Both plots are for 50-60% centrality bin and different symbols represent different particles. The vertical lines in data points show the statistical uncertainties [75].

Fig. 5.6 shows v_2 for π , K , and p upto $p_T = 2.7$ GeV/c for (50-60)%

centrality. A clear mass dependency of hadrons' $v_2(p_T)$ is observed for $p_T < 2$ GeV/c as it has been observed in Pb-Pb collisions [23, 94] earlier. Lower mass particles have higher v_2 . In particular, the pions and kaons show slightly more flow than proton for $p_T < 2.0$ GeV/c, whereas afterwards proton takes over the pions and kaons. According to the hydrodynamical calculations there is an interplay between radial and elliptic flow which may play an important role in determining this mass-ordering of v_2 at low- p_T . For $p_T > 2$ GeV/c, v_2 is separated according to baryons and mesons. The quark-coalescence mechanisms, [90, 91] which is able to explain flow at the intermediate or moderate p_T ranges has been considered for hadronization in AMPT-SM model used in our calculations.

Within AMPT mechanisms, when a quark and an anti-quark are close in phase space with their momenta very close to each other, they coalesce to form a meson. Similarly when three quarks come closer in phase space, they recombine to form a baryon. Since we assume that coalescence mechanism should work in the intermediate p_T region, the calculated elliptic flow of charged hadrons when divided by their coalesced constituent quark numbers, may exhibit n_q scaling behaviour. In Fig. 5.7 (a), we have shown number of constituent quarks, n_q , scaling of v_2 for π , K , and p for (50-60)% centrality. In present work, it is calculated as,

$$v_2^h(p_T) = n_q \cdot v_2^q(p_T/n_q), \quad (5.9)$$

where n_q is the number of constituent quarks for the charged hadrons considered in our work. However, the figure doesn't demonstrate the n_q scaling behaviour. We observe that scaled v_2 for protons doesn't match with those of mesons, π and K . Such a violation of n_q scaling has been observed for charged particles v_2 in Pb+Pb collisions at the LHC energies [23]. In Fig. 5.7 (b), we tried to demonstrate n_q scaling of the particles flow, where instead of p_T along x-axis, we have $(m_T - m_0)/n_q$, where $m_T = \sqrt{p_T^2 + m_0^2}$. We find that the v_2/n_q values as a function of $(m_T - m_0)/n_q$ show a scaling like behaviour which is similar to the observations for Pb+Pb collisions at

LHC energies [14]. However, we can not state conclusively that n_q scaling is observed although something similar to m_T scaling can be seen at low-momenta. The reason behind the failed n_q scaling may be due to the partons forming baryons occupying different phase space as compared to partons forming mesons. The study of the correlation of the relaxation and freeze-out times with the flow may shed some light on the difference in the flow among quarks at the partonic level [95]. This calls for a more deeper understanding of the relaxation of the bulk system of quarks and gluons.

5.1.3 Comparison with experimental data

Recently ALICE has published the v_2 measurements of charged particles in Xe+Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV [96] using two-particle correlations based on cumulant method [97]. Fig. 5.8 shows the comparison of v_2 vs p_T between data and AMPT-SM model for 50-60% centrality bin. It is found that AMPT result matches with data well at low p_T region ($p_T < 1$ GeV/c). Difference between data and AMPT increases as we go towards higher p_T . As there was no experimental results available before, we took the default parameter settings of AMPT-SM as it is mentioned in section II. It seems that to reproduce these latest experimental results, particularly at higher p_T one needs to tune the parameters of AMPT-SM model. It should be noted here that the methods adopted in this work and in the ALICE experimental paper for the measurement/estimation of v_2 are different. We have used the event plane method, whereas the experimental measurement uses the cumulant method. However, as discussed in Ref. [97] both the methods give similar v_2 -results.

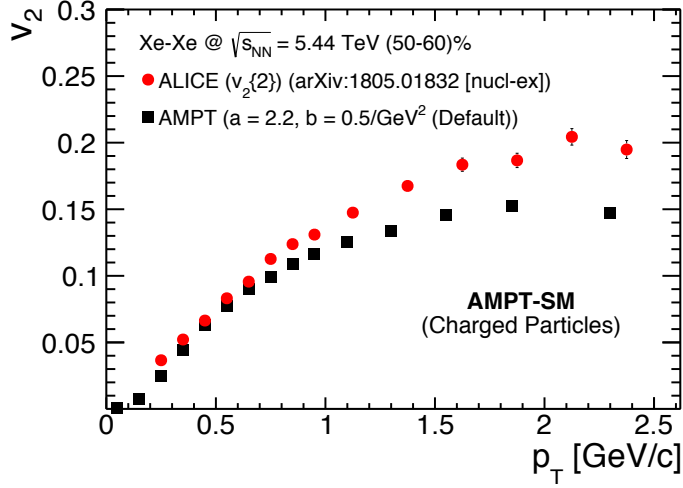


Figure 5.8: (Color online) v_2 vs transverse momentum, p_T of charged particles for ALICE data [96] (circles) and AMPT-SM model (squares) [75].

5.2 Nuclear Modification Factor and azimuthal anisotropy using non-extensive statistics

5.2.1 Formalism

The evolution of the particle distribution owing to its interaction with the medium particles can be studied through Boltzmann transport equation,

$$\frac{df(x, p, t)}{dt} = \frac{\partial f}{\partial t} + \vec{v} \cdot \nabla_x f + \vec{F} \cdot \nabla_p f = C[f], \quad (5.10)$$

where $f(x, p, t)$ is the distribution of particles which depends on position, momentum and time. $\vec{v}$ is the velocity and $\vec{F}$ is the external force. ∇_x and ∇_p are the partial derivatives with respect to position and momentum, respectively. $C[f]$ is the collision term which encodes the interaction of the probe particles with the medium. The Boltzmann Transport Equation has earlier also been used in relaxation time approximation to study the time evolution of temperature fluctuation in a non-equilibrated system [98].

Assuming homogeneity of the system ($\nabla_x f = 0$) and absence of external force ($F = 0$), the second and third terms of the above equation

become zero and Eq. 5.10 becomes,

$$\frac{df(x, p, t)}{dt} = \frac{\partial f}{\partial t} = C[f] \quad (5.11)$$

In relaxation time approximation [99, 100], the collision term can be expressed as,

$$C[f] = -\frac{f - f_{eq}}{\tau} \quad (5.12)$$

where f_{eq} is Boltzmann local equilibrium distribution characterized by a temperature T_{eq} . τ is the relaxation time, the time taken by a non-equilibrium system to reach equilibrium. With the ansatz in Eq. 5.12, Eq. 5.11 becomes,

$$\frac{\partial f}{\partial t} = -\frac{f - f_{eq}}{\tau} \quad (5.13)$$

Solving the above equation in view of initial conditions i.e. at $t = 0, f = f_{in}$ and at $t = t_f, f = f_{fin}$; leads to,

$$f_{fin} = f_{eq} + (f_{in} - f_{eq})e^{-\frac{t_f}{\tau}}, \quad (5.14)$$

where t_f is the freeze-out time. Using Eq. 5.14, the nuclear modification factor can be expressed as,

$$R_{AA} = \frac{f_{fin}}{f_{in}} = \frac{f_{eq}}{f_{in}} + \left(1 - \frac{f_{eq}}{f_{in}}\right) e^{-\frac{t_f}{\tau}} \quad (5.15)$$

Eq. 5.15 is the derived nuclear modification factor after incorporating relaxation time approximation, which is the basis of our analysis in the present paper. It involves a (power law-like) initial distribution and the equilibrium distribution. In this analysis, the initial distribution is parameterized using the thermodynamically consistent Tsallis distribution [101].

Tsallis statistics is widely used to analyse the detected particle spectra in high-energy collisions starting from e^+e^- , $p+p$ to heavy-ions [73]. Also, as the system stays away from thermal equilibrium during the formation

of highly energetic particles immediately after the collision, the particle distribution can be parameterized with the help of Tsallis distribution. A thermodynamically consistent non-extensive Tsallis distribution function, to be used as the initial distribution, is given by, [101]

$$f_{in} = \frac{gV}{(2\pi)^2} p_T m_T \left[1 + (q-1) \frac{m_T}{T} \right]^{-\frac{q}{q-1}}, \quad (5.16)$$

which is used for studying the particle distribution stemming from the proton-proton collisions as discussed in Ref. [101].

The Boltzmann equilibrium distribution is given by

$$f_{eq} = \frac{gV}{(2\pi)^2} p_T m_T e^{-\frac{m_T}{T_{eq}}} \quad (5.17)$$

Here, V is the system volume, $m_T = \sqrt{p_T^2 + m^2}$ is the transverse mass and q is the non-extensive parameter, which measures the degree of deviation from equilibrium. Using Eqs. 5.16 and 5.17 (both for mid-rapidity and for zero chemical potential) nuclear modification factor can be expressed as,

$$R_{AA} = \frac{e^{-\frac{m_T}{T_{eq}}}}{(1 + (q-1) \frac{m_T}{T})^{-\frac{q}{q-1}}} + \left[1 - \frac{e^{-\frac{m_T}{T_{eq}}}}{(1 + (q-1) \frac{m_T}{T})^{-\frac{q}{q-1}}} \right] e^{-\frac{t_f}{\tau}} \quad (5.18)$$

This will be compared to experimental results in the next section.

We have also considered Boltzmann-Gibbs Blast Wave (BGBW) function as f_{eq} , which is widely used by heavy-ion physics community. The distribution function is given by

$$f_{eq} = D \int_0^{R_0} r dr K_1\left(\frac{m_T \cosh \rho}{T}\right) I_0\left(\frac{p_T \sinh \rho}{T}\right), \quad (5.19)$$

where $D = \frac{gV m_T}{2\pi^2}$. Here g is the degeneracy factor, V is the system volume, and $m_T = \sqrt{p_T^2 + m^2}$ is the transverse mass, $K_1\left(\frac{m_T \cosh \rho}{T}\right)$ and

$I_0\left(\frac{p_T \sinh \rho}{T}\right)$ are the modified Bessel's functions and are given by

$$K_1\left(\frac{m_T \cosh \rho}{T}\right) = \int_0^\infty \cosh y \exp\left(-\frac{m_T \cosh y \cosh \rho}{T}\right) dy, \quad (5.20)$$

$$I_0\left(\frac{p_T \sinh \rho}{T}\right) = \frac{1}{2\pi} \int_0^{2\pi} \exp\left(\frac{p_T \sinh \rho \cos \phi}{T}\right) d\phi, \quad (5.21)$$

where ρ is a parameter given by $\rho = \tanh^{-1} \beta_r$, with $\beta_r = \beta_s \left(\xi\right)^n$ [102, 103]. β_s is the maximum surface velocity and $\xi = (r/R_0)$, with r as the radial distance. This is similar to the Hubble expansion of the universe ($v = Hr$, H is the Hubble constant). In the blast-wave model the particles closer to the center of the fireball move slower than the ones at the edges. The average of the transverse velocity can be evaluated as [104]

$$\langle \beta_r \rangle = \frac{\int \beta_s \xi^n \xi d\xi}{\int \xi d\xi} = \left(\frac{2}{2+n}\right) \beta_s. \quad (5.22)$$

In our calculation we use a linear velocity profile, ($n = 1$) and R_0 is the maximum radius of the expanding source at freeze-out ($0 < \xi < 1$). In this analysis, the initial distribution is parameterized using three different distributions: (i) the pQCD motivated power-law distribution which is given as,

$$f_{in} = \frac{gV}{(2\pi)^2} m_T \left[\frac{m_T}{T_{pp}}\right]^{-n}, \quad (5.23)$$

(ii) the distribution proposed by Hagedorn, which is a combination of exponential distribution for low- p_T and power-law distribution for high- p_T , is expressed as,

$$f_{in} = \frac{gV}{(2\pi)^2} m_T \left[1 + \frac{m_T}{T_{pp}}\right]^{-n}, \quad (5.24)$$

and (iii) the thermodynamically consistent non-extensive Tsallis distribution [101]

$$f_{in} = \frac{gV}{(2\pi)^2} m_T \left[1 + (q_{pp} - 1) \frac{m_T}{T_{pp}}\right]^{-\frac{q_{pp}}{q_{pp}-1}}. \quad (5.25)$$

Using all the above distributions, we have analyzed the R_{AA} spectra and it

is observed that the pQCD inspired power-law distribution could explain the high transverse momentum part but fails in low momentum range. Thus, we have used the Tsallis distribution to obtain the expression for the final distribution and nuclear modification factor. The thermodynamically consistent Tsallis distribution is used for studying the particle distributions stemming from the proton-proton collisions as discussed in Ref. [101]. T_{pp} is the Tsallis temperature and q_{pp} is the non-extensive parameter, which measures the degree of deviation from equilibrium. Using Eqs. 5.19 and 5.25, the final distribution can be expressed as,

$$f_{fin} = D \left\{ \int_0^{R_0} r dr K_1 \left(\frac{m_T \cosh \rho}{T} \right) I_0 \left(\frac{p_T \sinh \rho}{T} \right) + \left(\frac{1}{2} \left[1 + (q_{pp} - 1) \frac{m_T}{T_{pp}} \right]^{-\frac{q_{pp}}{q_{pp}-1}} - \int_0^{R_0} r dr K_1 \left(\frac{m_T \cosh \rho}{T} \right) I_0 \left(\frac{p_T \sinh \rho}{T} \right) \right) e^{\frac{-t_f}{\tau}} \right\}. \quad (5.26)$$

Using Eqs. 5.19 and 5.26 (both for mid-rapidity and for zero chemical potential) in Eq. 5.14, nuclear modification factor can be expressed as,

$$R_{AA} = \frac{f_{fin}}{f_{in}} = \frac{\int_0^{R_0} r dr K_1 \left(\frac{m_T \cosh \rho}{T} \right) I_0 \left(\frac{p_T \sinh \rho}{T} \right)}{\frac{1}{2} \left[1 + (q_{pp} - 1) \frac{m_T}{T_{pp}} \right]^{-\frac{q_{pp}}{q_{pp}-1}}} + \left(1 - \frac{\int_0^{R_0} r dr K_1 \left(\frac{m_T \cosh \rho}{T} \right) I_0 \left(\frac{p_T \sinh \rho}{T} \right)}{\frac{1}{2} \left[1 + (q_{pp} - 1) \frac{m_T}{T_{pp}} \right]^{-\frac{q_{pp}}{q_{pp}-1}}} \right) e^{\frac{-t_f}{\tau}}. \quad (5.27)$$

Here, T_{pp} and q_{pp} are extracted from the best fit to the particle spectra in $p + p$ collisions. The Eqs. 5.26 and 5.27 are used to fit the experimental results as discussed in the following section.

For the calculation of elliptic flow (v_2), ρ in the integrand is modified by $\rho = \tanh^{-1} \beta_r + \rho_a \cos(2\phi)$, with ρ_a as the anisotropy parameter in the

flow. The elliptic flow in the BTE-RTA framework is given by,

$$v_2(p_T) = \frac{P}{Q}, \quad (5.28)$$

where,

$$\begin{aligned} P = & D \int d\phi \cos(2\phi) \left[\int_0^{R_0} r dr K_1\left(\frac{m_T \cosh\rho}{T}\right) I_0\left(\frac{p_T \sinh\rho}{T}\right) \right. \\ & \left. + \left(\frac{1}{2} \left[1 + (q-1) \frac{m_T}{T_{ts}} \right]^{-\frac{q}{q-1}} - \int_0^{R_0} r dr K_1\left(\frac{m_T \cosh\rho}{T}\right) I_0\left(\frac{p_T \sinh\rho}{T}\right) \right) e^{\frac{-t_f}{\tau}} \right], \end{aligned} \quad (5.29)$$

$$\begin{aligned} Q = & D \int d\phi \left[\int_0^{R_0} r dr K_1\left(\frac{m_T \cosh\rho}{T}\right) I_0\left(\frac{p_T \sinh\rho}{T}\right) \right. \\ & \left. + \left(\frac{1}{2} \left[1 + (q-1) \frac{m_T}{T_{ts}} \right]^{-\frac{q}{q-1}} - \int_0^{R_0} r dr K_1\left(\frac{m_T \cosh\rho}{T}\right) I_0\left(\frac{p_T \sinh\rho}{T}\right) \right) e^{\frac{-t_f}{\tau}} \right]. \end{aligned} \quad (5.30)$$

5.2.2 Results and Discussion

We now proceed to the more detailed analysis of the experimental data with the model proposed above. Keeping all the parameters free, we fit the spectra for different particles in different centralities for Pb+Pb and Au+Au collisions using TMinuit class available in ROOT library [105] to get a convergent solution. The convergent solution is obtained by χ^2 minimization technique. Here T , q , t_f/τ , ρ_a and $\langle \beta_r \rangle$ are the fitting parameters for the experimental data. The equilibrium temperature T_{eq} is fixed to 160 MeV throughout the analysis.

Fig. 5.9 shows p_T -spectra for available identified particles for 0-5% centrality in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [106–108]. Eq. 5.26 is fitted to the p_T -spectra of different particles, which shows a very good description using the present formalism.

Then we move towards fitting the R_{AA} spectra using Eq. 5.18. In our

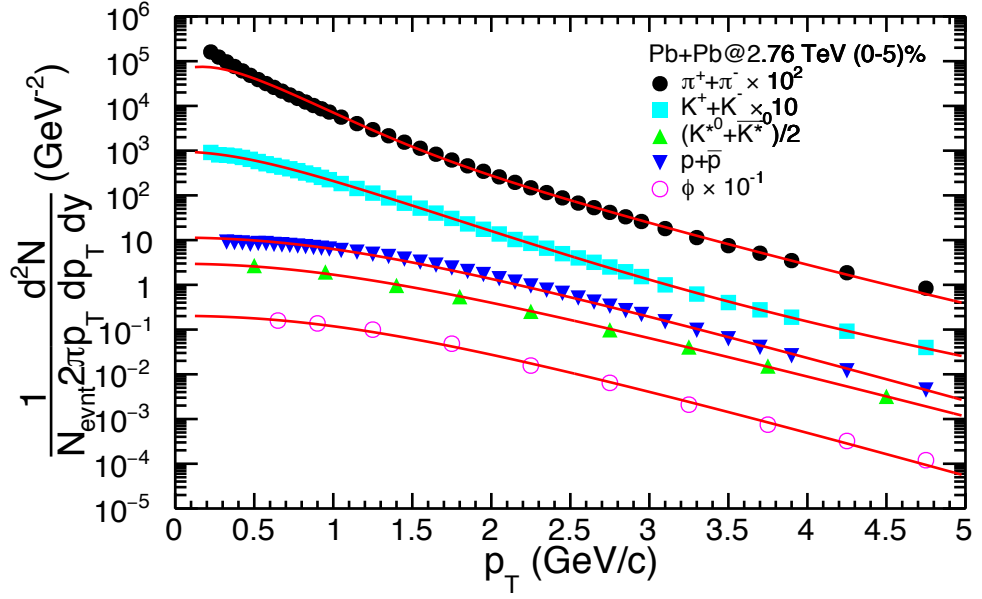


Figure 5.9: (Color online) Transverse momentum distribution of identified hadrons for 0–5% centrality in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [106–108]. Eq. 5.26 is fitted to the spectra of the identified particles [78].

analysis, it is observed that the fitting of low p_T for light flavor particles fails due to the reason that it involves different physical processes such as regeneration, coalescence, shadowing etc., which are out for the scope of present formalism. Also, for very high- p_T , our model fails to explain the increase in R_{AA} . The derived expression for R_{AA} fits the data in intermediate to high- p_T range. In Fig. 5.10, we show the fitting of experimental data for $\pi^+ + \pi^-$ (upper left), $K^+ + K^-$ (upper right), K_S^0 (lower left) and $p + \bar{p}$ (lower right) in most central Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The model considered here, fits the data from intermediate to high- p_T range.

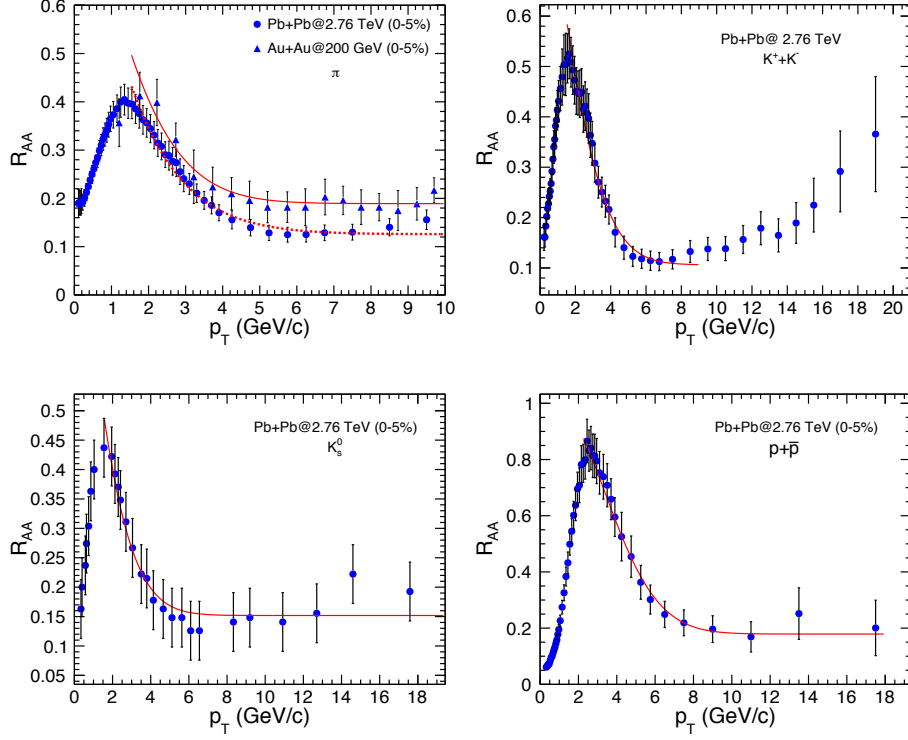


Figure 5.10: (Color Online) Fitting of experimental data for nuclear modification factor with our proposed model (Eq. 5.18) for π^0 [109] (blue triangles) in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV and $\pi^+ + \pi^-$ [106] (upper left), $K^+ + K^-$ [106] (upper right), K_S^0 (lower left) and $p + \bar{p}$ (lower right) in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV (blue dots). The solid red line shows the fitting for blue triangles and the dotted red line shows the fitting for blue dots [76].

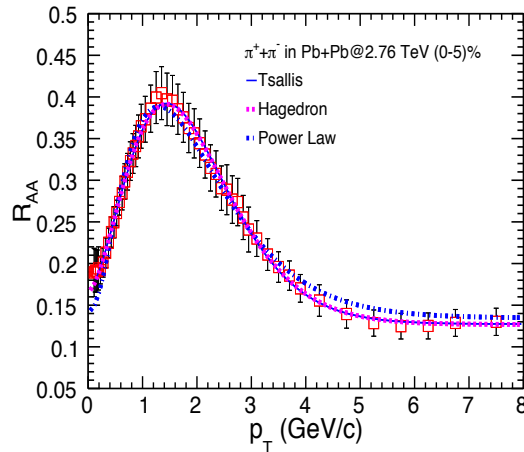


Figure 5.11: (Color online) Fitting of R_{AA} spectra for pions in most central Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, using three different initial distributions. The blue dotted line shows the fitting using the power-law distribution (Eq. 5.23), the magenta dotted line shows the fitting using the Hagedorn distribution (Eq. 5.24) and the blue line shows the fitting using the thermodynamically consistent Tsallis distribution (Eq. 5.25) [77].

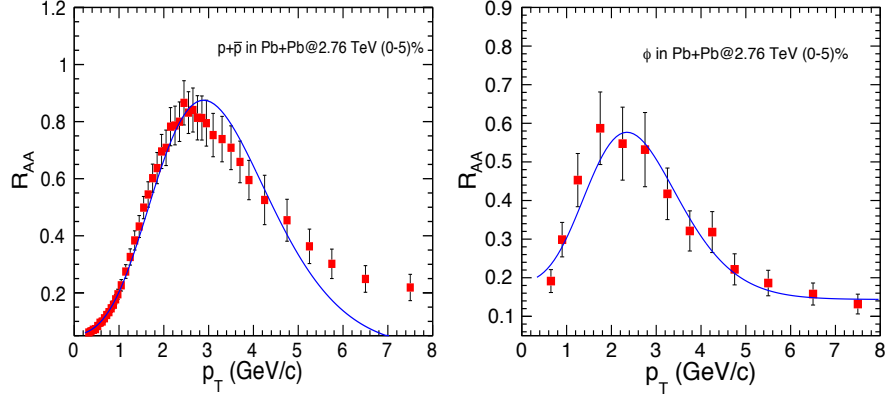


Figure 5.12: (Color online) Fitting of R_{AA} spectra for protons and ϕ meson in most central Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, using three different initial distributions. The blue line shows the fitting using the thermodynamically consistent Tsallis distribution (Eq. 5.25) [77].

Then we move to fit the data with the formulation with BGBW as equilibrium distribution function. Fig. 5.11 shows R_{AA} as a function of p_T for pions in most central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Here, we fit the experimental data by taking the various types of initial distributions as mentioned above (Eqs. 5.23, 5.24 and 5.25) in order to check the suitability of the initial distributions used as f_{in} in the definition of R_{AA} . It is observed that the pQCD inspired power-law distribution could explain the high transverse momentum part but fails in low momentum range compared to other two distributions. This is expected as the high- p_T contribution mostly comes from hard scatterings, which are described by pQCD. The distribution proposed by Hagedorn behaves as an exponential distribution in low- p_T and the power-law distribution in high- p_T domains, explains R_{AA} for the complete range of p_T . The thermodynamically consistent Tsallis distribution is also used to fit R_{AA} in comparison with the above mentioned initial distributions. We find that using the thermodynamically consistent Tsallis distribution as an initial distribution, the R_{AA} spectra are explained successfully. So, considering the whole p_T -range and taking the non-extensive statistics as an initial distribution, we further proceed towards studying R_{AA} of light flavours and resonances in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV at the LHC. We also notice that using the BGBW function as f_{eq} in the definition of R_{AA} gives a very good description in the

whole p_T -range, while our earlier version of R_{AA} formulation, which uses Boltzmann-Gibbs distribution as the equilibrium distribution, fails at the low- p_T domain. This suggests that the collective flow plays an important role in the study of R_{AA} spectra. Further, in the description of R_{AA} spectra of all other particles, we use the non-extensive Tsallis distribution function as f_{in} . This is because, in addition to a better description of p_T -spectra in $p + p$ collisions and the R_{AA} -spectra in nucleus-nucleus collisions in the present formalism, it also gives other thermodynamical properties of the system, which are quite useful in characterizing the matter formed at this energy. Figure 5.12 shows the R_{AA} -spectra of $p + \bar{p}$ (left), and ϕ (right) for the most central Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The spectra are fitted to the the function for R_{AA} given by Eq. 5.27, which is obtained in the present formalism of BTE with RTA and BGBW function as the equilibrium distribution.

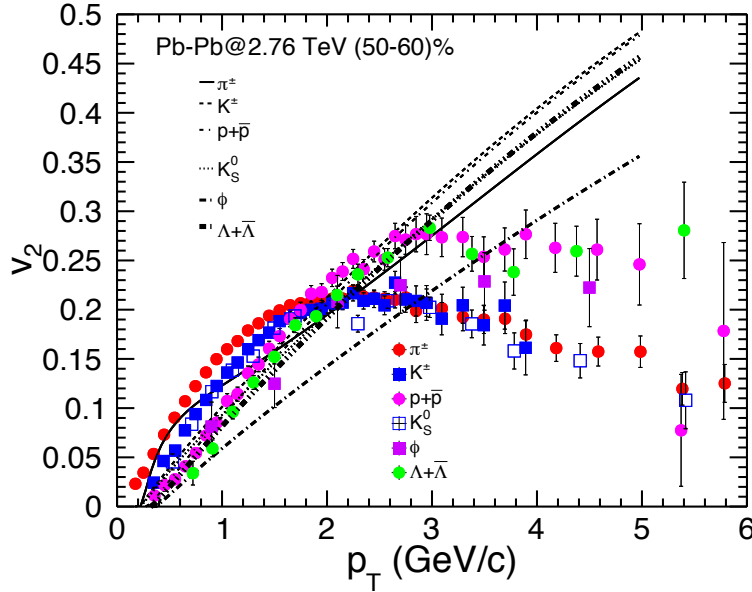


Figure 5.13: (Color online) Elliptic flow of identified hadrons for 50-60% centrality in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV using only BGBW (Eq. 5.19) [78].

Now, let us look how the formalism works in explaining the experimental data for elliptic flow. Fig. 5.13 shows elliptic flow of hadrons using only BGBW formalism given by Eq. 5.19. BGBW formalism is valid when

the system goes to complete local thermal equilibrium. In this figure, although we find that BGBW agrees with experimental data at low- p_T , it deviates completely from data points beyond $p_T > 2$ GeV/c. This indicates that particles with lower momenta seem to show a tendency of equilibration. To have a complete description of v_2 in the available p_T -range, we proceed to use the present formalism in its full form.

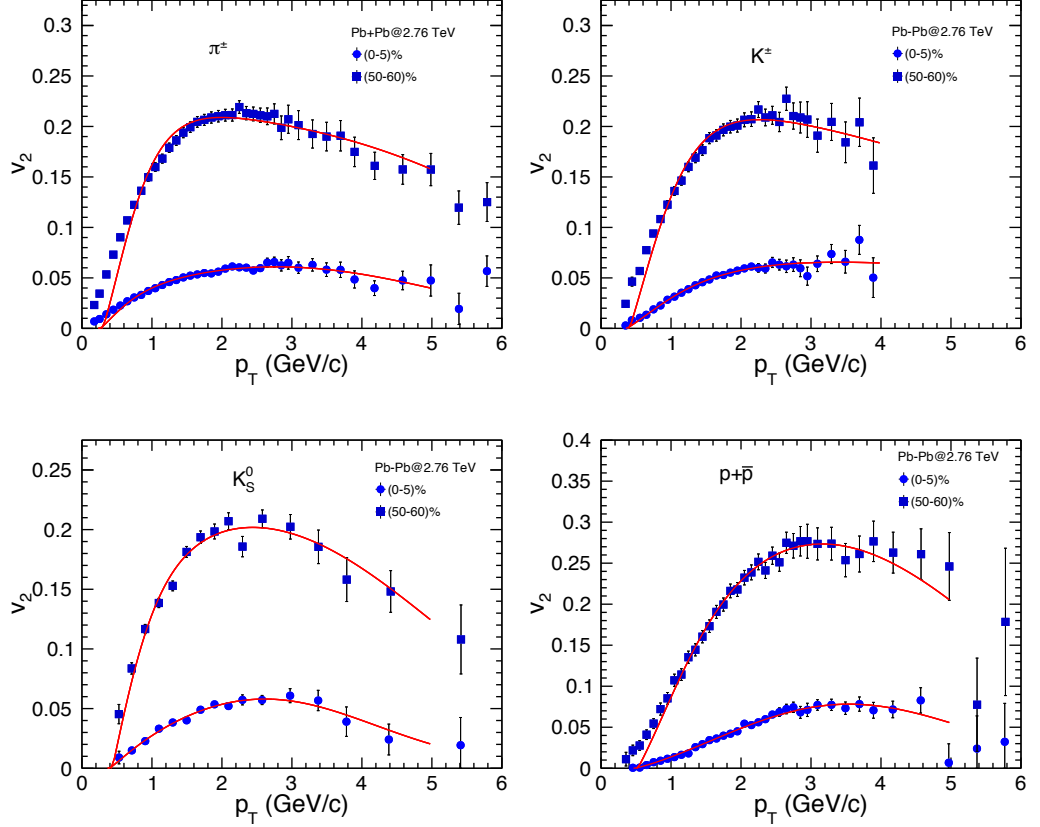


Figure 5.14: (Color online) Elliptic flow of identified particles for (0-5)% and (50-60)% centralities [110]. Fitting functions are the expectations from BTE-RTA formalism [78].

In Fig. 5.14, we have v_2 for hadrons using Tsallis distribution as input and BGBW as equilibrium distribution in BTE. The parametrization for the BGBW is taken at kinetic freeze-out surface which is identical to that of freeze-out in (2+1)-d hydrodynamical calculations. The v_2 plots are for most central (0-5%) and peripheral (50-60%) Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. For all of these, we have used Eq. 5.28 for the description of elliptic flow using the present formalism. We observe that the BTE with Tsallis distribution could explain the elliptic flow for all the measured hadrons at

both the centralities. The v_2 curve rises till $p_T \leq 2$ GeV/c and then it tends to fall, which shows that particles in these two different regions of p_T , have a distinct and opposite medium effect on their flow pattern. Comparing with a simple BGBW formalism, as shown in Fig. 5.13, one may infer that the particles with lower momenta have a tendency of equilibration. However as mentioned earlier, the freeze-out dynamics play a vital role in determining the flow pattern of any particle. This is evident from Fig. 5.14. The flow pattern included at the freeze-out surface gives the characteristic increase in the elliptic flow at low p_T region whereas, the non-extensivity in the initial distribution has profound effect on the particles at the mid and high p_T . The detailed study of the set of parameters should give us an indirect view of physics behind such a flow pattern and the extent of equilibration, effects of freeze-out dynamics on final hadron spectra. Let us now move to our next set of results where we would discuss the parameters in details. In upper left plot of Fig. 5.15, we have shown the parameter, t_f/τ vs mass, m of the identified hadrons. The two sets in the figure are for two different centralities. While τ depicts relaxation time or equilibration time for the particle, t_f is the time when the particle finally stops interacting. This particular ratio of parameters is interesting as it shows an interplay between relaxation and freeze-out time. The assumption in our calculation is that the equilibration time for the light flavours should always be less than kinetic freeze-out time, so that the ratio, t_f/τ is always greater than unity. Similarly, for the heavy quarks or jet particles with lower degree of drag and diffusion, this ratio might be less than unity [111, 112]. The plot shows that the parameter, t_f/τ increases with the mass of the particle. However, the rise in the values of t_f/τ with mass or the slope is more in central collisions as compared to peripheral collisions. This suggests more rapid equilibration for the particles at the central collision. In the present calculations, the hadrons having larger mass undergo a decrease in τ or an increase in t_f . In either case the ratio should increase with the mass as seen in our results. This leaves out further investigations to have a clear understanding of the interplay between thermalization and freeze-out. In

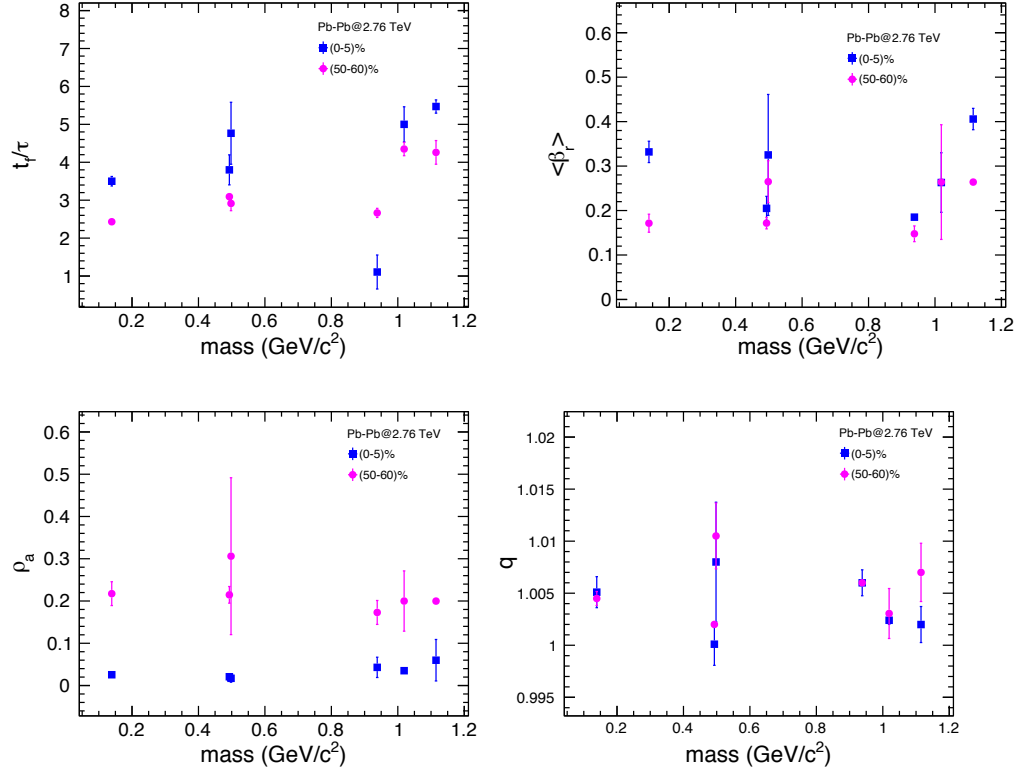


Figure 5.15: (Color online) The ratio of freeze-out time to relaxation time, t_f/τ (upper left), average radial flow (upper right), anisotropy parameter (lower left) and non-extensivity parameter (lower right) as a function of identified particle mass [78].

upper right plot of Fig. 5.15, we have shown the dependency of radial flow parameter, $\langle \beta_r \rangle$ on the mass of hadrons. In our radial flow profile, we have used $n=1$ assuming linear increase in the radial flow velocity. The radial flow parameter does not show a clear mass dependence, which hints for a collectivity in the system. However, the values for central collisions are higher than that of peripheral collisions. This goes inline with the earlier observations on centrality dependence of radial flow [113]. In lower left plot of Fig. 5.15, we have shown the dependence of anisotropy parameter, ρ_a on mass of the hadrons. Apart from $\langle \beta_r \rangle$ discussed in last paragraph, ρ_a is also important as it shows the extent of anisotropy embedded in the transverse rapidity, ρ . For the central collisions (0-5%), the parameter values do not change much with the mass, while for peripheral collisions, ρ_a seems mass independent. Although this is clearly visible in the experimental data (see Fig. 5.13) up to $p_T \sim 2$ GeV/c, the p_T -dependent dynamics dominated by

effects like recombination, jet-events, etc. take over for higher momentum range. In addition, it is evident that with centrality the anisotropy in the flow increases, which is expected. To make this statement more evident, the flow in general, could be understood as an interplay of radial flow and the elliptic flow, which arises from initial state momentum anisotropy. When the radial flow is higher in central collisions compared to the peripheral ones, the elliptic flow behaves differently. In lower right plot of Fig. 5.15, we have shown the mass dependence of non-extensive parameter, q . The parameter is an indirect measure of non-equilibration of any particle after evolving through thermal bath. Therefore, it is evident from the figure that different hadron species would show different q values. From this figure we find that with increase in mass, the values of q seem to decrease. Earlier in the discussion, while referring to upper right plot of Fig. 5.15, we found that the value of t_f/τ increases with increase in mass. However, in a scenario, where t_f is chosen the same for all particles through a choice of fixed kinetic freeze-out temperature, this translates to a lower value of relaxation time for high mass particles. In a kinetic theory, this is an indication that higher mass particles tend to equilibrate early in time. This is truly reflected from lower right plot of Fig. 5.15, where we do observe a decrease in the non-extensive parameter with increase of particle mass. Furthermore, for a given mass, the q values are higher for peripheral collisions in comparison with central collisions. This is also an indication that peripheral collisions have higher tendency to go out of equilibrium. This behaviour of q with centrality is in contrast with that of t_f/τ in upper right plot of Fig. 5.15.

The summary of the important results from this section is given in Section 5.4. Let us now move towards a complete picture of BTE using non-extensive statistics in the next section.

5.3 Transport properties of Hot and Dense Hadron Gas using Non-extensive Statistics

The aim of this work is to study various dissipative properties such as shear and bulk viscosities using the relativistic non-extensive Boltzmann transport equation (NBTE), where we employ the RTA for the collision term. In NBTE, we assume that a non-equilibrium system, which dissipates energy and produces entropy, measured by the non-extensive parameter q , relaxes to a local q -equilibrium after a certain relaxation time τ . The hadrons are treated as classical Boltzmann particles and the elastic scattering processes are taken into account. A similar approach has been employed in Ref. [74], where an extensive statistics is used in BTE to calculate the transport coefficients. Here, we extend the approach using Tsallis non-extensive statistics and calculate shear viscosity, bulk viscosity and their ratios over entropy density. First time, we quantify the isothermal compressibility for a hadronic matter using non-extensive statistics. We also calculate the squared speed of sound of hadron resonance gas at finite baryon chemical potential. In view of high-multiplicity events at the LHC and the observation of increase of particle multiplicity driving the system towards thermodynamic equilibrium [114], it becomes important to study these dissipative properties of the systems which are away from equilibrium.

5.3.1 Formulation

We follow the approach mentioned in Ref. [74] to calculate the dissipative properties such as shear and bulk viscosity for a hadronic matter using non-extensive statistics. We start with the BTE given by,

$$\frac{\partial f_p}{\partial t} + v_p^i \frac{\partial f_p}{\partial x^i} + F_p^i \frac{\partial f_p}{\partial p^i} = I(f_p), \quad (5.31)$$

where v_p^i is the velocity of i^{th} particle and F_p^i is an external force acting on i^{th} particle. $I(f_p)$ is the collision integral which gives the rate of change of the non-equilibrium distribution function f_p when the system approaches q -equilibrium.

Assuming no external force and proceeding with the RTA, the collision integral can be approximated as,

$$I(f_p) \simeq -\frac{(f_p - f_p^0)}{\tau(E_p)}, \quad (5.32)$$

where $\tau(E_p)$ is the relaxation time or collision time. We take non-extensive Tsallis distribution as f_p^0 [115] near the local rest frame of the fluid, where the system is described locally by T , μ_B and fluid velocity, $\mathbf{u}$, which change slowly in space and time [116]. The thermodynamically consistent Tsallis distribution, (f_p^0) [117] in the Boltzmann's approximation is given as,

$$f_p^0 = \frac{1}{\left[1 + (q-1)\left(\frac{E_p - \mathbf{p} \cdot \mathbf{u} - \mu}{T}\right)\right]^{\frac{q}{q-1}}}, \quad (5.33)$$

where $\mathbf{u}$ is the fluid velocity. T and μ are temperature and chemical potential, respectively. $\mu = b\mu_B + s\mu_s$, where b and s are baryon and strangeness quantum numbers, respectively. μ_B and μ_s are baryon and strange chemical potentials. For the sake of simplicity, we do not consider the strangeness neutrality condition.

Now, the stress-energy tensor ($T^{\mu\nu}$) can be written as,

$$T^{\mu\nu} = T_0^{\mu\nu} + T_{dissi}^{\mu\nu}, \quad (5.34)$$

where $T_0^{\mu\nu}$ is the ideal part and $T_{dissi}^{\mu\nu}$ is the dissipative part of the stress-energy tensor. In the hydrodynamical description of QCD, shear and bulk viscosities enter in the dissipative part of the stress-energy tensor, which can be written (in the local Lorentz frame) as [116],

$$T_{dissi}^{ij} = -\eta \left(\frac{\partial u^i}{\partial x^j} + \frac{\partial u^j}{\partial x^i} \right) - \left(\zeta - \frac{2}{3}\eta \right) \frac{\partial u^i}{\partial x^j} \delta^{ij}. \quad (5.35)$$

In terms of distribution function, this can be expressed as,

$$T_{dissi}^{ij} = \int \frac{d^3p}{(2\pi)^3} \frac{p^i p^j}{E_p} \delta f_p, \quad (5.36)$$

where δf_p is the deviation of the distribution function from the q -equilibrium and is given by (from Eqs. 5.31 and 5.32),

$$\delta f_p = -\tau(E_p) \left(\frac{\partial f_p^0}{\partial t} + v_p^i \frac{\partial f_p^0}{\partial x^i} \right). \quad (5.37)$$

Assuming a steady flow of the form $u^i = (u_x(y), 0, 0)$ and space-time independent temperature, Eq. 5.35 simplifies to $T^{xy} = -\eta \partial u_x / \partial y$. Now, from Eqs. 5.36 and 5.37, we get (using $\mu = 0$),

$$T^{xy} = \left\{ -\frac{1}{T} \int \frac{d^3p}{(2\pi)^3} \tau(E_p) \left(\frac{p_x p_y}{E_p} \right)^2 q(f_p^0)^{\frac{(2q-1)}{q}} \right\} \frac{\partial u_x}{\partial y}. \quad (5.38)$$

Thus the coefficient of shear viscosity for a single component of hadronic matter can be expressed as,

$$\eta = \frac{1}{15T} \int \frac{d^3p}{(2\pi)^3} \tau(E_p) \frac{p^4}{E_p^2} q(f_p^0)^{\frac{(2q-1)}{q}}. \quad (5.39)$$

The bulk viscosity (ζ) is related to the dissipation when the system is uniformly compressed. We take the trace of Eq. 5.35 and get,

$$(T_{dissi})_i^i = -3\zeta \frac{\partial u^i}{\partial x^i}. \quad (5.40)$$

Using Eq. 5.36, the above equation modifies as,

$$(T_{dissi})_i^i = \int \frac{d^3p}{(2\pi)^3} \frac{p^2}{E_p} \delta f_p. \quad (5.41)$$

Now, using the conservation law for energy-momentum *i.e.* $\partial_\mu T^{\mu\nu} = 0$, one can obtain [116],

$$\frac{\partial \varepsilon}{\partial t} = -w \nabla \cdot u, \quad (5.42)$$

and

$$w \frac{\partial u}{\partial t} = -\nabla P, \quad (5.43)$$

where, $w = \varepsilon + P$ is the enthalpy density, ε is the energy density and P is the pressure. Here, we cannot take steady flow. Thus, Eq. 5.37 takes the form,

$$\delta f_p = -\tau(E_p) \frac{q}{T} (f_p^0)^{\frac{(2q-1)}{q}} \left[E_p \frac{w}{C_V T} \nabla \cdot \mathbf{u} - (\mathbf{v} \cdot \nabla)(\mathbf{p} \cdot \mathbf{u}) \right], \quad (5.44)$$

where C_V is the heat capacity at constant volume. Using Eqs 5.41 and 5.44 and manipulating with the help of conservation laws, the expression for ζ is written as [116],

$$\zeta = \frac{1}{T} \int \frac{d^3 p}{(2\pi)^3} \tau(E_p) q (f_p^0)^{\frac{(2q-1)}{q}} \left(\frac{E_p w}{C_V T} - \frac{E_p}{3} + \frac{m^2}{3E_p} \right)^2. \quad (5.45)$$

Now, using $dP = s dT = w dT/T$, where s is the entropy density, the above equation is reduced to,

$$\zeta = \frac{1}{T} \int \frac{d^3 p}{(2\pi)^3} \tau(E_p) q (f_p^0)^{\frac{(2q-1)}{q}} \left(E_p c_s^2 - \frac{p^2}{3E_p} \right)^2. \quad (5.46)$$

Here, $c_s^2 = s/C_V$ is the squared speed of sound at constant baryon density. For a multi-component hadron gas at finite chemical potential, the shear and bulk viscosities are written as,

$$\eta = \frac{1}{15T} \sum_a \int \frac{d^3 p}{(2\pi)^3} \frac{p^4}{E_a^2} q \left(\tau_a (f_a^0)^{\frac{(2q-1)}{q}} + \bar{\tau}_a (\bar{f}_a^0)^{\frac{(2q-1)}{q}} \right), \quad (5.47)$$

and,

$$\begin{aligned} \zeta = & \frac{1}{T} \sum_a \int \frac{d^3 p}{(2\pi)^3} \tau_a q (f_a^0)^{\frac{(2q-1)}{q}} \left[E_a c_s^2 + \left(\frac{\partial P}{\partial n_B} \right)_\epsilon - \frac{p^2}{3E_a} \right]^2 \\ & + \frac{1}{T} \sum_a \int \frac{d^3 p}{(2\pi)^3} \bar{\tau}_a q (\bar{f}_a^0)^{\frac{(2q-1)}{q}} \left[E_a c_s^2 - \left(\frac{\partial P}{\partial n_B} \right)_\epsilon - \frac{p^2}{3E_a} \right]^2. \end{aligned} \quad (5.48)$$

Here $E_a^2 = p^2 + m_a^2$ and the barred quantities represent the antiparticles. f_a^0 is the distribution function for a^{th} particle. Now, the energy dependent

relaxation time is given as,

$$\tau^{-1}(E_a) = \sum_{bcd} \int \frac{d^3 p_b d^3 p_c d^3 p_d}{(2\pi)^3 (2\pi)^3 (2\pi)^3} W(a, b \rightarrow c, d) f_b^0, \quad (5.49)$$

where $W(a, b \rightarrow c, d)$ is the transition rate defined as,

$$W(a, b \rightarrow c, d) = \frac{2\pi^4 \delta(p_a + p_b - p_c - p_d)}{2E_a 2E_b 2E_c 2E_d} |\mathcal{M}|^2. \quad (5.50)$$

Here $|\mathcal{M}|$ is the transition amplitude. In the center-of-mass frame, Eq. 5.49 can be simplified as,

$$\begin{aligned} \tau^{-1}(E_a) &= \sum_b \int \frac{d^3 p_b}{(2\pi)^3} \sigma_{ab} \frac{\sqrt{s - 4m^2}}{2E_a 2E_b} f_b^0 \\ &\equiv \sum_b \int \frac{d^3 p_b}{(2\pi)^3} \sigma_{ab} v_{ab} f_b^0, \end{aligned} \quad (5.51)$$

where v_{ab} is the relative velocity and $\sqrt{s}$ is the center-of-mass energy. σ_{ab} is the total scattering cross-section in the process $a(p_a) + b(p_b) \rightarrow a(p_c) + b(p_d)$. For further simplification, $\tau(E_a)$ can be approximated to averaged relaxation time ($\tilde{\tau}$) [118] and it can be obtained from Eq. 5.51 by averaging over f_a^0 as,

$$\begin{aligned} \tilde{\tau}_a^{-1}(E_a) &= \frac{\int \frac{d^3 p_a}{(2\pi)^3} \tau^{-1}(E_a) f_a^0}{\int \frac{d^3 p_a}{(2\pi)^3} f_a^0} \\ &= \sum_b \frac{\int \frac{d^3 p_a}{(2\pi)^3} \frac{d^3 p_b}{(2\pi)^3} \sigma_{ab} v_{ab} f_a^0 f_b^0}{\int \frac{d^3 p_a}{(2\pi)^3} f_a^0} \\ &= \sum_b n_b \langle \sigma_{ab} v_{ab} \rangle, \end{aligned} \quad (5.52)$$

here $n_b = \int \frac{d^3 p_b}{(2\pi)^3} f_b^0$ is the number density of b^{th} hadronic species. The thermal average for the scattering of same species of particles with constant cross-section at zero baryon density can be calculated as follows [74, 119,

120].

$$\langle \sigma_{ab} v_{ab} \rangle = \frac{\sigma \int d^3 p_a d^3 p_b v_{ab} e_q^{-E_a/T} e_q^{-E_b/T}}{\int d^3 p_a d^3 p_b e_q^{-E_a/T} e_q^{-E_b/T}}. \quad (5.53)$$

Here $e_q^{(x)}$ is the q -exponential which is defined as $e_q^{(x)} = [1 + (q-1)x]^{q/(q-1)}$.

The momentum space volume elements can be written as,

$$d^3 p_a d^3 p_b = 8\pi^2 p_a p_b dE_a dE_b d\cos\theta. \quad (5.54)$$

The numerator in Eq. 5.53 is written as,

$$\begin{aligned} \sigma \int d^3 p_a d^3 p_b v_{ab} e_q^{-E_a/T} e_q^{-E_b/T} &= \sigma \int 8\pi^2 p_a p_b dE_a dE_b d\cos\theta e_q^{-E_a/T} e_q^{-E_b/T} \\ &\quad \times \frac{\sqrt{(E_a E_b - p_a p_b \cos\theta)^2 - (m_a m_b)^2}}{E_a E_b - p_a p_b \cos\theta}. \end{aligned} \quad (5.55)$$

and the denominator is written as,

$$\begin{aligned} \int d^3 p_a d^3 p_b e_q^{-E_a/T} e_q^{-E_b/T} &= \int 8\pi^2 p_a p_b dE_a dE_b \\ &\quad \times d\cos\theta e_q^{-E_a/T} e_q^{-E_b/T}. \end{aligned} \quad (5.56)$$

Now, using the generalized Tsallis non-extensive statistics for q -equilibrium, the $\langle \sigma_{ab} v_{ab} \rangle$ takes the following form,

$$\langle \sigma_{ab} v_{ab} \rangle = \frac{\sigma \int 8\pi^2 p_a p_b dE_a dE_b d\cos\theta e_q^{-E_a/T} e_q^{-E_b/T} \times \frac{\sqrt{(E_a E_b - p_a p_b \cos\theta)^2 - (m_a m_b)^2}}{E_a E_b - p_a p_b \cos\theta}}{\int 8\pi^2 p_a p_b dE_a dE_b d\cos\theta e_q^{-E_a/T} e_q^{-E_b/T}}. \quad (5.57)$$

Here σ is the cross-section used as a parameter in the calculations. E_a and E_b are integrated in the limit m_a to ∞ and m_b to ∞ , respectively. The limit of integration for $\cos\theta$ is -1 to 1. The relaxation time is calculated by using Eqs. 5.52 and 5.57. The other thermodynamical quantities in

non-extensive statistics are calculated as [117],

$$n = g \int \frac{d^3p}{(2\pi)^3} \left[1 + (q-1) \frac{E - \mu}{T} \right]^{-\frac{q}{q-1}} \quad (5.58)$$

$$\epsilon = g \int \frac{d^3p}{(2\pi)^3} E \left[1 + (q-1) \frac{E - \mu}{T} \right]^{-\frac{q}{q-1}} \quad (5.59)$$

$$P = g \int \frac{d^3p}{(2\pi)^3} \frac{p^2}{3E} \left[1 + (q-1) \frac{E - \mu}{T} \right]^{-\frac{q}{q-1}}. \quad (5.60)$$

n , ϵ and P are the number density, energy density and pressure of hadrons, respectively. The non-extensive entropy density, s can be calculated from the above expression as,

$$s = \frac{\epsilon + P - \mu n}{T}. \quad (5.61)$$

We use the basic expression for addition of entropies in non-extensive statistics while calculating for the multi-component hadron gas, which is given by,

$$s(A + B) = s(A) + s(B) - (q-1)s(A)s(B), \quad (5.62)$$

where $s(A + B)$ is the total entropy of A and B . $s(A)$ and $s(B)$ are the entropies of A and B , respectively. We have also calculated the isothermal compressibility for hadron gas using non-extensive statistics. The isothermal compressibility (κ_T) is defined as [121],

$$\kappa_T = -\frac{1}{V} \frac{\partial V}{\partial P}, \quad (5.63)$$

where V is the volume of the system. Again in terms of fluctuation and average number, isothermal compressibility can be expressed as [121, 122],

$$\langle (N - \langle N \rangle)^2 \rangle = \text{var}(N) = \frac{T \langle N \rangle^2}{V} \kappa_T. \quad (5.64)$$

Since we use the thermodynamically consistent Tsallis statistics, the above thermodynamical relation is valid in this case. Using the basic thermodynamical relation $\langle (N - \langle N \rangle)^2 \rangle = VT \frac{\partial n}{\partial \mu}$, Eq. 5.64 can further be expressed

in terms of number density and compressibility as,

$$\frac{1}{\kappa_T} = \sum_a \frac{n_{aq}^2}{\left(\frac{\partial n_{aq}}{\partial \mu}\right)}, \quad (5.65)$$

where $\frac{\partial n_q}{\partial \mu}$ is given as,

$$\frac{\partial n_q}{\partial \mu} = \frac{gq}{T} \int \frac{d^3p}{(2\pi)^3} \left[1 + (q-1) \frac{E-\mu}{T} \right]^{\frac{1-2q}{q-1}}. \quad (5.66)$$

In hydrodynamics, speed of sound plays an important role in understanding the Equation of State (EoS) and hence, the associated phase transition. This is because of the fact that speed of sound depends on the properties of the medium. The squared speed of sound (c_s^2) is defined as,

$$c_s^2 = \left(\frac{\partial P}{\partial \epsilon} \right)_{s/n}. \quad (5.67)$$

The expression of c_s^2 at finite baryon chemical potential is written as [123],

$$c_s^2(T, \mu_B) = \frac{\left(\frac{\partial P}{\partial T}\right) + \left(\frac{\partial P}{\partial \mu_B}\right) \left(\frac{d\mu_B}{dT}\right)}{\left(\frac{\partial \epsilon}{\partial T}\right) + \left(\frac{\partial \epsilon}{\partial \mu_B}\right) \left(\frac{d\mu_B}{dT}\right)}. \quad (5.68)$$

The term $\frac{d\mu_B}{dT}$ can be calculated using the constant entropy per particle (s/n) condition [123, 124], and given as,

$$\frac{d\mu_B}{dT} = \frac{s \left(\frac{\partial n}{\partial T}\right) - n \left(\frac{\partial s}{\partial T}\right)}{n \left(\frac{\partial s}{\partial \mu_B}\right) - s \left(\frac{\partial n}{\partial \mu_B}\right)}. \quad (5.69)$$

5.3.2 Results and Discussions

In this section, we present the results and discussions of the dissipative and thermodynamic properties of hadronic matter calculated in the NBTE using relaxation time approximation, where non-extensive statistics is used as the q -equilibrium distribution function. The non-extensive parameter, q represents the degree of non-extensivity or in other words the tendency

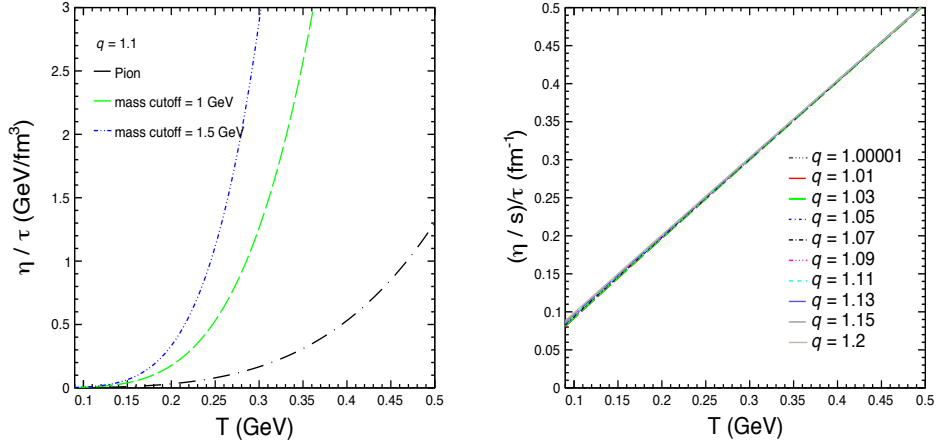


Figure 5.16: (Color online) η/τ (left) and $(\eta/s)/\tau$ (right) versus temperature for various mass cutoff at zero baryon chemical potential [79].

of the system to stay away from the thermodynamic equilibrium. The relaxation time of the system is thus correlated with the q -parameter. The non-extensive parameter, q is related to local temperature fluctuation and possible long-range correlation in the system [58], which is also responsible for the deviation of the system being away from the thermodynamic equilibrium. It has been reported that in the hadronic and elementary collisions where the spectral analysis shows a deviation of the system from the BG equilibrium, the q -value is 1.22 [125]. We study the response of the system as a function of q -parameter. The present study will be very important in view of the multiplicity dependent analysis done in $p + p$ collisions at the LHC. We have seen explicitly from the identified particle spectra in $p + p$ collisions that with higher multiplicity classes, the q -value goes towards one [114]. We consider all hadrons and their resonances with a mass cutoff of 2.0 GeV. First, we estimate various dissipative properties of hadron gas such as shear viscosity (η), bulk viscosity (ζ) and their ratios to entropy density at zero baryon chemical potential ($\mu_B = 0$). We use Eqs. 5.47 and 5.61 to estimate η and s , respectively for zero baryon chemical potential. Here, we calculate the relaxation time (τ) of a^{th} hadron by using Eq. 5.52, where a constant hadronic collision cross-section (σ) = 11.3 mb is taken [74]. In order to check the validity of formulations discussed above, we have presented the calculation of η/τ for pion and various mass cutoffs

at $q = 1.1$ in left plot of Fig. 5.16. We observe that η/τ initially varies very slowly with temperature and as temperature increases, it increases rapidly. The results for pion exactly matches with those of presented in Ref. [47], where the degeneracy (g) of pion is taken to be 1. As we add more hadrons and their resonances into the system, η/τ increases rapidly at a lower T . These findings suggest that the shear viscosity becomes large with the increasing number of particles into the system. We have also shown the variations of the ratio $(\eta/s)/\tau$ of pion with T at various q - values in right plot of Fig. 5.16. Again, we find the same behaviour as observed in Ref. [47] *i.e.* there is almost negligible effect of the non-extensive parameter on this ratio particularly at higher temperature. This is due to the fact that entropy density (s) also increases with the same amount as η/τ with q .

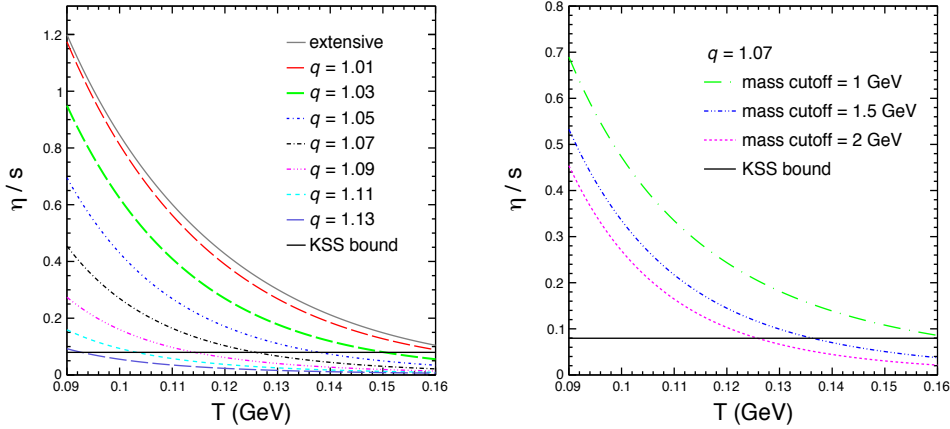


Figure 5.17: (Color online) Left panel shows η/s versus temperature for different q -values. Right panel presents the variations of η/s with respect to temperature at $q = 1.07$ for various upper mass cutoff of hadron resonance gas [79].

Left panel of Fig. 5.17 presents the variations of shear viscosity to entropy density ratio (η/s) with respect to temperature at zero baryon chemical potential, where different lines are for different q -values. Here, solid horizontal line is the KSS bound. The general behaviour of η/s is similar to that observed in Ref. [74]. This ratio decreases with T at all q -values due to rapid increase in entropy density. As the degree of non-

extensivity, q increases, the magnitude of η/s decreases and goes below the KSS bound at a higher T . The temperature at which η/s goes below the KSS bound decreases with increasing q . This can be understood as the drastic change in entropy density of multicomponent hadron gas with T , which makes the value of the ratio, η/s very small. This explanation has been given as a counter-example to the KSS bound in Ref. [126]. Also, in certain field theories [127–129] KSS bound has been shown to be violated. This is a very important finding while understanding the dissipative properties, non-extensivity and the effect of temperature of the system. For comparison, we have also shown the calculation of η/s for hadron gas at zero baryon chemical potential using Boltzmann-Gibbs distribution function. This is shown by the grey solid line in the left panel of Fig. 5.17. η/s as a function of temperature is presented in the right panel of the figure at $q = 1.07$ for various upper mass cutoff of hadrons. Study of the response of the system as a function of temperature for various mass cutoffs is a requirement at higher collision energies. With increase of collision energies heavier resonances are produced. We find that the magnitude of η/s decreases with the increase of mass cutoff due to the contributions of heavier resonances in entropy density of the system.

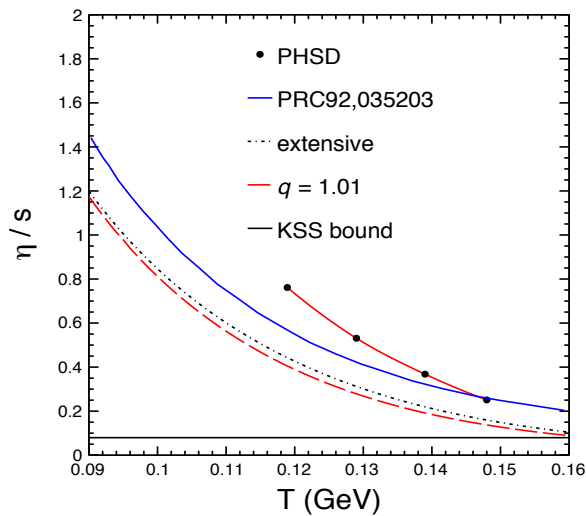


Figure 5.18: (Color online) Comparison of η/s results estimated in various theoretical models [79].

In Fig. 5.18, we have shown the comparison of η/s as a function of T obtained in different model calculations. Here, the red solid line with solid circle is η/s for hadron gas calculated using parton-hadron-string dynamics (PHSD) [130], where RTA with Boltzmann-Gibbs distribution as equilibrium distribution function is used. The blue line is the result taken from Ref. [74], where BTE with RTA is used and BG distribution is taken as the solution of BTE. The red dotted and black dash-dotted lines are the estimations of the present work for $q = 1.01$ and for extensive case ($q = 1$), respectively. The difference between the PHSD and our results for $q = 1.01(\sim 1)$ is due to the difference in estimation of relaxation time. Although we have followed a similar procedure as done in Ref. [74] using non-extensive distribution function, for simplicity, we do not include the excluded-volume correction in the estimation of thermodynamical observables such as number density, entropy density etc., as is done in Ref. [74]. We also see from the figure that when $q \rightarrow 1$, the results are closer to those obtained for extensive case.

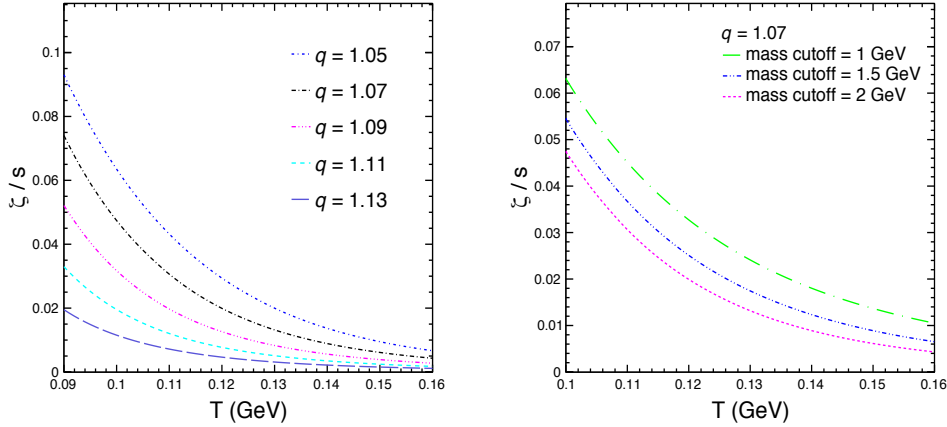


Figure 5.19: (Color online) Left panel shows ζ/s versus temperature for different q -values. Right panel presents the variations of ζ/s with respect to temperature at $q = 1.07$ for various upper mass cutoff of hadron resonance gas [79].

In Fig. 5.19, we discuss the results of bulk viscosity (ζ) and its ratio to entropy density (s) calculated by using Eqs. 5.48 and 5.61 at zero baryon chemical potential. Again, we take a constant value of hadronic cross-section (σ) equal to 11.3 mb while calculating the relaxation time (τ).

In the left panel of Fig. 5.19, we show the variations of bulk viscosity to entropy density ratio (ζ/s) at $\mu_B = 0$ for various q -values. We find that ζ/s decreases rapidly with T for all q . The value of ζ/s is lower for higher q -values. We also observe that ζ/s changes rapidly at a particular T , which is found to be lower for higher q -values. These findings suggest that the degree of approach towards an asymptotic value is sensitive to the non-extensive parameter, q . This goes inline with the expectations of dissipative properties of a system approaching thermal equilibrium. In the right panel, we show the upper mass cutoff dependence of ζ/s for $q = 1.07$. We observe a similar effect of mass cutoff on this ratio as observed in the case of η/s *i.e.* as we increase the upper mass cutoff of hadron resonance gas its magnitude decreases, which is due to increase of entropy density after adding the heavier resonances in the system.

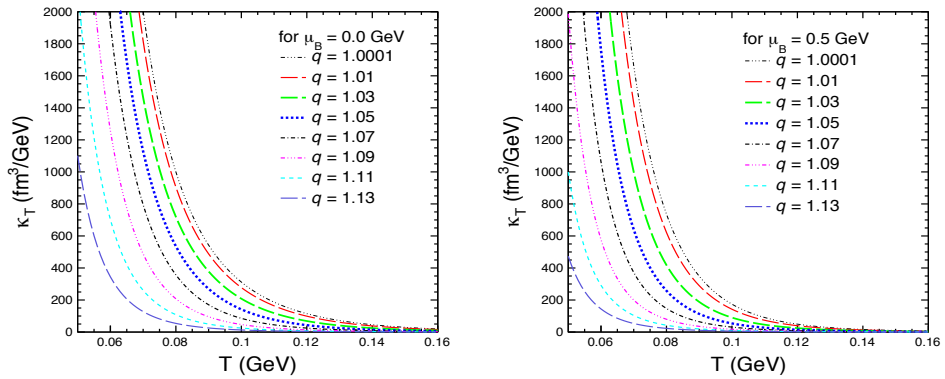


Figure 5.20: (Color online) Isothermal compressibility as a function of temperature for different values of q , with $\mu_B = 0$ (left) and $\mu_B = 0.5$ GeV (right) [79].

Next, we discuss one of the important thermodynamic observables *i.e.* isothermal compressibility (κ_T), which has drawn considerable interest in these days. It is very interesting to quantify this observable for a hot and dense hadron gas formed in hadronic and heavy-ion collisions. In Ref. [53], κ_T is first time estimated for hadrons produced in heavy-ion collisions in extensive statistics using Hadron Resonance Gas (HRG) model. In this work, we have used non-extensive statistics for the calculation of κ_T . In left panel of Fig. 5.20, results of κ_T as a function of temperature at $\mu_B = 0$ are

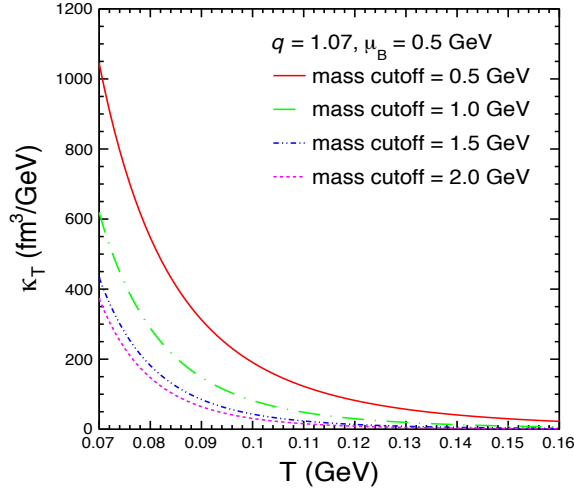


Figure 5.21: (Color online) Isothermal compressibility as a function of temperature for different mass cutoff, with $\mu_B = 0.5$ GeV and $q = 1.07$ [79].

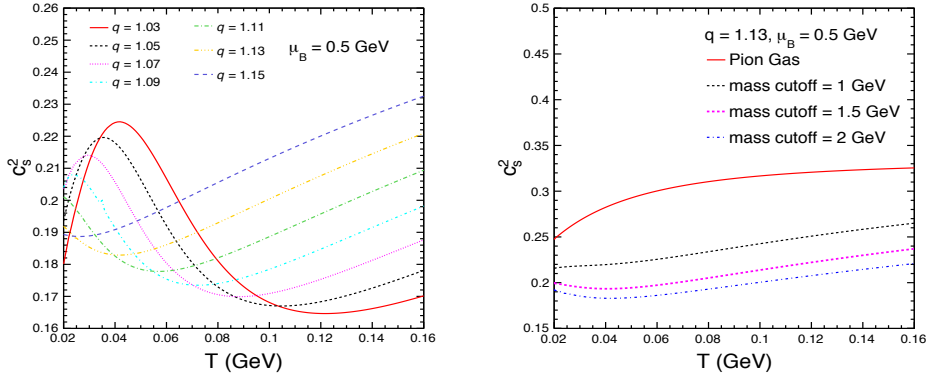


Figure 5.22: (Color online) Left panel shows the estimation of squared speed of sound (c_s^2) at $\mu_B = 0.0$ GeV for different q -values. Right panel presents c_s^2 at $\mu_B = 0.5$ GeV [79].

shown. It is observed that κ_T initially decreases rapidly at low temperatures and becomes constant at higher temperatures for all the q -values. The temperature at which κ_T becomes constant depends on the q -value. As q increases the value of κ_T decrease and the temperature at which it becomes constant shifts towards the lower values, which suggests that there is a strong dependence of κ_T on non-extensivity. The right panel of Figure 5.20 describes the dependence of isothermal compressibility on temperature at $\mu_B = 0.5$ GeV for various q . We find a similar behaviour of κ_T in this case as observed for zero baryon chemical potential but comparatively has

smaller values.

Further, in order to see the effect of upper mass cutoff of hadrons on κ_T , we proceed as follows. We calculate κ_T at $\mu_B = 0.5$ GeV for $q = 1.07$, which is shown in the Fig. 5.21 as a function of temperature. Again, a similar trend is obtained over all the temperatures as observed in the previous plots and as the upper mass cutoff increases, values of κ_T decrease. This effect is more pronounced upto mass cutoff of 1 GeV and after that it gets weaker. κ_T becomes independent of system temperature when higher resonances are added to the system. Hence a system is driven towards a critical behaviour, once we have resonances of higher masses as the ingredients of the system.

Another important thermodynamical observable is speed of sound. We use Tsallis statistics to calculate the squared speed of sound (c_s^2) for finite baryon chemical potential. In Ref. [131], the temperature and mass cutoff dependence of c_s^2 for various q -values have been studied in Tsallis statistics. It is noticed that the criticality in c_s^2 , which is seen as the q -dependent peak in c_s^2 , when studied as a function of temperature, disappears after $q = 1.13$. We have shown c_s^2 as a function of temperature at $\mu_B = 0.5$ GeV for different q -values in left panel of Fig. 5.22. We find that c_s^2 initially increases with T and after reaching at a maximum value it starts decreasing. The maximum in this observable, which is related to the criticality shifts towards lower T as q increases and disappears after $q = 1.13$. These findings are same as observed for the case of $\mu_B = 0$ in Ref. [131]. In right panel of Fig. 5.22, the mass cutoff dependence of c_s^2 is shown for $q = 1.13$ and $\mu_B = 0.5$ GeV. The criticality in c_s^2 disappears when lower mass cutoff is reached, which advocates that criticality of the system depends on the number of hadrons present in the system. Also, we find that c_s^2 decreases with the mass cutoff, which goes in line with the previous observations [131, 132].

With the above findings, we finally summarize all the important results in the next section.

5.4 Summary

Section 1: Xe+Xe collision may provide us with a partonic system whose size is approximately in between those produced by $p+p$ and Pb+Pb collisions. The experimental results on anisotropic flow in Xe+Xe and Pb+Pb collisions should provide us with an opportunity to study system size dependence of v_2 at the approximately same collision energies. In the present work we have used AMPT-SM model to calculate charged particles' v_2 for Xe+Xe collisions at $\sqrt{s_{NN}}=5.44$ TeV at mid-rapidity region $|\eta| < 0.8$ in $0 < p_T < 2.7$ GeV/c. A strong centrality dependence of the v_2 is observed. p_T differential v_2 is measured for identified particles such as, pions, kaons and protons and a clear mass ordering is observed for $p_T < 2$ GeV/c. We have also tried to demonstrate the number of constituent quarks, n_q of the elliptic flow as a function of p_T/n_q as well as with respect to $(m_T - m_0)/n_q$. We find that n_q scaling of v_2 is not observed for types of charged particles used for our studies. Also we haven't used any intrinsic deformations as a first approximation referring to earlier works, which suggest its small influence on observed particle spectra and v_2 beyond 15% centrality collisions. However, most of the results are presented for (50-60)% centrality bin where we do not expect the effects due to deformations. AMPT-SM underestimates the experimental results at higher p_T ($p_T > 1$ GeV/c) with default parameters. It suggests that one needs to tune the parameters to reproduce the experimental results. This study provides a baseline for the recent experimental results.

Section 2: We have used Boltzmann transport equation in relaxation time approximation with non-extensive Tsallis statistics for the first time to estimate nuclear modification factor and elliptic flow for the identified hadrons in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The important findings of this work could be summarized as follows:

1. In this formalism, we find that the final distribution function describes the transverse momentum spectra and the nuclear modification factor of pions, kaons, protons, K^{*0} and ϕ up to considerably

high p_T .

2. The non-extensivity parameter, q_{pp} is mass dependent and it decreases for higher mass particles. Higher mass particles have a tendency of fast equilibration.
3. The inclusion of radial flow, $\langle \beta_r \rangle$ in the theory, favours the non-extensivity, as is expected intuitively.
4. We have observed that a formalism with BGBW alone, could not explain v_2 data beyond $p_T > 1.5$ GeV/c. In order to improve upon this to describe v_2 for higher p_T values, we have incorporated non-extensive Tsallis statistics as the particle distribution in $p+p$ collisions as an input to BTE and evolve it to final distribution with BGBW as the equilibrium distribution. The present formalism could explain v_2 data for identified hadrons up to $p_T = 5$ GeV/c.
5. The present formalism successfully connects the particle production in hadronic collisions with nuclear collisions at the LHC energy.
6. We have found a correlation between the radial and anisotropic part of the transverse flow while explaining the v_2 spectra in different centralities. In central collisions, the radial part is higher than the anisotropic part whereas the reverse is observed in the peripheral collisions.
7. We have also observed that the ratio of freeze-out time to the relaxation time, t_f/τ has a contrasting behaviour with the non-extensive parameter, q in different centralities.
8. In heavy-ion collisions, the peripheral collisions, compared to the central ones, have a higher tendency to go out of equilibrium. This is inferred from the observation of the non-extensive parameter, q increasing towards peripheral collisions (deviating from the Boltzmann-Gibbs equilibrium value of $q = 1$).

9. Hadrons with higher mass are found to have a greater tendency of equilibration. This is evident from the observation of monotonically decreasing relaxation time with particle mass. This is also parallelly supported by the observation of the non-extensive parameter, q decreasing with the mass of the hadrons.

Section 3: In summary, we have studied the transport coefficients using the relativistic non-extensive Boltzmann transport equation (NBTE), where we employ the relaxation time approximation for the collision integral. Here, we have extended the approach using Tsallis non-extensive statistics as q -equilibrium distribution function and calculated shear and bulk viscosity to the entropy density ratios. We have also calculated isothermal compressibility and squared speed of sound using Tsallis statistics at finite baryon chemical potential for different q . The important findings of this work are summarized as follows:

1. We have found that the ratios of shear and bulk viscosity to entropy density have a strong dependence on non-extensivity. Their values decrease with the increasing q -parameter with the temperature.
2. We have observed the effect of mass cutoff on these ratios and as mass cutoff increases the magnitudes of these ratios decrease. These effects are more pronounced at higher values of temperature.
3. We have first time studied the effect of non-extensive parameter, q on isothermal compressibility. We have studied the temperature dependence of isothermal compressibility for various q -values and observed that it decreases rapidly with temperature and becomes constant at higher temperatures. The temperature at which the isothermal compressibility shows a saturation, may indicate an appearance of criticality in the system, which is dependent on q and shifts towards lower values of temperatures for higher q -values.
4. While studying the temperature dependence of isothermal compressibility for various q -values, it has been found that the values of κ_T are

smaller for higher q . It has also been found that, its values decrease at finite baryon chemical potential in comparison to that obtained at zero baryon chemical potential.

5. We have found that, isothermal compressibility strongly depends on the upper mass cutoff of hadron resonances and decreases with the increasing mass cutoffs. It becomes independent of system temperature when higher resonances are added to it. Hence a system is driven towards a critical behaviour, once we have resonances of higher masses.
6. It is observed that as the non-extensivity of the system increases the criticality observed as a peak in the squared speed of sound versus T plot shifts towards lower temperatures and disappears after $q = 1.13$. We have also noticed a strong dependence of criticality on mass cutoff. As upper mass cutoff decreases, the criticality of the system disappears.

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Chapter 6

Summary and Outlook

“What we know is a drop, what we don’t know is an ocean.”

– Sir Issac Newton

The research works discussed in this PhD thesis has been carried out at Indian Institute of Technology (IIT) Indore, India within the ALICE collaboration at the LHC, CERN, Geneva. The PhD project comprises of experimental data analysis as well as phenomenological study to understand the medium formation in hadronic-hadronic and nuclear collisions at ultra-relativistic energies.

In this thesis, the first measurements of ϕ meson in pp collisions at $\sqrt{s} = 5.02$ TeV with ALICE at the LHC along with the first measurements of ϕ meson in pp collisions at $\sqrt{s} = 5.02$ TeV as a function of charged particle multiplicity and transverse sphericity are reported. The efficiency-corrected minimum bias p_T -spectrum is compared with the results from other energies and it has been observed that the bulk production in minimum-bias pp collisions remains independent of collision energy. It is also observed that the p_T -spectra gets harder with increasing collision energy. The ratio of p_T spectra in different multiplicity classes to the minimum bias spectrum shows that the yield increases with increasing charged particle multiplicity. It is found that the integrated yield and mean transverse momentum are independent of collision energies and they solely depend on the charged-particle multiplicity. The comparison of the particle spectra in isotropic, jetty and sphericity integrated classes for different multiplicity classes show that the crossing point of the ratios to

sphericity integrated class for isotropic and jetty events depends on the multiplicity. These results can shed light to explore the QGP-like conditions in high-multiplicity pp collisions. However, for the final conclusion one should look into the corrected p_T spectra for different sphericity and multiplicity classes, which will be reported in future. The presented results on sphericity should serve as an outlook of the ongoing studies.

We have made an extensive study of various observables taking sphericity and event multiplicity in pp collisions at $\sqrt{s} = 13$ TeV using the pQCD inspired PYTHIA 8 model. The aim of the present study is to understand the high-multiplicity pp events at the highest LHC energy in view of a possible formation of QGP-droplet in pp collisions. In view of QGP-like behaviors observed in the LHC pp collisions and the fact that pp no longer serves as a baseline to understand a possible nuclear medium formation in heavy-ion collisions at the LHC energies, it is crucial to understand the mechanism of particle production in these high-multiplicity events. Through these simulation studies, we invoke the explicit inclusion of MPI and CR effects responsible for particle production in pp collisions and then through transverse sphericity and multiplicity dependent analysis we try to understand various aspects of identified particle production in LHC pp collisions.

In view of Xe-Xe collisions at the LHC bridging a multiplicity gap between pp, p-Pb and Pb-Pb, we found that it would be interesting to look into azimuthal anisotropy in Xe-Xe collisions. We have given predictions of the elliptic flow (v_2) of produced particles in Xe-Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV using A Multi-Phase Transport model (AMPT) with string melting version. A strong centrality dependence of the v_2 is observed. p_T differential v_2 is measured for identified particles such as, pions, kaons and protons and a clear mass ordering is observed for $p_T < 2$ GeV/c. We have also tried to demonstrate the number of constituent quarks, n_q of the elliptic flow as a function of p_T/n_q as well as with respect to $(m_T - m_0)/n_q$. We find that n_q scaling of v_2 is not observed for types of charged particles used for our studies. Also we haven't used any intrinsic deformations

as a first approximation referring to earlier works, which suggest its small influence on observed particle spectra and v_2 beyond 15% centrality collisions. However, most of the results are presented for (50-60)% centrality bin where we do not expect the effects due to deformations. AMPT-SM underestimates the experimental results at higher p_T ($p_T > 1$ GeV/c) with default parameters. It suggests that one needs to tune the parameters to reproduce the experimental results. This study provides a baseline for the recent experimental results.

Also, we phenomenologically attempt to formulate a model to characterize the heavy-ion collisions using relativistic kinetic theory in the form of Boltzmann Transport equation using relaxation time approximation. The present formalism successfully connects the particle production in hadronic collisions with nuclear collisions at the LHC energy. However, one should note here that the formalism is the simplistic picture and still crude. It can be modified to include more hadronization processes which is thought to be happening in heavy-ion collisions. In this formalism, we find that the final distribution function describes the transverse momentum spectra, the nuclear modification factor and elliptic flow of pions, kaons, protons, K^{*0} and ϕ up to considerably high p_T . We have observed that a formalism with BGBW alone, could not explain v_2 data beyond $p_T > 1.5$ GeV/c. In order to improve upon this to describe v_2 for higher p_T values, we have incorporated non-extensive Tsallis statistics as the particle distribution in $p + p$ collisions as an input to BTE and evolve it to final distribution with BGBW as the equilibrium distribution. The present formalism could explain v_2 data for identified hadrons up to $p_T = 5$ GeV/c. Hadrons with higher mass are found to have a greater tendency of equilibration. This is evident from the observation of monotonically decreasing relaxation time with particle mass. This is also parallelly supported by the observation of the non-extensive parameter, q decreasing with the mass of the hadrons. In heavy-ion collisions, the peripheral collisions, compared to the central ones, have a higher tendency to go out of equilibrium. This is inferred from the observation of the non-extensive parameter, q increasing towards peripheral

collisions (deviating from the Boltzmann-Gibbs equilibrium value of $q = 1$). We have also found a correlation between the radial and anisotropic part of the transverse flow while explaining the v_2 spectra in different centralities. In central collisions, the radial part is higher than the anisotropic part whereas the reverse is observed in the peripheral collisions. We will continue our investigation on particles' flow with other hadronization mechanisms such as fragmentation and coalescence/recombination model, within the framework of BTE-RTA mechanism.

In addition, we have also studied the transport coefficients using the relativistic non-extensive Boltzmann transport equation (NBTE), where we employ the relaxation time approximation for the collision integral. Here, we have extended the approach using Tsallis non-extensive statistics as q -equilibrium distribution function and calculated shear and bulk viscosity to the entropy density ratios. We have also calculated isothermal compressibility and squared speed of sound using Tsallis statistics at finite baryon chemical potential for different q . We have observed the effect of mass cutoff on these ratios and as mass cutoff increases the magnitudes of these ratios decrease. These effects are more pronounced at higher values of temperature. We have first time studied the effect of non-extensive parameter, q on isothermal compressibility. We have studied the temperature dependence of isothermal compressibility for various q -values and observed that it decreases rapidly with temperature and becomes constant at higher temperatures. The temperature at which the isothermal compressibility shows a saturation, may indicate an appearance of criticality in the system, which is dependent on q and shifts towards lower values of temperatures for higher q -values. We have found that, isothermal compressibility strongly depends on the upper mass cutoff of hadron resonances and decreases with the increasing mass cutoffs. It becomes independent of system temperature when higher resonances are added to it. Hence a system is driven towards a critical behaviour, once we have resonances of higher masses. It is observed that as the non-extensivity of the system increases the criticality observed as a peak in the squared speed of sound versus T plot shifts towards lower

temperatures and disappears after $q = 1.13$. We have also noticed a strong dependence of criticality on mass cutoff. As upper mass cutoff decreases, the criticality in the system disappears.

In the current scenario, with the discovery of QGP-like behavior in pp collisions at the LHC, the study of resonances like ϕ meson will play an important role in understanding the particle production mechanism in pp collisions. The unique and peculiar property of ϕ meson in strangeness sector makes it even more interesting. The usage of event shape observables like transverse sphericity along with charged particle multiplicity will allow us to disentangle the collisions based on its geometrical shape. The present attempt to formulate a model to characterize the heavy-ion collisions using relativistic kinetic theory in the form of Boltzmann Transport equation using relaxation time approximation may help to connect hadronic collisions to nucleus-nucleus collisions.