

Charged particle production in pp and Pb-Pb collisions at Large Hadron Collider (LHC) energies



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This thesis is submitted to

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I would like to dedicate this thesis to my loving parents.

Declaration

I hereby declare that this thesis is the result of my own research work which has been carried out under the guidance of *Prof. Buddhadeb Bhattacharjee* of Gauhati University. I further declare that this thesis as a whole or any part thereof has not been submitted to any university (or institute) for the award of any degree or diploma.

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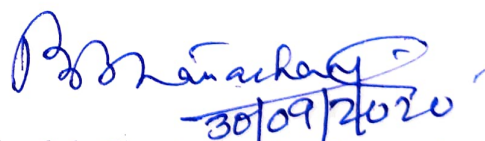
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Certificate

This is to certify that the thesis titled "*Charged particle production in pp and Pb-Pb collisions at Large hadron Collider (LHC) energies*" is the result of research work of *Nur Hussain*, carried under my supervision, submitted to Gauhati University for the award of the degree of Doctor of Philosophy in Physics.

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Abstract

The primary goal of A Large Ion Collider Experiment (ALICE) at the Large Hadron Collider (LHC) is to study the nuclear matter under extreme condition of temperature and energy density, where a transient state of matter known as Quark-Gluon Plasma (QGP) is believed to be created. Indications of its existence have already been provided by previous studies at the Super Proton Synchrotron (SPS) at CERN and the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory. At the LHC at CERN, a new energy regime is being studied, aiming at a better understanding and precise characterization of the QGP properties. Further, it is very much important to study the various thermodynamic properties to understand the different underlying physics processes involved during the entire space-time evolution of the system created in the collisions.

In this work, for the first time for Pb–Pb collisions with ALICE at the LHC, the transverse momentum spectra (p_T) of charged kaons are measured from their decay daughters using *kink topology* at $\sqrt{s_{NN}} = 5.02$ TeV. Using the same technique, the p_T spectra of the charged kaons have also been measured for minimum bias pp collisions at $\sqrt{s} = 5.02$ TeV. While for Pb–Pb collisions the purity of the analysis ranges from 99% at low p_T to 92% at high p_T , analysis for pp collisions shows better purity than Pb–Pb collisions, especially at high p_T , which ranges from 99% at low p_T to 96% at high p_T . The systematic uncertainties for both pp and Pb–Pb collisions have also been presented.

The p_T spectra of identified charged pions, kaons and protons in minimum bias pp and Pb–Pb collisions for different centrality classes at $\sqrt{s_{NN}} = 5.02$ TeV have been presented. A

clear centrality and mass-dependent flattening of the p_T spectra of identified particles has been observed. Such flattening of the spectra is found to be more pronounced in central collisions and for heavier mass hadrons, which is attributed to the presence of strong radial flow. Blast-wave fits of the p_T spectra indicate that in the most central collisions, radial flow is slightly larger (2%) at 5.02 TeV with respect to 2.76 TeV. While the radial flow velocity is found to increase with the increase of centrality, the kinetic-freeze-out temperature decreases with the increase of centrality. Particle ratios (p/π and K/π) as a function of p_T show distinct maxima at $p_T \sim 3$ GeV/c in central Pb–Pb collisions, which is again a clear signal of the presence of strong radial flow. Within uncertainties, the nuclear modification factors are found to be particle species independent for high p_T ($p_T > 10$ GeV/c) and are compatible with the measurements at $\sqrt{s_{NN}} = 2.76$ TeV.

Width of the rapidity distribution of identified particles is considered to be one of the important global observables that provides information about the final state rescattering of hadrons as well as the particle production mechanism. Earlier works [K. Dey and B. Bhattacharjee, Phys. Rev. C **89**, 054910 (2014)] on rapidity width of identified particles at Alternating Gradient Synchrotron (AGS) and low SPS energies, with both Monte Carlo (MC) model generated and experimental data, showed that width of the rapidity distribution follows a separate mass scaling for mesons and baryons and depends not only on the mass of the produced hadrons but also on their quark contents. The net baryon ($B - \bar{B}$) density distribution is found to influence the rapidity width to a considerable extent particularly to hadrons that have leading quarks as the constituent partons. In this work, an attempt has been made, with both experimental and MC model-generated data to extend the study on the dependence of rapidity width on net baryon density distribution to higher SPS (experimental and MC data), RHIC and LHC energies (with MC data only). From this investigation, it has been observed that the dependence of the width of the rapidity distribution of particles containing leading quarks, such as Λ , on the net baryon density

distribution is a general property, both for pp and Pb–Pb systems from AGS to SPS to RHIC and LHC energies for the situation for which $B - \bar{B} \neq 0$. However, for pp collisions for which $B - \bar{B} = 0$, this dependence of rapidity width on net baryon density distribution vanishes resulting same rapidity width for Λ and $\bar{\Lambda}$. Further, a multiplicity dependent study with PYTHIA8-generated data at the highest LHC energy confirms that the jump in the width of the rapidity distribution of Λ disappears for the highest multiplicity class. Therefore, for the highest multiplicity class, where the spectators' partons are either negligible or very small, the rapidity width of Λ becomes same with that of $\bar{\Lambda}$, which indicates that Λ s are mostly pair produced.

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1 | Introduction

Accelerator physics primarily aims to study the interaction of matter created in energetic collisions to explore the interior of the matter and hence the nature of fundamental interactions [1–5]. Lattice Quantum Chromodynamics (QCD) calculations predicted that at extremely high temperature and/or energy density the ordinary nuclear matter undergoes a phase transition from hadronic to a state of deconfined quarks and gluons known as *Quark-Gluon Plasma* (QGP) state, which is believed to have existed just a few microseconds after the Big Bang and presently exists at the core of the neutron star [6]. In laboratory, the ultra-relativistic heavy-ion collisions produce a very hot and dense nuclear matter, providing a possible environment to create a QGP state. The study of such extreme condition of nuclei and QGP, if formed, should be based on the signals or observables that provide evidences of its formation and permit characterization of its properties. If QGP is formed, the matter so produced would be in equilibrium, though for a time period of $\sim 10^{-23}$ sec and would be of very high temperature and density [7]. The constituents matter of QGP is expected to exhibit collective behaviour. The large density gradient created in the collisions is expected to translate into outward pressure which causes the system to explode at relativistic speed [8]. If the system attains a QGP equilibration, the expanding partons are expected to experience a common outward push. This collective nature of the system can be studied by measuring the transverse momentum spectra of the identified particles [9]. Again, the energetic partons which are produced via hard scattering events at the very early stages of the collisions can lose

energy and momentum by rescattering within the medium [8]. Therefore, the final state particle abundances produced from the early state partons that evolve through the dense medium, are expected to deplete as compared to those produced particles that do not evolve through such dense medium. The effect of the energy loss is usually quantified by what is called *nuclear modification factor*, which can be estimated by measuring the yield ratio measured in A–A collisions to pp collisions at the same colliding energy with proper normalization [10].

Another important aspect of studying of heavy-ion collisions, especially at the LHC energies, is to understand the production mechanism of the particles produced in the interaction. Traditionally, the rapidity distribution of identified particles is considered to be one of the important global observables that could be used to characterize the global reaction dynamics and kinematics of the system [11]. Further, widths of the rapidity distributions of the identified particles provide important information, such as the final state rescatterings, longitudinal dynamics, etc. [12–15]. Therefore, the study of such observables at different energy densities and temperatures from Super Proton Synchrotron (SPS) to the highest Large Hadron Collider (LHC) energies is of quite significance and are expected to extend the knowledge about the particle production mechanism.

In the following sections a few general topics of (ultra-)relativistic heavy-ion collisions have been discussed. Some of the important observables of heavy-ion collisions and their significance to trace the partonic nature and various thermodynamic properties of the hot and dense nuclear matter created in the collisions have also been discussed.

1.1 Fundamental interactions of matter

All the physically existing matters in the universe interact with each other via four fundamental interactions: *gravitational, weak, electromagnetic, and strong interactions*. These interactions are characterized based on some criteria, such as— relative strength of the

force, range of the force, mediators (bosons), etc. which are summarized in Table 1.1 [16–18].

Table 1.1 Fundamental interactions of matter.

Interaction	Effective coupling	Range (m)	Mediators (Bosons)	Spin of the bosons
Strong force	1	10^{-15}	8 gluons	1
Electromagnetic force	10^{-2}	∞	photon	1
Weak force	10^{-7}	10^{-18}	$W^{\pm}, Z^0$	1
Gravitation	10^{-39}	∞	graviton	2

The classification of all the fundamental particles and their interactions via the first three forces of Table 1.1 are described in a unified way in the Standard Model (SM), which was formulated during 1970s [18]. According to the SM, the elementary particles are classified into two categories: fermions and bosons. Fermions are spin (intrinsic angular momentum) $1/2$ particles and obey Fermi-Dirac statistics. They are composed of two families viz., six quarks (Table 1.2) and six leptons (Table 1.3), and are spread in three generations together with their antiparticles. On the other hand, bosons, the force mediators of the fundamental interactions, listed in the above table have integral spin and follow Bose-Einstein statistics.

Table 1.2 Classification of quarks [19, 20]. Q , U , D , C , S , T , and B represent charge, upness, downness, charmness, strangeness, topness and beauty, whereas RGB stands for red, green and blue respectively.

Generation	Quarks	Q	U	D	C	S	T	B	Baryon number	Mass	Color
1st	u	$+2/3$	1	0	0	0	0	0	$1/3$	$2.2^{+0.5}_{-0.4} \text{ MeV}/c^2$	R G B
	d	$-1/3$	0	-1	0	0	0	0	$1/3$	$4.7^{+0.5}_{-0.3} \text{ MeV}/c^2$	
2nd	c	$+2/3$	0	0	1	0	0	0	$1/3$	$1.275^{+0.025}_{-0.035} \text{ GeV}/c^2$	
	s	$-1/3$	0	0	0	-1	0	0	$1/3$	$95^{+9}_{-3} \text{ MeV}/c^2$	
3rd	t	$+2/3$	0	0	0	0	1	0	$1/3$	$173.0 \pm 0.4 \text{ GeV}/c^2$	
	b	$-1/3$	0	0	0	0	0	-1	$1/3$	$4.18^{+0.04}_{-0.03} \text{ GeV}/c^2$	

Table 1.3 Classification of leptons [19, 20]. Q , L_e , L_μ , and L_τ represent charge, electron lepton number, muon lepton number and tau lepton number respectively.

Generation	Leptons	Q	L_e	L_μ	L_τ	Mass
1st	e	-1	1	0	0	$0.511 \text{ MeV}/c^2$
	ν_e	0	1	0	0	$< 2 \text{ eV}/c^2$
2nd	μ	-1	0	1	0	$106 \text{ MeV}/c^2$
	ν_μ	0	0	1	0	$< 0.19 \text{ MeV}/c^2$
3rd	τ	-1	0	0	1	$1.78 \text{ GeV}/c^2$
	ν_{τ}	0	0	0	1	$< 18.2 \text{ MeV}/c^2$

The quarks carry color (red, green and blue (RGB)) charges and participate in the strong and weak interactions. The quarks also carry fractional electrical charges of $+\frac{2}{3}|e|$ or $-\frac{1}{3}|e|$ and are sensitive to the electromagnetic interactions as well. The leptons: electron (e), tau (τ) and muon (μ) carry an electric charge only and thus interact via the electromagnetic and weak interactions, whereas the corresponding neutrinos being electrically neutral, take part in the weak interaction only.

The gauge bosons, having spin 1, of the standard model, are defined as the force carriers, which mediate the electromagnetic, weak and strong interactions. The photon is massless and mediates the electromagnetic interactions, whereas $W^\pm$ and Z^0 bosons are massive and mediate the weak interactions. The gluons are massless and have color charges, which mediate the strong interaction between the quarks. In 2012, the LHC discovered the only spin-0 bosons (Higgs boson) of the Standard Model which is responsible for giving the mass to fundamental particles using the Higgs mechanism [21, 22].

1.2 Quantum Chromodynamics

The strong force is responsible for binding the nucleons into the nucleus and quarks into the hadrons. The quantum field theory which describes the strong interaction of hadrons is known as *Quantum Chromodynamics (QCD)*. This is a standard Yang-Mills theory with a gauge group SU(3) and several multiplets of Dirac fields in the fundamental representation of SU(3) [18]. In Quantum Electrodynamics (QED), the interaction takes place between the electrical charges. On the other hand, the charges responsible for strong interactions are color charges, and are the internal degrees of freedom of the QCD theory. In total, there are six color charges in the strong interaction, of which a quark can carry one of the three colors: red, green and blue, and its antiquark carries the corresponding anticolors: anti-red, anti-green and anti-blue. A hadron, consisting either of a quark-antiquark pair or three (anti)quarks, is thus a colorless particle with color-anticolor combination or three color (or three anticolor) combination. On the other hand, gluons, the mediators of quark-quark interactions carry one color and one anti-color, and thus there should be $3^2 = 9$ possible color combinations which are given by [18],

$$r\bar{g}, r\bar{b}, b\bar{g}, b\bar{r}, g\bar{b}, g\bar{r}, \frac{1}{\sqrt{2}}(r\bar{r} - b\bar{b}), \frac{1}{\sqrt{6}}(r\bar{r} + b\bar{b} - 2g\bar{g}), \frac{1}{\sqrt{3}}(r\bar{r} + g\bar{g} + b\bar{b}) \quad (1.1)$$

However, out of these 9 combinations, $1/\sqrt{3}(r\bar{r} + g\bar{g} + b\bar{b})$ is a colorless singlet, leaving 8 active states of gluons. It is important to note that the interquark force is independent of the colors involved in the interaction. Figure 1.1 shows an example of an exchange of color force, where in (a) an electromagnetic interaction between two charges via one-photon exchange compared with (b) a blue quark interacts with a red quark via the exchange of a red-antiblue gluon. Gluons also have self-interaction with triple gluon vertices, which is shown in Fig. 1.1 (c) [18].

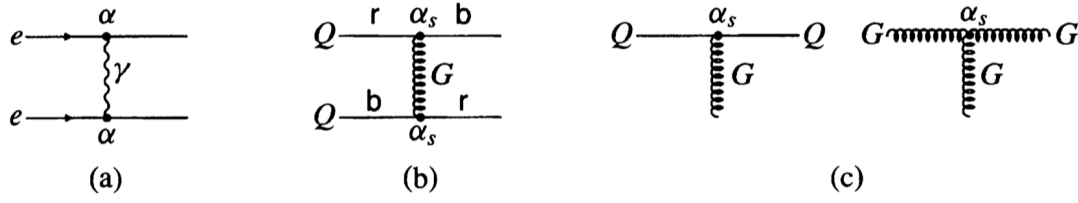


Fig. 1.1 Comparison of an electromagnetic interaction between two charges with a strong interaction between two quarks in (a) and (b). The basic quark-gluon and gluon-gluon vertices are shown in (c) [18].

The strength of the strong force is characterized by the QCD parameter, known as the strong coupling constant α_s . The quark-antiquark potential in terms of coupling constant is given by [18],

$$V_s = -\frac{4}{3} \frac{\alpha_s}{r} + kr, \quad (1.2)$$

where the first term dominates at small r (distance between the interacting color charges), which arises from a single-gluon exchange and is analogous to Coulomb-like term. The second term is a linear one and is associated with confinement at large r . Because of this linear term, it is difficult to separate a quark out of a hadron, rather such attempts simply result in the production of fresh $Q\bar{Q}$ (mesons). This is because of the fact that the lines of force of the color field are pulled together by gluon-gluon interaction forming a tube or string as shown in Fig. 1.2. Energetically pulling out of such string, the stored energy kr gradually reaches the point where it is more favourable to create a new $Q\bar{Q}$ pair and thus forms two new short strings.

In QCD, the strong coupling constant is not a fixed quantity and is termed as *running coupling constant*. This running coupling constant is conveniently expressed in terms of a scale parameter, Λ_{QCD} that limits the validation of perturbative QCD and is given by,

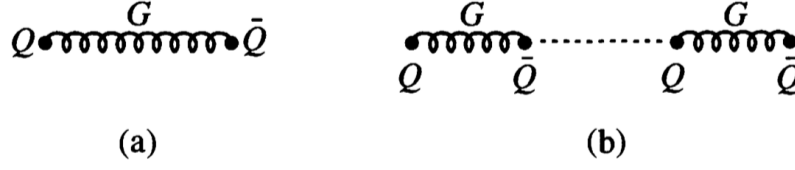


Fig. 1.2 Two quarks connected by a gluon string is shown in (a). (b) Shows the breaking of a string resulting the formation of new quark-antiquark pair forming two hadrons out of one [18].

$$\alpha_s(Q^2) = \frac{12\pi}{11N_c - 2N_f \ln \frac{Q^2}{\Lambda_{QCD}^2}}, \quad (1.3)$$

where N_c represents the number of colors and N_f represents the number of quark flavor. The Λ_{QCD} is a scale parameter having an approximate value of 250 MeV [23], and it provides the limit on the applicability of the perturbative QCD calculation. The hard processes correspond to the processes of large momentum transfer i.e. $Q \gg \Lambda_{QCD}$ and can be described by perturbative QCD. On the other hand, soft processes involving low momentum transfer i.e. Q approaches to Λ_{QCD} , can not be treated by perturbative QCD. These non-perturbative processes are treated by lattice QCD (also known as lattice regularised QCD), where the Euclidian space-time is discretised, usually on a hyperbolic lattice, with quarks fields placed on sites and Gauge fields on the links between the sites [20].

The results of several measurements of running coupling constant $\alpha_s(Q^2)$ as a function of momentum transfer is shown in Fig. 1.3. It is evident from the figure that towards small momentum transfer Q , which means large probed length scale, the coupling strength increases. This phenomenon is associated with the so-called *confinement* property, namely the fact that no isolated color object is found in nature. For large momentum transfer Q , which means a small probed length scale, the coupling decreases. In the limit, when coupling tends to zero, the quarks and gluons behave as free and this property is

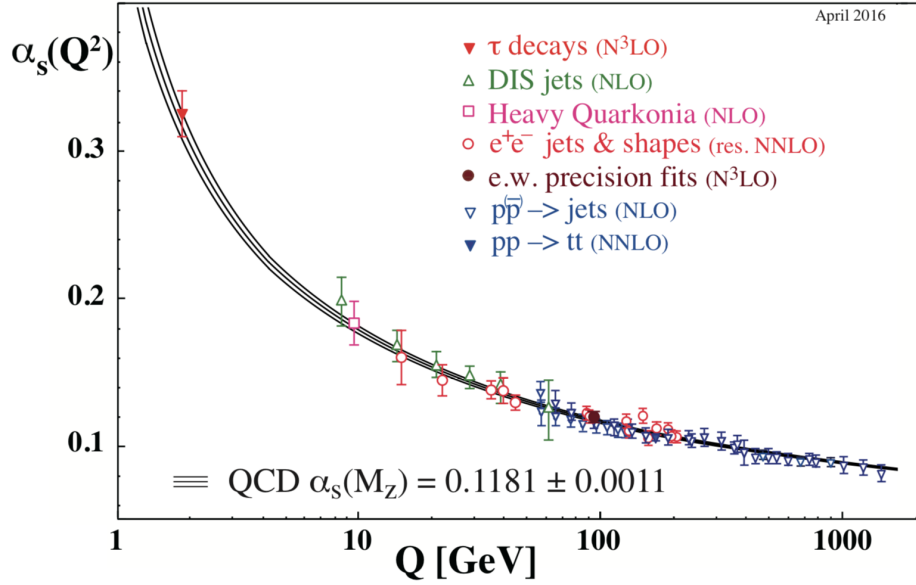


Fig. 1.3 Measurement of α_s as a function of energy scale Q . The brackets carry the respective degree of perturbative QCD theory used in the extraction of α_s , where NLO: next-to-leading order, NNLO: next-to-next-leading order, res. NNLO: NNLO matched with resummed next-to-leading logs, and $N^3\text{LO}$: next-to-NNLO [20].

called *asymptotic freedom*. Formation of QGP is a manifestation of this property of strong interaction.

1.3 A new phase of matter

In the confinement regime, the quarks and gluons are bound together within the hadrons because of the strong force between them, which increases with the increase of distance of separation. Therefore, free quarks and gluons can not be observed in the nature. However, under extreme conditions of temperature and energy density, Quantum Chromodynamical calculation revealed the possibility of the existence of free quarks and gluons, although for a small period of time. A lump of free quarks and gluons can be created in laboratory by means of heavy-ion collisions. The different possible stages of ‘fireball’ created in the heavy-ion collisions with of the possible formation of QGP is depicted in Fig. 1.4.

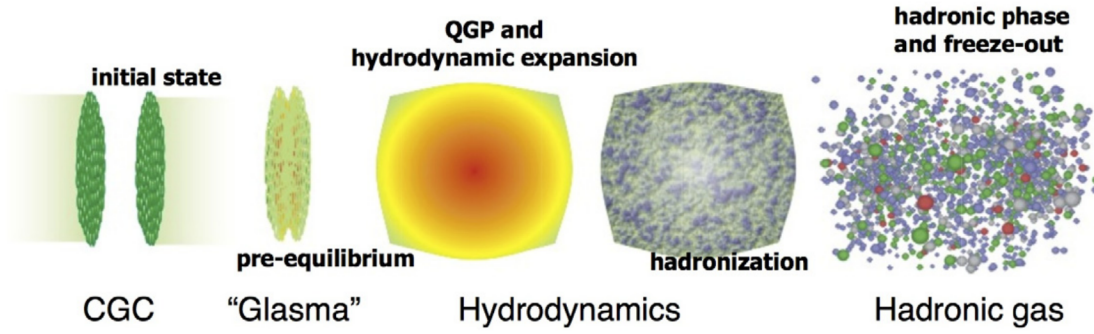


Fig. 1.4 Possible stages of a relativistic heavy-ion collision [26].

In heavy-ion collisions, a situation could be achieved (at AGS/SPS energies [24, 25]) where the nuclear matter density becomes 5 – 10 times the normal nuclear density. Under such situations, the hadrons are compressed into one another. In such cases, the quarks find a considerably large number of neighbouring quarks within a hadron radius and thus cannot identify the original partners in the hadron anymore. When the distance between such quarks with their neighbour is short enough, the attractive force among them becomes very small due to small α_s . They thus feel free and can, therefore, move over an extended volume and the phenomenon is known as *deconfinement* of quarks and gluons. On the other hand, at sufficiently high temperature (at RHIC and LHC energies), hadron might melt producing a large number of quarks-antiquarks pairs in a small volume, which effectively reduce the distances between the quarks making the hadron boundaries disappear [27].

Figure 1.5 shows the lattice QCD phase diagram of strongly interacting matter, with temperature along the vertical axis and the net baryon density along the horizontal axis. The normal nuclear matter has a finite baryon density at low temperature, where the coupling is strong and quarks and gluons are confined inside the hadrons. At a fixed temperature, if the nuclear density is increased about 10 times the normal nuclear matter density ($\rho_0 = 0.16 \text{ GeV}/f m^3$) [28], the wave function of a single hadron overlaps with the spatial region covered by multiple such hadrons. This is termed as a phase transition

from normal nuclear matter to QGP state which corresponds to the core of the super-dense neutron star. The nature of the phase transition of these conditions is a first-order phase transition [29, 30]. Another type of possible transition could be observed during the compression of the baryonic matter at low temperature, where an attractive interaction between quarks in the deconfined baryon-rich phase results in the formation of colored bosonic diquark pairs, similar to Cooper pairs in QCD [31]. At sufficiently low temperature, these diquarks can then condense to form color superconducting state.

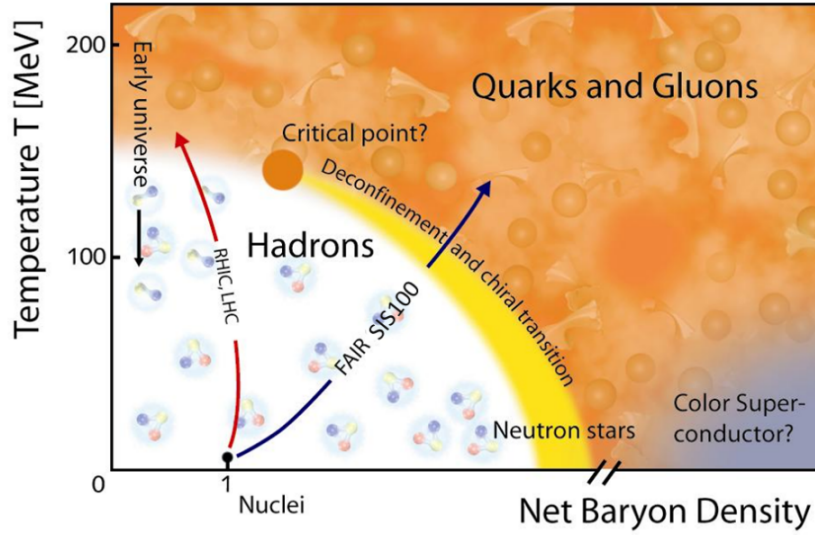


Fig. 1.5 QCD phase diagram of nuclear matter [31].

As shown in Fig. 1.5, the endpoint of the phase boundary of the first-order phase transition line is known as the *critical point*. The exact location of the phase boundary and the critical point is still under investigation and has been of a topic of long-term debate. Depending on the assumptions about the studied systems, the predicted critical value of the temperature T_c ranges from 150 - 170 MeV [28]. At very high temperatures and very small or zero baryon density, the transition is believed to be smooth crossover [32]. This condition of high temperature and vanishing net baryon density is thought to be the analogous situation of the early universe, just after a few microseconds of the Big Bang

and could be reproduced by colliding heavy ions in particle accelerators at the RHIC and LHC.

1.4 A brief review of high-energy heavy ion collision experiments

The term *heavy-ion collision* means the bombardment of two heavy nuclei at any energy, whereas the term *(ultra-)relativistic heavy-ion collision* means the bombardment of heavy nuclei in the energy regime where the kinetic energy exceeds significantly the rest mass energy [33]. One of the most important goals of current theoretical and experimental (ultra-)relativistic heavy-ion research is to study the QCD phase diagram of strongly interacting matter over a range of baryon density and temperatures. The different regions of the phase diagram can be probed through high energy experiments by varying the collision energy [34]. With this exciting hypothesis in mind, over the many decades, studies on (ultra-)relativistic heavy-ion collisions have occupied central stage and several heavy-ion experiments were launched with facilities of colliding various nuclei with a wide range of kinetic energies.

In the early 1970s, systematic experimental studies of relativistic heavy-ion collisions in laboratory conditions started at the Lawrence laboratory in Berkely, USA, and at the Joint Institute of Nuclear Research in Dubna, Russia [28]. In this program light nuclei were accelerated to energies of a few GeV per nucleon, using the old proton synchrotron, which yields compressed nuclear matter at few times of normal nuclear density. Consequently, several accelerators, yielding relativistic beams of heavy ions were developed at various places. The first ultra-relativistic heavy-ion experiments started in 1986 at Brookhaven National Laboratory (BNL) and the European Organization for Nuclear Research (CERN). The Alternating Gradient Synchrotron (AGS) at BNL accelerated ^{28}Si beams up to 14 GeV

per nucleon, whereas, at CERN, the Super Proton Synchrotron (SPS) accelerated ^{16}O beams at 60 and 200 GeV per nucleon. During 1987-1990, the SPS at CERN accelerated ^{32}S beams at 200 GeV per nucleon. In 1992, beams of ^{197}Au were accelerated at 11 GeV per nucleon at BNL, whereas for the first time, the SPS at CERN accelerated ^{208}Pb beams at 158 GeV per nucleon.

The Relativistic Heavy Ion Collider (RHIC) at BNL was the first collider experiment started in the year of 2000 with the designing luminosity of 1400 Au–Au collisions per second. In 2000, during the first run, RHIC collected data of Au–Au collisions up to the maximum centre-of-mass energy of 130 GeV per nucleon pair. In the next three runs, during 2001-2004, RHIC collected data up to the maximum energy of $\sqrt{s_{NN}} = 200$ GeV. Moreover, RHIC also collected data for various colliding systems, such as pp, d–Au and Cu–Cu collisions at various energies (maximum $\sqrt{s_{NN}} = 200$ GeV) to get a proper reference point for the more complicated Au–Au collisions. RHIC comprises of four experiments namely, BRAHMS, PHOBOS, PHENIX and STAR having different experimental motivations.

In 2009, the Large Hadron Collider (LHC) at CERN has become the world's largest and highest-energy particle accelerator with successful operation for Run1 data. LHC is designed to study extensively proton-proton, proton-lead and lead-lead collisions at the TeV energy ranges. It comprises of four big experiments namely, Compact Muon Solenoid (CMS), A Large Ion Collider Experiment (ALICE), A Toroidal LHC Apparatus (ATLAS) and Large Hadron Collider beauty (LHCb). ALICE is a general-purpose, heavy-ion detector system, which is dedicated to study the strongly interacting matter at extreme temperature and energy density. Chapters 2 and 3 contain the details of data analysis and results of the ALICE Run 2 data for pp and Pb–Pb collisions.

1.5 Space-time evolution of heavy ion collisions

The space-time evolution of relativistic heavy-ion collisions is schematically shown in Fig. 1.6. The various forms of the QCD matter formed during the evolution are discussed below:

Before the collision, the nuclei are accelerated nearly with the speed of light in opposite directions. Due to Lorentz-contraction, they look like thin disks in the centre-of-mass frame, which are contracted along the longitudinal direction by a factor of ~ 100 than the radial extent in the transverse plane [35].

At $z = 0$ and $\tau = 0$, the two incoming nuclei collide with each other and the space-time evolution has two possible scenarios: (a) if the energy density and temperature created in the collisions do not attain the critical value necessary for the formation of QGP, the system will behave as of hadronic gas only (left side of Fig. 1.6) and (b) when the initial energy density and/or temperature is very high where quarks and gluons might get free producing QGP. In this scenario, hard particles, such as hadronic jets, dileptons pairs, heavy quarks, direct photons, etc. are produced via hard processes, where the interactions involve large momentum ($Q \gtrsim 10$ GeV) transfer. The semi-hard processes corresponding to the momentum transfer of $Q \sim 1$ GeV, start to develop at a time $\tau \sim 0.2$ fm/c, where the bulk of the partonic constituents are liberated by the collisions. At this stage, most of the multiplicity in the final state are generated via various processes, such as fragmentation of the initial state gluons which undergo a complex evolution. If the produced partons do not interact with each other or the interactions are negligible, they would evolve independently and separate rapidly without an equilibrium state, which is analogous to the situations of low multiplicity pp events at LHC. However, data for the Pb-Pb collisions and high multiplicity pp collisions exhibit collective phenomena which indicates that the partons liberated in the collisions interact strongly. Due to these interactions, the

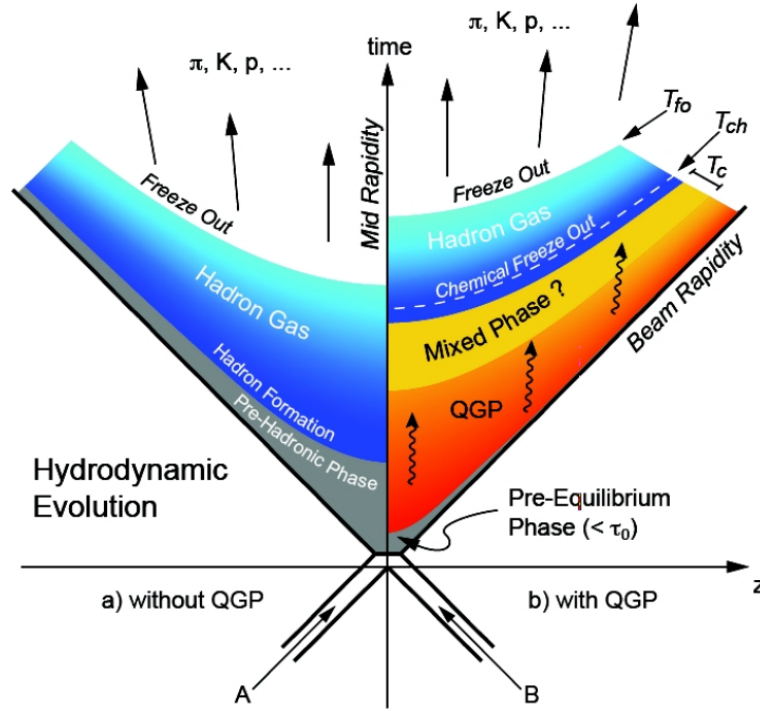


Fig. 1.6 Space-time evolution of relativistic heavy-ion collisions.

partonic matter rapidly approaches towards thermal equilibrium with relatively short thermalisation time of the order of 1 fm/c. This equilibrated state is known as *quark-gluon plasma* state, which is well established by the theoretical lattice QCD calculations. The partonic matter, thus produced, gradually expands and cools down, and eventually at critical temperature $T_c = (150 - 170)$ MeV, the colored partons get confined again within colorless hadrons [28]. This hadronization occurs in Pb-Pb collisions at the LHC at time $\tau \sim 10$ fm/c.

If the phase transition from partonic to hadronic state is of the first order, a mixed-phase is expected comprising of quarks and gluons together with the hadrons. Eventually, the hadronic system continues to expand and reach a temperature T_{ch} (chemical freeze-out temperature), where the inelastic collisions among the hadrons cease and the relative abundances do not change any more for the hadron species. As the system continues to expand, at time $\tau \sim 20$ fm/c, thermal freeze-out occurs at temperature T_{fo} , where the

system size becomes smaller as compared to the mean free path of hadrons. At this stage, the elastic scattering between the hadrons cease and the particles come out from the system freely.

1.6 Observables of heavy ion collisions

In heavy-ion collision studies, there is no unique signature that allows one to study the formation and evolution of QGP state in its entirety. Indeed, various observables in relativistic heavy-ion physics are proposed to realize the possible formation of QGP and study other thermodynamic properties like energy density, temperature, pressure etc. of the matter produced in such heavy-ion collisions [36]. Some of the important observables are briefly discussed in the following subsections.

1.6.1 Charged particle multiplicity

Charged particle multiplicity (N_{ch}) is the total number of charged particles produced in a collision [37]. It is a measure of rigorousness of collision and is also related to the collision geometry. For a particular system, the largest multiplicity corresponds to the most central collisions that are most rigorous. The total number of charged particles (multiplicity) is an important global observable that provides information about the entropy of the system as well as the gluon density of the initial state of the evolving system. Due to the extended nature of the incoming nuclei, their collisions can be characterized by collision geometry or otherwise by collision centrality, which is parameterised in terms the impact parameter of the collision. If the nuclei collide with relatively small impact parameter, many elementary nucleon-nucleon collisions occur and thus copious number of particles are produced, which is termed as *central collision*. On the other hand, collision with large impact parameter, known as *peripheral collisions* results less number of particles. Fig. 1.7

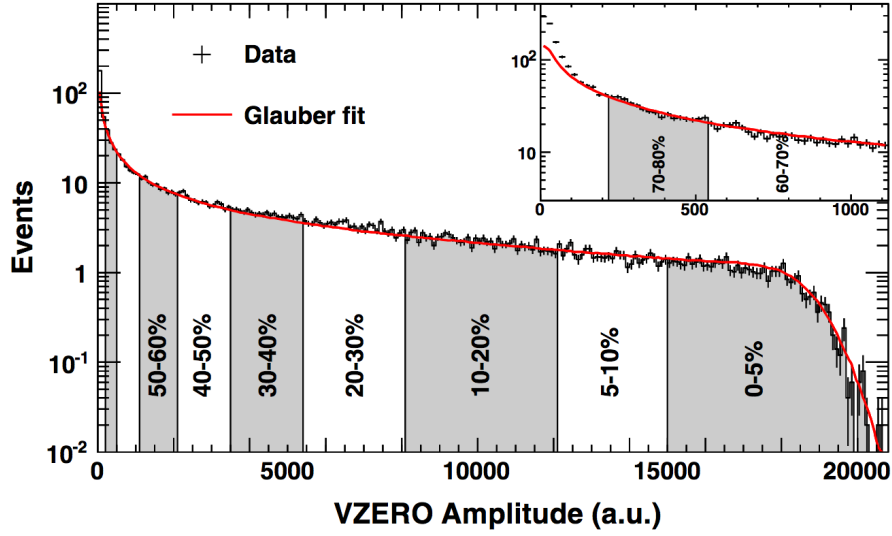


Fig. 1.7 Distribution of summed amplitude of VZERO detectors (VZERO-A +VZERO-C detectors) of ALICE experiment in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [37]. The solid lines represents the Glauber model fit to the measurement [38]. The vertical lines separate the different centrality class.

represents the charged particle multiplicity distribution in terms of summed amplitude of VZERO detectors of ALICE experiment in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [37]. The solid line represents the multiplicity distribution obtained from Glauber model calculation [38] for nuclear collisions. Based on the model fit to the data, centrality of the collisions are determined by integrating the measured distributions.

1.6.2 Rapidity and pseudorapidity distributions

The rapidity and/or pseudorapidity distributions are the important indicators for the global reaction dynamics and kinematics of the system created in high-energy collisions [11]. According to the Landau hydrodynamic model, the rapidity density (dN/dy) or pseudorapidity density ($dN/d\eta$) is proportional to the entropy of the system and hence to the energy density produced in the collisions [39]. The amount of particle production depends on the kinetic energy loss of the incoming hadrons during the collisions. This is

determined by mean rapidity loss given by,

$$\langle \delta y \rangle = y_b - \langle y_b \rangle, \quad (1.4)$$

where y_b is the incoming projectile rapidity and $\langle y_b \rangle$ average net baryon rapidity. Therefore, if the average net baryon rapidity decreases the mean rapidity loss increases which in turns enhance the particle production.

The production of charged hadrons in pp and nucleus-nucleus collisions is dominated by soft pions ($p_T < 1$ GeV/c) which contributes about 85% of the total yield. The evolution of the rapidity distribution of charged pions (π^-) with the centre-of-mass energy ($\sqrt{s_{NN}}$) in Au–Au and Pb–Pb collisions from AGS to RHIC energies ($2.7 \leq \sqrt{s_{NN}} \leq 200$ GeV) is shown in Fig. 1.8 (a) [40]. These rapidity distributions are well described by the Gaussian

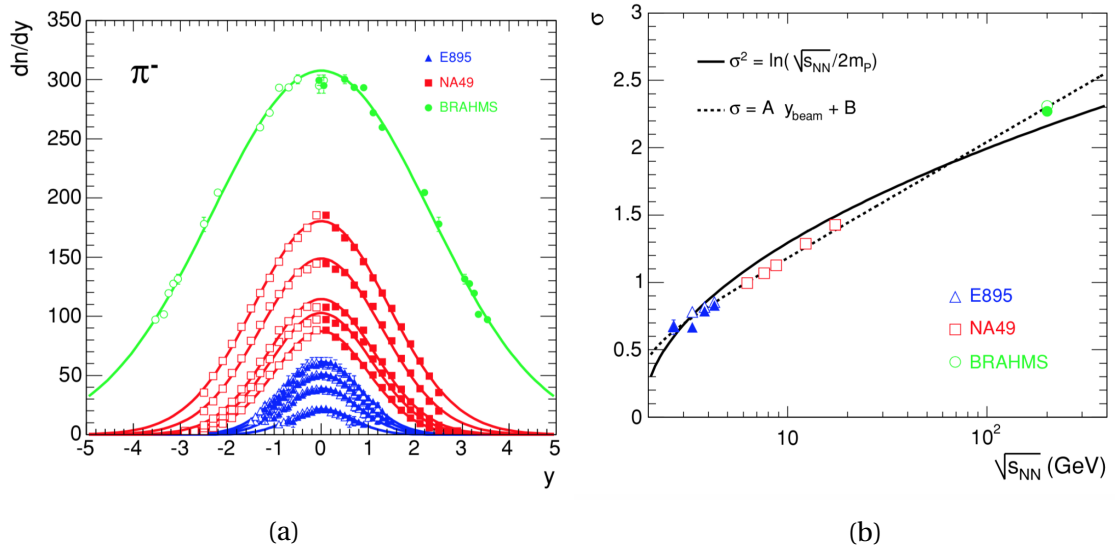


Fig. 1.8 (a) Rapidity distribution of π^- in central Au–Au and Pb–Pb collisions from AGS to RHIC energies [40] and (b) width of the rapidity distribution as a function of $\sqrt{s_{NN}}$.

function and the widths of the rapidity distributions of π^- at various centre-of-mass energies are shown in Fig. 1.8 (b). The widths are well predicted by the hydrodynamical

model proposed by Landau [41, 42],

$$\sigma^2 \propto \ln\left(\frac{\sqrt{s_{NN}}}{2m_p}\right), \quad (1.5)$$

where $\sqrt{s_{NN}}$ is the collision centre of mass energy and m_p is the mass of the proton. It is evident from Fig. 1.8 (a) that with the increase of the beam energy, more and more energy is deposited in the collision, resulting in more production of the charged pion. A clear energy dependence of the width of the rapidity distribution could be seen in Fig. 1.8 (b). It has been reported in Refs. [43, 44] that widths of the rapidity distributions of produced particles in A–A collisions at the SPS energies depends on the rest mass of the produced particles (kinematic behaviour) as well as on their quark content. An increase in the rapidity width of the particles containing leading quarks (u and d) has been observed at AGS and low SPS energies which was attributed to the net baryon density distribution effect [44]. On the other hand, widths of the rapidity distributions of particles containing produced quarks only do not follow the pattern of the net baryon density distribution. Thus, studies on rapidity distribution and the widths of the rapidity distributions of various hadrons are quite informative about the dynamics of the created system, and hence, the particle production mechanism itself. This discussion will be done in further detail in Chapter 4.

1.6.3 Transverse momentum spectra

Transverse momentum spectrum of produced particles is one of the most essential observables of heavy-ion collision studies as it provides important information about the entire space-time evolution of the system created in the collisions [45]. About 99% of the particles produced in the heavy-ion collisions is associated with momentum less than 2 GeV/ c . For example, the transverse momentum distributions of identified particles (π , K and p) for most central Au–Au and Pb–Pb collisions at RHIC and LHC energies are

shown in Fig. 1.9, where a majority of the particles are produced in the low transverse momentum region [46, 47]. A number of important information of the evolving system,

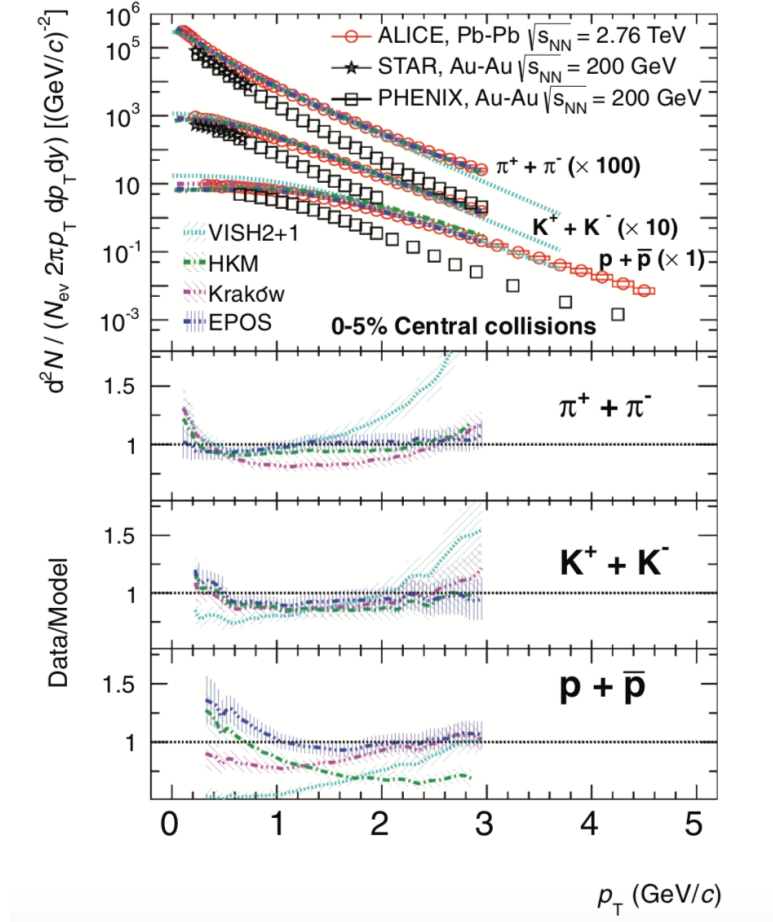


Fig. 1.9 Transverse momentum (p_T) spectra of identified charged pions, kaons and protons for centrality bin 0 – 5% in Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV [46, 47] and Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ GeV [48]. The dotted lines represent p_T distributions with various model-generated data. The lower panels represent the data-to-model ratios.

such as kinetic freeze-out temperature (T_{kink}), transverse or radial flow velocity (β_T), etc. could be extracted from the transverse momentum spectra of identified particles [49].

The kinetic freeze-out temperature describes the excitation degree of the interacting system at the stage of kinetic and thermal equilibrium in which the transverse momentum spectra of particles become fixed [50]. Hydrodynamics-inspired models such as the blast wave model [51–54] can successfully describe the kinetic freeze-out scenario with a

common freeze-out temperature and average transverse radial flow velocity which reflects the expansion in the transverse direction. Details of the extraction of kinetic freeze-out parameters in Pb–Pb collisions will be discussed in Chapter 3.

Although the majority of the particles are produced in the low transverse momentum region, particles produced with the intermediate transverse momentum provide important information about the particle production mechanism. Several studies at RHIC [55–57] and LHC [58] observed a large increase in the baryon-to-meson ratio in central A–A collisions compared to pp collisions in the intermediate momentum regime ($2 < p_T < 6$ GeV/c). Various mechanism [59–62] have been proposed to explain this behaviour and will be discussed in more detail in Chapter 3.

Further, particles with high transverse momentum ($p_T > 10$ GeV/c), originating mainly from hard processes in the early stages of collisions, lose energy in the medium via elastic (collisional energy loss) and inelastic (radiative energy loss) scatterings [63]. While the elastic energy loss is dominant at low collisional energy, the radiative energy loss is dominant in high energy collisions. When a parton with high momentum traverses a QGP medium, it loses energy by the medium induced multiple gluon emission. Thus in heavy-ion collisions, if the parent parton suffers energy loss in the medium, the energy associated with the hadrons produced from such partons is reduced and consequently, their spectrum is depleted compared to the pp collisions. In Chapter 3, the transverse momentum spectra of high p_T particle has also been attempted.

1.6.4 Jet quenching

The early stage partons of the colliding hadrons undergo elastic ($2 \rightarrow 2$) or inelastic ($2 \rightarrow 2 + X$) scattering, resulting in the production of two or more partons in the final state. The outgoing partons which travel in opposite direction carry large momentum and subsequently lose energy by radiating gluons and/or splitting into quarks-antiquarks pair

[64, 65]. Such a parton branching evolution is governed by the QCD radiation probability, which subsequently fragments into a set of final state hadrons. This collimated shower of hadrons produced from the fragmentation of an outgoing parton is called a ‘jet’. During

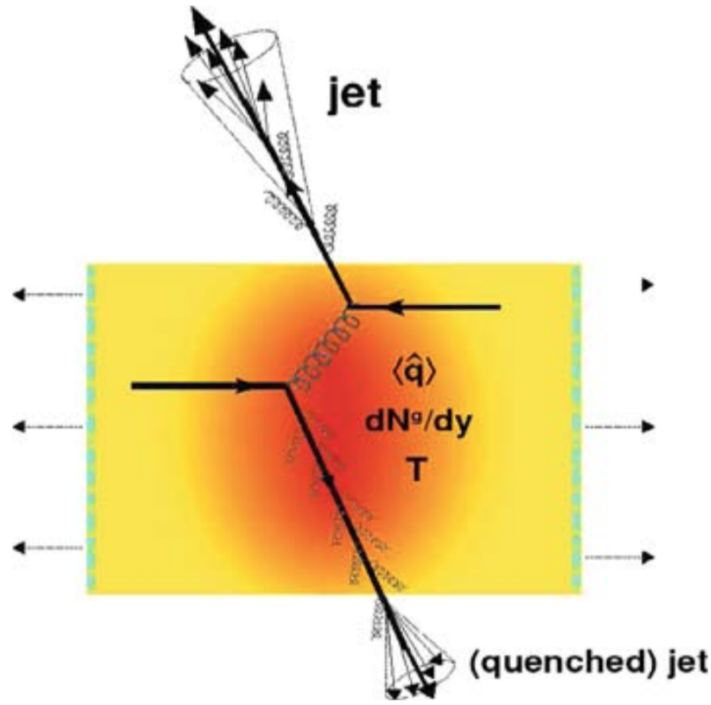


Fig. 1.10 Jet quenching in central nucleus-nucleus collisions [64].

the propagation of the outgoing parton through the medium, it loses energy in the dense plasma produced in the reaction resulting attenuation or even disappearance of shower of hadrons. This energy loss phenomenon is known as ‘jet quenching’ and the amount of energy loss (ΔE) depends on the particle characteristics as well as the plasma properties. Thus the energy loss ΔE provides fundamental information about the medium created in the collision. Fig. 1.10 shows the possible jet quenching in a head-on nucleus-nucleus collisions when two incoming quarks suffer a hard scattering. While one of the parton goes out directly to the vacuum and hadronises by radiating a few gluons, another parton goes through the dense medium produced in the collision, suffers energy loss and finally fragments into a quenched jet [64]. Therefore jet measurements in heavy-ion collisions

could be used as an important probe to characterize the hot and dense medium created in the collisions.

1.6.5 Photons and dileptons

Photons and dileptons ($e^\pm, \mu^\pm$) have been proposed as the most promising and efficient tool to characterize the initial stage of the heavy-ion collisions. While the hadrons are produced from the freeze-out surface after suffering intense rescattering, the electromagnetic probes come from each and every phase of the expanding fireball. The electromagnetic probes have a long mean free path compared to the typical system size (≈ 10 fm). Further, being electromagnetic in nature, they interact very weakly, and thus escape and reach the detectors with minimum interaction with the medium produced in the heavy-ion collisions. Thus, they carry the undistorted information about the early stage of the deconfined plasma [64].

Photons were studied to obtain some important information, such as the temperature of the plasma, evolution of the system size [66–69], momentum anisotropy of the initial partons [70, 71] etc. On the other hand, dileptons are considered as the most reliable observables of the QGP formation (J/Ψ suppression) as well the medium modification of vector meson [72].

1.7 Goal of this thesis

1.7.1 Background of present investigation

Relevance of identification of charged particles

The ultimate goal of heavy-ion collisions at the LHC energies is to study the strongly interacting matter created in the collisions [48]. The RHIC experiment has already reported that the matter created in such collisions exhibits strong collectivity, behaving as a nearly

perfect fluid [73, 74]. The behaviour of collective radial expansion of the particles emitted from the system created in the collisions, can be studied through the transverse momentum distribution of the identified particles [9, 75]. Several studies at RHIC [46, 76–78] reported the transverse momentum distribution of the identified particles like charged $\pi^\pm$, $K^\pm$, and $p(\bar{p})$ in pp and Au–Au collisions at $\sqrt{s_{NN}} = 62.4$ and 200 GeV as shown in Figs. 1.11 and 1.12 respectively. While the shapes of the identified charged pions spectra were found to be similar at all the centrality classes in Au–Au collisions, a centrality dependent hardening of the transverse momentum spectra could be seen for charged kaons and protons. The hardening of the spectra was found to be more pronounced with

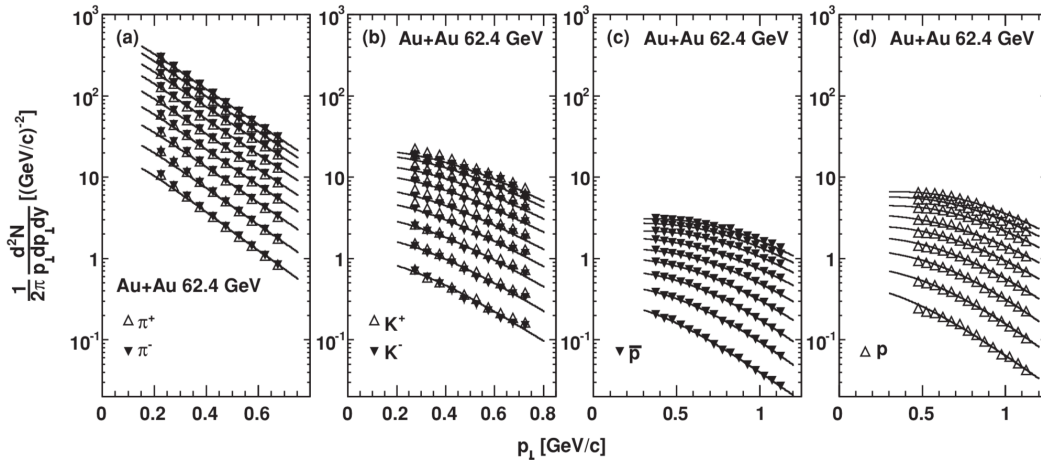


Fig. 1.11 Transverse momentum spectra of identified charged $\pi^\pm$, $K^\pm$, and $p(\bar{p})$ at midrapidity ($|y| < 0.1$) in Au + Au collisions at $\sqrt{s_{NN}} = 62.4$ GeV for nine different centrality classes [46].

increasing centrality and particle mass at both the RHIC energies. They suggested that this centrality and mass-dependent hardening of the spectra is a consequence of radial flow. While the shape of the p_T spectra can be quantified by measuring the mean transverse momentum ($\langle p_T \rangle$) of the identified particles, the radial flow velocity can be extracted from the identified p_T spectra using hydrodynamics-inspired models such as the blast wave model [51–54]. Therefore, the identification of particles produced in the collisions is essential to study the particle mass and collision energy dependent radial flow effect.

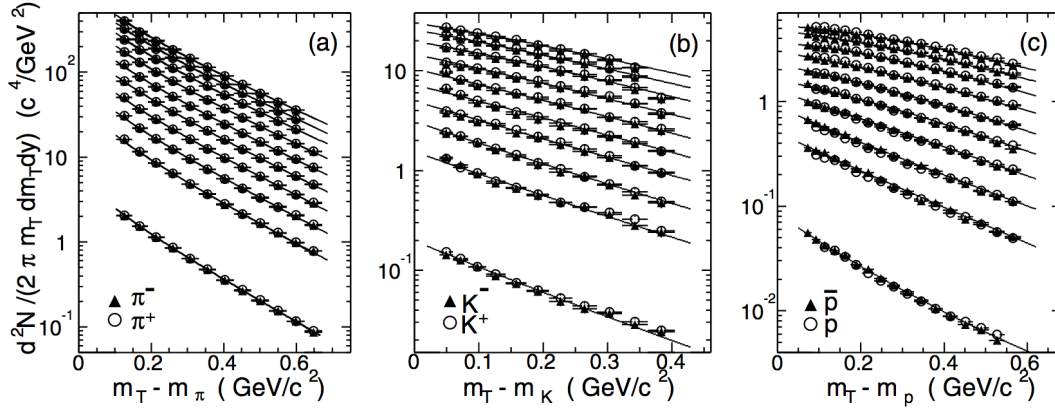


Fig. 1.12 Transverse mass spectra of identified charged $\pi^\pm$, $K^\pm$, and $p(\bar{p})$ at midrapidity ($|y| < 0.1$) for pp (bottom spectra) and Au–Au events at 200 GeV from 70 – 80% (second from the bottom spectra) to 0 – 5% (top spectra) centrality classes [76].

Further, the partons that are produced in the early stage of the collisions through hard processes will lose energy during the evolution of the system due to inelastic scatterings with the dense medium, modifying their final state particle abundances. This energy loss effect is quantified by the nuclear modification factor. The study on nuclear modification factor of identified particles, at the highest LHC energy, is of quite significance as such measurement will provide particle flavour dependent energy-loss information in the dense nuclear medium.

Therefore, precise identification of the final state particles, at the highest LHC energy, is very much important for better understanding of the various thermodynamic properties of the entire space-time evolution of the fireball. The advantage of the ALICE detectors at the LHC is that they have excellent capabilities to identify the various particles produced in the collisions.

Importance of charged K-meson

The study of strange particles production in heavy-ion collisions is of quite significance as it essentially provides ‘first suggested in 1982 by Rafelski and Muller [79]’ information

about the formation of quark-gluon plasma state. Rafelski and Muller argued that due to difference in production mechanism of strange particles in partonic and hadronic media the production of strange particle would be more abundant in the partonic than the hadronic scenario. All the strange particles detected in the detectors are produced in the collision itself as the net strangeness in the colliding nuclei before the collision is zero. The threshold energy for the creation of strange particles in hadron gas is quite large as compared to the partonic medium. In hadron gas, the strange particles are predominantly produced via the reaction $\pi + N \rightarrow K + \Lambda$, with threshold energy ~ 530 MeV. In a partonic medium, the strange-anti-strange quark pairs can be produced by the fusion of two gluons or two light quarks and the threshold energy required for such process is equal to ~ 300 MeV, approximately twice of the mass of the strange quarks. Production of strange quark pairs will be enhanced even more because of the high-density gluonic medium. It is important to note that apart from the QGP information, strange particles also carry information about the dynamics of the entire space-time evolution of the system. Since the charged kaons are the lightest strange hadrons, they dominate the strange particle production in the heavy-ion collisions. Therefore, a systematic investigation about the production of charged kaons might provide crucial input for understanding the matter created in the heavy-ion collisions.

Limitation of the identification of charged K-meson using conventional technique with ALICE detectors

Although the low momentum charged kaons dominate the nucleus-nucleus collisions, measurement of intermediate and high momentum charged kaons is very much essential for the study of some important observables, such as particle ratios, nuclear modification factor, etc. for better understanding of particle production mechanism and characterization of the medium created in the collisions. ALICE detectors have excellent capabilities

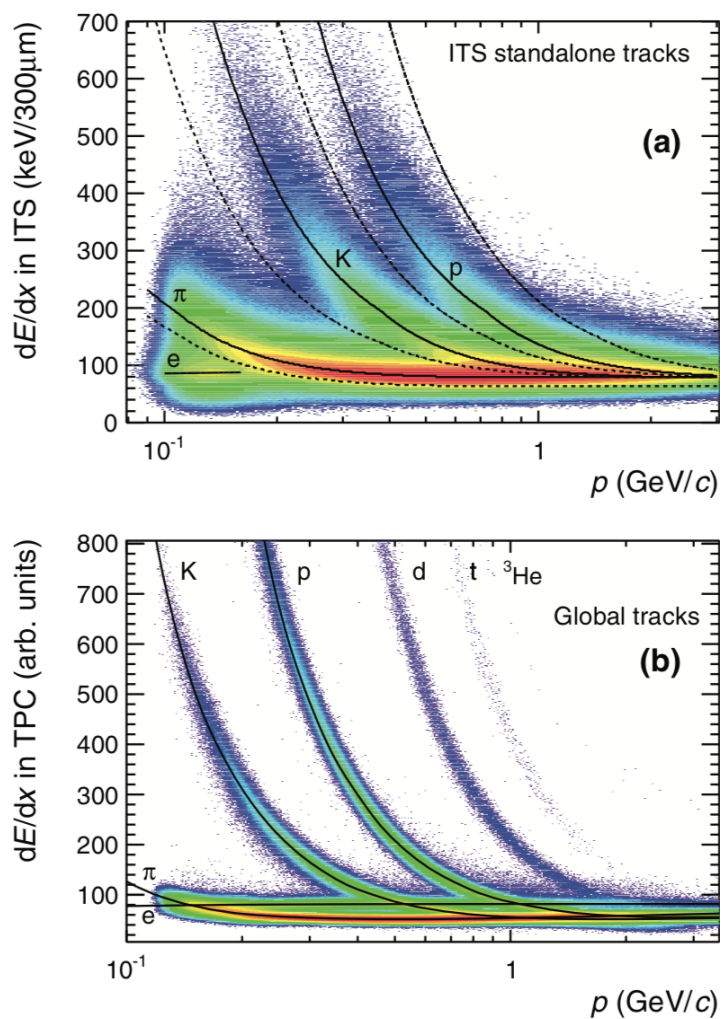


Fig. 1.13 Particle identification performance by measuring the specific energy loss (dE/dx) in (a) ITS and (b) TPC detectors [48] and the continuous curves represent the parametrization of Bethe-Bloch equation.

to identify the charged kaons. Based on the detecting principles, various detectors, such as ITS, TPC, TOF and HMPID can identify charged kaons in different momentum regions. However, not a single detector can identify the charged kaons over the whole (wide) momentum range. As reported in Ref. [80], charged particles like π , K and p can be identified in different momentum ranges with various detectors for pp collisions at $\sqrt{s} = 7$ TeV is shown in Table 1.4. From the table it can be asserted that charged kaons can be identified with kink topology over a wide momentum range.

Table 1.4 Range of transverse momentum in GeV/ c covered by different analysis.

Analysis	π	K	p
ITS-sa	0.1–0.6	0.2–0.5	0.3–0.6
TPC-TOF	0.25–1.2	0.3–1.2	0.45–2.0
TOF	0.5–2.5	0.5–2.4	0.8–4.0
HMPID	1.5–3.0	1.5–3.0	1.5–6.0
Kinks	–	0.2–6.0	–

The specific energy loss (dE/dx) of various charged particles against their momentum (p) using ITS and TPC detectors is illustrated in Fig. 1.13 [48]. It could be readily seen from the figures that the bands (measured dE/dx values) of the particle species, such as pions and protons start to overlap with the charged kaons for the momentum region greater than 1 GeV/ c and thereby, the identity of charged kaons become ambiguous. Therefore, to overcome this difficulty of identifying particles with high momentum, alternative particle identification technique has always been welcomed. The decay topology, known as *kink topology* technique could be successfully applied first time in ALICE Pb–Pb data analysis to identify the charged kaons over a wide momentum range, including the overlap region.

Advantage of kink topology

The main advantage of the kink topology lies on its ability to identify charged kaons over

a wide momentum range. Fig. 1.14 shows the existing results of p_T spectra of identified charged π , K and p in pp collisions at $\sqrt{s} = 7$ TeV using various PID techniques [80], where all the PID techniques are found to be in good agreement (can be seen in the overlap region). It could be clearly seen from the figure that the kink topology could be applied successfully to identify charged kaons in the momentum region of $0.2 < p_T < 6.0$ GeV/c in pp collisions.

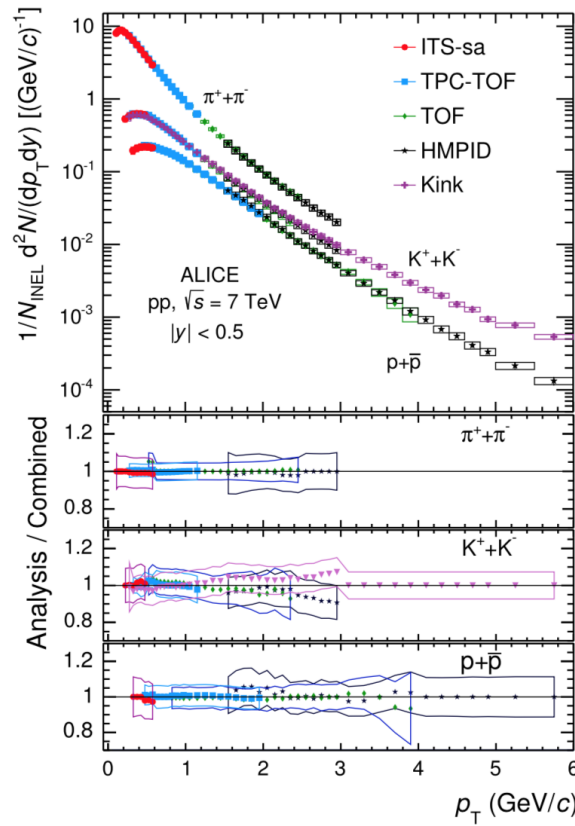


Fig. 1.14 Transverse momentum spectra of identified charged π , K and p in pp collisions at $\sqrt{s} = 7$ TeV (upper panel) with identified with different PID techniques. The lower panel represent the ratio of individual technique to the combined spectra [80].

In this technique, the charged kaons can be identified from the decay topology, where a parent charged particle decays to a charged daughter and a charge neutral particle. The dominant decay modes of the charged kaons are (a) $K \rightarrow \mu^\pm + \nu_\mu$ with a branching ratio of 62.56% and (b) $K \rightarrow \pi^\pm + \pi^0$ with a branching ratio of 20.67%. The main background

in this analysis comes from charged pion which also decays to muon as $\pi^\pm \rightarrow \mu^\pm + \nu_\mu$ with a branching ratio of 99.99%. The kink technique has a very good purity about 97% in pp collisions as reported in Refs. [80, 81]. Although Pb–Pb collisions contain larger contaminations, with the advantage of kinematic properties of the kink topology, these backgrounds are expected to be removed easily. *With this expectation, for the first time, kink topology will be applied to the ALICE Pb–Pb data at the highest LHC energy to identify charged kaons over a wide momentum range and is discussed in detail in Chapter 2.*

1.7.2 Goal of the present investigation

A) Kinetic freeze-out temperature and average expansion velocity: The transverse momentum spectra of identified particles like π , K, and p at the LHC energies can be well described by the models based on relativistic hydrodynamics up to a few GeV/c [9]. These distributions encode information about the kinetic freeze-out temperature T_{kin} and the transverse expansion velocity β_T at the moment when the hadrons decouple from the system. The report on heavy-ion collisions at $\sqrt{s_{NN}} = 200$ GeV at RHIC [83] suggested that the kinetic freeze-out temperature decreases with the increase of collision centrality, whereas the average transverse expansion velocity increases with the increase of centrality, indicating the presence of the strong radial flow. With the availability of Pb–Pb LHC data at $\sqrt{s_{NN}} = 2.76$ TeV [9], the average transverse expansion velocity is found to increase further and kinetic freeze-out temperature decrease further for the highest centrality class as compared to the results measured at $\sqrt{s_{NN}} = 200$ GeV at RHIC. Such observation suggest the significance of studying these observables at the highest LHC energy ($\sqrt{s_{NN}} = 5.02$ TeV). *An attempt has therefore been made to measure the kinetic freeze-out temperature and average expansion velocity in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The result of such measurement has been furnished in Chapter 3 of this dissertation.*

B) Particle ratios: Particle production mechanism in the intermediate momentum range ($2.0 < p_T < 6.0$ GeV/c) is a complicated issue and not yet well understood. The large p/π ratio in heavy-ion central collisions with respect to minimum bias pp collisions in this momentum range has already been observed by various reports at RHIC [84–86]. Recent results by ALICE collaboration in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV also reported even more increase in p/π ratio [9]. Such increase in the p/π ratio is attributed to the radial flow effect, where the low momentum particles are pushed towards intermediate momentum range, effect is more for the hadrons with heavier mass. Further, the hadronisation mechanism like parton recombination model also gives a possible hint for this increased production of proton via the recombination of quarks from the dense partonic medium [87, 88]. Moreover, the observed increase in meson-to-meson (K/π) ratio in central Pb–Pb collisions with respect to minimum bias pp collisions at $\sqrt{s_{NN}} = 2.76$ TeV at the LHC indicates some new hydrodynamic effects [89, 90]. *Therefore, the measurement of such observables at the highest LHC energy is expected to provide more insight into the particle collision dynamics and production mechanism and is reported in Chapter 3.*

C) Nuclear modification factor: The high momentum partons that are produced via hard processes in the early stages of the collisions are expected to carry the information of the medium through which they evolve. In the medium, during their passage, such partons are expected to lose energy by means of inelastic scattering, depleting their final state particle yields. The measurable observable for such study is termed as *nuclear modification factor* (R_{AA}). A strong suppression of nuclear modification factor was reported by RHIC for Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV for $p_T > 8$ GeV/c [91]. Recent study [92] revealed that the energy loss at $\sqrt{s_{NN}} = 2.76$ TeV is 40% larger than the measured values at $\sqrt{s_{NN}} = 200$ GeV. *With the Pb–Pb data at the highest LHC energy, such study will further extend the knowledge about the nature of the hot and dense nuclear matter*

produced in such collisions. The results of studies on nuclear modification factor R_{AA} have been furnished in Chapter 3.

D) Width of the rapidity distribution of identified particles: Study on particle production mechanism is considered to be yet another important aspect of heavy-ion collisions. Measurement of the width of the rapidity distribution of various mesons and baryons is of prime interest as such measurement provides information about the final state re-scattering, longitudinal dynamics, etc. which in turn helps in understanding the particle production mechanism itself [12–15]. NA49 collaboration [43] reported that the widths of the rapidity distributions of various mesons and baryons at all the SPS energies follow a mass ordering due to the obvious reason of the mass dependence of the scattering of the produced particles. However, in Ref. [44] it was shown that at AGS and low SPS energies, in addition to the mass dependence, the widths of the rapidity distribution strongly depend on the quark contents of the particle (non-kinematic behaviour). The rapidity distribution of the particles containing leading quarks (u and d) are found to follow the pattern of the net baryon density distribution, whereas particles containing produced quarks only do not follow such dependency. It is important to note here that the net baryon density distribution is sensitive to the degree of stopping of the colliding nuclei, or in other words the transparency of the collision. At SPS energies, due to the degree of stopping of the incoming nuclei, the net baryon density is found to populate the mid rapidity only [44], whereas at the RHIC and LHC energies, such distribution is expected to populate the extreme rapidities only. Therefore, the evolution of the width of the rapidity distribution of identified particles with beam energies from lowest SPS to the highest LHC energies, with available experimental and model generated data, is expected to provide some important information about the role of net baryon density distribution on the width of the rapidity distributions of the produced particles. Due to the limitation

of the detector acceptance, no experimental results are available over the full rapidity range at the RHIC and LHC energies. Therefore, such rapidity-dependent studies have been carried out with the available experimental (SPS) data and Monte-Carlo (SPS, RHIC and LHC energies) generated events.

It is worth mentioning to note here that in case of pp collisions at RHIC and LHC energies, the colliding protons are considered to be extended objects consisting of many partons [93] and resemble the situation similar to the heavy-ion collision. Whereas the spectator regions of heavy-ion collisions are composed of hadronic matter, the spectator regions of pp collisions are composed of partonic matter only. In the case of heavy-ion collisions it has been observed that the spectator hadrons play an important role in particle production mechanism, in particular in Λ production. It would be interesting to investigate the role of spectator partons of pp collisions in the particle production mechanism. The details of such studies have been included in Chapter 4.

2 | Experimental setup and analysis details

2.1 Introduction

Over the century, various experiments were devised to study the internal structure of matter and the interactions among their constituent particles. In 1911, Ernest Rutherford carried out the famous experiment with gold foil as a target and alpha particle as a projectile, which revealed the concept of the atomic nucleus. During 1920s and 1930s, few more experiments revealed further details of the substructure of the atomic nucleus. One of the substructures is positively charged, which Rutherford eventually referred to a *proton*, and in 1932 his student James Chadwick identified another sub-particle of nucleus which is electrically neutral and was termed as *neutron* [94].

Although it was a big challenge for physicists to study the substructure of the atomic nucleus due to its smaller size, an incredible idea developed by Louis de Broglie solved this difficulty. He proposed that all matter has wave properties. If we impart more and more energy to a given particle, its momentum increases and accordingly the wavelength of the associated matter-wave decreases following the equation $\lambda = \hbar/p$. As the wavelength decreases more and more with the further increase of momentum of the particle, it becomes possible to explore the smaller and smaller building block of matter using

energetic particles. Therefore, the structure of the proton and neutron can be studied by firing energetic particle to them. Based on this idea, various accelerators were designed and developed and experiments using those accelerators were conducted during 1950s and 1960s. From such experiments it was found that both protons and neutrons are not elementary in nature, rather are composite structure [94]. The fundamental constituents of these protons and neutrons are *quarks and gluons* that interact through strong interactions. To study such strongly interacting matter in further detail, a number of large particle accelerators were constructed during past decades at few places over the world. Among these, one at Lawrence laboratory in Berkely, USA and the other at the Brookhaven National Laboratory, New York, USA, where the energy of the bombarding nuclei reached up to 14 GeV per nucleon, conducted some path breaking experiments. The beam energies were further boosted in various experiments at the Super Proton Synchrotron (SPS) at CERN, Switzerland, where the beam energy reached up to 158 AGeV. While in a fixed-target experiment, the accelerated projectile collides with a fixed target, in a collider experiment, collisions take place between two beams of accelerated particles directed against each other. Therefore, a huge amount of energy can be deposited to the resulting system in a collider experiment as compared to a fixed-target experiment. The first collider experiment was performed at the Relativistic Heavy Ion Collider (RHIC) at the BNL, where two accelerated beams of Au-Au collided at the centre of mass energy of 200 GeV. To increase the beam energy further and for better and precise measurement of various physics observables, the world's largest machine, the Large Hadron Collider (LHC) was built at CERN. The ultra-relativistic heavy-ion collision at the unprecedented energy in the TeV range, at the LHC, produces a large number of particles and necessitates precise measurement of different parameters of these emitted particles. For this purpose, various detectors with bigger size and excellent capabilities were installed at different interaction points of the LHC experiment. A Large Ion Collider Experiment (ALICE) is one of the main

experiments of the LHC and the major portion of the present dissertation is based on the description of ALICE data analysis procedure and providing the physics interpretation of the analysed data.

In order to study the various physics observables of heavy-ion collisions as discussed in Chapter 1, it is essentially important to identify precisely various charged particles, such as pion, kaon, proton, etc. produced in the collisions. Different ALICE sub-detectors, such as Inner Tracking System (ITS), Time Projection Chamber (TPC), Time Of Flight (TOF), High Momentum Particle IDentification (HMPID), etc. have excellent particle identification capabilities. Based on the working principle, each detector provides a different technique to identify charged particles for some limited momentum range and will be discussed in detail later in this chapter.

For the present investigation, identification of charged kaon is of special significance. The ITS and TPC detectors are widely used to identify charged kaons by measuring the specific energy loss (dE/dx) information, especially at the low transverse momentum where the Bethe Bloch plots of the particle species are well separated. For high momentum region, the energy loss information becomes almost same for all the particle species, and hence it becomes difficult to separate charged kaons from pions and protons. *Kink topology* is an alternative particle identification technique, that could be used to identify the charged kaons from their decay daughters, even in the momentum region where the specific energy loss of different particle species becomes almost same. In this work, identification of charged kaons within the TPC volume using this decay topology, over a wide momentum range, has been carried out for the first time in heavy-ion (Pb–Pb) collisions in ALICE and will be discussed in detail in this chapter. This chapter also includes the details of the analysis technique, such as event and track selections, correction factors incorporated, purity of the analysis, the comparison between the experimental and Monte Carlo data, and both statistical and systematic error estimation.

2.1.1 The Large Hadron Collider (LHC) accelerator at CERN

The Large Hadron Collider (LHC) accelerator is the world's largest and the most powerful particle accelerator located at CERN, Switzerland and was set up inside the existing 27 km tunnel of the Large Electron-Positron Collider (LEP). It is located around 50 – 175 m underground between the borders of Switzerland and France.

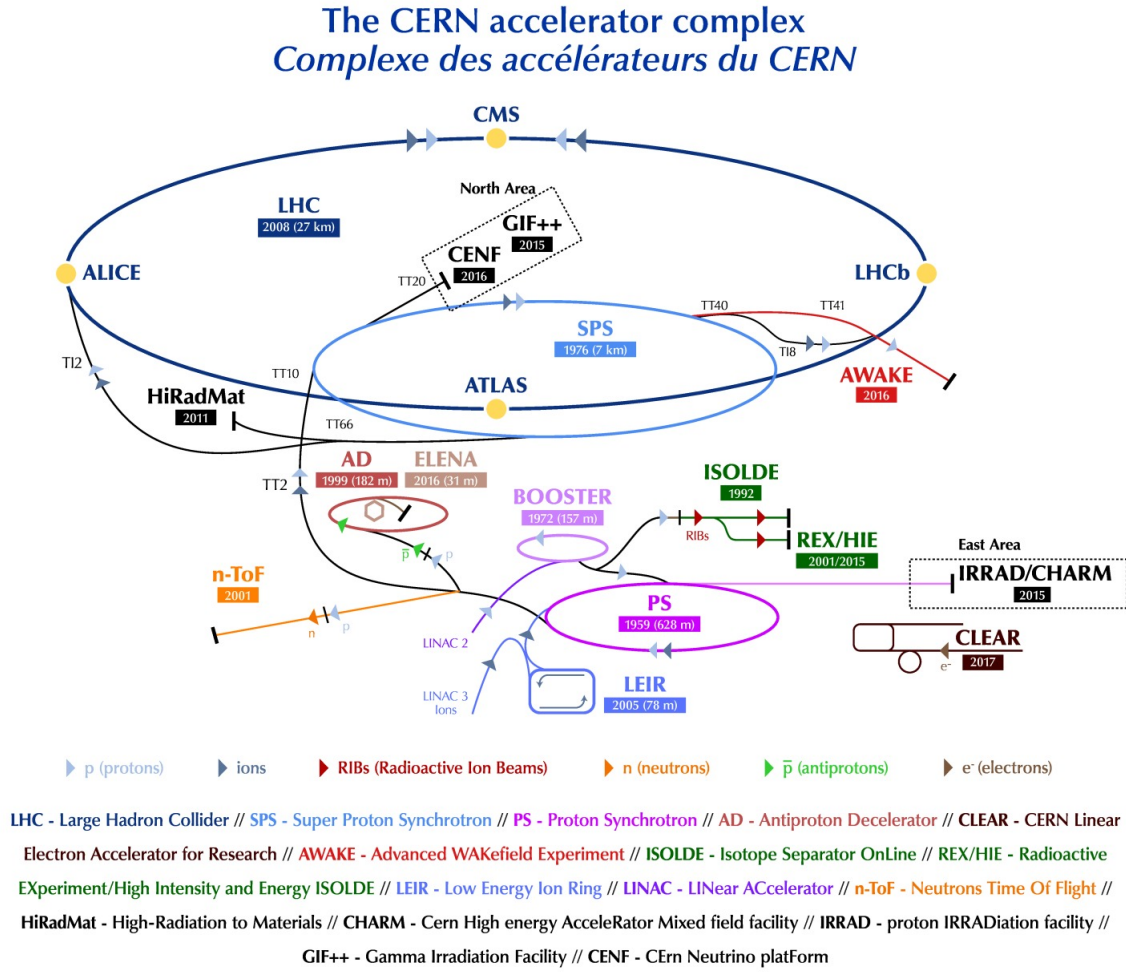


Fig. 2.1 The CERN accelerator complex [97].

The CERN accelerator complex is depicted in Fig. 2.1, comprising of various particle accelerators used for the subsequent increment of energy at each position before injecting it to the LHC beam pipe. Each accelerator works in a sequence and boosts the speed of

the beam particle, before injecting it to the next one [95, 96]. In the beginning, electrons are removed from the hydrogen atoms to obtain proton for acceleration. These protons are injected to the Proton Synchrotron Booster from the linear accelerator (LINAC2), then to the Proton Synchrotron (PS), where protons are accelerated up to 25 GeV. Then it is injected to Super Proton Synchrotron (SPS) to enhance the energy up to 450 GeV and finally injected to the Large Hadron Collider (LHC). On the other hand, lead ions are prepared from a source of vaporised lead that enter LINAC3 and accelerated in the low energy Ion Ring (LEIR) and subsequently follows the same route of proton for further acceleration.

Though LHC started its operation on 10th of September 2008, there was a long technical stop due to the serious damage of its superconducting magnets and the beams again started to circulate in November 2009, for the preparation of Run 1 program to take physics data. In Run 1 program, LHC was able to collide proton beam in March 2010 at the centre of mass energy of 7 TeV, while in April 2012 the beam energy reached up to 8 TeV. The LHC is capable of colliding heavy-ion as well, and the first heavy-ion collisions for Pb–Pb system was registered in November 2010 at the centre of mass energy of 2.76 TeV. For the first time, in September 2012, LHC also took data for p–Pb collisions at the centre of mass energy of 5.02 TeV. Run 1 program ended with a long shutdown during 2013 – 2014 with a large number of consolidation and upgrade activities [98]. After this long shutdown, Run 2 program started in 2015 and continued until the end of 2018. During 2015 to 2018, LHC registered data for pp collisions at the centre of mass energy of 13 TeV and Pb–Pb data at the centre of mass energy of 5.02 TeV.

At the LHC, the protons or heavy-ions are injected into two rings as trains of bunch and circulate in opposite directions. All bunches cross, and some of them collide at four interaction points named as IP1, IP2, IP5, and IP8, which correspond to the experiments ATLAS, ALICE, CMS, and LHCb respectively as shown in Fig. 2.1.

The general-purpose detectors of ATLAS and CMS have the same physics goals; generally, investigate a wide range of physics related to Standard Model and Higgs bosons to understand the extra dimension, and about the candidates of the dark matter. On the other hand, ALICE is designed to study the strongly interacting matter at extreme temperature and energy density, where a new state of matter, widely known as *Quark-Gluon Plasma* is supposed to be created. The LHCb experiment is dedicated to studying the deeper physics about the matter and anti-matter asymmetry.

2.1.2 A Large Ion Collider Experiment (ALICE) at the LHC

ALICE is one of the largest experiments of the LHC devoted to the investigation of strongly interacting matter at extreme temperature and energy density. It allows a comprehensive study of hadrons, muons, electrons and photons produced in heavy-ion collisions (Pb–Pb and Xe–Xe). To vary the interaction volume and energy density, ALICE also takes the data for various colliding systems, such as pp and p–Pb. ALICE project involves an international collaboration of more than 1,800 physicists, engineers, technicians, and graduate students from 178 institutes of 41 countries across the world. ALICE of the LHC is a composite detector consisting of 18 sub-detectors and is situated at 56 m underground. It is 26 m long, 16 m high, 16 m wide, and weights about 10,000 tons [99]. The details of the ALICE detectors have been discussed in the section [2.1.4](#).

2.1.3 ALICE coordinates system

For a better assessment of the ALICE detectors and data analysis, it is very much important to get familiar with the ALICE coordinate system. Taking the beam interaction point as the origin $(x,y,z) = (0,0,0)$, ALICE coordinate system is described in terms of the right-handed Cartesian coordinate system. The coordinate system is discussed as follows [100]:

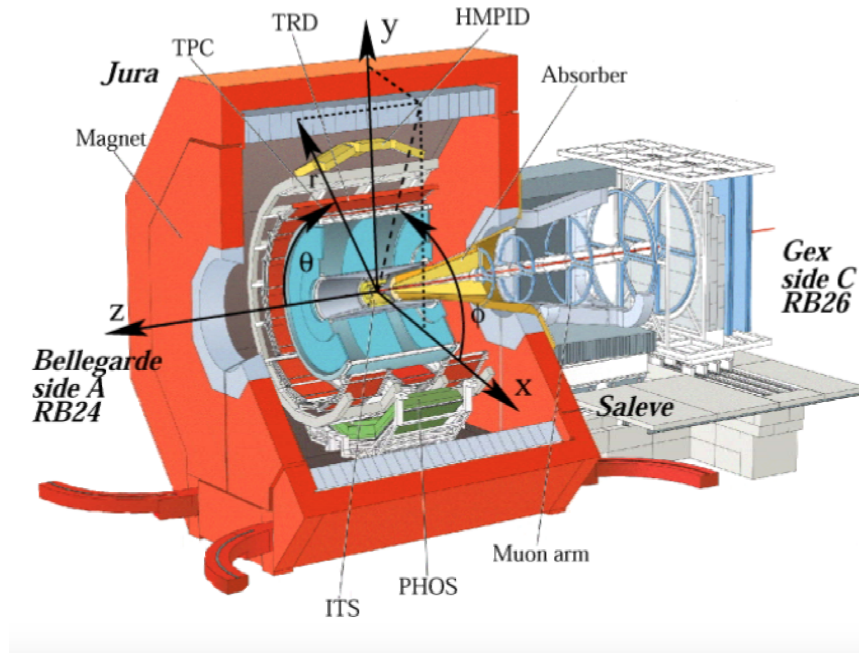


Fig. 2.2 The ALICE coordinate system [100].

1. **z-axis:** The z-axis is taken along the beam direction known as *longitudinal direction* (Fig. 2.2). The positive direction of the z-axis is taken from the origin towards the A(ATLAS)-side, whereas the negative z-axis is towards the C(CMS)-side. For example, the muon chamber of the ALICE detector is situated at negative z.
2. **x-axis:** The x-axis is transverse to the z-axis, which is aligned to the local horizontal and pointing towards the accelerator centre. From the origin $(x,y,z) = (0,0,0)$ to the accelerator centre is designated as positive x, whereas the negative x is from the point of origin to the outward direction.
3. **y-axis:** It is pointing upward and perpendicular to the x-axis. From the point of origin $(x,y,z) = (0,0,0)$ to the upward direction is designated as positive y, whereas the negative y is from the point of origin to the downward direction.

4. Azimuthal angle (ϕ): It is measured with respect to the x-axis in counter-clockwise. In this case, the observer is to be positioned at positive z-axis and to be observed in the direction of RB26 as shown in Fig. 2.2.
5. Polar angle (θ): It is measured from z-axis to x-y plane.

2.1.4 ALICE detectors

The current setup of ALICE detector [99, 101], containing 18 sub-detectors is shown in Fig. 2.3. The whole ALICE detector system is mainly categorized into two components– a) the central barrel, contained inside the large L3 magnet and the containing detectors are devoted mainly to hadron detection. This component covers the pseudorapidity range of $-0.9 < \eta < 0.9$ over the full azimuth, (b) the forward muon spectrometer, dedicated to studying the muons pair produced in the interactions. It covers the pseudorapidity range of $2.5 < \eta < 4.0$. Further, the forward detectors having $\eta > 4.0$ are dedicated to the determination of the photon multiplicity and charged-particle multiplicity [102].

In the central barrel, the Time Projection Chamber (TPC) detector surrounds the Inner Tracking System (ITS) as shown in Fig. 2.3. The TPC and ITS detectors are mainly dedicated to the determination of primary and the secondary vertices and tracking of low-momentum particles. Outside of TPC, the Transition Radiation Detector (TRD) is placed for electron identification. The Time of Flight (TOF) detector is used to identify various particles like pion, kaon, proton, etc. Further, there are two single armed detectors– the Photon Spectrometer (PHOS) and an array of RHICH counters optimized for High Momentum Particle Identification (HMPID). At very forward angles, Zero Degree Calorimeter (ZDC) measures the energy flow. Two additional detectors V0A and V0C are mainly used for event classification and trigger purposes, which are located on the both sides of the ALICE central barrel. A brief introduction of different ALICE detectors and their significance are discussed below:

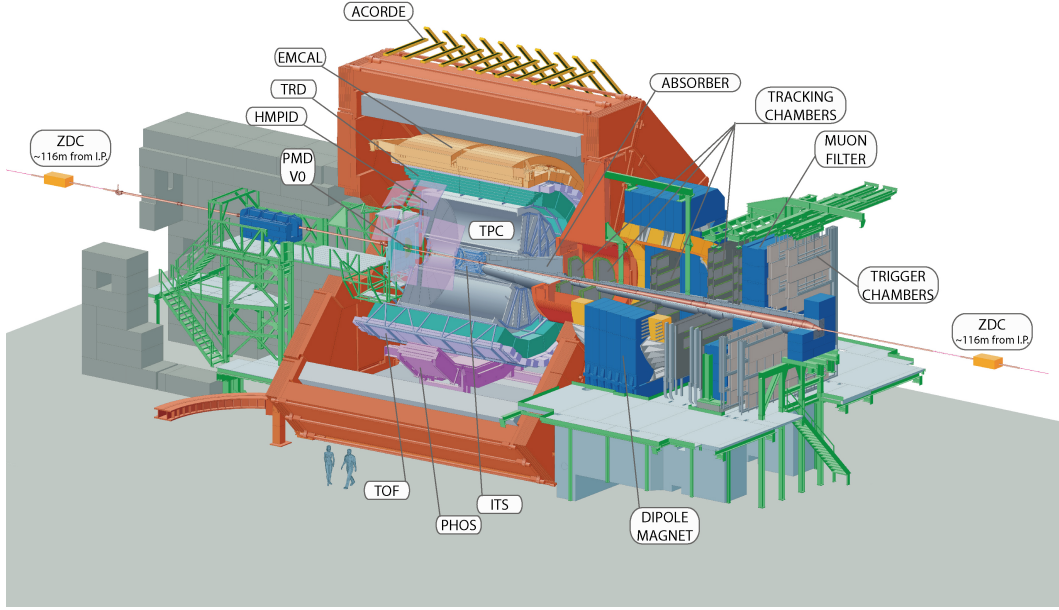


Fig. 2.3 Detector setup of A Large Ion Collider Experiment (ALICE) at the LHC[103].

2.1.4.1 Inner tracking system (ITS)

ITS is a cylindrical silicon tracker detector, installed at the closest to the interaction point, with the pseudorapidity coverage of $-0.9 < \eta < 0.9$ [99]. ITS consists of three detector sub-systems (Fig. 2.4) having six layers– (a) the two innermost layers, known as Silicon Pixel Detectors (SPD), (b) the two intermediate layers, known as Silicon Drift Detectors (SDD), and (c) the Silicon Strips Detectors (SSD) are the two outermost layers. ITS is mainly used for the reconstruction of primary and secondary vertices with a resolution better than $100 \mu m$, which allows tracking for low momentum particles down to $p_T = 80$ MeV/ c , enabling hadron identification at low transverse momentum.

2.1.4.2 Time projection chamber (TPC)

TPC is the main tracking detector of ALICE, installed in the central barrel, with the pseudorapidity coverage of $-0.9 < \eta < 0.9$ [104]. The layout of the TPC detector is shown in

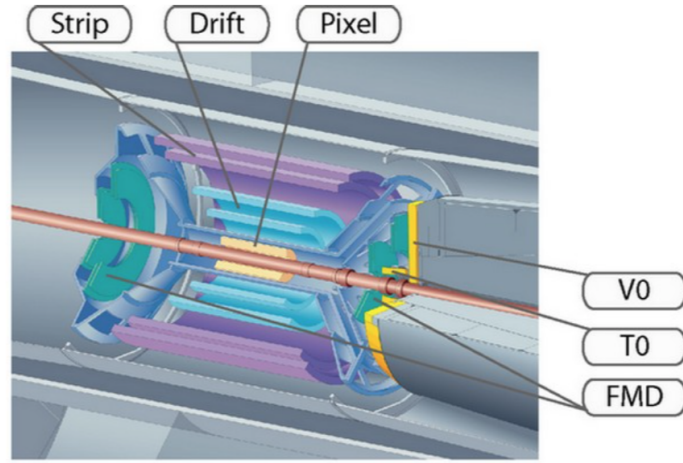


Fig. 2.4 Layout of the three detector sub-systems of ITS.

Fig. 2.5. In addition to tracking, TPC also provides the specific energy loss information

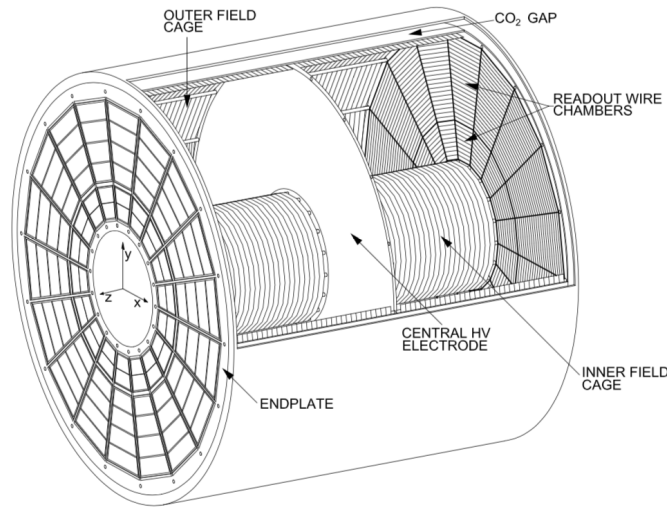


Fig. 2.5 Layout of Time Projection Chamber (TPC) detector at the ALICE [104].

of the traversing charged particles and widely used for identification of various hadrons. It comprises of a hollow cylinder whose axis is aligned with the LHC beam direction (z -axis). The total sensitive volume of the TPC detector is 88 m^3 , filled with a gas mixture of $Ne - CO_2 - N_2$, having an inner radius of 85 cm and outer radius of 250 cm [104]. The over-

all TPC length along the beam direction is 510 *cm*. The active volume of the TPC detector is divided into two drift regions by the central electrode, charged at 100 kV, located at its axial center. Inside the field cage, the central electrode and the end caps anodes produce a uniform electric field of 400 V/cm along the beam axis. Charged particles traversing the TPC volume ionize the gas along their path, producing electron clouds that drift towards the readout chamber in the end caps. The readout chambers are a system of multi-wire proportional chambers (MWPC) designed to cope with high track density expected in heavy-ion collisions at the LHC. The pads of each sector are organized in rows and the longitudinal coordinate is given by the drift time of the electron.

2.1.4.3 Time Of Flight (TOF)

The TOF detector is situated at the central barrel of ALICE detector, covering the pseudo-rapidity range of $|\eta| < 0.9$ over the full azimuth [105]. With full azimuthal coverage (except

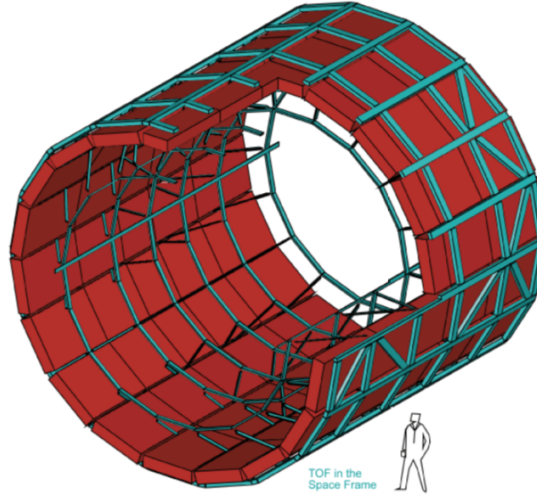


Fig. 2.6 Layout of Time Of flight (TOF) detector at the ALICE [109].

a small hole for PHOS detector), the TOF detector is dedicated mainly to the particle identification in the intermediate momentum range ($0.6 < p_T < 2.5$ GeV/c) [106–108]. In a collision, a majority of charged particles are produced in this momentum range and thus,

the performance of the TOF detector is of quite importance. The length of the TOF detector is 7.45 m, placed at the radial distance of 377–399 cm from the interaction point. There are 18 sector modules of the TOF detector in the azimuthal plane and five modules are placed along the beam direction. The TOF detector layout is shown in Fig. 2.6. It uses 1638 strips, which is designed based on the technology of Multi-gap Resistive-Plate Chamber (MRPC). The basic aspect of MRPC is that a sufficiently high and uniform electric field is applied over the sensitive gas volume of the TOF detector. The travelling charged particles ionise the gas along their trajectory and it generates a signal in the electrodes with the gas avalanche process. The time of flight (t) of a charged particle measured by the TOF detector is given by, $t = T_{TOF} - T_0$, where T_{TOF} is the time measured by the TOF detector and T_0 is the event collision time. The T0 detector provides information about the event collision time. The length l of the charged particle trajectory is measured from the primary vertex to the TOF detector by the tracking detectors like ITS and TPC. Consequently, the velocity of the charged particles is measured with the formula, $v = l / t$.

2.1.4.4 High Momentum Particle IDentification (HMPID)

HMPID detector is designed as a single arm-array with an acceptance of 5% of the central barrel phase-space, located at a radial distance of 470 cm with pseudorapidity and azimuthal coverage of $|\eta| < 0.6$ and $1^\circ - 57.6^\circ$ respectively. The detector geometry was optimized for the high momentum particle yields both for pp and heavy-ion collisions. HMPID consists of seven identical proximity focusing type Ring Imaging Cherenkov Counter (RICH), having dimension 1.5 m x 1.5 m each [110]. The modules are equipped with three radiator vessels, providing 15 mm radiator thickness. The first particles produced in the collisions create Cherenkov photons traversing the HMPID radiator of low chromaticity liquid C_6F_{14} . These Cherenkov photons are detected on the pad cathodes of Multi-Wire Pad Chamber (MWPC). The main role of HMPID detector is to enhance the

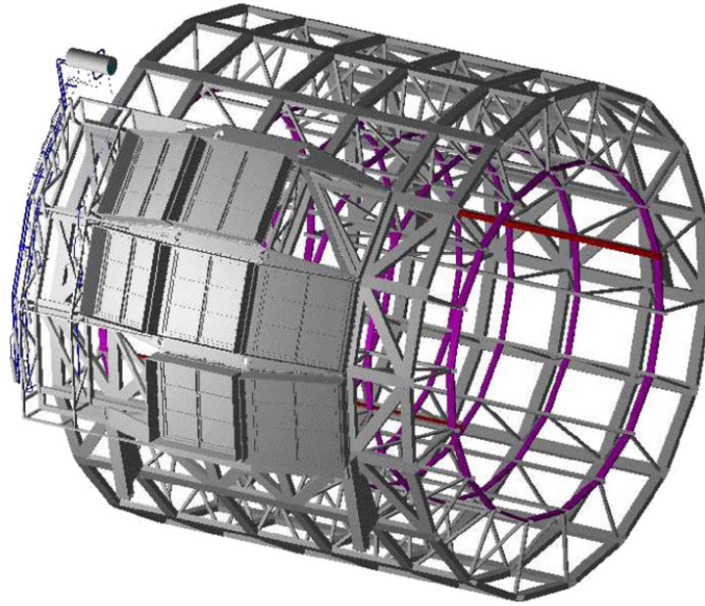


Fig. 2.7 Layout of High Momentum Particle Identification (HMPID) detector at the ALICE [110].

particle identification capabilities of ALICE beyond the momentum range achieved by the ionisation energy loss measurements of the individual detectors– ITS, TPC, and TOF.

2.1.4.5 Transition Radiation Detector (TRD)

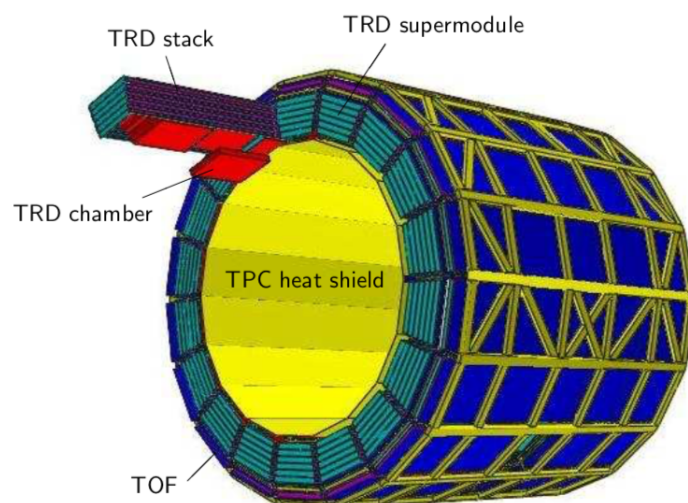


Fig. 2.8 Layout of TRD detector array in the ALICE space frame [106].

Transition Radiation Detector (TRD) is one of the ALICE central barrel detectors, which covers the pseudorapidity range of $-0.84 < \eta < 0.84$ over the full azimuth [111]. The TRD fills the space between TPC and TOF from 2.9 m to 3.68 m from the beam axis, consisting of 6 individual layers [112]. Depending upon the azimuthal angle, the TRD detector is divided into 18 sectors and has 5-fold segmentation along the beam direction and there are in total 540 detector modules. TRD is widely used to identify electrons above $p_T = 1$ GeV/ c . In conjunction with the information from ITS and TPC, the TRD detector also provides the facility to study the production of light and heavy vector-meson resonances and the dilepton continuum both in pp and heavy-ion collisions [111].

2.1.4.6 PHOton Spectrometer (PHOS)

PHOton Spectrometer (PHOS) is an electromagnetic calorimeter consisting of 17,280 detecting channels having dimension of $2.2 \times 2.2 \times 18 \text{ cm}^3$. The PHOS is positioned on the bottom of the ALICE set up at a distance of 460 cm from the interaction point, which covers the pseudorapidity region of $-0.12 < \eta < 0.12$ and 100° in azimuthal angle with respect to the x-axis [106, 113]. The total area of PHOS detector is 8 m^2 and the total crystal volume is $\sim 1.5 \text{ m}^3$. The main objective of PHOS detector is to measure photons, π^0 , and η mesons in the momentum range of $\sim 0.5 - 10$ GeV/ c , $1 - 10$ GeV/ c , and $2 - 10$ GeV/ c respectively.

2.1.4.7 Muon Spectrometer

Muon spectrometer is a unique detector which is dedicated to measure the hard probes, such as heavy-quarkonia states from $\mu^+ \mu^-$ decay channel and its pseudorapidity coverage is $-4.0 < \eta < -2.5$ [106, 114]. The main design criteria are– (a) the tracking detector of muon spectrometer must be able to handle the high particle multiplicity with large acceptance, (b) for the measurement of direct J/ Ψ , it is necessary to have large acceptance and

the measurement of low- p_T charmonium is possible in the forward region at small angles, and (c) the dimuon invariant-mass resolution should be optimum and the spectrometer is to be equipped with selective dimuon trigger system. The spectrometer consists of a passive front absorber, a high granularity tracking system of 10 detection planes, a large dipole magnet, a passive muon filter wall with four planes of trigger chambers and an inner beam shield [106].

2.1.4.8 T0 detector

T0 detector [115] consists of two arrays of Cherenkov counters, containing 12 counters in each array and the arrays are positioned on the opposite sides of the interaction point. As shown in Fig. 2.9, one of the arrays, labelled as $T0_R$ is placed at 70 cm from the nominal vertex, having pseudorapidity range of $2.9 \leq \eta \leq 3.3$ [106]. On the opposite side, the second array is labelled as $T0_L$ is situated at about 350 cm away from the IP, which covers the pseudorapidity range of $-5 \leq \eta \leq -4.5$. To maximize the triggering efficiency, both the T0 arrays are placed very close (minimum distance to allow) to the beam pipe. The main task

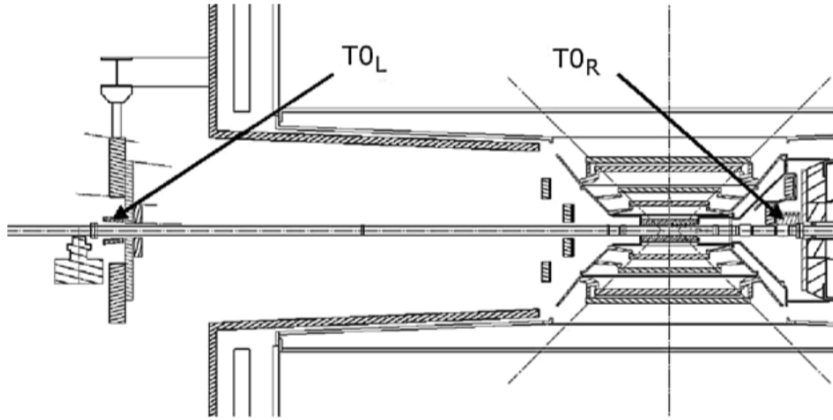


Fig. 2.9 Layout of T0 detector array inside the ALICE [106].

of T0 detector is to probe fast timing signal for L0 trigger, to provide a wake-up call for

TRD detector and to provide a collision time reference for TOF detector [115].

2.1.4.9 V0 detector

The V0 system consists of 2 arrays known as V0A and V0C, one positioned towards the ATLAS and the other towards the CMS. These are positioned on either side of the IP. V0A covers the pseudorapidity range of $2.8 < \eta < 5.1$, whereas V0C covers the pseudorapidity range of $-3.7 < \eta < -1.7$ [116]. As shown in Fig. 2.10, each of the V0 arrays is segmented in four rings in the radial direction and is divided into eight sections in the azimuthal direction. V0 detector provides multiple roles such as– a minimum bias trigger for central

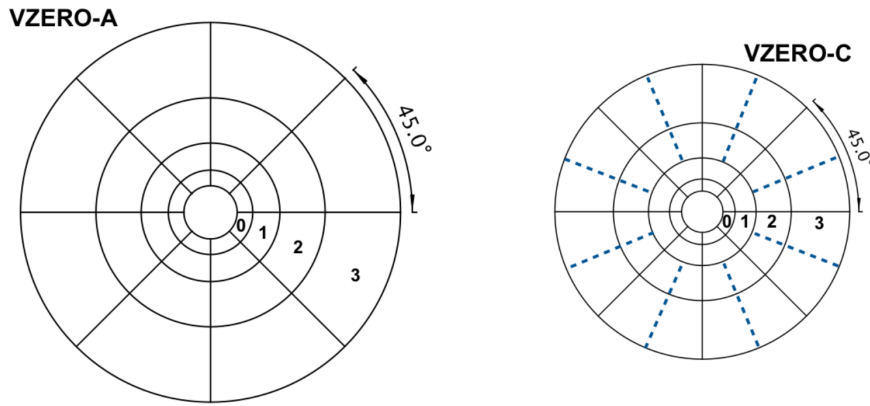


Fig. 2.10 Sketches of V0A and V0C arrays with their segmentation [117].

barrel detectors, a centrality indicator, two centrality triggers for Pb–Pb collisions with control of the luminosity and a validation signal for the muon trigger [106].

2.1.4.10 Forward Multiplicity Detector (FMD)

The Forward Multiplicity Detector (FMD) consists of a set of 5 rings of silicon strip detectors. These detectors are placed at 3 different positions from the ALICE nominal IP,

having different pseudorapidity coverages as shown in Fig. 2.11. The detector is designed based on a silicon sensor, which is a $300\ \mu\text{m}$ thick piece of n- type silicon with p+ type

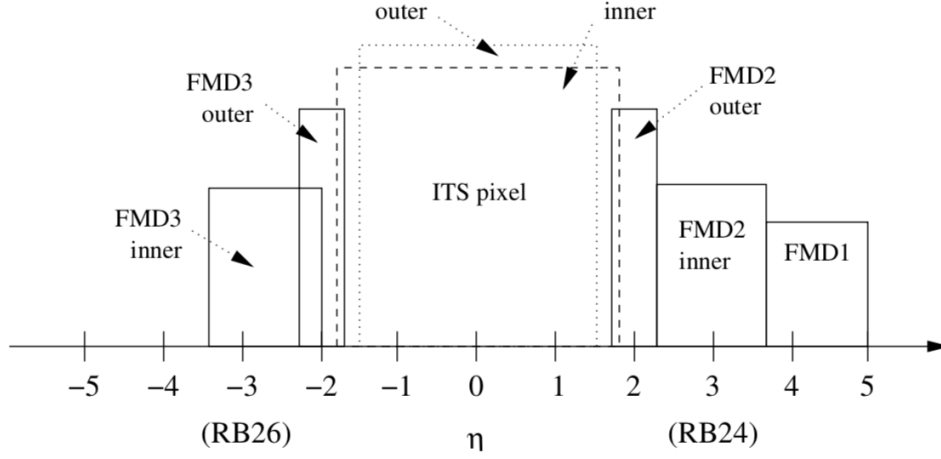


Fig. 2.11 Different pseudorapidity acceptance of FMD detector [118].

implants. The main role of FMD detector is to provide precise measurement of charged-particle multiplicity in the pseudorapidity range of $-3.4 < \eta < -1.7$ and $1.7 < \eta < 5.0$ [115]. Thus, together with the ITS detector, the FMD provides the facility to measure the charge particle multiplicity for all types of collision systems in the wide pseudorapidity range of $-3.4 < \eta < 5.0$. The FMD also allows one to study the multiplicity fluctuations on the event by event basis as well as flow studies.

2.1.4.11 Zero Degree Calorimeter (ZDC)

The vital role of Zero Degree Calorimeter (ZDC) is to measure the energy carried in the forward direction by spectator nucleons to determine the overlap region of the two colliding nuclei [119]. Therefore, ZDC plays a very important role in ALICE experiment as some important observables are directly related to the geometry of the collisions. It is composed of four calorimeters, which are located at 115 m away from the interaction

point on both sides, two of them are used to detect protons and other two are used to detect neutrons. ZDCs are made of “spaghetti calorimeters” with quartz fibres [119, 120].

2.1.4.12 Photon Multiplicity Detector (PMD)

The Photon Multiplicity Detector (PMD) is a preshower detector, which measures the multiplicity and spatial distribution of photons on the event by event basis. PMD is a forward detector of ALICE with full azimuthal coverage in the pseudorapidity region of $1.8 \leq \eta \leq 2.6$ [106, 121]. PMD consists of two identical planes of detectors, separated by a thick lead converter as shown in Fig. 2.12. The information of charged particles hits are

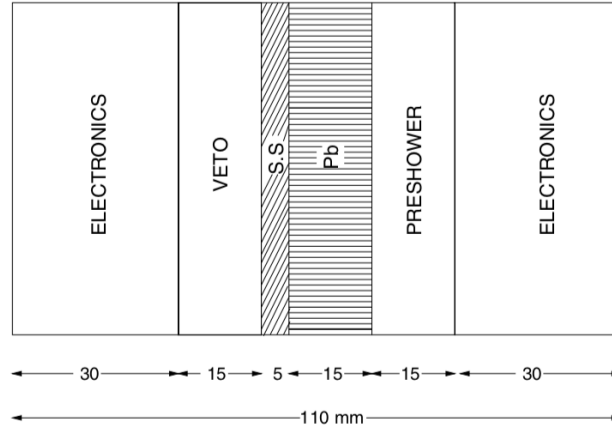


Fig. 2.12 Schematic cross section of the PMD detector, showing the preshower plane, lead converter and veto plane [106].

recorded in the front detector plane and the detector plane behind the converter is the preshower plane which records hits from both photons and charged hadrons. The details of the PMD detector technology could be found in Refs.[106, 121].

2.2 ALICE analysis framework

2.2.1 ROOT framework

ROOT framework was developed by Rene Brun and Fons Rademakers to solve the challenges of high energy physics data analysis [122, 123]. They started the ROOT project in the context of the NA49 experiment at CERN, where a huge amount of raw data, in the order of 10 terabytes were generated per run.

ROOT is user-friendly software framework as it uses Object-Oriented Programming written in C++ and offers considerable benefits compared to Procedure-Oriented Programming. The input and output (I/O) subsystem of ROOT allows one to store and retrieve C++ object. ROOT provides a large selection of high energy framework utilities with a set of interacting classes and a good environment for the development of software packages and a complete data analysis framework [122, 124]. ROOT offers advanced statistical analysis tools such as multidimensional histogramming, random number generators, commonly used mathematical functions, multi-parametric fit, algorithms of cluster finding, minimization procedures, etc.

PROOF, the parallel ROOT facility provides the inherent parallelism in event data, widely used to optimize the I/O and CPU utilization in heterogeneous clusters with distributed storage. In addition to parallelism, PROOF inherits with the advantage of a well-performing object storage system, advanced visualization and statistical tools. One of the important components of ROOT is CINT C++ interpreter, which execute C++ scripts and C++ command-line input. CINT provides extensive RTTI capabilities in ROOT for the essential completeness of C++.

The software packages of ROOT are widely used for event generation, detector simulation, event reconstruction, and data acquisition. Therefore, ROOT became very much important in the field of particle and nuclear physics, specially in all the major experimen-

tal high energy laboratories in the world. The application of ROOT is widely increasing in other fields like biology, genetics, astronomy, pharmaceutical, finance, insurance, etc.

ROOT framework is extensively used in the LHC experiments. Recently in the ALICE experiment at the LHC, ROOT has been interfaced with an emerging Grid middleware system known as *AliEn* [125]. In conjunction with the PROOF system, AliEn provides the facility of realization and demonstration of a distributed parallel computing system for large scale analysis.

2.2.2 AliRoot framework

AliRoot, the ALICE offline framework, is based on Object-Oriented technique for programming, written in C++, and is a supporting framework on the ROOT system [122, 126]. AliRoot is complemented by the AliEn system which gives access to the CERN computing Grid. The schematic diagram of AliRoot is shown in Fig. 2.13.

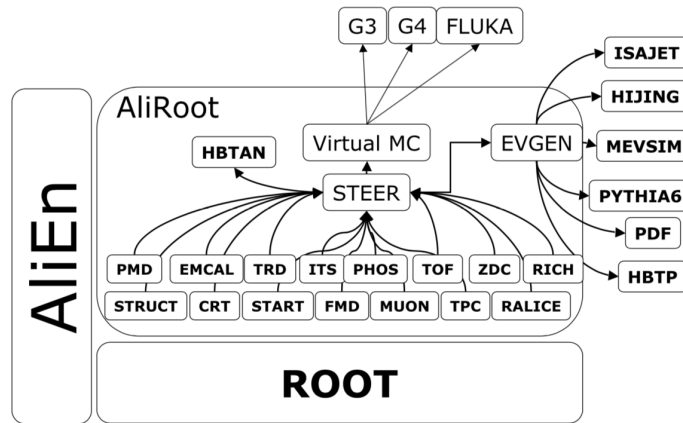


Fig. 2.13 Schematic view of ALICE-AliRoot framework [126].

The AliRoot framework is widely used for simulation, calibration, alignment, reconstruction, visualization, and analysis of the experimental data. Since 1998, AliRoot has been in continuous development and was used to perform simulation studies to optimize the design of all the ALICE detector subsystems. Before the start of the ALICE data taking,

AliRoot was utilized to study the physics performance of all the optimized detectors, that would be used in ALICE experiment to collect the data of pp, p-Pb and Pb-Pb collisions.

Fig. 2.14 shows the main tasks of the AliRoot framework. Monte Carlo event generators are used to generate simulated data. These generated data contains full information such as– particle type, charge, momentum, mother–daughter relationship, etc. These particles are then transported through different detectors via detector simulation packages such as GEANT3 [127], FLUKA [128] and GEANT4 [129], which generate a detailed energy deposition in each detector known as hits. These hits are then converted into digits, taking into account the detector response and associated electronics response function. In the final stage, these digits are stored as raw data in the specific hardware format of each detector, where the reconstruction chain is activated. The detector in the chain starts local reconstruction like clusterisation and then a seeding procedure is done for tracking using Kalman filter [130]. The simulated events are processed through the whole cycle and

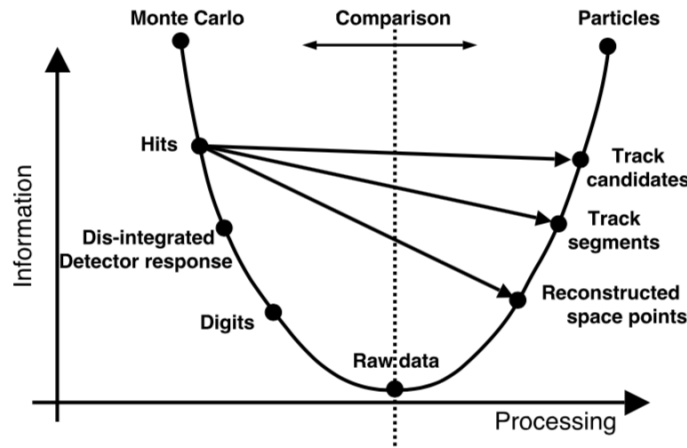


Fig. 2.14 Data processing framework of AliRoot [126].

finally, the reconstructed particles are compared to the generated one, and thus AliRoot framework plays an important role to evaluate the detector and software performance.

2.3 Details of ALICE data analysis

2.3.1 Primary vertex finding

One of the major requirements of the data processing in ALICE is the primary vertex finding. The ideal detector to perform the fast vertex measurement is the Silicon Pixel Detector (SPD), located in the two innermost layers of the ITS. The main advantages of using the ITS detector for fast vertex measurement are: (a) it is the closest detector to the interaction point, (b) it provides fast response, and (c) it has an excellent resolution in the transverse plane, because of its high granularity [131].

In ALICE software [132], two methods are implemented for the primary vertex measurement using ITS, which are given by (a) VertexerSPDz, and (b) VertexerSPD3D. These reconstructions are performed based on *tracklets* built by the associating pairs of the reconstructed points in the two SPD layers discussed below:

(a) VertexerSPDz: In AliRoot, VertexerSPDz algorithm provides the measurement of the z-coordinate of the primary vertex. This is estimated based on the algorithm consists of the correlation of reconstructed points belonging to the first layer of the SPD with reconstructed points belonging to the second layer within a small azimuthal window (~ 0.01 rad) [131], and matching the pairs of points on these two SPD layers is defined as a candidate for tracklet. For each tracklet i , the interaction point z_i can be estimated with respect to the beam axis and from the distribution of z_i , a Region Of Interest (ROI) is defined around the peak point of the distribution. A weighted mean of z_i falling in the selected ROI is usually implemented for the determination of the z-axis of the primary vertex, which is given by [131],

$$z_{\text{mean}} = \frac{\sum_i^N z_i / \sigma_i}{\sum_i^N 1 / \sigma_i}, \quad (2.1)$$

where N is the number of tracklets and σ_i are the errors measured from the pixels of the SPD layers on the z_i points.

(b) VertexerSPD3D: VertexerSPD3D algorithm measures the primary vertex from 3-dimensional measurement based on SPD tracklets. The algorithm of this technique is discussed below:

- 1) Tracklet finding: The tracklet must cross a cylindrical fiducial region where the interaction point is expected to be located. The center and size of the fiducial region are changed for two separate vertex reconstruction passes. The required condition is that the two points in each tracklet must fall within a given azimuthal window and the tracklet must not be displaced to a large distance with respect to the center of the fiducial volume.
- 2) Tracklet selection: Here the selection is applied to pairs of tracklets. After applying a cut on the distance of closest approach ($DCA < 1$ mm), the crossing point of the tracklets c_{ij} for pairs of tracklets are estimated, considering the crossing point within the fiducial region. The bin with the maximum density of the interactions of the tracklets c_{ij} can be found from a 3-D histogram of c_{ij} . The tracklets having interaction point far away from the peak are removed.
- 3) Vertex determination: Based on the criteria discussed above the primary vertex has been determined. A cut on the interaction tracklets with distance > 1 mm from the found vertex are removed for the calculation of the coordinate of the primary vertex.

There is another algorithm in AliRoot, used for the measurement of the primary vertex is VertexerTracks. The algorithm provides a 3-D measurement of the primary vertex from the reconstructed tracks.

2.3.2 Track and event reconstruction

1. Track reconstruction in SPD: The interaction vertex is determined from the correlation of tracklets in SPD using VertexerSPD3D as discussed in the previous section. Also, the events in which the algorithm fails, only the position along the beam axis is determined using the VertexerSPDz algorithm and the reconstructed vertex are stored in the Event Summary Data (ESD).
2. Track reconstruction in TPC: Inside the TPC detector, the tracks are reconstructed from outside to inward direction using the algorithm known as Kalman filtering [133]. Each track is created using the information from the innermost pad rows, n ($n \approx 15$) and the primary vertex position.
3. Track reconstruction in ITS: ITS also reconstruct the track in the inward direction, where the TPC reconstructed tracks are matched to the outermost layer of ITS and followed to the innermost pixel layer. In ITS, the track finding is done in two passes: (a) in the first pass, the position of the primary vertex is estimated using SPD pixel to maximize the efficiency of the primary tracks, (b) the second pass does not use the vertex information, which helps to reject the tracks with large displacement from primary vertex.
4. The tracks are back-propagated to the outermost layer of ITS, and then to the TPC outermost radius. Further, the tracks are extrapolated to the six layers of TRD detector.
5. In the last step, the reconstructed tracks are refitted inward from TRD to TPC and then to the primary vertex reconstructed by the ITS detector. TPC only primary vertex is also reconstructed from the set of tracks with parameters associated with

the TPC only. These reconstructed vertexes, tracks, and as a whole the reconstructed events are used for various physics analysis.

2.4 Particle IDentification (PID) using ALICE detectors

For the measurements of various physics observables, such as transverse momentum distribution, nuclear modification factor, particle ratios etc., one of the basic requirements is the identification of various charged particles like charged pions, kaons, protons, etc. Based on the detecting principles and limitations, different PID techniques using ITS, TPC, TOF, and HMPID detectors are traditionally applied in ALICE data analysis. Identification of charged kaons in heavy-ion collisions, over a wide momentum range using decay topology (kink topology) inside the TPC volume, is of prime interest of the present investigation and will be extensively discussed in the sections– [2.5.8–2.5.11](#).

2.5 Analysis details

Identification of charged particles ($\pi/K/p$) using various PID techniques is carried out both in pp and Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The PID strategy contains different steps, such as the selection of genuine event, tracks, different PID cuts, various correction factors, etc. Due to the biases in standard cuts applied for tracking and various PID selections, it is very much important to estimate the systematic uncertainties for the analysis. The details are discussed in the sections– [2.5.11.1–2.5.11.10](#).

2.5.1 Data sets

The analysis done for the present investigation is carried out with the experimental data sets of both pp and Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, which were recorded by ALICE at

the end of 2015. In ALICE, these data sets are termed as LHC15n and LHC15o productions dedicated for pp and Pb–Pb collisions respectively.

In general, a large fraction of experimental data of ALICE is accompanied by simulated events that are eventually termed as ALICE Monte Carlo (MC) productions. Different MC event generators, such as HIJING, PYTHIA, and DPMJET are frequently used to simulate similar pp and Pb–Pb collisions, after which the ALICE detector responses are simulated using the GEANT code. The prime motivation for analysing MC events is that it enables the analysers to estimate the various correction factors, such as reconstruction efficiency, PID efficiency, acceptance, purity, etc. It also enables to study the difference between the expected and reconstructed observables. The details of the experimental and Monte Carlo data sets are discussed below.

- **Experimental data sets**

- **pp collisions:** The LHC15n data period is dedicated to the pp collisions at $\sqrt{s} = 5.02$ TeV, which was taken during the period of 19-11-2015 to 23-11-2015. Out of the different productions of LHC15n period (pass1, pass2, pass3 and pass4), the latest pass4 production has been taken for this analysis, which contains 27 good runs [134]. The pass4 production contains improved calibration of TOF time resolution, a new treatment for TPC cluster error assignment and fixes some bugs in the assignment of the particle identification procedures in the first and last tracking stages. The run numbers are: 244340, 244343, 244351, 244355, 244359, 244364, 244377, 244411, 244416, 244418, 244421, 244453, 244456, 244480, 244481, 244482, 244483, 244484, 244531, 244540, 244542, 244617, 244618, 244619, 244626, 244627, 244628. These run numbers have the interaction rate of $\sim 20 - 50$ kHz. LHC15n pass4 also contains three runs (244411, 244416 and 244418) with a high interaction rate of ~ 100 kHz and are excluded from the analysis.

- **Pb–Pb collisions:** The LHC15o data period of ALICE has been dedicated for Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, recorded with ALICE detectors during the period of 25-11-2015 to 13-12-2015. This data taking period contains two productions, namely, lowIR (low interaction rate $\sim 300 - 400$ Hz) and highIR (high interaction rate $\sim 1 - 7.5$ kHz). The production of lowIR data set contains 13 good runs, whereas the highIR data set contains 87 good runs [135]. Since kink analysis is associated with the decay topology, it requires larger statistics and therefore highIR production containing large events (with all the runs) has been used for this analysis. HighIR data set contains two passes, viz., pass1 and pass2, where the data of pass2 is basically an improved version for the PID analysis with TOF detectors which fixes some bugs in the TOF maxi-pad trigger during January 2018 [135]. The kink analysis does not require any PID information from TOF detector and thus pass1 production has been used for the same. The run numbers used in this analysis are (total 87 runs): 246994, 246991, 246989, 246984, 246982, 246980, 246948, 246945, 246928, 246851, 246847, 246846, 246845, 246844, 246810, 246809, 246808, 246807, 246805, 246804, 246766, 246765, 246763, 246760, 246759, 246758, 246757, 246751, 246750, 246495, 246493, 246488, 246487, 246434, 246431, 246428, 246424, 246276, 246275, 246272, 246271, 246225, 246222, 246217, 246185, 246182, 246181, 246180, 246178, 246153, 246152, 246151, 246115, 246113, 246089, 246087, 246053, 246052, 246049, 246048, 246042, 246037, 246036, 246012, 246003, 246001, 245954, 245952, 245949, 245923, 245833, 245831, 245829, 245705, 245702, 245700, 245692, 245683.

- **Monte Carlo data sets**

- **pp collisions:** The dedicated Monte Carlo (MC) production anchored with LHC15n pass4 data set of pp collisions at $\sqrt{s} = 5$ TeV is LHC17e2, which uses

PYTHIA Monash tuned event generator. This production contains similar run numbers with the experimental data sets.

- **Pb–Pb collisions:** The LHC16g1, LHC16g1a, LHC16g1b and LHC16g1c data sets are the HIJING-generated general-purpose MC productions of Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, anchored to the experimental data sets of LHC15o pass1 high interaction rate. The production LHC16g1 is a general-purpose data set with minimum bias setting, whereas LHC16g1a, LHC16gb and LHC16gc are for different centrality classes: 0 – 10%, 10 – 50% and 50 – 90% respectively [136].

2.5.2 Event and centrality selection

For both pp and Pb–Pb collisions, all the events have been taken with a Minimum Bias (MB) trigger. This requires hits in the forward scintillator hodoscopes– V0A and V0C, situated at two different pseudorapidity regions at $2.8 < \eta < 5.1$ and $-3.7 < \eta < -1.7$ respectively. A coincidence between V0A and V0C detectors is known as a trigger. V0 signal (also known as V0 amplitude) is proportional to the charged particle multiplicity and is used for the definition of centrality classes. In general, the centrality of a collision is expressed as a percentage of the total nuclear interaction cross-section σ [137]. In A–A collisions with an impact parameter b , the centrality percentile c is defined by integrating the impact parameter distribution $d\sigma/db'$,

$$c = \frac{\int_0^b d\sigma/db'}{\int_0^\infty d\sigma/db'} = \frac{1}{\sigma_{AA}} \int_0^b \frac{d\sigma}{db'} db' \quad (2.2)$$

In ALICE data analysis, the centrality is defined as the percentile of the hadronic cross-section corresponding to a particle multiplicity above a given threshold ($N_{\text{ch}}^{\text{THR}}$),

$$c \approx \frac{1}{\sigma_{AA}} \int_{N_{\text{ch}}^{\text{THR}}}^{\infty} \frac{d\sigma}{dN'_{\text{ch}}} dN'_{\text{ch}} \quad (2.3)$$

The distributions of V0 amplitude of all triggered Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV is shown in Fig. 2.15 [138]. The distribution is fitted with Glauber Monte Carlo model [38] to compute the fraction of the hadronic cross-section to a desired set of range of the V0 amplitude that defines the various centrality class of the collisions.

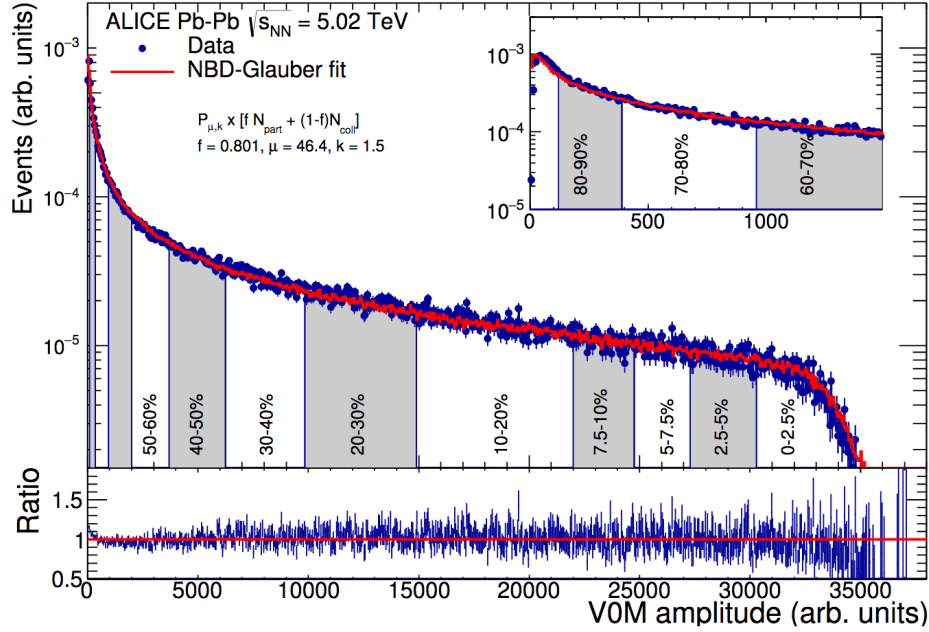


Fig. 2.15 Distribution of sum of the V0 amplitude (multiplicity) for Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The solid line represents the Glauber fit to the data and the insert plot shows the zoomed version of the peripheral collisions. This result has been taken from the ALICE public note dedicated to the centrality determination [138].

In this analysis the centrality classes are taken as– 0 – 5%, 5 – 10%, 10 – 20%, 20 – 30%, 30 – 40%, 40 – 50%, 50 – 60%, 60 – 70%, 70 – 80% and 80 – 90%. There are some difficulties for the extraction of 90 – 100% centrality class for its low track multiplicity and significant contribution from the QED processes [139] and is therefore excluded from the analysis.

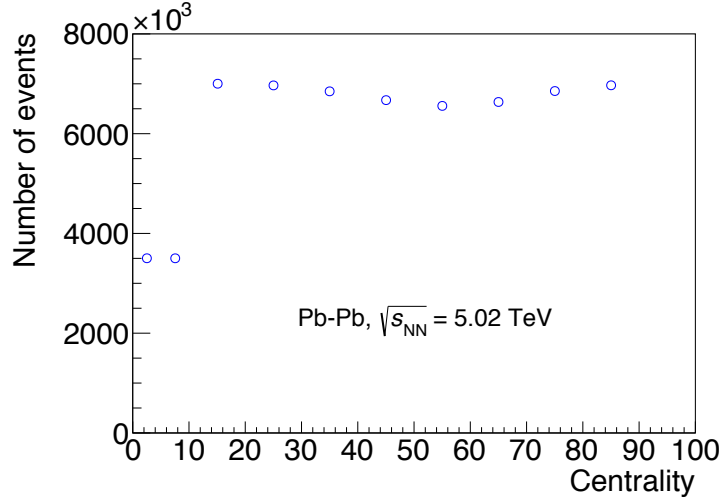


Fig. 2.16 Number of events as a function of centrality in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV after applying all the event selection cuts.

The events far away from the primary vertex ($|z\text{-vertex}| < 10$ cm) are considered as background events and are rejected from the sample. At LHC, one single bunch-crossing may contain multiple events. The unwanted overlapping events whose vertices are not distinguishable are termed as same-bunch-crossing pileup events and are removed from genuine events. On the other hand, there are some pile up events that might come from the different bunches. These are termed as out-of-bunch-crossing pileup events which can be separated from the genuine events from the information of readout time recorded on the detectors. With all the event selection cuts, the number of genuine events as a function of centrality classes have been shown in Fig. 2.16.

2.5.3 Track selection

The analysis is carried out with the primary particles, defined as the particles having mean proper lifetime $\tau > 1$ cm/c, which is either (i) produced directly in the interaction, or (ii) from the decays of the particles with $\tau < 1$ cm/c.

The track selection criteria have been optimized to select the best quality of the track with the minimum background. Both in pp and Pb–Pb collisions, the global tracks which

are reconstructed by combining the information from the ITS and TPC detectors, are taken into account. To remove the contaminated tracks coming from the wrongly associated hits as well as the secondary particles, the global tracks are allowed to pass at least 70 TPC readout rows having χ^2 normalized to the number of space-points in the TPC $\chi^2/\text{NDF} < 2$. The particle identification with kink topology requires a lower number of TPC clusters, which is taken as 30 with a χ^2/NDF value less than 4. Further, some tight cuts on the number of TPC cluster as a function of some kinematical parameters (details are discussed in section– 2.5.11.3) of kink-topology have been applied for better purity of the kink analysis. In order to select the primary particles, the distance of the closest approach (DCA) to the interaction vertex parallel to the beam axis is restricted in the region of $-2 < \text{DCA}_z < 2$ cm. For further removal of the background and secondary tracks, a p_T dependent cut on the DCA in the $x y$ plane has been applied.

2.5.4 Particle identification using the ITS detector

In the sensitive volume of the ITS detector, the SDD and SSD provide the energy loss information of the traversing particles. From this energy loss information, charged particles can be identified, specially in the low p_T region below 600 MeV/c. In general, ITS standalone mode (ITSsa) is exclusively used for hadrons, such as $\pi^\pm$, $K^\pm$, and $p(\bar{p})$ identification. ITSsa analysis uses the pure standalone tracks which are reconstructed using all the clusters in the ITS. The identification technique is based on the specific energy loss ($dE/dx \propto 1/v^2$) information in the SDD and SSD, which are used to separate particles with the same momentum but different mass. The expected energy loss dE/dx is calculated using a p_T dependent hybrid parametrisation of Bethe Bloch function. For comparatively high p_T region, the Bethe Bloch parametrisation is given by [140],

$$\frac{dE}{dx} = E_0 \beta^{-2} (b + 2 \ln - \beta^2), \text{ for } \beta\gamma \geq 0.7, \quad (2.4)$$

where E_0 is an overall constant and b characterises the overall strength of the logarithmic rise. On the other hand, for comparatively low p_T region, a third-degree polynomial is coupled with the Eq. 2.4 and is given by,

$$\frac{dE}{dx} = p_0 + p_1/(\beta\gamma) + p_2/(\beta\gamma)^2 + p_3/(\beta\gamma)^3, \text{ for } \beta\gamma \leq 0.7, \quad (2.5)$$

Here, p_0 , p_1 , p_2 and p_3 are the free parameters and can be extracted from the fitting. The particle identification strategy uses a selection of the number of σ (known as $N\sigma$) cut, which is estimated from the following relation,

$$N_{\sigma,i} = \frac{dE/dx_{\text{expected},i} - dE/dx_{\text{measured}}}{\sigma_{dE/dx_{\text{measured}}}}, \quad (2.6)$$

where $\sigma_{dE/dx_{\text{measured}}}$ is the resolution of the measurement of dE/dx inside the detector and the index i represents different particle type such as pion, kaon, and proton.

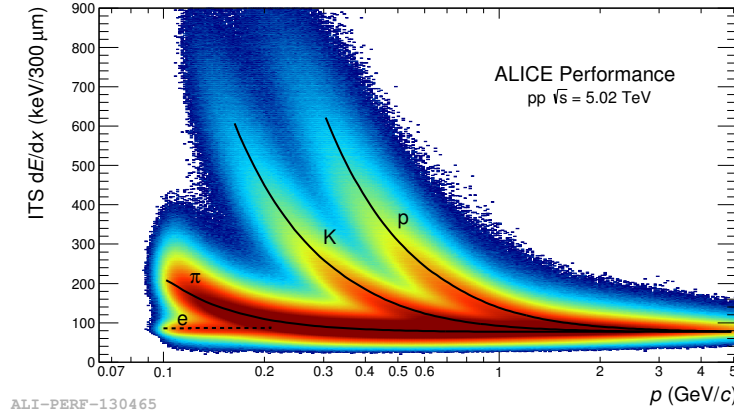


Fig. 2.17 dE/dx distribution as a function of momentum in pp collisions at $\sqrt{s} = 5.02$ TeV measured with ITS detector [141].

The dE/dx as a function of momentum in pp collisions at $\sqrt{s} = 5.02$ TeV is shown in Fig. 2.17, where the band of the different particle species are clearly visible. The distance from the theoretical line to the different points on the band for each particle hypothesis has been estimated using Eq. 2.6. For a particular momentum, the PID is based on the

mean values of the expected Bethe-Bloch functions. The $(p, dE/dx)$ plane is divided into some identification regions, where each point is directly assigned to a particle identity. For example, the projection of Fig. 2.17 in the momentum range $0.4 < p_T < 0.45$ GeV/c is shown in Fig. 2.18. To extract the yields, the signals are fitted with a Gaussian function.

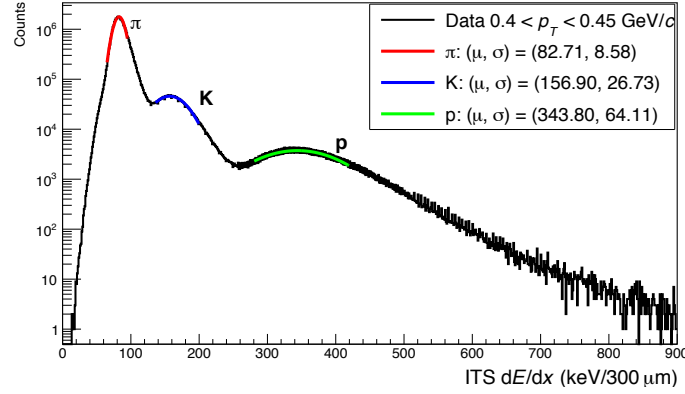


Fig. 2.18 Projection of Fig. 2.17 for a particular p_T range. Gaussian fits are done in order to extract the signals.

2.5.5 Particle identification using the TPC detector

Using the TPC detector, particles can be identified for two different p_T regions. To carry out such measurement, different PID techniques can be used. At low momentum, $p_T < 0.8$ GeV/c as well as for high momentum, $p_T > 3$ GeV/c, the specific energy loss technique is useful [142].

The specific energy loss is usually described by the Bethe-Bloch function given by [143],

$$\left\langle \frac{dE}{dx} \right\rangle = \frac{4\pi N e^4}{mc^2} \frac{Z^2}{\beta^2} \left(\ln \frac{2mc^2 \beta^2 \gamma^2}{I} - \beta^2 - \frac{\delta(\beta)}{2} \right), \quad (2.7)$$

where mc^2 = the rest energy of the electron, Z = the projectile charge, N = the number density of electrons in the traversed medium, e = the elementary charge, β = the projectile velocity, and I is the mean excitation energy of the atom. For a better description of the

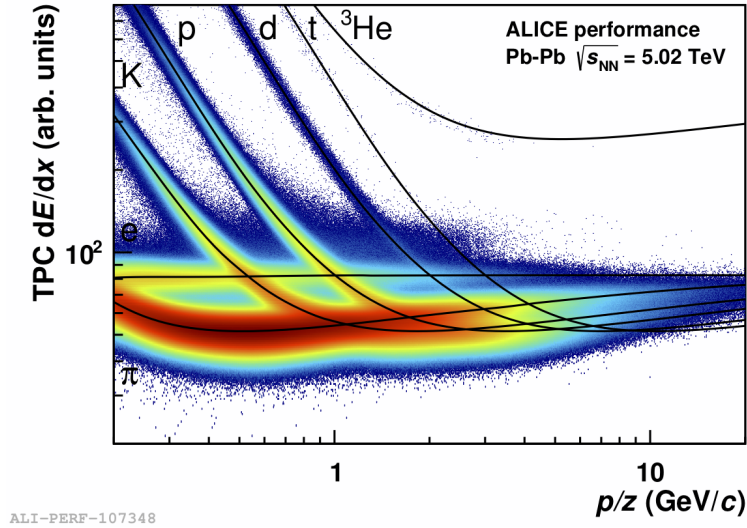


Fig. 2.19 dE/dx measurement inside the TPC detector as a function of momentum.

experimental data, standard parametrisation of the Bethe-Bloch function (Eq. 2.7) are often used. Here, the parametrisation proposed by the ALEPH experiment [144] has been used which is given by,

$$f(\beta\gamma) = \frac{P_1}{\beta^{P_4}} \left(P_2 - \beta^{P_4} - \ln \left(P_3 + \frac{1}{(\beta\gamma)^{P_5}} \right) \right), \quad (2.8)$$

where $\beta = v/c$, $\gamma = 1/(1 - \beta^2)$, and P_{1-5} are the fit parameters.

In the TPC analysis, the resolution of the measurement of dE/dx is very important, which is about 6.5% of energy for the minimum ionizing particle for central Pb–Pb collisions. Particle identification at low momentum region with this detector is based on the fits to the number of sigmas ($N\sigma$ defined in Eq. 2.6) estimated from the dE/dx measurement of the particles. The TPC dE/dx distribution as a function of momentum is shown in Fig. 2.19. In the low p_T region, the PID using the TPC detector is quite good and useful for the momentum ranges– (i) 0.3 – 0.7 GeV/c for pions, (ii) 0.25 – 0.45 GeV/c for kaons, and (iii) 0.5 – 0.8 GeV/c for protons and anti-protons.

High p_T ($3 < p_T < 20$ GeV/c) particle identification comprises the region of relativistic rise of dE/dx measurement in the TPC detector, where the loss of energy increases as $\ln\beta\gamma$ ($3 < \beta\gamma < 1000$). In this region, the calibration of dE/dx measurement is obtained by using the truncated mean, where the mean is estimated considering only 60% lowest cluster charge values to remove the tail of the Landau-like cluster charge distribution. Though the specific energy loss (dE/dx) depends on $\beta\gamma = p/m$, the truncated mean technique also depends on other parameters, such as actual cluster length, i.e., the TPC pad length and/or inclination of the track over the pad. dE/dx is well calibrated as a function of pseudorapidity ($|\eta|$) to estimate the mean and width from dE/dx distribution for a particular momentum range. For a particular momentum and $|\eta|$ intervals, a sum of four Gaussian functions are used to fit the dE/dx distribution, each of the Gaussian distribution is associated with pion, kaon, proton and electron with total 12 parameters. However, with proper calibration of dE/dx , 8 parameters of mean and width of the signals are kept fixed, and only the four unknown parameters are yields, which can be estimated from the fitting.

2.5.6 Particle identification using the TOF detector

The particle identification strategy using the TOF detector mainly relies on the measurement of time of flight of a track measured by the TOF detector. The tracks are reconstructed using the ITS and TPC detectors, which are extended to the TOF detector. The assignment of a TOF cluster to the propagated track allows precise measurement of the arrival time of the particle inside the detector. This time information along with the event time measurement is used for particle identification in the intermediate transverse momentum range. The measurement of particle velocity using TOF detector as a function of momentum in pp and Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV is shown in Fig. 2.20. The particle identification technique in TOF is based on a statistical approach of the time-of-flight of

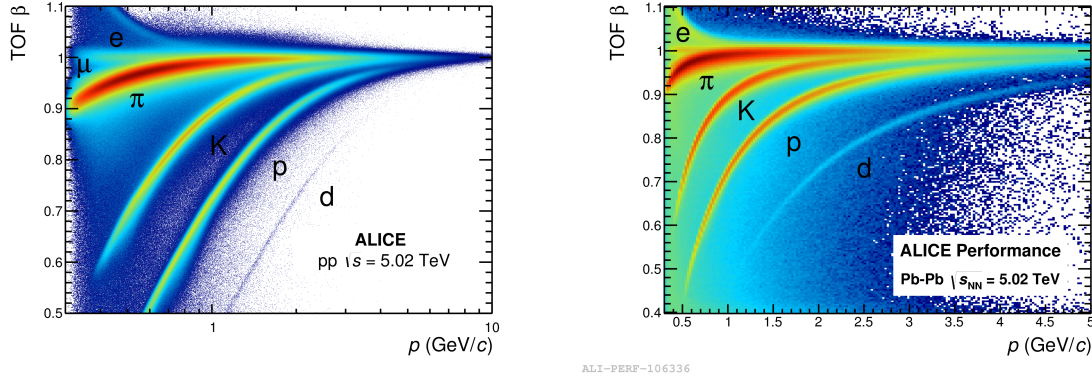


Fig. 2.20 Velocity measurement using TOF detector as a function of momentum in pp (left panel) and Pb-Pb (right panel) collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The visible bands represent various particle types.

the traversing particle to the TOF detector. The time of flight of particle is given by the following relation,

$$time - of - flight(t) = T_{TOF} - T_0, \quad (2.9)$$

where T_{TOF} is the time measured by the TOF detector and T_0 is the start time. For each particle type, the expected time-of-flight ($t_{ext,i}$) can be estimated for each track by taking into account the length of the track and the energy loss in the material. The resolution of time-of-flight can be given by the following relation,

$$\sigma_t^2 = \sigma_{TOF}^2 + \sigma_{T_0}^2, \quad (2.10)$$

The number of sigma separation in the TOF detector is defined as,

$$n\sigma_i = \frac{t - t_{ext,i}}{\sigma_{total}}, \quad (2.11)$$

where the σ_{total} is the total uncertainty which can be given by,

$$\sigma_{total}^2 = \sigma_t^2 + \sigma_{ext}^2 = \sigma_{TOF}^2 + \sigma_{T_0}^2 + \sigma_{ext}^2 \quad (2.12)$$

The particles are identified via correctly parameterizing the signal of the TOF detector. The TOF signal is described by a composite function consists of a Gaussian function convoluted with an exponential tail on the right side of the peak which is given by,

$$f(t) = \begin{cases} N \cdot Gaus(x, \mu, \sigma) & x \leq \mu + \tau \\ N \cdot Gaus(\mu + \tau, \mu, \sigma) \cdot e^{-\tau \cdot (x - \mu - \tau) / \sigma^2} & x > \mu + \tau \end{cases} \quad (2.13)$$

where N is the normalization constant. This TOF signal is used to build the templates for each particle species. For both pp and Pb–Pb collisions the raw yields are extracted by the template fits to the $\frac{t - t_{ext,i}}{\sigma_i}$ distribution. The template fit is performed by the package of ROOT known as ROOFit package, and the normalization of the template shapes give the yield for a given particle type. The signal parameters τ and σ are estimated by the fitting of TOF signal for pion ($t - t_{ext,i} - t_0$) with the signal parameterization function given by Eq. 2.13. An example of yield extraction fit for central Pb–Pb collisions for the pion hypothesis is shown in Fig. 2.21 for a particular momentum interval.

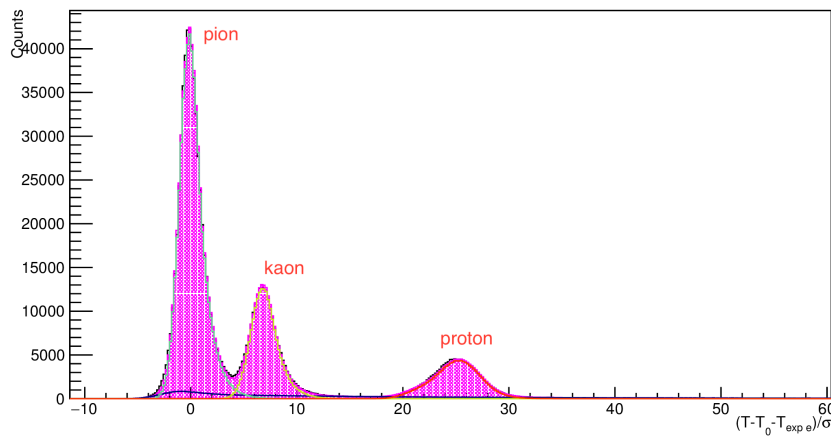


Fig. 2.21 Yield extraction fit for central Pb–Pb collisions for the pion hypothesis. The templates of the three particles species (pion, kaon and proton) are shown in different colors, whereas the blue curve represents the mismatch template.

2.5.7 Particle identification using the HMPID detector

The HMPID detector allows one to identify the charged pions, kaons and protons in the intermediate momentum range. The PID is performed by measuring the Cherenkov angle θ , which is given by,

$$\begin{aligned} \cos\theta_{Ch} &= \frac{1}{n\beta} \\ \Rightarrow \theta_{Ch} &= \arccos\left(\frac{\sqrt{p^2 + m^2}}{np}\right), \end{aligned} \quad (2.14)$$

where n is the refractive index of the radiator used in the detector, p is the momentum and m is the mass of a given particle. The photon angle measurement in the HMPID detector requires the primary tracks to be extracted from the central tracking detectors of ALICE and associated with the corresponding cluster of the minimum ionizing particle in the cathode plane of the HMPID detector. Starting from the photon cluster coordinates, a back-tracking algorithm is used to calculate the corresponding Cherenkov angle. Background discrimination is performed using the Hough Transform Method (HTM) [145]. For each track, the average of the Cherenkov angle ($\langle \theta_{Ch} \rangle$) is estimated which belongs to the same ring. For a particular momentum interval, the Cherenkov angle distribution follows a Gaussian function. The HMPID detector can identify the charged pions and kaons with 3σ separation, in the momentum range of $1 < p_T < 3$ GeV/c, whereas the proton can be identified in the momentum range of $1.5 < p_T < 5$ GeV/c.

In this analysis the background is prominent for central and semi-central Pb–Pb collisions and the background rejection is done using HTM as mentioned above. However, such rejection is not needed for the pp and most peripheral Pb–Pb collisions. For a narrow momentum bin, the reconstructed Cherenkov angle distribution follows a three Gaussian function and the distribution strongly increases with the angle, which corresponds to

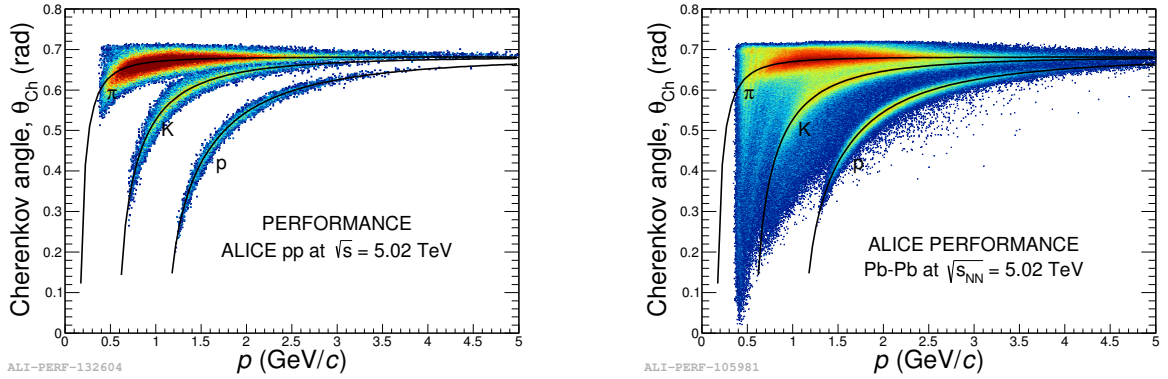


Fig. 2.22 Measurement of Cherenkov angle using HMPID detector as a function of momentum in pp (left panel) and Pb–Pb (right panel) collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

the misidentified tracks and termed as background. Each of the three Gaussian peaks corresponds to the real signal from the pion, kaon and proton.

For a particular momentum interval, the particle yields are extracted from three-Gaussian fits to the Cherenkov angle distributions along with a polynomial function of 6th order to fit the background. The fitting is given by,

$$f(\theta) = \frac{Y_\pi}{\sigma_\pi \sqrt{2\pi}} e^{-\frac{(\theta - \langle \theta_\pi \rangle)^2}{2\sigma_\pi^2}} + \frac{Y_K}{\sigma_K \sqrt{2\pi}} e^{-\frac{(\theta - \langle \theta_K \rangle)^2}{2\sigma_K^2}} + \frac{Y_p}{\sigma_p \sqrt{2\pi}} e^{-\frac{(\theta - \langle \theta_p \rangle)^2}{2\sigma_p^2}} + pol6(\theta), \quad (2.15)$$

where Y_i (with $i = \pi, K$ and p) represents the integral of the three-Gaussian functions, which gives the raw yields. The σ_i and $\langle \theta_i \rangle$ are the standard deviations and means of the Cherenkov angle distributions of the three particle species respectively. The fitting function (Eq. 2.15) contains 9 parameters, namely, 3 yields, 3 sigmas and three means. For the best evaluation of the particle 3 yields, the other 6 parameters need to be fixed. This is done in two steps. In the first step, all the 9 parameters are kept as free parameters. The mean values of the Gaussian distributions are constrained in a region close to the peak value in the region $[\langle \theta_{Ch} \rangle + \sigma, \langle \theta_{Ch} \rangle - \sigma]$ and the sigma values are constraint in the range $[\sigma + 0.3 \cdot \sigma, \sigma - 0.3 \cdot \sigma]$, where the refractive index is tuned to the Cherenkov angle value obtained at saturation, and the sigma values are taken from the Monte Carlo distribution

for the given momentum bin. In the second step, the trend of the parameters as a function

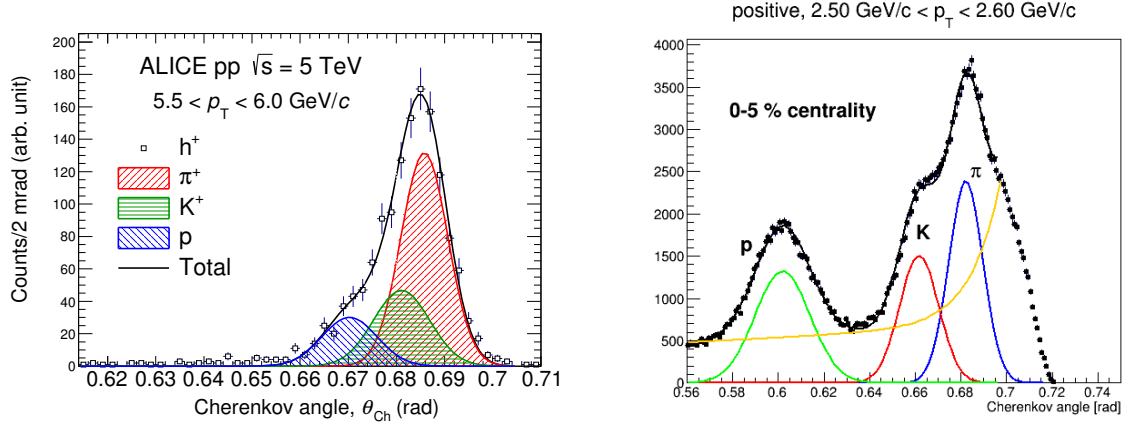


Fig. 2.23 Distribution of Cherenkov angle measured in HMPID detector for positive particles fitted with the three Gaussian function in pp (left panel) and most central Pb–Pb (right panel) collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The yellow line represents the background fit.

of momentum obtained from the first step is fitted with a continuous function and the fit is repeated to leave the yield as a free parameter. Thus, for a particular momentum range, the raw yield of a particle is obtained from the free parameter of the fitting, which is constrained to the total entries of the histogram. The distribution of the Cherenkov angle measured in the HMPID detector for positive particles fitted with the three Gaussian function in pp (left panel) and most central Pb–Pb (right panel) collisions at $\sqrt{s_{NN}} = 5.02$ TeV is shown in Fig. 2.23.

2.5.8 Particle identification using kink topology

A significant number of produced particles in heavy-ion collisions, specially at the LHC energies, decay to their daughter products while traversing through the detector volume and depositing their energy. Among the different possibilities, the geometrical signature of 1–prong decay of a charged particle inside the detector volume is known as a *kink*, where a charged parent particle decays to a charged daughter and a neutral daughter particle.

The schematic diagram of a charged particle producing a kink is shown in Fig. 2.24. The particle identification technique based on the decay topology is known as *kink topology*.

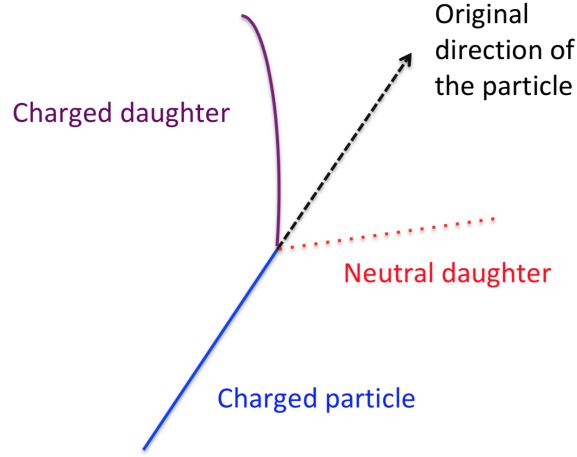


Fig. 2.24 Topological signature of 1-prong decay of a charged particle.

2.5.9 Importance of kink topology

Using the ITS detector, charged particles can be identified by measuring the specific energy loss (dE/dx) of the produced particles from the SDD and SSD in the momentum range of $0.2 < p_T < 0.5$ GeV/c [146]. In the case of TPC detector, the PID technique is based on the measurement of specific energy loss of the produced particle in the drift gas of the TPC volume [146]. Using this technique, charged kaon identification is possible both at low ($0.3 < p_T < 1.2$ GeV/c [146, 147]) and high ($3.0 < p_T < 20.0$ GeV/c [147]) momentum regions. Further, as reported in Ref. [147], charged kaons produced in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, can be identified with TOF and HMPID detectors in the momentum regions of $0.5 < p_T < 2.4$ GeV/c and $1.5 < p_T < 4.0$ GeV/c respectively. Therefore, not a single detector can identify the charged kaons over a wide momentum range. This limitation can be understood from Figs. 2.17 and 2.19, where the specific energy loss (dE/dx) distributions of the various particle species start to overlap with

each other in the higher momentum region and their identities become ambiguous. To overcome this difficulty, alternative techniques are needed for the identification of charged kaons, specially at the higher momentum region. Kink topology is one such technique, which could be applied to identify the charged kaons over a wide momentum range ($0.2 < p_T < 6.0$ GeV/c, however, this range is sensitive to the available statistics of the data sets) inside the fiducial volume of the TPC detector. This technique has been applied for the first time in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in the ALICE collaboration.

2.5.10 Kink finding algorithm

The kink reconstruction algorithm is based on the decay angle or kink angle, which is defined as the angle made by daughter charge particle with respect to the original direction of the mother particle. The algorithm is divided into two categories:

(a) For large decay angle: Kinks associated with large angle are reconstructed by associating the pair of tracks that intersect in the specified region of space having the same charge. The tracks within the fiducial volume of the TPC detector are selected for kink reconstruction. The selection criteria are: a pair of tracks are selected which should not pass far away from each other, the total number of clusters associated with the two tracks should not cross some nominal value, and the track should have the same charge. For each pair of tracks, a cut on the distance of closest approach (DCA) (Fig. 2.25) in the interaction point or in the bending plane is applied for a specified fiducial region within the TPC volume. The track pairs not fulfilling these criteria are rejected from the sample. Also, the secondary vertex is reconstructed by the numerical minimization of the distance in space between the two helices representing the tracks using 3-dimensional helix parametrization. Only those pair having reconstructed kink position within the TPC volume are kept. The fiducial volume of the TPC detector is restricted by the inner and outer radius of the TPC detector and the range is taken as $R = 120 - 220$ cm. For further

removal of the wrong tracks, the track cluster densities before and after the DCA position are estimated for each pair of tracks and a set of selection cuts are applied.

Finally, for all the selected kink sample, the tracks are refitted towards the decay vertex and an additional improvement is done based on the cuts on the kink angle. If a track belongs to several kink candidates, only the best combination such as the longest tracks with smallest DCA, and highest cluster density will keep the genuine kink candidate.

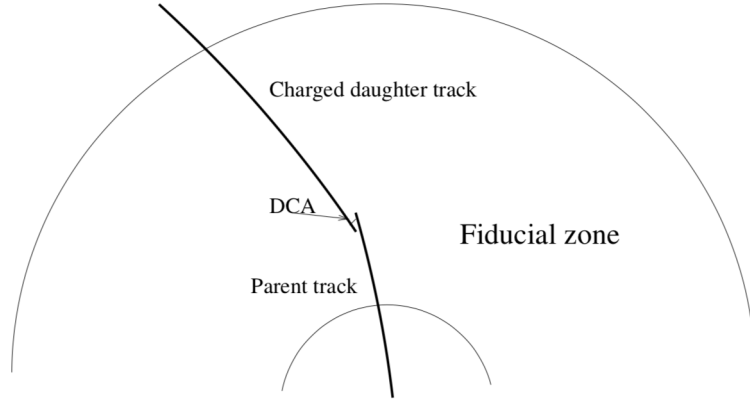


Fig. 2.25 Geometrical representation of the kink reconstruction.

(b) For small decay angle: Here, the kink finding algorithm is associated with the high momentum tracks ($p > 1.4 \text{ GeV}/c$). Therefore, the tracks having $p < 1.4 \text{ GeV}/c$ associated with the kink candidate found previously are rejected. Further, the kink candidate which share at least half of their associated cluster and the track which has less than 80 clusters are rejected. For a particular track, three fits for the track parameters are done at each of the hit of the selected track. One fit is to the part of the track upstream, one fit is to the part of the track downstream, and one fit is to the whole of the selected track. Subsequently, the change in the direction of the track is recorded explicitly. For the determination of a kink, the upstream and downstream parts of the tracks require the decay vertex within the fiducial TPC volume. The track breakpoint is determined at the location of the track

for which the biggest change in track direction is recorded. These selected kinks have to pass some selection criteria which require at least 30 clusters for the mother tracks, at least 20 clusters for the daughter tracks, the DCA between the tracks is less than 0.5 cm, the decay vertex should be within the fiducial volume, and the momentum of the mother track should be greater than 1.4 GeV/c.

2.5.11 Identification strategy using decay topology

The identification of charged kaons using decay topology relies on two effects based on the basic law of momentum and energy conservation. Firstly, it relies on the angle formed between the mother and daughter charged particles. Secondly, it relies on the momentum difference between the mother and the corresponding daughter particle, where the daughter particle always carries the smaller momentum. Therefore, if decay occurs between two-track segments k and $k + 1$, then we expect significantly different state vector at k of the track segment behind the decay than that of the state vector at the same position k obtained using back-extrapolation from the track segment in front of the decay. The reconstruction of a kink is only possible if both the track segments are obtained in the tracking system and the signature of the decay vertex is obtained. The geometrical representation of various kink parameters is shown in Fig. 2.26.

The different types of muonic and hadronic channels of charged kaons are shown in Table 2.1 with their corresponding branching ratios (BR). The main sources of the kinks from the decay of charged kaons are: $K^\pm \rightarrow \mu^\pm + \nu_\mu$ (muonic channel) with BR = 63.56% and $K^\pm \rightarrow \pi^\pm + \pi^0$ (hadronic channel) with BR = 20.67%. Pions also decays to μ and ν_μ with BR = 99.99% and will be treated as one of the main backgrounds in this analysis. There are other sources for kaon-kinks with comparatively low branching ratio, for example $K^\pm \rightarrow \pi^\pm + \pi^+ + \pi^-$ (BR = 5.58%), $K^\pm \rightarrow e^\pm + \pi^0 + \nu_e$ (BR = 5.07%), $K^\pm \rightarrow \pi^\pm + \pi^0 + \pi^0$ (BR

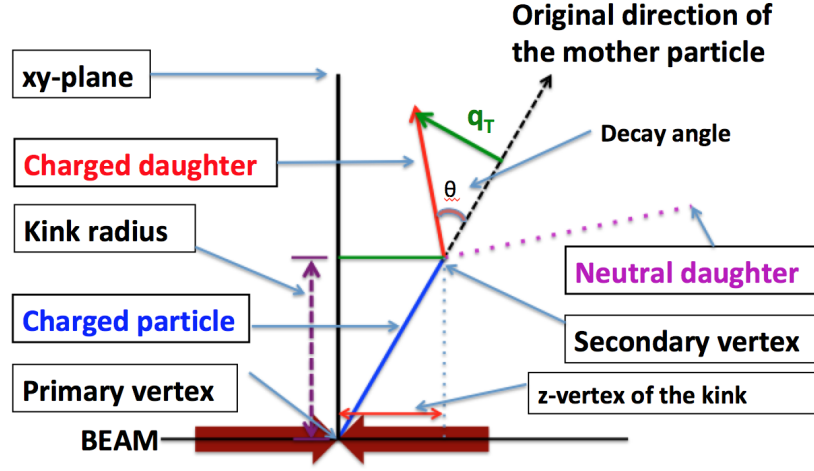


Fig. 2.26 Geometrical representation of various kink parameters.

$= 1.76\%$) and $K^\pm \rightarrow \pi^\pm + \mu^\pm + \pi^\pm + \nu_\mu$ (BR = 3.35%). In the following subsection, various steps for identification of charged kaons are discussed in details.

Table 2.1 Decay channels of charged kaons and pions [20]

Decay modes	Branching ratio
$K^\pm \rightarrow \mu^\pm + \nu_\mu$	63.56%
$\pi^\pm \rightarrow \mu^\pm + \nu_\mu$	99.99%
$K^\pm \rightarrow \pi^\pm + \pi^0$	20.67%
$K^\pm \rightarrow \pi^\pm + \pi^+ + \pi^-$	5.58%
$K^\pm \rightarrow e^\pm + \pi^0 + \nu_e$	5.07%
$K^\pm \rightarrow \pi^\pm + \pi^0 + \pi^0$	1.76%
$K^\pm \rightarrow \pi^\pm + \mu^\pm + \pi^\pm + \nu_\mu$	3.35%

2.5.11.1 Daughter transverse momentum

The kink analysis relies on the topology of two-body decays of charged π and K where a simple method can be applied for the determination of kink angle and the momentum of the decay products. In ALICE coordinate system, the decay of the charged meson is isotropic in the rest frame, which means that there is no special direction for either of the decay products.

Let us consider the muonic decay channel of charged kaons, $K \rightarrow \mu + \nu_\mu$. In the parent's rest frame, let $P_K = (M_K, 0)$, p_μ and p_ν be the momenta of the parent and the daughter particles. For well defined masses of the daughter particles, we have the constraints: $p_\mu^2 = m_\mu^2$ and $p_\nu^2 = m_\nu^2 = 0$ (considering neutrino to be massless). From the conservation of energy we get,

$$\begin{aligned}
 P_K &= p_\mu + p_\nu \\
 \Rightarrow p_\nu^2 &= (P_K - p_\mu)^2 = P_K^2 - 2P_K \cdot p_\mu + p_\mu^2 \\
 \Rightarrow 0 &= M_K^2 - 2M_K E_\mu + m_\mu^2 \\
 \Rightarrow E_\mu &= \frac{M_K^2 + m_\mu^2}{2M_K}
 \end{aligned} \tag{2.16}$$

Using Eq. 2.16 the momentum of the daughter particle can be written as,

$$\begin{aligned}
 p_\mu &= \sqrt{E_\mu^2 - m_\mu^2} \\
 \Rightarrow p_\mu &= \frac{M_K^2 - m_\mu^2}{2M_K}
 \end{aligned} \tag{2.17}$$

In the parent's rest frame p_μ can be written as,

$$p_\mu = \sqrt{q_T^2 + q_L^2}, \tag{2.18}$$

where $q_T = p_\mu \sin\theta$ = components of p_μ orthogonal to the momentum vector P_K , $q_L = p_\mu \cos\theta$ = components of p_μ parallel to the momentum vector P_K , and θ is the decay angle.

From Eqs. 2.17 and 2.18, it could be seen that the maximum value of the daughter transverse momentum $(q_T)_{max}$ depends on the parent as well as the daughter masses. Hence, for different particles with different masses and/or with different decay channels,

the $(q_T)_{max}$ values differ strongly. The $(q_T)_{max}$ value for the decay channel of $K \rightarrow \mu + \nu_{\mu}$ is estimated as 235.52 MeV/c, whereas for the decay channel of $\pi \rightarrow \mu + \nu_{\mu}$, the value is estimated as 27.79 MeV/c. Similarly, the $(q_T)_{max}$ value for the decay channel of $K \rightarrow \pi^{\pm} + \pi^0$ is estimated as 205 MeV/c.

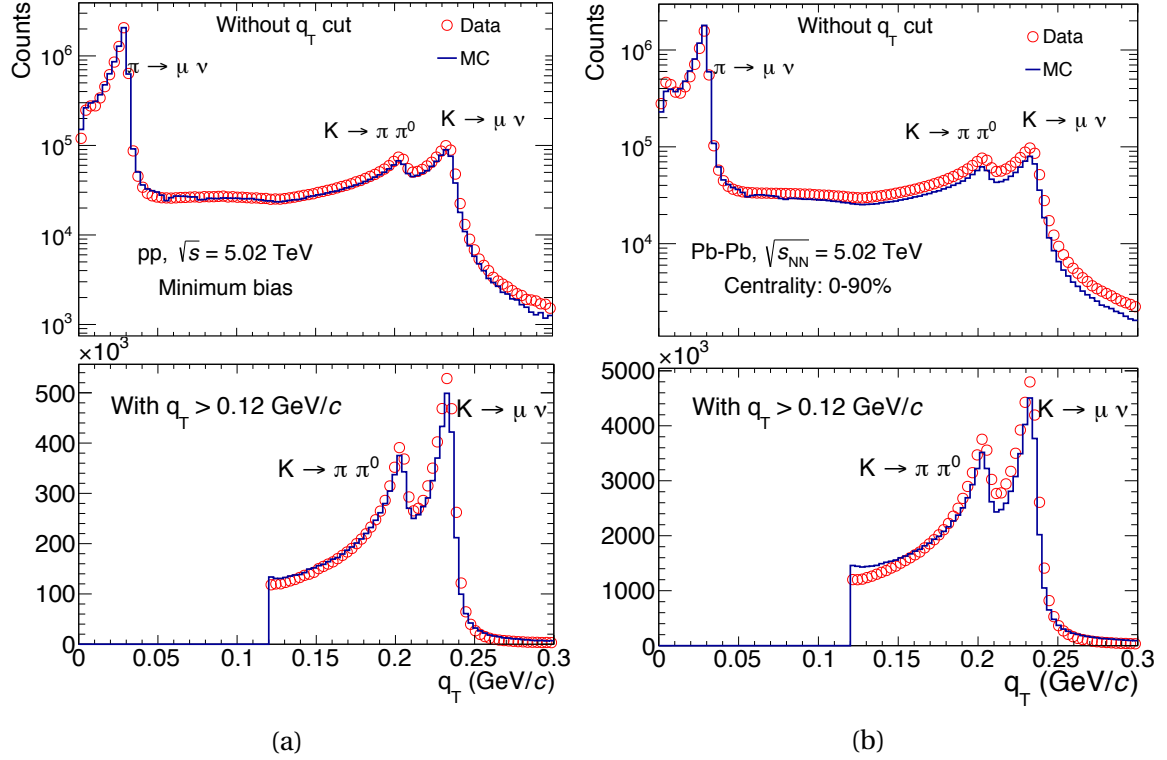


Fig. 2.27 Transverse momentum of daughter track (kink) with respect to the mother's momentum in laboratory system without any q_T cut (upper panel) and with $q_T > 0.12$ GeV/c in (a) pp and (b) Pb–Pb collisions. The circular symbols represent the data points whereas the blue solid lines represent the MC values.

In the practical scenario, within the pseudorapidity range of $-0.8 < \eta < 0.8$, the transverse momentum distributions of all the available daughter tracks inside the TPC volume are shown in the upper panels of Fig. 2.27 (a) and (b) for pp and Pb–Pb collisions respectively. From the above calculation of $(q_T)_{max}$ values for different decay channels, it could be clearly distinguishable from the figure that the leftmost sharp peak with lower q_T values corresponds to the daughter tracks for the decay channel of $\pi \rightarrow \mu + \nu_{\mu}$. The rightmost

peak corresponds to the daughter tracks for the decay channel of $K \rightarrow \mu + \nu_\mu$, whereas the next from the right peak corresponds to the daughter tracks for the decay channel of $K \rightarrow \pi^\pm + \pi^0$. On the other hand, the plateau region with wide q_T range corresponds to the various decay channels of charged kaons as mentioned in Table 2.1 with very small branching ratios.

Since the analysis is aimed to identify the charged kaons, the daughter tracks (kinks) corresponding to the charged pions have to be removed from the sample. As the pion kinks correspond to the lower values of the q_T distribution, a proper selection of the kinks based on the q_T distribution could be an intelligent idea to remove them. Based on the estimation of $(q_T)_{max}$ for pion kinks, a selection cut $q_T > 0.12$ GeV/c is applied to all the available sample of the daughter tracks, which mostly remove the pion kinks. The q_T distributions of the daughter tracks having $q_T > 0.12$ GeV/c are shown in the lower panels of Fig. 2.27 (a) and (b).

2.5.11.2 Decay angle

The second important kinematical selection cut for the kink analysis is the ‘decay angle’ or ‘kink angle’, which is defined as the angle made by the daughter charged particle with respect to the original direction of the parent charged particles. For generalisation, let us re-define the above mentioned parameters as follows:

$p_\mu = p$ = momentum of the charged daughter,

$m_\mu = m$ = mass of the charged daughter,

$E_\mu = E$ = energy of the charged daughter,

$P_K = P$ = momentum of the parent particle and

$M_K = M$ = mass of the parent particle.

In the laboratory system the components of the charged daughter momentum and decay angle can be estimated from Lorentz transformation as follows:

$$\begin{aligned}
 (p_T)_{LAB} &= p_{CM} \sin\theta_{CM} \\
 (p_L)_{LAB} &= \gamma q_L + \gamma\beta E_{CM} = \gamma p_{CM} \cos\theta_{CM} + \gamma\beta E_{CM} \\
 \tan\theta_{LAB} &= \frac{(p_T)_{LAB}}{(p_L)_{LAB}} = \frac{p_{CM} \sin\theta_{CM}}{\gamma p_{CM} \cos\theta_{CM} + \gamma\beta E_{CM}}
 \end{aligned} \tag{2.19}$$

where,

$$\beta = \frac{P}{\sqrt{P^2 + M^2}}, \gamma = \frac{\sqrt{P^2 + M^2}}{M}, \text{ and } E = \frac{M^2 + m^2}{2M} \tag{2.20}$$

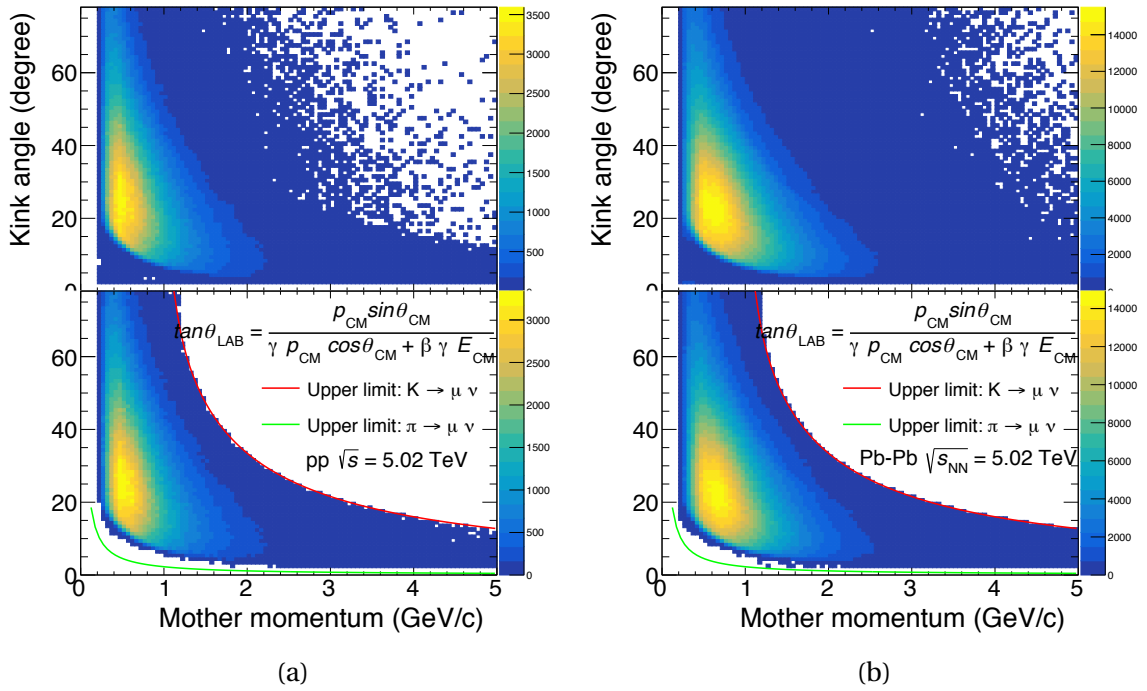


Fig. 2.28 Decay angle of kinks as a function of mother's momentum with $q_T > 0.12$ (GeV/c) in Pb-Pb collisions. Upper panel shows without topological cut whereas lower panel shows with topological selection. The red curve stands for the upper limit of $K \rightarrow \mu + \nu_\mu$ and the green one stands for the upper limit of $\pi \rightarrow \mu + \nu_\mu$.

It could be readily seen from Eqs. 2.19 and 2.20 that the kink angle θ_{LAB} associated with the decaying charged particle is a function of $\cos\theta$ and momentum of the decaying meson. For a particular decay channel, if all the quantities are in the CM system, then $\tan\theta$ will be maximum if,

$$\begin{aligned} (\tan\theta_{LAB})_{max}^2 &= \frac{p^2}{\gamma^2 E^2} \frac{1}{\left(\beta^2 - \left(\frac{p}{E}\right)^2\right)} \\ \Rightarrow (\tan\theta_{LAB})_{max} &= \frac{p}{\gamma E} \frac{1}{\sqrt{\left(\beta^2 - \left(\frac{p}{E}\right)^2\right)}} \end{aligned} \quad (2.21)$$

The advantage of Eq. 2.21 is that the θ_{max} value depends only on the momentum of the decaying meson. For a particular momentum of the decaying meson, the maximum kink angle for pion-kink is much smaller than the kaon-kink, due to the small difference of the mass between the pion and muon. Therefore, in addition to the daughter transverse momentum cut, kink angle is the another important selection parameter to separate the kaon-kink from the pion-kink.

In the fiducial volume of the TPC detector, the distributions of all the available kink angles (in degree) as a function of mother momentum is shown in Fig. 2.28 for both (a) pp and (b) Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The upper panels are without any topological selection cut, whereas the lower panels are with proper topological selection cuts. Using Eq. 2.21, the upper limits of kink angles for the decay channel of $K \rightarrow \mu + \nu_\mu$ is represented by the red line, whereas the green line represents the upper limit of the kink angles for the decay channel of $\pi \rightarrow \mu + \nu_\mu$. It is evident from the lower panels of Fig. 2.28 that the kink angles corresponding to the pion decay channel are much smaller than the kaon decay channel. So, in addition to this cut, kink angle < 2 degree cut has been applied to remove most of the possible pion-kink.

2.5.11.3 Selection on kink radius and the number of the TPC clusters

For the identification of charged kaons from their decay daughters, the kink-finding algorithm is implemented to reconstruct the kink vertex inside the fiducial volume of the TPC detector. The inner and outer radii of the TPC detector are 85 cm and 250 cm respectively. Since the decay lengths of the charged kaon and pion are 371.3 cm and 780.4 cm respectively, from the point of view that the decays are exponential, a sufficient number of kinks could be reconstructed within the TPC volume. To know the availability of these kinks explicitly within the TPC volume, a parameter called *kink vertex radius* or simply *kink radius* has been defined. Kink radius is already shown geometrically in Fig. 2.26, defined as the distance from the primary vertex to the projection of the secondary vertex on the xy-plane. From the kink finding algorithm, as discussed before, it was obvious that the nominal cut of the kink radius was taken in the range of $R = 120 - 220$ cm. However, the present analysis shows some large background in this range and based on the studies on purity using MC-generated data, the standard range is taken as $R = 130 - 200$ cm, which gives reasonably smaller background. The kink finding algorithm is also sensitive to the number of TPC clusters. For proper selection cut on the number of TPC cluster, distribution of the number of available TPC cluster as a function of kink vertex radius is shown in Fig. 2.29. It is evident from the figure that there is a strong correlation between the number of TPC clusters and the kink radius with a band of deep concentration along a line, which represents the real TPC cluster for the available kink sample. Two straight line fittings with proper parameters have been done: one above the concentration and one below the concentration in such a way that the background of the analysis becomes minimum. The fitting becomes more sensitive to the background for Pb–Pb collisions because the band spreads over larger region as compared to the pp collisions.

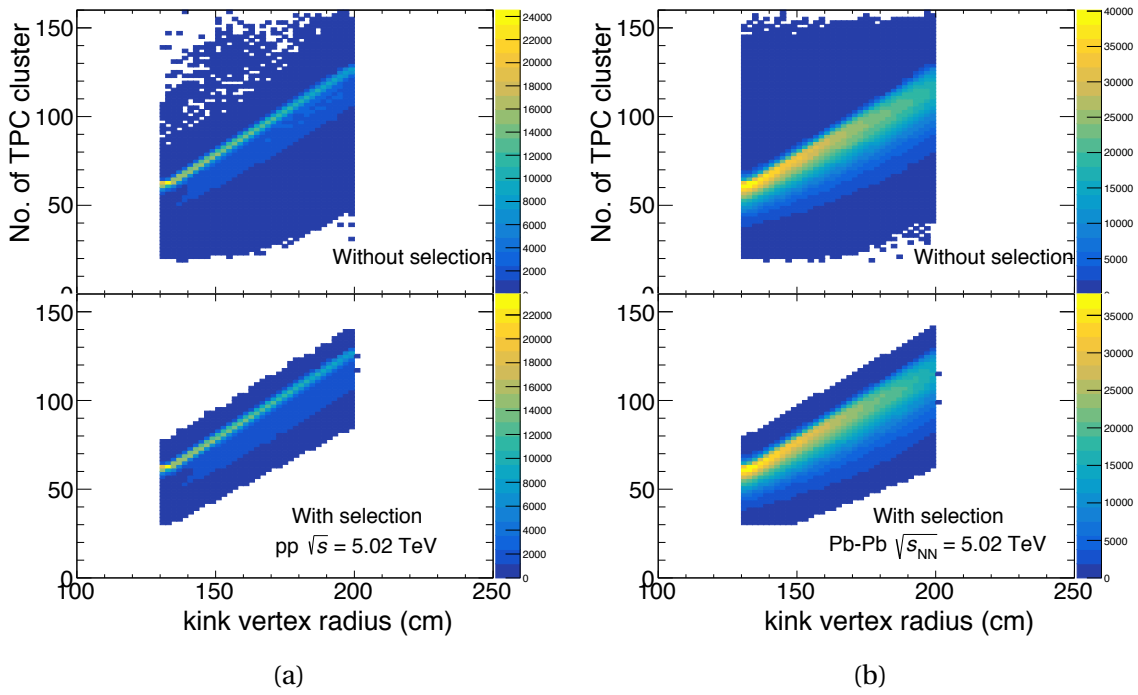


Fig. 2.29 Distribution of TPC clusters of mother tracks as a function of kink vertex radius ($130 < R < 200 \text{ cm}$) and kink angle > 2.0 degree in (a) pp and (b) Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Upper panel is plotted without any cut whereas lower panel includes the proper selection cuts.

2.5.11.4 Z-vertex of the kink

From the geometry of the decaying meson, as shown in Fig. 2.26, the z-vertex of the kink is defined as the distance from the primary vertex to the projection of the secondary vertex of the track on the beam axis. The z-vertexes of kink candidates also play an important role to remove the unwanted background. The background is generally estimated with the information of Monte Carlo studies. The background in the kink analysis is generally

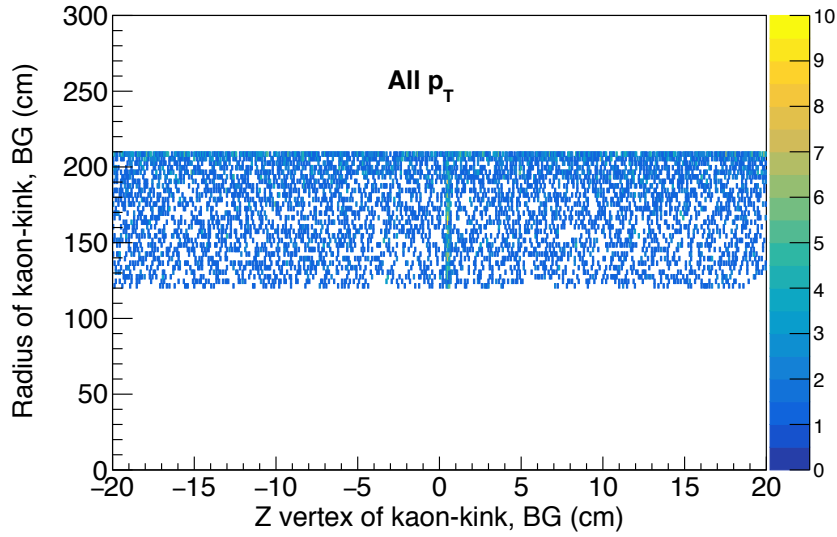


Fig. 2.30 Distribution of z-vertex of the kink as a function of the kink radius of wrongly identified kinks.

defined as the reconstructed kink, identified as a kaon that is not originally generated as a kink, which could be easily done from the information of the respective PID code of kaon and muon in the Monte Carlo data. The distribution of z-vertex of the kink as a function of the kink radius of wrongly identified kink is shown in Fig. 2.30. It could be readily seen from this figure that there is some concentration of wrongly identified kinks in the mid-point of the z-vertex of the kink. Also, for the kink radius within 200 – 210 cm, over the entire z-vertex, contains large background as compared for the kink radius < 200 cm. The idea to remove these backgrounds is to reject those kinks with large contaminated

regions. Therefore, the kink sample within the region of $130 < \text{kink radius} < 200$ cm as well as by rejecting the kinks that fall within the region of $0.4 < z\text{-vertex of kink} < 0.6$ cm is taken into account. Owing to the constraint of the TPC volume, the kinks having $z\text{-vertex}$ of the kink > 225 cm are also rejected from the sample.

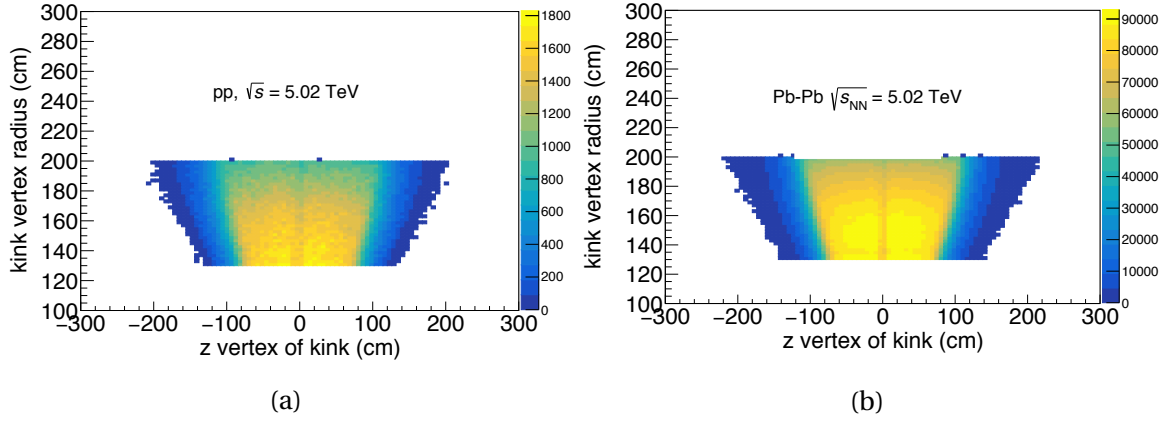


Fig. 2.31 Kink-vertex radius as a function of $z\text{-vertex}$ of kink with all the topological selection cuts in (a) pp and (b) Pb–Pb collisions.

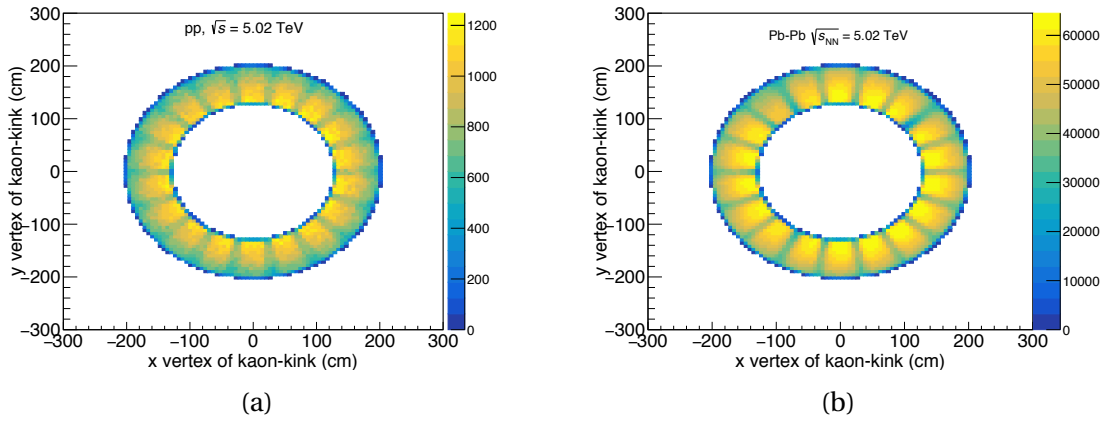


Fig. 2.32 Distribution of the $x\text{-vertex}$ of the kaon-kink as a function $y\text{-vertex}$ of the kaon-kink with all the topological selection cuts in (a) pp and (b) Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

After implementing all the topological selection cuts as discussed above, the distributions of the kink radius as a function of $z\text{-vertex}$ of the kink are shown in Fig. 2.31 (a) and (b) for pp and Pb–Pb collisions respectively at $\sqrt{s_{NN}} = 5.02$ TeV. From this figure, it could

be clearly seen that after implementing all the topological selections, a sufficient amount of kinks are available for further analysis within the selected zone of the TPC volume. Also, the distribution of the x-vertex of the kink as a function of y-vertex of the kink is shown in Fig. 2.32, from which the uniformity of the distribution of the kink in the xy-plane could be observed.

2.5.11.5 Measurement of specific energy loss

All the topological selections as discussed in the previous sections are sufficient enough to reconstruct the charged kaons from their decay daughters without the information of specific energy loss of the particle species in the TPC and thus kink topology is reliable to

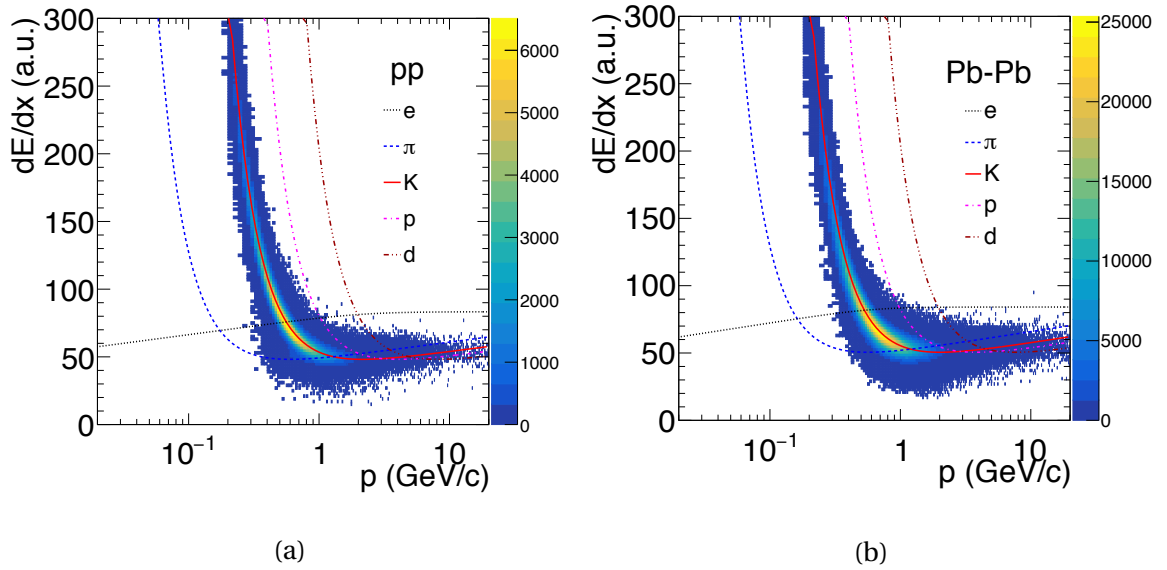


Fig. 2.33 Distribution of specific energy loss (dE/dx) as a function of mother momentum of the selected kaons from kinks within the topological regions of TPC volume for (a) pp (left panel) and (b) Pb-Pb (right panel) collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The solid and dotted curves are the theoretical values of Bethe-Bloch equation for different particle species.

identify high momentum charged kaons in the overlap region of the dE/dx distribution. However, to remove some possible contamination (very small) from other particle species, a 3.0σ cut on the dE/dx measurement of charged kaons has been applied at the final

stage. The distribution of dE/dx of the identified charged kaons from kinks within 3.0σ is shown in Fig. 2.33 which shows a good agreement with the theoretical calculation of the Bethe-Bloch equation using ALEPH parametrization [144] as discussed in previous section of Eq. 2.8.

2.5.11.6 Invariant mass distribution of the identified particles

Assuming zero neutrino mass, the invariant mass of charged kaon ($K \rightarrow \mu + \nu_\mu$) can be calculated from the momentum conservation law as follows:

p_m = mother's momentum

p_d, p_v = daughters' momenta

m_m, E_v = mother's mass and daughter's (ν) energy

$$\begin{aligned}
 \vec{p}_m &= \vec{p}_d + \vec{p}_v \\
 \Rightarrow \vec{p}_v &= \vec{p}_m - \vec{p}_d = \Delta \vec{p} \\
 E_v &= \sqrt{p_v^2 + m_v^2} = p_v = \Delta p \\
 m_m &= \sqrt{E_m^2 - p_m^2} = \sqrt{(E_d + E_v)^2 - p_m^2} \\
 \Rightarrow m_m &= \sqrt{(\sqrt{p_d^2 + m_d^2} + \Delta p)^2 - p_m^2}
 \end{aligned}$$

Using the above equation, the invariant mass distributions of all the decaying charged particles without any topological selection cuts are shown in the upper panels of Fig. 2.34 for minimum bias (a) pp and (b) Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The various topological selection cuts applied systematically on the selected data sample, which removes the fake daughter tracks from the kaon-kinks sample and the reconstructed signals of the charged kaons are shown in the lower panels of Fig. 2.34. The two distinct invariant mass peaks of the identified charged kaons correspond to the two different decay channels: (i) K

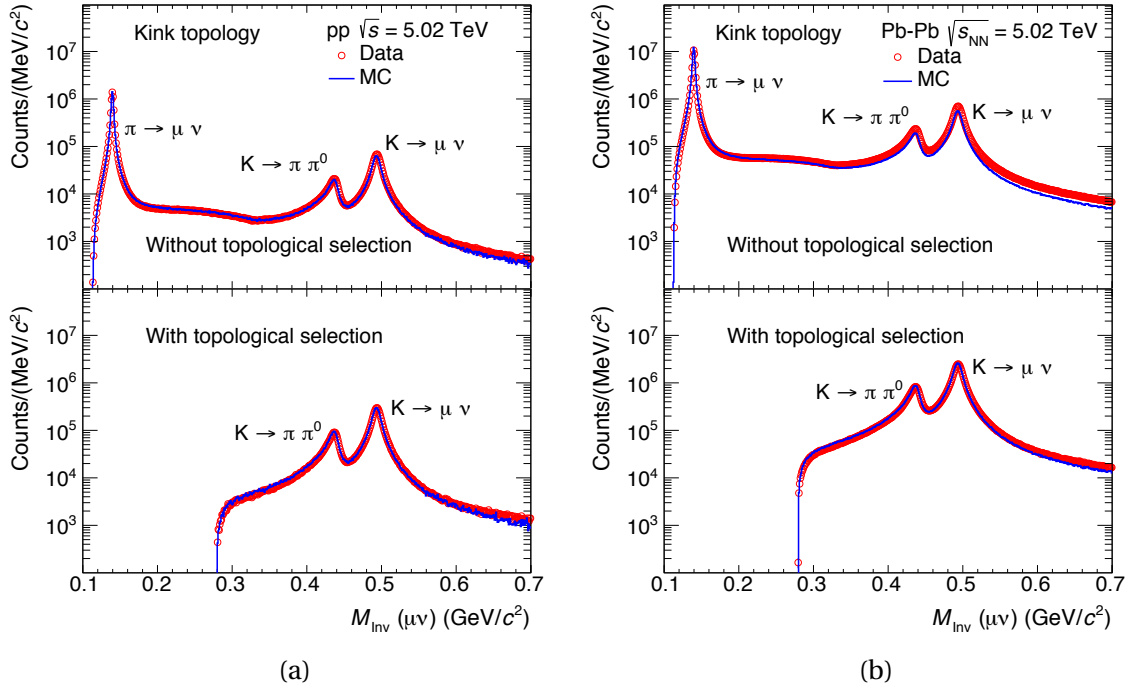


Fig. 2.34 Invariant mass distribution of identified charged kaons from their decay products in (a) pp and (b) Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The red circles and blue lines represent the experimental data and Monte Carlo simulation respectively. The upper panel represents the invariant mass distribution without the topological selection cuts whereas the lower panel shows with the topological selection cuts. The peak centered at $M_{\mu\nu} = 0.49 \pm 0.028$ GeV/c^2 is for the decay channel $K \rightarrow \mu + \nu_\mu$ (BR = 63.55%), whereas the peak centered at $M_{\mu\nu} = 0.43 \pm 0.017$ GeV/c^2 is for the decay channel $K \rightarrow \pi + \pi^0$ (BR = 20.66%), the invariant mass of which is calculated with the pseudo mass hypothesis.

$\rightarrow \mu + \nu_\mu$ with B.R. = 63.55% centered at $M_{\mu\nu} = 0.49 \pm 0.028 \text{ GeV}/c^2$ and (ii) $K \rightarrow \pi + \pi^0$ with B.R. = 20.66% centered at $M_{\pi\pi^0} = 0.43 \pm 0.017 \text{ GeV}/c^2$. For a particular transverse momentum (p_T) interval, these signals are considered as the raw signals of the identified charged kaons which are then extracted by integrating over the entire regions containing the two peaks of the lower panels of Fig. 2.34 (a) and (b). It is worth mentioning that the 3-body and 4-body decay channels of charged kaons with comparatively very small branching ratios as shown in Table 2.1 are not considered in this analysis.

2.5.11.7 Raw transverse momentum spectrum

The kink topology technique can be applied over a wide momentum range irrespective of the behaviour of the specific energy loss of the particles inside the TPC volume. However, this technique solely depends on the statistics of the available data sets. With the available statistics of the above-mentioned data sets, identification of the charged kaons is carried out reasonably well in the momentum range of $0.2 < p_T < 6.0 \text{ GeV}/c$. The transverse momentum (p_T) distribution of the identified charged kaon, for a selected rapidity window ($|y| < 0.5$) and p_T bin is defined as,

$$\text{Raw } p_T \text{ spectra} = \frac{1}{N_{ev}} \frac{d^2 N}{dy dp_T} \quad (2.22)$$

In the the rapidity coverage of $-0.5 < y < 0.5$, the yields of the identified charged kaons for each p_T bin in minimum bias pp collisions and different centrality classes in Pb–Pb collisions are shown in Fig. 2.35 and 2.36 respectively.

2.5.11.8 Monte Carlo prediction

Monte Carlo event generators are widely used to make a prediction for collider experiment and to develop techniques to propose for various experiment [148]. In ALICE data analysis, MC events are extremely important for predictive and precise simulation of the detector

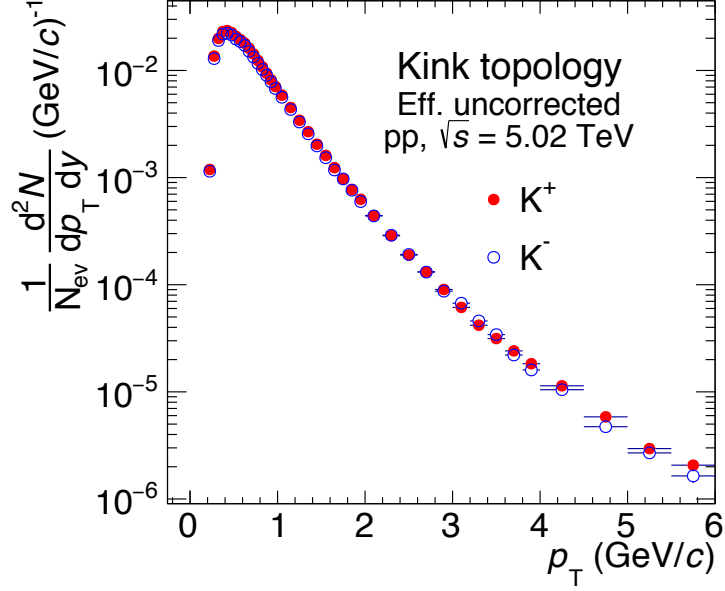


Fig. 2.35 Efficiency uncorrected p_T spectra of identified charged kaons from kinks in pp collisions at $\sqrt{s} = 5.02$ TeV.

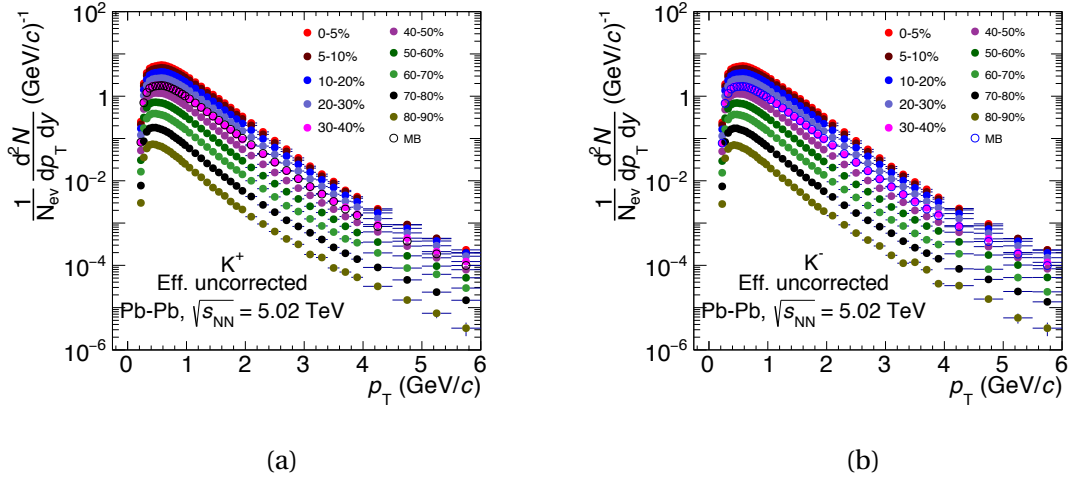


Fig. 2.36 Efficiency uncorrected transverse momentum spectra of identified (a) K^+ (left panel) and (b) K^- (right panel) from kinks in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The open markers represent the transverse momentum spectrum for minimum bias collisions, whereas the solid markers with different colours represents the transverse momentum spectra at different centrality classes.

response. Different external event generators such as HIJING, PYTHIA and DPMJET are extensively used for these purposes. In this analysis, the HIJING (Heavy-Ion Jet Interaction Generator) event generator tuned with the LHC data has been used for the prediction of results in Pb–Pb collisions, whereas PYTHIA8-Monash tuned event generator has been used for the prediction of pp collisions results.

For the simulation of ALICE detector response, different Monte Carlo transport packages, such as GEANT3, GEANT4 and FLUKA are extensively used. These packages have different user interfaces for geometry definition and signal scoring. They are interfaced to the virtual Monte Carlo abstract in ROOT, which are then used for the simulation via AliRoot.

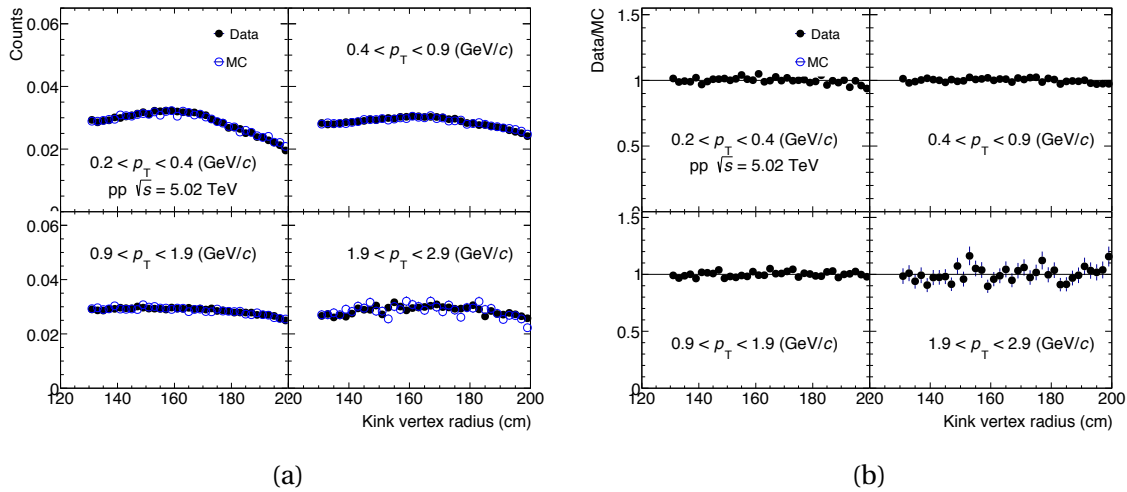


Fig. 2.37 Comparison of kink vertex radius of real data with MC prediction at different p_T ranges in pp collisions at $\sqrt{s} = 5.02$ TeV are shown in (a), whereas their ratios are shown in (b). The solid and open marker symbols represent the real data and MC prediction respectively.

The details of the Monte Carlo run periods used in this analysis have already been discussed in the subsection 2.5.1. To compare the Monte Carlo prediction with the results of the experimental data, similar event and track selection criteria have been implemented to the MC data. From the predictions with MC data, the daughter transverse momentum distributions of all the kinks available in the selected kinematic regions are already shown

in Fig. 2.27, which shows a good agreement with the data. Further, the MC predicted invariant mass distribution of charged pions and kaons show good agreement with the experimental results which is shown in Fig. 2.34.

Another important MC prediction in kink analysis is the kink vertex radius associated with the decay length of the decaying particles. As discussed earlier, the kink vertex radius is perpendicular to the beam axis inside the kinematic region of the TPC detector ($130 < R < 200$ cm). In general, the decay track length reflects the exponential weak decay of charged kaons with a decay length of 371 cm, and thus due to this exponential weak decay property, a sufficient number of the kinks could be found in the kinematical region of the TPC volume. The measurement of kink radius in data and its prediction from MC studies might provide important information about the behaviour of the identified kaons from kinks concerning the decay length of the kaons.

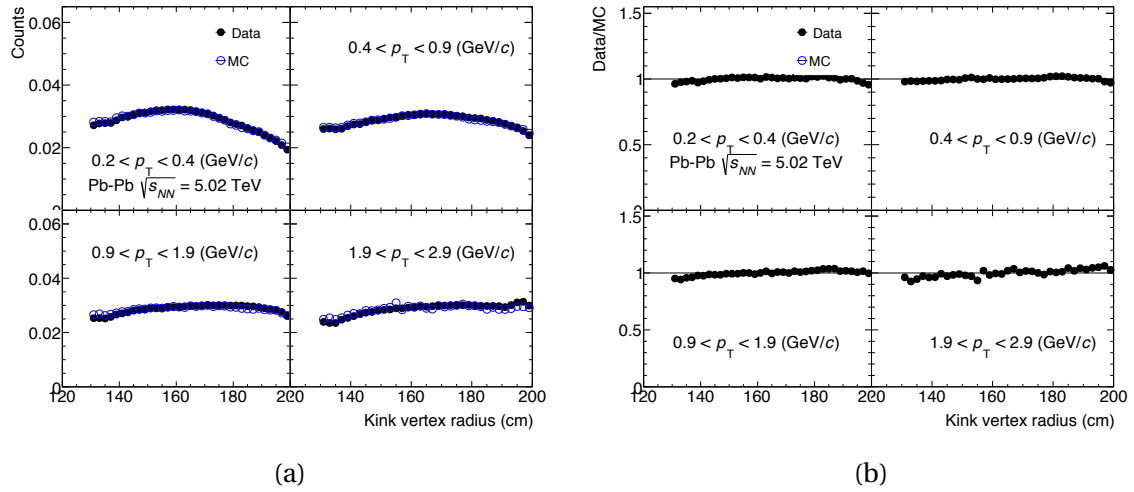


Fig. 2.38 Comparison of kink vertex radius of real data with MC prediction at different p_T ranges in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV are shown in (a), whereas their ratios are shown in (b). The solid and open marker symbols represent the real data and MC prediction respectively.

In Figs. 2.37 (a) and 2.38 (a), the kink vertex radius measured in experimental data is compared with the MC predicted kink radius for different p_T ranges for pp and Pb–Pb collisions respectively. Their ratios, data/MC, are shown in Figs. 2.37 (b) and 2.38 (b),

which are found to be close to unity at all the p_T ranges. This provides a good evidence that the decay length of real data is close to the nominal one (MC prediction) and the identified kaons from kinks are true kaons. However, the contamination in the analysis is quantitatively discussed in the following sections.

2.5.11.9 Correction factors

In ALICE, based on the performance and physics motivation, various detectors are installed at different kinematic regions. Particle identification depends on various factors of the dedicated detectors, based on their performance. Various correction factors, such as kink reconstruction efficiency, acceptance, PID efficiency, purity, etc. are essentially important for complete signal extraction and derive the physics message which can be studied using the dedicated Monte Carlo based event generators.

As the Monte Carlo-generated events provide primarily the particle level information, however, this can be used as reconstruction-level quantities by transporting them through dedicated simulation packages as mentioned in the previous subsection (2.5.11.8). To estimate the various correction factors, both generated and reconstructed level information are needed.

The similar selection criteria of the real data have also been applied for track reconstruction of the decaying charged kaons to the MC data sample. Here, the particle level selection criteria for generated events have been applied to select the primary vertex position and consequently, the decay vertex is determined based on the Particle Data Group (PDG) information. Further, the various topological selection on the mother and daughter particles of the MC-generated events, similar to the real data have also been applied systematically to estimate the various correction factors.

The various correction factors used for kink analysis are described below:

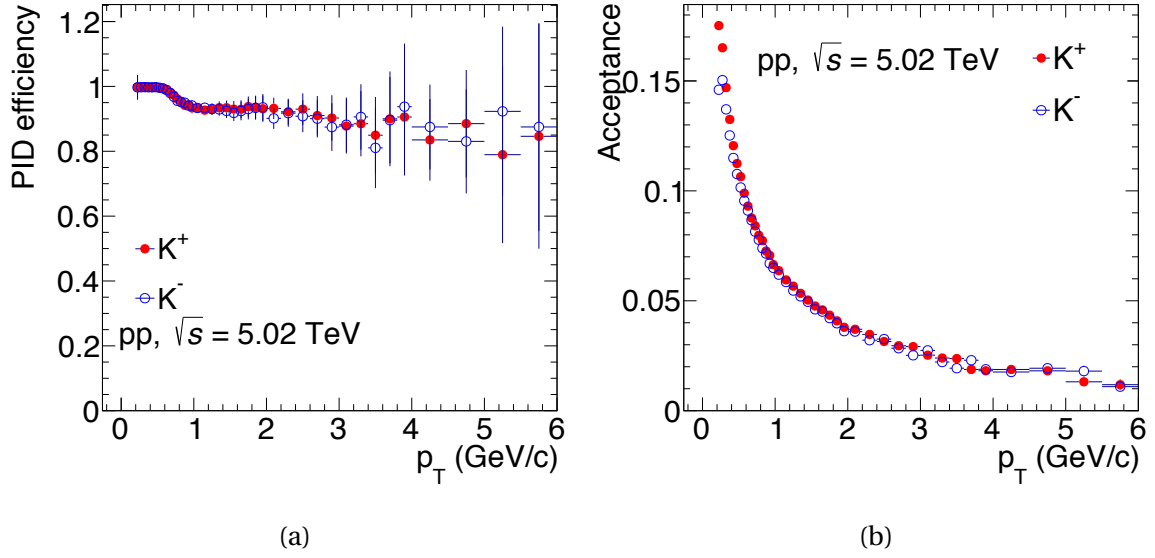


Fig. 2.39 (a) Distribution of particle identification efficiency and (b) acceptance of $K^\pm$ in minimum bias pp collisions at $\sqrt{s} = 5.02$ TeV. The solid and open markers represent the K^+ and K^- respectively.

a) $\text{Acceptance} = N_{GAcc}(K) / N_{Gall}(K),$

where, $N_{Gall}(K) \rightarrow$ number of all the generated primary kaons within the rapidity and p_T interval.

$N_{GAcc}(K) \rightarrow$ number of findable weak decaying kaons as generated above, inside the fiducial volume of the TPC detector.

b) $\text{Efficiency (reconstructed + identified)} = N_{GRI}(K) / N_{GAcc}(K),$

where, $N_{GRI} \rightarrow$ number of identified kaons from reconstructed kinks using the kink algorithm.

c) $\text{PID efficiency} = N_{GRIPure}(K) / N_{GR}(K),$

where, $N_{GRIPure}(K) \rightarrow$ number of reconstructed kinks, identified as kaons which were originally kaons.

$N_{GR}(K) \rightarrow$ number of reconstructed kinks which were originally generated as kaons.

d) $\text{Purity} = N_{GRIPure}(K) / N_{GRI}(k)$

e) Contamination = $N_{RFake}(K)/N_{GRI}(K)$,

where, $N_{RFake}(K) \rightarrow$ number of reconstructed kinks, identified as kaons that were not generated originally as kinks.

The PID efficiency and the ‘acceptance’ correction factor are depicted in Fig. 2.39 for minimum bias pp collisions at $\sqrt{s} = 5.02$ TeV. Both K^+ and K^- show a good PID efficiency of $\sim 99.7\%$ for $p_T < 0.6$ GeV/c and decreases to 80% at higher p_T . From the definition, the ‘acceptance’ physically provides a correction factor of the decaying kaons to obtain quantitatively all the primary kaons produced in the collisions. The ‘reconstructed + PID’ efficiency is reasonably large, around 60%, which shows a slightly decreasing trend with momentum as shown in Fig. 2.40 (a). It is clearly seen from Fig. 2.40 (b) that the purity of the kink analysis is quite reasonable with $\sim 2\%$ contamination. From the quantitative approach for a particular p_T bin, the total quantity ‘purity + background’ should be equal to 1. The purity becomes maximum for the momentum below 1 GeV/c, then decreases with the increase of momentum.

Both the acceptance and efficiency (reconstructed + PID) are primarily important for correcting the raw spectra. The quantity ‘efficiency x acceptance’ is termed as *physical efficiency* and is shown in Fig. 2.41 for pp collisions at $\sqrt{s} = 5.02$ TeV. From Fig. 2.40 (a) it is seen that there are some statistical fluctuations for high p_T region which reflects in the physical efficiency as shown in Fig. 2.41. This small fluctuation potentially affects the final corrected p_T spectra. The idea to overcome this issue is to fit with a proper function and use it for the correction of the raw spectra. The ‘efficiency x acceptance’ plot follows a landau distribution function (Fig. 2.41). The general distribution function provided by Landau is given by [149, 150],

$$f(\lambda) = \frac{1}{\pi} \int_0^\infty e^{-u \ln u - \lambda u} \sin(\pi u) du, \quad (2.23)$$

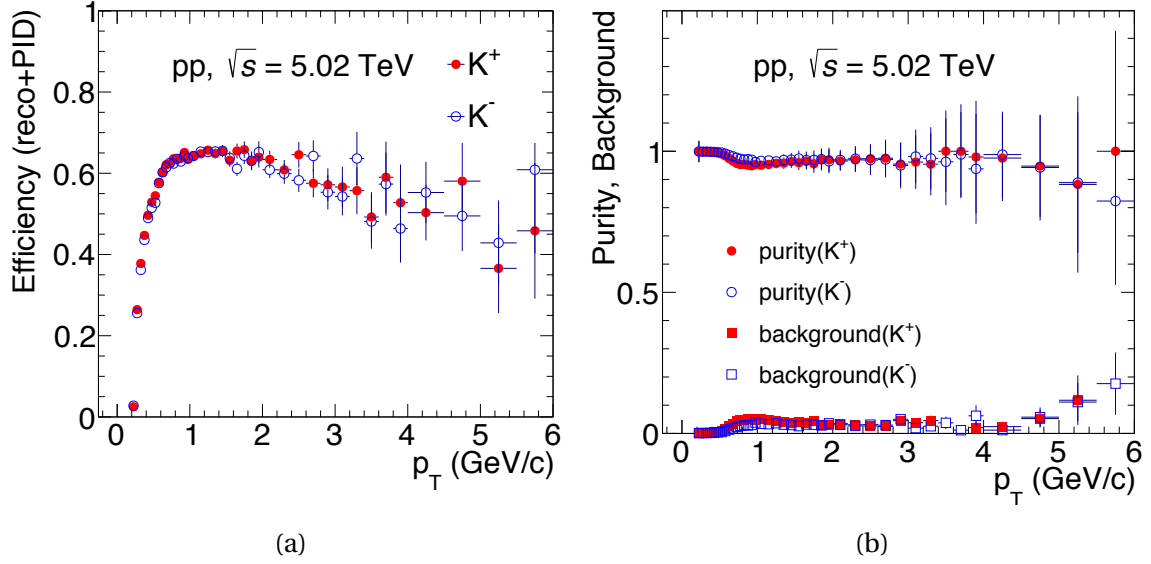


Fig. 2.40 (a) Distribution of 'reconstruction + PID' efficiency and (b) purity as well as the contamination of $K^\pm$ in minimum bias pp collisions at $\sqrt{s} = 5.02$ TeV. The solid and open circular markers represent the K^+ and K^- respectively. On the other hand, the solid and open rectangular symbols represent the contaminations of K^+ and K^- respectively.

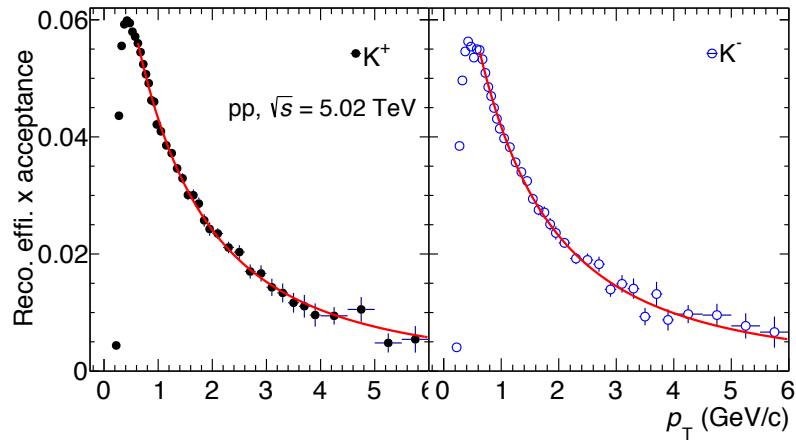


Fig. 2.41 Distribution of physical efficiency of identified charged kaons in pp collisions at $\sqrt{s} = 5.02$ TeV.

where,

$$\lambda = \frac{\Delta - \Delta_0}{\xi}, \quad (2.24)$$

where, Δ is the actual energy loss, Δ_0 is the location parameter and ξ is the material property.

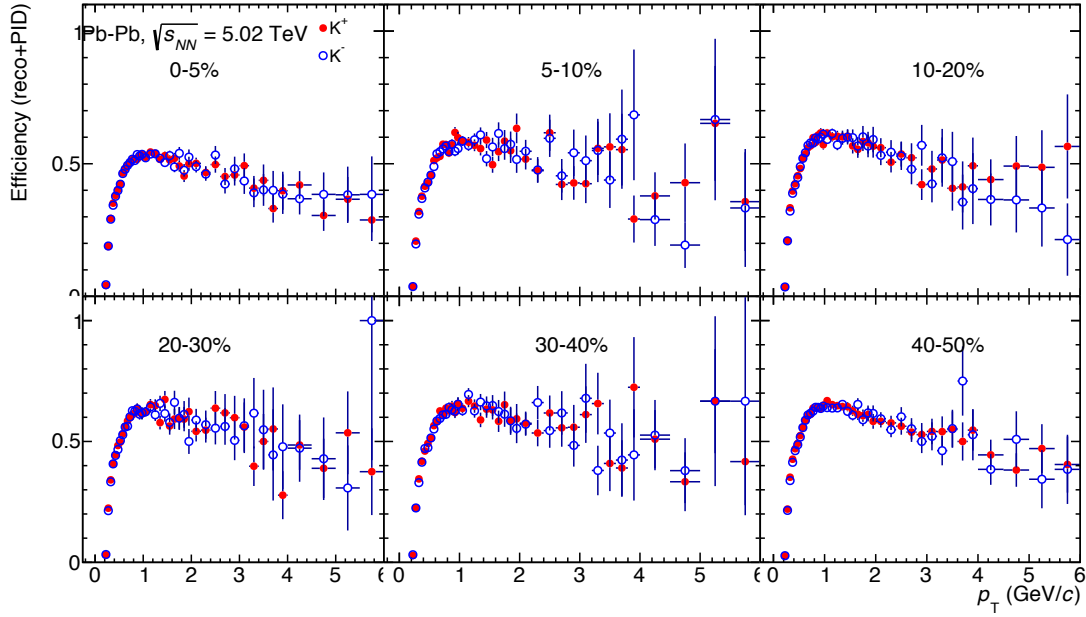


Fig. 2.42 Distribution of ‘reconstructed + PID’ efficiency of reconstructed charged kaons from kinks in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for the centrality classes of 0 – 5%, 5 – 10%, 10 – 20%, 20 – 30%, 30 – 40%, and 40 – 50%. The solid and open markers stand for K^+ and K^- respectively.

Similarly, for Pb–Pb collisions, the ‘reconstruction + PID’ efficiency as a function of p_T has been plotted for different centrality classes in Figs. 2.42 and 2.43. A small centrality dependent efficiency has been observed with 52% for most central collisions which increases gradually and becomes 65% for the most peripheral collisions. This behaviour has a natural explanation: for the most central collisions, the maximum amount of energy is deposited due to head-on-collisions, producing a large number of particles than the peripheral collisions where the energy deposition is comparatively less. Consequently,

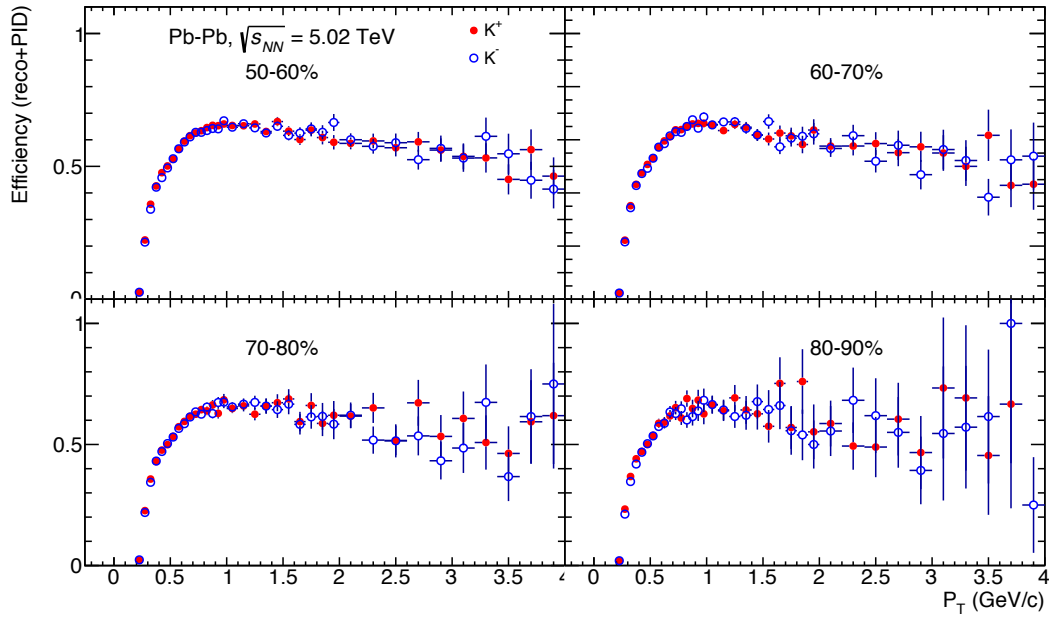


Fig. 2.43 Distribution of ‘reconstructed + PID’ efficiency of reconstructed charged kaons from kinks in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for the centrality classes of 50 – 60%, 60 – 70%, 70 – 80%, and 80 – 90%. The solid and open markers stand for K^+ and K^- respectively.

due to the higher occupancy of the tracks for central collisions, some of the genuine tracks are lost due to the overlapping, resulting lower efficiency than the peripheral collisions.

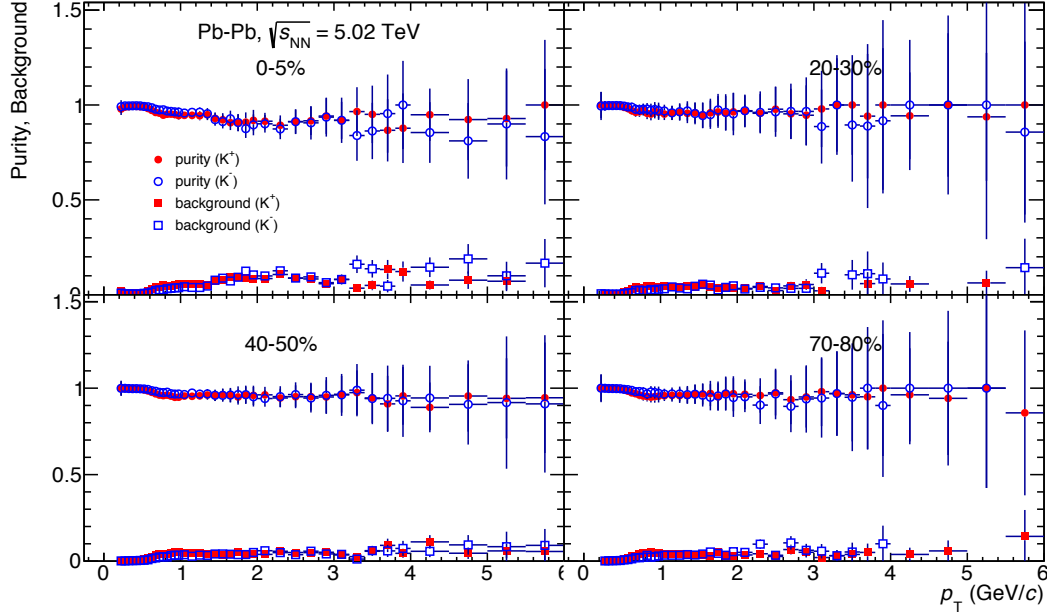


Fig. 2.44 Distribution of purity and background as a function of p_T in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for the centrality classes of 0 – 5%, 20 – 30%, 40 – 50%, and 70 – 80%. The solid and open circular markers represent the purity of K^+ and K^- respectively, whereas the solid and open rectangular symbols represent the contamination in the analysis.

The distributions of purity and background as a function of p_T in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV have been shown in Fig. 2.44 for the centrality classes– 0 – 5%, 20 – 30%, 40 – 50%, and 70 – 80%. The purity ranges from 99% at low p_T to 92% at high p_T , whereas for peripheral collisions it improves gradually. Figs. 2.45 and 2.46 show the distribution of physical efficiency for all the centrality classes fitted with the Landau distribution function similar to the pp collisions as discussed before. The behaviour of the physical efficiency of K^- is similar with K^+ and thus not shown in the figure. Further, a correction for the MC simulation packages of GEANT/FLUKA is also necessary to take into account the imprecise description of the energy loss in the material. This correction is important particularly for the low p_T negative kaon which is shown in Fig. 2.47.

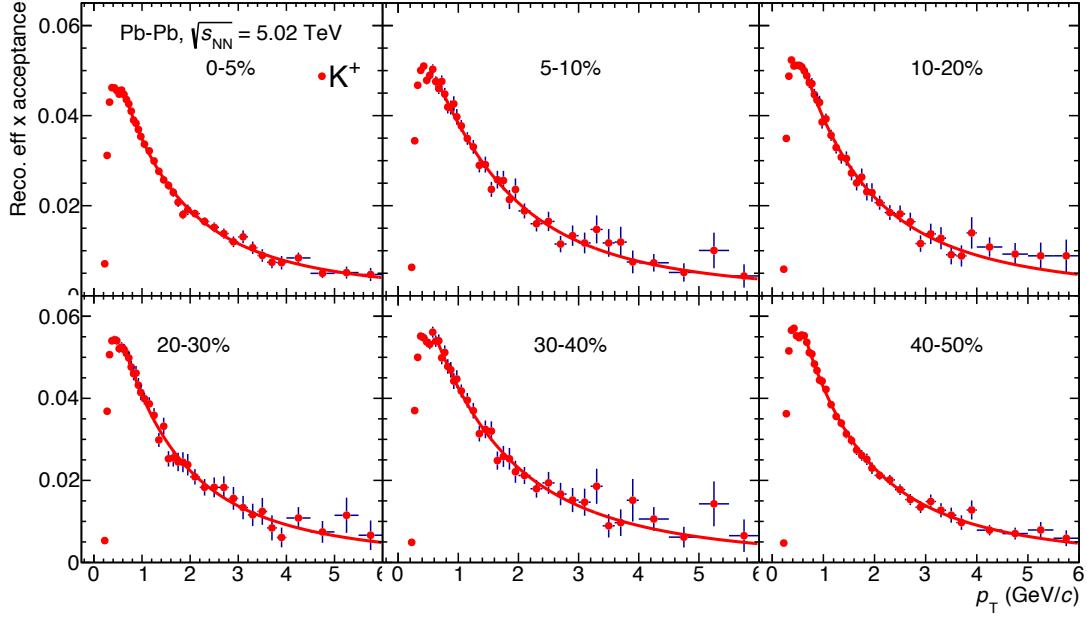


Fig. 2.45 Distribution of physical efficiency of reconstructed K^+ from kinks in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for the centrality classes of 0–5%, 5–10%, 10–20%, 20–30%, 30–40%, and 40–50%.

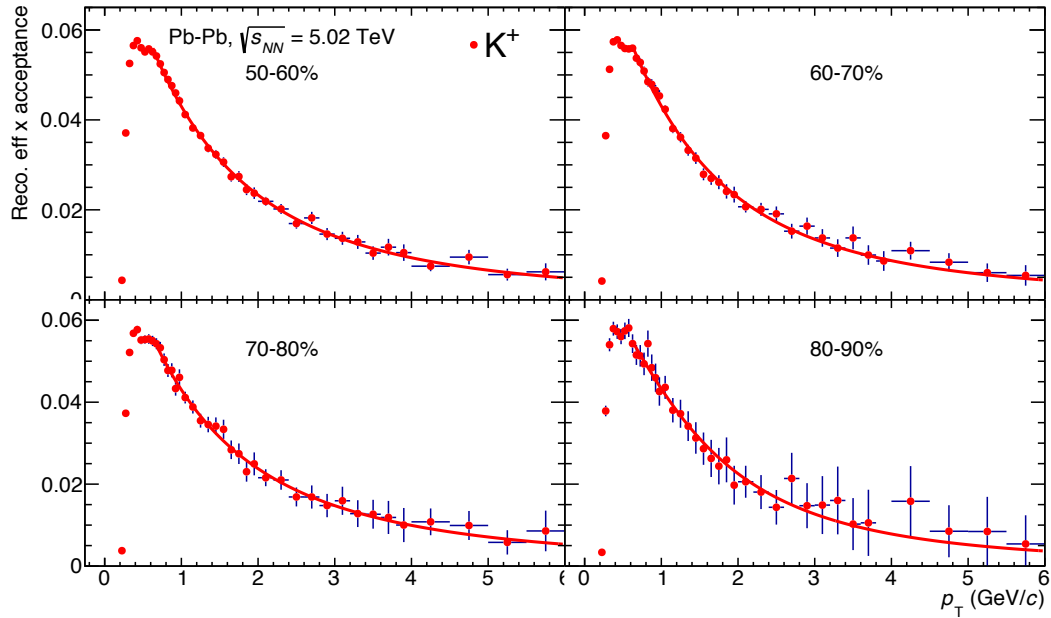


Fig. 2.46 Distribution of physical efficiency of reconstructed K^+ from kinks in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for the centrality classes of 50–60%, 60–70%, 70–80%, and 80–90%.

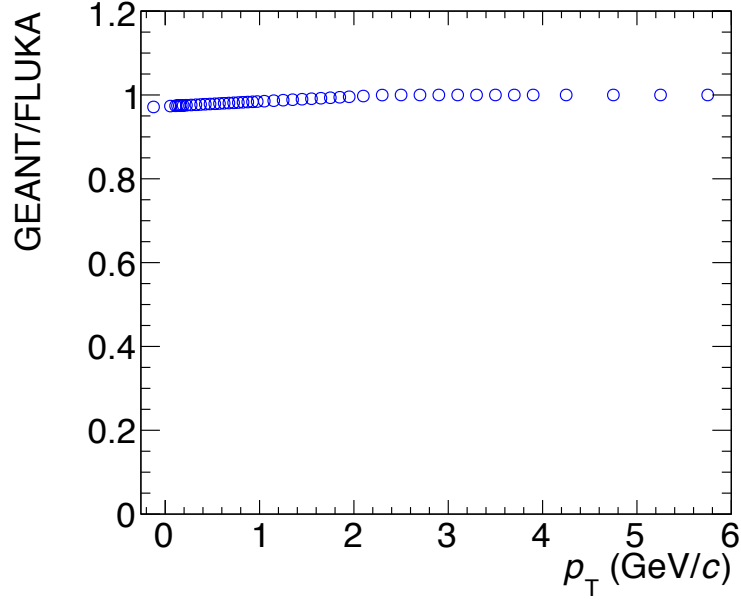


Fig. 2.47 GEANT/FLUKA correction factor for K^- .

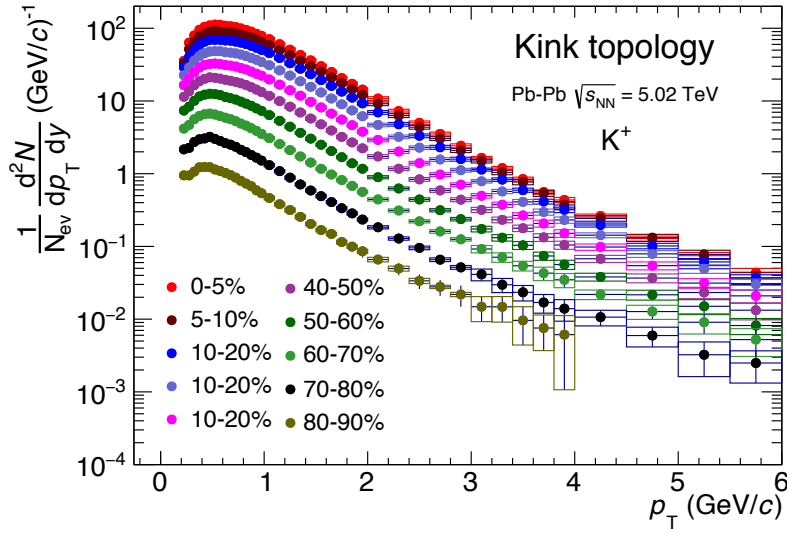


Fig. 2.48 Efficiency corrected p_T spectra of charged K^+ in Pb-Pb collisions for different centrality classes. The boxes represent the systematic uncertainties.

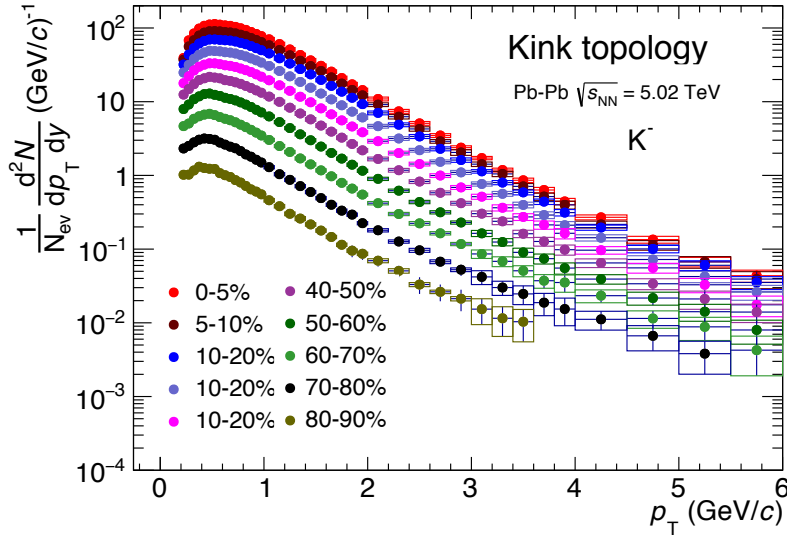


Fig. 2.49 Efficiency corrected p_T spectra of charged K^- in Pb-Pb collisions for different centrality classes. The boxes represent the systematic uncertainties.

The raw transverse momentum spectra are normalised by the number of events ($N_{eventSel}$) that pass all the event selection criteria for the rapidity coverage of $|y| < 0.5$. The corrected transverse momentum distribution is given by:

$$\frac{1}{N_{ev}} \frac{d^2N}{dy dp_T} = \frac{1}{N_{eventSel}} \frac{dN}{dy dp_T} \frac{1}{(Acceptance) \cdot (Efficiency)} \cdot (purity) \quad (2.25)$$

The corrected p_T distribution of identified charged kaons using kink topology in Pb-Pb collisions for different centrality classes are shown in Fig. 2.48 and 2.49. The corrected p_T spectra also contain the systematic uncertainties, the origin and the extent of which is discussed in the following sections.

2.5.11.10 Error estimation

All the measurements, however scientific and careful, are subjected to some extent of uncertainties. In general, error analysis includes both the study and evaluation of these uncertainties. The errors or uncertainties are generally defined as the difference between

the observed or calculated value and the true value. We do not know exactly the true value of a measurement; otherwise, there would be no reason for performing the various experiments. However, either from the past experiments or theoretical calculations, we may know approximately the true value. Such approximation can serve as guidance which insists one to measure the quantity systematically from the data and the experimental condition themselves. In general, there are two types of error in a measurement, namely, random error and systematic error.

The random error arises mainly from the limited number of measurements. The precision of an experiment depends upon how well one can overcome random error, and hence the fluctuations in the observation that produce different results for each time when the experiment is repeated. If the random error arises from the statistical fluctuations in a limited number of the measurements, they can be reduced to a large extent by repeating the experiment.

On the other hand, the systematic uncertainty arises from the faulty calibration of an experiment or the bias on the part of the observer. The accuracy of an experiment generally depends on how well one can control or compensate for the systematic error. For the minimization of the systematic error, the faulty calibration of the experiment must be eliminated or minimized. Further, by improving the method of the measurement and the bias of the technique, one can minimize the systematic error. In this section, the details of the systematic error associated with the kink analysis will be discussed.

Systematic uncertainties in Pb–Pb collisions: In high energy data analysis, different authors suggest different tools to estimate the systematic uncertainties. According to Roger Barlo [151], the best way to do the analysis is to: 1) devise the cut, known as standard cut and get the result, 2) analyze different data sub-sets, 3) alter the standard cuts and put in a table, 4) change the histogram bin size, 5) change the parametrisation and change the fit technique, and 6) add the variations in a quadrature and quote them as a systematic

error. In ALICE data analysis, the systematic uncertainties are mostly estimated from the cut variations and the maximum deviation from the standard results are considered (sometimes the RMS value are also taken), and then added them in quadrature.

Based on the cut variations, the various contributors to the systematic uncertainties for Pb–Pb collisions are listed below:

1. The minimum number of TPC cluster is varied from 30 to 20 and 40,
2. The kink vertex radius is varied from 130–200 cm to 125–205 cm,
3. The lower value of the q_T cut is varied from 120 MeV to 100 and 130 MeV,
4. Number of σ cut is varied from $n\sigma = 3.0$ to 3.5,
5. Kink reconstruction efficiency, which has been estimated from the MC studies and added together with the above-mentioned cut variations,
6. Track selection, and
7. The contamination of the analysis

To evaluate the stability of the chosen sets of cut values for the topological selection, the effects of the tightening and loosening of the cuts were investigated. For each set of cut variations, new raw p_T spectra have been obtained. To take into account the effect of the correction factors, similar cut variations have also been applied to the corresponding anchored MC data sets.

Number of TPC cluster: In this analysis, the minimum number of TPC cluster was taken as 30 (standard), whereas for systematic study it is changed to 30 ± 10 . The correction factors have been estimated with MC-generated data using a similar set of cuts and used to obtain the corrected new p_T spectra. The ratios between the new p_T spectra to the nominal one, for both the set of cuts are shown in Figs. 2.50 and 2.51 for 20 and 40 respectively. A slight p_T dependent variation between the nominal and the new spectra has been observed and the difference is found to be similar for both the cut variations.

Due to this observation, the cut variation of TPC cluster > 20 has been taken into account to extract the systematic uncertainties.

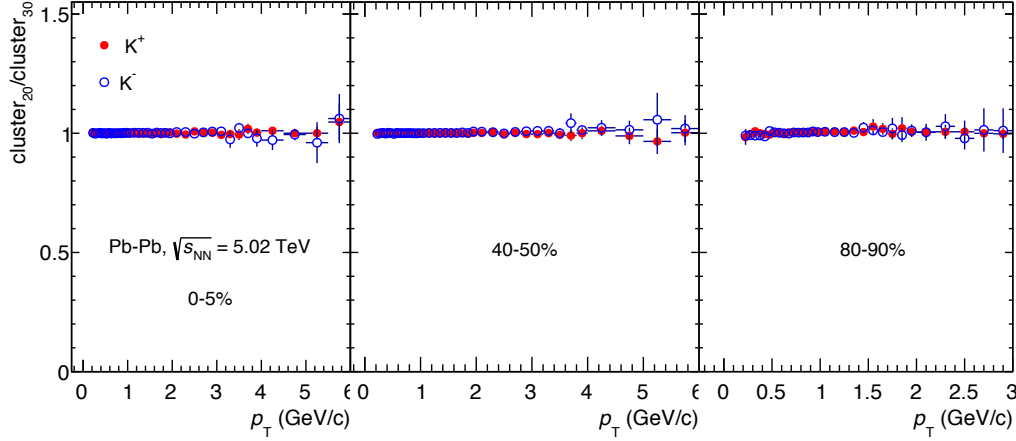


Fig. 2.50 Ratio between the p_T spectra obtained with the cut variation on the number of TPC cluster (from 30 to 20) to the nominal one in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for the centrality classes of 0 – 5%, 40 – 50%, and 80 – 90%. The solid and open marker symbols represent the ratio plots of K^+ and K^- respectively.

Kink vertex radius: The standard range of kink-vertex radius was taken as $130 < R < 200$ cm, whereas for the systematic uncertainty, it is taken as $125 < R < 205$ cm. The ratio plots between the new spectra and the default one are shown in Fig. 2.52. A small p_T dependent variation has been observed in the new spectra with respect to the default one and the deviation from the standard one is taken as systematic uncertainty.

Daughter transverse momentum: The background in this analysis arises mainly from pion kinks. An upper limit cut of $q_T > 120$ MeV/c, separate the pion kinks from the kaon kinks. A stringent cut, such as $q_T > 130$ MeV/c does not affect the spectra significantly and hence $q_T > 100$ MeV/c has been used for the systematic uncertainties. The comparison plots as a ratio between the new and the standard one are shown in Fig. 2.53 for three centralities, namely, 0 – 5%, 40 – 50% and 80 – 90%. The plots show a small p_T dependent difference between the two.

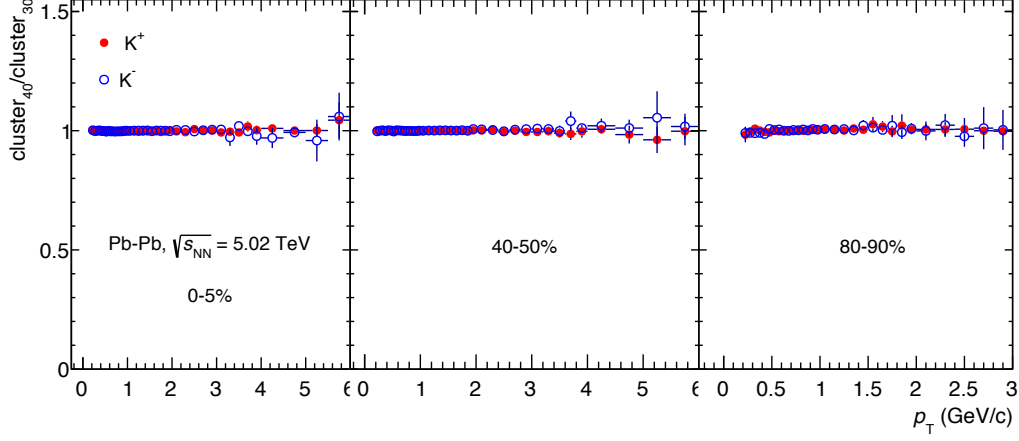


Fig. 2.51 Ratio between the p_T spectra obtained with the cut variation on the number of TPC cluster (from 30 to 40) to the nominal one in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for the centrality classes of 0 – 5%, 40 – 50%, and 80 – 90%. The solid and open marker symbols represent the ratio plots of K^+ and K^- respectively.

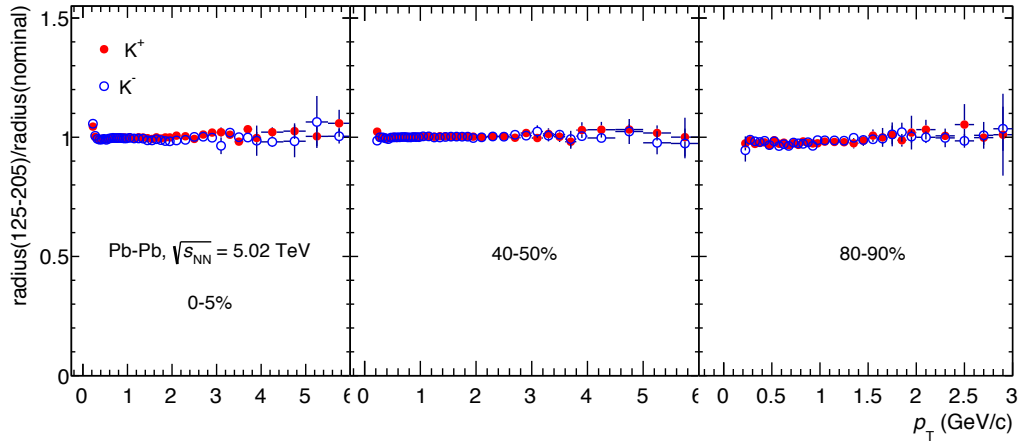


Fig. 2.52 Ratio between the p_T spectra obtained with modified kink vertex radius and the default one in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for the centrality classes of 0 – 5%, 40 – 50%, and 80 – 90%. The solid and open marker symbols represent the ratio plots of K^+ and K^- respectively.

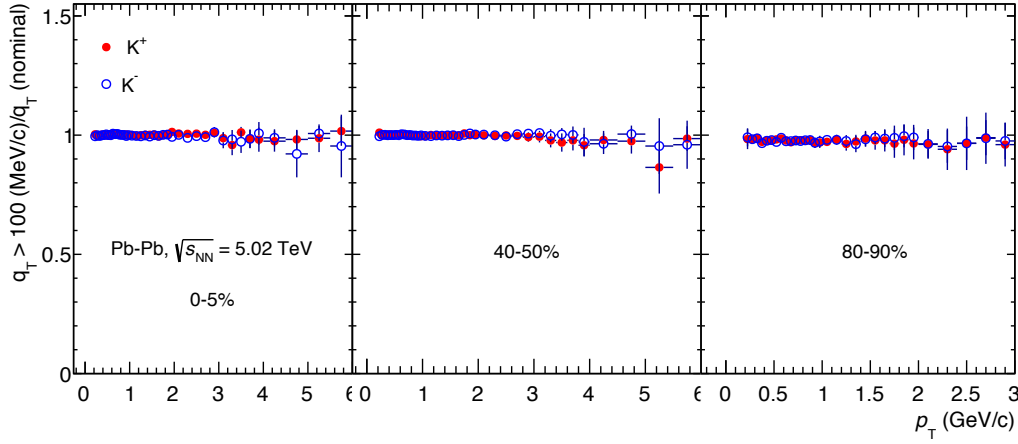


Fig. 2.53 Ratio between the p_T spectra obtained with modified q_T cut and the default one in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for the centrality classes of 0 – 5%, 40 – 50%, and 80 – 90%. The solid and open marker symbols represent the ratio plots of K^+ and K^- respectively.

TPC dE/dx selection: Though the specific energy loss (TPC dE/dx) information for the charged kaons has no major role in kink analysis, it affects the spectra significantly at low p_T regions, particularly for the most central collisions. To take into account the maximum mother charged kaons, a number of TPC sigma, $n\sigma < 3.0$ has been applied on the mother charged kaons as a standard cut and $n\sigma < 3.5$ is used for the systematic uncertainties. Fig. 2.54 shows the ratio between the two, with a significant difference in the low p_T region, especially for the most central collisions. Going from central to peripheral collisions, the difference decreases continuously and become negligible for the most peripheral collisions.

Background: The background or contamination as a function of p_T in Pb–Pb collisions for three centrality classes is shown in Fig. 2.55. The contamination is very small at low p_T ($p_T < 0.6$ GeV/c), which increases gradually and saturates at around $p_T \approx 1 - 2$ GeV/c within some statistical fluctuations. Therefore, to obtain a reasonable and stable uncertainties, for p_T above 1 GeV/c, the distribution is fitted with straight line.

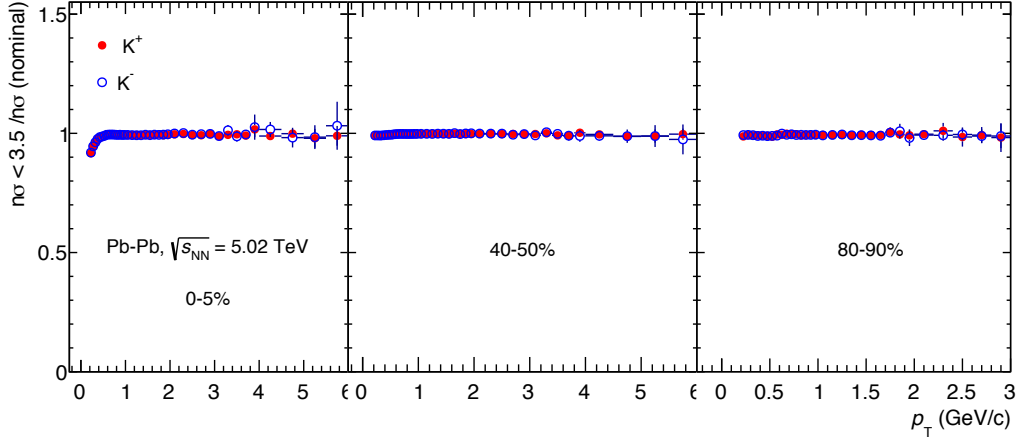


Fig. 2.54 Ratio between the p_T spectra obtained with modified $n\sigma$ cut and the default one in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for the centrality classes of 0 – 5%, 40 – 50%, and 80 – 90%. The solid and open marker symbols represent the ratio plots of K^+ and K^- respectively.

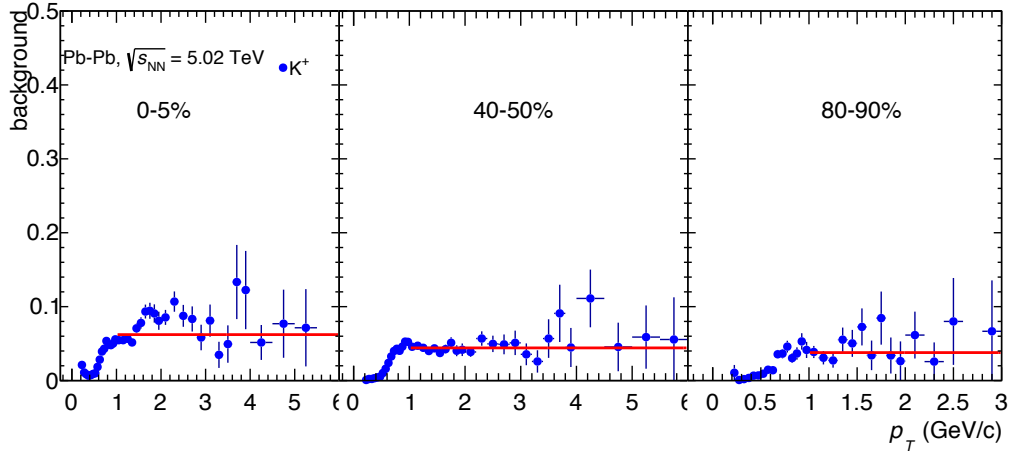


Fig. 2.55 Distribution of contamination as a function of p_T for K^+ in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for the centrality classes of 0 – 5%, 40 – 50%, and 80 – 90%. Above 1 GeV/c the background is fitted with straight line.

Track selection: In kink analysis, primarily the global tracks are selected. Then, a set of standard cuts (such as DCAz vertex cut, DCA cut in xy plane, the minimum number of TPC cluster, χ^2/NDF , etc.) has been applied to select the genuine tracks for this analysis. Some of the standard track selection cuts, which are expected to have some significant influence on the spectra are varied for the estimation of systematic uncertainties. For example, the p_T dependent cut on DCA in the xy-plane has been changed from 7σ (standard) to 6σ and 8σ , and their ratio plots with respect to the nominal one are shown in Figs. 2.56 and 2.57 respectively. No significant variation is observed for 6σ cut, but a small p_T and centrality dependent variation has been observed for 8σ cut. Similarly, χ^2/NDF which is sensitive to the number of TPC cluster has changed from $\chi^2/NDF > 4$ to $\chi^2/NDF > 5$, and their ratio plot is shown in Fig. 2.58. Further, the variation on the distance of the closest approach along the z-axis has been studied and changed from 2 cm (nominal) to 1.5 cm and 2.5 cm respectively, and their ratio plots are shown in Figs. 2.59 and 2.60 respectively. A very weak dependence on the DCA_z cut has been observed. All the cut variations for track selection show a weak dependence on p_T and centrality and found to be $\sim 3\%$ from all the track selection cuts.

Total systematic uncertainties: The systematic uncertainties of identified K^+ and K^- from various sources in Pb–Pb collisions as discussed above are shown in Figs. 2.61 and 2.62 for three centrality classes. The total systematic uncertainty is obtained by adding all the contributions in quadrature which is denoted by the black solid line in the figures. A sharp increase of the total systematic at low $p_T < 400$ MeV/c, particularly for the most central collisions has been observed, which arises mainly from the selection of TPC dE/dx on the mother kaons applied at the very end of all the topological selections. In central collisions, the total systematic uncertainty tends to become stable above $p_T = 1$ GeV/c reaching around 10% at the highest p_T . The behaviour of the total systematic of K^+ and K^- looks almost similar.

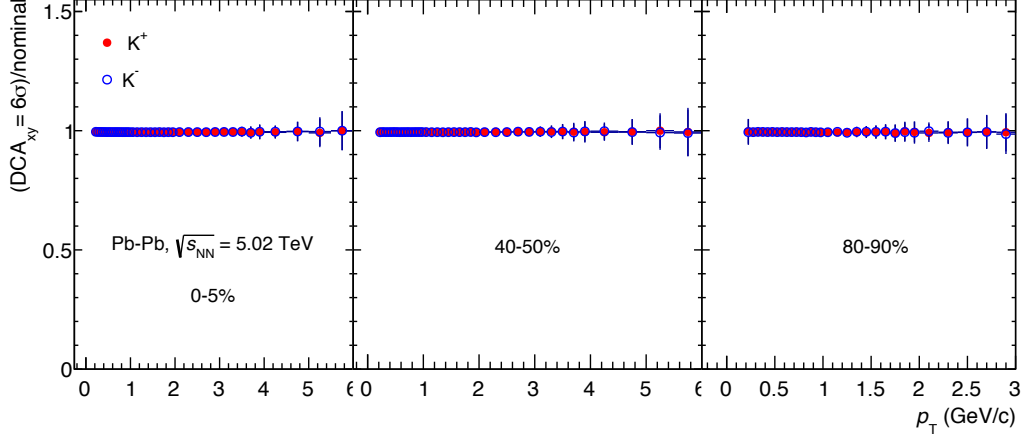


Fig. 2.56 Ratio between the spectra obtained with modified of $DCA_{xy} = 6\sigma$ and the default one in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for the centrality classes of 0 – 5%, 40 – 50%, and 80 – 90%. The solid and open marker symbols represent the ratio plots of K^+ and K^- respectively.

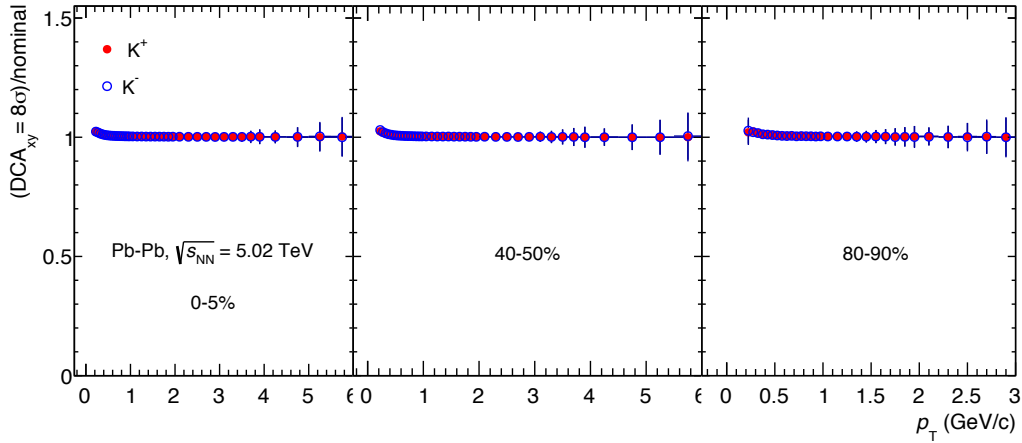


Fig. 2.57 Ratio between the spectra obtained with modified of $DCA_{xy} = 8\sigma$ and the default one in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for the centrality classes of 0 – 5%, 40 – 50%, and 80 – 90%. The solid and open marker symbols represent the ratio plots of K^+ and K^- respectively.

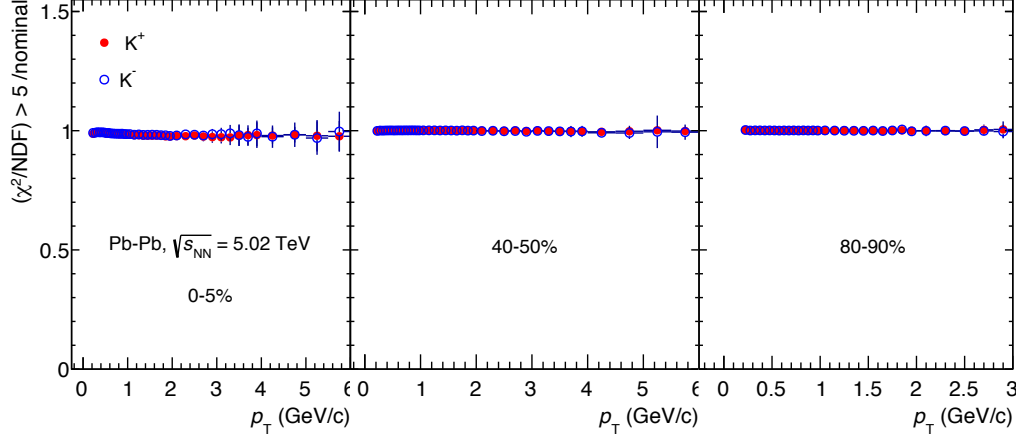


Fig. 2.58 Ratio between the spectra obtained with modified of $\chi^2/NDF > 5$ and the default one in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for the centrality classes of 0 – 5%, 40 – 50%, and 80 – 90%. The solid and open marker symbols represent the ratio plots of K^+ and K^- respectively.

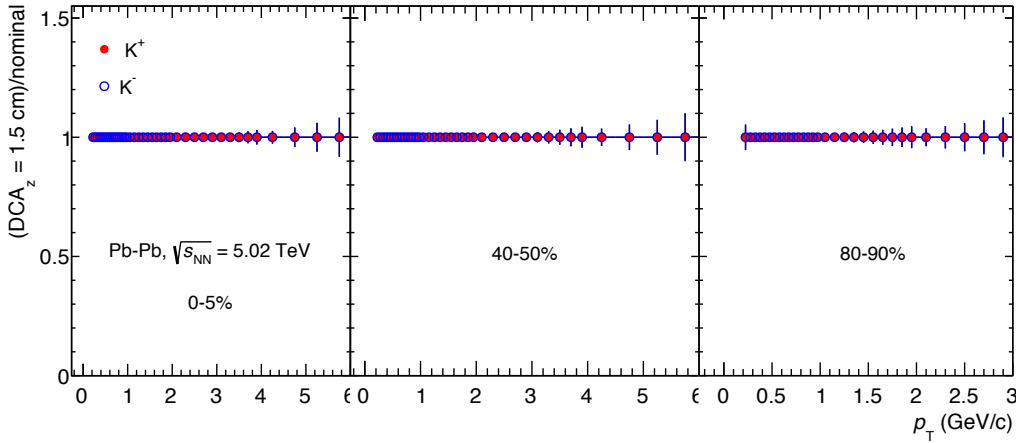


Fig. 2.59 Ratio between the spectra obtained with modified of $DCA_z = 1.5$ cm and the default one in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for the centrality classes of 0 – 5%, 40 – 50%, and 80 – 90%. The solid and open marker symbols represent the ratio plots of K^+ and K^- respectively.

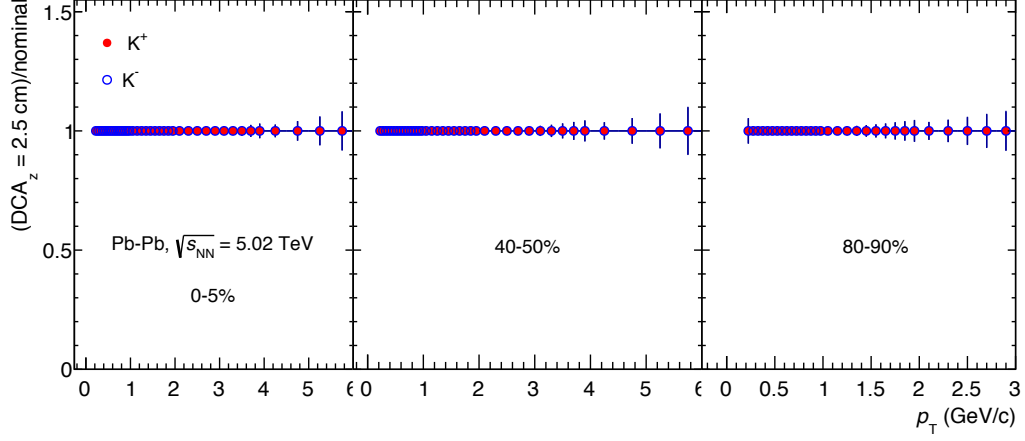


Fig. 2.60 Ratio between the spectra obtained with modified of $DCA_z = 2.5$ cm and the default one in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for the centrality classes of 0 – 5%, 40 – 50%, and 80 – 90%. The solid and open marker symbols represent the ratio plots of K^+ and K^- respectively.

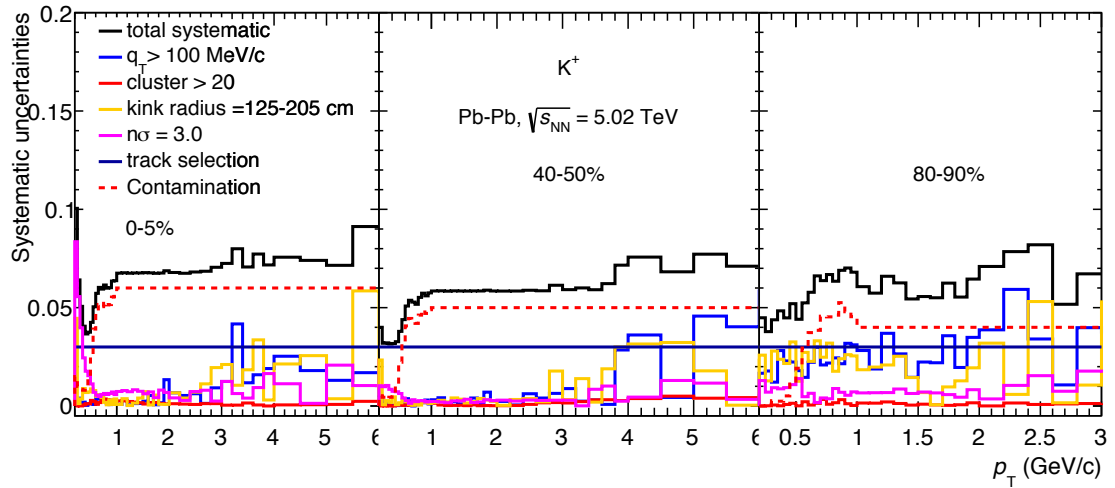


Fig. 2.61 Systematic uncertainties of different contributions of K^+ in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for the centrality classes of 0 – 5%, 40 – 50%, and 80 – 90%. The black solid lines represents the total systematic uncertainty added in quadrature.

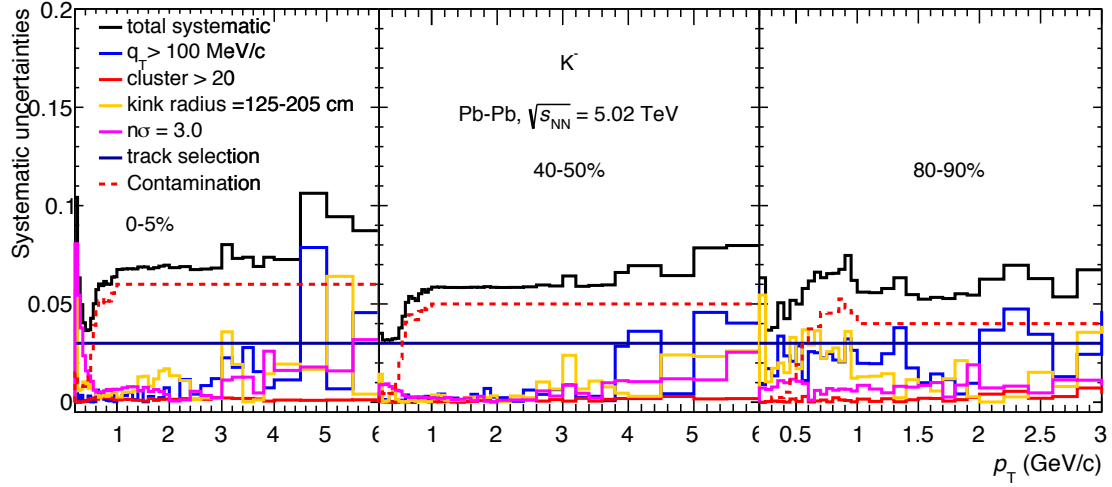


Fig. 2.62 Systematic uncertainties of different contributions of K^- in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for the centrality classes of 0 – 5%, 40 – 50%, and 80 – 90%. The black solid lines represents the total systematic uncertainty added in quadrature.

Systematic uncertainties in pp collisions: The cut variations for pp collisions are also same to that of the Pb–Pb collisions. The cut on the TPC dE/dx for kaons has no significant effect on the spectra and hence omitted, and the contribution from the track selection is taken as 3%, considering the fact that the track selection criteria for both pp and Pb–Pb collisions are same. It is also important to note that the systematic uncertainties for almost all the sources in pp collisions exhibit a very weak dependence on p_T and taken as a constant value which is obtained by fitting them with ‘pol0’ function. Some of the fitting plots are shown in Figs. 2.63, 2.64 and 2.65. The different contributions and the total systematic uncertainties are shown in Fig. 2.66.

Estimation of uncorrelated systematic uncertainties: The estimation of uncorrelated systematic uncertainty in Pb–Pb collisions is based on the changes of uncertainty with centrality. The fractional deviation observed in each centrality class is compared with the fractional deviation observed in the minimum bias collisions. For each of the systematic variation of a measurement S , the deviation (R_{var}) is measured as,

$$R_{var} = \frac{\left(\frac{S_{var}^i}{S^i}\right)}{\left(\frac{S_{var}^{MB}}{S^{MB}}\right)}, \quad (2.26)$$

where S^i is the signal for the centrality class i , S^{MB} is the signal for the minimum bias, and S_{var} denotes the systematic variation being studied. The deviation of R_{var} from unity quantifies how much the deviation in centrality class i differs from the value of minimum bias. The systematic uncertainty due to the systematic source ‘var’ is given by, $1 - R_{var}$ and the total uncorrelated systematic uncertainty is estimated by adding them in quadrature. Figs. 2.67 - 2.70 shows the distributions of $1 - R_{var}$ for different systematic sources, whereas the total uncorrelated systematic uncertainties of K^+ and K^- are shown in Figs. 2.71 and 2.72 respectively.

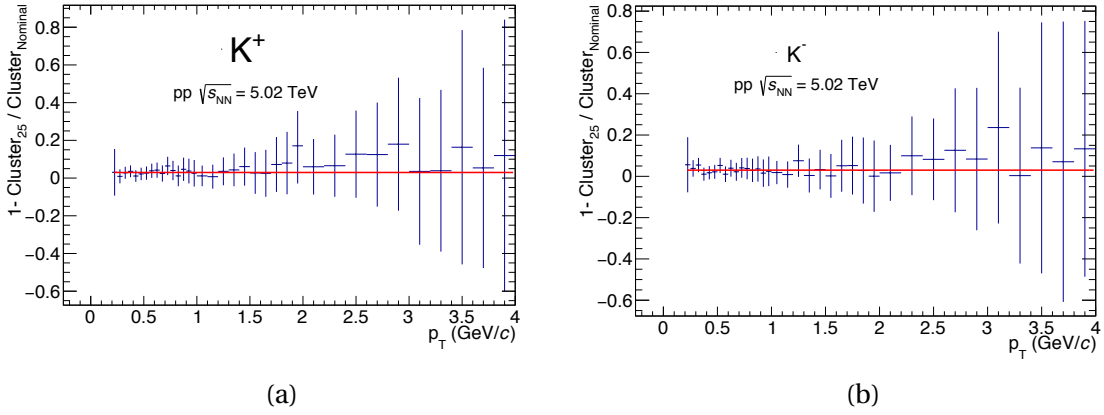


Fig. 2.63 Extraction of systematic uncertainties of (a) K^+ and (b) K^- for the modified cut on the number of TPC cluster in pp collisions. The red solid line represents the fits of ‘pol0’ function.

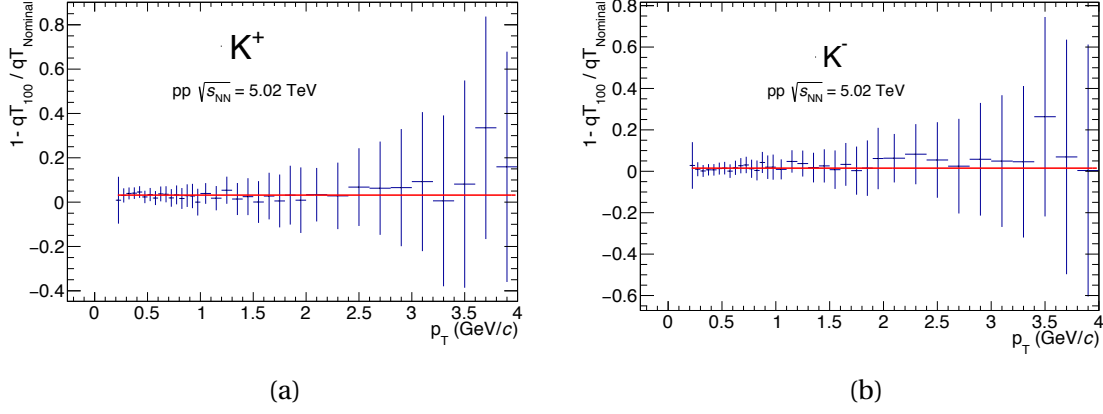


Fig. 2.64 Extraction of systematic uncertainties of (a) K^+ and (b) K^- for the modified cut on the daughter transverse momentum in pp collisions. The red solid line represents the fits of 'pol0' function.

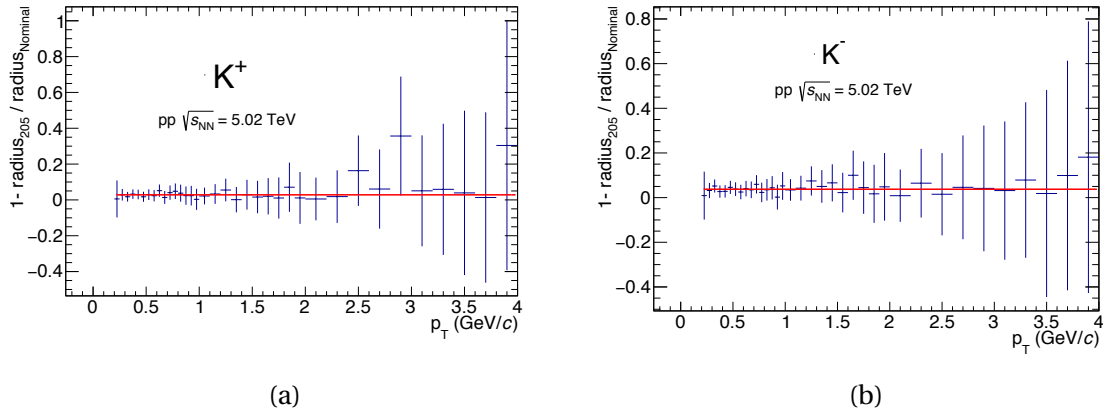


Fig. 2.65 Extraction of systematic uncertainties of (a) K^+ and (b) K^- for the modified cut on the kink vertex radius in pp collisions. The red solid line represents the fits of 'pol0' function.

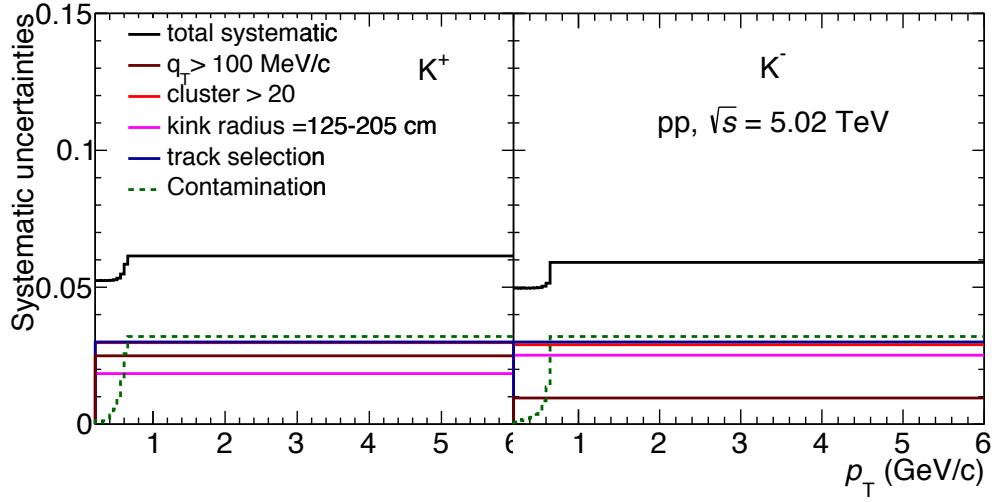


Fig. 2.66 Systematic uncertainties of different contributions of K^+ and K^- in pp collisions. The black solid lines represents the total systematic uncertainty added in quadrature.

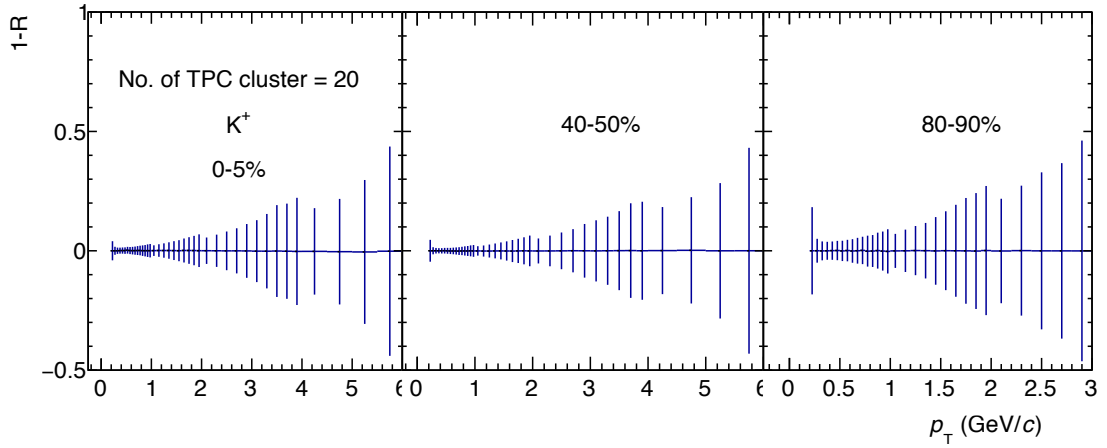


Fig. 2.67 Estimation of $1 - R$ for the cut variation on the number of TPC cluster in Pb-Pb collisions.

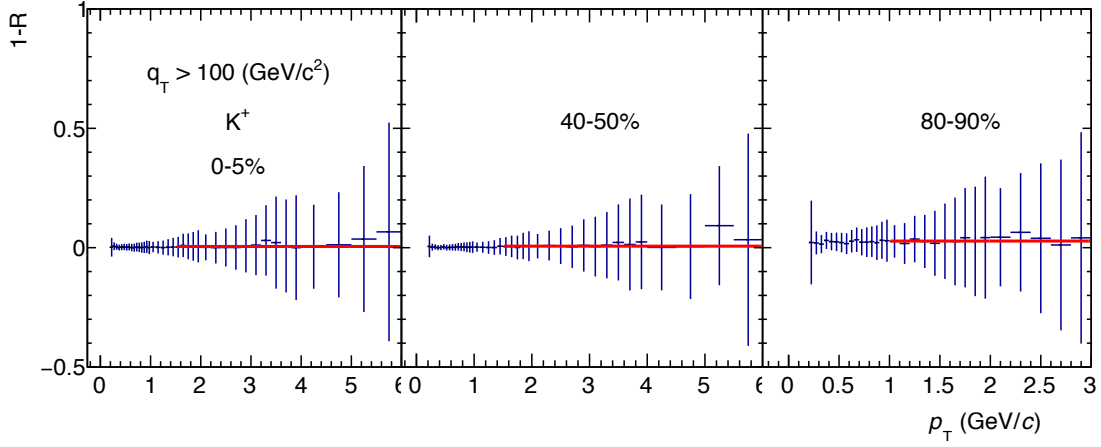


Fig. 2.68 Estimation of $1 - R$ for the cut variation on the daughter transverse momentum in Pb-Pb collisions for the centrality classes of 0 – 5%, 40 – 50%, and 80 – 90%. The red solid line represents the straight line fitting to omit the statistical fluctuations.

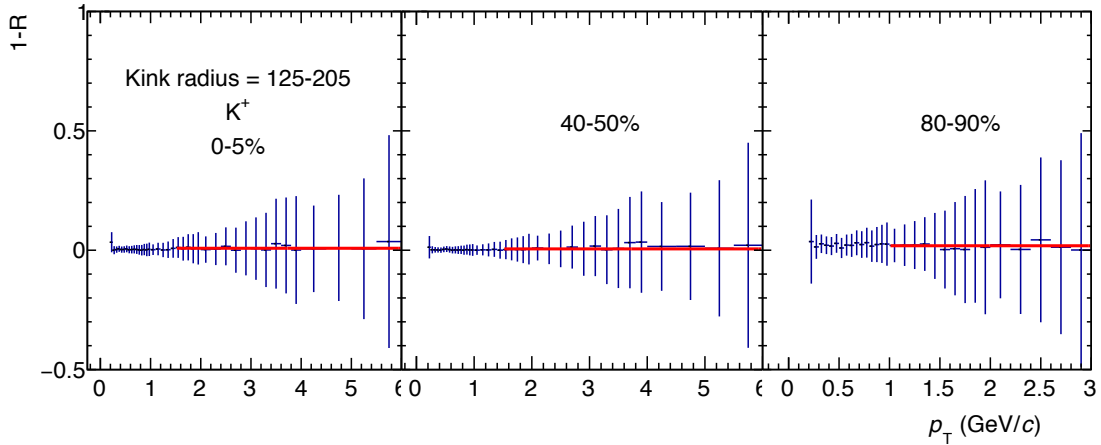


Fig. 2.69 Estimation of $1 - R$ for the cut variation on the kink vertex radius in Pb-Pb collisions for the centrality classes of 0 – 5%, 40 – 50%, and 80 – 90%. The red solid line represents the straight line fitting to omit the statistical fluctuations.

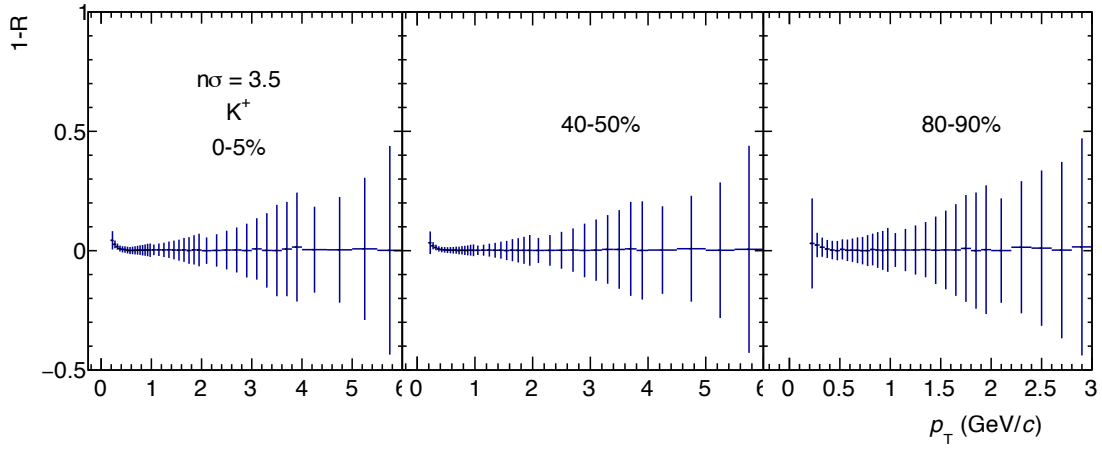


Fig. 2.70 Estimation of $1 - R$ for the cut variation on the $n\sigma$ values in Pb-Pb collisions for the centrality classes of 0 - 5%, 40 - 50%, and 80 - 90%.

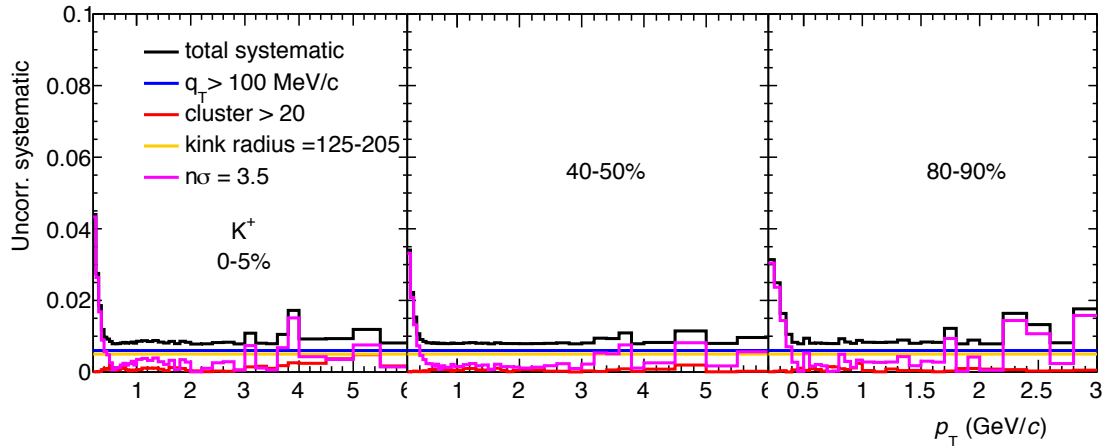


Fig. 2.71 Total uncorrelated systematic uncertainty of K^+ in Pb-Pb collisions for the centrality classes of 0 - 5%, 40 - 50%, and 80 - 90%. The black solid line represents the total systematic uncertainty, whereas the various colors (other than black) represent the different contributions to the uncorrelated systematic uncertainties.

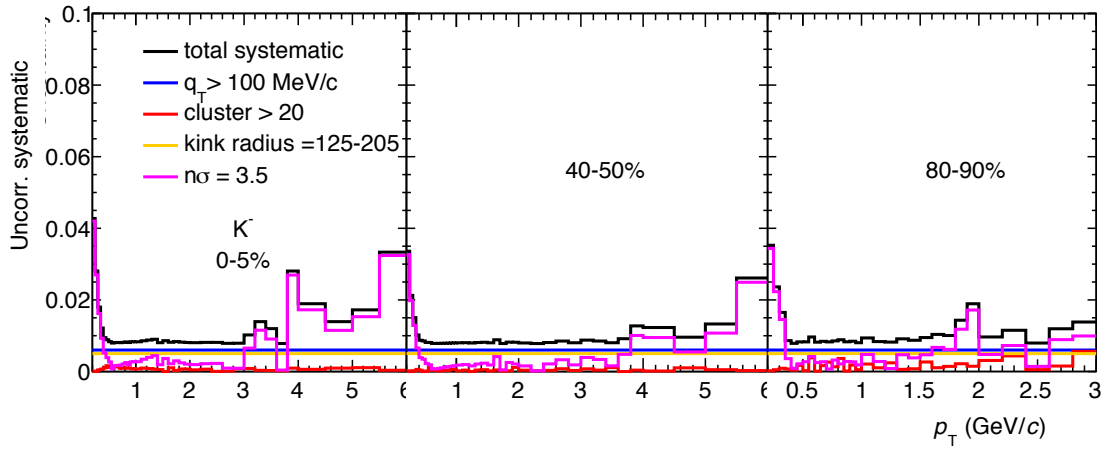


Fig. 2.72 Total uncorrelated systematic uncertainty of K^- in Pb-Pb collisions for the centrality classes of 0 – 5%, 40 – 50%, and 80 – 90%. The black solid line represents the total systematic uncertainty, whereas the various colors (other than black) represent the different contributions to the uncorrelated systematic uncertainties.

2.6 Summary

The experimental setup of ALICE and various detectors used for different purposes during data taking and data analysis have been briefly discussed. The challenges of the high energy physics data analyses were solved by the advanced user-friendly software packages known as ROOT and its application to the ALICE data analysis framework known as *AliRoot* have been introduced briefly. One of the major requirements of the ALICE data processing is the determination of the primary vertex and event reconstruction. The details of the vertex determination using the ITS detector and the event reconstruction using the various detectors have been discussed. The identification of charged pion, kaon and proton, using various identification techniques, such as measurement of specific energy loss, time-of-flight, and Cherenkov angle with the ITS, TPC, TOF, and HMPID detectors have been presented along with their performance plots.

Identification of charged kaons over a wide momentum range is of prime interest of the present work, which is carried out with a technique known as *kink topology*. A kink is measured as a secondary vertex, when the mother tracks appear to change its original direction instantaneously resulting a daughter track, having the same charge with that of the mother track and an invisible neutral particle. To reconstruct the charged kaons, two body decay channels, namely, $K \rightarrow \mu + \nu_\mu$ and $K \rightarrow \pi + \pi^0$ with the branching ratios of 63.55% and 20.66% respectively, have been taken into account. Several topological selection cuts, such as daughter transverse momentum (q_T), decay angle, etc. have been implemented. After applying all the topological selection cuts, the purity of the analysis for Pb–Pb collisions is found to be 99% at low p_T and 92% at the high p_T . *Such measurements suggests that decay topology can be successfully applied to identify charged kaons with good purity in heavy-ion collisions at the highest LHC energies.* Further, with Monte Carlo generated data, various correction factors, such as kink reconstruction efficiency,

acceptance, PID efficiency, purity, etc. have been estimated to correct the raw p_T spectra of identified charged kaons. The error estimation in the ALICE data analysis plays a very crucial role. The significant contributions to the systematic uncertainties mainly arise from the transverse momentum of the charge daughter particle, number of TPC cluster, kink vertex radius, track selection, contamination, etc. To obtain the total systematic uncertainty, all the contributions are added in quadrature. A slight centrality and p_T dependent systematic uncertainties have been observed for Pb–Pb collisions, whereas for pp collisions it is almost p_T independent and thus taken as constant.

The sensitivity of the standard cut on the geometry of the collisions in Pb-Pb collisions has been checked and the fractional deviation observed in each centrality class is compared with the fractional deviation observed in the minimum bias collision, where the ratio between the two is termed as R_{var} . The deviation from the unity of R_{var} is taken as uncorrelated systematic uncertainties. The total uncorrelated systematic uncertainties for K^+ and K^- are found to be $< 4\%$.

3 | Charged pions, kaons and protons production in pp and Pb–Pb collisions at the LHC energy

3.1 Introduction

The hot and dense medium created in such collisions may evolve through various space-time scenarios, such as pre-equilibrium, a thermal equilibrium of partons, formation of a possible mixed-phase of QGP and hadron gas, a state of hadronic gas, and a final non-interacting hadronic state [47]. Various observables, such as transverse momentum spectra, mean transverse momentum, particle ratios, nuclear modification factor, etc. are traditionally studied by measuring the final state particles to get insight into the entire space-time evolution of heavy-ion collisions.

Several reports [152, 153] at RHIC energies revealed that the matter created in heavy-ion collisions exhibits strong collectivity, behaving as nearly a perfect fluid. These collective properties of the system created in the collisions, can be studied by measuring the transverse momentum spectra of identified particles as a function of collisions geometry (centrality). Various relativistic hydrodynamic models have found to be very successful in describing the observables, such as transverse momentum (p_T) distribution of identified

particles, up to a few GeV/c. It has been shown in Refs. [154, 155] that the transverse momentum distribution of the produced particles contains the information about the transverse expansion and the temperature of the system when the hadrons decoupled from the system. In the intermediate p_T region ($2 < p_T < 10$ GeV/c), the particle production mechanism is still not well understood. However, various results at RHIC [84–86], such as the increase of p/π and K/π ratios in central A–A collisions with respect to the minimum bias pp collisions, revealed the presence of strong radial flow. Further, the large increase of p/π ratio also provides a hint that the particle production mechanism in this momentum range is dominated by a new hadronisation mechanism of parton recombination [156–158]. On the other hand, high p_T particles which are produced in the early stages of the collisions through high momentum transfer processes, experience the full evolution of the system. If the system evolves through a deconfined state of color charges, the quarks and gluons are expected to suffer radiative energy loss in the medium, hence the high p_T particles are expected to carry the information about the early stage of the system created in the collisions [159, 160]. Therefore, precise measurements of various properties of the final state hadrons, such as transverse momentum spectra of identified light flavoured particles ($\pi/K/p$), mean transverse momentum, particle ratios, nuclear modification factor, etc. are very much important to understand and characterize the various underlying physics activities of the various stages of the phase-space evolution of the fireball.

In this chapter, an attempt has been made to study the various physics observables associated with different momentum regimes. For better understanding and characterization of the observed results of the present analysis, a comparative study with various model predicted results has been undertaken as well with the existing ALICE results.

3.2 Significance of transverse momentum spectra and overview of recent results

The transverse momentum spectra of identified particles reflect conditions of the later stage of the reaction, as well as the integrated effects of the entire space-time evolution of the fireball from the beginning of the collisions [45]. Based on the behaviour of the observed transverse momentum spectra of identified particles, three distinct transverse momentum regions can be catagorized:

(a) $0 < p_T < 2$ GeV/c: Particles of this momentum interval are termed as *soft probes*, where the hydrodynamic consideration plays an important role. In this momentum regime, the transverse momentum spectra of identified particles encode information about the kinetic freeze-out temperature (T_{kin}) and average transverse expansion velocity ($\langle\beta_T\rangle$) of the evolving system. The RHIC [83] and LHC [9] experiments have already reported such results as shown in Fig. 3.1. It is evident from Fig. 3.1 that as the collision becomes more and more central, the system appears to grow cooler at the kinetic freeze-out and to develop stronger radial flow [83]. This observation indicates a more rapid expansion of the system after the chemical freeze-out with increasing collision centrality [83]. The analysis with Pb–Pb LHC data at the highest collision energy ($\sqrt{s_{NN}} = 5.02$ TeV) might provide more information about these observables.

The mean transverse momentum spectra ($\langle p_T \rangle$) as a function of charged particle multiplicity or collision centrality is traditionally studied to characterize the change in the shape of the transverse momentum spectra of identified particles [45]. Previous studies at RHIC ($\sqrt{s_{NN}} = 200$ GeV) [46, 161, 162] and LHC ($\sqrt{s_{NN}} = 2.76$ TeV) [9] energies revealed that the $\langle p_T \rangle$ of identified particles increases with the increase of centrality, where the increasing trend was found to be more prominent for heavier mass hadrons (like proton). This observation is consistent with the presence of centrality and mass

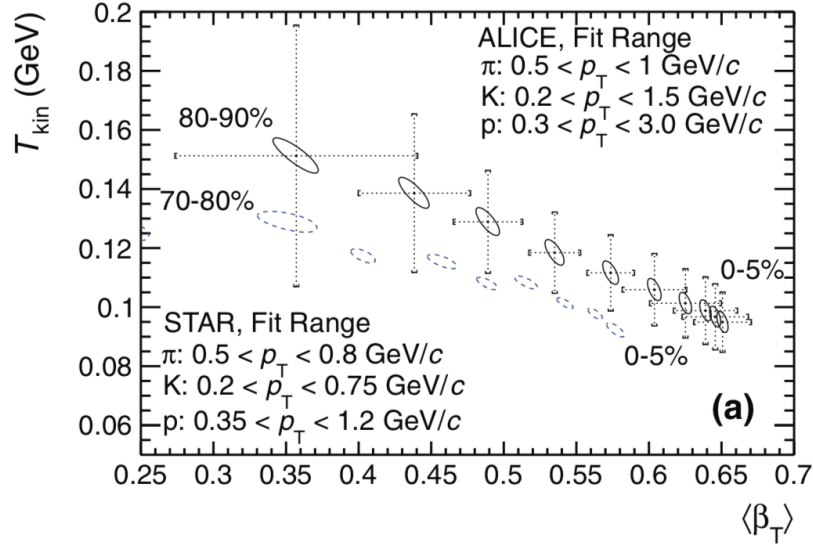


Fig. 3.1 Correlation of kinetic freeze-out temperature and average transverse expansion velocity in Au–Au and Pb–Pb collisions at $\sqrt{s_{NN}} = 200$ GeV (dotted ellipse) at the STAR [83] and 2.76 TeV (solid ellipse) at the LHC [9] respectively. The elliptical symbols represent the uncertainty which include the effect of the bin-by-bin systematic uncertainties, while the vertical errors bars represent the full systematic uncertainties.

dependent collective expansion (radial flow) velocity. Further, p_T -integrated ratios of K/π and p/π as reported at RHIC [46, 162, 163] and LHC [9] energies provide important message about the mechanism of meson and baryon production. A precise study of these observables at the highest available LHC energy is expected to provide detail information about the particle production mechanism.

(b) $2 < p_T < 10$ GeV/c: Various measurements at RHIC [84–86] reported a large baryon-to-meson ratio in Au–Au collisions with respect to the minimum bias pp collisions in the intermediate p_T region. In addition to the presence of strong radial flow, they made numerous speculations that the degrees of freedom of the medium are partonic in nature which recombine during the hadronization to give rise to distinct properties of meson and baryon [88, 156–158]. Further, recent results (Fig. 3.2) by ALICE collaboration [9] in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV also reported similar large increase in the particle ratios, which was attributed to the presence of strong radial flow. Therefore, a detailed study with

the LHC data at the unprecedented collision energy might provide deeper information about these observables.

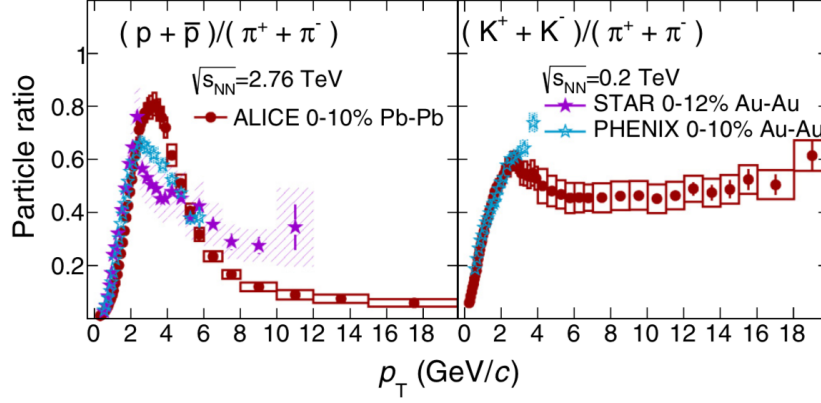


Fig. 3.2 p/π and K/π ratios as a function of transverse momentum in Au–Au and Pb–Pb collisions at $\sqrt{s_{NN}} = 200$ GeV and 2.76 TeV respectively for central collisions [9, 55, 164].

(c) $p_T > 10$ GeV/c: In this momentum regime, the particle production is dominated mostly by hard processes which involve high momentum transfer. During the early stages of the collisions, some of the incoming partons experience scattering with large momentum transfer and lose energy in the very hot and dense medium. This energy loss is usually quantified by nuclear modification factor R_{AA} which is normalized yield ratio of particles in A–A to pp collisions. If the evolving partons do not lose energy in the medium, the R_{AA} values are expected to be one. Figs. 3.3 shows the nuclear modification factor of all charged particles in p–Pb and Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ and 2.76 TeV, whereas Fig. 3.4 shows the recent results of R_{AA} of identified particles in p–Pb collisions measured at $\sqrt{s_{NN}} = 5.02$ TeV [165]. In case of p–Pb collisions, no suppression of R_{AA} above 2 GeV/c has been observed, indicating the absence of strong QCD medium. On the other hand, a strong suppression of R_{AA} of all charged particles could be seen for central Pb–Pb collisions (Figs. 3.3). This observation indicates that the suppression of R_{AA} in central Pb–Pb collisions is related to the energy loss of the evolving partons inside the dense QCD matter. As shown in Fig. 3.5 [90], a clear centrality and mass dependent

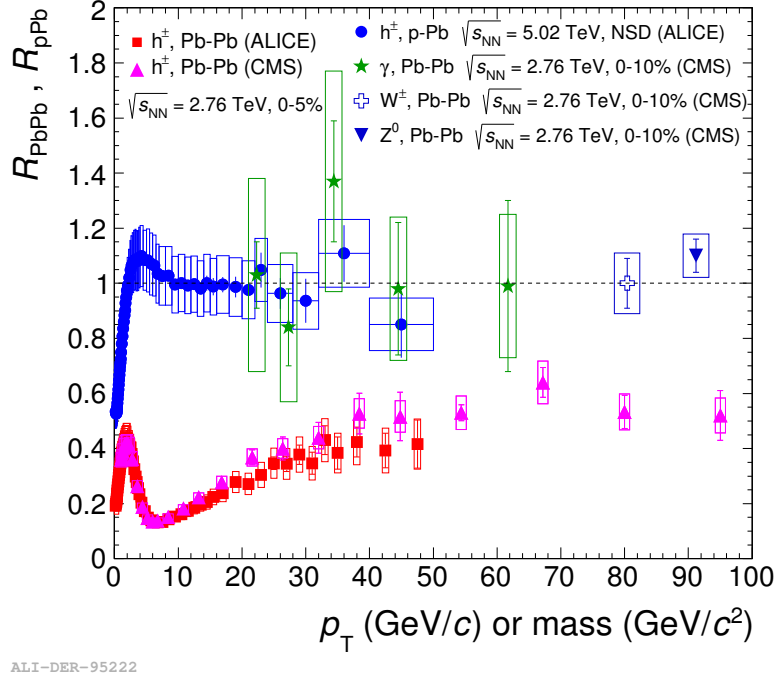


Fig. 3.3 Nuclear modification factor of all charged particles in p–Pb and Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and 2.76 TeV respectively [165].

R_{AA} of identified particles has been observed in the intermediate p_T at $\sqrt{s_{NN}} = 2.76$ TeV, whereas the suppression in central Pb–Pb collisions at high p_T is found to be particle species independent and be more prominent than the peripheral one. With the advent of the highest collision energy at the LHC, such study with identified particles is of quite significance for better understanding of the dense QCD medium.

3.3 Results and discussion

3.3.1 Transverse momentum spectra of identified particles

Using various particle identification techniques, the primary charged pions, kaons and protons are identified as discussed in the previous chapter. To obtain the full p_T spectra, with the available statistics, the charged $\pi^+ + \pi^-$, $K^+ + K^-$ and $p + \bar{p}$ are combined together over the studied momentum range (up to 20 GeV/c). For this purpose, the weighted

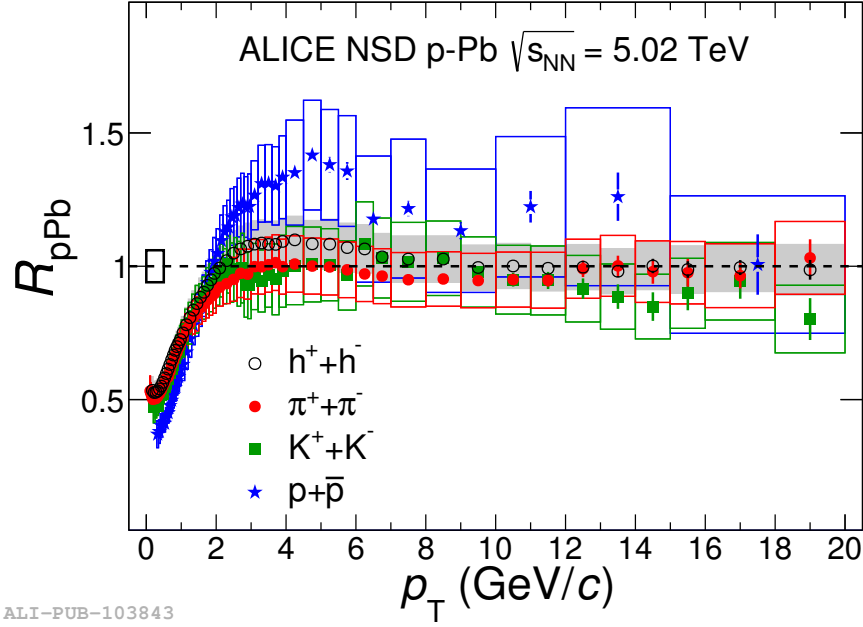


Fig. 3.4 The nuclear modification factor of identified particles in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [165].

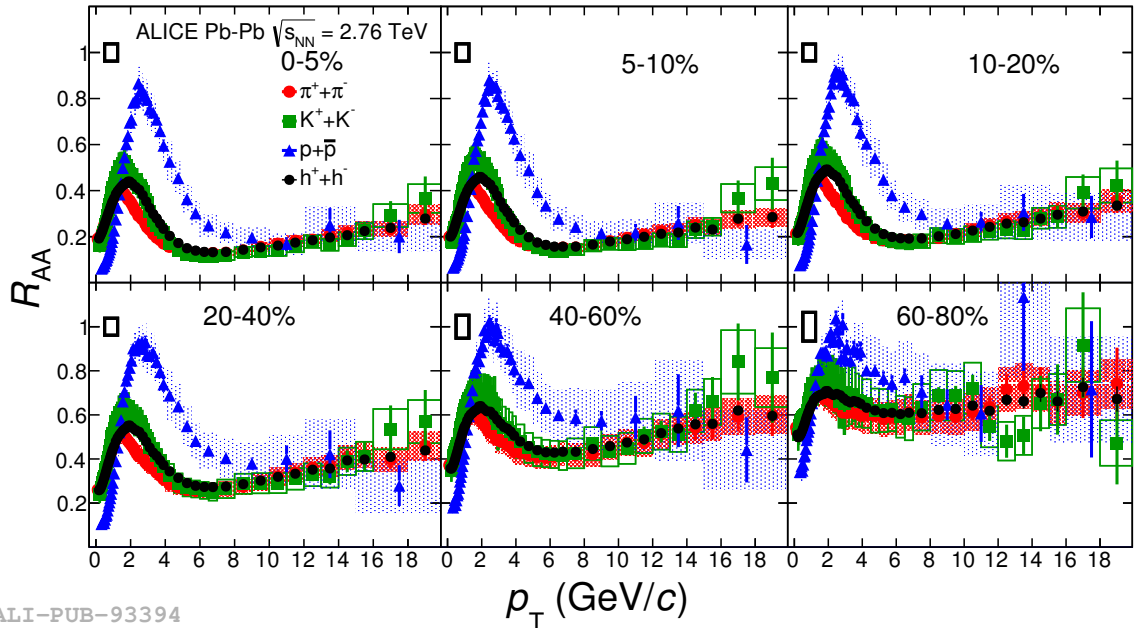


Fig. 3.5 Nuclear modification factor of identified charged π , K and p as well as inclusive all charged particles in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV for different centrality classes [90].

average has been calculated for the spectrum points which are superimposed with each other. The uncommon systematic and statistical errors are added in quadrature and are taken as the weight to the combined p_T spectra. The comparison of the p_T spectra obtained from the different techniques with the combined spectra, for example, the identified charged kaons are shown in Fig. 3.6 for three centrality classes and minimum bias pp collisions. From this figure, it is clearly seen that all the PID techniques are in good agreement within the systematic uncertainties.

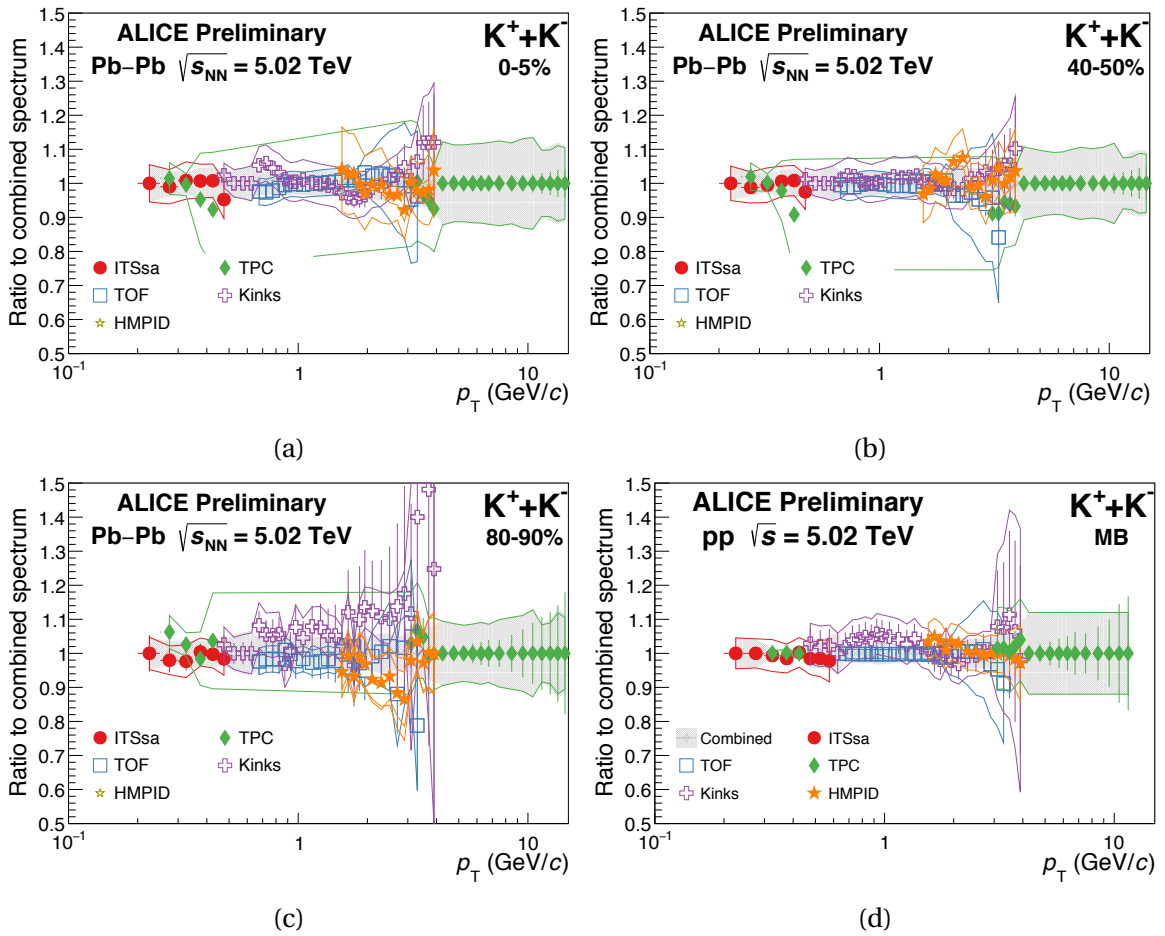


Fig. 3.6 Comparison of different PID techniques to the combined p_T spectra of charged kaons in Pb–Pb collisions for three centrality classes (a, b and c) and minimum bias pp collisions (d) at $\sqrt{s_{NN}} = 5.02$ TeV.

The combined p_T spectra of the identified particles ($\pi/K/p$) are shown in Fig. 3.7 for minimum bias pp and for various centrality classes in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

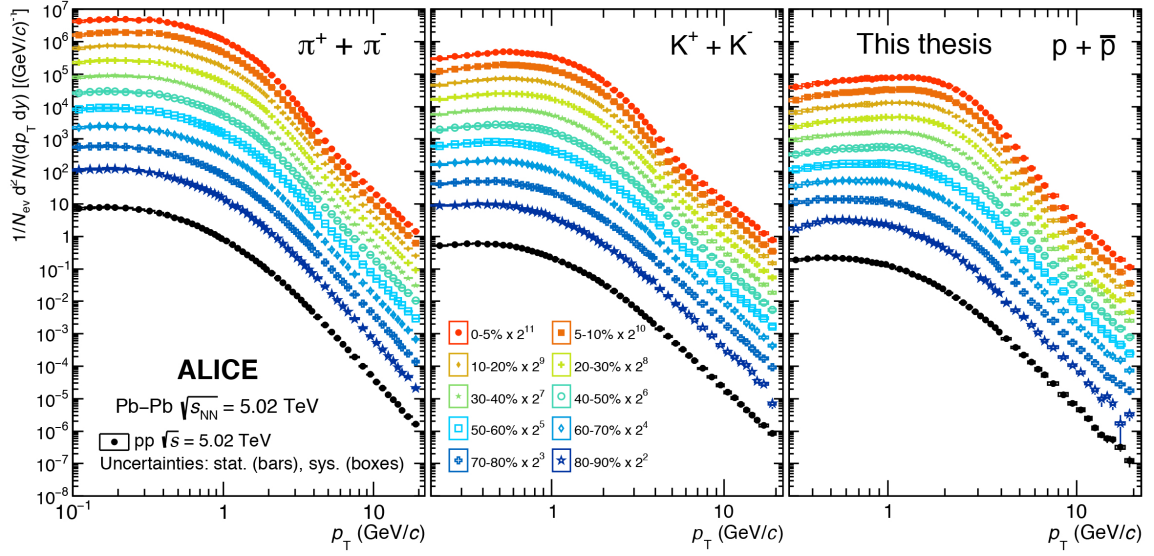


Fig. 3.7 Transverse momentum spectra of identified π , K and p in MB pp and Pb-Pb collisions for various centrality classes at $\sqrt{s_{NN}} = 5.02$ TeV. The black marker symbols represent the p_T distribution of minimum bias pp collisions, whereas the symbols with various colors, other than the black color represent the p_T distributions of identified particles for different centrality classes in Pb-Pb collisions.

From this figure it is clearly seen that in the low p_T region, a mass-dependent flattening of the p_T spectra has been observed, which increases with the increase of centrality. As reported in Ref. [166], this mass-dependent flattening (or hardening) is a characteristic consequence of the radial flow. That is: due to the internal outward push of the evolving system, the particles with low transverse momentum are pushed towards the higher momentum region and thereby these particles, particularly the particles with heavier masses tend to populate the intermediate momentum region. For central Pb-Pb collisions, more energy is deposited, creating more internal pressure during the evolution of the fireball and thus the evolving particles experience more radial push than the peripheral one. Among the three studied hadrons, protons are highly affected by this radial push due to its heavier mass than the pions and kaons.

3.3.2 Particle production at low transverse momentum

The transverse momentum distribution of the identified particles can be well described by the Boltzmann-Gibbs blast-wave function given by [167, 168],

$$\frac{1}{p_T} \frac{dN}{dp_T} \propto \int_0^R r dr m_T I_0 \left(\frac{p_T \sinh \rho}{T_{\text{kin}}} \right) K_1 \left(\frac{m_T \cosh \rho}{T_{\text{kin}}} \right), \quad (3.1)$$

where ρ is the velocity profile and is given by,

$$\rho = \tanh^{-1} \beta_T = \tanh^{-1} \left(\left(\frac{r}{R} \right)^n \beta_s \right), \quad (3.2)$$

where R is the radius of the fireball, r is the radial distance in the transverse plane, $m_T = \sqrt{p_T^2 + m^2}$ is the transverse mass, I_0 and K_1 are the modified Bessel functions, n is the exponent of the velocity profile, and β_s is the transverse expansion velocity at the surface. The free parameters of Eqs. 3.1 and 3.2 are the kinetic freeze-out temperature (T_{kin}), the exponent of the velocity profile (n), and the average transverse velocity ($\langle \beta_T \rangle$).

To quantify the centrality dependence of spectral shapes at low p_T , the Boltzmann-Gibbs blast-wave function has been simultaneously fitted to the charged pion, kaon and (anti-)proton p_T spectra, using a common set of parameters but different normalization factors and masses. It is important to note here that from the fit to a single particle type, no physics message can be attached to the parameters, and therefore, a combined fit to different particle species provides the physics insight on the freeze-out parameters [168]. Although the absolute values of the parameters have a strong dependence on the p_T range used for the fit [168], the evolution of the parameters with $\sqrt{s_{NN}}$ can still be compared across different collision energies by using the same fitting ranges. The present analysis uses the same p_T intervals employed for fitting as in Ref. [168], namely, 0.5–1 GeV/c, 0.2–1.5 GeV/c and 0.3–3 GeV/c for charged pions, kaons and (anti-)protons, respectively. Figure 3.8 shows the ratios of the spectra to results of the fits for different

centrality classes and particle species. If the shape of the p_T distributions over the full measured p_T range was purely driven by the collective radial expansion of the system, the functions determined by fitting the data in a limited p_T range would be expected to describe the spectral shapes in the full p_T range. Within uncertainties, this is only observed for the proton p_T spectra (up to 4 GeV/c) in 0 – 20% Pb–Pb collisions. A different situation is observed for pions where, due to their small mass and the large centrality-dependent feed-down contribution from resonance decays, the agreement with the model is worse than that observed for kaons and (anti-)protons. The p_T interval where the model describes the data within uncertainties gets wider going from peripheral to central Pb–Pb collisions. The various blast-wave fit parameters n , T_{kink} , and $\langle \beta_T \rangle$ in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV are listed in Table 3.1.

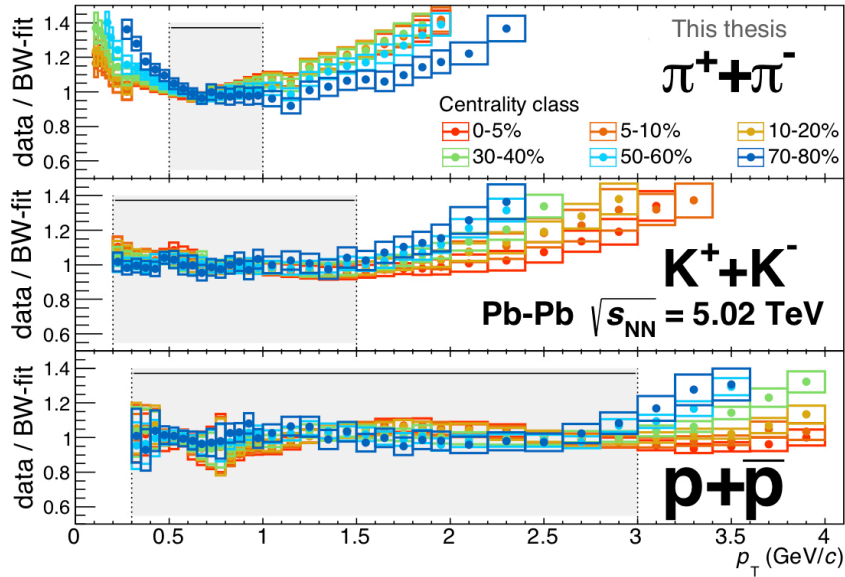


Fig. 3.8 Ratios of centrality dependent p_T spectra to the blast-wave model predictions in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for π , K, and p. The grey shaded areas represent the fit ranges.

Table 3.1 The different parameters of combined Boltzmann-Gibbs blast-wave fits to the particle spectra in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The values of the charged particles multiplicities are taken from Refs.[169, 170].

Centrality	$\langle dN_{ch}/d\eta \rangle$	$\langle \beta_T \rangle$	T_{kin} (GeV/c)	n
0–5%	1943 ± 56	0.663 ± 0.003	0.090 ± 0.003	0.735 ± 0.013
5–10%	1587 ± 47	0.660 ± 0.003	0.091 ± 0.003	0.736 ± 0.013
10–20%	1180 ± 31	0.655 ± 0.003	0.094 ± 0.003	0.739 ± 0.013
20–30%	786 ± 20	0.643 ± 0.003	0.097 ± 0.003	0.771 ± 0.014
30–40%	512 ± 15	0.622 ± 0.003	0.101 ± 0.003	0.828 ± 0.015
40–50%	318 ± 12	0.595 ± 0.004	0.108 ± 0.003	0.908 ± 0.019
50–60%	183 ± 8	0.557 ± 0.005	0.115 ± 0.003	1.052 ± 0.024
60–70%	96.3 ± 5.8	0.506 ± 0.008	0.129 ± 0.005	1.262 ± 0.043
70–80%	44.9 ± 3.4	0.435 ± 0.011	0.147 ± 0.006	1.678 ± 0.088
80–90%	17.5 ± 1.8	0.355 ± 0.016	0.161 ± 0.006	2.423 ± 0.208

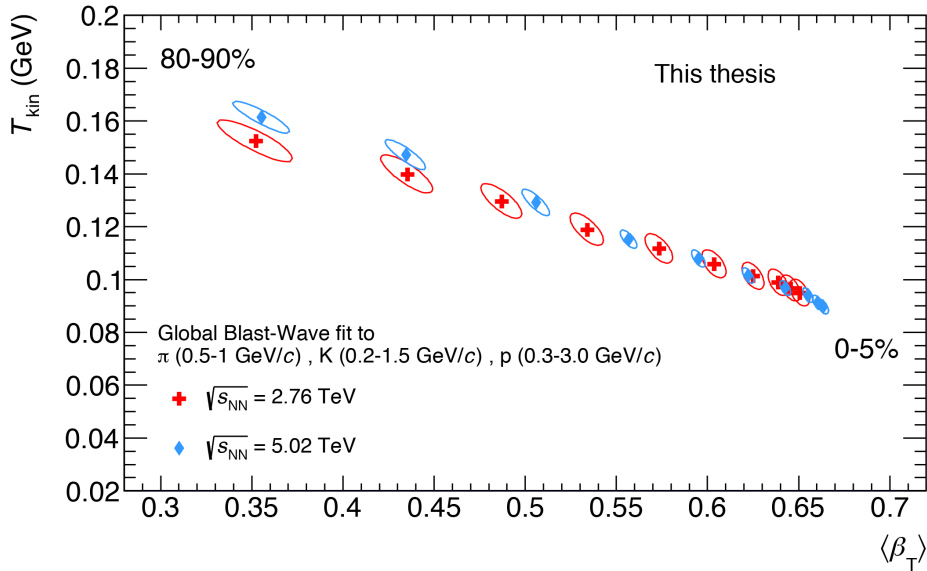


Fig. 3.9 Variation of kinetic freeze-out temperature against average expansion velocity obtained from the blast-wave fitting to the measured π , K and p in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and compared with the existing results at 2.76 TeV [9].

The correlation between T_{kin} and $\langle\beta_T\rangle$ obtained from the blast-wave fitting in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV is shown in Fig. 3.9 and compared with the existing results at $\sqrt{s_{NN}} = 2.76$ TeV [9]. It could be readily seen from the figure that at $\sqrt{s_{NN}} = 5.02$, the $\langle\beta_T\rangle$ increases with the increase of centrality and becomes maximum ($\langle\beta_T\rangle = 0.663 \pm 0.003$) for the most central collisions. *This observation can be interpreted as a possible indication of a more rapid expansion of the created system with increasing centrality.* On the other hand, T_{kin} decreases with the increase of centrality and becomes $T_{\text{kin}} = 0.089 \pm 0.003$ GeV for the most central collisions. In case of peripheral collisions, the higher value of T_{kin} as compared to the central collisions, is consistent with the expectation of a shorter-lived fireball with stronger radial pressure gradients [171]. For the most central collisions, a small increase of $\langle\beta_T\rangle$ (2%) and small decrease of the T_{kin} have been observed with respect to the results measured at $\sqrt{s_{NN}} = 2.76$ TeV. For the most peripheral collisions, the kinetic freeze-out temperature is slightly higher at 5.02 TeV than that at 2.76 TeV. This is in contrast with the interpretation for central collisions where a larger volume has the kinetic freeze-out later allowing the kinetic temperature to decrease further. It is worth questioning whether the blast wave formalism is applicable for this smaller system as well and it will be interesting to see if models, which can also describe small systems, can explain this changing pattern. Moreover, it is to be noted here that event and geometry biases may also play a role in the peripheral Pb-Pb collisions [172].

In order to extrapolate to $p_T = 0$ GeV/c for the extraction of the mean transverse momentum ($\langle p_T \rangle$) and integrated yields, the transverse momentum spectra are fitted individually using the blast-wave function (Eq. 3.1) for Pb-Pb collisions and Levy-Tsallis [173] function for pp collisions. The Levy-Tsallis function is given by,

$$\frac{d^2N}{dydp_T} = p_T \frac{dN}{dy} K \left(1 + \frac{m_T - m_0}{cC} \right)^{-n}, \quad (3.3)$$

where,

$$K = \frac{(n-1)(n-2)}{nC(nC + m_0(n-2))}, \quad (3.4)$$

$m_T = \sqrt{p_T^2 + m_0^2}$, m_0 is the rest mass of the particle and n , C and dN/dy (the yield) are the free parameters. The systematic uncertainty on the yield extraction comes from the fitting. For Pb–Pb collisions, the systematic uncertainties on the extrapolated part has been estimated using the different fit functions: Levy-Tsallis, m_T -exponential [174] and Fermi-Dirac [175]. For pp collisions, the systematic uncertainties are estimated using Bylinkin [176] and Boltzmann fit functions [177, 178]. The maximum deviation from the blast-wave for the case of Pb–Pb collisions and Lavy-Tsallis for the case of pp collisions have been taken for the estimation of systematic uncertainties. The average

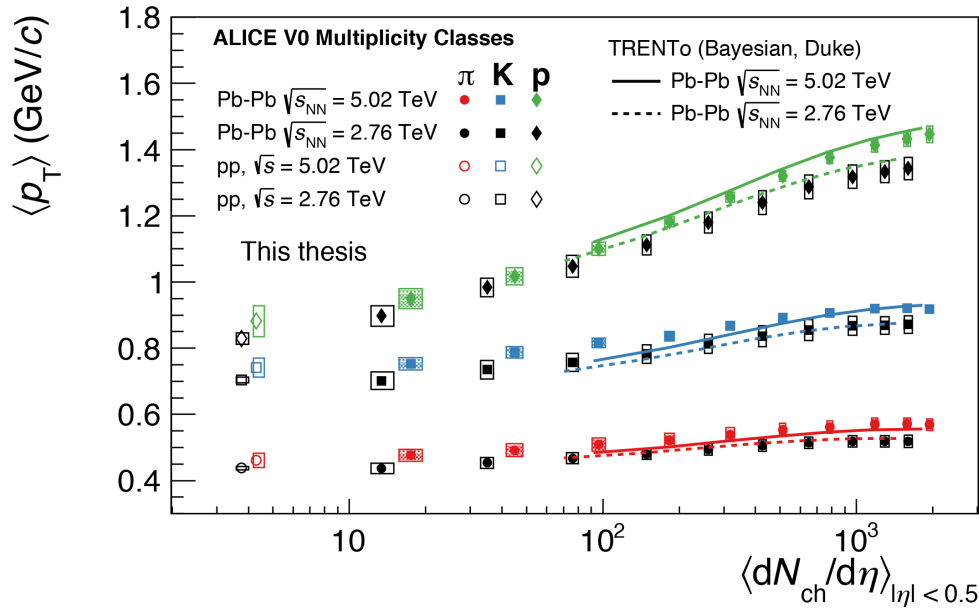


Fig. 3.10 Distribution of mean transverse momentum as a function average charged particle multiplicity density ($\langle dN_{ch}/d\eta \rangle$) of identified charged pions, kaons and protons in minimum bias pp and Pb–Pb collisions for different centrality classes at $\sqrt{s_{NN}} = 5.02$ TeV. The values are compared with the existing results at $\sqrt{s_{NN}} = 2.76$ TeV [9]. The red green, blue and red solid markers represent the results of Pb–Pb collisions, whereas the open markers represent the results for pp collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The black solid markers represent the $\langle p_T \rangle$ in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The solid lines represent the model predicted results.

mean transverse momentum $\langle p_T \rangle$ as a function of average charged particle multiplicity density ($dN_{ch}/d\eta$) of identified charged pions, kaons and protons in minimum bias pp and Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV is shown in Fig. 3.10 and compared with the model-generated data. Further, the results are compared with the existing results of Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. From Fig. 3.10 it is evident that the $\langle p_T \rangle$ increases from low multiplicity to high multiplicity and the plots for hadrons (particularly the proton) with heavier mass become steeper. This observation is consistent with the claim of mass-dependent radial flow of the produced particles. Within uncertainties and for comparable charged particle multiplicity densities, the results for both energies are consistent for 20 – 90% Pb–Pb collisions. For 0 – 20% Pb–Pb collisions, $\langle p_T \rangle$ is slightly higher at 5.02 TeV than at 2.76 TeV. This larger value of $\langle p_T \rangle$ for central collisions originates from the low p_T part of the spectra. Again, this is an effect consistent with a stronger radial flow in Pb–Pb collisions at the highest collision energy.

The integrated yields have been estimated by integrating the p_T spectra of the individual particle, where the low p_T extrapolation (up to $p_T = 0$ GeV/c) has been done by fitting the blast-wave function (Eq. 3.1) for Pb–Pb collisions and Lavy-Tsallis function (Eq. 3.4) for pp collisions. The systematic uncertainties on the integrated ratios have been evaluated using the uncertainties on the p_T -dependent ratios, taking into account the part of the uncertainties correlated among the different particle species. The p_T integrated yield ratios of K/π and p/π as a function of $\langle dN_{ch}/d\eta \rangle$ have been shown in Fig. 3.11. The K/π ratio hints a small increase with centrality. The effect is consistent with the observed increase of strange to non-strange hadron production in heavy-ion collisions compared to inelastic pp collisions [179]. On the other hand, the decreasing trend of p/π ratio is consistent with the hypothesis of antibaryon-baryon annihilation in the hadronic phase [180, 181]. This effect is expected to be less significant for the more dilute system created in peripheral collisions. The particle ratio is found to be almost independent on collision

energy, indicating that there is small or no dependence of the hadrochemistry on the collision energy.

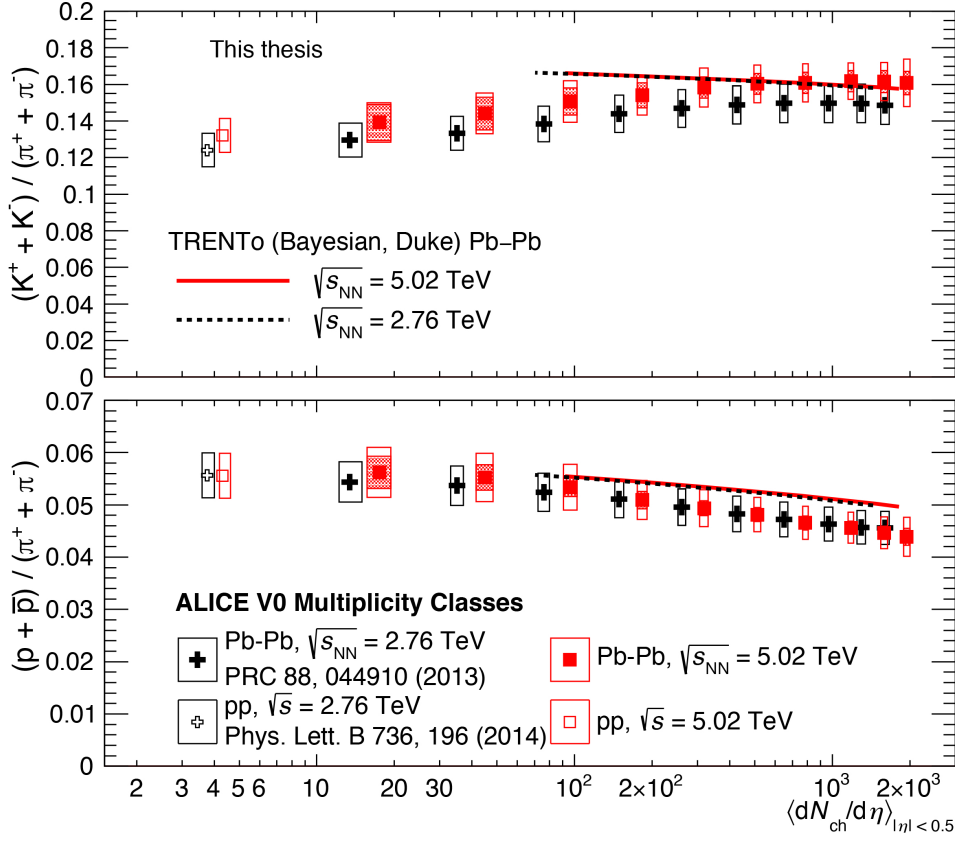


Fig. 3.11 Distribution of p_T integrated K/π (upper panel) and p/π (lower panel) ratios as a function of $\langle dN_{ch}/d\eta \rangle$ in pp and Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and compared with the results at $\sqrt{s_{NN}} = 2.76$ TeV [9]. The red solid and open square symbols represent the Pb–Pb and pp results at $\sqrt{s_{NN}} = 5.02$ TeV respectively, whereas the black full and open cross symbols represent the Pb–Pb and pp results at $\sqrt{s_{NN}} = 2.76$ TeV respectively. The solid and dotted lines represent the model-predicted particle ratios at $\sqrt{s_{NN}} = 5.02$ and 2.76 TeV respectively.

The Reduced Thickness Event-Event Nuclear Topology (TRENTo) is a multi parametrized initial-conditioned model, which uses Bayesian statistics and consists of viscous hydrodynamics and hadronic cascade processes [182]. The TRENTo model-generated data [183] were used to predict the average transverse momentum distributions and particle

ratios (K/π and p/π ratios) which are plotted in Figs. 3.10 and 3.11 respectively. The average transverse momentum as a function of $\langle dN_{ch}/d\eta \rangle$ is quite well reproduced by the model. The model predicts that the kaon-to-pion ratio should decrease with increasing charged particle multiplicity density while data show an increase with $\langle dN_{ch}/d\eta \rangle$. Within uncertainties, the model agrees with the data for the most central Pb–Pb collisions. The trend of the proton-to-pion ratio is well described by the model but the values of the centrality-dependent ratios are overestimated.

3.3.3 Particle production in the intermediate momentum range

In the intermediate momentum region, the study of K/π and p/π ratios as a function of transverse momentum is believed to provide some important information about the different hadronization mechanism. Fig. 3.12 (top panel) shows the distribution of K/π ratio as a function of transverse momentum in minimum bias pp and Pb–Pb collisions for different centrality classes at $\sqrt{s_{NN}} = 5.02$ TeV and are compared with the results measured at $\sqrt{s_{NN}} = 2.76$ TeV [9]. For the most central collisions, a clear increase in K/π ratio with respect to the minimum bias pp collisions has been observed in the intermediate p_T region ($2 < p_T < 10$ GeV/c). *This increase of K/π ratio in the most central collisions is believed to be a consequence of strong radial flow as reported in Ref. [9], which is expected to affect prominently the charged kaons due to its heavier mass than the charged pions.* Going from most central to peripheral collisions, the increase of K/π ratio in the intermediate p_T region decreases and it becomes similar (within the systematic uncertainties) to the results of minimum bias pp collisions. *This observation provides a hint that for the most peripheral collision, the overlap region of the system is very small similar to the pp system, thereby contains vanishing radial flow effect. However, for $p_T > 10$ GeV/c, the K/π ratios, for all centrality classes become similar with the minimum bias pp collisions, which signifies that particle production is mainly influenced by the process of fragmentation.*

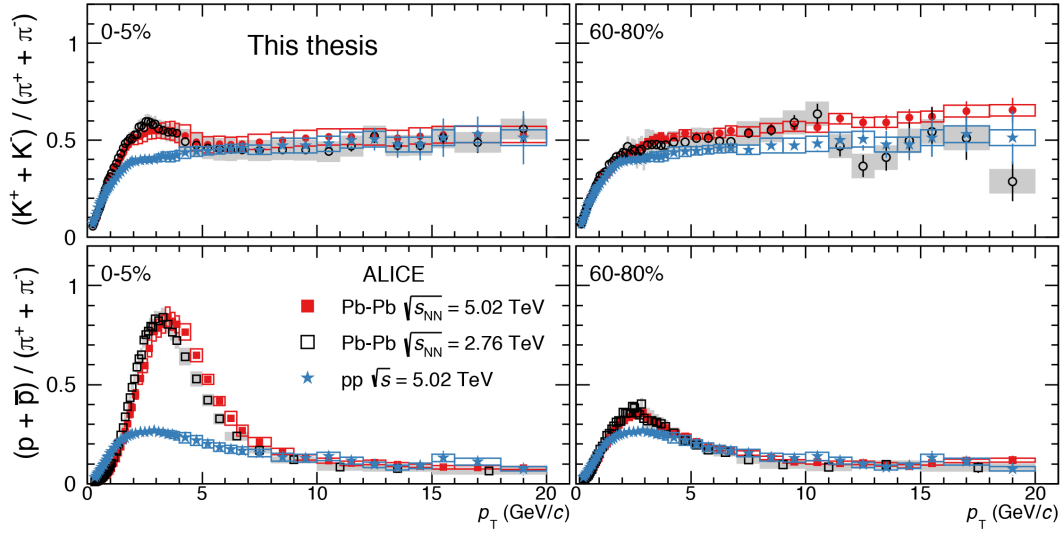


Fig. 3.12 Distributions of K/π (top) and p/π (bottom) ratios as a function of transverse momentum in minimum bias pp and Pb–Pb collisions for 0 – 5% and 60 – 80% centrality classes at $\sqrt{s_{NN}} = 5.02$ TeV and compared with the results at $\sqrt{s_{NN}} = 2.76$ TeV [9]. The solid circle and solid star markers represent the particle ratios for Pb–Pb and pp collisions at $\sqrt{s_{NN}} = 5.02$ TeV respectively, whereas the open marker symbols represent the results of the particle ratios in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV.

The p/π ratio as a function of transverse momentum in minimum bias pp and Pb–Pb collisions for different centrality classes at $\sqrt{s_{NN}} = 5.02$ TeV is shown in Fig. 3.12 (bottom panel) and compared with the results measured at $\sqrt{s_{NN}} = 2.76$ TeV [9]. It is clearly evident from Fig. 3.12 that for Pb–Pb collisions, the increase of p/π ratio in the intermediate momentum region is more prominent than K/π ratio. *This large increase of p/π ratio in the central collisions is attributed to the strong radial flow, affecting mainly the proton due to its heavier mass.* Further, recombination picture of the particle production mechanism might play an important role which favours more baryon production than the mesons. However, since recombination mainly affects baryon-to-meson ratios, it would not explain the bump which is also observed in the kaon-to-pion ratio. The shift of the peak towards higher p_T in the proton-to-pion ratio is consistent with the larger radial flow measured in Pb–Pb at $\sqrt{s_{NN}} = 5.02$ TeV compared to the one measured at

$\sqrt{s_{NN}} = 2.76$ TeV. The mass dependence of the radial flow explains also the observation that the maximum of the p/π ratio is located at a larger p_T as compared to the K/π ratio. The radial flow is expected to be stronger in the most central collisions, this explains the slight shift in the location of the maximum when central and peripheral data are compared. *Similar to K/π ratios, for $p_T > 10$ GeV/c, p/π ratios become same with the minimum bias pp collisions which is again attributed to the vacuum-like fragmentation process of the particle production mechanism.*

3.3.4 Particle production at high transverse momentum

The particles having high transverse momentum are mainly produced from hard scattering events in the early stages of the collisions and are expected to carry the full information about the entire space-time evolution of the fireball. If the system created in the ultra-relativistic heavy-ion collisions evolves through deconfined color charges, the evolving quarks and gluons are expected to suffer radiative energy loss in the medium. This energy loss is traditionally quantified by what is called *nuclear modification factor* (R_{AA}). The R_{AA} is defined as the yield ratio in AA collisions to the pp collisions at the same energy with proper normalization and is given by [63],

$$R_{AA}(p_T) = \frac{d^2 N^{AA}(p_T)/(dy dp_T)}{\langle T_{AA} \rangle d^2 N^{pp}(p_T)/(dy dp_T)}, \quad (3.5)$$

where, $d^2 N^{AA}/(dy dp_T)$ and $d^2 N^{pp}(p_T)/(dy dp_T)$ are the yields in Pb–Pb and pp collisions respectively for a particular p_T bin and rapidity window. $\langle T_{AA} \rangle$ is the average nuclear overlap function, obtained from the Glauber model [184] and is given by,

$$\langle T_{AA} \rangle = \frac{\langle N_{coll} \rangle}{\sigma_{NN}^{inel}}, \quad (3.6)$$

where $\langle N_{coll} \rangle$ is the average number of binary collisions for a given centrality class in AA collisions and σ_{inel}^{NN} is the total nucleon-nucleon cross-section. Any deviation of R_{AA} from unity, such as a suppression at high p_T might indicate strong nuclear medium effects.

The nuclear modification factor as a function of p_T of identified particles at $\sqrt{s_{NN}} = 5.02$ TeV is shown in Fig. 3.13. A clear particle mass dependent R_{AA} has been observed for low and intermediate p_T region. For $p_T < 10$ GeV/c, the R_{AA} values of the protons are less suppressed. This observation is consistent with the results of the particle ratios as shown in Fig. 3.12, and attributed to the radial flow effect. It could be readily seen from Fig. 3.13 that for $p_T > 10$ GeV/c, the R_{AA} values of all the particle species are equally suppressed. *This suppression of R_{AA} in the high p_T region demonstrates the presence of strong nuclear matter effects where the evolving particles equally suffer radiative energy loss in the dense QCD medium.* It could also be evident from the figure that for the most peripheral collisions, the R_{AA} values are less suppressed as compared to the most central collisions. This could be due to the fact that the energy loss in the medium depends on the traversed path length of the parton [10]. *Due to this path dependency, the total energy loss is expected to be larger in central heavy-ion collisions than the peripheral collisions. Further, it is important to note here that the central collisions are expected to create a hotter and denser medium than the peripheral collisions and hence experience more energy loss.*

The comparison of R_{AA} of the identified particles at $\sqrt{s_{NN}} = 5.02$ and 2.76 TeV is shown in Fig. 3.14. *No energy dependent R_{AA} has been observed, which gives a hint that the medium created at both the energies may behave in the similar way where the evolving particles are equally suffered the strong nuclear matter effect.*

3.4 Model comparison

In general, the space-time evolution of the fireball created in the relativistic heavy-ion collisions is a multi-stage phenomenon. Based on this concept, several hybrid hydrodynamic

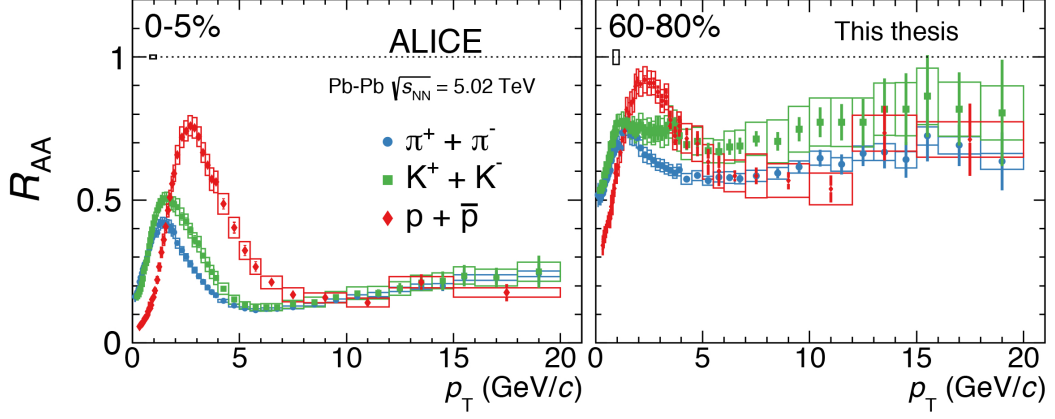


Fig. 3.13 Distribution of nuclear modification factor of identified π , K and p as a function of transverse momentum in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for central (0 – 5%) and peripheral (60 – 80%) collisions.

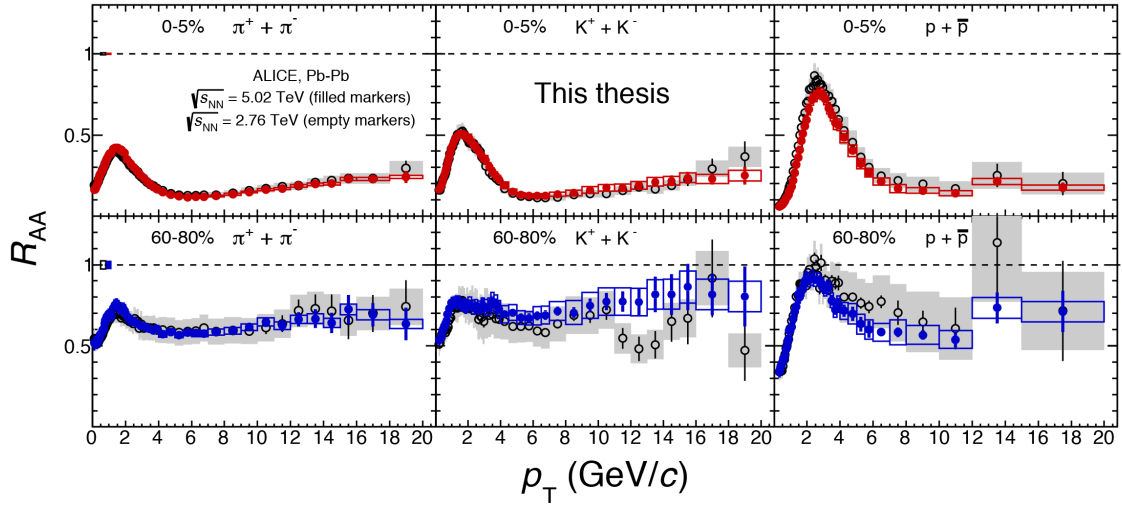


Fig. 3.14 Distribution of nuclear modification factor of identified π , K and p as a function of transverse momentum in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for 0 – 5% and 60 – 80% centrality classes and compared with the results at $\sqrt{s_{NN}} = 2.76$ TeV.

models have been developed to describe and understand the underlying physics activities of the various stages of the system. The identified particle spectra of $\pi/K/p$ have been compared with the several hybrid hydrodynamic model calculations. The various models used to compare with the experimental data have been discussed briefly in the following:

- **iEBE-VISHNU hybrid model:** The iEBE-VISHNU is an event-by-event simulation package for relativistic heavy-ion collisions. It uses a hybrid approach which includes an initial condition generator known as superMC, a 2+1-dimensional viscous hydrodynamic simulator (VISH2+1), a particle sampler (iSS) and a hadron cascade simulator [185]. This model uses the TRENTo or AMPT (A Multi-Phase Transport Model) [186] as the initial conditions, whereas the viscous hydrodynamic simulator describes the expansion of the strongly interacting QCD matter. A switching hyper-surface is identified at the very end of the hydrodynamic simulation and the fluid cells on this switching hyper-surface are converted into individual particle using the particle sampler, iSS. These particles are fed into the hadronic rescattering cascade model (UrQMD) [187] which follows the particles macroscopically until they stop interacting and decay. The hydrodynamical evolution of the QGP stage combined with the hadronic cascade model forms a hybrid algorithm with the name VISHNU (VISH2+1 ‘n’ UrQMD) [185].
- **McGill prediction:** The McGill group [188] provided the predictions and comparison of the p_T spectra and flow observables of identified particles in Pb–Pb collisions at 2.76 and 5.02 TeV. Their predictions were based on hydrodynamic and hadronic cascade hybrid approach. In this approach, the initial conditions rely on a new formulation of IP Glasma model [189], which provides event-by-event fluctuations and nonzero equilibrium flow in a realistic way at the early stage of the heavy-ion collisions. The individual collision systems are evolved using relativistic hydrodynamics with bulk and nonzero shear viscosities [190]. As the density of the system

decreases, various hadrons are formed from the fluid cells and further propagated microscopically using a hadronic cascade model.

- **EPOS model:** The EPOS model stands for **E**nergy-conserving quantum mechanical multiple scattering approach, based on **P**artons (parton ladders), **O**ff-shell remnants, and **S**plitting of parton ladders [191]. It is a quantum mechanical multiple scattering approach with parton-based model, where the cross-section and particle productions are calculated consistently, taking into account the energy conservation in both the cases. It is based on the Gribov-Regge multiple scattering theory, perturbative QCD and string fragmentation [192]. The latest version of the EPOS model (EPOS3) implements the saturation in the initial state as predicted by the Color Glass Condensate model [193], a full viscous hydrodynamic simulation of the core, and a hadronic cascade. EPOS3 also includes a new physics process that accounts for hydrodynamically expanding bulk matter, jets, and the interaction between the two, important for particle production at intermediate p_T [194] and reminiscent of the recombination mechanism [88, 87].

The ratios of the experimental p_T spectra of identified particles to the various model-predicted results in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV are shown in Fig. 3.15 for $p_T < 4$ GeV/c for three different centrality classes. It could be readily seen from the figure that all the model predicted results, in general, describe the centrality dependent identified spectra at $p_T \sim 1$ GeV/c within 20%, whereas the agreement is around 30% for $p_T \sim 3$ GeV/c. In the case of the identified proton, the model-predicted results show a good agreement with the experimental results over a wide momentum range than kaons and pions. This mass hierarchy is expected from the hydrodynamic expansion, where larger mass particles experience a larger p_T boost. It is also clearly seen from Fig. 3.15 that for the most central collisions, the model describe the data over a wide p_T range than the peripheral. *This observation gives a hint that the size of the fireball created in the central*

collision is larger than the peripheral one, thereby the hydrodynamic expansion lasts longer, resulting in the stronger flow.

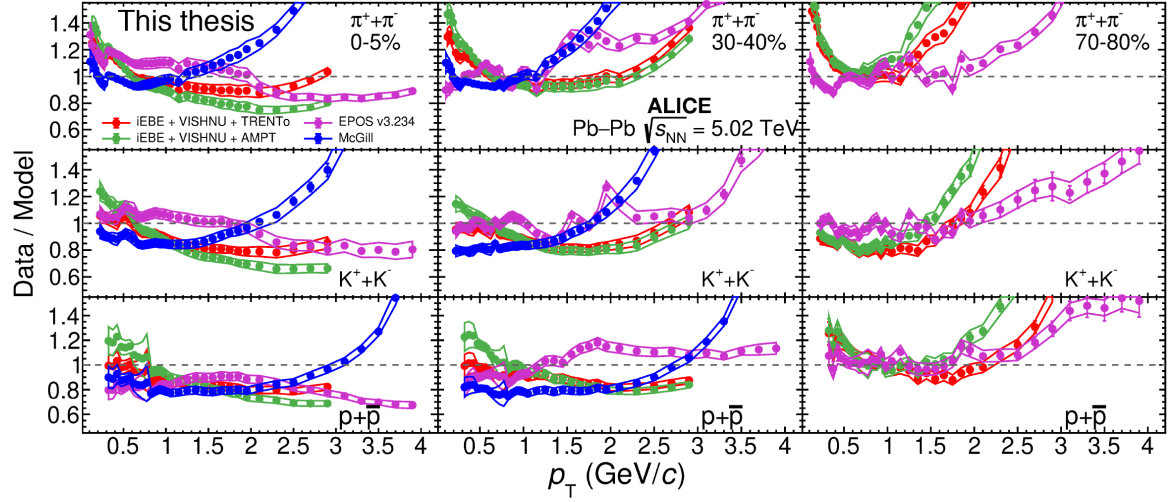


Fig. 3.15 Data/model ratios of identified charged pion, kaon and proton in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for three different centrality classes. The statistical and systematic uncertainties are shown as error bars and bands around the data points, respectively.

Fig. 3.16 shows the ratio of experimental p_T spectra to EPOS3 model-predicted p_T spectra of identified particles over a wide momentum range. It could be readily seen from the figure that EPOS3-predicted results show a good agreement for $p_T < 5$ GeV/c for all the studied hadrons for most central collisions. However, the model-predicted values are quite off (a factor of ~ 2) for $p_T > 5$ GeV/c for most central collisions. On the other hand, for semi-central (30 – 40%) and peripheral (70 – 80%) collisions, the EPOS3-predicted results show good agreement for $p_T < 3$ GeV/c.

Figs. 3.17, 3.18 and 3.19 show the comparison of experimental p_T dependent K/π and p/π ratios with iEBE-VISHNU, McGill and EPOS3 model-predicted results in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for three different centrality classes. It is observed from the ratio plots of the bottom panels of these figures that the VISHNU and McGill predicted K/π and p/π ratios show a fair agreement with the experimental results, whereas EPOS3 predicted K/π ratio comparatively shows a better agreement with data. On the other hand,

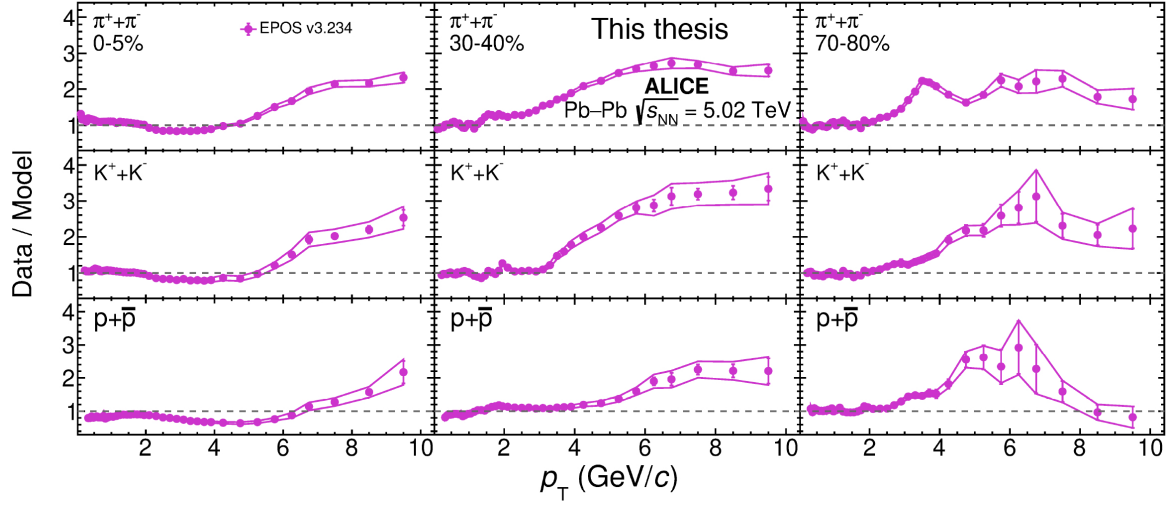


Fig. 3.16 Data/EPOS3 ratio of identified charged pion, kaon and proton in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for three different centrality classes for wider momentum range. The statistical and systematic uncertainties are shown as error bars and bands around the data points, respectively.

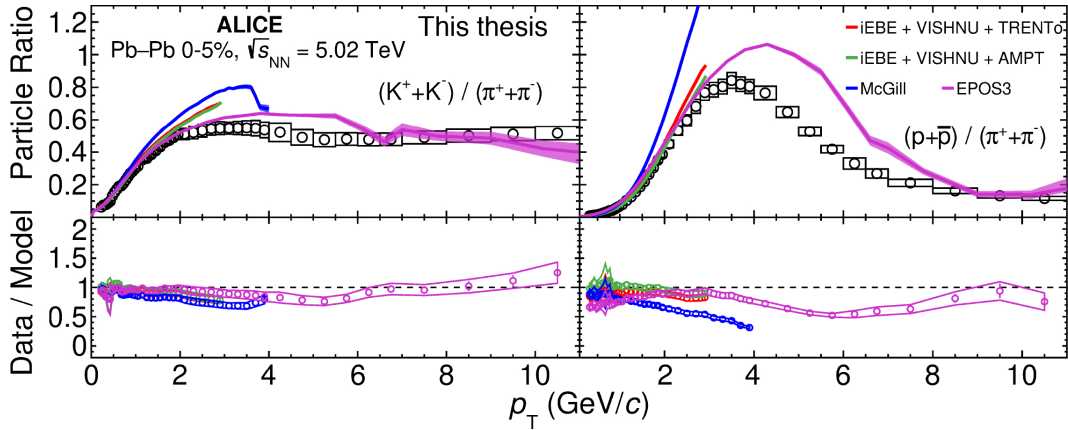


Fig. 3.17 Particle ratios as a function of p_T in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for 0–5% centrality class and compared with the various model predicted particle ratios. The bottom panels shows the data/model ratios. The statistical and systematic uncertainties are shown as error bars and bands around the data points, respectively.

the larger EPOS3 model-predicted p/π ratio can be found in Fig. 3.16, where pions yields are underestimated by the EPOS3 model.

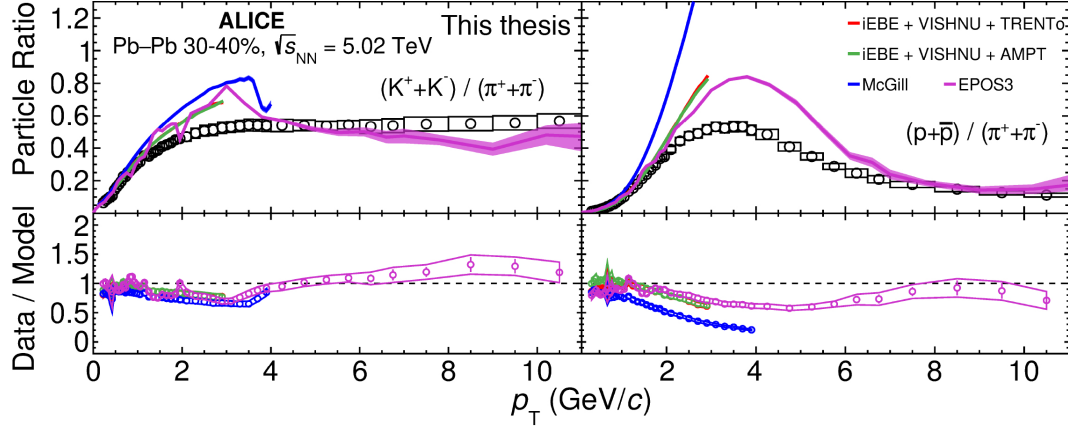


Fig. 3.18 Particle ratios as a function of p_T in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for 30 – 40% centrality class and compared with the various model predicted particle ratios. The bottom panels shows the data/model ratios. The statistical and systematic uncertainties are shown as error bars and bands around the data points, respectively.

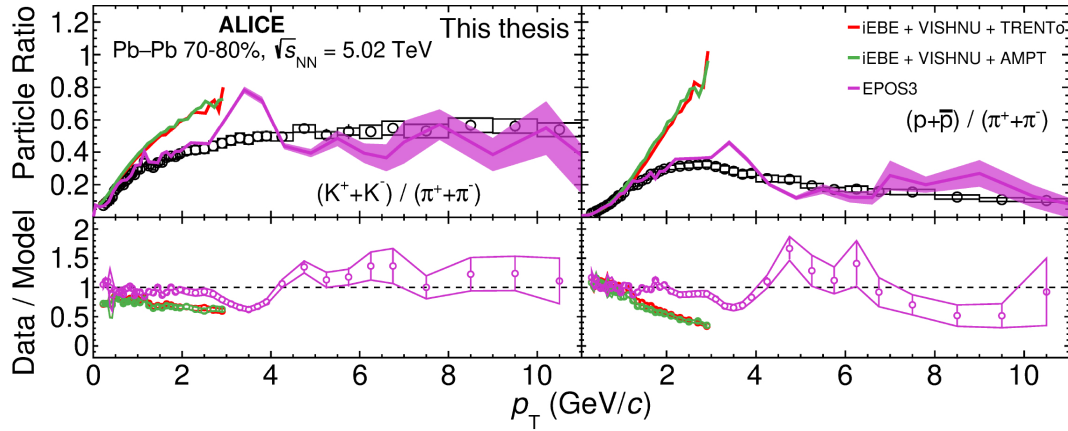


Fig. 3.19 Particle ratios as a function of p_T in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for 70 – 80% centrality class and compared with the various model predicted particle ratios. The bottom panels shows the data/model ratios. The statistical and systematic uncertainties are shown as error bars and bands around the data points, respectively.

3.5 Summary

The transverse momentum spectra of the identified charged pions, kaons and protons in minimum bias pp and for different centrality classes in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, over a wide momentum range have been presented. Going from minimum bias pp and peripheral Pb–Pb collisions to central Pb–Pb collisions, a clear mass dependent flattening (hardening) of the transverse momentum spectra at low p_T has been observed, which is more prominent in the case of heavier mass hadrons. These features are compatible with the development of a strong collective flow with centrality. The low p_T spectra are fitted with the Boltzmann-Gibbs blast-wave function, and it is found that the average transverse expansion velocity ($\langle\beta_T\rangle$) extracted from this fitting increases from peripheral to the central collisions. *This can be interpreted as a possible indication of a more rapid expansion of the created fireball with increasing centrality.* On the other hand, the kinetic freeze-out temperature is found to decrease from peripheral to the central collisions. In the most central Pb–Pb collisions (0 – 5%), the average transverse expansion velocity is found to be of $\langle\beta_T\rangle = 0.663 \pm 0.00459$ which is $\sim 2\%$ larger than the result measured at $\sqrt{s_{NN}} = 2.76$ TeV.

From the measurement of the average transverse momentum ($\langle p_T \rangle$) of the identified particles as a function of charged particle multiplicity density, the $\langle p_T \rangle$ is found to increase from low multiplicity to high multiplicity, where the increasing trend is found to be more prominent for hadron with heavier mass (e.g., proton). *This observation is consistent with the presence of strong radial flow as observed in the transverse momentum spectra.*

The increasing trend of p_T -integrated K/π ratio as a function of charged particle multiplicity density ($dN_{ch}/d\eta$) provides a hint of more strange particle production in the high multiplicity events. On the other hand, the decreasing trend of the p/π ratio as a function

of $dN_{ch}/d\eta$ gives an important message about the baryon and anti-baryon annihilation process in the hadronic phase.

Particle production in the intermediate p_T region has been discussed in terms of the K/π and p/π ratios as a function of transverse momentum for different centrality classes in Pb–Pb and minimum bias pp collisions. A clear increase of K/π ratio in the most central collisions with respect to the minimum bias pp collisions has been observed in the intermediate p_T region, *which is attributed to the strong radial flow effect. Further, p/π ratio shows a large increase in the most central collisions, which is again attributed to the presence of strong radial flow, affecting mainly the particles having heavier mass.* In addition to the presence of strong radial flow, recombination picture of the particle production mechanism might play an important role which favours the production of more baryons than mesons. The increase of p/π and K/π ratios in the intermediate p_T region decreases with the decrease of centrality and in the most peripheral collisions, they become similar (within the systematic uncertainties) to the results of minimum bias pp collisions. *The interpretation of this observation is that the overlap region of the system in the most peripheral collision is very small, similar to the pp system, thereby, contains vanishing radial flow effect. For $p_T > 10$ GeV/c, both K/π and p/π ratios become similar with minimum bias pp collisions, indicating the possible vacuum like fragmentation process of the particle production mechanism.*

From the study of the nuclear modification factor, a clear mass dependent R_{AA} has been observed in the low and intermediate p_T regions. Again this observation is consistent with the radial flow effect as observed in the particle ratios. On the other hand, for $p_T > 10$ GeV/c, all the particle species are equally suppressed. *This observation demonstrates the presence of strong nuclear matter effects. From the comparison of R_{AA} at the two different LHC energies, it may be asserted that the medium created at both the energies may behave*

in the similar way where the final state particles equally suffer the nuclear matter effect during the space-time evolution of the fireball.

The transverse momentum distributions of identified particles has been compared with various models, such as iEBE-VISHNU, McGill and EPOS3, which are found to describe the observed trend satisfactorily. For $p_T \sim 1$ GeV/c, the model predicted p_T spectra are found to describe the data within 20%, whereas for $p_T \sim 3$ GeV/c, the agreement is within 30%.

4 | Role of net baryon density distribution on the rapidity widths of identified particles in heavy ion and pp collisions at the LHC energies

4.1 Introduction

Rapidity distribution of produced particles is considered to be one of the important global observables of heavy-ion collisions which provides valuable information about the reaction dynamics of such collisions [195]. Widths of the rapidity distributions of particles are considered to be a measure of their final-state rescattering and are found to follow a mass ordering [12, 43]. In addition to the final-state rescattering, the rapidity width is also sensitive to a number of other parameters such as longitudinal dynamics, the velocity of sound, etc. [13–15]. Recently, in Ref. [44], it has been shown that the width of the rapidity distribution of a particle, in addition to its mass dependence, also depends on the nature of its quark content. In that report, from a study on Ultrarelativistic Quantum Molecular Dynamics (UrQMD) generated Au-Au data at 10, 20, 30, and 40A GeV and its comparison with NA49 experimental results, it has been shown that the

width of the rapidity distribution of a particle like Λ (uds), containing leading quarks, exhibits an additional dependence on net baryon density distribution, whereas particles not containing leading quarks, such as $\bar{\Lambda}$ ($\bar{u}\bar{d}\bar{s}$), do not exhibit any such dependence on net baryon density distribution. In rapidity space, the Λ distribution is shown to reflect the pattern of net baryon density distribution, whereas $\bar{\Lambda}$ does not. Since the net baryon density distribution depends on the transparency of collision, evolution of rapidity width of identified particles with energies from the lowest SPS energy to the highest RHIC and the LHC energies is expected to provide some important information about the role of net baryon density distribution on rapidity width at different energy densities and temperatures and as such on the particle production mechanism itself. In this work, an attempt has therefore been made to trace this signature of net baryon density distribution on rapidity width over the entire SPS energies such as 20, 30, 40, 80, and 158A GeV with UrQMD-3.4-generated and available experimental data and to extend the study with Monte Carlo (MC) data to RHIC and LHC energies. The ultimate motivation of the present investigation is to check if this dependence of rapidity width on net baryon density distribution is a general characteristic of the rapidity distribution of the produced particles of heavy ion collisions.

For A-A collisions at AGS and low SPS energies, the net baryon density mostly populates the midrapidity region. With further increase of beam energy at high SPS and RHIC energies, the transparency of the collisions increases and the net baryon density, unlike AGS and low SPS energies, populates the extreme rapidity regions with a minimum in $B - \bar{B}$ at and around midrapidity. It is reported in Ref. [44] that for A-A collisions, with UrQMD-generated data, a situation could not be reached even at the highest RHIC energy ($\sqrt{s_{NN}} = 200$ GeV) for which $B - \bar{B} = 0$ and thus, in such case, it could not be ascertained if the rapidity width of Λ is free from net baryon density distribution effect or otherwise if the Λ s are produced through pair production only. However, it has been reported in Ref. [196]

by ALICE collaboration that $\bar{\Lambda}/\Lambda$ ratio becomes unity at midrapidity in pp collisions at 7 TeV. It may, therefore, be expected that for such situation $B - \bar{B}$ would become zero and thus the Λ production might be independent of net baryon density distribution. Here it is worth mentioning that the colliding protons at the ultra-relativistic energies are considered not only to be composite but also extended objects consisting of many partons, which resembles a situation similar to heavy-ion collisions where the collision ranges from central (high multiplicity) to peripheral (low multiplicity) one [93]. While in A-A collisions, the spectator regions are composed of hadronic matter, in case of pp collisions the spectators are made up of partonic matter only. As it has been seen in Ref. [44] for heavy-ion collisions that the spectator hadrons play a significant role in particle production, particularly in Λ production, it would be interesting to see how these spectator partons of pp collisions play its role in particle production. Thus, multiplicity dependent study on the width of the rapidity distribution of Λ ($\bar{\Lambda}$) produced in pp collisions at the LHC energies could be of quite significance.

It has been claimed in a number of reports [197–199] that UrQMD is quite successful in describing heavy-ion collisions data over a wide range of energies. In Ref. [217] it has also been shown that UrQMD is equally successful in describing the experimental results of pp, Au-Au, and Pb-Pb collisions from 17.3 GeV at the SPS to 1.8 TeV at Fermilab. It is therefore expected that UrQMD could be successfully applied for small system like pp at LHC energies as well. On the other hand, PYTHIA has been found to be quite successful in explaining the pp experimental results particularly at higher energies like that of LHC [233, 234]. Therefore, in this chapter an attempt has also been made, with UrQMD-3.4 and PYTHIA8 (Monash and 4C tuned) generated pp events, to estimate the widths of the rapidity distributions of various produced particles including Λ and $\bar{\Lambda}$ at different beam energies to examine how the rapidity width of Λ (and $\bar{\Lambda}$) behave in pp collisions for situation for which $B - \bar{B} = 0$. Further, a study on the widths of the rapidity distributions

of different hadrons for various multiplicity classes of pp collisions at the highest LHC energy using PYTHIA8 Monash-generated data has been carried out to evaluate the role of spectator partons, particularly on Λ production.

4.2 Significance of net baryon density in high energy collisions

A considerable fraction of the available energy in heavy-ion collisions is carried away by the baryons [200–203]. The net baryon ($B - \bar{B}$) density distribution over the entire rapidity (y) space mainly provides the information about the opacity or in other words, the transparency of the collisions. Further, in an interaction, the baryon number is a conserved quantity, thereby, $B - \bar{B}$ keeps track of the energy-momentum carried by the incoming particles [204].

Since the proton (uud) contains 3 leading quarks, some experiments presented their results in terms of net-proton ($p - \bar{p}$) which carries similar physics message like that of net baryon. The BRAHMS collaboration presented its results in terms of net baryon, whereas the NA49 and AGS experiments presented their results in terms of net-proton [205–211]. Fig. 4.1 shows the rapidity distributions of (a) net-proton ($p - \bar{p}$) at AGS and SPS energies, and (b) net baryon in heavy-ion collisions at RHIC energies [205–211]. From Fig. 4.1 it could be readily seen that at AGS energy ($E_{lab} = 10A$ GeV), due to the stopping of the incoming nucleus, the net-proton distribution tends to populate the midrapidity. As the beam energy increases, for example, the experiments at the SPS, the transparency of the collision increases, and hence the net-proton distribution at midrapidity tends to decrease. As the beam energy further increases, such as the experiment at the RHIC, the net baryon distribution mostly populates the extreme rapidities with a clear dip at midrapidity (Fig. 4.1 (b)). At the LHC energies, due to extreme transparency of the collision,

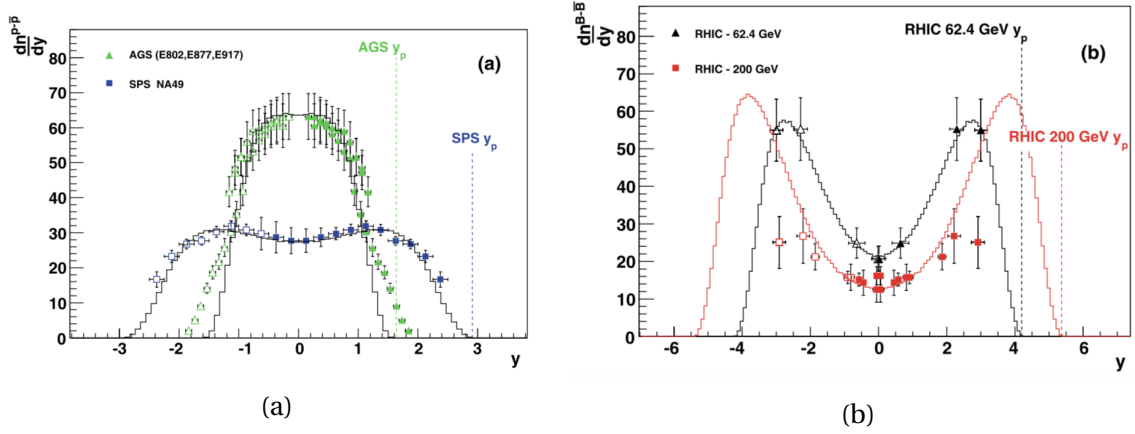


Fig. 4.1 Rapidity distributions of (a) net-proton ($p - \bar{p}$) at AGS and SPS energies, and (b) net baryon in heavy-ion collisions at RHIC energies [205–211]. The solids lines are the results from the model prediction [204].

net baryon distribution is expected to be zero at midrapidity. However, due to the limited acceptance of the detectors at the LHC, the experimental measurement of net baryon density is not possible at the extreme rapidities. In this chapter, an attempt has therefore been made with various Monte Carlo model-generated and experimental data to trace the nature of the net baryon density distribution and its role on the particle production mechanism, both for A-A and pp collisions, over the full rapidity range from the SPS (MC and experimental) to the LHC energies (MC only).

4.3 Significance of (pseudo)rapidity distribution and overview of the recent results

Rapidity : In collider experiments, the beam line is conventionally taken along the z -axis and is known as *longitudinal direction*, whereas, direction perpendicular to it is termed as *transverse direction*. For example, the 3-momentum can be regarded as the longitudinal component denoted by p_z , and the transverse component denoted by $p_T = \sqrt{p_x^2 + p_y^2}$.

The dimensionless variable called rapidity is then defined as [64],

$$y = \frac{1}{2} \ln \frac{E + p_z}{E - p_z}, \quad (4.1)$$

where E is the energy of the particle. The geometrical representation of the rapidity is shown in Fig. 4.2. If a particle is emitted along the xy -plane, the value of p_z will be very

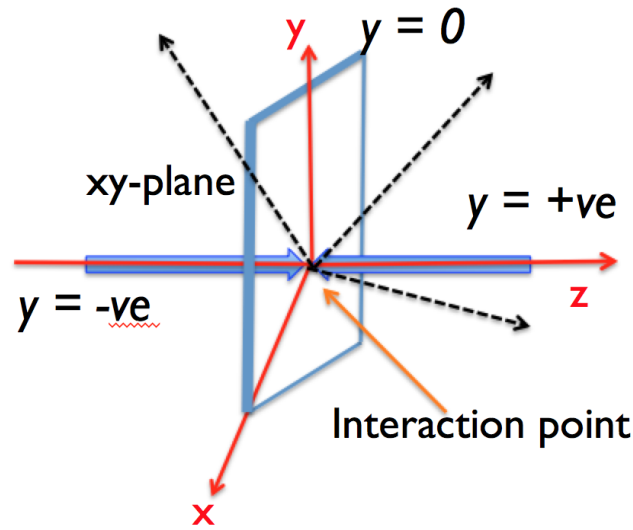


Fig. 4.2 Geometrical representation of rapidity. The black dotted lines represent the direction of the emission of particles from the interaction point.

small and thus from Eq. 4.1 it could be found that the rapidity of this particle will become zero. On the other hand, if the produced particle is predominantly emitted along the $+z$ and $-z$ axes, the corresponding rapidities will be $y \rightarrow \infty$ and $y \rightarrow -\infty$ respectively. Thus, physically rapidity is related to the angle between the xy -plane and the direction of the emission of the particle.

Rapidity for non-relativistic particles: If $\beta (= \sqrt{v/c})$ be the longitudinal velocity of a particle travelling along the z -direction having rest mass m , the longitudinal momentum

(p_z) and energy (E) will be,

$$p_z = \gamma\beta m, \text{ where, } \gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} \text{ and} \quad (4.2)$$

$$E = \gamma m,$$

Then the rapidity of the particle will be,

$$y_\beta = \frac{1}{2} \ln \frac{E + p_z}{E - p_z} = \frac{1}{2} \ln \frac{\gamma m + \gamma\beta m}{\gamma m - \gamma\beta m} = \frac{1}{2} \ln \frac{1 + \beta}{1 - \beta}, \quad (4.3)$$

In the non-relativistic limit when β is small, expanding y_β in terms of β leads to,

$$y_\beta = \beta + \text{higher order terms} \quad (4.4)$$

Thus the rapidity of the particle is the relativistic realization of its velocity.

Pseudorapidity: Similar to rapidity, pseudorapidity is commonly used to characterize the direction of the particle emission and is defined as,

$$\eta = -\ln \tan\left(\frac{\theta}{2}\right), \quad (4.5)$$

where θ is the polar angle of the particle measured anticlockwise with respect to the beam direction. From the energy-mass relation and the velocity of light (c) in the rapidity

variable we get,

$$\begin{aligned}
 y &= \frac{1}{2} \ln \frac{E + p_z c}{E - p_z c} \\
 \Rightarrow y &= \frac{1}{2} \ln \left(\frac{(p^2 c^2 + m^2 c^4)^{\frac{1}{2}} + p_z c}{(p^2 c^2 + m^2 c^4)^{\frac{1}{2}} - p_z c} \right) \\
 \Rightarrow y &= \frac{1}{2} \ln \left(\frac{pc(1 + \frac{m^2 c^4}{p^2 c^2})^{\frac{1}{2}} + p_z c}{pc(1 + \frac{m^2 c^4}{p^2 c^2})^{\frac{1}{2}} - p_z c} \right) \\
 \Rightarrow y &\simeq \frac{1}{2} \ln \left(\frac{pc + p_z c + \frac{m^2 c^4}{2pc} + \dots}{pc - p_z c + \frac{m^2 c^4}{2pc} + \dots} \right) \\
 \Rightarrow y &\simeq \frac{1}{2} \ln \left(\frac{1 + \frac{p_z}{p} + \frac{m^2 c^4}{2p^2 c^2} + \dots}{1 - \frac{p_z}{p} + \frac{m^2 c^4}{2p^2 c^2} + \dots} \right)
 \end{aligned} \tag{4.6}$$

Again, $p_z/p = \cos\theta$ and hence,

$$\begin{aligned}
 1 + \frac{p_z}{p} &= 1 + \cos\theta = 1 + \left(\cos^2 \frac{\theta}{2} - \sin^2 \frac{\theta}{2} \right) = 2\cos^2 \frac{\theta}{2} \\
 1 - \frac{p_z}{p} &= 1 - \cos\theta = 1 - \left(\cos^2 \frac{\theta}{2} - \sin^2 \frac{\theta}{2} \right) = 2\sin^2 \frac{\theta}{2}
 \end{aligned} \tag{4.7}$$

Incorporating these values in Eq. 4.6 and neglecting the higher order terms for ultra-relativistic heavy-ion collisions we get,

$$\begin{aligned}
 y &\simeq \frac{1}{2} \ln \frac{\cos^2 \frac{\theta}{2}}{\sin^2 \frac{\theta}{2}} \\
 y &\simeq \eta \simeq -\ln \tan \left(\frac{\theta}{2} \right)
 \end{aligned} \tag{4.8}$$

Thus for highly relativistic particle emission, rapidity is equivalent to pseudorapidity.

The NA49 collaboration [43] reported the rapidity distributions of identified particles for central Pb–Pb collisions at $E_{lab} = 20, 30, 40, 80$, and $158A$ GeV over a wide rapidity range as shown in Fig. 4.3. The rapidity distributions were well described by the Gaussian

function. The widths of the rapidity distributions of various identified particles of Fig. 4.3

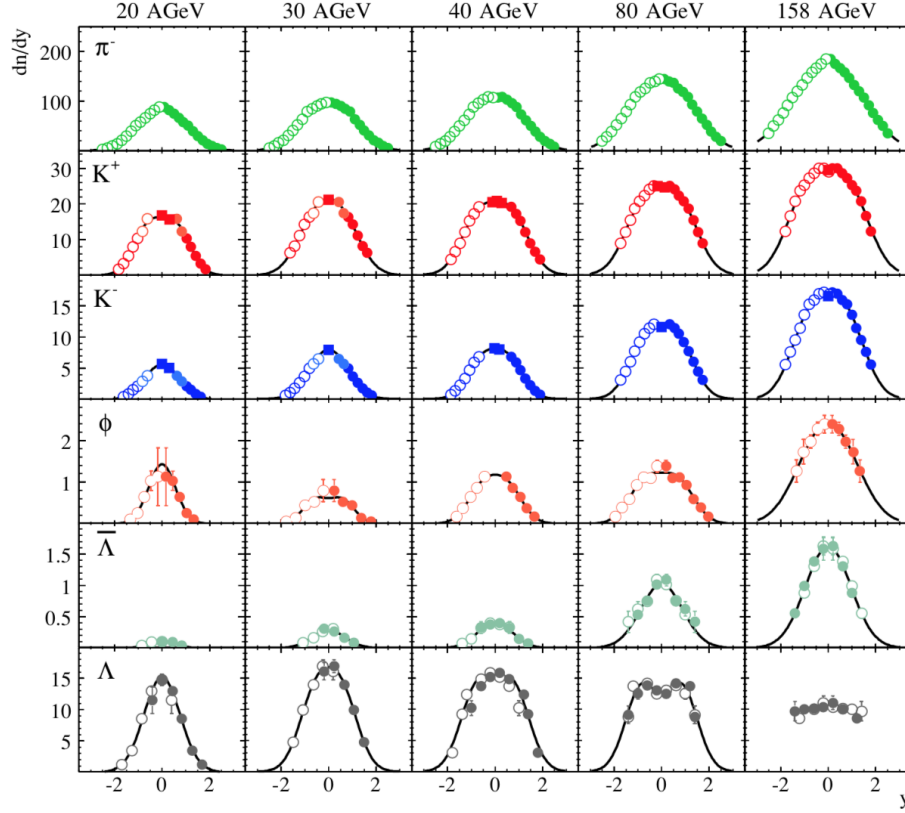


Fig. 4.3 Rapidity distributions of identified hadrons in central Pb–Pb collisions at various SPS energies [43]. The solid symbols represent the experimental points whereas the open symbols represent their reflected points with respect to midrapidity.

as a function of their rest masses are shown in Fig. 4.4 [43], where a clear mass ordering in the width of the rapidity distribution has been observed. The lighter hadrons show higher rapidity widths than the heavier hadrons. During the space-time evolution of the created system, the lighter hadrons undergo larger scattering than the heavier one, resulting higher rapidity width. It is important to note here that, as a significant contribution to Λ production comes from Σ^0 and thus contributes to feed down error, NA49 collaboration reported their results taking $\bar{\Lambda}$ instead of Λ particle. However, in a recent work [44], from the prediction of UrQMD-generated data and available experimental results, taking Λ instead of $\bar{\Lambda}$ into consideration, it has been shown that the width of the

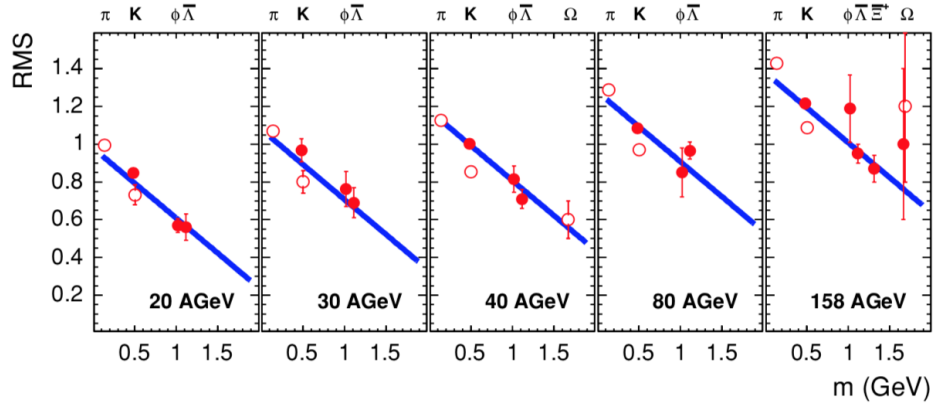


Fig. 4.4 Widths of the rapidity distributions of various identified particles as a function of their rest masses at various SPS energies of NA49 collaboration [43].

rapidity distribution of a particle, in addition to its mass dependence, also depends on the nature of its quark content. Fig. 4.5 shows the UrQMD-predicted widths of the rapidity

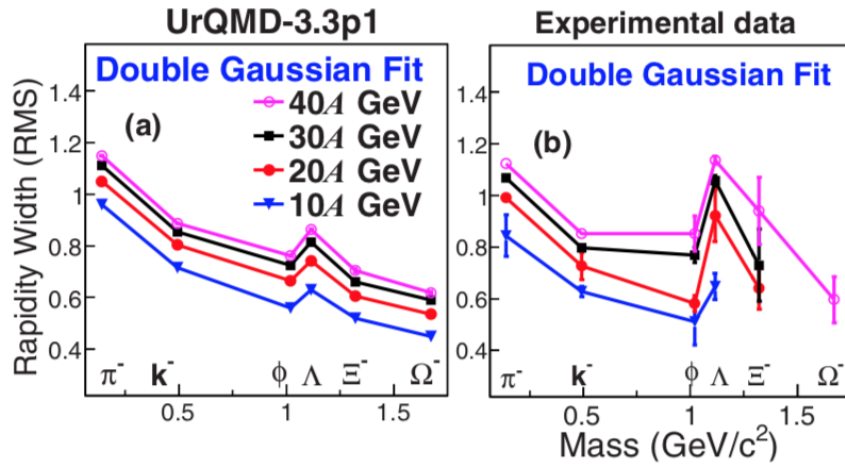


Fig. 4.5 Rapidity widths of various identified particles as a function of their rest masses at AGS and low SPS energies using UrQMD-generated events (left panel) [44] and compared with the existing experimental results of low SPS energies (right panel) [43].

distributions of the various mesons and baryons at AGS and low SPS energies, and the existing experimental results of NA49 collaborations [43] at low SPS energies. A clear jump in the rapidity width of Λ could be seen for both the UrQMD-predicted and NA49 collaboration results. Such a jump in the width of the rapidity distribution of Λ is attributed

to the net baryon density distribution effect [44]. As mentioned earlier, at AGS and low SPS energies, the net baryon density mostly populates the midrapidity region due to the stopping of the incoming particle in the target nucleus. As the collision energy increases, the transparency of the collision increases with maximum $B - \bar{B}$ populating the beam and target rapidities. The rapidity distribution of Λ , containing two leading quarks, but not $\bar{\Lambda}$ (containing produced quarks only), is sensitive to this net baryon density distribution and tends to follow its shape. Since the net baryon density distribution depends on the transparency of the collision, in this work, a study on the rapidity widths of identified particles at various energies from the lowest SPS to RHIC and LHC, has been undertaken to investigate the role of net baryon density on the rapidity width and hence on particle production mechanism over all SPS, RHIC and available LHC energies.

4.4 Generation of Monte Carlo events

For the present work, Monte-Carlo event generators such as UrQMD and PYTHIA are used. Since the production probability of multi-strange particles, such as Ξ^- and Ω^- , is very low, a sufficiently large number of events are required to generate for a reasonable statistics. A High Performance Computing Cluster (HPCC) facility (Fig. 4.6) has been developed at the Nuclear and Radiation Physics Research Laboratory of Department of Physics, Gauhati University and has been extensively used to generate various MC events. The HPCC is made up of four HP blade servers having a total of 84 *nodes* and 168 *threads*. It is equipped with the Rock-7.0 Cluster implementation software, which is implemented on CentOS 7.6 operating system. For generating the events, parallel jobs are submitted to the machine via the scheduler Known as Sun Grid Engine (SGE). The HPCC is connected to an external storage system of 20 TB.



Fig. 4.6 Block diagram of the High Performance Computing Cluster (HPCC) of the Nuclear and Radiation Physics Research Laboratory of Department of Physics, Gauhati University.

4.5 Monte Carlo event generators

At present, several theoretical models are available, which provide some important information about the dynamics of heavy-ion collisions over a wide range of energies. These models were developed based on the different reaction mechanisms, such as particle and resonance production at low and intermediate energies, string-excitation and fragmentation or parton fragmentation at relativistic and ultra-relativistic energies, etc. At low and intermediate energies the particle production mechanism is generally described in terms of hadronic (resonances) degrees of freedom, whereas at the high energies quarks and gluons are considered to be the dominant degrees of freedom [212].

4.5.1 UrQMD event generator

The Ultra-relativistic Quantum Molecular Dynamics (UrQMD) is a microscopic transport model and is based on a phase-space description of the reaction. It contains a set of unknown parameters, which are usually checked and fixed with the help of experimental data or by incorporating further model assumptions. Based on the classical covariant equation of motion, the UrQMD model describes the time-evolution of the many-body system. The time evolution of many-body system propagates in $8N$ -dimensional phase-space. Out of $8N$ dimensional space, $6N$ degrees of freedom represents the classical configuration and momentum space, and the remaining $2N$ degrees of freedom represents the energy and eigentime of each particle [212]. The UrQMD represents a Monte Carlo solutions of a large set of coupled partial integro-differential equations for the time evolution of various phase-space densities $f_i(x, p)$, where i stands for various particle species. Non-relativistically, the solution is assumed to be the Boltzmann form [213],

$$\frac{df_i(x, p)}{dt} \equiv \frac{\partial p}{\partial t} \frac{\partial f_i(x, p)}{\partial p} + \frac{\partial x}{\partial t} \frac{\partial f_i(x, p)}{\partial x} + \frac{\partial f_i(x, p)}{\partial t} = \text{St } f_i(x, p), \quad (4.9)$$

where x and p represent the position and momentum of the particle respectively, whereas $f_i(x, p)$ represents the collisions or source term of these particles. This source term is connected to any other particle species f_k .

In UrQMD, the projectile and target nuclei are modelled according to fermi-gas ansatz. The density of the nucleons are represented by Gaussian shaped distributions [212],

$$\psi_j(x_j, t) = \left(\frac{2\alpha}{\pi}\right)^{\frac{3}{4}} \exp\left\{-\alpha(x_j - r_j(t))^2 + \frac{i}{\hbar}p_j(t)x_j\right\} \quad (4.10)$$

The total wave function of the nucleus is defined as the product of the individual wave function,

$$\phi = \prod_j \psi_j(x_j, t) \quad (4.11)$$

And the radius of the nucleus should be,

$$R(A) \approx r_0 \cdot A^{\frac{1}{3}} \quad (4.12)$$

However, in the configurational space, the centroids of the Gaussians of the nucleus are randomly distributed within a sphere and thus the radius takes the form,

$$R(A) \approx r_0 \left(\frac{1}{2} \left[A + (A^{\frac{1}{3}} - 1)^3 \right]\right)^{\frac{1}{3}}, \quad (4.13)$$

where in UrQMD, the parameter r_0 is a function of nuclear matter density (ρ_0) at ground state and is given by,

$$r_0 = \left(\frac{3}{4\pi\rho_0}\right)^{\frac{1}{3}} \quad (4.14)$$

In UrQMD, the collision term contains 55 different baryon species and 32 different meson species. The collision term is also supplemented by all the corresponding anti-particle and all iso-spins projected states. Here the hadron-hadron collisions are performed stochastically like the original cascade model as reported in Ref. [214], where the cross-

section of the collision is interpreted geometrically as an area. Two particles interact if their distance d fulfil the following condition,

$$d \leq d_0 = \sqrt{\frac{\sigma_{total}}{\pi}}, \quad \sigma_{total} = \sigma(\sqrt{s}, \text{type}), \quad (4.15)$$

where σ_{total} is the total cross-section and it depends on the centre-of-mass energy ($\sqrt{s}$) and on the species and quantum number of the incoming particles. In 3 dimensional configurational space, d is the relative distance between the two colliding particles.

Thus, the UrQMD event generator is a many-body microscopic Monte Carlo transport model for generating events of pp , p -A and A-A collisions at relativistic and ultrarelativistic energies. The recent versions of UrQMD models include PYTHIA (which is discussed in the following section) to incorporate hard perturbative QCD effects [215, 216]. The UrQMD model is based on mesonic and baryonic degrees of freedom associated with constituent quarks, diquarks, and covariant propagation of color strings [217]. It also includes the excitation and fragmentation of color strings, formation and decay of hadronic resonances, and rescattering of particles. UrQMD could be applied successfully via fragmentation of strings and hard scattering to explore heavy ion reactions from AGS to SPS energies ($E_{lab} = 20A$ to $158A$ GeV) and the full RHIC energies ($\sqrt{s_{NN}} = 19.6$ to 200 GeV) [218, 219]. In Ref. [217], from a comparison on UrQMD calculations with experimental results of p - $\bar{p}$, Pb-Pb, and Au-Au collisions from 17.3 GeV at the SPS to 1.8 TeV at Fermilab, it has been shown that UrQMD has a valid basis for further extrapolation in energy to make predictions at LHC energies.

4.5.2 PYTHIA event generator

For this work, the PYTHIA model has been used to generate high-energy pp events. In general, PYTHIA is a standalone event generator, consisting of a coherent set of physics models, which describes the evolution of high-energy collisions from a few-body hard-

scattering processes to a complex multiparticle final state [220, 221]. The present version of the PYTHIA model contains a library of hard processes, models for initial and final state parton showers, multiple parton-parton interaction, string fragmentation, particle decays and beam remnant [221, 222]. The available high precision experimental data allow detailed model comparisons and motivate the effort on model development and tuning of the existing models towards more precise predictions. One of the dedicated tunings of PYTHIA8 event generator is PYTHIA8 4C, which is used to predict the Run 1 LHC data and the modified parameters are reported in Ref. [223]. As reported in Ref. [224], the latest PYTHIA8 version is tuned with Monash with the present available LHC data of Run 2. For the present investigation, 50 to 80 million pp inelastic events have been generated at each studied energies using PYTHIA8 4C and Monash tuning models.

4.6 Results and discussions

4.6.1 Width of the rapidity distribution of identified particles in A-A collisions

To start with, events were generated with UrQMD-3.4 event generator, for Pb-Pb collisions at all the beam energies of SPS at $E_{lab} = 20, 30, 40, 80$, and $158A$ GeV. The event statistics of generated data for minimum biased events is shown in the Table 4.1.

Table 4.1 Event statistics of UrQMD-3.4-generated data for various SPS energies.

System	Energy (A GeV)	Events (million)	$\pi^- \times 10^8$	$K^- \times 10^6$	$\phi \times 10^5$	$\Lambda \times 10^7$	$\Xi^- \times 10^5$	$\Omega^- \times 10^3$
Pb - Pb	20	1.49	1.040	4.05	2.173	6.94	2.74	3.60
	30	1.25	1.06	4.92	2.81	6.60	2.85	5.07
	40	1.30	1.27	6.46	3.79	7.42	3.40	7.21
	80	0.40	0.59	3.55	2.26	2.98	1.56	4.86
	158	0.76	1.27	8.61	5.86	5.62	3.32	13.89

Rapidity distributions of π^- , K^- , ϕ , and Λ with generated data of central Pb-Pb collisions at all the SPS energies from $E_{lab} = 20A$ to 158A GeV are shown in Fig. 4.7 and compared with the NA49 results [43, 82, 225–227]. While the rapidity distributions of π^- meson of UrQMD-

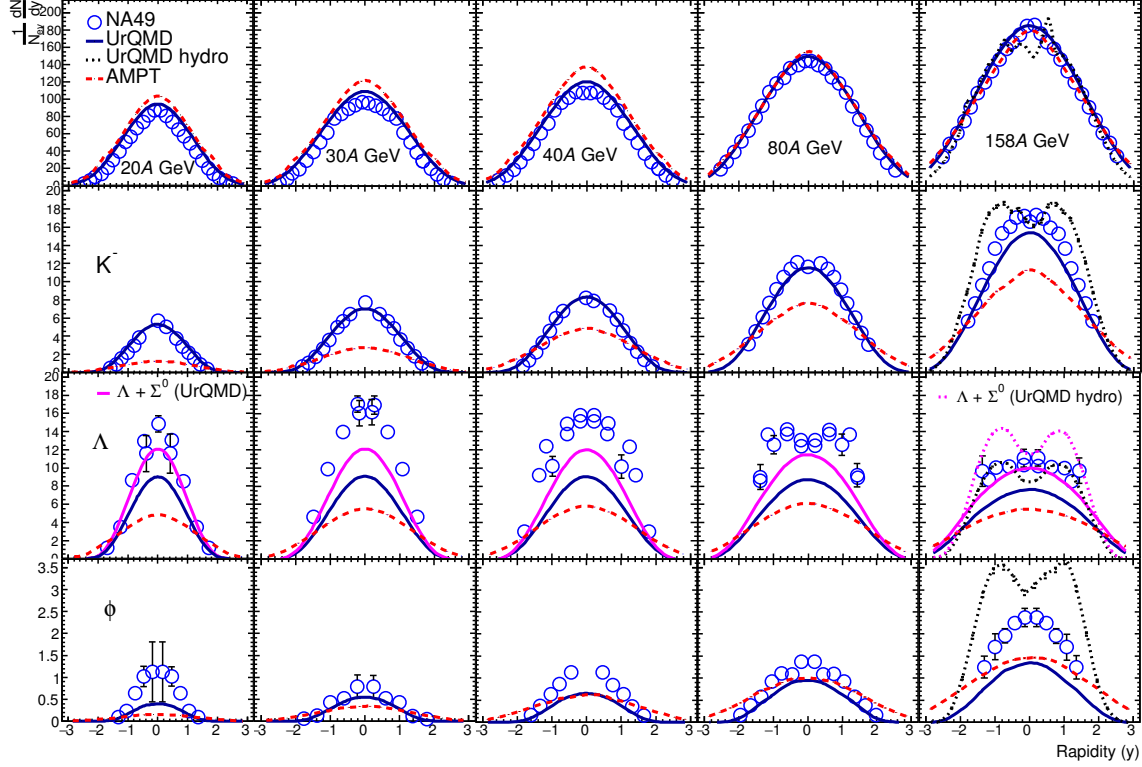


Fig. 4.7 Comparison of experimental (NA49) rapidity distributions of π^- , K^- , ϕ and Λ in Pb-Pb collisions with UrQMD-3.4, AMPT (string melting) generated data at $E_{lab} = 20, 30, 40, 80$ and 158A GeV and UrQMD (Hydro) at 158A GeV [43, 82, 225–227]. The blue open circular symbols represent the experimental results of NA49, whereas the blue solid, black dotted and red dashed curves denote the results of UrQMD-3.4, UrQMD-3.4 (Hydro) and AMPT (string melting) [186] generated data respectively. The magenta solid and dotted curves represent the rapidity distributions of $\Lambda + \Sigma^0$ using UrQMD-3.4 and UrQMD-3.4 (Hydro) generated data.

generated events are found to be in good agreement with experimental results of all the studied energies, the model-generated rapidity distributions of K^- are found to agree well with experimental results only up to 80A GeV. The model somewhat underestimates the experimental values around midrapidity at the highest SPS energy, i.e., 158A GeV. Since the experimental Λ has a contribution from the decay of Σ^0 , UrQMD-generated $\Lambda + \Sigma^0$ is

compared with the experimental rapidity distribution of Λ . At all the SPS energies, the MC values of $\Lambda + \Sigma^0$ are found to be less than the experimental Λ values. However, the disagreement decreases with the increase of energy. In the case of the ϕ meson, UrQMD underestimates the experimental values significantly at all energies and the disagreement is more at higher energies.

The experimental rapidity spectra of various identified particles have also been compared with the prediction of other event generators such as AMPT (string melting) at all the SPS energies and UrQMD (Hydro) at 158A GeV (as the disagreement in the rapidity spectra of ϕ is maximum at this energy for UrQMD-generated and experimental data). It is readily evident from Fig. 4.7 that the disagreement with the experimental values is even more for data generated by both these models and hence they have not been considered for further analysis.

Rapidity distributions of UrQMD-generated and experimental π^- , K^- , ϕ , Λ , Ξ^- , and Ω^- at all SPS energies are parameterized by the following double Gaussian function [44, 82]:

$$\frac{dN}{dy} \propto (e^{-\frac{(y-\bar{y})^2}{2\sigma^2}} + e^{-\frac{(y+\bar{y})^2}{2\sigma^2}}), \quad (4.16)$$

where the symbols have their usual significance. Widths of the rapidity distributions of all the studied hadrons, both generated and experimental, are listed in Table 4.2 and plotted as a function of their rest mass in Fig. 4.8.

It could be readily seen from Fig. 4.8 that, as reported in Ref. [44] for AGS and low SPS energies, a jump in the widths of Λ does exist even at higher SPS energies ($E_{lab} \geq 80A$ GeV) for both generated and experimental data.

Because of the obvious reason of limited detector acceptance, no report on rapidity distribution of identified particles at RHIC and LHC energies could be found in the litera-

Table 4.2 Widths of the rapidity distributions of all the studied hadrons as estimated using Eq. (4.16) for UrQMD-3.4-model-generated data and experimental data. While the experimental values of widths (r.m.s.) of π^- , K^- , ϕ , and Ω^- are taken from Ref. [43] and Λ , $\bar{\Lambda}$, and Ξ^- are taken from Ref. [82].

Particles	20A GeV	30A GeV	40A GeV	80A GeV	158A GeV
π^-	1.063 ± 0.00098 (0.991 ± 0.01)(data)	1.133 ± 0.0012 (1.068 ± 0.01)	1.185 ± 0.0014 (1.123 ± 0.01)	1.317 ± 0.0047 1.288 ± 0.01	1.441 ± 0.0065 (1.432 ± 0.01)
K^-	0.816 ± 0.0027 (0.727 ± 0.034)	0.890 ± 0.0038 (0.798 ± 0.009)	0.944 ± 0.0045 (0.852 ± 0.069)	1.062 ± 0.0067 (0.9711 ± 0.01)	1.167 ± 0.0036 (1.087 ± 0.01)
ϕ	0.670 ± 0.0044 (0.565 ± 0.040)	0.751 ± 0.0051 (0.710 ± 0.095)	0.805 ± 0.0049 (0.815 ± 0.0701)	0.937 ± 0.0079 (0.851 ± 0.127)	1.062 ± 0.0065 (1.190 ± 0.176)
Λ	0.806 ± 0.0024 (0.70 ± 0.01)	0.907 ± 0.0039 (0.89 ± 0.02)	0.977 ± 0.0047 (1.11 ± 0.08)	1.133 ± 0.0049 (1.28 ± 0.02)	1.327 ± 0.0065 (1.97 ± 0.35)
$\Lambda + \Sigma^0$	0.810 ± 0.02020	0.910 ± 0.0032	0.984 ± 0.0040	1.143 ± 0.0042	1.343 ± 0.0029
$\bar{\Lambda}$	0.722 ± 0.0202 (0.62 ± 0.14)	0.824 ± 0.038 (0.69 ± 0.05)	0.935 ± 0.0417 (0.77 ± 0.05)	1.108 ± 0.0023 (0.83 ± 0.05)	1.083 ± 0.0854 (1.00 ± 0.03)
Ξ^-	0.671 ± 0.0050 (0.64 ± 0.08)	0.754 ± 0.0075 (0.73 ± 0.08)	0.808 ± 0.0085 (0.94 ± 0.13)	0.946 ± 0.012 (0.98 ± 0.25)	1.073 ± 0.0094 (1.18 ± 0.18)
Ω^-	0.577 ± 0.0380	0.637 ± 0.024	0.664 ± 0.032 (0.596 ± 0.09)	0.800 ± 0.033	0.919 ± 0.0550 (1.200 ± 0.396)

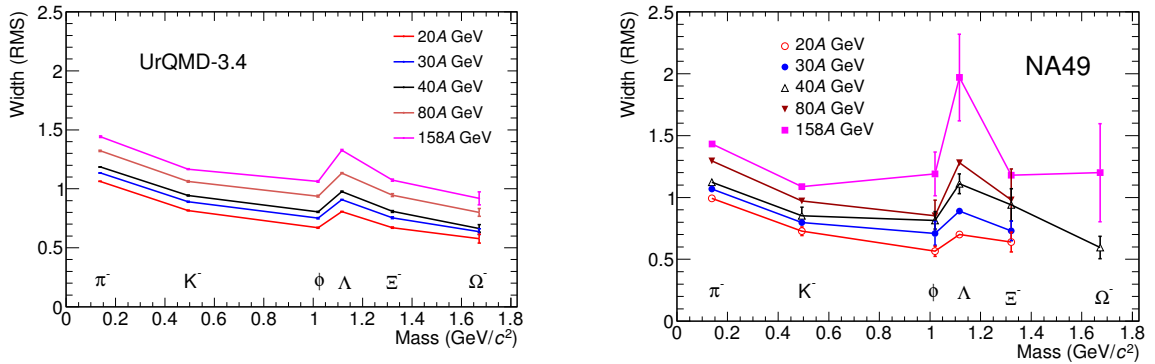


Fig. 4.8 Width of the rapidity distribution as a function of their rest masses of π^- , K^- , ϕ , Λ , Ξ^- , and Ω^- in Pb-Pb collisions at all the SPS energies using UrQMD-3.4-generated events (left panel) and NA49 results (right panel) [43, 82].

ture and hence the possible existence of the bumps in the experimental data of rapidity width of Λ at these energies could not be ascertained. In the following, an attempt is made with MC data to examine if this behavior persists at RHIC and LHC energies too. It may be mentioned here that there are results of PHOBOS and ALICE experiments on pseudorapidity distributions of all charged particles at various RHIC and LHC energies. Both these experimental results on pseudorapidity distributions of unidentified charged particles excluded all contributions from the weak decays. To check how far the UrQMD-3.4 model is successful in describing the phase space evolution of particles produced in such heavy ion collisions at RHIC and LHC energies, two additional sets of central collision events have been generated for all the studied RHIC and LHC energies using UrQMD-3.4 event generator with default mode as well as by switching off all such weak decays. The model predicted pseudorapidity distributions of all charged particles in Au-Au collisions at $\sqrt{s_{NN}} = 19.6, 62.4, 130$, and 200 GeV and in Pb-Pb collisions for 2.76 TeV and 5.02 TeV are compared with the existing results of PHOBOS and ALICE experiments [217, 228] and are shown in Figs. 4.9 and 4.10 respectively.

Even though the default mode is found to overestimate the experimental values of pseudorapidity distribution significantly over the entire pseudorapidity range, the pseudorapidity spectra of generated events, excluding weak decays, are found to be in good agreement with the experimental results of both RHIC and LHC energies. The agreement between the UrQMD-3.4-model-generated data and experimental data is found to be much better than the earlier works of Refs. [217] and [228]. The right panel of Fig. 4.10 shows the pseudorapidity spectra of all charged particles at 5.02 TeV for Pb-Pb collisions with model-generated data to date; no published result at this energy is available with experimental data thus far.

Using MC data with weak decay switched off, rapidity spectra of various identified particles are drawn for various RHIC and LHC energies and the widths of the rapidity

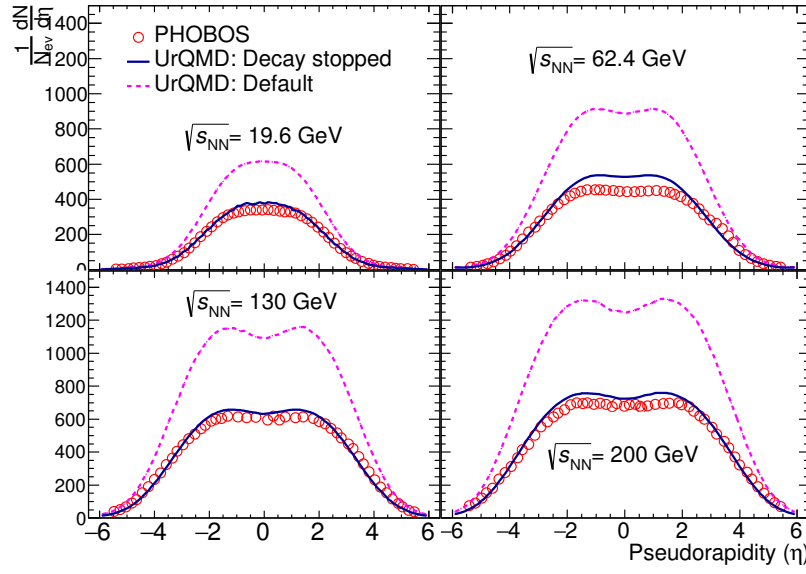


Fig. 4.9 Pseudorapidity distributions of all charged particles in Au-Au collisions at different RHIC energies $\sqrt{s_{NN}} = 19.6, 62.4, 130$, and 200 GeV (3% central) and compared with existing experimental results of PHOBOS collaboration [229]. The red open circular symbols represent the experimental results of PHOBOS collaboration, whereas the magenta dotted and blue solid curves denote the UrQMD-3.4-generated data with default mode and switching off the weak decay channels.

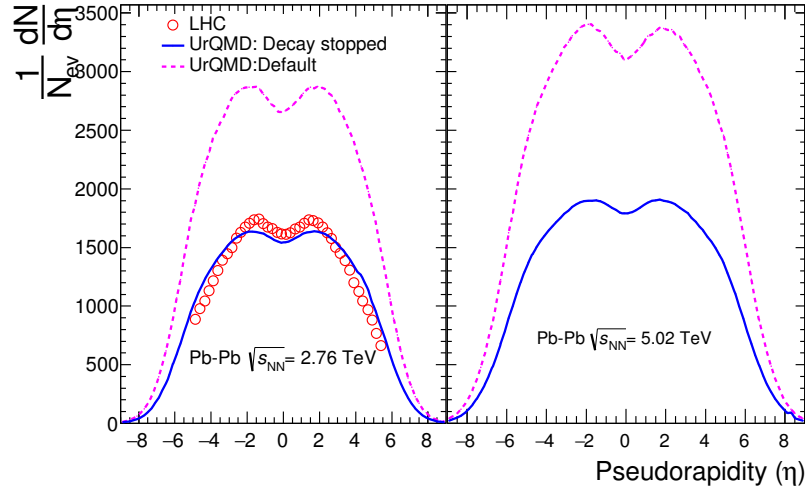


Fig. 4.10 Pseudorapidity distributions of all charged particles in Pb-Pb collisions at LHC energies, $\sqrt{s_{NN}} = 2.76$ (left panel) and 5.02 TeV (right panel) for 0 – 5% centrality and compared with existing experimental results of ALICE at 2.76 TeV [228]. The red open circular symbols represent the experimental results of ALICE, whereas the magenta dotted and blue solid curves denote the UrQMD-3.4-generated data with default mode and switching off the weak decay channels.

distribution of each of the studied hadron are estimated as the r.m.s. values of the fitting function (4.16); the values are tabulated in the Table 4.3.

Table 4.3 Widths of the rapidity distributions of all the studied hadrons with UrQMD-3.4-generated events at RHIC and LHC energies.

Particles	19.6 GeV	62.4 GeV	130 GeV	200 GeV	2.76 TeV	5.02 TeV
π^-	1.431 ± 0.00297	1.855 ± 0.0001	2.127 ± 0.0036	2.349 ± 0.0022	3.603 ± 0.0010	4.026 ± 0.0072
K^-	1.191 ± 0.0038	1.637 ± 0.0050	1.971 ± 0.0086	2.207 ± 0.0067	3.399 ± 0.0036	3.735 ± 0.0100
ϕ	1.1087 ± 0.013	1.509 ± 0.0176	1.832 ± 0.0342	2.05 ± 0.0220	3.240 ± 0.02010	3.460 ± 0.0480
Λ	1.297 ± 0.0043	1.955 ± 0.00943	2.487 ± 0.021	2.866 ± 0.0380	3.807 ± 0.0094	4.247 ± 0.0313
Ξ^-	1.097 ± 0.013	1.614 ± 0.0148	1.949 ± 0.0320	2.170 ± 0.0230	3.320 ± 0.0340	3.509 ± 0.0456
Ω^-	0.894 ± 0.062	1.421 ± 0.092	1.877 ± 0.279	1.958 ± 0.0780	3.053 ± 0.0340	3.241 ± 0.0878

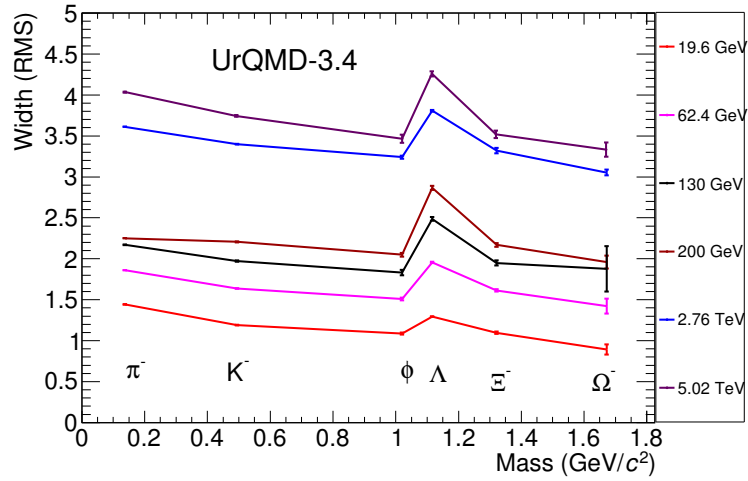


Fig. 4.11 Width of the rapidity distribution of various produced particles as a function of their rest masses for Au-Au and Pb-Pb collisions at RHIC and LHC energies using UrQMD-3.4-generated events. The solid lines with different colors correspond to various beam energies.

The UrQMD-3.4 model predicted rapidity widths as functions of masses of the studied mesons and baryons in Au-Au and Pb-Pb collisions at RHIC and LHC energies are shown in Fig. 4.11. As seen at AGS and SPS energies, a clear jump in the width of the rapidity distribution of Λ could be seen at all the RHIC and LHC energies. *Such observation confirms that the enhanced width of rapidity distribution of Λ is a characteristic feature of*

heavy ion collision data from AGS [44] and SPS to RHIC and highest available LHC energies. For Ξ^- (dss) containing only one leading quark, the rapidity width is seen to be more or less equal to the rapidity width of ϕ (Fig. 4.12), compensating for the broadening due to net baryon density effect by the mass-dependent kinematic narrowing effect. However, the separate mass ordering for the studied mesons and baryons are seen to exist even at RHIC and LHC energies.

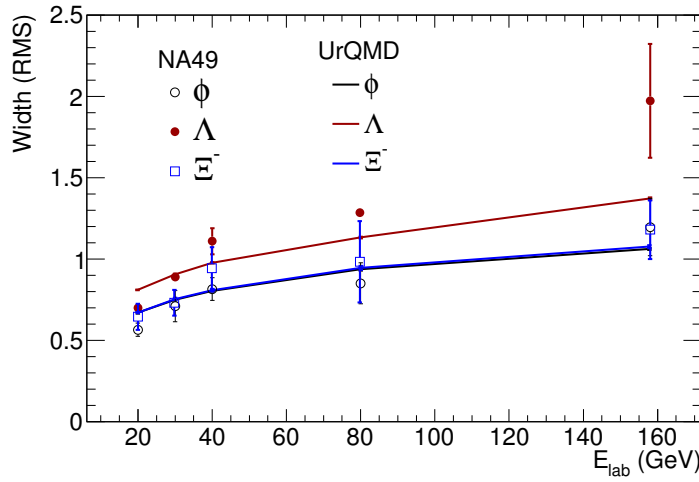


Fig. 4.12 Variation of the width of the rapidity distribution of various produced particles as a function of collision energy for Pb-Pb collisions at all the SPS energies for both NA49 and UrQMD-3.4-generated events. The solid lines and different marker symbols with different colors respectively denote the UrQMD-3.4-generated data and experimental results of various identified particles.

4.6.2 Width of the rapidity distribution of identified particles in pp collisions

For the present study, events were generated with UrQMD-3.4 and PYTHIA8 (4C and Monash tuned) models for pp collisions at various colliding energies from SPS to the highest LHC energies and the event statistics are presented in Tables 4.4 and 4.5.

Table 4.4 Event statistics of UrQMD-3.4-generated data for pp collisions at all the studied energies.

Energy (GeV) $\sqrt{s} (E_{lab})$	Events (million)	$\pi^- \times 10^7$	$K^- \times 10^6$	$\bar{p} \times 10^5$	$\phi \times 10^5$	$\Lambda \times 10^6$	$\Xi^- \times 10^4$	$\Omega^- \times 10^2$
(20)	67.04	4.42	1.13	1.38	0.26	2.13	0.56	0.26
(30)	134.43	11.67	4.20	8.42	1.13	5.76	3.43	7.93
(40)	46.87	4.87	2.09	5.27	0.61	2.40	2.16	8.25
(80)	61.53	9.38	5.33	17.40	1.96	4.44	7.33	49.85
(158)	53.62	11.05	7.38	26.67	3.25	4.91	11.52	103.13
19.6	42.91	9.74	6.80	25.14	3.19	4.21	10.08	103.22
53	31.00	12.35	10.63	45.23	7.67	4.45	18.85	222.82
62.4	31.71	13.48	11.84	51.53	9.17	4.75	21.04	247.80
130	43.34	23.25	22.03	106.03	22.84	7.645	38.85	400.50
200	51.71	31.70	31.32	161.38	38.62	10.06	54.29	450.09
546	48.41	42.34	45.42	288.96	73.60	12.71	76.95	279.38
900	113.91	119.54	131.3	862.67	223.43	33.80	220.76	580.82
2760	90.26	147.04	166.80	1111.75	365.66	36.56	279.12	714.76
5020	72.28	142.78	163.24	1091.39	286.23	33.96	274.19	717.36
7000	42.68	93.00	106.88	713.95	187.40	21.70	179.43	475.75
13000	29.60	76.25	88.12	589.00	154.67	17.28	148.34	395.27

Table 4.5 Event statistics of PYTHIA8 (Monash) generated data for pp collisions at different collision energies.

Energy (GeV) $\sqrt{s}$	Events (million)	$\pi^- \times 10^7$	$K^- \times 10^6$	$\bar{p} \times 10^5$	$\phi \times 10^5$	$\Lambda \times 10^6$	$\Xi^- \times 10^4$	$\Omega^- \times 10^2$
200	17.99	5.08	9.54	49.64	11.18	2.25	18.47	60.60
546	24.99	10.34	20.43	108.07	24.58	3.98	41.49	140.87
900	36.00	16.40	32.68	173.29	39.57	6.13	61.10	229.30
2760	69.99	46.98	96.71	514.52	118.97	15.83	204.29	732.92
5020	35.99	29.80	62.20	330.59	77.12	9.60	132.80	478.27
7000	53.99	50.20	105.53	559.97	131.42	15.79	226.50	825.48
13000	78.27	90.15	191.72	1013.58	240.50	27.36	413.29	1521.55

In the previous section, it has been shown that UrQMD-3.4-generated (pseudo)rapidity distributions of produced particles show a good agreement with the experimental results at all the SPS, RHIC, and LHC energies for Au-Au and Pb-Pb systems. With the present sets of generated data, pseudorapidity distributions of all primary charged particles are compared with the various existing experimental results of pp collisions of UA5 and ALICE collaborations. Pseudorapidity distributions of all primary charged particles using UrQMD-3.4 and PYTHIA8-generated events of pp collisions at $\sqrt{s} = 53$ (only UrQMD), 200, 546, and 900 GeV are compared with the results of UA5 collaboration [232] and is shown in the left panel of Fig 4.13. Though the MC data reproduces well the shape of the experimental pseudorapidity distributions of UA5 collaboration, around midrapidity, the models somewhat under-predict the experimental values at all the studied energies of UA5 collaboration. However, in the right panel of Fig 4.13, all sets of generated data (UrQMD-3.4, PYTHIA8 4C, and PYTHIA8 Monash) at $\sqrt{s} = 900$ GeV show a better agreement with the experimental results of ALICE collaboration [233, 234].

It may be mentioned here that the cause of observed small difference in the pseudorapidity distributions of UA5 and ALICE collaborations (e.g., at $\sqrt{s} = 900$ GeV) is discussed in Ref. [233] and is attributed to the facts that– (i) UA5 collaboration used a $1/M_x$ variation of single diffractive cross sections [235] and (ii) inconsistent UA5 internal data as discussed in Ref. [236]. It may further be noted that, while the comparison of PYTHIA8 4C- and PYTHIA8 Monash-generated pseudorapidity distributions of all primary charged particles with experimental data of ALICE collaboration could also be found in Refs. [233, 234], UrQMD-3.4-generated pseudorapidity distributions at LHC energies, to the best of our knowledge, have been compared for the first time in this report. From Fig 4.13 it is clearly seen that PYTHIA8 Monash tuned pseudorapidity distribution of primary charged particles lies between PYTHIA8 4C and UrQMD-3.4 predicted results. Considering the fact that

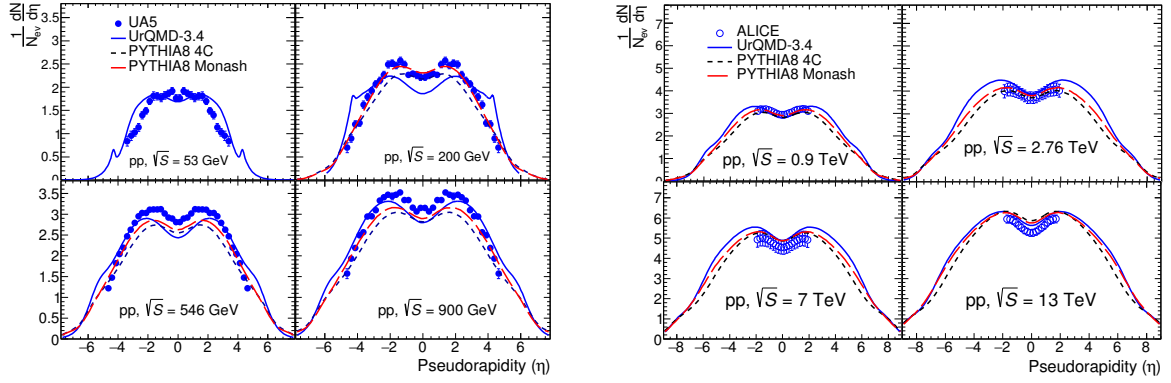


Fig. 4.13 Comparison of pseudorapidity distributions of all primary charged particles with UrQMD-3.4, PYTHIA8 4C, and PYTHIA8 Monash generated events in pp collisions at $\sqrt{s} = 53, 546, 200$, and 900 GeV with UA5 collaboration [232] (left panel), and at $\sqrt{s} = 0.9, 2.76, 7$, and 13 TeV with ALICE collaboration [233, 234] (right panel). The blue solid and open circular symbols represent the experimental results of UA5 and ALICE collaborations respectively, whereas blue solid, black small dashed and red long dashed lines represent the results of UrQMD-3.4, PYTHIA8 4C, and PYTHIA8 Monash generated data respectively.

all the three sets of model-predicted pseudorapidity distributions are in good agreement with the experimental results of appropriate energies, further analysis is carried out with all the three, i.e., UrQMD-3.4, PYTHIA8 4C, and PYTHIA8 Monash model-generated data.

UrQMD-3.4- and PYTHIA8 (4C and Monash)-generated rapidity distributions of π^- , K^- , $\bar{p}$, ϕ , Λ , Ξ^- , and Ω^- at all the studied energies for pp collisions are parameterized by the same double Gaussian function as mentioned above in Eq. 4.16. Using this fitting function, widths of the rapidity distributions of generated data of all the studied hadrons are estimated and listed in Tables 4.6 and 4.7. The variation of the rapidity widths of various mesons and baryons as a function of their rest masses at all the SPS, lower RHIC, and all the LHC energies for the rapidity space $|y| < 7$ are shown in Figs. 4.14 and 4.15.

It could be readily seen from Figs. 4.14 and 4.15 that, as observed for heavy-ion collisions from AGS to LHC energies, a similar jump in the rapidity width of Λ does exist also in the case of minimum bias pp collisions from low SPS to the highest LHC energies for both UrQMD-3.4 and PYTHIA8 (4C and Monash tuned) models generated data. Such an increase in the width of the rapidity distribution of Λ (uds) and not $\bar{\Lambda}$ ($\bar{u}\bar{d}\bar{s}$) [43],

was attributed to the dependence of Λ production on net baryon density distribution or otherwise on associate production of Λ [44].

Table 4.6 Widths of the rapidity distributions of all the studied hadrons with UrQMD-3.4-generated pp events at all the SPS, lower RHIC, and all the LHC energies. At LHC energies, rapidity widths of Λ s are estimated using double Gaussian function excluding the extreme two peaks, whereas rapidity widths estimated using triple Gaussian function including all the three peaks are shown in the parentheses.

Energy $\sqrt{s} (E_{lab})$	π^-	K^-	$\bar{p}$	ϕ	Λ	Ξ^-	Ω^-
(20 GeV)	1.045 ± 0.001	0.622 ± 0.002	0.570 ± 0.003	0.558 ± 0.011	0.728 ± 0.001	0.468 ± 0.017	-
(30 GeV)	1.078 ± 0.001	0.762 ± 0.002	0.644 ± 0.003	0.627 ± 0.007	0.826 ± 0.001	0.536 ± 0.009	0.419 ± 0.084
(40 GeV)	1.115 ± 0.002	0.779 ± 0.006	0.701 ± 0.008	0.678 ± 0.017	0.883 ± 0.002	0.586 ± 0.022	0.590 ± 0.240
(80 GeV)	1.230 ± 0.001	0.916 ± 0.007	0.832 ± 0.005	0.818 ± 0.014	1.040 ± 0.002	0.731 ± 0.014	0.630 ± 0.120
(158 GeV)	1.369 ± 0.001	1.039 ± 0.002	0.979 ± 0.003	0.942 ± 0.008	1.273 ± 0.001	0.883 ± 0.010	0.774 ± 0.029
19.6 GeV	1.414 ± 0.001	1.137 ± 0.002	1.031 ± 0.002	0.993 ± 0.005	1.352 ± 0.001	0.963 ± 0.006	0.833 ± 0.017
546 GeV	3.174 ± 0.002	3.043 ± 0.007	2.913 ± 0.007	2.842 ± 0.013	3.204 ± 0.024	2.754 ± 0.035	2.337 ± 0.014
900 GeV	3.254 ± 0.002	3.122 ± 0.006	3.056 ± 0.002	2.989 ± 0.014	3.487 ± 0.036 (4.55 ± 0.019)	2.909 ± 0.042	2.461 ± 0.093
2.76 TeV	3.766 ± 0.001	3.681 ± 0.001	3.587 ± 0.002	3.479 ± 0.002	4.417 ± 0.014 (5.091 ± 0.003)	3.444 ± 0.007	3.237 ± 0.030
5.02 TeV	3.861 ± 0.002	3.735 ± 0.002	3.704 ± 0.002	3.604 ± 0.004	4.583 ± 0.028 (5.152 ± 0.008)	3.611 ± 0.015	3.301 ± 0.065
7 TeV	4.060 ± 0.001	3.987 ± 0.001	3.897 ± 0.001	3.860 ± 0.003	4.650 ± 0.013 (5.158 ± 0.003)	3.871 ± 0.010	3.662 ± 0.043
13 TeV	4.267 ± 0.001	4.178 ± 0.001	4.138 ± 0.001	4.129 ± 0.003	4.690 ± 0.009 (5.180 ± 0.003)	4.140 ± 0.012	3.953 ± 0.051

In pp collisions, as shown in the left panel of Fig. 4.16, the net baryon density is found to be maximum at extreme rapidities even at low SPS energies and minimum but not zero at zero-rapidity, unlike in heavy-ion collisions, the spectator regions of pp collisions consists of partonic rather than hadronic matter and therefore the observed maximum net baryon density at extreme rapidity space in pp collisions are not due to the leading hadrons but due to the hadrons produced out of leading partons (partons of the spectators). As the collision energy increases, the minimum value of the net baryon density decreases reaching zero at lower LHC energies ($\sqrt{s} = 0.9$ TeV) (Figs. 4.16 and 4.17).

Table 4.7 Widths of the rapidity distributions of all the studied hadrons with PYTHIA8 Monash-generated inelastic pp events from 564 GeV to the top LHC energies. At LHC energies, rapidity widths of Λ s are estimated using double Gaussian function excluding the extreme two peaks, whereas rapidity widths estimated using triple Gaussian function including all the three peaks are shown in the parentheses.

Energy $\sqrt{s} (E_{lab})$	π^-	K^-	$\bar{p}$	ϕ	Λ	Ξ^-	Ω^-
546 GeV	3.078 ± 0.001	2.796 ± 0.002	2.609 ± 0.001	2.533 ± 0.003	3.738 ± 0.144	2.490 ± 0.007	2.156 ± 0.020
900 GeV	3.174 ± 0.001	2.876 ± 0.001	2.761 ± 0.001	2.705 ± 0.002	3.770 ± 0.044 (4.352 ± 0.010)	2.606 ± 0.005	2.307 ± 0.017
2.76 TeV	3.647 ± 0.001	3.390 ± 0.001	3.248 ± 0.001	3.227 ± 0.003	4.056 ± 0.023 (4.655 ± 0.007)	3.080 ± 0.006	2.845 ± 0.021
5.02 TeV	3.880 ± 0.001	3.639 ± 0.001	3.520 ± 0.001	3.493 ± 0.004	4.248 ± 0.015 (4.826 ± 0.006)	3.352 ± 0.005	3.143 ± 0.020
7 TeV	3.985 ± 0.001	3.748 ± 0.001	3.631 ± 0.001	3.599 ± 0.002	4.283 ± 0.011 (4.925 ± 0.005)	3.468 ± 0.005	3.267 ± 0.017
13 TeV	4.291 ± 0.002	4.075 ± 0.002	4.007 ± 0.002	3.981 ± 0.005	4.489 ± 0.011 (5.085 ± 0.006)	3.864 ± 0.009	3.762 ± 0.037

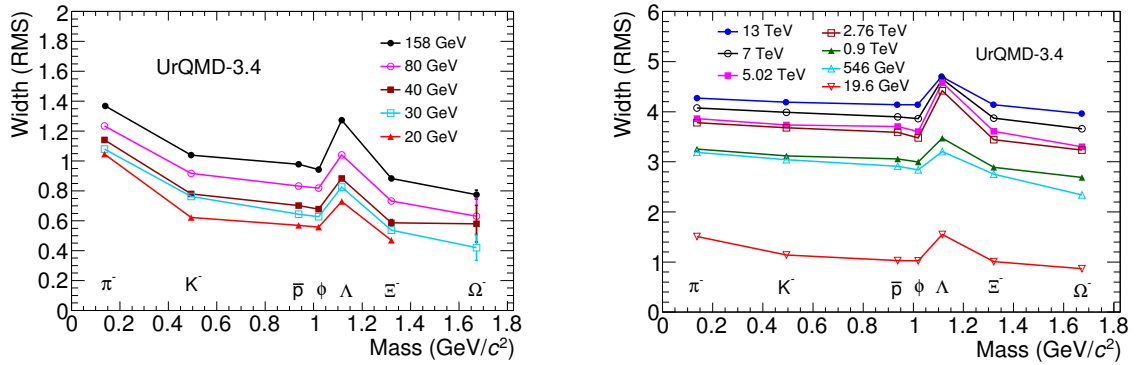


Fig. 4.14 Widths of the rapidity distributions of various produced particles as a function of their rest masses in pp collisions at all the SPS energies (left panel), lower RHIC, and all the LHC energies (right panel) using UrQMD-3.4-generated events. The different markers with different colors correspond to various beam energies. The solid lines with different colors are to guide the eyes only.

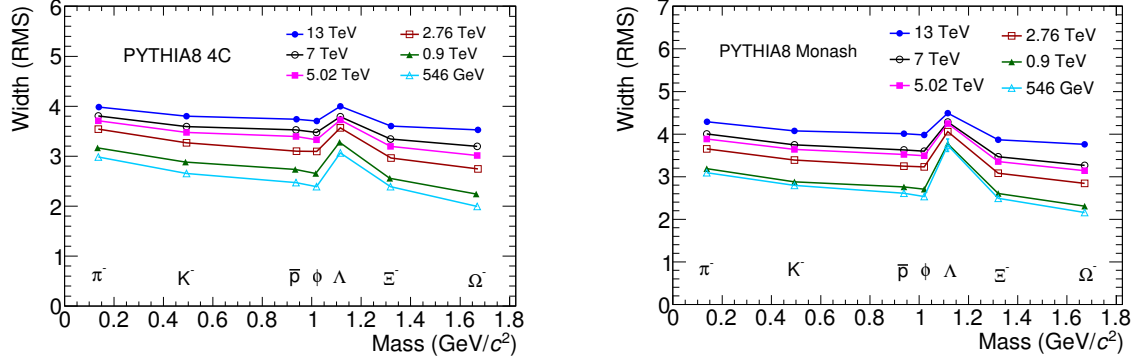


Fig. 4.15 Widths of the rapidity distributions of various produced particles as a function of their rest masses in pp collisions from $\sqrt{s} = 0.546$ to 13 TeV using PYTHIA8 4C (left panel) and PYTHIA8 Monash (right panel) generated inelastic events. The different markers with different colors correspond to various beam energies. The solid lines with different colors are to guide the eyes only.

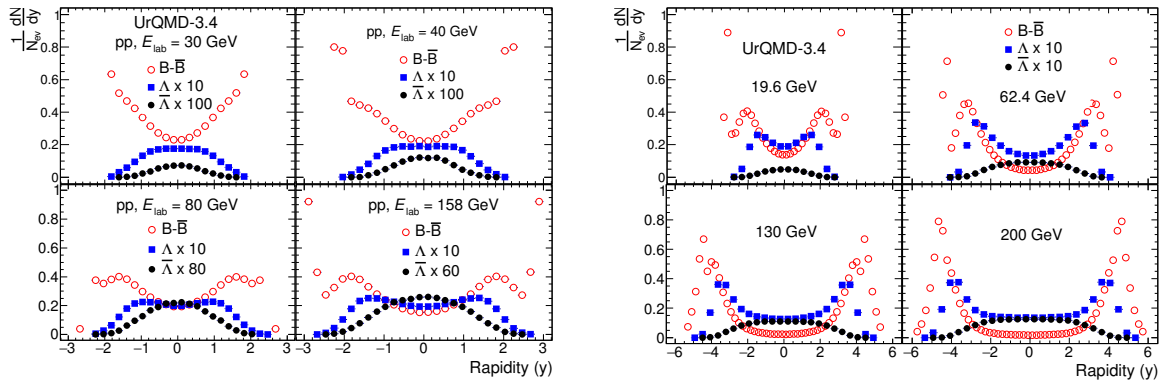


Fig. 4.16 Distributions of $B - \bar{B}$, Λ , and $\bar{\Lambda}$ over the entire rapidity space using UrQMD-3.4-generated events in pp collisions at various SPS (left panel) and RHIC (right panel) energies. The open circular, filled square, and filled circular symbols represent the rapidity distributions of $B - \bar{B}$, Λ , and $\bar{\Lambda}$ respectively.

Further, with the increase of the collisions energies, the minimum net baryon density region extends over more rapidity space around midrapidity. At SPS and RHIC energies, $B - \bar{B} > 0$ at all rapidity space and thus the rapidity distribution of Λ follows the net baryon density distribution pattern resulting a jump in the rapidity width vs. mass plot. At LHC energies, $B - \bar{B} = 0$ over a wide rapidity range and the rapidity distributions of both Λ and $\bar{\Lambda}$ follow the same Gaussian pattern over the rapidity space for which $B - \bar{B} = 0$. Thus in pp collisions at LHC energies, the rapidity distributions of Λ become independent of net baryon density distribution pattern and resemble exactly that of $\bar{\Lambda}$ over the rapidity space for which $B - \bar{B} = 0$. Thus, in a scenario where net baryon density is zero, the widths of rapidity distributions of Λ and $\bar{\Lambda}$ become equal or in other words, the rapidity width of Λ does not exhibit any non-trivial (non-kinematic) contribution for a situation for which $B - \bar{B} = 0$.

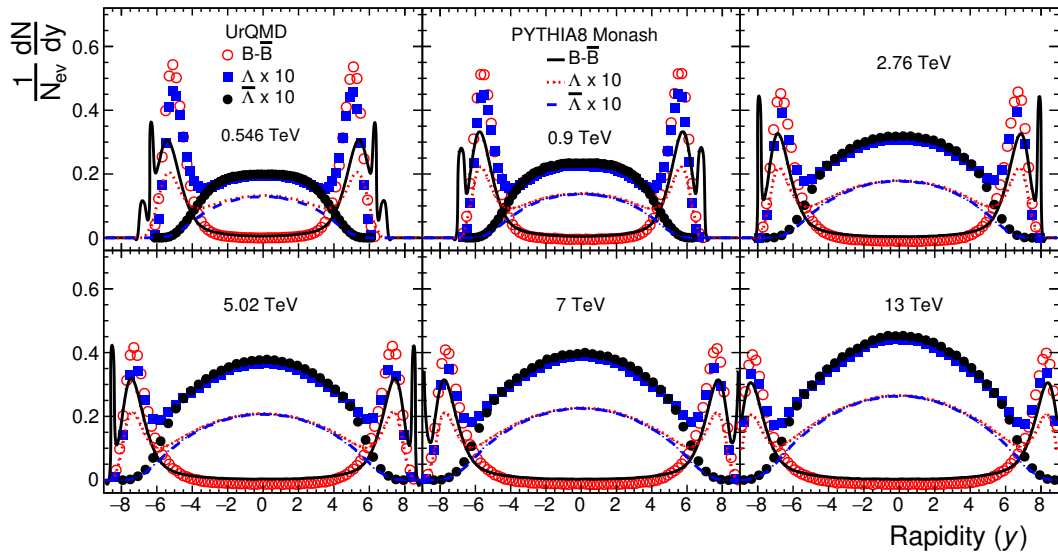


Fig. 4.17 Distributions of $B - \bar{B}$, Λ and $\bar{\Lambda}$ over the entire rapidity space using UrQMD-3.4 and PYTHIA8-generated events in pp collisions at various energies of UA5 and ALICE collaborations. The open circular, filled square, and filled circular symbols represent the UrQMD-3.4-generated rapidity distributions of $B - \bar{B}$, Λ , and $\bar{\Lambda}$ respectively. The black solid, red dotted, and blue dashed lines represent PYTHIA8 Monash-generated rapidity distributions of $B - \bar{B}$, Λ , and $\bar{\Lambda}$ respectively.

To have a cross-check on the above observation, another 80 million pp inelastic events were generated at the highest LHC energies ($\sqrt{s} = 13$ TeV) using PYTHIA8 Monash tuned event generator. The rapidity distribution of Λ , $\bar{\Lambda}$ and net baryon density, and the variation of the widths of the rapidity distribution of various hadrons as a function of the rest masses have plotted in Figs. 4.18 and 4.19 respectively.

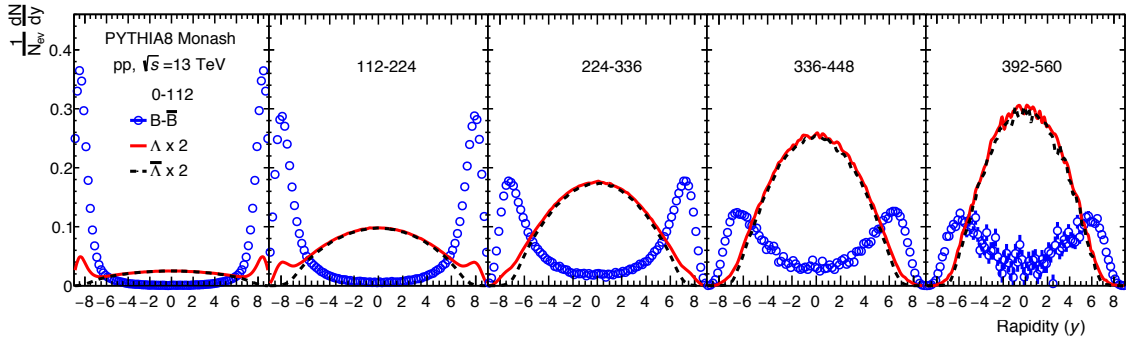


Fig. 4.18 Rapidity distributions of $B - \bar{B}$, Λ and $\bar{\Lambda}$ in pp collisions at $\sqrt{s} = 13$ TeV for different multiplicity classes using PYTHIA8 Monash-generated inelastic events. The open blue circular, red dashed and black dotted markers represent the rapidity distributions of $B - \bar{B}$, Λ and $\bar{\Lambda}$ respectively.

It is evident from Fig. 4.18 that the net baryon density, which arises due to the difference in produced hadrons and their anti-particles created out of spectators' partons, i.e., beam remnants, is more in the extreme rapidity regions for low multiplicity classes. A non-zero value of $B - \bar{B}$ at extreme rapidity for low multiplicity pp collisions suggests the presence of more quarks than antiquarks in the extreme rapidity regions favouring the production of more baryons than antibaryons. Thus, at LHC energies, the beam protons, which are considered to be extended balls of partons are composed of more quarks than antiquarks favouring baryon asymmetry at extreme rapidity regions. The hadron (particularly Λ) production in such low multiplicity pp events, has a substantial contribution from the partons of the spectators [93], which may be the main reason of the increase in the width of the rapidity distribution of Λ as shown in Fig. 4.19. Further, it is clearly seen from Fig. 4.19 that the width of the rapidity distributions of all the studied hadrons decreases

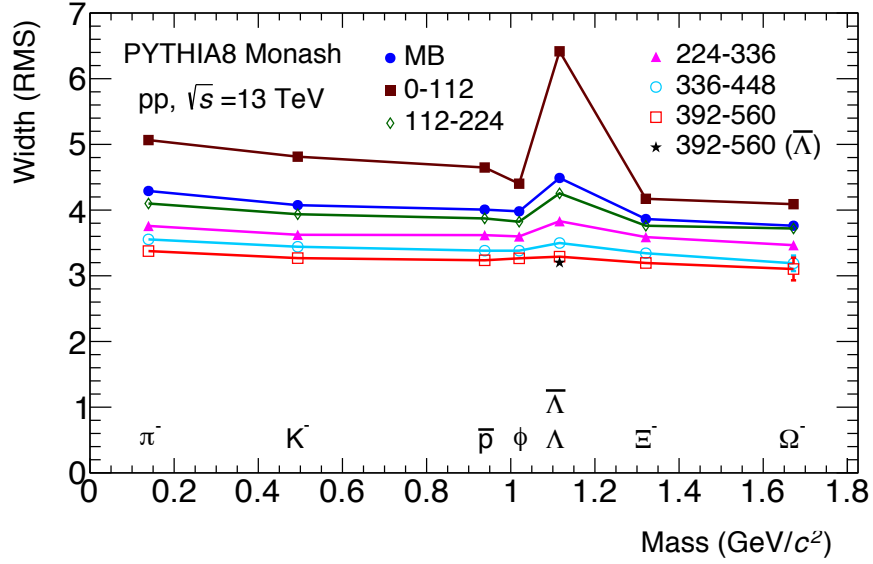


Fig. 4.19 Width of the rapidity distributions as a function of their rest masses for various multiplicity classes in pp collisions at $\sqrt{s} = 13$ TeV with PYTHIA8 Monash-generated inelastic events. Different marker symbols represent the widths of the rapidity distributions of various hadrons for different multiplicity classes. The star marker symbol represents the rapidity width of $\bar{\Lambda}$ for the multiplicity class of 392–560.

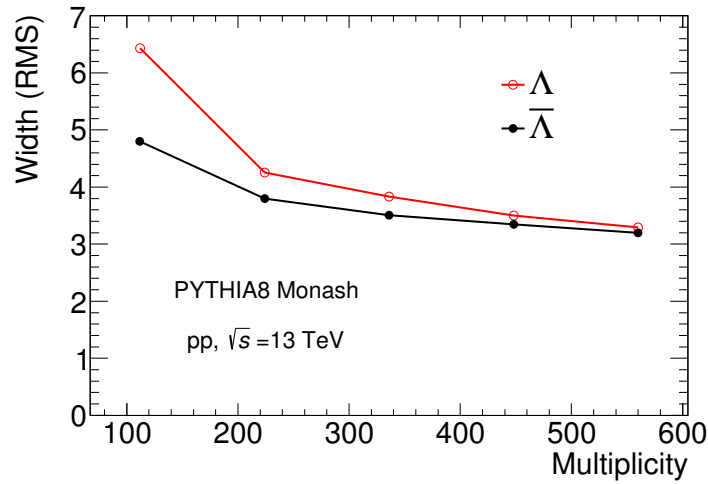


Fig. 4.20 Widths of the rapidity distributions of Λ and $\bar{\Lambda}$ as a function of charged particle multiplicity in pp collisions at $\sqrt{s} = 13$ TeV using PYTHIA8 Monash-generated inelastic events. The open and solid markers represent the widths of Λ and $\bar{\Lambda}$ respectively.

with increasing multiplicity or otherwise centrality and for the highest multiplicity class when there is no beam remnants, the jump in the rapidity width of Λ almost disappears. Therefore, for the most central collisions, in absence of spectator, the production of Λ s becomes independent of the nature of the net baryon density distribution and hence, the width of the rapidity distribution of Λ becomes the same as that of $\bar{\Lambda}$ (Fig. 4.20). *Such observation reveals that in high multiplicity p-p collisions, where the spectator part is either absent or negligible, the Λ s might be pair produced.*

4.7 Summary

From the study on the width of the rapidity distribution of identified particles such as π^- , K^- , ϕ , Λ , Ξ^- , and Ω^- in Pb-Pb collisions at all the SPS energies using UrQMD-3.4-model-generated data and experimental data, it is readily seen that an increase in the width of the rapidity distribution of Λ does exist at all the SPS energies from 20 to 158A GeV.

UrQMD-3.4-model-generated data, with weak decays stopped, could be seen to describe well the experimental pseudorapidity spectra both at RHIC and LHC energies. *With generated data, the jump in the rapidity width of Λ could be seen at all the RHIC and LHC energies as well, thereby indicating its universal nature from the AGS and SPS to RHIC and highest LHC energies.* To check if the rapidity distribution of Λ (and $\bar{\Lambda}$) is still dependent on the net baryon density distribution even at RHIC and LHC energies, the distributions of $B - \bar{B}$, Λ , and $\bar{\Lambda}$ over the rapidity space at these energies are plotted in Figs. 4.21 and 4.22 respectively using UrQMD-3.4-generated events. It could be readily seen from these figures that just like at AGS and SPS energies [44], the rapidity distribution of Λ (uds), but not $\bar{\Lambda}$ ($\bar{u}\bar{d}\bar{s}$), takes the shape of net baryon density distribution even at RHIC and LHC energies. It is known that in heavy ion collision, a strange hadron like Λ is produced either through associated strangeness production in NN collisions of incom-

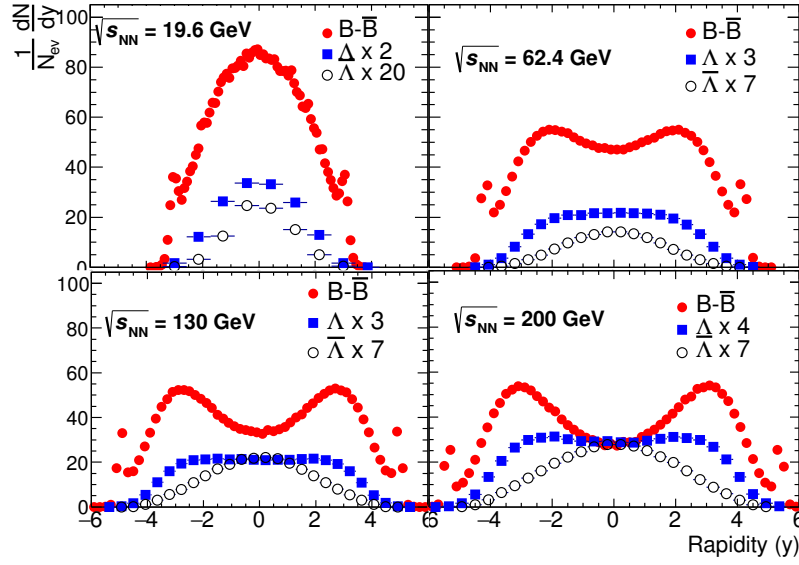


Fig. 4.21 Distributions of $B - \bar{B}$, Λ , and $\bar{\Lambda}$ over the rapidity space at RHIC energies using UrQMD-3.4-generated events. The filled circular symbols denote the $B - \bar{B}$ rapidity distributions, whereas the filled squares and open circular symbols respectively represent the rapidity distributions of Λ and $\bar{\Lambda}$.

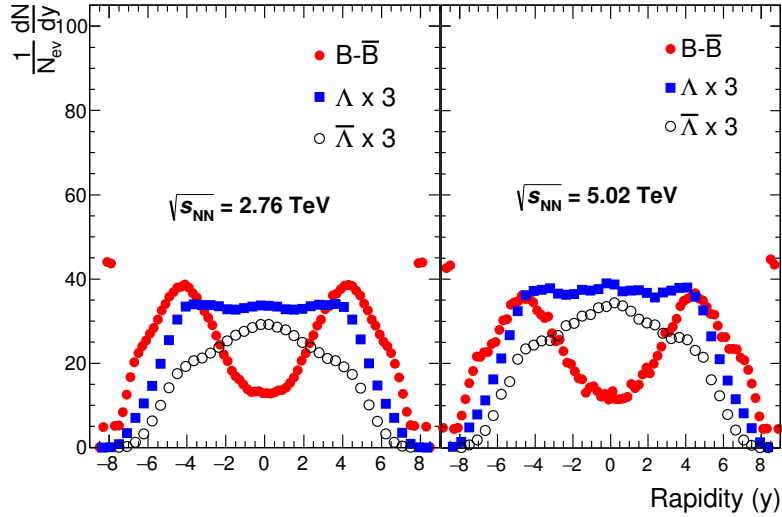


Fig. 4.22 Distributions of $B - \bar{B}$, Λ , and $\bar{\Lambda}$ over the rapidity space at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV using UrQMD-3.4-generated events. The filled circular symbols denote the $B - \bar{B}$ rapidity distributions, whereas the filled squares and open circular symbols respectively represent the rapidity distributions of Λ and $\bar{\Lambda}$.

ing and produced hadrons or through pair production [230, 231]. While the associated strangeness production is dominant at relatively lower incident beam energies, the pair production mechanism is supposed to be dominant at higher incident beam energies. With the increase of transparency of collision, the net baryon number tends to populate the extreme rapidity regions, thereby increasing the population of baryons (like Λ) over antibaryons (like $\bar{\Lambda}$) at higher rapidity regions, which in turn increases the width of the rapidity distribution of particles [containing leading quark(s)] over antiparticles [containing produced quark(s) only]. *Thus, such dependence of rapidity width of Λ at RHIC and LHC energies, as seen from Figs. 4.21 and 4.22, suggests that pair production may not be the only mechanism of particle production in heavy ion collisions even at the highest LHC energy.* However, with MC data, over the entire studied energy range, no sign of violation of separate mass ordering of the width of rapidity distribution of mesons and baryons, as proposed in Ref. [43] could be seen for the studied hadrons.

Further, UrQMD-3.4 and PYTHIA8-generated pseudorapidity distributions of all primary charged particles of pp collisions are compared with the existing experimental results of UA5 and ALICE collaborations which show good agreement between model generated and experimental results for the studied energies. An increase in the rapidity width of Λ , as observed in heavy-ion data, could be seen with the generated data of pp collisions as well at all the SPS energies. *When the study is extended to RHIC and LHC energies, a similar increase in the rapidity width of Λ could be observed for the consideration of full rapidity space indicating that the increase in the rapidity width of Λ is a general characteristic of both pp and A–A collisions from SPS to RHIC and LHC energies.* For pp collisions at various RHIC and LHC energies, even though $B - \bar{B} = 0$ at the midrapidity, a small non-zero $B - \bar{B}$ at higher rapidity regions is responsible for the observed jump in the rapidity width of Λ . A plot of widths of the rapidity distributions of Λ and $\bar{\Lambda}$ as a function of rapidity window (Fig. 4.23), shows that at the rapidity windows for which

$B - \bar{B} = 0$, the widths of rapidity distributions of Λ and $\bar{\Lambda}$ become same. Also, widths of the rapidity distributions of Λ and $\bar{\Lambda}$ become the same for high multiplicity pp events over the entire rapidity regions (Fig 4.20), where the system has the maximum probability of multiple parton interactions. *Such observations suggest that at LHC energies at and around mid-rapidity as well as for high multiplicity pp events over the entire rapidity region, Λ and $\bar{\Lambda}$ are mostly pair produced.*

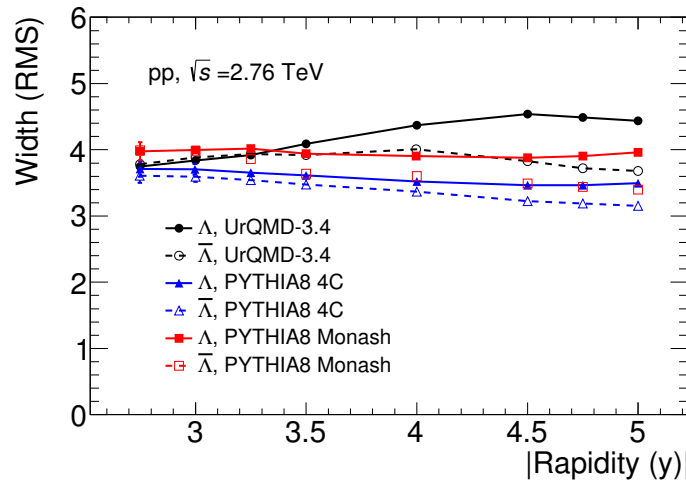


Fig. 4.23 Widths of the rapidity distributions as a function of rapidity window of Λ and $\bar{\Lambda}$ using UrQMD-3.4-generated events in pp collisions at $\sqrt{s} = 2.76$ TeV. The solid circle, triangle, and square symbols with different colors represent the widths of the rapidity distributions of Λ for UrQMD-3.4, PYTHIA8 4C, and PYTHIA8 Monash respectively, whereas the corresponding open marker symbols represent the widths of the rapidity distributions of $\bar{\Lambda}$.

5 | Summary and outlook

5.1 Summary

For the first time, *kink topology* has been applied to ALICE Pb–Pb data to identify charged kaons over a wide momentum range. A *kink* is detected when a charged particle decays to a charged daughter and an invisible neutral daughter particle. While the neutral daughter particle could not be detected by the detector, identification of the mother charged particles are being carried out by reconstructing the charged daughter particle using various topological selection cuts. For such reconstruction, the kink-algorithm is applied within the fiducial volume of the TPC detector ($130 < R < 200$ cm), to ensure that an adequate number of clusters is found to reconstruct the tracks of both the mother and the daughter with the necessary precision so as to identify the parent particle without any ambiguity. For the selection of tracks of the stable primary particle, the number of TPC clusters is generally taken as 70 to 80. But in this decay topology technique, the minimum number of TPC cluster is taken as 30, because the tracks of the decaying kaons are shorter compared to the tracks of stable primaries. Assuming the neutrino to be massless, the invariant mass of the decaying particle is estimated from the track of the charged decay product and the momentum of the neutrino. The main contribution to background of this analysis arises from charged pion decays, $\pi \rightarrow \mu + \nu_\mu$ (BR = 99.99%), which also gives rise to a kink topology.

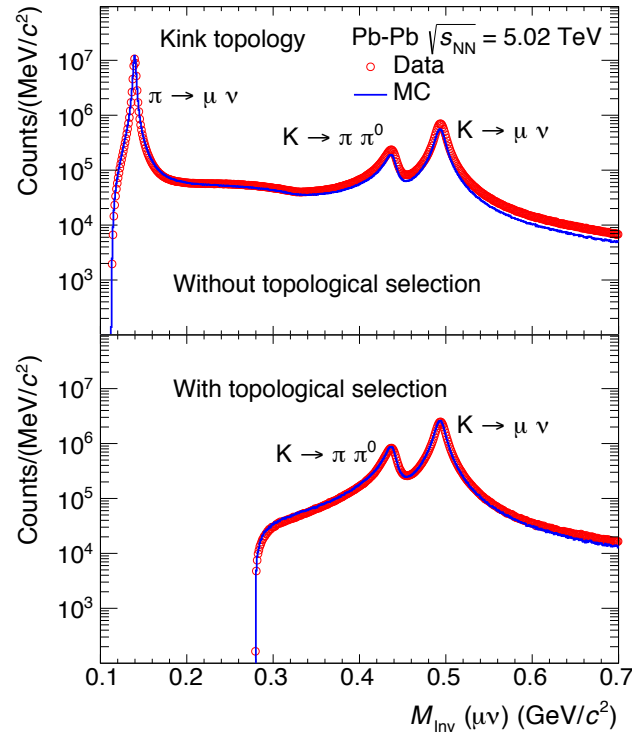


Fig. 5.1 Invariant mass distribution of identified charged kaons from their decay products in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The red circles and blue lines represent the experimental data and Monte Carlo simulation respectively. The upper panel represents the invariant mass distribution without the topological selection cuts whereas the lower panel plot is with the topological selection cuts. The peak centered at $M_{\mu\nu} = 0.49 \pm 0.028$ GeV/c^2 is for the decay channel $K \rightarrow \mu + \nu_\mu$ (BR = 63.55%), whereas the peak centered at $M_{\mu\nu} = 0.43 \pm 0.017$ GeV/c^2 is for the decay channel $K \rightarrow \pi + \pi^0$ (BR = 20.66%), the invariant mass of which is calculated with the pseudo mass hypothesis.

A proper q_T selection, where q_T is the transverse momentum of the daughter track with respect to the mother's direction at the kink, can separate most of the pion kink background from the kaon kinks. Since the upper limit of q_T values for the decay channels $\pi \rightarrow \mu + \nu_\mu$ and $K \rightarrow \mu + \nu_\mu$ are 30 MeV/ c and 236 MeV/ c respectively, a selection of $q_T > 120$ MeV/ c rejects the pion background more than 80% in central Pb–Pb collisions (85% in pp collisions). For further removal of the contamination from pion decays, an additional selection on kink opening angle has been implemented. Finally, the TPC dE/dx of the mother tracks is required to have $|n\sigma^K| < 3$, which improves the purity of the sample. After these selections, the purity ranges from 99% at low p_T to 92% in Pb–Pb collisions (96% in pp collisions) at high p_T . The remaining very low background is supposed to come from random association of charged tracks reconstructed as fake kinks. After applying all these topological selection criteria, the invariant mass of kaons ($M_{\mu\nu}$) obtained from the reconstruction of their decay products integrated over the momentum is shown in Fig. 5.1. *Such measurement suggests that the kink topology can also be successfully applied to identify charged kaons with good purity in Pb–Pb collisions at the highest available LHC energy.*

Systematic uncertainties in kink analysis arise due to bias on the part of the various selection cuts. The stability of the chosen sets of selection cut values was investigated by tightening and loosening the different cuts. Similar cut variations have also been applied to the anchored Monte Carlo data sets to be taken into account the effects from the various correction factors. The main contributions to the systematic uncertainties are the number of TPC cluster, kink vertex radius, daughter transverse momentum, TPC dE/dx selection cut, track selection cuts, and the background of the analysis. All the systematic uncertainties are added in quadrature. The summary of the total systematic uncertainties has been shown in Table 5.1.

Table 5.1 Main sources of systematic uncertainties expressed in % for three centrality classes. The contribution from the track selection is found to be almost centrality independent and therefore the value for the minimum bias has been put for the same.

Effects	Uncertainties in %
Kink PID + reconstruction efficiency (0 – 5%)	1.0 – 10.4
Kink PID + reconstruction efficiency (30 – 40%)	0.5 – 4.5
Kink PID + reconstruction efficiency (80 – 90%)	0.7 – 5.5
Track selection	3.0
Contamination (0 – 5%)	0.6 – 0.5
Contamination (30 – 40%)	0.6 – 0.5
Contamination (80 – 90%)	0.6 – 0.4

In order to derive concrete physics messages as discussed in Chapter 3, the transverse momentum spectra of charged pions, kaons, and protons identified with various PID techniques using ITS, TPC, TOF, and HMPID detectors were combined all together to get the full transverse momentum spectra, both for minimum bias pp and for different centrality classes Pb–Pb collisions. While the shape of the p_T spectra of minimum bias pp and peripheral Pb–Pb collisions were found to be similar, a clear mass-dependent flattening of the transverse momentum spectra has been observed when viewed from peripheral to central Pb–Pb collisions. This flattening was found to be more prominent in case of the heavier mass particle (proton), which is indicative of the existence of strong radial flow.

The entire p_T spectrum is categorized into three parts: (i) low p_T ($0 < p_T < 2.0$ GeV/c), (ii) intermediate p_T ($2.0 < p_T < 10.0$ GeV/c) and (iii) high p_T ($p_T > 10.0$ GeV/c).

The low p_T spectra have been fitted with Boltzmann-Gibbs blast-wave function to extract the kinetic freeze-out temperature and the average transverse expansion (radial flow) velocity. *The $\langle \beta_T \rangle$ values were found to increase from peripheral to the central Pb–Pb collisions (Fig. 5.2), which indicates that the system expands more rapidly with increasing centrality.* On the other hand, the T_{kin} values were found to decrease from peripheral to the central collisions. *In peripheral collisions this is consistent with the*

expectation of a shorter lived fireball with stronger radial pressure gradient [171]. Further, a small increase (2%) of $\langle \beta_T \rangle$ at $\sqrt{s_{NN}} = 5.02$ TeV in the most central collisions has been observed with respect to the results measured at $\sqrt{s_{NN}} = 2.76$ TeV.

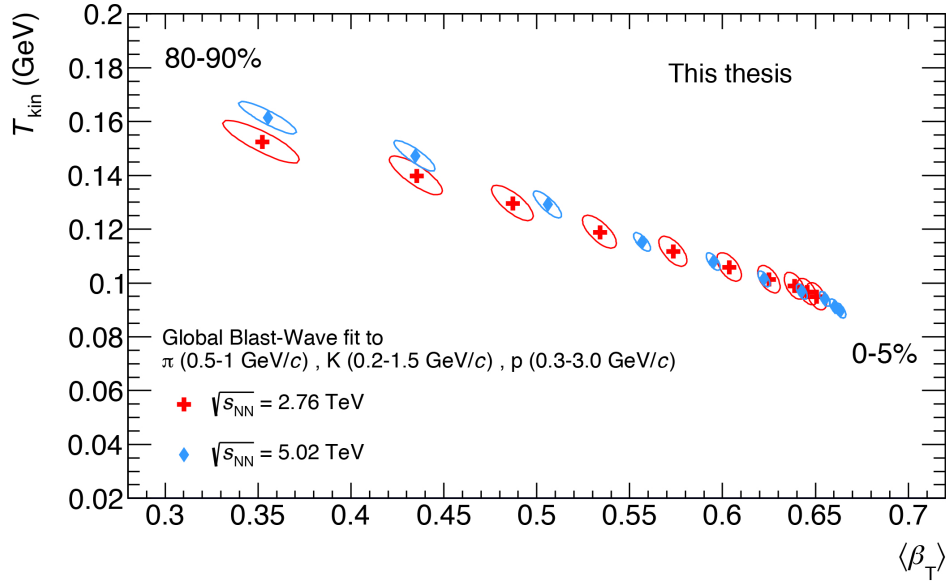


Fig. 5.2 Distribution of kinetic freeze-out temperature and average expansion velocity obtained from Blast-wave fitting to measure π , K and p in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and compared with $\sqrt{s_{NN}} = 2.76$ TeV.

The average transverse momentum spectra of identified particles as a function of average charged particle multiplicity density were found to increase from low multiplicity to high multiplicity events. The $\langle p_T \rangle$ values were found to exhibit a steeper rising trend for protons than pions and kaons, *which is again indicative of the presence of strong radial flow*.

In the intermediate p_T region, the present investigation has been conducted on two main observables, namely, p_T -dependent K/π and p/π ratios. A clear increase in the K/π ratio (Fig. 5.3 top panel) with respect to the minimum bias pp collision has been observed for the most central Pb–Pb collisions in the intermediate momentum region, which is a consequence of strong radial flow effect. On the other hand, for peripheral Pb–Pb collisions, the jump of K/π ratio in the intermediate p_T region disappeared and

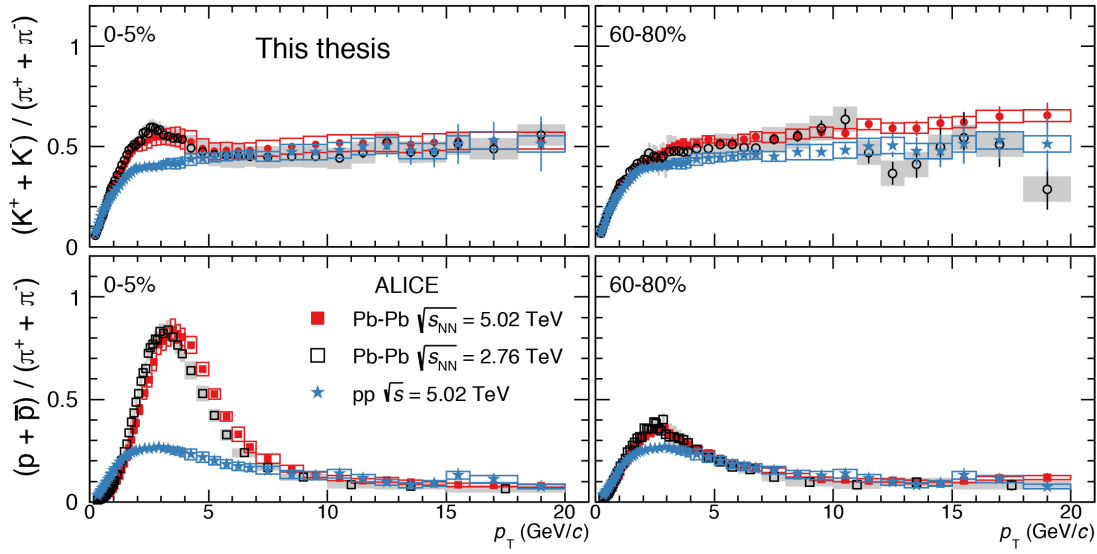


Fig. 5.3 Centrality dependence of the K/π (top) and p/π (bottom) ratios as a function of transverse momentum, measured in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and compared with the existing results at $\sqrt{s_{NN}} = 2.76$ TeV [9].

became same (within systematic uncertainties) with the results measured in minimum bias pp collisions. Such observation is attributed to the fact that in the most peripheral collisions, the interaction zone of the created system is very small and becomes similar to the system created from pp collisions. *Thus, in case of peripheral Pb–Pb collisions, the energy deposition is very small as compared to central collisions and becomes similar to pp collisions, and thereby, contains almost vanishing radial flow effect.* On the other hand, for the most central Pb–Pb collisions, the p/π ratios with respect to minimum bias pp collisions were found to be more prominent than K/π ratios as shown in the lower panel of Fig. 5.3, indicating again the mass-dependent radial flow effect. *Further, the position of the p_T peak shifts slightly towards the high p_T with the increase of energy, in particular for the proton-to-pion ratio, indicating that the initial hotter system is longer lived so that radial flow is stronger.* At high p_T , both particle ratios at $\sqrt{s_{NN}} = 5.02$ TeV were found to be similar to those measured at $\sqrt{s_{NN}} = 2.76$ TeV and in pp collisions, suggesting that vacuum-like fragmentation processes dominate particle production mechanism.

The measurement of high momentum particles is of quite significance as such particles are produced in the early stages of the collisions through hard processes that involve high momentum transfer and are expected to carry the full information of the entire space-time evolution of the fireball. During the evolution, the early stage partons undergo rescattering and lose energy in the very hot and dense medium, which is quantified by the nuclear modification factor R_{AA} . In the low momentum region, particle mass-dependent R_{AA} has been observed, where particles with higher mass are found to be less suppressed. This mass-dependent hierarchy of R_{AA} is again attributed to the presence of strong radial flow. On the other hand, for $p_T > 10$ GeV/c, the nuclear modification factor has found to be same for all the particle species (Fig. 5.4). Such suppression at the high p_T region signifies the presence of strong nuclear matter effects, where the evolving partons equally suffer radiative energy loss in the dense medium. Going from central to the peripheral collisions, the suppression of the nuclear modification factor has found to decrease systematically, *which could be due to the fact that the energy loss in the medium depends on the traversed path length of the partons*. Therefore, the total energy loss is larger in the most central

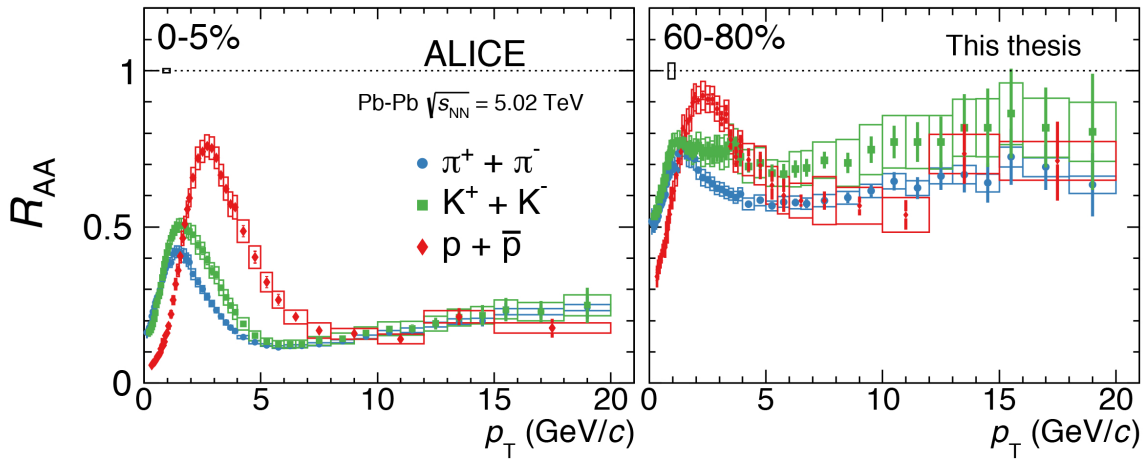


Fig. 5.4 Centrality dependence of the nuclear modification factor of charged $\pi^\pm$, $K^\pm$ and $(\bar{p})p$ as a function of transverse momentum, measured in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

collision than the peripheral one. *Another possibility is that for the most central collisions,*

the resulting medium is expected to be hotter and denser than the peripheral one and hence experiences more energy loss. The nuclear modification factor at $\sqrt{s_{NN}} = 5.02$ TeV has found to be same with the results measured at $\sqrt{s_{NN}} = 2.76$ TeV. This observation gives a hint that the medium created at both the LHC energies may behave in a similar way where the evolving partons equally suffer strong nuclear matter effect.

Among the other global observables of heavy-ion collisions, the (pseudo)rapidity distribution of the produced particles is considered to be an important tool to study the particle production mechanism and their interaction during the space-time evolution of the fireball. Due to limited acceptance of the ALICE detectors, no such studies with ALICE data over the full (pseudo)rapidity space could be conducted and therefore rapidity dependent studies with model generated events is of quite significance. The UrQMD-3.4-generated pseudorapidity distributions of all primary charged particles were found to describe well the experimental results of the pseudorapidity distributions of RHIC and ALICE collaborations. From the study of the widths of the rapidity distributions of

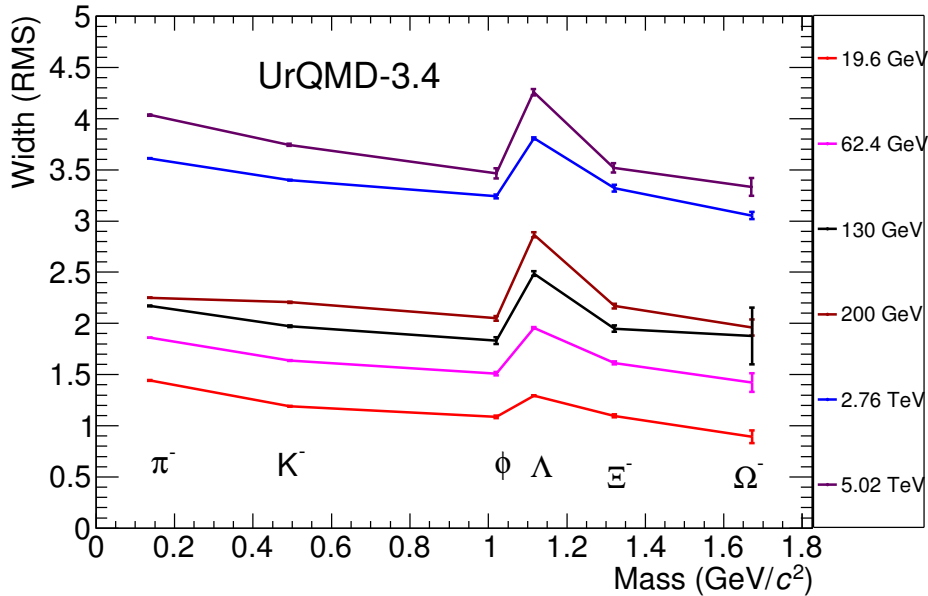


Fig. 5.5 Widths of the rapidity distributions of various hadrons with UrQMD-3.4-generated data at all the RHIC and LHC energies.

identified particles, such as π^- , K^- , ϕ , Λ , Ξ^- , and Ω^- in Pb–Pb collisions with UrQMD-3.4-model-generated data and available experimental results, it has been observed that an increase in the width of the rapidity distribution of Λ does exist at all the SPS energies. *When the study has been extended to RHIC and LHC energies with MC generated data, the jump in the width of the rapidity distribution of Λ is found to still exists (Fig. 5.5), thereby, indicating its universal nature from AGS and SPS to RHIC and highest LHC energies.* With the increase of collision energy, the net baryon density is found to populate the extreme rapidities, thereby producing a significant number of Λ at the extreme rapidity regions, thus, increasing the width of the rapidity distribution of Λ . *Such observation of the role of net baryon density distribution on rapidity width of Λ , suggests that in heavy-ion collisions at even the highest available LHC energy, pair production may not be the only mechanism of particle production.*

For small system like pp collisions, the UrQMD-3.4 and PYTHIA8 (Monash) generated pseudorapidity distributions of all primary charged particles are found to describe well the experimental pseudorapidity distributions of UA5 and ALICE collaborations. An increase in the width of the rapidity distribution, as found in heavy-ion collision, has also been observed in pp collisions even at the highest LHC energy for consideration of full rapidity width (-7 to $+7$). *Such observation indicates that the increase of the width of the rapidity distribution of Λ is a general characteristic of both pp and A–A collisions from SPS to RHIC and LHC energies for situation for which $B - \bar{B} \neq 0$.* However, in pp collisions, the increase in the width of the rapidity distribution of Λ is found to vanish for the rapidity region for which the net baryon density distribution becomes zero ($B - \bar{B} = 0$).

The increase in the rapidity width of Λ in pp collisions is supposed to be due to the role played by the spectators' partons. A multiplicity dependent study on the width of the rapidity distribution of Λ in such collisions suggests that the increase in the rapidity width of Λ is more prominent for low multiplicity pp events. The net baryon density

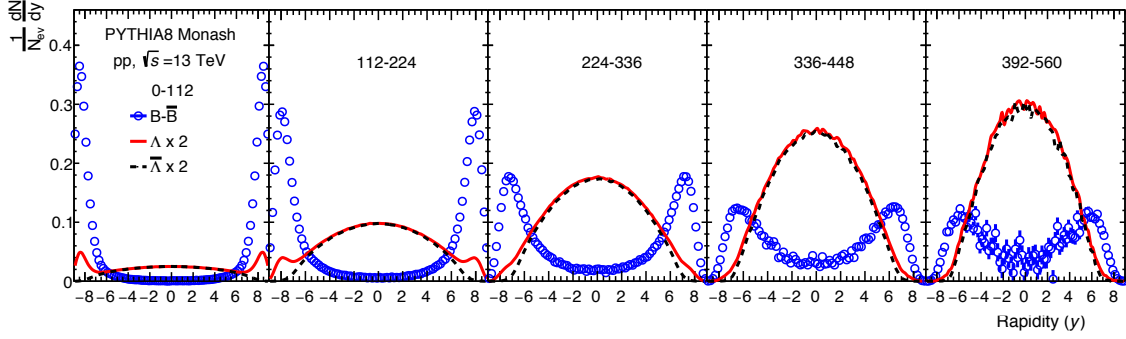


Fig. 5.6 Rapidity distributions of $B - \bar{B}$, Λ and $\bar{\Lambda}$ in pp collisions at $\sqrt{s} = 13$ TeV for different multiplicity classes with PYTHIA8 Monash-generated inelastic events. The open blue circular, red dashed and black dotted markers represent the rapidity distributions of $B - \bar{B}$, Λ and $\bar{\Lambda}$ respectively.

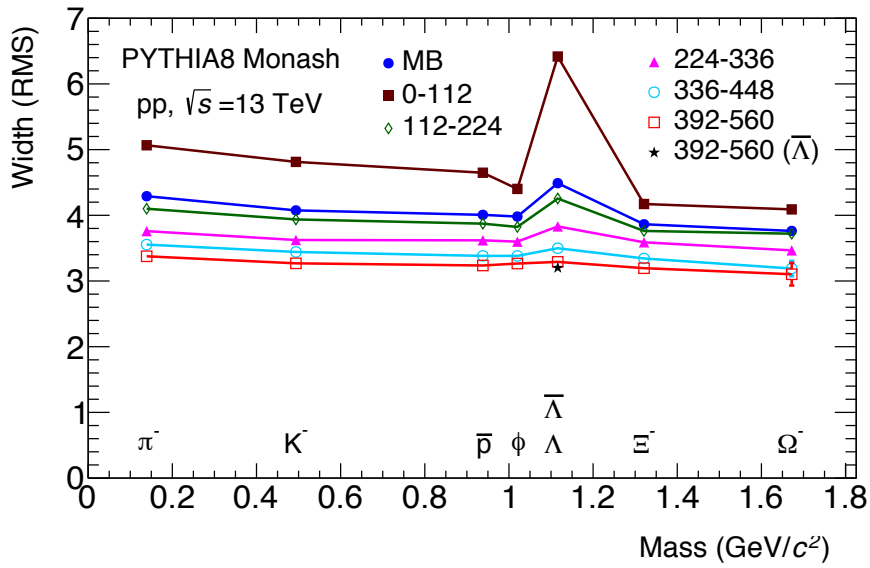


Fig. 5.7 Width of the rapidity distributions as a function of their rest masses for various multiplicity classes in pp collisions at $\sqrt{s} = 13$ TeV with PYTHIA8 Monash-generated inelastic events. Different marker symbols represent the widths of the rapidity distributions of various hadrons for different multiplicity classes. The star marker symbol represents the rapidity width of $\bar{\Lambda}$ for the multiplicity class of 392–560.

distributions were found to be maximum at the extreme rapidity regions for low multiplicity classes (Fig. 5.6), which is due to the difference in produced hadrons and their anti-particles created out of the beam remnant, i.e., spectators' partons. A non-zero value of $B - \bar{B}$ at extreme rapidity for low multiplicity pp collisions suggests the presence of more quarks than antiquarks in the extreme rapidity space favouring more baryons than antibaryons production. Thus, at LHC energies, the beam protons, which are considered to be extended balls of partons are composed of more quarks than antiquarks favouring baryon asymmetry at extreme rapidity regions. The hadrons, particularly Λ (and p) production has a substantial contribution from the partons of the spectators, thereby increasing its rapidity width. As shown in Fig. 5.7 the widths of the rapidity distributions of the studied hadrons were found to decrease with the increase of multiplicity and for the highest multiplicity class, the jump in the rapidity width of Λ disappears. *Therefore, for the highest multiplicity class, where the spectators' partons are either negligible or very small, the rapidity width of Λ becomes same with that of $\bar{\Lambda}$ (as shown in Figs. 5.7 and 5.8), which indicates that Λ s are mostly pair produced.*

5.2 Outlook

From the present study, it has been found that the identification of charged kaon using kink topology can be carried out successfully with good purity at LHC energies in Pb–Pb collisions as well. It is important to note that this technique can also be applied to identify charged pions over a wide momentum range. This could be done applying the topological selection on the mother-daughter tracks with smaller decay angle and daughter transverse momentum. Thus, identification of charged $\pi^\pm$ and $K^\pm$ mesons over a wide momentum range can be carried out using kink topology with sufficient statistics, with the upcoming

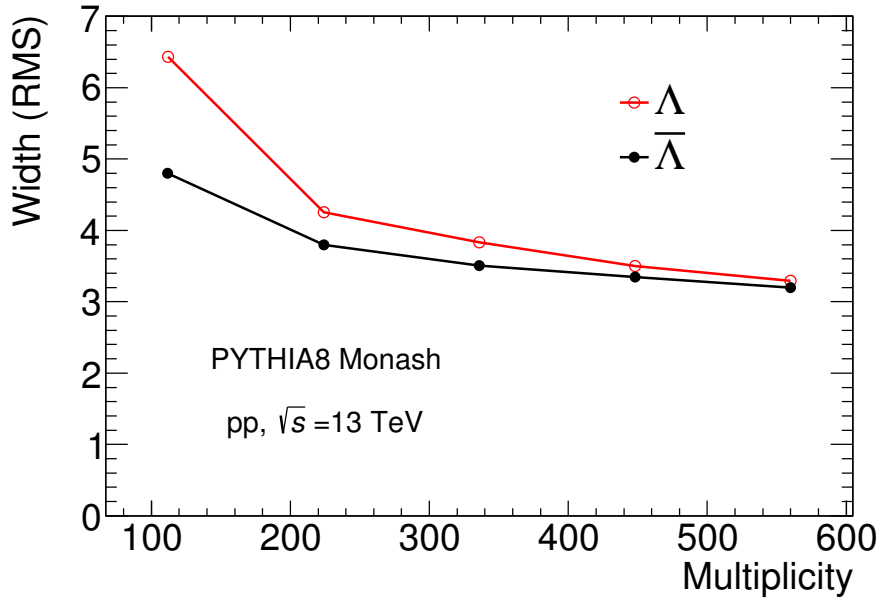


Fig. 5.8 Distributions of rapidity widths of Λ and $\bar{\Lambda}$ as a function of charged particle multiplicity in pp collisions at $\sqrt{s} = 13$ TeV using PYTHIA8 Monash-generated inelastic events. The open and solid markers represent the rapidity widths of Λ and $\bar{\Lambda}$ respectively.

ALICE data for Pb–Pb collisions. *The transverse momentum distribution of charged $\pi^\pm$ and $K^\pm$ mesons identified with kink topology over a wide momentum range, and hence, the study of p_T -dependent and p_T -integrated K/π ratios, as well as the study on the observable of nuclear modification factor of these mesons, would be possible at even higher energies and would provide important information about the space-time evolution of more hot and dense medium to be created in the collisions in the next run.*

The collective expansion of the matter created in heavy-ion collisions proved to be one of the important probes to study the detailed properties of the transient QGP state [237]. The collective expansion, also called *flow*, originates from the initial pressure gradients in the created fireball of hot and dense matter. These pressure gradients transform the initial inhomogeneities and spatial deformations of the created fireball into the momentum anisotropies of the final state particle production [238, 239]. These momentum anisotropies of the final state particles are characterized by so-called *flow harmonics*.

From the present study, it has been revealed that in heavy-ion collisions from SPS to the highest LHC energies, the net baryon density distribution plays an important role on the particle production, particularly on those hadrons that contain leading quarks. Particles like p , Λ , Ξ^- (but not their antiparticles like $\bar{p}$, $\bar{\Lambda}$, Ξ^+), etc. that contain leading quarks, due to their associate production, populates extreme rapidity space in heavy-ion collisions at ultra-relativistic energies. *Since p & $\bar{p}$ and Λ & $\bar{\Lambda}$ populate different phase-space due to difference in their production mechanism, it would be quite interesting to see if these pairs of particles, having relatively more number of leading quarks, i.e., p & $\bar{p}$ and Λ & $\bar{\Lambda}$, in spite of their same masses, exhibit different flow values due to difference in their spatial distributions.*

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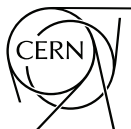
A | List of publications

Publications in referred journals

1. Production of charged pions, kaons and (anti)protons in Pb-Pb and inelastic pp collisions at $\sqrt{s_{NN}} = 5.02$ TeV.
- ALICE collaboration (Paper committee members: Giacomo Volpe, Yasser Corrales Morales, **Nur Hussain**, Nicolo Jacazio, Antonio Ortiz Velasquez, Ivan Ravasenga and Omar Vazquez Rueda), Phys. Rev. C **101**, 044907 (2020)
DOI: <https://doi.org/10.1103/PhysRevC.101.044907>, arXiv:1910.07678 [nucl-ex]
2. Role of net baryon density on rapidity width of identified particles from the lowest energies available at the CERN Super Proton Synchrotron to those at the BNL Relativistic Heavy Ion Collider and at the CERN Large Hadron Collider.
- **Nur Hussain** and Buddhadeb Bhattacharjee, Phys. Rev. C **96**, 024903 (2017).
DOI: <https://doi.org/10.1103/PhysRevC.96.024903>, arXiv:1709.02660 [nucl-th]
3. Disappearance of non-trivial net baryon density distribution effect on the rapidity width of identified particles of pp collisions.
- **Nur Hussain** and Buddhadeb Bhattacharjee. arXiv:1809.03161 [nucl-th]

Conference contributions

1. Enhancement in the rapidity width of Λ in pp and heavy-ion collisions at the LHC energies.
- **Nur Hussain** and Buddhadeb Bhattacharjee, DAE-BRNS Symposium on Nuclear Physics, December 23-27, 2019, Lucknow University, Lucknow, India.
Proceedings contribution No. E27 (2019), ISBN: 818372083-8
2. Identification of charged kaons using kink topology in pp and Pb-Pb collisions with ALICE at the LHC.
-**Nur Hussain** for ALICE Collaboration, Quark Matter, 2018, Venice, Italy
3. Transverse momentum spectra and nuclear modification factor of identified light flavour hadrons in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with ALICE at the LHC.
- **Nur Hussain** for the ALICE collaboration, Proceedings of the DAE Symp. on Nucl. Phys. 62 (2017). ISBN: 818372081-1
4. Prediction of rapidity dependent K/π ratio in Pb-Pb collisions at LHC energy using Monte Carlo event generator.
-**Nur Hussain** and Buddhadeb Bhattacharjee, Xth Binnial National Conference of Physics Academy of North East, November, 10-12, 2016, St. Anthony College, Meghalaya, Assam, India.



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Letter of reference/consent for Nur Hussain

Dear Sir or Madam,

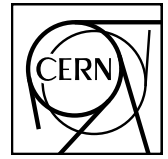
It is a pleasure to write a reference letter for Nur Hussain, who is a very reliable and efficient contributor to the activities of the ALICE Physics Working Group on Light Flavour Hadrons (PWG-LF). We are very satisfied with the work of Nur Hussain and with this letter, I certify that

1. Nur Hussain is associated with analysing pp and Pb-Pb data at $\sqrt{s} = 5.02$ TeV in the PWG-LF group of the ALICE collaboration and is one of the authors of the analysis note entitled “Productions of pions, kaons and protons in pp and Pb-Pb collisions at $\sqrt{s} = 5.02$ TeV”.
2. Nur Hussain is also one of the paper committee members of the proposed paper entitled “Production of charged pions, kaons, and (anti)protons in Pb-Pb and minimum bias pp collisions at $\sqrt{s} = 5.02$ TeV”.

The PWG-LF as such has no objection to allow him to include the results from the aforementioned contributions in his thesis within the conditions set out by the ALICE constitution. Results presented in figures must be labelled "this thesis" according to the ALICE constitution. Please do not hesitate to contact me in case of any questions.

With best regards

(Alexander Kalweit — Convener of ALICE PWG-LF)



ALICE-ANA-2016-xxx
August 29, 2019

2

3 **Production of pions, kaons and protons in pp and Pb-Pb**
4 **collisions at $\sqrt{s} = 5.02$ TeV**

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8 **Abstract**

9 In this document we describe the analysis details to measure the production of charged pions, kaons
10 and (anti)protons in pp and Pb-Pb collisions at $\sqrt{s} = 5.02$ TeV from hundreds of MeV/c up to 12
11 GeV/c.

Production of charged pions, kaons, and (anti-)protons in Pb-Pb and inelastic pp collisions at $\sqrt{s_{NN}} = 5.02$ TeV

S. Acharya *et al.**
(ALICE Collaboration)



(Received 14 November 2019; accepted 2 March 2020; published 29 April 2020)

Midrapidity production of $\pi^\pm$, $K^\pm$, and $(\bar{p})p$ measured by the ALICE experiment at the CERN Large Hadron Collider, in Pb-Pb and inelastic pp collisions at $\sqrt{s_{NN}} = 5.02$ TeV, is presented. The invariant yields are measured over a wide transverse momentum (p_T) range from hundreds of MeV/ c up to 20 GeV/ c . The results in Pb-Pb collisions are presented as a function of the collision centrality, in the range 0–90%. The comparison of the p_T -integrated particle ratios, i.e., proton-to-pion (p/π) and kaon-to-pion (K/π) ratios, with similar measurements in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV show no significant energy dependence. Blast-wave fits of the p_T spectra indicate that in the most central collisions radial flow is slightly larger at 5.02 TeV with respect to 2.76 TeV. Particle ratios (p/π , K/π) as a function of p_T show pronounced maxima at $p_T \approx 3$ GeV/ c in central Pb-Pb collisions. At high p_T , particle ratios at 5.02 TeV are similar to those measured in pp collisions at the same energy and in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Using the pp reference spectra measured at the same collision energy of 5.02 TeV, the nuclear modification factors for the different particle species are derived. Within uncertainties, the nuclear modification factor is particle species independent for high p_T and compatible with measurements at $\sqrt{s_{NN}} = 2.76$ TeV. The results are compared to state-of-the-art model calculations, which are found to describe the observed trends satisfactorily.

DOI: [10.1103/PhysRevC.101.044907](https://doi.org/10.1103/PhysRevC.101.044907)

I. INTRODUCTION

Previous observations at the Relativistic Heavy-Ion Collider (RHIC) and at the CERN Large Hadron Collider (LHC) demonstrated that in high-energy heavy-ion (A-A) collisions, a strongly interacting quark-gluon plasma (sQGP) [1–5] is formed. It behaves as a strongly coupled near-perfect liquid with a small viscosity-to-entropy ratio η/s [6]. The experimental results have led to the development and adoption of a standard theoretical framework for describing the bulk properties of the QGP in these collisions [7]. In this paradigm, the beam energy dependence is mainly encoded in the initial energy density (temperature) of the QGP. After formation, the QGP expands hydrodynamically as a near perfect liquid before it undergoes a chemical freeze-out. The chemical freeze-out temperature is nearly beam-energy independent for center-of-mass energy per nucleon pair larger than 10 GeV [7,8]. The hadronic system continues to interact (elastically) until kinetic freeze-out. We report in this paper a comprehensive study of bulk particle production at the highest beam energy for A-A collisions available at the LHC. We probe the highest

QGP temperature, to further study this paradigm and address its open questions.

Transverse momentum distributions of identified particles in Pb-Pb collisions provide information on the transverse expansion of the QGP and the freeze-out properties of the ensuing hadronic phase. By analyzing the p_T -integrated yields in Pb-Pb collisions it has been shown that hadron yields in high-energy nuclear interactions can be described assuming their production at thermal and chemical equilibrium [9–12], with a single chemical freeze-out temperature, $T_{ch} \approx 156$ MeV, close to the one predicted by lattice QCD calculations for the QGP-hadronic phase transition, $T_c = (154 \pm 9)$ MeV [13]. Indeed, the Pb-Pb data from LHC Run 1 [14] showed an excellent agreement with the statistical hadronization model with the exception of the proton and antiproton, $(\bar{K}^*)K^*$ and multi-strange particle yields [9,12]. The deviation could be in part due to interactions in the hadronic phase, which result in baryon-antibaryon annihilation that is most significant for (anti-)protons [15–18]. Proposed explanations for the observed discrepancy with respect to the thermal model predictions can be found in Refs. [18–22]. Moreover, at $\sqrt{s_{NN}} = 2.76$ TeV the proton-to-pion $[(p + \bar{p})/(\pi^+ + \pi^-) \equiv p/\pi]$ ratio exhibits a slight decrease with centrality and a slightly lower value than measured at RHIC. New measurements at $\sqrt{s_{NN}} = 5.02$ TeV, which exploit the currently highest medium density, could provide an improved understanding of the particle production mechanisms [22].

The spectral shapes at low p_T ($p_T < 2$ GeV/ c) in central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV showed a stronger radial

*Full author list given at the end of the article.

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Role of net baryon density on rapidity width of identified particles from the lowest energies available at the CERN Super Proton Synchrotron to those at the BNL Relativistic Heavy Ion Collider and at the CERN Large Hadron Collider

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Widths of the rapidity distributions of various identified hadrons generated with the UrQMD-3.4 event generator at all the Super Proton Synchrotron (SPS) energies have been presented and compared with the existing experimental results. An increase in the width of the rapidity distribution of Λ could be seen with both Monte Carlo (MC) and experimental data for the studied energies. Using MC data, the study has been extended to Relativistic Heavy Ion Collider (RHIC) and Large Hadron Collider (LHC) energies. A similar jump, as observed in the plot of rapidity width versus rest mass at Alternating Gradient Synchrotron (AGS) and all SPS energies, persists even at RHIC and LHC energies, confirming its universal nature from AGS to the highest LHC energies. Such observation indicates that pair production may not be the only mechanism of particle production at the highest LHC energies. However, with MC data, the separate mass scaling for mesons and baryons is found to exist even at the top LHC energy.

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I. INTRODUCTION

Widths of the rapidity distributions of particles are considered to be a measure of their final-state rescattering and are found to follow a mass ordering [1,2]. In addition to the final-state rescattering, the rapidity width is also sensitive to a number of other parameters such as longitudinal dynamics, the velocity of sound, etc [3,4]. Recently, in Ref. [5], it has been shown that the width of the rapidity distribution of a particle, in addition to its mass dependence, also depends on the nature of its quark content. In that report, from a study on ultrarelativistic quantum molecular dynamics (UrQMD)-generated Au+Au data at 10, 20, 30, and 40A GeV and its comparison with NA49 experimental results, it has been shown that the width of the rapidity distribution of a particle like Λ (uds), containing leading quarks, exhibits an additional dependence on net baryon density distribution, whereas particles not containing leading quarks, such as $\bar{\Lambda}$ ($\bar{u}\bar{d}\bar{s}$), do not exhibit any such dependence on net baryon density distribution. In rapidity space, the Λ distribution is shown to reflect the pattern of net baryon density distribution, whereas $\bar{\Lambda}$ does not. Since the net baryon density distribution depends on the transparency of collision, evolution of rapidity width of identified particles with energies from the lowest Super Proton Synchrotron (SPS) energy to the highest Relativistic Heavy Ion Collider (RHIC) and Large Hadron collider (LHC) energies is expected to provide some important information about the role of net baryon density distribution on rapidity width at different energy densities and temperatures and as such on the particle production mechanism itself. In this paper, an attempt has therefore been made to trace this signature of net baryon density distribution on rapidity width over the entire SPS energies such as 20, 30, 40, 80, and 158A GeV with UrQMD-

3.4-generated and available experimental data and to extend the study with Monte Carlo (MC) data to RHIC and LHC energies. The ultimate motivation of the present investigation is to check if this dependence of rapidity width on net baryon density distribution is a general characteristic of the rapidity distribution of the produced particles of heavy ion collisions.

II. RESULTS

The ultrarelativistic quantum molecular dynamics (UrQMD) event generator is a many-body microscopic Monte Carlo model for generating events of pp , p -A, and A-A collisions at relativistic and ultrarelativistic energies. The recent versions of UrQMD models include PYTHIA to incorporate hard perturbative QCD effects [6,7]. The UrQMD model is based on mesonic and baryonic degrees of freedom associated with constituent quarks, diquarks, and covariant propagation of color strings [8]. It also includes the excitation and fragmentation of color strings, formation and decay of hadronic resonances, and rescattering of particles. UrQMD could be applied successfully via fragmentation of strings and hard scattering to explore heavy ion reactions from AGS to SPS energies ($E_{\text{lab}} = 20$ to 158A GeV) and the full RHIC energies ($\sqrt{s_{NN}} = 19.6$ to 200 GeV) [9,10]. In Ref. [8], from a comparison on UrQMD calculations with experimental results of $p + \bar{p}$, Pb + Pb, and Au + Au collisions from 17.3 GeV at the SPS to 1.8 TeV at Fermilab, it has been shown that UrQMD has a valid basis for further extrapolation in energy to make predictions at LHC energies. Therefore, to start with, events were generated using the latest version, UrQMD-3.4, for Pb-Pb collisions at all the beam energies of SPS at $E_{\text{lab}} = 20, 30, 40, 80$, and 158A GeV. The event statistics of generated data for minimum biased events is shown in the Table I.

Rapidity distributions of π^- , K^- , ϕ , and Λ with generated data of central Pb-Pb collisions at all the SPS energies from $E_{\text{lab}} = 20$ to 158A GeV are shown in Fig. 1 and compared

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Disappearance of non-trivial net baryon density distribution effect on the rapidity width of identified particles in pp collisions at Large Hadron Collider energies

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Abstract. Pseudorapidity distributions of all primary charged particles using UrQMD-3.4- and PYTHIA8-generated events for pp collisions at various Relativistic Heavy Ion Collider (RHIC) and Large Hadron Collider (LHC) energies are presented and compared with the existing results of UA5 and ALICE collaborations. With UrQMD and PYTHIA data, rapidity widths of different mesons and baryons of pp collisions at various Super Proton Synchrotron (SPS), RHIC, and LHC energies are estimated and their variations with the rest mass of the studied hadrons are presented. An increase in the width of the rapidity distributions of Λ , similar to heavy ion data, could be seen from SPS to the highest LHC energies when the entire rapidity space is considered. However, at LHC energies, in the rapidity space where $B - \bar{B} = 0$, the shape of the rapidity distribution of Λ takes the same Gaussian shape as that of $\bar{\Lambda}$ and the widths of both the distributions become same suggesting pair production as the only possible mode of Λ production.

Keywords: UrQMD, PYTHIA, Rapidity width, LHC, Net-baryon density