



**ϕ (1020) MESON PRODUCTION IN p-Pb COLLISIONS WITH ALICE
DETECTOR AT THE LHC**

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*Dedicated To My
Family
&
Friends*

October 2022

DECLARATION

I declare that the thesis entitled " ϕ (1020) meson production in p-Pb collisions with ALICE detector at the LHC" has been prepared by me under the guidance of Dr. Lokesh Kumar, Department of Physics, Panjab University, Chandigarh. No part of this thesis has formed the basis for the award of any degree or fellowship previously.

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CERTIFICATE

I clarify that Sandeep Dudi has prepared his thesis entitled " **$\phi(1020)$ meson production in p-Pb collisions with ALICE detector at the LHC** " for the award of PhD degree of the Panjab University, Chandigarh under my guidance. He has carried out the work at Department of Physics, Panjab University, Chandigarh.

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Abstract

Quantum Chromodynamics (QCD) describes quarks and gluons interactions. Due to asymptotic freedom, a sufficiently high energy density can lead matter to transition into the Quark-Gluon Plasma (QGP), a deconfined form of matter. In heavy-ion collisions, a medium governed by strong interactions is formed, and its evolution can be studied by the produced particles. The primary objective of the heavy-ion programme at the Large Hadron Collider (LHC) at CERN in Geneva, Switzerland, is to search for the possible formation of the QGP. The ALICE experiment at the LHC is designed to study the hot and dense medium produced in ultrarelativistic heavy-ion collisions.

Hadronic resonances have shorter lifetimes relative to other stable hadrons, which is analogous to the time taken by the dense nuclear matter to reach its final state. This can be used to explore the hadronic phase's characteristics that results from heavy-ion collisions. The yield of resonances might be modified with respect to the expectations due to in-medium effects such as re-scattering and regeneration. The study of resonance production in p-Pb collisions fills the gap between pp and heavy-ion (Pb-Pb, Xe-Xe) collisions and helps us understand initial state effects due to cold nuclear matter. In this thesis, we study the ϕ (1020) mesons production using invariant mass reconstruction from their decay daughters (kaons) in p-Pb collisions. The kaon particles are identified by the Time Projection Chamber (TPC) and Time of Flight (TOF) in the ALICE experiment. The details of ALICE detector and its subsystems are described in this thesis.

We present the measurement of ϕ mesons production in p-Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV using the ALICE detector. Resonances are reconstructed via their hadronic decay channels in the rapidity interval $-0.5 < y < 0$ and the transverse momentum spectra are measured up to $p_T = 16$ GeV/ c for various multiplicity classes (0-5%, 5-10%, 10-20%, 20-40%, 40-60%, 60-80%, 80-100% and 0-100%). The x_T scaling for the ϕ mesons production is newly tested in p-Pb collisions and found to hold in the high p_T region at LHC energies. The nuclear modification factors (R_{pPb}) as a

function of p_T for ϕ mesons at $\sqrt{s_{NN}} = 8.16$ TeV are presented and compared with R_{pPb} measurements of K^{*0} , ϕ , Ξ , and Ω at $\sqrt{s_{NN}} = 5.02$ TeV. At intermediate p_T (2-8 GeV/c), R_{pPb} of Ξ , Ω show a Cronin-like enhancement, while K^{*0} and ϕ show no or little nuclear modification. At high p_T (> 8 GeV/c), the R_{pPb} values of all hadrons are consistent with unity within uncertainties. The R_{pPb} of ϕ mesons at $\sqrt{s_{NN}} = 8.16$ and 5.02 TeV show no significant energy dependence. The results are compared with EPOS-LHC, DPMJET and HIJING models predictions.

We also present the first measurement of multiplicity and rapidity dependence of ϕ mesons production in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The transverse-momentum (p_T) spectra of ϕ mesons measured with the ALICE detector up to $p_T = 16$ GeV/c for various multiplicity classes in five rapidity intervals ($-1.2 < y < -0.9$, $-0.9 < y < -0.6$, $-0.6 < y < -0.3$, $-0.3 < y < 0$ and $0 < y < 0.3$) in the rapidity range $1.2 < y < 0.3$. The measured p_T distributions show a dependence on both multiplicity and rapidity at low p_T , whereas no significant dependence is observed at high p_T . A rapidity dependence is observed in the p_T -integrated yield (dN/dy), whereas the mean transverse momentum ($\langle p_T \rangle$) shows a flat behavior as a function of rapidity. The rapidity asymmetry (Y_{asym}) at low p_T (< 5 GeV/c) is more significant for higher multiplicity classes. At high p_T , no significant rapidity asymmetry is observed in any of the multiplicity classes. The nuclear modification factor (Q_{CP}) as a function of p_T shows a Cronin-like enhancement at intermediate p_T , which is more prominent at higher rapidities (Pb-going direction) and in higher multiplicity classes. At high p_T (> 5 GeV/c), the (Q_{CP}) values are greater than unity and no significant rapidity dependence is observed. The results are compared with EPOS-LHC, DPMJET, Pythia8, EPOS3 and HIJING models predictions.

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Chapter 1

Introduction

In High Energy Physics (HEP), researchers explore what the universe consists of and how it works at the tiniest and the largest scales, seeking to make new discoveries from the smallest particles to the furthest reaches of space. The study of elementary particle physics is concerned with the fundamental constituents of all the matter. This science is relevant to the life on the earth as well as life at very edge of the universe and it is believed to be valid always and will remain so in the future as well. In the first moments after the Big Bang, particle physics laws governed the properties of this highly dense and hot soup of matter called the Quark Gluon Plasma (QGP), which evolved into the enormous variety of particles that we know today. Despite decades of work by thousands of physicists, many of the fundamental laws are still not understood. Over the time, massive particle accelerators have been built to recreate the state of matter at ever decreasing time scales after the Big Bang. Experimental studies of high energy heavy-ion collisions are designed to examine the fundamental properties of matter and radiation. The constituents of matter are molecules which are composed of atoms. The atoms are made up of nucleus and electrons revolving around it. It was later discovered that protons [1] and neutrons [2] are constituents of the nucleus, explaining many of the nuclear properties. Experimental studies of electron scattering from protons, often called ‘Deep Inelastic Scattering (DIS)’, revealed the composite nature of proton and revealed

the presence of partons, which were later determined to be fractionally charged Quarks [3,4]. Quarks are not seen as free particles, but rather confined within hadrons by the interquark potential. Research at the DESY (Deutsches Elektronen-Synchrotron) laboratory in Germany led to the discovery of the Gluon [5] in e^+e^- annihilation for the first time in 1979. According to current understanding, all matter is a combination of quarks, gluons and leptons, which are fundamental particles. The Standard Model (SM) of particle physics is an established theoretical framework that describes the theory of fundamental interactions - ElectroMagnetic (EM), weak and strong. These interactions are described in terms of exchange of Bosons - Photons, W and Z Bosons, and Gluons. Some of these Bosons - including W, Z, and Gluons - were predicted in the SM, and their presence is now confirmed experimentally. A key prediction of the Standard Model has been confirmed with the discovery of the Higgs boson [6-8]. All the particles gain mass through their coupling with Higgs boson. Experiments have confirmed the validity of the SM in high precision. There are many different quantum numbers associated with each of the particles in the SM, including spins, charges, charms, baryon and lepton numbers etc. The quarks and the leptons both have spin of $1/2$ and are thus fermions; however, they differ from one another in various other properties. The lepton family has three charge particles (electron, muon and tau) and three neutral particle (electron neutrino, muon neutrino and tau neutrino). The six quarks are following: up, down, charm, strange, top and bottom. The up, charm and top quarks have electrical charge $\frac{2}{3}e$, while down, strange and bottom quarks are charged by $-\frac{1}{3}e$. There is also a particular property of quarks known as color charges: each quark carries one of three colors: red, green, or blue. A corresponding anti-particle exists for every particle, that has the exact same mass but all the quantum numbers are inverted. In terms of color, it is described as ‘anti-red’, ‘anti-green’ and ‘anti-blue’. In addition, the model has four spin 1 bosons, including gluons, photons, $W^\pm$ and Z with eight states of gluons and two states of W bosons, as well as the spin 0 Higgs boson. The SM describes the way elementary particles interact via boson exchange. According to the SM, the three different kinds of interactions: strong,

electromagnetic and weak are all characterized by their strengths and mediators, such as gluons, photons and W and Z bosons, respectively. Figure 1.1 illustrates the schematic representation of particles in the SM [9].

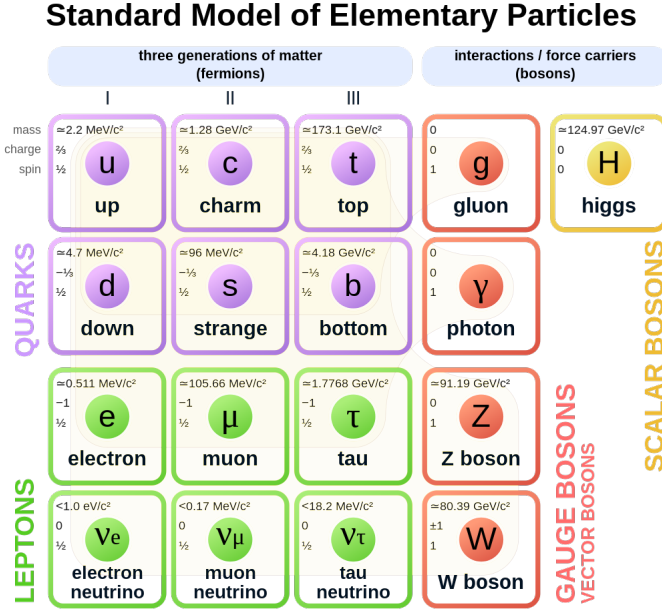


Figure 1.1: An overview of all fundamental particles in the Standard Model. The three families of quarks and leptons are listed by their respective columns. A shaded background indicates with what fermions each gauge boson pairs [9].

The theoretical framework used to describe these interactions is Gauge Invariance, also known as Gauge Theories. Amongst the three interactions mentioned above, the theoretical framework that describes the strong interactions, is also a gauge theory and is known as Quantum Chromodynamics (QCD).

1.1 Quantum Chromodynamic (QCD) and quark-gluon plasma

According to the QCD, quarks interact with gluons and distinguishable by their color quantum numbers. Mesons and baryons are composed of quarks and gluons and are colorless. Each baryon consists of three quarks (qqq), whereas mesons are

made up of a pair of quarks and antiquarks ($q\bar{q}$). According to QCD, the potential for interaction is as follows:

$$V_{QCD}(r) = -\frac{4}{c} \frac{\alpha_s}{r} + kr \quad (1.1)$$

where, ' α_s ' represents running coupling constant, 'r' is the distance between two interacting partons (quarks and gluons) and k is color string tension Constant. The QCD coupling constant [10] that depends on momentum transfer Q^2 between partons is described as:

$$\alpha_s(Q^2) = \frac{12\pi}{(11N_c - 2N_f) \ln(Q^2/\lambda_{QCD}^2)}. \quad (1.2)$$

where,

N_C = Number of color charges,

N_f = Number of quark flavors,

λ_{QCD} = Non-perturbative QCD scale parameter

For small value of α_s , the perturbative QCD is applicable. The α_s as a function of Q is shown in Fig. 1.2. Two fundamental properties of QCD are ensured by equation 1.2: quark confinement and asymptotic freedom. The α_s between quarks and gluons becomes large at small Q or large λ_{QCD} , according to eq. 1.2. So, at small α_s quarks and gluons are confined inside hadrons, known as Quark Confinement [11]. However, QCD coupling constant become small at large momentum transfers or small distance scales, creating a free state of quarks and gluons. In QCD, this property is known as 'Asymptotic Freedom'. QCD coupling constant as function of momentum transfer shows good agreement between experiment results and QCD based theoretical calculations as shown in Fig. 1.2. The 2004 Nobel prize in physics was awarded to David Gross [12,13], Frank Wilczek [12,13], and David Politzer [14] for their theoretical contributions toward the discovery of asymptotic freedom.

In 1974, T.D. Lee [15] proposed that a high nucleon density applied over a large volume could result in dense nuclear matter containing asymptotically free

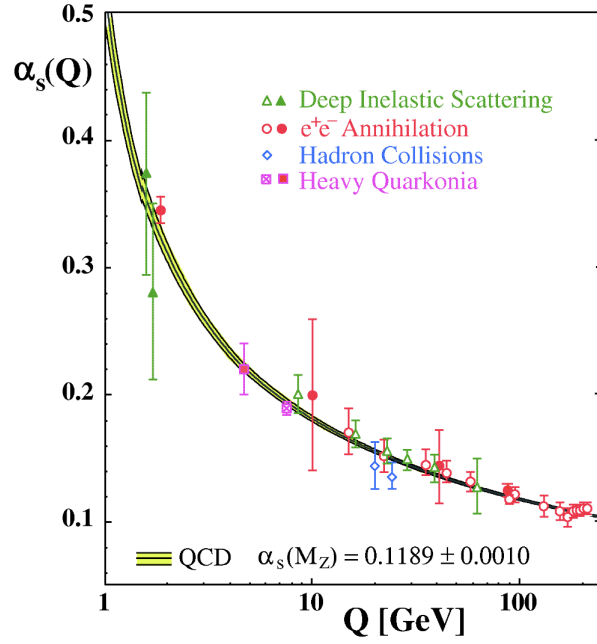


Figure 1.2: The QCD running coupling constant measurement from various experiments are compared in wide range of momentum transfer. This plot has been taken from [10].

quarks and gluons. Such a dense nuclear state is known as the ‘Quark-Gluon Plasma’ (QGP). Experimentally QGP is defined as, ‘a (locally) thermally equilibrated state of matter in which quarks and gluons are de-confined from hadrons, so that color degrees of freedom become manifest over nuclear, rather than merely nucleonic volume’ [16]. The QGP state at high temperature is also predicted by QCD (Lattice-QCD) calculations [17–20]. In Fig. 1.3, normalized energy density is plotted as function of temperature, based on LQCD calculations of quarks flavors. The significant increase in normalised energy density at critical point indicates the increase in the number of degree of freedom, suggesting hadronic matter converting to a state of free quarks and gluons.

The different phases of QCD matter can be mapped using a phase diagram (like that of water) that shows at what value of temperature (T) and the baryon chemical potential (μ_B), a transition occurs from a normal hadron phase into a deconfined QGP phase. The various phases of QCD matter are shown in Fig. 1.4. At low T and low μ_B quarks and gluons are confined into hadrons, whereas at high

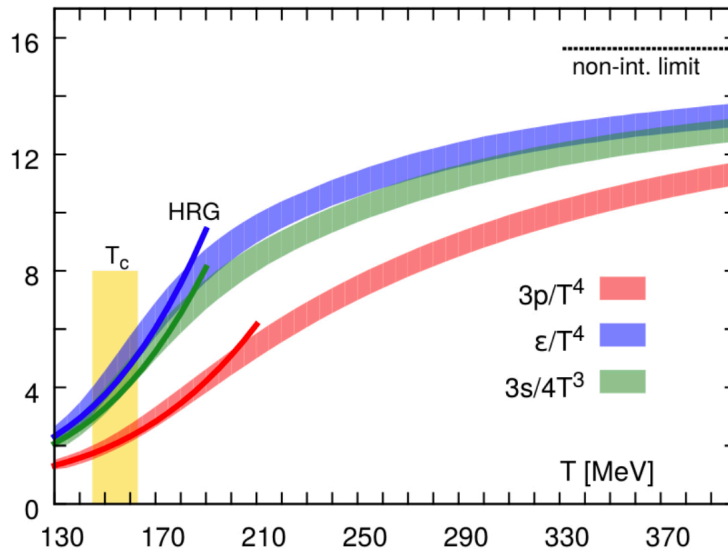


Figure 1.3: The normalized energy density (normalized to quadratic power of temperature) (blue color), pressure density (red color) and entropy from LQCD calculation at zero baryon chemical potential density (green color) are plotted as a function of temperature. T_c (yellow color) represents the critical temperature. Results are for (2+1) quark flavor. Hadron Resonance Gas (HRG) model calculations are shown by solid lines at low temperature. Result for non-interacting quark gluon gas is shown by dashed line at high temperature. This plot has been taken from [21].

At high T and low μ_B the quarks and gluons may exist in deconfined state. A smooth phase transition from hadronic gas to QGP phase is predicted by LQCD calculations at high T and low μ_B while at high μ_B , the phase transition is predicted by several models to be a first-order phase transition [22]. The energy scope of the ALICE experiment corresponds to $\mu_B = 0$ and is appropriate for the study of QGP and phase transition from hadrons to QGP.

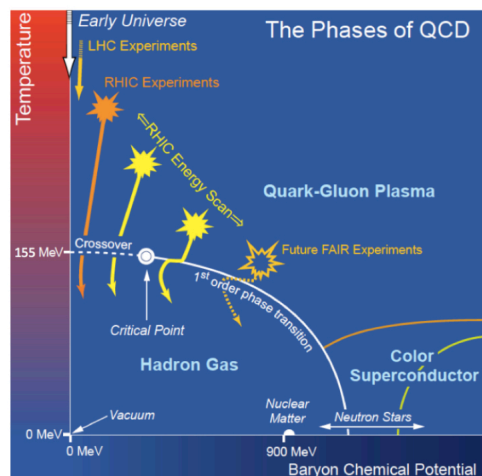


Figure 1.4: A schematic illustration of the QCD phase diagram [23].

1.2 Space-Time Evolution

In the early universe, just after the Big Bang, the QGP is believed to have existed. Now the various experiment are creating the QGP by colliding relativistic heavy-ions. The hot and dense matter created in these experiments evolve through various stages. The space-time evolution of heavy-ion collisions is shown in Fig. 1.5. Two Lorentz contracted nuclei (due to relativistic speed) are collided at $t = 0$, time of collision. During the collision, the overlapping region between the incoming nuclei is compressed, ejecting the enormous amount of kinetic energy that is carried by the incoming nuclei within a very small volume of space in a very short time frame. The formation of deconfined states of quarks and gluons after collision is expected if the energy density is sufficiently high. In the early stages of deconfinement, the

state produced might not be in thermal equilibrium. It may take the matter about 1 fm/c to reach a state of local thermal equilibrium, known as the QGP, after the pre-equilibrium state. By assuming plasma behaves like a fluid, we are able to describe the state's evolution. As a consequence of the pressure gradient, the QGP matter expands and it cools down. A hadron gas is formed when quarks and gluons hadronize at $T = T_c$, the 'critical temperature'. As the hadron gas expands, the inelastic interactions between hadrons cease at $T = T_{ch}$ to be known as 'chemical freeze-out temperature'. Following T_{ch} , the chemical composition of the system isn't affected; there is no change in the relative abundance of particles. As the temperature drops below T_{ch} , elastic interactions between hadrons continue until the freeze out temperature ' T_{fo} '. The mean free path of hadrons reaches a large value near the T_{fo} compared to the dynamical size of the system. Thereafter, hadrons are free to flow. The particles that emerge from the collision region are measured in the experiment, and their measurements provide indirect evidence of the QGP. However, it is possible that these signatures may already be distorted by the interactions occurring during and after the freeze-out. Therefore, it is not feasible to directly measure the QGP phase during a high-energy physics experiment. Instead, a series of signatures provides the evidence.

1.3 Relativistic kinematics in high energy particle physics

At the LHC (Large Hadron Collider), the coordinate system for ALICE experiment is chosen such that the z-direction is parallel to the beam direction. From the origin, positive z is directed to the V0A detector, whereas negative z is directed to the V0C, details in section [2.1.3.3](#). The origin (0,0,0) in the co-ordinate system is defined as the Nominal Interaction Point where the two beams will collide at the center of Inner Tracking System (ITS) detector. Collisions typically occur around the point of interaction, and the primary vertex of the collision can be determined using the

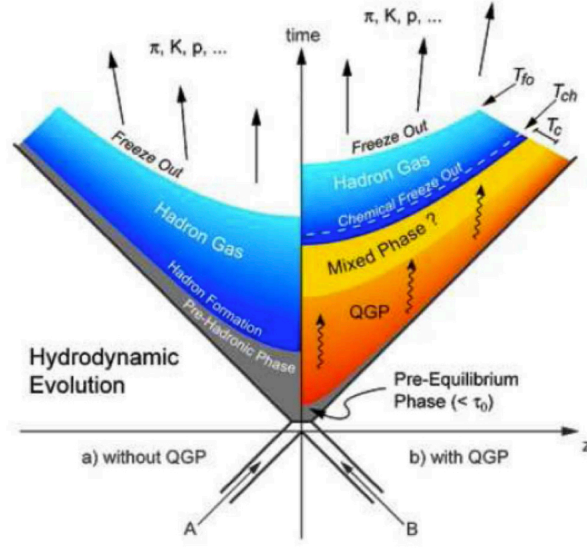


Figure 1.5: A schematic diagram representing the space-time evolution in heavy-ion collisions [24].

tracking information from the data. The primary vertex is required for most analysis that uses reconstructed tracks.

1.3.1 Transverse Momentum

The particle momentum can be divided into two parts. One along the beam direction is called longitudinal momentum (p_z) and another is the transverse momentum (p_T), which is the momentum projected in the transverse plane (xy). The p_T of a particle is defined as :

$$p_T = p_x^2 + p_y^2 \quad (1.3)$$

Where, p_x = momentum component along the x-axis,
 p_y = momentum component along the y-axis
The p_T is a Lorentz invariant quantity.

1.3.2 Rapidity

In high energy particle physics, rapidity (y) of a particle is a measure of its relativistic velocity. Velocity does not have an additive nature in the relativistic limit. Rapidity has the advantage of being additive under Lorentz transformation. The rapidity is defined as:

$$y = \frac{1}{2} \ln \frac{E + p_z}{E - p_z} \quad (1.4)$$

where, E is particle energy and p_z is the longitudinal momentum. In the non-relativistic limit, the rapidity is equivalent to the particle's velocity where the momentum (p) has a value comparable to or smaller than its mass (m_0).

Rapidity variable preserves the shape of the rapidity distribution under longitudinal Lorentz boost. If we go from center-of-mass frame (CMS) to lab frame (LS), then rapidity remains the same, but y -scale is shifted by y_{cm} . In p-Pb collisions the rapidity is shifted by -0.465 as we change the reference frame from LS to CMS, details in section [3.1](#).

1.3.3 Pseudorapidity

Pseudorapidity is defined for the situations, where it is difficult to identify the particles i.e., mass and momentum of the particle is not available. It is expressed both in terms of momentum and θ (polar angle) as:

$$\eta = \frac{1}{2} \ln \frac{p + p_z}{p - p_z} = -\ln \left\{ \tan \left(\frac{\theta}{2} \right) \right\} \quad (1.5)$$

where, θ is the angle between the produced particle and the beam direction. It is also possible to express the pseudorapidity in terms of the transverse mass ($m_T = \sqrt{m_0^2 + p_T^2}$) and the rapidity [\[25\]](#) as:

$$\eta = \frac{1}{2} \ln \frac{\sqrt{m_T^2 \cosh^2 y - m^2} + m_T \sinh y}{\sqrt{m_T^2 \cosh^2 y - m^2} - m_T \sinh y} \quad (1.6)$$

1.4 QGP signatures

1.4.1 Jet quenching

The study of high momentum (p_T) particles gives the information about the medium created during the heavy-ion collisions. High momentum partons are produced in high energy heavy-ion collisions by the initial hard scattering. As these particles fragment, they form a collimated shower of particles called the jet. During the propagation of the jets through the hot and dense medium created by relativistic nuclear collisions, they will interact with the medium constituents and suffer energy loss due to collisions and gluon radiation [11]. As a result of energy loss, high- p_T yields will be suppressed and it is known as Jet Quenching [26]. During the traversal of these energetic partons through the dense medium, it is expected that the energy loss is proportional both to the initial density of gluons [11, 26] and to the lifetime of dense matter [27]. Experimentally, jet quenching is measured by nuclear modification factor (R_{AA}), which is defined as:

$$R_{AA}(p_T) = \frac{1}{\langle N_{\text{coll}} \rangle} \frac{\sigma_{\text{inel}}^{\text{AA}} \frac{d^2 N^{\text{AA}}}{dp_T dy}}{\sigma_{\text{inel}}^{\text{pp}} \frac{d^2 N^{\text{pp}}}{dp_T dy}}, \quad (1.7)$$

where, $\langle N_{\text{coll}} \rangle$ represents the mean number of binary collisions (nucleon to nucleon) in heavy ion collisions whereas σ_{inel} represents inelastic cross section and $\frac{d^2 N}{dp_T dy}$ represents the transverse momentum spectra. If we assume AA collisions are simple superpositions of pp collisions, the R_{AA} will be one, and any deviation from unity will indicate the presence of medium effects. The Nuclear modification factor of π^0 and inclusive charged hadron measured in central heavy-ion collisions at SPS (Super Proton Synchrotron) $\sqrt{s_{NN}} = 17.3$ GeV, at the RHIC (Relativistic Heavy-ion

Collisions) $\sqrt{s_{NN}} = 200$ GeV and at the LHC $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV are shown in Fig. 1.6. The R_{AA} at LHC energies shows a strong suppression at p_T 6-7 GeV/c. Although the p_T spectrum in pp collisions is flatter at the LHC, the nuclear modification factor at $p_T = 6-7$ GeV/c is smaller than at the RHIC, suggesting greater energy loss and a denser medium formation at the LHC.

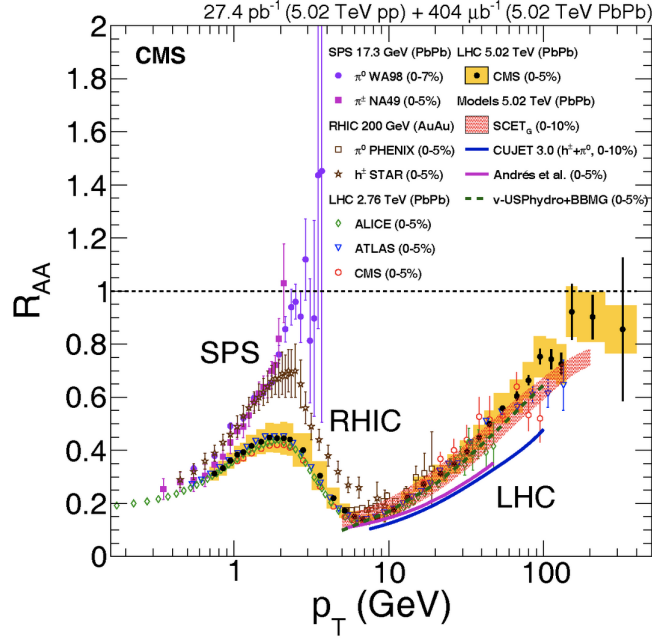


Figure 1.6: Nuclear modification factor (R_{AA}) for π^0 and $h^\pm$ as a function of p_T in central heavy-ion collisions at SPS, RHIC, and the LHC [28].

Hard scattering produces di-jets back to back due to momentum conservation. There is a possibility that a jet can be produced at the edge of the medium, called the ‘near-side jet’, but due to momentum conservation, another jet will be produced inside the medium, called the ‘away-side jet’. Due to its larger propagation through the medium, the away-side jet would be quenched more than the near-side jet, this process is known as Jet quenching. An experimental method for observing this is by taking an azimuthal correlation between a particle with a high p_T and its associated particles. Di-hadron correlations between trigger hadrons ($p_T > 4$ GeV/c) and associated hadrons ($p_T > 2$ GeV/c) are shown for pp at $\sqrt{s} = 200$ GeV, d-Au, and Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV in Fig. 1.7. From the figure it is observed that in Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV the away side peak (around 3.14 radians) is

suppressed with respect to near side peak (around 0 radians). This effect is due to the away side jet being more quenched than the near side jet. No such suppressions are observed in pp and d-Au collisions suggest that jet quenching effect are absent in small collision systems.

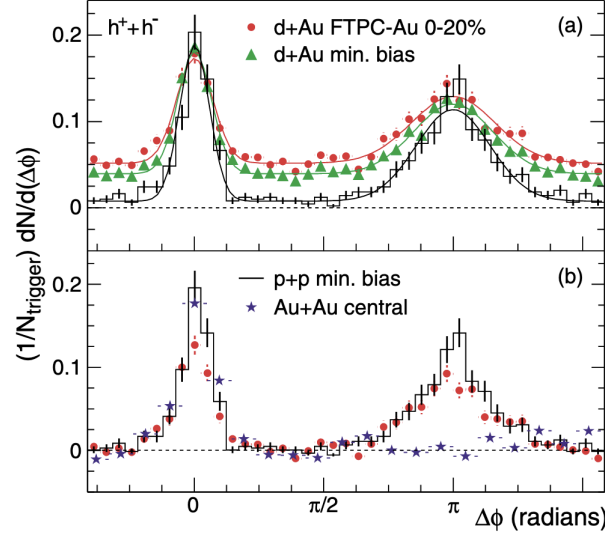


Figure 1.7: Jet azimuthal correlations for pp, d-Au and Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV measured with STAR experiment [29].

1.4.2 Strangeness enhancement

Enhanced formation of strange particles in heavy-ion collisions is considered to be a primary sign of QGP production [30]. Since the colliding nuclei only contain ‘u’ and ‘d’ quarks and the valence strange quarks are not present in the nucleons, therefore the production of strange particle gives information about reaction dynamics in partonic and hadronic phases. The production of strange quarks is mainly due to two types of processes, $gg \rightarrow s\bar{s}$ and $q\bar{q} \rightarrow s\bar{s}$. Since QGP has a high gluon density, the formation of the $s\bar{s}$ pair from the channel $gg \rightarrow s\bar{s}$ dominated the annihilation of light quarks, $q\bar{q} \rightarrow s\bar{s}$. In pp collisions, where the QGP medium formation is not expected, the strange quarks are mainly produced through annihilations of light quarks process. Experimentally, the ‘strangeness enhancement’ is estimated as,

$$E = \frac{2}{\langle N_{\text{part}} \rangle} \frac{\frac{dN^{\text{AA}}}{dy}}{\frac{dN^{\text{pp}}}{dy}} \quad (1.8)$$

where, $\langle N_{\text{part}} \rangle$ corresponds to number of participants in the collision and $\frac{dN}{dy}$ represents the strange particle yield. If the value of ‘E’ is greater than unity, it can attribute to strangeness enhancement. According to the canonical suppression picture [31], strange particles created by pp collisions can be suppressed, hence, $E > 1$. The net strangeness of $\phi(s\bar{s})$ meson is zero. So, ϕ -meson production in pp collisions will not be affected by canonical suppression, whereas production of hadrons having open strangeness can be canonical suppressed. It is therefore crucial to measure the ϕ meson in order to fully understand and quantify the strangeness enhancement. The strangeness enhancement (E) in Cu-Cu and Au-Au collisions at $\sqrt{s_{\text{NN}}} = 62.4$ and 200 GeV [32] for K, ϕ , Λ and Ξ particles is shown in Fig. 1.8. The observation of an enhanced ϕ meson production in Cu-Cu and Au-Au collisions indicates a formation of dense partonic medium, which leads to strangeness enhancement. At the LHC energies, the development of strangeness enhancement increases as a function of charge particle multiplicity from low-multiplicity pp to high multiplicity p-Pb collisions, reaching the value seen in Pb-Pb collisions. This may indicate that there is a similar underlying physics process that gradually compensates for the strangeness suppression that occurs during fragmentation [33].

1.4.3 J/ ψ suppression

The J/ ψ meson is a bound state formed by the coupling of a charm quark and its antiquark. Due to the large charm mass, charm quarks are almost exclusively created during hard partonic scattering processes. J/ ψ production is a major insight into the formation of a QGP in heavy-ion collisions. The Cornell Potential describes the bonding between a charm quark and its antiquark, can be expressed as:

$$V(r) = k \cdot r - \frac{\alpha}{r} \quad (1.9)$$

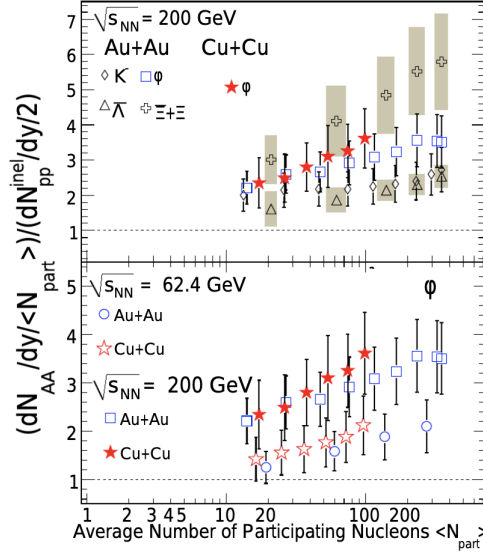


Figure 1.8: dN/dy of K , ϕ , $\bar{\Lambda}$ and $\Xi + \bar{\Xi}$ in heavy-ions scaled by those of pp and $\langle N_{\text{part}} \rangle / 2$ as a function of $\langle N_{\text{part}} \rangle$ at $\sqrt{s_{\text{NN}}} = 200$ GeV measured with STAR experiment [32].

where, ‘ k ’ is string constant, ‘ r ’ represents the radial distance between two quarks, and α is the running coupling constant. In a QGP medium, when $c\bar{c}$ is present, the interaction potential between the two quarks will be affected by the free color charge available and this phenomenon is called screening of the potential. As a result, the modified Cornell potential between the $c\bar{c}$ in presence of QGP will be expressed as,

$$V(r) = -\frac{\alpha}{r} e^{-r/\lambda_D} \quad (1.10)$$

where, λ_D represents the Debye length and it depends on temperature. In QGP medium, λ_D decreases to the value lower than the binding length, as a result the $c\bar{c}$ will be no more in bound state [34]. This will effect the final yield of J/ψ production in heavy-ion collisions and the final yields will be suppressed with respect to yield in pp collisions, where the QGP formation is not expected. Experimentally, the suppression of J/ψ yield was first observed by SPS [35] and confirmed at RHIC [36, 37] and later at the LHC [38].

Figure 1.9 shows the Nuclear Modification Factor (R_{AA}) of J/ψ meson as a

function of $\langle N_{\text{part}} \rangle$ in Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV in the ALICE experiment at LHC [38]. These measurement are compared with PHENIX results at the RHIC energies. From the plot it is clear that the R_{AA} is less than unity, which refers to the suppression of J/ψ at both RHIC and LHC energies.

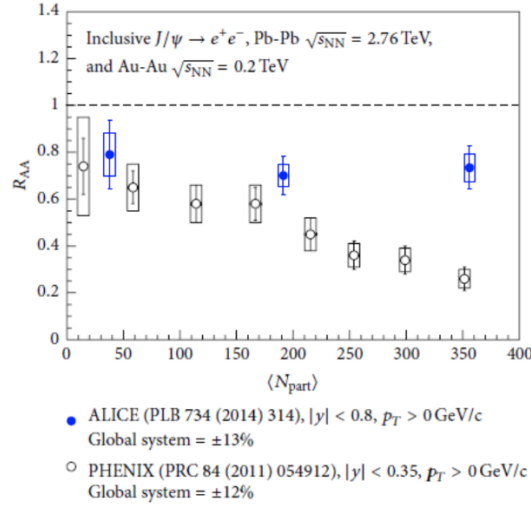


Figure 1.9: Nuclear Modification Factor (R_{AA}) of J/ψ at mid-rapidity as a function of $\langle N_{\text{part}} \rangle$ in Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV, compared with PHENIX measurement at $\sqrt{s_{\text{NN}}} = 200$ GeV [38].

The suppression is increasing at PHENIX as we go from lower (peripheral collisions) $\langle N_{\text{part}} \rangle$ to higher (central collision). In case of R_{AA} at the LHC energy, no centrality dependence is found. The measured J/ψ suppression is decreased (R_{AA} value increased) from the RHIC to the LHC energies. At the LHC energy, these observations support the formation of QGP medium that suppresses J/ψ production while a fraction of $c\bar{c}$ pairs coalesce and enhances J/ψ production because charm cross section at LHC energies is higher.

1.4.4 Elliptic flow

Observations of elliptic flow are important for understanding collective behavior of the system, as well as the degrees of freedom and the initial conditions of a fireball. When two colliding nuclei overlap in non-central collisions, the overlapping region has an almond shape. Interactions between constituents in the overlapping region

generate a pressure gradient, which transforms the initial spatial anisotropy into momentum anisotropy. The azimuthal momentum anisotropy of produced particle can be expressed in terms of Fourier Expansion,

$$\frac{dN}{d\phi} \propto 1 + 2v_1 \cos(\phi - \psi) + 2v_2 \cos(2(\phi - \psi)) + \dots, \quad (1.11)$$

where, ϕ is azimuthal angle and ψ is the angle made by reaction plane (plane formed by beam direction and impact parameter vector) with x-axis as shown in Fig. 1.10. The first Fourier coefficient (v_1) is directed flow and second coefficient (v_2) is elliptic flow and so on. The v_2 can be expressed as $\langle \cos(\phi - \psi) \rangle$, where $\langle \rangle$ represents the average of all particles across all events.

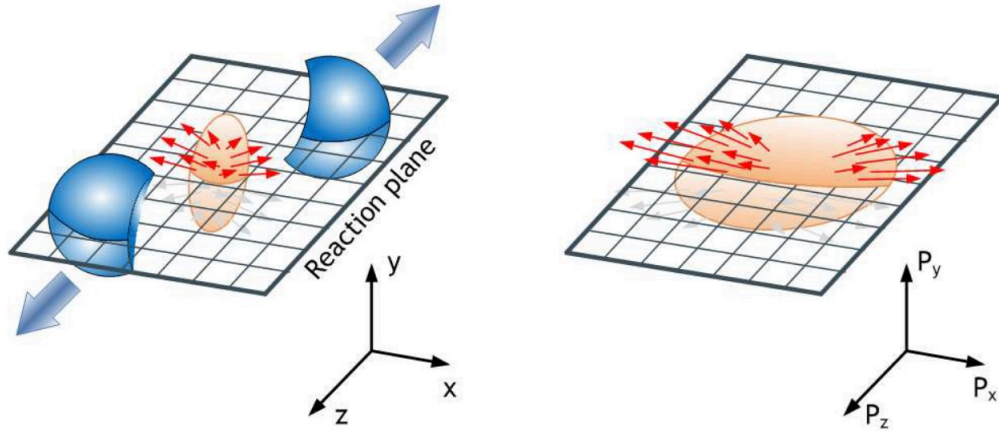


Figure 1.10: An illustration of reaction plane is shown in left figure. The overlap zone is depicted in orange, spectators are indicated in blue, and the pressure gradient is illustrated by the red arrows in the left figure. Momentum anisotropy is shown in right figure. The figure is taken from [39]

Figure 1.11 shows the elliptic flow (v_2) scaled by n_q as a function p_T scaled by n_q for K_s^0 , π , Ω , Ξ , Λ and p measured by STAR collaboration [40]. All hadrons follow the same line within statistics excluding pions. The discrepancy in the v_2 of pions from other particles may be due to Goldstone Boson nature (its mass is less than the total sum of its constituents quarks mass) or due to the resonance decay effect (high mass resonances decay to pion) [40]. The good agreement between v_2 of $p(uud)$, $\Omega(sss)$, $\Xi(dss)$ and $\Lambda(uds)$ suggests that all u , d and s quarks flow similarly.

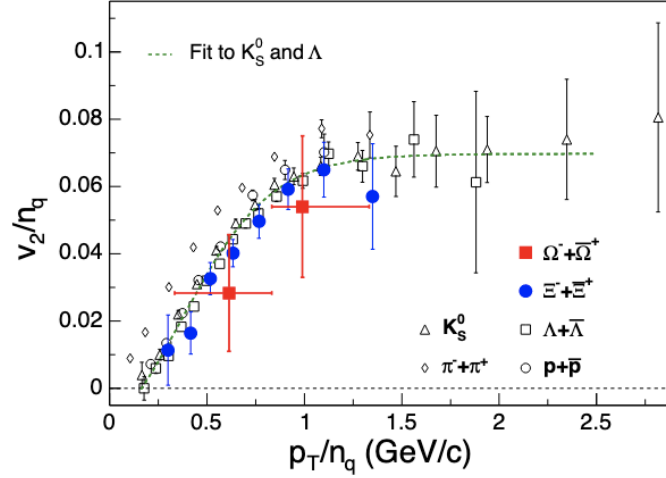


Figure 1.11: v_2 scaled by number of constituent quarks (n_q) as a function of n_q scaled p_T for various particles in Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV at STAR experiment [40].

Elliptic flow (v_2) is shown in Fig. 1.12 for π , K and p as a function of p_T in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [41]. The results are also compared with measurements done by STAR [42] and PHENIX [43] collaborations. From the plot, it is observed that the measured values of v_2 at low p_T are comparable at both the LHC and the RHIC. The results follow the hydrodynamic models predictions. The larger radial flow at the LHC energies compared to the RHIC energies is believed to contribute to the higher p_T integrated v_2 at the LHC [44]. The large values of v_2 observed at LHC can be explained by hydrodynamical model [45].

1.5 Resonance production in p-Pb collisions

The resonances are short lived particles having lifetime (τ) around few fm/c and decay into their daughter particles by strong interaction. During the lifetimes of these particles, they can only travel a few femtometers, before they decay. Resonance widths (Γ) and lifetimes (τ) are related by Heisenberg's uncertainty relation ($\Delta E \Delta t > \frac{\hbar}{4\pi}$, $\Delta E = \frac{\Gamma}{2}$, where E and t represents energy and time, respectively.). The resonances are reconstructed using their decay daughter particles, as they decay just after their production due to their short lifetimes. According to the experimen-

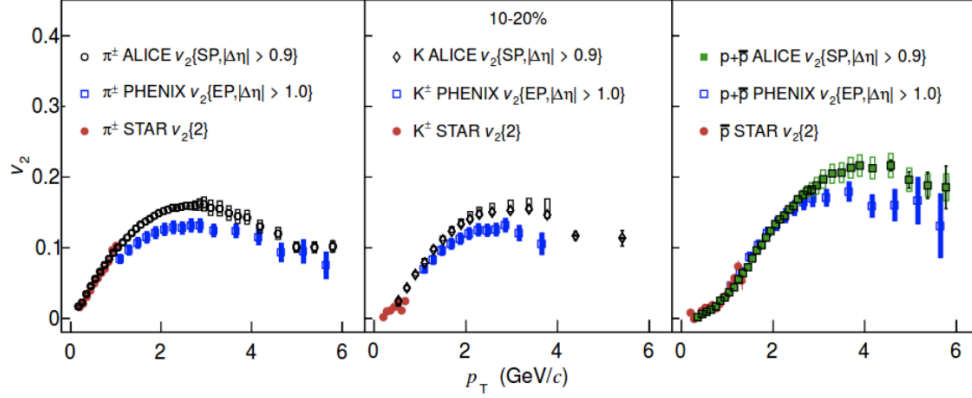


Figure 1.12: v_2 of identified hadrons as a function of p_T in Pb-Pb and Au-Au collisions at the LHC and the RHIC energies, respectively [41].

tal measurements, hadronic resonance lifetimes range from 1.1 fm/c to 46 fm/c. It has been estimated that the fireball created in the heavy-ion collisions at the LHC has a lifetime of 10 fm/c [46]. As a result, the resonances can be used to understand various in-medium phenomena and to study system evolution on different scales. In heavy-ion collisions, the hadronic resonances are produced in the expand-

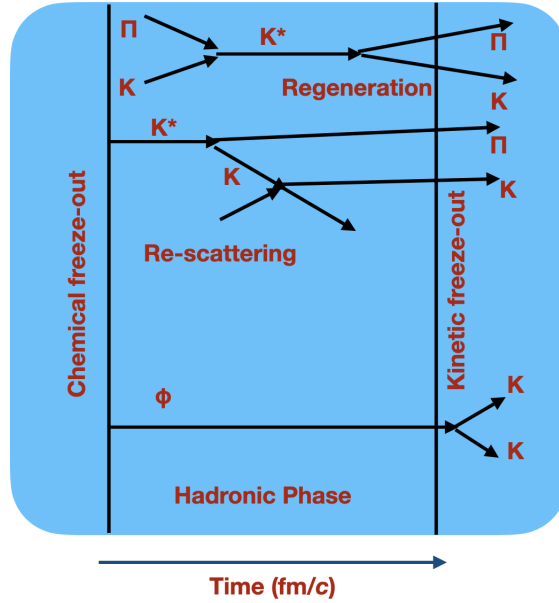


Figure 1.13: The schematic diagram demonstrating regeneration and re-scattering processes in hadronic phase.

ing medium, and these resonances can decay while they are still inside the medium.

In the hadronic phase between the chemical and kinetic freeze-out, the momentum of the decay daughter particles can be changed due to the interaction with the other particles. As a result, reconstructed invariant mass of the parent resonance particle will be different and the final resonance yield will be suppressed. This phenomenon is known as ‘Re-scattering Effect’. Alternatively, resonances can be generated by pseudoelastic collisions in the hadronic phase of the medium, resulting in the enhancement of the resonances yields. The schematic diagram of regeneration and re-scattering processes in hadronic phase is shown in Fig. 1.13. The study of resonance particles like $K^{*0}(892)$ and $\phi(1020)$ mesons having lifetimes $4.16 \pm 0.05 \text{ fm}/c$ and $46.3 \pm 0.4 \text{ fm}/c$, respectively, will help us to understand the in-medium effects. As the lifetime of ϕ meson is 10 times higher than the K^{*0} , therefore the effects of re-generation and re-scattering will be only seen in case of K^{*0} (lifetime is comparable to the hadronic phase lifetime). For understanding these effects experimentally, the resonances yields are scaled with the yield of stable charged particle (K) in heavy-ion collisions and compared with the results from pp collisions. It has been observed from K^{*0}/K ratio that the re-scattering effect dominates over regeneration effect, whereas flat behaviour of ϕ/K ratio indicates absence of such effects for ϕ mesons which is expected due to its large lifetime [47–50]. The ϕ mesons contains quark($s\bar{s}$), having a net strangeness of zero. According to the recent results of the LHC [51], ϕ meson behaves as a particle with net strangeness of 1 or 2.

1.6 Thesis Motivation

The high-energy heavy-ion collisions (AA) aim to create the QGP which evolves through time and cools down into hadrons gas. Asymmetric collision systems, such as proton-nucleus and deuteron-nucleus collisions, can be considered as control experiments, where QCD medium formation is not anticipated and can disentangle cold nuclear matter effects from hot dense matter produced in nucleus-nucleus collisions. Multiplicity dependent study in small systems, i.e, pp, p-Pb, p-Au, d-Au, and ^3He -Au collisions at various energies have shown features like collective flow,

strangeness enhancement and ridge like effects. In this context, a systematic study of the multiplicity and rapidity dependence of hadron production allows us to understand the mechanism of particle production and the nature of the QCD medium produced in these collisions.

1.6.1 ϕ meson production at mid rapidity in p-Pb collisions

In this thesis, we have reported the first measurement of ϕ meson at mid rapidity in p-Pb collisions at $\sqrt{s_{\text{NN}}} = 8.16$ TeV. The measurement is performed for various multiplicity classes including the minimum bias events. The results include the p_{T} spectra, integrated particle yield, mean transverse momentum ($\langle p_{\text{T}} \rangle$) and nuclear modification factor. The validations of x_{T} scaling at high p_{T} is also tested in p-Pb collisions at $\sqrt{s_{\text{NN}}} = 8.16$ TeV. The results are compared with the previous ALICE measurement in pp collisions at $\sqrt{s} = 7$ and 13 TeV [52, 53], in p-Pb collision at $\sqrt{s_{\text{NN}}} = 5.02$ TeV [54], and in Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ and 5.02 TeV [55, 56]. The results are also compared with the model predictions EPOS-LHC [57], HIJING [58] and DPMJET [59] for p-Pb collisions at $\sqrt{s_{\text{NN}}} = 8.16$ TeV.

1.6.2 Rapidity and multiplicity dependence study of ϕ meson production in p-Pb collisions

In this thesis, we have reported the rapidity and multiplicity dependence study of ϕ mesons production in p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. The p_{T} spectra, integrated yield and $\langle p_{\text{T}} \rangle$ are shown for various rapidity and multiplicity classes. In addition, the rapidity asymmetry and nuclear modification factor are also measured and discussed. The results are compared with various model predictions including EPOS-LHC [57], HIJING [58], DPMJET [59], EPOS3 [60–63], and PYTHIA8 [64].

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Chapter 2

A Large Ion Collider Experiment (ALICE)

The Large Hadron Collider (LHC) is the largest and highest-energy particle accelerator ever built in the world. The LHC was built between 1998 and 2008 at CERN (Conseil Européen pour la Recherche Nucléaire) by European Organization for Nuclear Physics in collaboration among research labs and Universities from all over the world. In the LHC ring, first beam was injected in 2009 and has so far accelerated and collided proton and Pb beams at center-of-mass energy up to 13 TeV and 5.02 TeV, respectively. A Large Ion Collider Experiment (ALICE) is one of the major experimental setup among all the experiments at the LHC. The ALICE detector is dedicated to heavy-ion physics, which includes the study of strongly interacting matter at high temperature and high energy density. In this chapter, an overview of the LHC and its experimental setup at the CERN is discussed. The ALICE detector is described in detail with its sub-detectors in the following subsections.

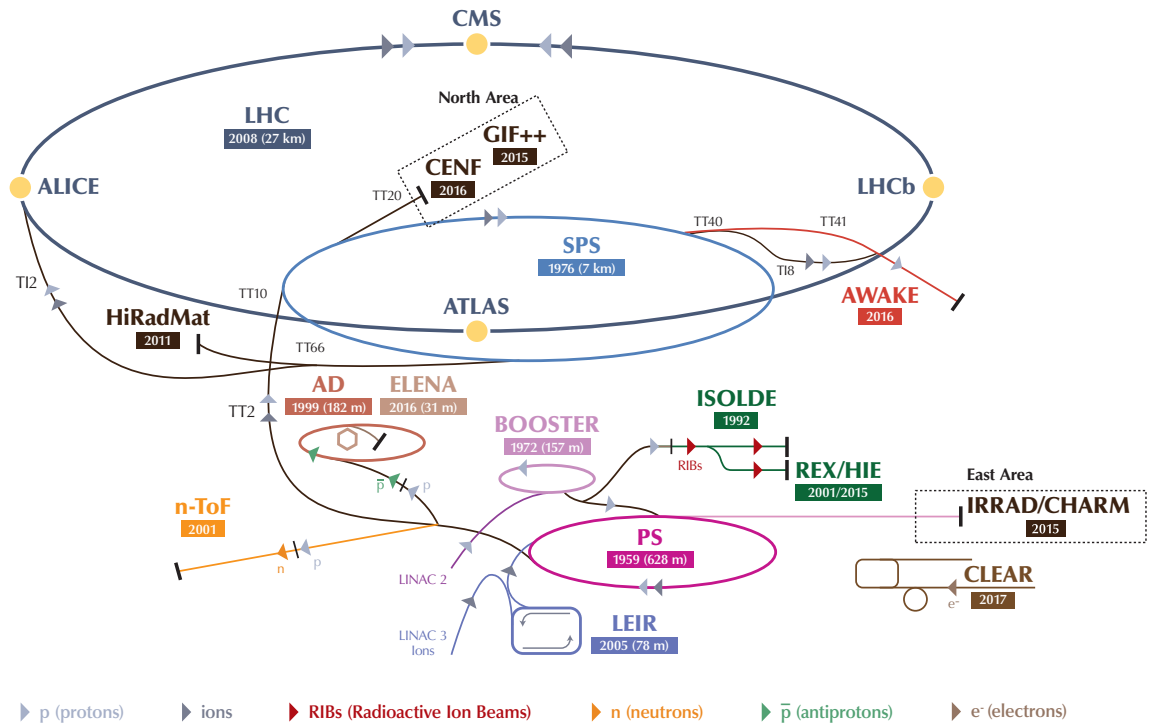
2.1 The Large Hadron Collider (LHC)

The LHC accelerator is built as an underground ring of the circumference of 27 kilometers and it is as deep as 50-175 meters from the ground surface on the France

and Switzerland border near Geneva city. The LHC ring is made up of superconducting magnets with several accelerating structures to boost the energy of the particle along its way. The CERN accelerator complex is shown in Fig. 2.1, which consists of several accelerating systems such as Super Proton Synchrotron (SPS), Proton Synchrotron (PS), Antiproton Decelerator (AD), CERN Linear Electron Accelerator for Research (CLEAR), Advanced WAKEfield Experiment (AWAKE), Isotope mass Separator On-Line DEvice (ISOLDE), Low Energy Ion Ring (LEIR) and LINer ACcelerator (LINAC), etc. Each of the accelerators is used to boost the energy of the injected particle before the final injection to the LHC ring. The proton source is created from a bottle of hydrogen gas, which is connected to a machine called a “duoplasmatron”. In duoplasmatron, the hydrogen gas is separated into its electrons, plasma of proton, and molecular ions. The plasma expands towards the extraction electrode and a proton beam is formed. Then the proton beam is injected into the linear accelerator LINAC2, which ramps up the energy of the proton up to 50 MeV. The beam from the LINAC2 is passed through the PS booster consisting of four storage rings, each is filled with one bunch. The booster accelerates the proton bunches to 1.4 GeV before injecting them into PS. After that, the beam is passed through SPS to accelerate it to the LHC injection energy, 450 GeV. From the SPS, the beams are transported to the LHC injection point by two transfer lines (TI 2 and TI 8) of 3 km. The lead ions are created from isotopically pure solid lead-208. The lead metal is first heated to 500°C, which produces vapours of lead atoms, which is the source of the lead (Pb) ion beam. Few electrons are removed from the Pb atom using an electric field, and the newly formed Pb ions are then first accelerated by a LINAC 3 up to an energy of 4.2 MeV per nucleon. The Pb ions undergo further electron removal in LINAC 3. The beam coming from the LINAC3 is passed through the following accelerators LEIR, PS, and SPS, before final injection to the LHC ring.

The particle beam is injected into the LHC ring in clockwise direction from point 2 (location of the ALICE experiment) and in counter-clockwise direction at point 8 (location of the Large Hadron Collider beauty (LHCb) experiment). Both beams

The CERN accelerator complex *Complexe des accélérateurs du CERN*



LHC - Large Hadron Collider // SPS - Super Proton Synchrotron // PS - Proton Synchrotron // AD - Antiproton Decelerator // CLEAR - CERN Linear Electron Accelerator for Research // AWAKE - Advanced WAKEfield Experiment // ISOLDE - Isotope Separator OnLine // REX/HIE - Radioactive Experiment/High Intensity and Energy ISOLDE // LEIR - Low Energy Ion Ring // LINAC - LINEar ACcelerator // n-ToF - Neutrons Time Of Flight // HiRadMat - High-Radiation to Materials // CHARM - Cern High energy AccelERator Mixed field facility // IRRAD - proton IRRADIation facility // GIF++ - Gamma Irradiation Facility // CENF - CErn Neutrino platForm

Figure 2.1: CERN accelerator complex and location of PS and SPS including four major LHC experiments: ALICE, CMS, LHCb and ATLAS along the LHC ring [1].

follow the same injection scheme. The energy of the beam in the LHC ring is boosted by a strong magnetic field maintained by superconducting electromagnets. The beams travel in two separate beam pipes in opposite directions, the beam pipes are kept at ultrahigh vacuum. The beams inside the LHC ring are made to collide at four locations corresponding to the four main particle detector, A Toroidal LHC ApparatuS (ATLAS), the Compact Muon Solenoid (CMS), the ALICE, and the LHCb. The maximum colliding energy reached at the LHC accelerator with current facilities are $\sqrt{s} = 14$ TeV and $\sqrt{s_{NN}} = 5.5$ TeV for proton-proton and heavy-ion collisions, respectively.

2.1.1 The ALICE experiment setup at the LHC

ALICE experiment is primarily dedicated to the heavy-ion physics at the LHC. It is designed to study the physics of strongly interacting matter at extremely high temperatures and high energy densities. Under these extreme conditions a de-confinement state of quarks and gluons is formed, which is called “Quark-Gluon Plasma” (QGP). The dimensions of the ALICE detector are 26 m long, 16 m high, 16 m wide, and it weighs around 10,000 tons. The ALICE detector is set up in a vast cavern around 56 m below the ground surface near the St Genis-Pouilly village in France. The systematic representation of the ALICE detector with its 19 sub-detectors is shown in Fig [2.2](#).

In the ALICE, the co-ordinate system is described in terms of a right-handed Cartesian coordinate system. The beam interaction point is taken as origin $(x,y,z) = (0,0,0)$. The beam direction towards the muon chamber is taken as the negative z -axis, also known as the longitudinal direction. The positive x -axis direction is transverse to the z -axis and it points towards the LHC center, whereas the negative x -axis is outward from the center. From the origin, in the upward direction and perpendicular to the x -axis, is designed as positive y -axis, while downward direction from origin is taken as the negative y -axis. The azimuthal angle (ϕ) is measured with respect to the x -axis and the polar angle (θ) is measured from the z -axis to

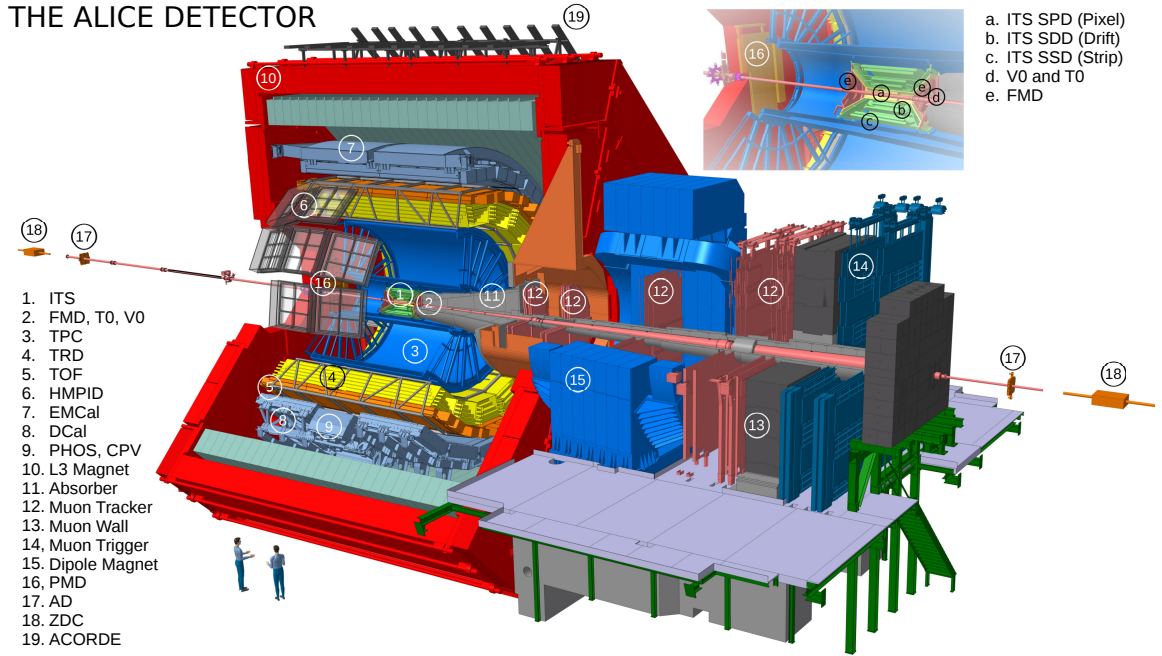


Figure 2.2: Systematic representation for the ALICE detector systems [2]

the x-y plane. The whole ALICE detector has three components: the central barrel detectors, forward detectors, and the muon spectrometer. The following detectors: ITS, TPC, TOF, and V0, are mainly used in the analysis of ALICE data presented in the thesis. In the following sub-sections, these detectors are briefly described along with the other sub-detectors. The details of the position, η , and ϕ acceptance and purposes of the ALICE detector subsystems are listed in table 2.1.

2.1.2 Central Barrel Detectors

2.1.2.1 Inner Tracking System (ITS)

The Inner Tracking System (ITS) consists of six cylindrical layers of silicon detector surrounding the beam pipe located in the central barrel of ALICE as shown in Fig 2.3. The distance of the innermost layer from the nominal beam axis is 3.9 cm and for the outmost layer is 43 cm. The smallest amount of lightest material is used to make the ITS as lightweight and delicate as possible. ITS is based on three different technologies (pixel, drift, and strip), each of which has two layers: Silicon

Table 2.1: Summary of the position, η , and ϕ acceptance and purposes of the ALICE detector subsystems [3].

Detector	Positions (in cm)	η acceptance	ϕ acceptance (in $^\circ$)	Purpose
Central barrel detector:				
SPD	$r = 3.9$	$ \eta < 2.0$	$0^\circ < \phi < 360^\circ$	tracking, vertex
	$r = 7.6$	$ \eta < 1.4$	$0^\circ < \phi < 360^\circ$	tracking, vertex
SDD	$r = 15.0$	$ \eta < 0.9$	$0^\circ < \phi < 360^\circ$	tracking, particle identification
	$r = 23.9$	$ \eta < 0.9$	$0^\circ < \phi < 360^\circ$	tracking, particle identification
SSD	$r = 38.0$	$ \eta < 1.0$	$0^\circ < \phi < 360^\circ$	tracking, particle identification
	$r = 43.0$	$ \eta < 1.0$	$0^\circ < \phi < 360^\circ$	tracking, particle identification
TPC	$85 < r < 247$	$ \eta < 0.9$	$0^\circ < \phi < 360^\circ$	tracking, particle identification
TRD	$290 < r < 368$	$ \eta < 0.8$	$0^\circ < \phi < 360^\circ$	tracking, $e^\pm$ identification
TOF	$370 < r < 399$	$ \eta < 0.9$	$0^\circ < \phi < 360^\circ$	particle identification
PHOS	$460 < r < 478$	$ \eta < 0.12$	$220^\circ < \phi < 320^\circ$	photons
EMCAL	$430 < r < 455$	$ \eta < 0.7$	$80^\circ < \phi < 187^\circ$	photons
HMPID	$r = 490$	$ \eta < 0.6$	$1^\circ < \phi < 59^\circ$	particle identification
ACORDE	$r = 850$	$ \eta < 1.3$	$30^\circ < \phi < 150^\circ$	cosmic
Forward detector:				
PMD	$z = 850$	$2.3 < \eta < 3.9$	$0^\circ < \phi < 360^\circ$	photons
FMD	$z = 320$	$3.6 < \eta < 5.0$	$0^\circ < \phi < 360^\circ$	charged particles
	$z = 80$	$1.7 < \eta < 3.7$	$0^\circ < \phi < 360^\circ$	charged particles
	$z = -70$	$-3.4 < \eta < -1.7$	$0^\circ < \phi < 360^\circ$	charged particles
V0	$z = 329$	$2.8 < \eta < 5.1$	$0^\circ < \phi < 360^\circ$	charged particles
	$z = -88$	$-3.7 < \eta < -1.7$	$0^\circ < \phi < 360^\circ$	charged particles
T0	$z = 370$	$4.6 < \eta < 4.9$	$0^\circ < \phi < 360^\circ$	time, vertex
	$z = -70$	$-3.3 < \eta < -3.0$	$0^\circ < \phi < 360^\circ$	time, vertex
ZDC	$z = \pm 11300$	$ \eta > 8.8$	$0^\circ < \phi < 360^\circ$	forward neutrons
	$z = \pm 11300$	$6.5 < \eta < 7.5$	$ \phi < 10^\circ$	forward neutrons
	$z = -730$	$4.8 < \eta < 5.7$	$ 2\phi < 32^\circ$	photons
Muon spectrometer:				
MCH	$-1420 < z < -540$	$-4.0 < \eta < -2.5$	$0^\circ < \phi < 360^\circ$	muon tracking
MTR	$-1710 < z < -1610$	$-4.0 < \eta < -2.5$	$0^\circ < \phi < 360^\circ$	muon trigger

Pixel Detector (SPD), Silicon Drift Detector (SDD), and Silicon Strip Detector (SSD), and it covers the pseudorapidity window $|\eta| < 0.9$. The main task of the ITS is to reconstruct the primary and secondary vertices with a resolution better than $100 \mu\text{m}$ and improving the ALICE barrel tracking capabilities in the vicinity of the interaction point. Another task of ITS is to track and identify charged particles with low p_T cutoff ($p_T = 80 \text{ MeV}/c$) and to improve the momentum resolution at high p_T . It also helps in better measurement of momentum and angle in the Time Projection Chamber (TPC) detector.

The basic building block of the ALICE SPD is the ladder, consisting of a pixel detector matrix flip-chip bonded to 8 front-end chips [4]. The detector matrix consists of 256×256 cells, each measuring $50 \mu\text{m}$ in the $r\phi$ direction by $300 \mu\text{m}$ in the z direction. Each detector ladder measures 13.8 mm ($r\phi$) $\times$ 82 mm (z). The fine granularity makes it possible to detect the positions of the charged track traversing the detector to very high precision. The inner and outer SPD layers are located at 3.9 cm and 7.6 cm from the beam axis, respectively, and extend 282 mm in the longitudinal direction. In order to avoid radiation of heat towards the SDD layers, which are very sensitive to temperature, an Al-coated carbon-fiber external shield surrounds the SPD barrel.

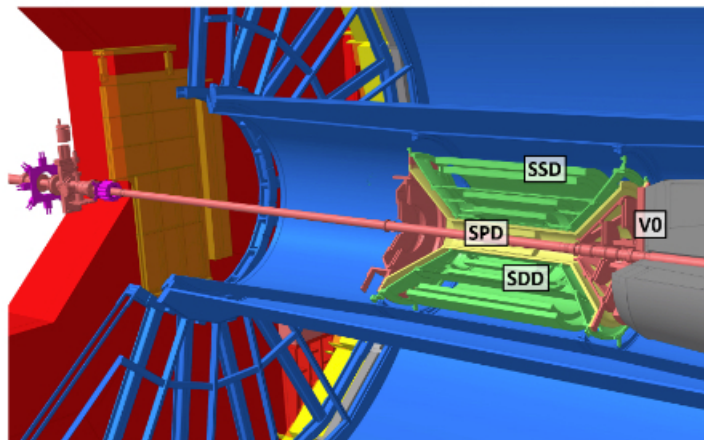


Figure 2.3: Systematic representation for the ITS detector in ALICE [5].

The SDD is mounted on linear structures called ladders. The layers are located in between the radius of 14.9 cm and 23.8 cm from the beam axis, and the length of

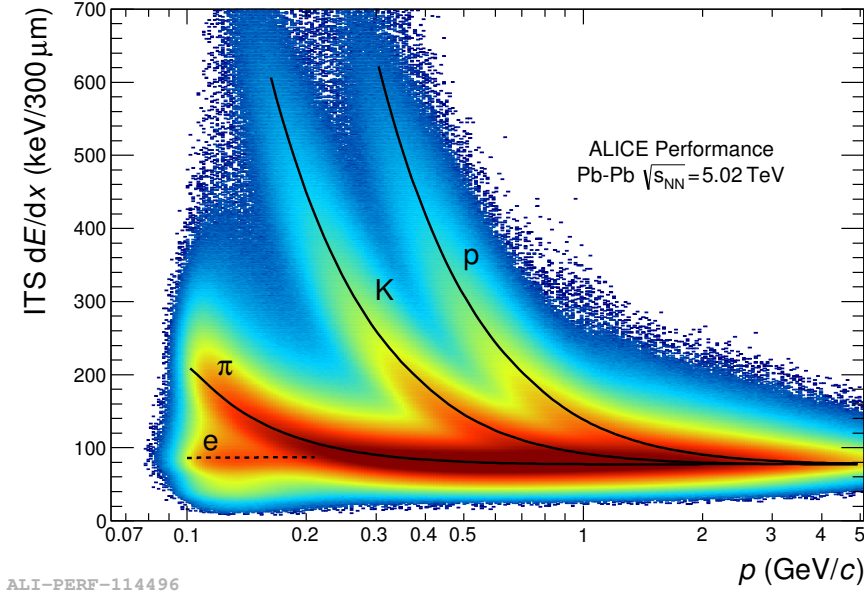


Figure 2.4: Energy loss (dE/dx) of particles in ITS detector as a function of momentum in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV are shown. Expected theoretical values are shown by solid lines [6].

the layers are 443 mm and 593 mm in the z directions, respectively. The two layers are made of 14 and 22 ladders respectively. The ladders hold six detectors for the inner layer, and eight detectors for an outer layer. The detector overlaps slightly both in $r\phi$ and in z to provide full coverage for particles originating from vertices in any locations within the $\pm 1\sigma$ interaction diamond. The SSDs, like gaseous drift detectors, the charged cloud, originated by the ionizing event, drift in a static field with constant speed and carries the pieces of information on both coordinates of the impact point. The low-capacitance readout anodes give an optimal energy resolution.

The SSD detectors are built of double layers of silicons strips 782 (layer 5) and 988 (layer 6), with a 35 mrad stereo angle. Therefore, a particle crossing any one of the SSD will give rise to a signal in both strip layers, which gives a detection at the crossing point. The dE/dx information is measured from the collected charge carrier in the SSD. The strips are 40 mm long and tilted at an angle of 17.5 mrad concerning to the short side of the detector. In this way, a stereo pair is created allowing a 2D reconstruction of track position. The two layers of SSD are located

at 38 cm (inner) and 43 cm (outer) from the beam axis and extend 86 cm and 98 cm in the longitudinal direction, respectively. The energy loss measured by the ITS detector is shown in Fig 2.4.

2.1.2.2 Time Projection Chamber (TPC)

The Time Projection Chamber (TPC) is the main detector in the central barrel of ALICE, which is used for particle identification and tracking of charged particles [7]. The 3D view of the TPC field cage is shown in Fig. 2.5. The combined information of charged particles from TPC, ALICE Transition Radiation Detector (TRD), and the Inner Tracking System (ITS) is used to study vector meson resonances, ‘charm’, and ‘beauty’ through the measurement of the leptonic observable. The TPC is a cylindrical shape detector filled with a conducting gas mixture of Ne-CO₂-N₂. The inner and outer radii of the TPC is 85 cm and 250 cm, respectively. The TPC is operated at 0.5 T solenoidal magnetic field parallel to the beam axis, which is provided by the L3 solenoidal magnet. It is divided into two drift regions separated by a central HV electrode located at its axial center.

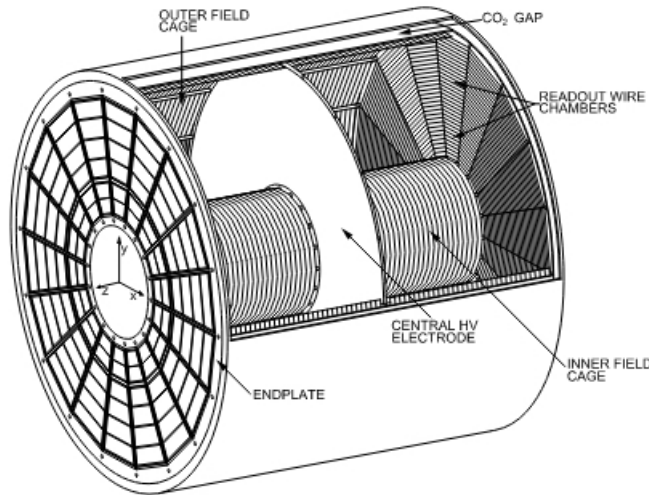


Figure 2.5: 3D view of the TPC field cage. The high voltage electrode is located at the center of the drift volume. The endplates with 18 sectors and 36 readout chambers on each end are shown [8].

The electrode is charged to 100 kV, provides, together with a voltage dividing network at the surface of the inner and outer cylinder, an axial electric field of 400 V/cm. It covers the pseudo-rapidity region $|\eta| < 0.9$ and full (2π) azimuthal direction. The charged particles passing through the active region will ionize the gas along their path. The ionized electrons drift toward the endplate of the cylinder due to the electric field. The cylindrical plane co-ordinates are precisely measured at the endplates. The trajectory of the all charged particle in TPC can be determined with the help of accurate measurement of arrival time (relative to beam collision time from the LHC) and cylindrical co-ordinate. The TPC is used for the identification of charged particles with the help of specific ionization loss (dE/dx) and momentum of the particles in the TPC gas. The charged particles can be distinguished from their dE/dx information. For better measurement of dE/dx , it should be calculated from the number of clusters (n_{cl}), and $n_{cl} > 50$ (which is out of maximum 159 TPC pad rows), which are assigned to the track. The average energy loss of charged particles is describe by Bethe-Bloch Equation. For heavy charged particle it is given by the equation:

$$\frac{-dE}{dx} = \frac{4\pi e^4}{m_0} \frac{z^2}{v^2} N Z \left\{ \ln\left(\frac{2m_0 v^2 \gamma^2}{I}\right) - \beta^2 - \delta^2 - \frac{2C}{Z} \right\} \quad (2.1)$$

where,

z = Charge of primary particle

m_0 = Rest mass of electron

v = Velocity of charged particle

N = Number density of absorber material

Z = Atomic Number of absorber material

I = Mean excitation potential

$\beta = v/c$, c = Velocity of light

$\gamma = \frac{1}{\sqrt{1-\beta^2}}$

δ = Density Correction factor

C = Shell Correction factor

Electrons and positrons, because of their small masses, they follow a modified Bethe-Bloch equation, where bremsstrahlung is the main source of energy loss. The energy loss (dE/dx) is a function of momentum for identified charged particles as shown in Fig 2.6. From the figure, it can be seen that the charged particles can be easily distinguished at low momentum in the TPC, whereas it is difficult to distinguish them at intermediate and high momentum. Time Of Flight (TOF) detector information is used at intermediate momentum for particle identification.

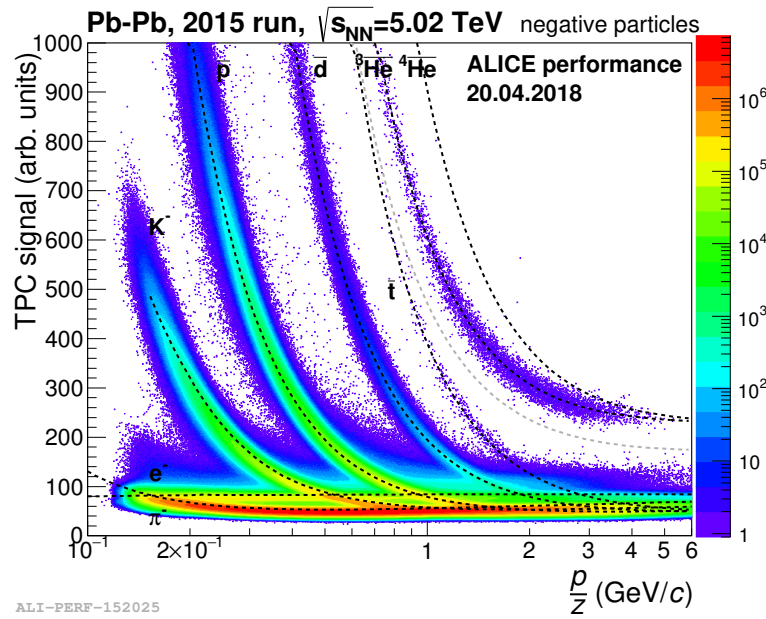


Figure 2.6: Energy loss (dE/dx) of particles in TPC detector as a function of momentum in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Expected theoretical values are shown by solid lines [9].

2.1.2.3 Transition Radiation Detector (TRD)

A Transition Radiation Detector (TRD) can identify and trigger electrons and jets, providing a trigger decision in about 7 microseconds. The TRD performs the electron identification at higher momenta above 1 GeV/c. It provides excellent performance in distinguishing electrons from pions for particles above 1 GeV/c at an electron efficiency of 90 % [10]. The TRD consists of 522 detectors, located in 18 sectors in azimuth. Each sector consists of 5 stacks with 6 layers in longitudinal direction. The TRD cylinder has a diameter of around 7 m and a length of about 7 m. A

mixture of xenon and CO₂ is used as the active gas in the TRD.

2.1.2.4 Time Of Flight (TOF)

The Time Of Flight (TOF) detector is extensively used to identify the charged particles in the intermediate momentum range. The combined information of time measurement from TOF, momentum, and track length from the tracking detectors (TPC and ITS) is used to calculate the particle mass. In the TOF detector, the charged particles with the same momenta can be distinguished by their time of flight.

The time of flight (t) refers to the distance travelled by a particle, in this case, to reach the TOF detector from the interaction point. The T0 detector provides the start time (t_0), which is placed each on the opposite sides of the interaction point. The particle mass is defined by following equation:

$$m = p \sqrt{\frac{t^2}{L^2} - 1} \quad (2.2)$$

where, p represents the momentum, t is the time-of-flight and L is the track length. The mass resolution components are expressed as following:

$$\left(\frac{\delta m}{m}\right)_p \propto \frac{\delta p}{p}; \left(\frac{\delta m}{m}\right)_L \propto \left(\frac{p}{m}\right)^2 \frac{\delta L}{L}; \left(\frac{\delta m}{m}\right)_t \propto \left(\frac{p}{m}\right)^2 \frac{\delta t}{t} \quad (2.3)$$

The ALICE TOF detector has a cylindrical shape with an inner radius of 3.7 m, covering 45-135 degrees polar angle over full azimuth [11]. The structure is divided into 18 sectors in ϕ ; each of which is further divided into 5 modules along the beam axis. The modules contain the multigap resistive plate chambers (MRPCs) detector element, which has time resolution in the range of 50 ps. During normal running conditions the average total TOF time resolution of 80 ps can be achieved, which allows well separation of K/ π and p/K up to 3σ at p_T up to 2.5 and 4.0 GeV/ c respectively, where σ represents the time resolution of TOF detector. The MRPC is made up of a series of resistive glass plates as shown in Fig. 2.7. A strong voltage

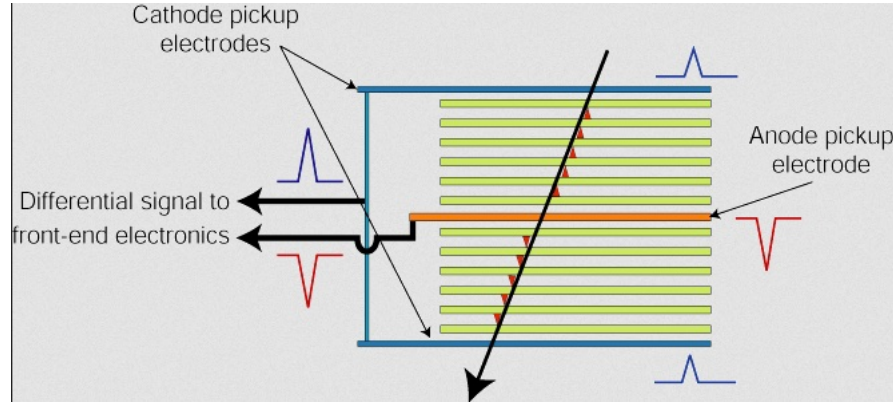


Figure 2.7: A schematic illustration of the working principle of multigap resistive plate chamber (MRPC) in TOF [11].

is given to the stack's exterior surfaces. Pickup electrodes are placed outside it. A charged particle ionizes the gas, which is amplified by an electron avalanche due to the strong electric field. The resistive plates prevent avalanche formation in each gap, but they are transparent to the rapid signal created on the pickup electrodes by the electron mobility. As a result, the total signal is the sum of the signals from all gaps (the purpose for numerous gaps is to achieve high efficiency), however, the signal's time jitter is determined by the gap width. The measured β distribution of particles as a function of momentum in Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV is shown in Fig. 2.8.

2.1.2.5 ElectroMagnetic CALorimeter (EMCal)

The ALICE can now measure highly energetic photons, electrons, neutral pions, and jets, as well as the correlations between them, using the Electro Magnetic Calorimeter (EMCal) [13]. EMCal is a shashlik-type lead-scintillator sampling calorimeter comprised of 4416 individual modules arranged into twenty Super Modules (SM). Each module is composed of four optically isolated towers, resulting in a total of 17664 towers. In each tower, wavelength-shifting fibers are coupled to Avalanche PhotoDiodes (APD's) that provide optical readouts. Triggering systems are available in both EMCal and DCal. The signals of 44 groups of nearby towers are combined, and a peak finding method is utilised to locate a signal peak, giving

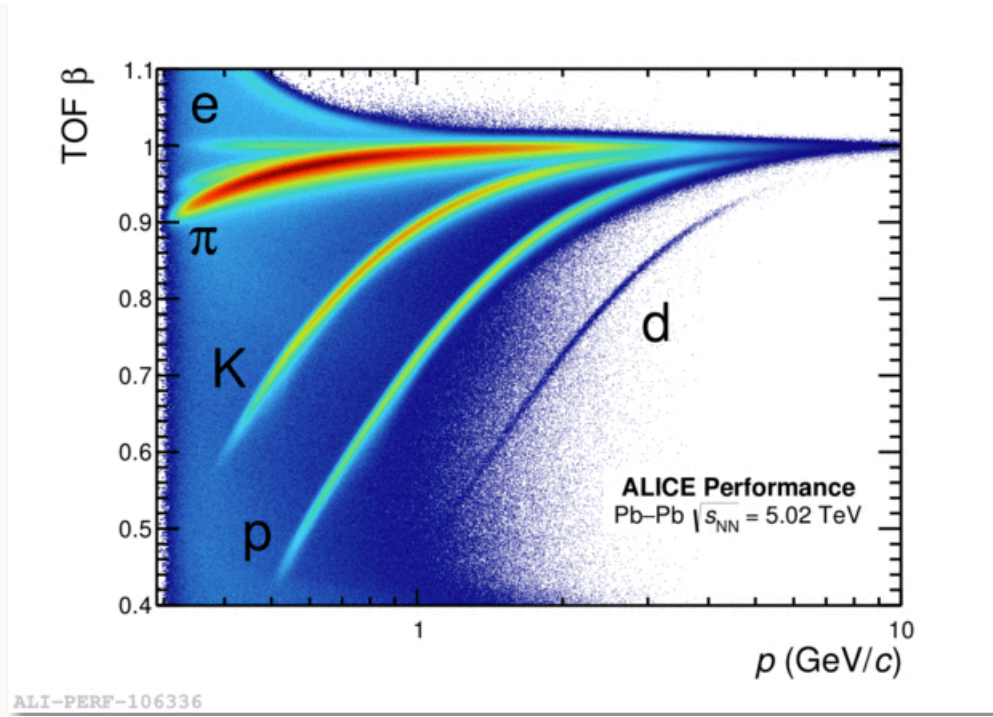


Figure 2.8: β distribution of particles measured by the TOF detector as a function of momentum in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [12].

L0- and L1-level triggers to the ALICE Central Trigger Processor, allowing online selection of high-energy particles such as photons and electrons.

2.1.2.6 PHOton Spectrometer (PHOS)

The PHOS is devoted to the search of electromagnetic radiation from hot strongly interacting matter in high-energy nucleus-nucleus interactions, as well as measurements of hadron spectra via their radiative decays. The PHOton Spectrometer (PHOS) is a high-resolution electromagnetic calorimeter with 17280 detector channels made of lead-tungstate crystals (PbWO_4) (or PWO) [14]. It is placed at a distance of 460 cm from the interaction point outer side of the TOF detector. The PHOS has a pseudorapidity range of $-0.12 < \eta < 0.12$ and azimuthal angle range $220^\circ < \phi < 320^\circ$.

2.1.2.7 High Momentum Particle Identification Detector (HMPID)

The ALICE High Momentum Particle Identification Detector (HMPID) detects charged particles (pions, kaons, and protons) with large momenta [15]. It enhances the PID capability of ALICE detector to separate the π/K and K/p upto 3 and 5 GeV/c, respectively. The HMPID is a Ring Imaging Cherenkov detector with two primary components: a radiator medium that produces Cherenkov light and a photon detector that provides patterns for particle identification.

2.1.2.8 ALICE COsmic Ray DEtector (ACORDE)

ACORDE [16] provides a fast trigger signal (Level-0), which is used for the calibration, commissioning, and alignment procedures of few ALICE tracking detectors. ACORDE detects atmospheric muons and multi-muon events (muon bundles) in conjunction with the TPC, TRD, and TOF, allowing high-energy cosmic rays to be studied in the ‘knee energy region’ of the cosmic ray spectrum. ACORDE consists of a series of plastic scintillator counters placed on the upper surface of the L3 magnet, each having an effective area of $190 \times 20 \text{ cm}^2$, and are stacked on top of each other and read out simultaneously. The detector consists of 60 modules covering the pseudorapidity range of $|\eta| < 1.3$.

2.1.3 Forward Detectors

2.1.3.1 Photon Multiplicity Detector (PMD)

The PMD [17] detector performs the measurement of multiplicity distribution of inclusive photons (mainly decay from π^0) in forward pseudorapidity region ($2.3 < \eta < 3.7$, full azimuth). It is made up of two gas chambers/planes called as Preshower plane and Charged Particle Veto (CPV), a lead converter is sandwiched between them. The plane consists of many cells, each of them acts as a gaseous proportional counter. Preshower plane is placed at the back side of the lead plates, whereas CPV is located towards the interaction point. The CPV technique is employed to improve

the photon-hadron discrimination.

2.1.3.2 Forward Multiplicity Detector (FMD), T0 Detector

The FMD system is primarily used to obtain (offline) precise information on the multiplicity of charged particles in the range of pseudorapidity $-3.4 < \eta < -1.7$ and $1.7 < \eta < 5.0$ [18]. There are 51,200 silicon strip channels in the FMD, distributed over five ring counters each with 20 and 40 sectors in azimuthal angle, respectively. Together with the ITS pixel system, the FMD will provide particle multiplicity distributions for all collision types in the range $-3.4 < \eta < 5.0$. The FMD will also be able to examine multiplicity fluctuations on an event-by-event basis and perform flow analysis (using azimuthal segmentation).

The T0 detector [18] is comprised of two arrays of PMTs equipped with Cherenkov radiators, placed on opposite sides of the Interaction Point (IP). The main role of T0 is to provide fast timing signals that will be used in the L0 trigger for ALICE, to provide a wake-up signal for TRD, and to deliver collision time references for the TOF detector. The pseudorapidity range covered by T0 is $-3.3 < \eta < -2.9$ and $4.5 < \eta < 5$. The T0 trigger time resolution is better than 50 ps. It is also used to find out the IP location with an accuracy of better than 1.5 cm.

2.1.3.3 VZERO (V0) detector

The VZERO (V0) detector is made up of two V0A and V0C arrays of 32 scintillating counters located on each side of the ALICE interaction point of the two LHC beams [18]. The counters are further distributed into 4 rings, the segmentation is shown in Fig. 2.9. This detector is used for many purposes. In p-p and A-A collisions, it offers minimum bias and centrality triggers for the central barrel detectors. In each of the 64 channels, it monitors the charge of the particles as well as the timing of their arrival.

The V0A is placed on the opposite side of the muon spectrometer at 340 cm

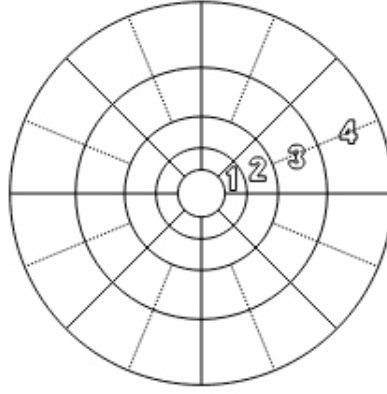


Figure 2.9: Segmentation of the V0A and V0C arrays [18].

away from the vertex, whereas V0C is placed 90 cm from the vertex on the front face of the hadronic absorber as shown in Fig. 2.10.

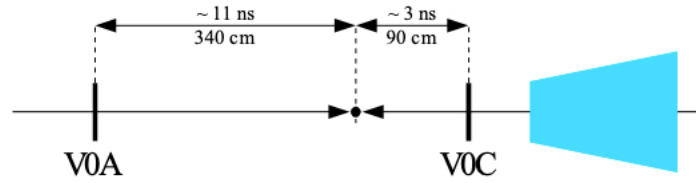


Figure 2.10: Location of V0A and V0C from interaction point [18].

The pseudorapidity range covered by the V0A and V0C are $2.8 < \eta < 5.1$ and $-3.7 < \eta < -1.7$, respectively. They are divided into counters that are arranged in four rings. During normal operation, both V0A and V0C (AND mode) are required to provide triggers. The centrality is calculated by adding the energy deposited in the two VZERO disks. Energy deposition is proportional to the number of primary particles produced in the collision and, as a result, to the centrality. In the Van Der Meer scans method, V0 detector is taken as reference to calculate the shape and size of the colliding ion beams and, as a result, the luminosity is measured for the experiment.

2.1.3.4 Zero Degree Calorimeter (ZDC)

The Zero Degree Calorimeter (ZDC) [19] measures the energy of spectator nucleons so that the overlap region for nucleus-nucleus collisions can be determined. The ZDC consists of two identical sets of calorimeters located on either side of the interaction point IP2, 112.5 meters away from it. In that region, two beams are circulated in two different pipes. Each set of calorimeters consists of neutron (ZN) and proton (ZP) calorimeter. The ZN is positioned with respect to the LHC axis at zero degrees, between the two beam pipes, whereas the ZP is external to the outgoing beam pipe. The ZDC, enables us to select the minimum bias events and measures the centrality of the heavy-ion collisions from the spectator nucleons, as well as measuring the event plane using the neutron spot on the ZN front face.

2.1.4 Muon Spectrometer

The ALICE muon spectrometer measures the spectrum of heavy quarkonia ($J/\psi, \psi', \gamma, \gamma', \gamma''$) as they decay in the $\mu^+\mu^-$ channel. The spectrometer pseudorapidity acceptance is $2.5 < \eta < 4$ and it is capable of measuring the resonances down to zero transverse momentum. Dimuon spectrometer [20] consists of an absorber to filter out background, tracking chambers in front, inside and after the magnet, and triggering chambers. The front absorber uses carbon and concrete to reduce multiple scattering and energy loss of muons coming from the interaction vertex. It suppresses all particles except muons. A tracking system consists of 10 cathode pad/strip chambers that are arranged into 5 stations of two chambers each. In order to provide the required spatial resolution, all the chambers are made from composite materials ($< 3\%$ X0 (radiation length) per chamber) to minimize muon scattering. The trigger system is used to select heavy quark resonance decays. It selects muons based on their transverse-momenta (p_T). Four RPCs (Resistive Plate Chambers) in two-station arrangement are built behind a passive muon filter, which provides transverse momentum. The dipole magnet is located about 7 m from the interaction vertex, making it one of the world's largest warm dipoles. Its magnetic

field is governed by the requirements of the mass resolution.

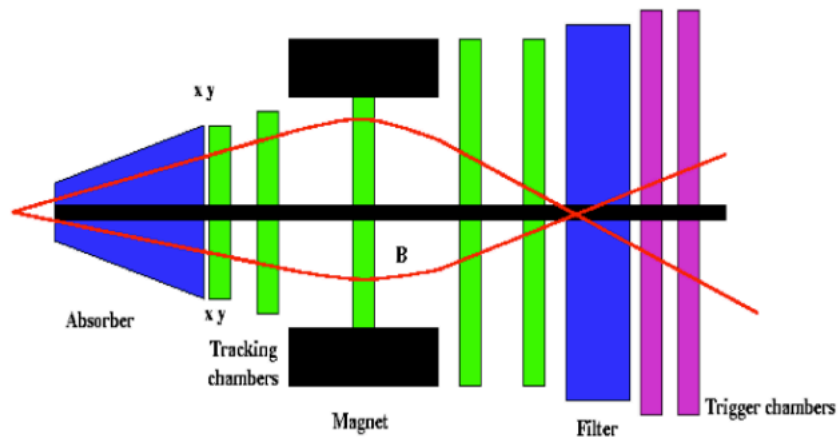


Figure 2.11: Schematic diagram showing main components of muon spectrometer.

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Chapter 3

ϕ meson production at mid-rapidity in p-Pb collisions

The resonances are short lived particles having life time (τ) around few fm/ c and they decay into their daughter particles by strong interaction. The resonances are produced in the expanding medium, and they can decay while traveling through the medium. As a result, the resonance can be used to understand various in-medium phenomena and to study system evolution on different time scales. Particle production in p-Pb collisions, in contrast to pp, is expected to be sensitive to nuclear effects in the initial state. The role of the initial and final state effects can be understood from the measurement of identified particle spectra. The ϕ meson has the following properties: mass = 1019.46 ± 0.02 MeV/ c^2 , width = 4.16 fm/ c , lifetime = 46.4 fm/ c , quark content = $s\bar{s}$, and it decays to K^+K^- with branching ratio 49.2%. The lifetime of ϕ ($\tau = 46.4$ fm/ c) meson is approx. 10 times higher than the K^{*0} ($\tau = 4.16$ fm/ c). Measurements of $\phi(1020)$ meson production along with $K^{*0}(896)$ will help to study the re-scattering and regeneration effects in hadronic phase. The ϕ meson has net strangeness zero ($s\bar{s}$), whereas recent ALICE measurements suggest that it behaves like a particle having strangeness 1 or 2 [1]. The multiplicity dependent study of ϕ meson production in p-Pb collisions will give insight on strangeness production mechanism in small system. Additionally, multiplicity dependent ϕ meson produc-

tion in p-Pb collisions would be useful in understanding the particle production mechanism from pp to A-A collisions. In this chapter, we present the measurements of $\phi(1020)$ mesons production in p-Pb collisions at $\sqrt{s_{\text{NN}}} = 8.16$ TeV by using the ALICE detector at the LHC. The measurements are performed for various multiplicity classes including the minimum bias spectrum. The yield of $\phi(1020)$ mesons is extracted from kaons (K^+K^-) invariant mass distribution as a function of transverse momentum. The obtained results are also compared with various model predictions. The details of the analysis technique are discussed in the following sections.

3.1 Analysis Details

The measurement of ϕ mesons production are performed by using the data taken during LHC run 2 in 2016 for p-Pb collisions at $\sqrt{s_{\text{NN}}} = 8.16$ TeV. Invariant-mass technique is used to reconstruct the resonances from their decay products. The used decay channel for ϕ meson in this study is K^+K^- having branching ratio 49.2% [2,3]. In the p-Pb configuration, the ^{208}Pb beam with energy of 2.56 TeV per nucleon collides with a proton beam with an energy of 6.5 TeV resulting in collisions at a nucleon-nucleon center-of-mass energy $\sqrt{s_{\text{NN}}} = 8.16$ TeV [3]. The p-Pb collision system is asymmetric as a result there is a shift in the rapidity in the center-of-mass frame $\delta y = -0.465$ in the direction of the proton beam with respect to the laboratory frame [3]. The measurements are performed in the rapidity range $-0.5 < y < 0$ for various multiplicity classes along with a multiplicity-integrated class. Here, ‘ y ’ corresponds to the center-of-mass rapidity.

3.1.1 Event selection

The analysis is performed with 29 M minimum bias events selected after implementation of all event selection criteria in p-Pb collisions at $\sqrt{s_{\text{NN}}} = 8.16$ TeV with ALICE at the LHC. The minimum bias events are selected using the kINT7 trigger. The trigger was configured to select events by requiring at least a coincidence signal

in both the V0A and V0C detector. The V0 detector system consists of two arrays of 32 scintillator detectors, one on each side of the interaction point covering the full azimuthal angle in the pseudorapidity regions $2.8 < \eta < 5.1$ (V0A) and $-3.7 < \eta < -1.7$ (V0C) [4,5]. Through the use of timing information from the V0 and the ZDC, the background events caused by beam-gas interaction and other machinery-induced background collisions are rejected [6]. The primary vertex of a collisions is determined by reconstructing the charged tracks in the ITS [7] and the TPC [8]. We select events whose primary vertex position (V_z) lies within ± 10 cm of the nominal interaction point along the beam axis. The V_z distribution is shown in Fig. 3.1.

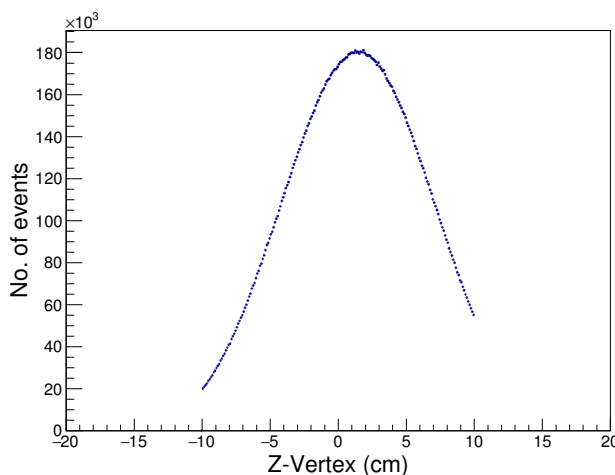


Figure 3.1: The distribution of z-position (V_z) of the vertex in p-Pb collisions at $\sqrt{s_{\text{NN}}} = 8.16$ TeV.

For multiplicity selection V0A detector is used. The multiplicity estimation is based on the V0A amplitude, which is proportional to the ionization energy deposited in the detector in the pseudorapidity range $2.8 < \eta < 5.1$. The V0A amplitudes are fitted by Glauber model convoluted with a Negative Binomial Distribution (NBD), with assumption that $N_{\text{part}}/2$ represents the number of sources, parametrised with k and μ , where k manages the contribution at higher multiplicity and μ is the average multiplicity per source. The V0A amplitude distribution fitted with NBD-Glauber is shown in Fig. 3.2. After the implementation of multiplicity selection, the number of events as a function of multiplicity is shown in Fig. 3.3.

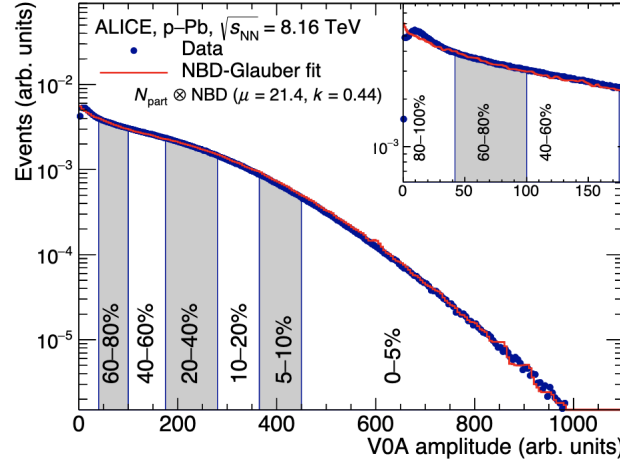


Figure 3.2: Total V0A amplitude distribution (Pb-going side) and the red line shows NBD-Glauber fit in p-Pb collisions at $\sqrt{s_{\text{NN}}} = 8.16$ TeV. Multiplicity classes are indicated by vertical lines and the most peripheral events are also shown by inset plot [5].

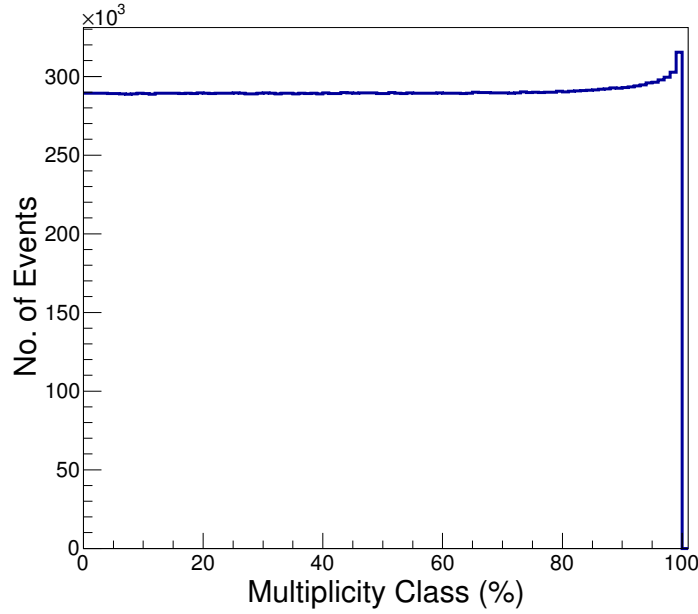


Figure 3.3: Multiplicity class distribution from V0A in p-Pb collisions at $\sqrt{s_{\text{NN}}} = 8.16$ TeV.

The minimum bias (0-100%) events are further divided into multiplicity classes, which are defined as fraction of total charged particle multiplicity. The 5% events with the highest charged particle multiplicity (V0A amplitude) is considered as 0-5% multiplicity class. Similarly the following multiplicity classes are selected: 0-5%(highest multiplicity), 5-10%, 10-20%, 20-40%, 40-60%, 60-80%, and 80-100%(lowest multiplicity). The mean charged particle multiplicity densities ($\langle dN_{\text{ch}}/d\eta \rangle$) for various multiplicity classes are given in Table 3.1. All the event cuts implemented in the analysis are listed below [9]:

1. kINT7 trigger.
2. InComplete Data Acquisition (DAQ) check. It is used to check if DAQ has set the incomplete event attributes.
3. Pileup Rejection using AliAnalysisUtils::IsPileUpEvent(). The events are rejected which have multiple vertices while reconstruction in the SPD.
4. SPD Cluster vs Tracklet Check using AliAnalysisUtils::IsSPDClusterVsTrackletBG() with default parameters. It is used to check the correlation between number of clusters and number of tracklets.
5. Event has a track or SPD primary vertex identified. Events that have a primary collision vertex that has been reconstructed using the SPD detector are chosen.
6. SPD vertex-z resolution < 0.25 cm. This cut is optimized for successfully matching tracks between the ITS and the TPC and reject the events with poor vertex-z resolution.
7. SPD vertex dispersion < 0.04 . This is the size of the window opened to define the tracklets used in the determination of the vertex.
8. z-position difference between track and SPD vertex < 0.5 cm. This cut is applied to reject events with badly reconstructed track vertex, typically events with true collision at very large z with badly reconstructed track vertex.
9. Vertex-z position : $|v_z| < 10$ cm. This v_z cut value is optimized using the real data and Monte Carlo (MC) simulation and it is varied while estimating the systematic uncertainty.

Table 3.1: The mean charged particle multiplicity densities ($\langle dN_{\text{ch}}/d\eta \rangle$) measured in pseudorapidity range $|\eta_{\text{lab}}| < 0.5$, corresponding to the various multiplicity classes defined using V0A detector in p-Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV [5].

V0A multiplicity classes (in %)	$\langle dN_{\text{ch}}/d\eta \rangle_{ \eta_{\text{lab}} < 0.5}$
0-5	53.22 ± 1.38
5-10	42.40 ± 1.10
10-20	35.49 ± 0.92
20-40	26.89 ± 0.70
40-60	18.39 ± 0.48
60-80	10.97 ± 0.29
80-100	4.47 ± 0.14

3.1.2 Track selection and particle identification

The ϕ meson is reconstructed by invariant mass technique using charged K tracks, known as primary track as they are originated from the collision vertex. Using track selection criteria, we aim at limiting the contamination caused by secondary particles, maximizing tracking efficiency, enhancing dE/dx and momentum resolution, and ensuring optimal particle identification (PID) quality. The charged tracks coming from the primary vertex are selected within the pseudorapidity interval $|\eta| < 0.8$ with $p_T > 0.15$ GeV/ c . This ensures the uniform acceptance for the central barrel detectors. A Kalman filter algorithm is used to reconstruct primary tracks using the ITS and TPC detectors. The tracks are refitted from TPC outermost layer to the ITS innermost layer and extended upto primary vertex and vice versa. The track should have signal in one of the SPD layers, track is reconstructed from the hits in the detector and it is fitted with a set of measurements. The value of the obtained χ^2 per cluster must be less than 36. The contamination from secondary particles originating from weak decays and beam background events are reduced by applying a selection on the distance of closest approach to the primary vertex in the transverse plane (DCA_{xy}) and along the longitudinal direction (DCA_z). A p_T -dependent cut of $\text{DCA}_{xy} (p_T) < (0.0105 + 0.035 p_T^{-1.1})$ cm, with p_T in GeV/ c , is used, which is less than 7 times p_T resolution. The track DCA_z is required to be less than 2 cm along the beam direction. The charged tracks are selected which have crossed

at least 70 out of maximum 159 horizontal segments along the transverse readout plane of the TPC having χ^2 per cluster value less than 4, obtained from TPC cluster fitting. Additionally, a cut on the ratio of crossed rows over findable clusters (> 0.8) is implemented in the TPC. The kink daughter tracks are also rejected for ensuring good quality tracks.

The identification of charged particles are perform by using TPC [10] and TOF [10] detectors. The particle identification of decay daughters (kaons) of ϕ meson in TPC is based on the dE/dx of each particle in the medium of the TPC and particles are identified by their time of flight information in TOF. A p_T -dependent PID cuts are applied in TPC with wider PID ($n\sigma_{\text{TPC}}$) cut at low momentum. The charged tracks are identified as kaons if the specific energy loss measured by TPC is within $6\sigma_{\text{TPC}}$, $3\sigma_{\text{TPC}}$ and $2\sigma_{\text{TPC}}$ from the expected $\langle dE/dx \rangle$ values in the momentum range $p < 0.3 \text{ GeV}/c$, $0.3 < p < 0.5 \text{ GeV}/c$ and $p > 0.5 \text{ GeV}/c$, respectively. In addition to the TPC, if the TOF information is available, the charged tracks are identified by requiring the time-of-flight values within $3\sigma_{\text{TOF}}$ of the expected values for the full momentum range. If track information is not available in TOF, no TOF cut is applied. σ_{TPC} denote the dE/dx resolution of TPC and it is expressed as,

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

where dE/dx_{measured} is average energy loss of kaon track measured inside TPC, dE/dx_{expected} is the expected energy loss of kaon track, measured using modified Bethe-Bloch function [11].

In the TOF detector, the combined information of time measurement from TOF, momentum, and track length from the tracking detector (TPC and ITS) is used to calculate the particle mass or identification of the particle. The T0 detector is used to measure the start time (collision time) for every event. $n\sigma_{\text{TOF}}$ is expressed as:

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

where t_{measured} is the flight time of the particles measured in the TOF detector and t_{expected} is the expected time measured from the momentum and track length considering that the track is of kaon particle. The σ_{TOF} is time resolution of TOF and its value is around ~ 56 ps.

3.2 Signal Extraction

The ϕ meson signal is extracted by invariant mass method from their decay daughters through hadronic decay channel ($\phi \rightarrow K^+K^-$) with branching ratio 49.2% at mid-rapidity ($0.5 < y < 0$). The invariant mass of ϕ meson is reconstructed with four momentum of K^+ and K^- . The Invariant mass distribution in terms of energy and momentum is expressed as,

$$M_{KK} = \sqrt{(E_{KK} + E_{KK})^2 - |\vec{p}_{KK} + \vec{p}_{KK}|^2} \quad (3.3)$$

Where E is the energy and $\vec{p}$ is the momentum of the kaon (K) particle.

The invariant mass distribution of unlike charged pairs (K^+K^-) from same events in 0-100% p-Pb collisions for $0.6 \leq p_T < 0.8$ GeV/ c at mid rapidity is shown in Fig. 3.4. Since not all charged $K^\pm$ in each event originate from the ϕ meson decays, the ϕ meson signal extracted in this way sit above a large combinatorial background of uncorrelated pairs. The combinatorial background constructed through the invariant mass of $K^\pm$ from one event is paired with $K^\mp$ from other events. To minimize effects from statistical fluctuations, each event is mixed with five other events. The two events that are mixed must have similar characteristics in order to reproduce the combinatorial background. The events which are mixed should have z-vertex difference within 1 cm. Effects from multiplicity fluctuations are minimized by selecting two events to be mixed with a multiplicity difference less than 5. The mixed event distribution statistics are five times higher than the same event signal distribution. The mixed event background is normalized to the same event signal distributions in the range $1.04 < m_{KK} < 1.15$ GeV/ c^2 , which is away

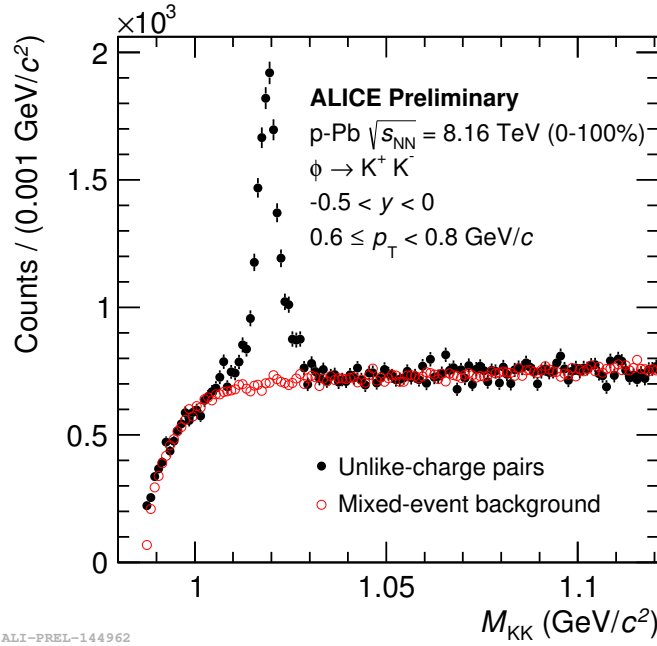


Figure 3.4: Invariant mass distribution for ϕ meson in the multiplicity class 0-100% and transverse momentum range $0.6 \leq p_T < 0.8$ GeV/c in p-Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV. The unlike charge (KK pair) invariant mass distribution is shown by solid marker and normalized mixed event background is shown by open marker.

from signal peak. The invariant mass distribution of unlike $K^\pm$ of both same events and normalized mixed event background is shown in Fig. 3.4

The ϕ meson signal peak is extracted by subtracting the normalized mixed event combinatorial background from the same event invariant mass distribution. The extracted signal peak still left with some background, known as residual background. The residual background arises due to correlated pairs from jets, misidentification of the decay daughters of resonances and decay of other particles [12]. At low momentum, the dE/dx bands for charged particles are clearly separated and particles can be cleanly identified. However, as the momentum increases, the bands start to overlap and therefore the $n\sigma$ cut imposed for kaon identification also allows a fraction of electron, pion and protons to be included as kaon candidates in the signal distribution. This contributes to the residual background remaining after the subtraction of mixed events.

The ϕ meson signal peak is fitted with a Voigtian function (convolution of

Breit-Wigner and Gaussian functions) and a second order polynomial function is used to describe the shape of the residual background. The Voigtian function along with 2nd order polynomial function is described as,

$$f(m_{KK}) = \frac{Y\Gamma}{2\pi^{3/2}\sigma} \int_{-\infty}^{\infty} \exp\left(\frac{(m_{KK} - m')^2}{2\sigma^2}\right) \frac{dM_{KK}}{(M_{KK} - M_0)^2 + \frac{\sigma^2}{4}} + AM_{KK}^2 + BM_{KK} + C \quad (3.4)$$

Where M_0 , Γ and σ are the mass, width and mass resolution of ϕ meson. Y parameter corresponds to the area under the Voigtian distribution and will give ϕ meson raw yield. Figure. 3.5 shows ϕ meson signal fitted with Voigtian function after mixed event background subtraction in 0-100% p-Pb collisions. The width is fixed to PDG value and resolution is kept as free parameter while fitting the signal. The resonance peak position and resolution as a function of p_T from the signal fitting function is shown in Fig. 3.6 and Fig. 3.7. The significance of signal peak is ratio of peak integral divided by $\sqrt{\text{signal} + \text{background}}$ and it is shown in Fig. 3.8. The ϕ meson signal peak is observed from $p_T = 0.4$ GeV/ c upto 16 GeV/ c . The signal at low p_T ($p_T < 0.4$ GeV/ c) is not considered due to low significance of signal peak. The upper limit of p_T changes with multiplicity classes according to the available statistics.

3.2.1 Raw yield extraction

Raw yield can be extracted from bin counting method and function integration. The width was fixed to PDG value for each p_T bin and resolution was taken as free parameter, therefore a systematic error is added to the final spectra keeping width as a free parameter and fixed resolution. The yield of ϕ meson is calculated using two different methods: Bin counting and function integration, where bin counting is used as default and function integration is used for systematic study.

Bin Counting (Y_{BC}) :

To extract the yield, first we integrate the invariant-mass histogram (after the combinatorial background subtraction) over the region (1.011, 1.028) GeV/ c^2 and then

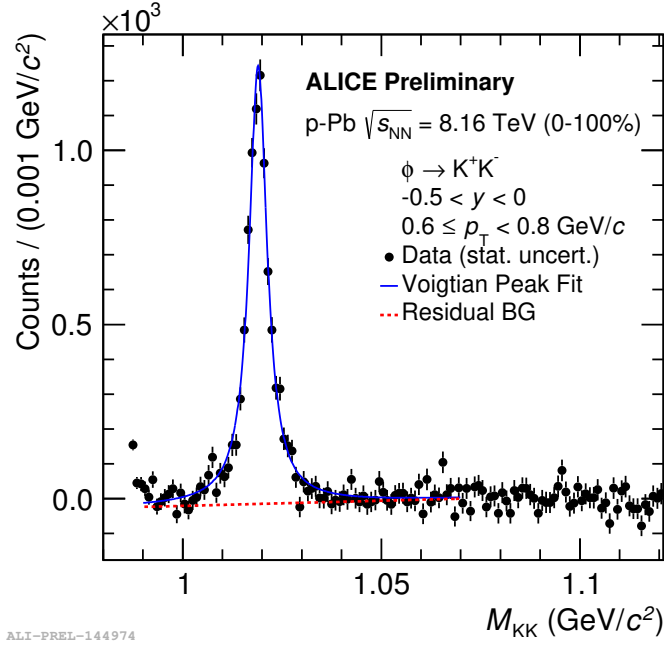


Figure 3.5: Invariant mass distribution for ϕ meson after mixed event background subtraction in the multiplicity class 0-100% and transverse momentum range $0.6 \leq p_T < 0.8$ GeV/c in p-Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV. The signal peak is fitted by a Voigtian function and the residual background is fitted by 2nd order polynomial function.

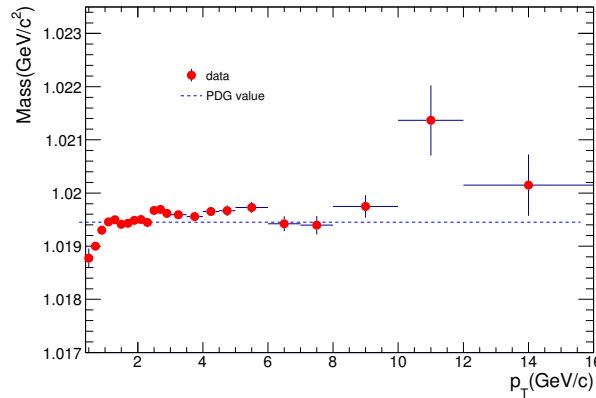


Figure 3.6: ϕ meson mass as a function of p_T for p-Pb collision at $\sqrt{s_{NN}} = 8.16$ TeV in multiplicity class (0-100%). The dashed line represents the PDG value 1019.45 MeV/c².

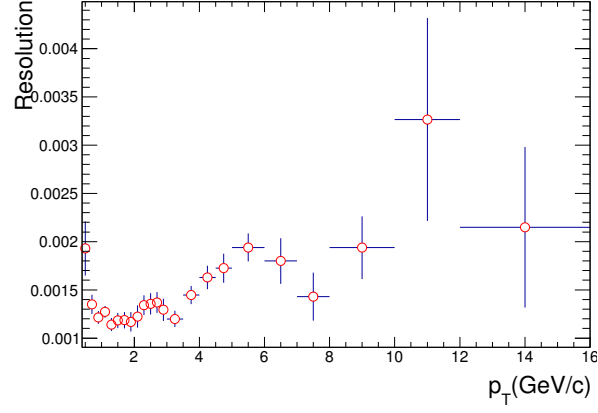


Figure 3.7: ϕ meson resolution as a function of p_T for p-Pb collision at $\sqrt{s_{NN}} = 8.16$ TeV in multiplicity class (0-100%).

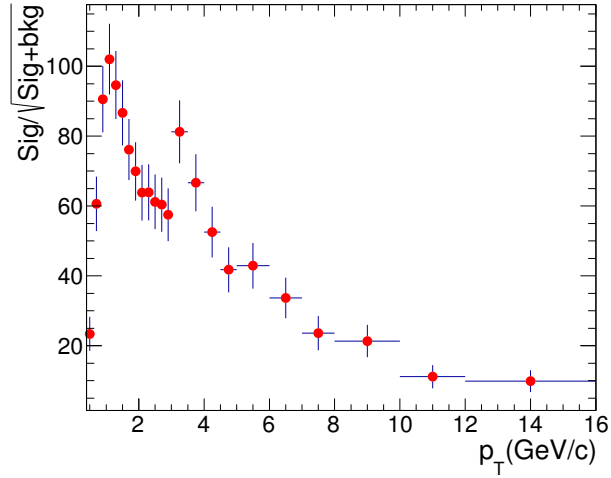


Figure 3.8: ϕ meson significance as a function of p_T for p-Pb collision at $\sqrt{s_{NN}} = 8.16$ TeV in multiplicity class (0-100%).

we subtract the integral of the residual background contribution (from the polynomial function used to describe the residual background) over the same interval from the integrated yield.

$$N_{raw} = N_{counts} - N_{RB} \quad (3.5)$$

Where N_{counts} : total number of counts in signal histogram in mass bins which satisfy condition lower value (lval) $\leq$ Bin Center $\leq$ upper value (hval) (These lower and upper values are equivalent to $M(\text{PDG}) - 2\Gamma$ and $M(\text{PDG}) + 2\Gamma$ respectively). N_{RB} : integral of the polynomial (used for residual background) in the same mass range mentioned above. As we only count the yield in a limited mass range ($M(\text{PDG}) - 2\Gamma$ and $M(\text{PDG}) + 2\Gamma$) so we need to correct the same for the tail part. To correct the tail part of the signal we adopt two different methods. We estimate the tail contribution from the peak fit function in the mass region $(2M_{K^+}) < m_{inv} < 1.011 \text{ GeV}/c^2$ and $1.028 < m_{inv} < \infty \text{ GeV}/c^2$

$$N_{low} = \int_{M_K + M_K}^{M_{PDG} - 2\Gamma} fit(m_{inv}) dm_{inv} \quad (3.6)$$

$$N_{high} = \int_{M_{PDG} + 2\Gamma}^{\infty} fit(m_{inv}) dm_{inv} \quad (3.7)$$

We added the lower and the higher invariant mass tail contribution to the bin counting yield. The final yield is :

$$Y_{BC1} = N_{low} + N_{raw} + N_{high} \quad (3.8)$$

The uncertainty in Y_{BC1} is quadratical sum of the uncertainty in N_{low} , N_{raw} and N_{high} .

Function Integral (Y_{Fl}) :

The yield is extracted by integrating the peak fitting function over the region

$$2M_{K^+K^-} < m_{inv} < \infty$$

$$Y_{Fl} = \int_{M_K + M_\pi}^{\infty} fit(m_{inv}) dm_{inv} \quad (3.9)$$

The raw yield of ϕ meson as a function of p_T measured by integral and bin counting method is shown in Fig. 3.9.

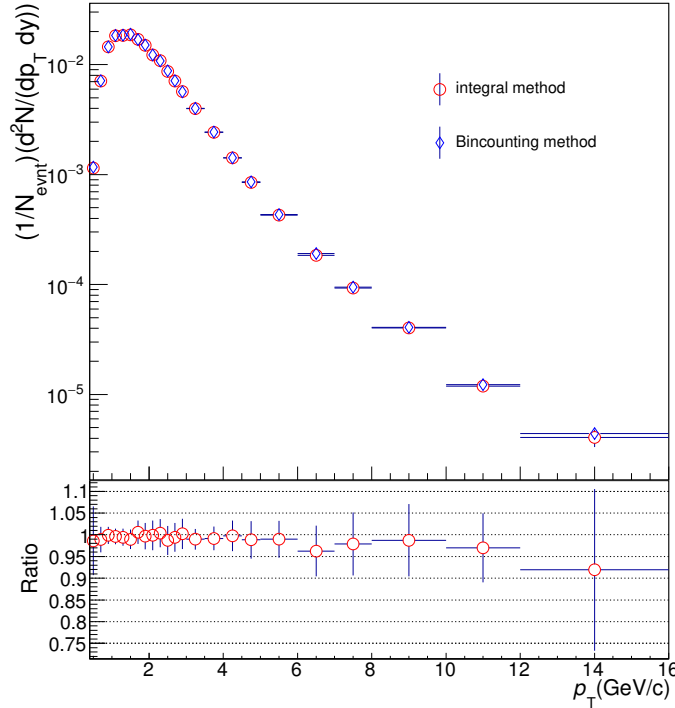


Figure 3.9: The raw spectrum of ϕ meson as a function of p_T in multiplicity class (0-100%) p-Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV.

3.3 Raw Yield Correction

Due to inefficiency of detector we need to apply some correction factors like efficiency, acceptance to the measured ϕ meson yield. These factors can not be obtained from the real data. So a simulated data set is analyzed in order to extract the ϕ meson reconstruction efficiency times acceptance.

In this study we use the MC production, which is produced by DPMJET event

generator, while the particle interactions with the ALICE detector are simulated using GEANT3. The tracks which are identified by the reconstruction algorithms and which pass the track selection and PID cuts (same as in real data) are referred to as reconstructed tracks. A Tune On Data option (to ensure same processes as in real data) is used in simulation while selecting the kaons.

The reconstructed efficiency is defined as the ratio between number of ϕ mesons reconstructed to the number of ϕ mesons generated in each transverse momentum bin. The Efficiency $\times$ Acceptance is expressed as:

$$\epsilon_{rec} = \frac{N_{reconstructed}}{N_{generated}} \quad (3.10)$$

The $N_{reconstructed}$ are the reconstructed ϕ meson which include the detector effect, pass the analysis cut and reconstructed algorithms and $N_{generated}$ are the generated ϕ meson by the event generator DPMJET. Both number are counted within a rapidity region of $-0.5 < y < 0$. The reconstructed efficiency is shown in the Fig. 3.10. It has strong dependence on transverse momentum at low p_T . The uncertainty in ϵ_{rec} is calculated using the Bayesian approach described in [13]. The standard deviation in an efficiency $\epsilon_{rec} = k/n$, where the numerator k is a subset of the denominator n , is:

$$\sigma_{\epsilon} = \sqrt{\frac{k+1}{n+2} \left(\frac{k+2}{n+3} - \frac{k+1}{n+2} \right)} \quad (3.11)$$

The fractional statistical uncertainty in ϵ_{rec} is added in quadrature with the statistical uncertainty in the uncorrected ϕ meson yield to give the total statistical uncertainty of the corrected ϕ meson yield. It is to be noted that due to large statistical uncertainties at high p_T , we have used ϵ_{rec} value in the combined p_T bins 6-16 GeV/ c for all $p_T > 6$ GeV/ c . The ϵ_{rec} for all multiplicity classes are found to be similar. The minimum bias (0-100%) efficiency $\times$ acceptance is used to correct all multiplicity classes p_T spectra.

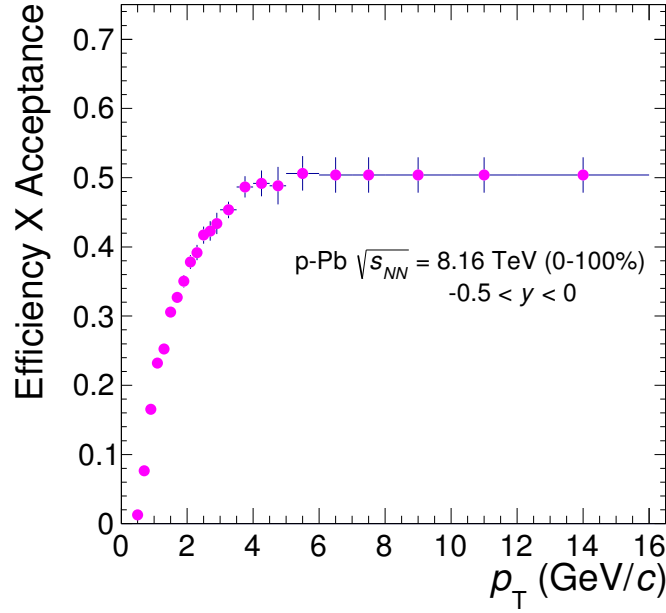


Figure 3.10: The reconstruction efficiency of ϕ meson as a function of p_T in multiplicity class (0-100%).

3.3.1 Re-weighted Efficiency

It is observed that at low p_T the generated ϕ meson spectra has different shape than measured p_T spectra. So it is necessary to weight the generated and reconstructed ϕ meson spectra in these simulation. Thus, a re-weighting procedure is performed on simulated p_T spectra to take into consideration the shape of simulated p_T distributions as well as the change in efficiency $\times$ acceptance across the width of p_T bins at low p_T . Fig. 3.11 shows the generated and reconstructed ϕ meson spectra plotted with the (corrected) measured ϕ meson spectrum and the Levy-Tsallis fit of that measured spectrum. An iterative procedure is performed to determine the correct weighting (and therefore the correct ϵ_{rec}). The procedure is described as follows:

1. The unweighted ϵ_{rec} is calculated.
2. This ϵ_{rec} is used to correct the measured ϕ meson p_T spectrum.
3. The corrected ϕ meson spectrum is fitted with Levy-Tsallis function.
4. This fit is used to weight the MC generated ϕ meson spectra. A p_T dependent weight is applied to the generated ϕ meson spectrum so that it follows the fit (see

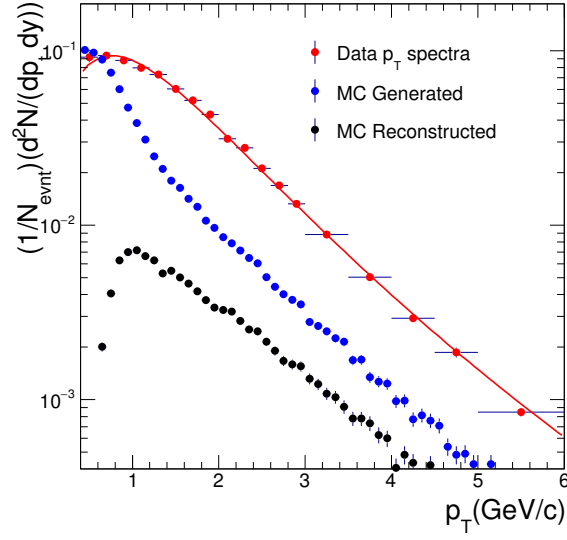


Figure 3.11: The corrected ϕ meson spectrum with Levy-Tsallis fit. Also shown are unweighted generated and reconstructed ϕ meson spectra.

Fig. 3.12). The same weight is applied to the reconstructed ϕ meson spectrum.

5. The (weighted) ϵ_{rec} is calculated.
6. Steps 2-5 are repeated (with the weighted ϵ_{rec} from step 5 used as the input for step 2) until the ϵ_{rec} values are observed to change by $< 0.1\%$ (relative) between iterations. It is observed that two iterations are usually sufficient for this procedure to converge. The procedure is followed as implemented in the macro ALICE PHYSICS/PWGLF/RESONANCES/macros/utis/ReweightEfficiency.C in ALICE software system aliroot. The net effect of the weighting procedure is very small, as shown in Fig. 3.13. Here only upto $p_T = 6$ GeV/c re-weighted procedure is shown as we expected no change in high p_T .

3.3.2 Correction factor for multiplicity distribution

A weighting factor is used in invariant mass distribution for flattening the multiplicity distribution around 80-100% multiplicity class. The weighting factor R_i is obtained as :

1. First we calculate the average number of event (A_{avg}) in (0-80%) multiplicity class
2. Calculate the number of event (N_i) in each multiplicity bins

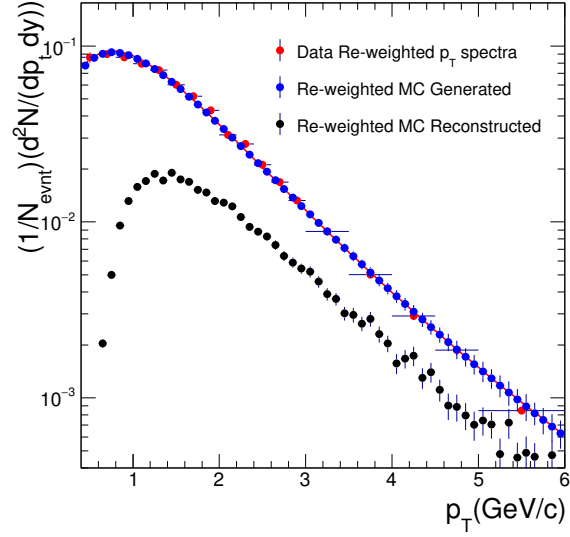


Figure 3.12: The weighted corrected ϕ meson spectrum with Levy-Tsallis fit. Also shown are re-weighted generated and reconstructed ϕ meson spectra after iteration 2.

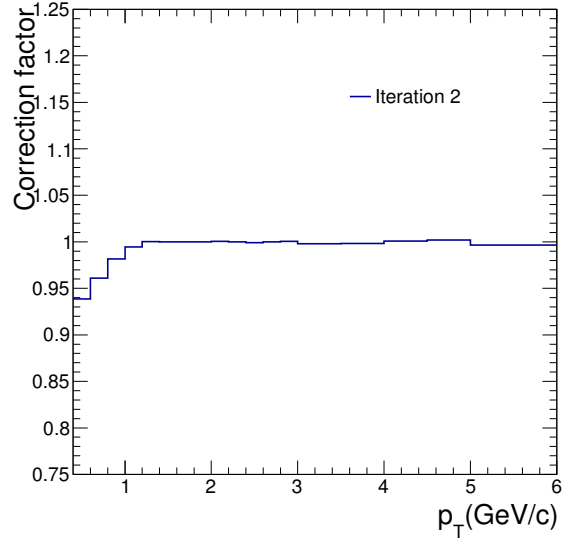


Figure 3.13: Ratio of ϕ meson re-weighted to unweighted efficiency $\times$ acceptance after iteration 2.

from 81 to 100

$$R_i = \frac{A_{avg}}{N_i} \quad (3.12)$$

where i is for multiplicity bins from 81 to 100. So we used R_i to correct the invariant mass distribution and mixed event background for each multiplicity bin in multiplicity class (80-100%). Then combine all the multiplicity bins and after that same procedure as mention above is used to measured the spectra in multiplicity class (80-100%).

3.4 Corrected p_T spectra

The raw spectra is corrected for the efficiency $\times$ acceptance of the detector and branching ratio. The normalized corrected spectra is obtained using the following formula:

$$\frac{d^2N}{dp_T dy} = \frac{RawCounts}{N_{evt} \times BR \times dp_T \times dy \times \epsilon_{rec}} \times f_{norm} \times f_{SL} \times f_{vtr} \quad (3.13)$$

Here BR (branching ratio) = 0.489, dy (rapidity window) = 0.5, ϵ_{rec} is efficiency $\times$ acceptance and the factor f_{norm} represents the normalized correction factor for trigger efficiency and event selection for Non-Single-Diffractive (NSD) events in p-Pb collisions for MB analysis. NSD events include double-diffractive interactions, in which both nucleons break up by producing particles separated by a large rapidity gap, and other inelastic interactions [2,14]. The offline analysis selects events having a coincidence of signals in both V0A and V0C in order to reduce the contamination from single-diffractive (SD) and electromagnetic (EM) events to a negligible amount [2]. The factor f_{SL} accounts for losses of ϕ mesons due to trigger and event-selection cuts. The factor f_{vtr} accounts for the signal loss introduced by the requirement that a primary vertex must be reconstructed.

3.4.1 Signal-Loss Correction and Event-loss Correction

The signal-loss correction factor f_{SL} account for the losses of ϕ mesons due to the use of the kINT7 trigger, which does not select the full sample of inelastic collisions. Applying this factor allows the inelastic p_T spectrum to be recovered. To calculate f_{SL} we define three event selection schemes:

Set A : Generated V_z within ± 10 cm (no other cuts) [for 0-100% (NSD)]

Set B: Trigger selection and generated V_z within ± 10 cm (no other cuts)

Set C: Trigger and all event-selection cuts

The signal-loss correction for 0-100% (NSD) is defined as:

$$f_{SL}(NSD) = \frac{\phi \text{ meson spectrum}|_{\text{setA}}}{\phi \text{ meson spectrum}|_{\text{setC}}} \quad (3.14)$$

The signal-loss correction for multiplicity bins is defined as:

$$f_{SL}(\text{multiplicity}) = \frac{\phi \text{ meson spectrum}|_{\text{setB}}}{\phi \text{ meson spectrum}|_{\text{setC}}} \quad (3.15)$$

In signal-loss correction the numerator and denominator are normalized with the corresponding number of events, so it incorporated the event-loss correction into signal-loss correction.

The signal-loss correction factor for minimum bias (0-100%) is shown in Fig. [3.14](#) and for various multiplicity classes shown in Fig. [3.15](#). We can see that the signal-loss is independent of p_T so we fit the distribution with a constant value. Then the constant value taken as a signal-loss correction factor. The f_{SL} value are shown in Table [3.2](#).

Table 3.2: Signal loss correction factor of minimum bias(NSD) and various multiplicity classes in p-Pb collisions at $\sqrt{s_{NN}}= 8.16$ TeV.

V0A multiplicity classes(in %)	f_{SL}
0-100	0.983
0-5	0.996
5-10	1.01068
10-20	1.0001
20-40	1.0014
40-60	1.001
60-80	1.003
80-100	0.9921

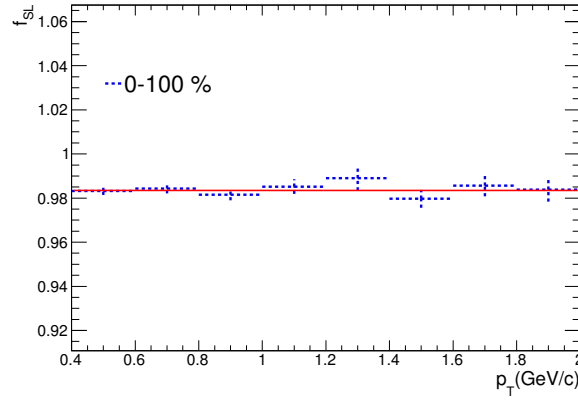


Figure 3.14: Signal-loss correction factor f_{SL} for the ϕ meson in minimum bias (0-100%) is calculated using simulation production. The f_{SL} is fitted with a constant value. The extracted value from the fit is 0.983.

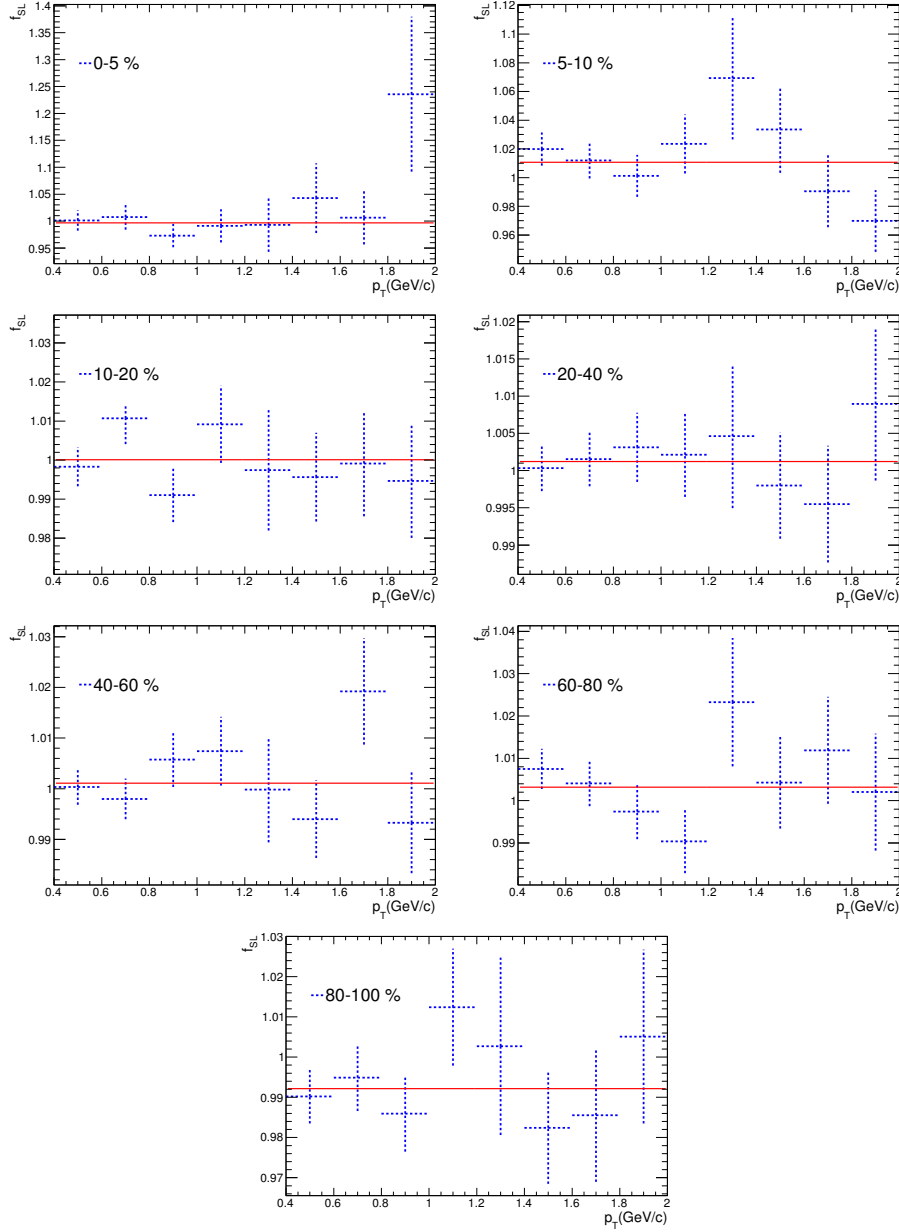


Figure 3.15: Signal-loss correction factor f_{SL} for the ϕ meson in various multiplicity classes is calculated using simulation production. The f_{SL} is fitted with a constant value.

3.5 Systematic Uncertainty

The sources of systematic uncertainties of the measurement of ϕ meson production are signal extraction, track selection criteria, particle identification, global tracking efficiency, uncertainty in the material budget of the ALICE detector and the hadronic interaction cross section in the detector material. The systematic uncertainty due to material budget and hadronic interaction cross section are taken from the ref. [12].

Barlow check [15] is performed to check whether the particular variation is source of systematics uncertainty or the variation is just the statistical fluctuation. If the variation fails the Barlow check, it is considered as source of systematic uncertainty. Systematic error is extracted by following the prescription as described below:

Let us consider two cases, where one measurement is due to the default settings and another is due to the alternative systematic measurements (e.g. normalization range variations). Let us denote the yield in the default case as y_{def} with statistical error σ_{def} and yield in the systematic case as y_{sys} with statistical error σ_{sys} . Then the difference between the yields is denoted as $\Delta = y_{def} - y_{sys}$ and the quadrature difference of their statistical error is $\sigma = \sqrt{\sigma_{def}^2 - \sigma_{sys}^2}$.

Then we define a factor $n = \Delta/\sigma$;

Now, this n is calculated for each p_T bin and a distribution of n or Δ/σ is plotted. In general, if two measurements are consistent, it is expected that the distribution of n would have a mean near 0, a standard deviation near 1. If $n < 1$ then the variation passes Barlow check and is consistent with default measurement with the corresponding statistical error, hence excluded from systematic uncertainties. We consider following steps to do Barlow check:

step1: For a systematic variation we calculate the factor n for each p_T bin.

step2: Plot the histogram or frequency distribution of n [3.16].

step3: If two measurements are statistically consistent then the n distribution should have following criteria:

1) Mean at 0, 2) $RMS < 1.0$, 3) In $|n| < 1$ there will be $> 68\%$ of counts, 4) In $|n|$

<2 there will be > 95% of counts

step4: As the entries are less so a modified criteria is proposed for passing the Barlow check.

- 1) $|\text{Mean}| < 0.3$, 2) $\text{RMS} < 1.1$, 3) In $|n| < 1$ there will be > 58 to 68% of counts,
- 4) In $|n| < 2$ there will be > 65 to 95% of counts.

If any 3 of these above mention criteria is passed for a given source then we consider that the source pass Barlow check.

step5: If a source passes the Barlow checks, we exclude it from systematic uncertainties as the variation is governed by statistical uncertainty.

For more than two variations in a given cut, the systematic uncertainty has been determined as the RMS (eqn. 3.16) of the available measurements otherwise the same is the absolute difference between them. The frequency distribution of n for fitting range source of systematic is shown in Fig. 3.16. Its mean and RMS value are outside the Barlow criteria, so the Barlow check is failed and this source of systematic is included in the total systematic uncertainty.

$$\delta_{sys} = \sqrt{\frac{1}{N} \sum_{i=1}^N (y_{def} - y_i)^2} \quad (3.16)$$

Where δ_{sys} refers to the systematic uncertainty, N is the number of variations for a given source of systematic, y_{def} is the yield in default case, and y_i is the yield for varied source of systematics.

3.5.1 Systematic uncertainty due to signal extraction

The uncertainties due to signal extraction include variations of the signal peak fitting range, variations of width and mass resolution, mixed event background normalization region, choice of residual background function and combinatorial background. The fitting range of the signal peak and the mixed event background normalization

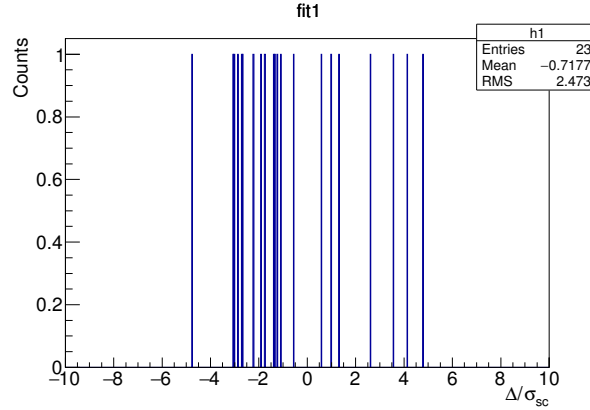


Figure 3.16: Barlow check due to fitting range in 0-100% p-Pb collisions for ϕ meson at $\sqrt{s_{\text{NN}}} = 8.16$ TeV. It fails the Barlow check criteria and included in total systematic uncertainty.

region are varied for systematic uncertainty. The width is taken as free parameter while keeping the resolution parameter fixed to the value measured from monte-carlo simulations. As a result, the changes in the yield with respect to default value is taken in systematic uncertainty. The polynomial function of order 1 and 3 (order 2 taken as default) is used as the residual background function for systematic study. The combinatorial background is varied by like sign method for systematic study, whereas the mixed event method was used as default. The contribution of systematic uncertainties due to the signal extraction is 2.8-4.5% for ϕ mesons.

3.5.2 Systematic uncertainty due to particle identification

For the PID systematic uncertainty, the particle selections based on the TPC dE/dx and TOF time-of-flight are varied. Three variations are taken: (i) Momentum dependent PID selection of $5\sigma_{\text{TPC}}$ ($0 < p < 0.3$), $2.5\sigma_{\text{TPC}}$ ($0.3 < p < 0.5$), $1.5\sigma_{\text{TPC}}$ ($p > 0.5$) with $3\sigma_{\text{TOF}}$, (ii) momentum-independent selection; $2\sigma_{\text{TPC}}$ with $3\sigma_{\text{TOF}}$ and (iii) $2\sigma_{\text{TPC}}$ only. The variation in the yield with respect to default (section 3.1.2) will be consider in systematic uncertainty. This results in systematic uncertainties of 1.9-3.5% for the ϕ meson.

3.5.3 Systematic uncertainty due to track and event selections

The systematic effects due to the charged track selection are studied by varying the criteria based on the number of crossed readout rows in the TPC and the distance of closest approach to the primary vertex of the collision. The variations also include the variations of χ^2 of ITS and TPC refit while reconstruction of the track, and the variations of the cross row over findable clusters in the TPC detector. The relative contribution of uncertainties due to the track selection is about 4.4-5.5%.

3.5.4 Systematic uncertainty due to global tracking

The tracking uncertainty due to the uncertainty in ITS-TPC matching, is derived for the ϕ meson as follows. First of all the single-particle tracking uncertainty is calculated from the momentum information of ϕ meson decay particles and it is taken from p-Pb collision at $\sqrt{s_{NN}} = 5.02$ TeV, shown in Fig. 3.17. Then the two-particle ($\phi \rightarrow K^+K^-$) uncertainty is derived from the single-particle uncertainty through weighting. A DPMJET simulation is used to find the p_T distributions of the ϕ decay daughters as functions of the ϕ meson transverse momentum. These decay-daughter distributions are then used to obtain the weighted average of the tracking uncertainty for each ϕ meson transverse-momentum bin. The calculation is also weighted so that the simulated ϕ meson p_T spectrum has a realistic shape. Let $w(p_{T\phi})$ be the ratio between the measured and generated ϕ meson p_T spectra. Let $u(p_T)$ be the single-particle tracking uncertainty. Let p_{T1} and p_{T2} be the transverse momenta of the first and second decay daughters of each simulated ϕ meson. Let $N(p_{T\phi}, p_{T1}, p_{T2})$ be the number of ϕ with $p_{T\phi}$ that decay to kaons with p_{T1} and p_{T2} . The two-particle tracking uncertainty is the ratio of two histograms (a weighted average):

Numerator : the sum, for all generated ϕ mesons, $N(p_{T\phi}, p_{T1}, p_{T2}) w(p_{T\phi})$

$$(u(p_{T1}) + u(p_{T2})).$$

Denominator : the sum, for all generated ϕ mesons, $N(p_{T\phi}, p_{T1}, p_{T2})w(p_{T\phi})$.

The calculation assumes that the tracking-efficiency uncertainties of the two decay daughters are fully correlated. The uncertainty are shown in Fig. [3.17](#)

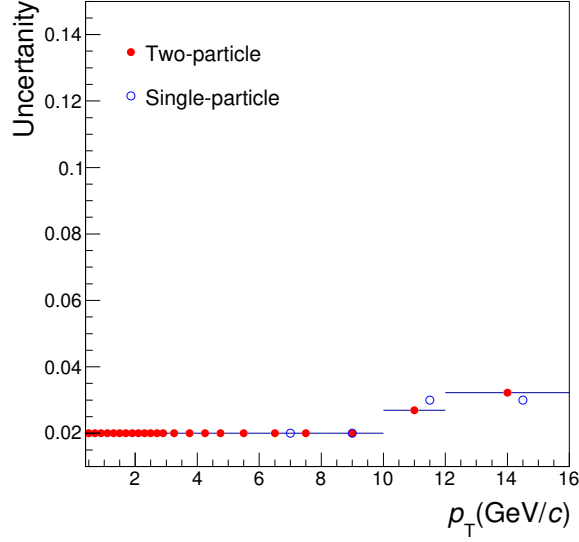


Figure 3.17: The two-particle Global tracking efficiency uncertainty (solid marker) and single-particle Global tracking efficiency uncertainty (open marker) as function of p_T for p-Pb collision at $\sqrt{s_{NN}} = 8.16$ TeV and $\sqrt{s_{NN}} = 5.02$ TeV, respectively.

The systematic uncertainties exhibit a few fluctuations from bin to bin, While one might expect a smooth behavior of the systematic uncertainties. We smoothed the dips and spikes in systematic uncertainties by averaging over the nearest bins in order to obtain a more uniform set of systematic uncertainties. The each source of systematic uncertainty is smoothed individually.

The total systematic uncertainty is the quadrature sum of all sources. For the systematic study we repeat the measurement by varying one parameter at a time. A Barlow check has been performed for each measurement to verify whether it is due to a systematic effect or a statistical fluctuation. It is observed that yield extraction by integral method and residual background function polynomial 3 pass the Barlow check so we exclude these two variations for systematic uncertainty. The total systematics uncertainties including contribution from various source of

Table 3.3: The sources of systematic uncertainties for ϕ meson yields in p-Pb collisions at $\sqrt{s_{\text{NN}}} = 8.16$ TeV. For each source the average uncertainties are listed for low and high p_{T} interval.

Systematic variation	ϕ	
	p_{T} (GeV/ c)	
	0.4–4.0	4.0–16
Yield extraction (%)	2.8	4.5
Track selection (%)	4.4	5.5
Particle identification (%)	1.9	3.5
Global tracking efficiency (%)	2.0	2.3
Material budget (%)	2.2	< 0.5
Hadronic Interaction (%)	2.4	< 1
Total (%)	6.7	8.3

systematics after smoothing of 0-100% p-Pb collisions is shown in Fig. 3.18. It is observed that no multiplicity dependence in systematic uncertainty is found, so 0-100% total systematic uncertainty is propagated in various multiplicity classes. A summary of total systematic uncertainty are listed in Table 3.3 for low and high p_{T} interval.

3.5.5 Systematic uncertainty on integrated yield due to extrapolation

The ϕ meson yield is extrapolated in the unmeasured region ($p_{\text{T}} < 0.4$ GeV/ c) by fitting a Levy-Tsallis function [34] to the measured p_{T} spectra in all multiplicity classes. The difference of yields contribution at low p_{T} due to different fitting function (i.e Exponential, Boltzmann, m_{T} -exponential, Bose-Einstein and Boltzmann-Gibbs Blast-Wave function) compared to Levy-Tsallis function are included in systematic uncertainties. The relative contribution of uncertainties due to different fitting function is about 2-3%.

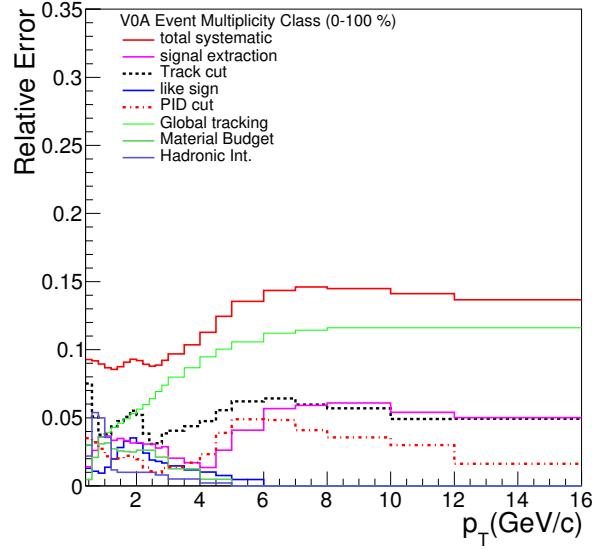


Figure 3.18: Total systematic uncertainty as a function of p_T for p-Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV in the multiplicity class (0-100%). The red solid line represent the total systematic uncertainty. The different color lines represents the different sources of systematic uncertainty.

3.5.6 Uncorrelated systematic uncertainty among multiplicity classes

A study is performed in order to extract the component uncorrelated across multiplicity for each class. The same variation in the selection criteria will generally cause similar spectrum deviations for different multiplicity classes. This is because the error is largely correlated across multiplicity. However a fraction of the total error could be dependent on the multiplicities considered. To isolate that part, particular deviations are compared to the ones in the minimum bias sample. We follow the same procedure adopted in p-Pb at $\sqrt{s_{NN}} = 5.02$ TeV [12]. The following ratio will determine the uncorrelated component of the total systematic uncertainty for each selection cut in a given multiplicity class i :

$$R = \frac{Y_{modified-cut}^{Mult-i}}{Y_{default-cut}^{Mult-i}} / \frac{Y_{modified-cut}^{MB}}{Y_{default-cut}^{MB}} \quad (3.17)$$

This ratio R is evaluated for each source of systematic uncertainty discussed

above. The factor $|1 - R|$ is the part of systematic uncertainty which is uncorrelated over p_T . The quadratic sum of all the contributions gives the fraction of systematic uncertainty which is uncorrelated over multiplicity. The fraction of systematic uncertainty uncorrelated over multiplicity is shown in Figure 3.19 for all multiplicity classes. The main contribution of multiplicity uncorrelated systematic uncertainties are from yield extraction and the cut variations are (i) Fit Range, (ii) Normalization range, (iii) Free Width, and (iv) Residual background variations.

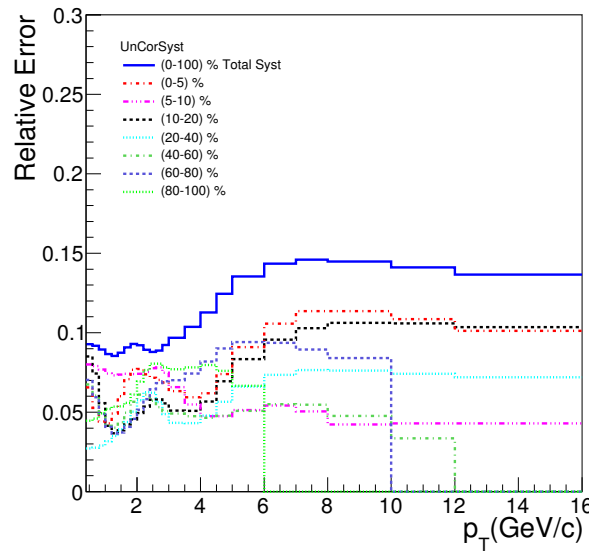


Figure 3.19: Uncorrelated systematic uncertainty in various multiplicity classes with respect to minimum bias systematic uncertainty as function of p_T . The blue solid line represents the total systematic uncertainty for 0-100% multiplicity class. The dashed color lines represent the maximum uncorrelated systematic uncertainty for various multiplicity classes.

3.6 Results and discussion

3.6.1 Transverse momentum spectra

The measurement of ϕ meson production performed in the rapidity interval $-0.5 < y < 0$ up to $p_T = 16$ GeV/c in p-Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV [1]. The NSD corrected spectra are fit with a Levy-Tsallis function [17,18] described below.

This function gives a good description of data for both the exponential shape of the spectrum at low p_T and the power-law distribution at high p_T , quantified by the inverse slope parameter T and the exponent parameter n .

$$\frac{d^2N}{dp_T dy} = p_T \times \frac{dN}{dy} \times \frac{(n-1)(n-2)}{nT[nT + m(n-2)]} \left[1 + \frac{m_T - m}{nT}\right]^{-n} \quad (3.18)$$

Where m is the mass of ϕ meson, $m_T = \sqrt{m^2 + p_T^2}$ is the transverse mass, T is inverse slope parameter and n is exponent parameter. The function gives a good description of the data and used to estimate p_T integral yield (dN/dy) and mean transverse momentum ($\langle p_T \rangle$). The function is fit to the spectra over the full p_T range as shown in Fig. 3.20.

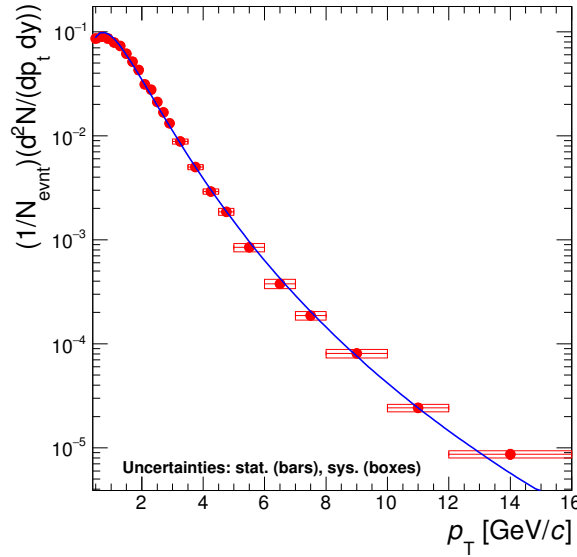


Figure 3.20: The NSD corrected ϕ meson p_T spectrum is fitted with Levy-Tsallis function in p-Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV. The blue solid line represents the Levy-Tsallis function. The statistical and systematic uncertainty on the data points are shown as bars and boxes, respectively.

Figure 3.21 shows the ϕ meson NSD p_T spectrum comparison with the prediction from EPOS-LHC [19, 20], DPMJET [21] and HIJING [22] models. The bottom panel of Fig. 3.21 show the ratios of p_T spectra from these models to the data.

The EPOS MC event generator is a hadronic interaction parton model based

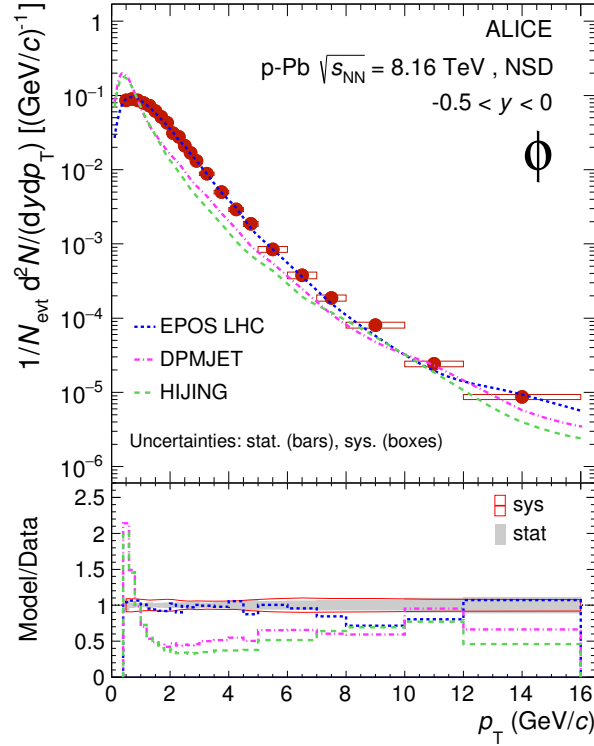


Figure 3.21: Top panel: Transverse momentum spectrum of ϕ meson as a function of p_T for the NSD events, measured in the rapidity range $-0.5 < y < 0$ for p-Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV. The statistical and systematic uncertainties are shown as bars and boxes, respectively. The NSD spectrum is compared to the predictions from EPOS-LHC [19], DPMJET [21] and HIJING [22] models. Bottom panel: The ratios of p_T spectra from model to data. The shaded bands around unity describe the statistical and systematic uncertainties on the data point.

on Gribovs Reggeon field theory formalism which includes the feature of collective hadronization and the core-corona mechanism from pp to AA collisions [23–25]. If the string segments of the final state parton have high energy density that region is known as the core, whereas the region with strings of low energy density surrounding the core is called the corona. The core evolves hydrodynamically and subsequently hadronizes to form the bulk of the system whereas the strings in the corona region break through the production of quark-antiquark pairs, which is hadronized as fragmentation processes in vacuum. EPOS-LHC [19] is a tune of EPOS1.99 [26] that incorporates a parameterization of flow based on LHC data. The EPOS1.99 model is different from EPOS2.x [27] and EPOS3.x [20] as it does not use the complete 3D hydro calculation followed by the hadronic cascade but instead relies on the fast covariant approach. It describes various observables in the minimum bias heavy-ion collisions as well as small collision systems up to a few GeV/c at LHC energies. DPMJET is a QCD-inspired dual parton model based on the Gribov-Glauber approach that treats the soft and hard scattering interaction processes differently. HIJING combines the perturbative QCD process with soft excitation, the production of multiple minijets, the interactions of jets in dense hadronic matter, and nuclear shadowing of parton distribution functions. The EPOS-LHC model, where a different parametrization of flow is introduced in small collision systems like pp than the large volume produced in heavy-ion collisions, gives a better description of the transverse momentum distributions for ϕ meson in p-Pb collisions. The EPOS-LHC model describes the ϕ meson p_T spectrum relatively better than the DPMJET and HIJING for all p_T .

Figure 3.22 shows the $\sqrt{s_{NN}}$ dependence of the transverse momentum spectra of ϕ meson for NSD events in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ and 8.16 TeV. The upper panel of Fig. 3.22 shows a comparison of the transverse momentum spectra of ϕ meson at $\sqrt{s_{NN}} = 5.02$ and 8.16 TeV whereas the lower panel shows the ratio of these spectra and comparison of the ratio with the results obtained from the EPOS-LHC, DPMJET and HIJING model. The uncertainties of the ratios are obtained as the quadrature sum of the uncertainties of the spectra at the two energies, which

are largely uncorrelated. The differential yield ratio seems to be independent of p_T within systematic uncertainties and values are close to unity up to 1 GeV/ c for ϕ meson. This suggests that the particle production in the soft scattering region is not strongly dependent on collision energy. The slope of the differential yield ratios increases as a function of p_T for $p_T > 1$ GeV/ c . Similar behavior is also observed in pp collisions in Ref. [9]. The p_T differential yield ratios obtained from EPOS-LHC, DPMJET, and HIJING are consistent with the measurements within the systematic uncertainties and reproduce well the energy dependence trend for ϕ meson in p-Pb collisions

Figure 3.23 shows the transverse momentum distributions of ϕ meson in various multiplicity classes. The ratios of p_T spectra in various multiplicity classes to the p_T spectrum for NSD events are shown in the bottom panel of Fig. 3.23. For $p_T < 4$ GeV/ c (bottom panel of Fig. 3.23), the inverse slopes of the p_T spectra increase from low to high multiplicity classes, whereas the spectral shapes are similar at high p_T for all multiplicity classes. This indicates that processes like radial flow, which lead to a change in the shape of the p_T spectra for various multiplicity classes, dominate mainly at low p_T [29]. The increase in the inverse slope of p_T spectrum with multiplicity is reflected in Fig. 3.24 for $\langle p_T \rangle$ as a function of multiplicity. A similar behavior was also observed for ϕ meson in p-Pb collisions [12] at $\sqrt{s_{NN}} = 5.02$ TeV. This increase of slope of the p_T spectra with charged particle multiplicity was also reported for inclusive charged hadron spectra, π , K, p, K_S^0 , λ , Σ , and Ω in pp collisions at LHC energies [3, 4, 32, 33], where different models with multi-parton interactions were shown to describe these effects.

3.6.2 Integrated particle yield and mean transverse momentum

The p_T -integrated yields (dN/dy) and mean transverse momentum ($\langle p_T \rangle$), are extracted from transverse momentum spectra in the measured range and using the fit function in the unmeasured region. The ϕ meson yield is extrapolated in the

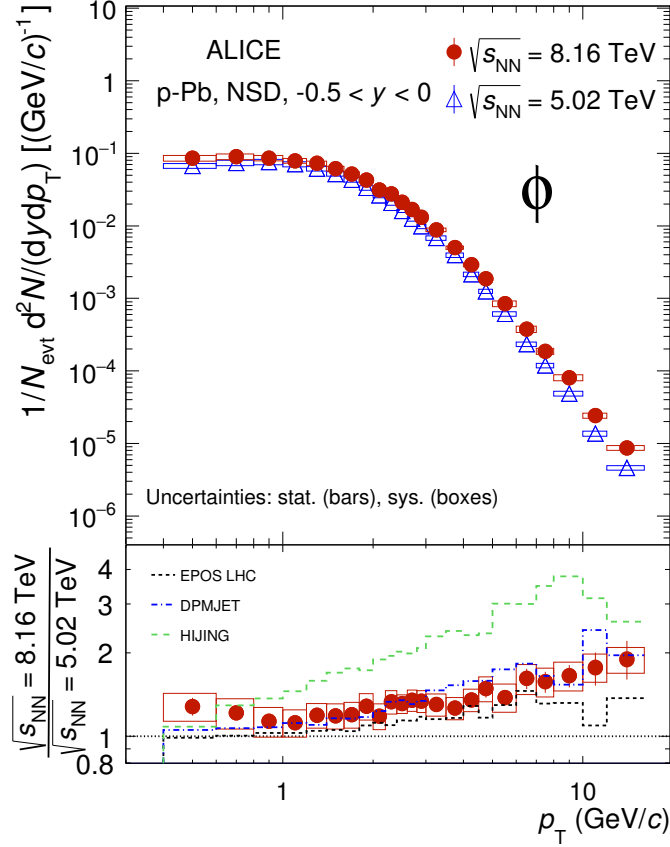


Figure 3.22: Top panel: Energy dependence of the transverse momentum spectra of ϕ meson as a function of p_T for the NSD events, measured in the rapidity range $-0.5 < y < 0$ for p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ and 8.16 TeV. Bottom panel: The ratio of p_T spectrum at $\sqrt{s_{NN}} = 8.16$ TeV to the p_T spectrum at $\sqrt{s_{NN}} = 5.02$ TeV. The ratio is compared to the predictions from EPOS-LHC [19], DPMJET [21] and HIJING [22] models. The statistical and systematic uncertainties are shown as bars and boxes, respectively.

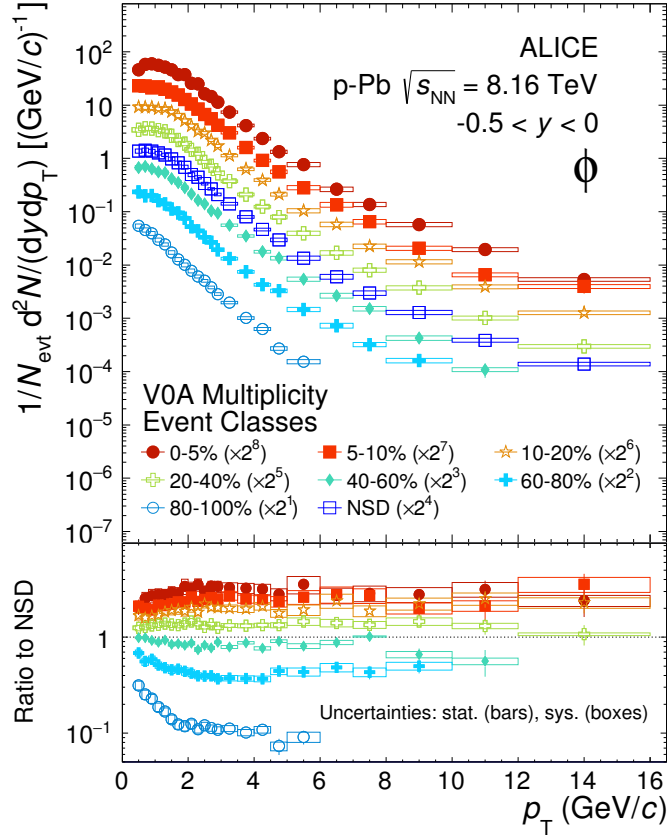


Figure 3.23: Top panel: The transverse momentum spectra of ϕ meson for various multiplicity classes, measured in the rapidity range $-0.5 < y < 0$ for p-Pb collisions at $\sqrt{s_{NN}} = 8.16 \text{ TeV}$. Bottom panel: The ratios of p_T spectrum of a given event multiplicity class to the NSD spectrum are shown. The statistical and systematic uncertainties are shown as bars and boxes, respectively.

Table 3.4: The yield dN/dy and mean transverse momenta $\langle p_T \rangle$ are obtained from data in the measured range and using the Levy-Tsallis fit function in the extrapolation region, and are listed as (value $\pm$ stat. $\pm$ uncorr. syst. $\pm$ total syst.), where the errors are the statistical uncertainty, multiplicity uncorrelated and total systematic uncertainty, respectively. The fraction of total yield obtained by extrapolation (“Extr.”) are also reported.

Multiplicity (%)	Extr.	dN/dy (data + extr.)	ϕ $\langle p_T \rangle$ (GeV/c)
0–5	0.089	$0.455 \pm 0.008 \pm 0.026 \pm 0.041$	$1.496 \pm 0.015 \pm 0.021 \pm 0.022$
5–10	0.088	$0.356 \pm 0.007 \pm 0.028 \pm 0.033$	$1.482 \pm 0.017 \pm 0.021 \pm 0.022$
10–20	0.093	$0.292 \pm 0.004 \pm 0.018 \pm 0.028$	$1.468 \pm 0.013 \pm 0.016 \pm 0.021$
20–40	0.101	$0.217 \pm 0.003 \pm 0.008 \pm 0.020$	$1.409 \pm 0.011 \pm 0.010 \pm 0.025$
40–60	0.104	$0.146 \pm 0.002 \pm 0.007 \pm 0.014$	$1.342 \pm 0.011 \pm 0.021 \pm 0.029$
60–80	0.122	$0.084 \pm 0.001 \pm 0.004 \pm 0.008$	$1.249 \pm 0.013 \pm 0.020 \pm 0.025$
80–100	0.141	$0.0313 \pm 0.0008 \pm 0.002 \pm 0.003$	$1.097 \pm 0.016 \pm 0.008 \pm 0.029$
NSD	0.103	$0.161 \pm 0.0015 \pm 0.0147$	$1.393 \pm 0.008 \pm 0.024$

unmeasured region ($p_T < 0.4$ GeV/c) by fitting a Levy-Tsallis function [34] to the measured p_T spectra in all multiplicity classes. The difference of yields contribution at low p_T due to different fitting function (i.e Exponential, Boltzmann, m_T -exponential, Bose-Einstein and Boltzmann-Gibbs Blast-Wave function) compared to Levy-Tsallis function are included in systematic uncertainties. The low p_T extrapolation accounts for 8.9% (14.1%) of the total yield in the 0-5%(80-100%) multiplicity class. The contribution of extrapolated fraction of the yield is negligible for $p_T > 16$ GeV/c for ϕ meson. The values dN/dy and $\langle p_T \rangle$ of ϕ meson for various multiplicity classes are summarized in the Table. 3.4.

The multiplicity-scaled integrated yields ($dN/dy / \langle dN_{ch}/d\eta \rangle_{|\eta|<0.5}$) for ϕ meson is shown in upper panel of Fig. 3.24 as a function of $\langle dN_{ch}/d\eta \rangle_{|\eta|<0.5}$. These results are compared with other ALICE measurements in pp collisions at $\sqrt{s} = 7$ and 13 TeV [3, 4], in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [12], and in Pb-Pb collisions at 2.76 and 5.02 TeV [6–8]. The scaled integrated yields evolve smoothly as a function of multiplicity from pp, p-Pb to Pb-Pb collision systems. While the geometry of collisions and dynamics of systems are different, the scaled integrated yields of ϕ meson are similar for all colliding systems and energies. For similar $\langle dN_{ch}/d\eta \rangle_{|\eta|<0.5}$,

these values are consistent within uncertainties for different colliding systems and at various LHC energies. This indicates that event multiplicity drives the resonance production, irrespective of the colliding systems and energies [3, 4, 12].

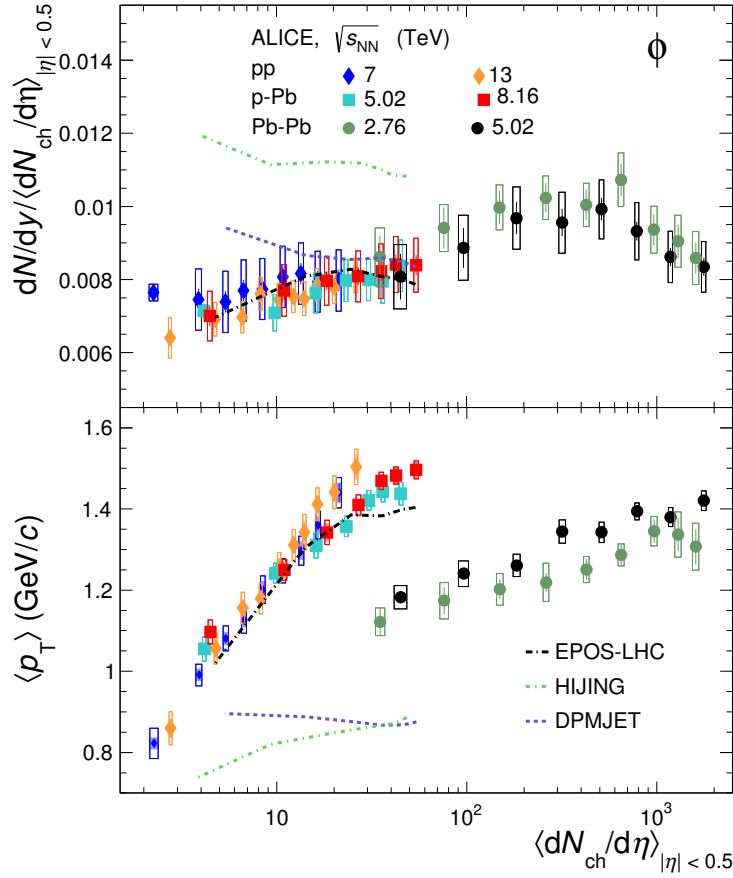


Figure 3.24: The multiplicity-scaled integrated yield ($dN/dy / \langle dN_{ch}/d\eta \rangle_{|\eta|<0.5}$) (upper panel) and mean transverse momentum ($\langle p_T \rangle$) (bottom panel) for ϕ meson as a function of $\langle dN_{ch}/d\eta \rangle_{|\eta|<0.5}$ measured in the ALICE central barrel in pp collisions at $\sqrt{s} = 7, 13$ TeV, in p-Pb collisions at $\sqrt{s_{NN}} = 5.02, 8.16$ TeV and Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76, 5.02$ TeV. Measurements are compared to the predictions from EPOS-LHC, DPMJET and HIJING models. Statistical uncertainties are represented as bars, and boxes indicate total systematic uncertainties.

The scaled integrated yields of ϕ meson show a slight increasing trend with multiplicity from pp collisions to mid-central Pb-Pb collisions. The total increase is 12% with a 1.5σ significance in going from the lowest multiplicity bin to the highest multiplicity bin in p-Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV. The significance is

calculated using statistical and multiplicity uncorrelated systematic uncertainties, added in quadrature. In general the integrated yield ratios of resonances with longer lived particles, π , K and p are computed to study their production mechanism. Previously, various particle ratios of ϕ meson resonance with stable hadron have been studied as a function of multiplicity in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [12]. In Ref. [12] ϕ/π ratio shows an increasing trend in going from lowest multiplicity to highest multiplicity bin in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with a significance of 1.5σ which is discussed in context of a hint of strangeness enhancement effect. The future results of π and K yields in p-Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV will be useful to study these effects. The EPOS-LHC model describes the scaled integrated yields for ϕ meson whereas HIJING model overestimates the data for all multiplicities. The DPMJET model describes the scaled integrated yield of ϕ meson at higher multiplicities. The mean transverse momentum, $\langle p_T \rangle$ shows an increasing trend as a function of $\langle dN_{ch}/d\eta \rangle_{|\eta| < 0.5}$ for ϕ meson in various colliding systems and energies as shown in the bottom panel of Fig 3.24. The increase in $\langle p_T \rangle$ is faster for pp and p-Pb than Pb-Pb and for a common multiplicity coverage the values of $\langle p_T \rangle$ in pp and p-Pb are larger than Pb-Pb.

Similar studies have been reported in [12, 35], where it was suggested that the moderate increase of $\langle p_T \rangle$ in $Pb - Pb$ collisions is due to the presence of collective flow. The strong increase of $\langle p_T \rangle$ with $\langle dN_{ch}/d\eta \rangle_{|\eta| < 0.5}$ in small collision systems can be understood by systematic studies of $\langle p_T \rangle$ from different models in pp and p-Pb collisions which incorporates processes like effect of color reconnection between strings produced in multi-parton interactions, different string fragmentation processes and core-corona mechanism. It was observed in [4] that PYTHIA8 model with color reconnection which introduces a flow like effect and EPOS-LHC model which uses parameterized flow are able to reproduce the increasing trend of $\langle p_T \rangle$ as a function of multiplicity for ϕ meson in pp collisions at $\sqrt{s} = 13$ TeV. The p-Pb measurements are important as in Ref. [35] it is shown that $\langle p_T \rangle$ of charged hadrons as a function of multiplicity shows similar behavior as pp in low multiplicity whereas it seems to approach a similar but less prominent trend of saturation as Pb-Pb at

high multiplicity.

The model comparison to p-Pb data shows that EPOS-LHC describes the increasing trend of $\langle p_T \rangle$ with multiplicity for ϕ meson, and it gives a better agreement for ϕ meson at higher multiplicity values. DPMJET and HIJING models fail to describe the observed trend in $\langle p_T \rangle$ for ϕ meson and underpredict the data for all multiplicity.

3.6.3 x_T scaling

Invariant cross section of particle production have been found to follow a universal scaling at high p_T , which is known as x_T scaling, where $x_T = 2p_T/\sqrt{s_{NN}}$. This scaling behavior is predicted by general principles of hard scattering, factorization of the reaction into parton distribution functions, fragmentation functions for the scattered partons and a short-distance parton-parton hard-scattering cross-section [36,37].

The x_T scaling has been tested in pp collisions for identified hadrons in STAR [38], for charged particles in CMS [40] and for identified hadrons in ALICE [39]. In this paper, the validity of x_T scaling is tested using ϕ meson measurements in p-Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV reported here and those obtained at $\sqrt{s_{NN}} = 5.02$ TeV [12]. The invariant cross sections are determined from the measured invariant yield as $Ed^3\sigma/d^3p = \sigma_{\text{inel}} \times Ed^3N/d^3p$, where $\sigma_{\text{inel}} = 72.5 \pm 0.5$ mb is the inelastic cross section in pp collisions at $\sqrt{s} = 8.16$ TeV [41].

At fixed x_T , the invariant cross section $Ed^3\sigma/d^3p$ scales as p_T^{-n} , where the exponent of scaling n depends on x_T and $\sqrt{s_{NN}}$, and is calculated using the following equation

$$n(x_T, \sqrt{s_{NN1}}, \sqrt{s_{NN2}}) = \frac{\ln(\sigma^{\text{inv}}(x_T, \sqrt{s_{NN2}})/\sigma^{\text{inv}}(x_T, \sqrt{s_{NN1}}))}{\ln(\sqrt{s_{NN1}}/\sqrt{s_{NN2}})}, \quad (3.19)$$

The distributions of n values as a function of x_T for ϕ meson are shown in Fig. 3.25. In the low x_T region, where the particle production is dominated by soft processes, the values of n are found to increase with x_T whereas the n values seem to saturate

at high x_T . The n values is obtained by fitting the $n(x_T, \sqrt{s_{NN}})$ distribution by a constant in x_T range $1.3 \times 10^{-3} < x_T < 4 \times 10^{-3}$ for ϕ meson. The systematic uncertainties on the exponent n are calculated by changing the fit range in n vs. x_T distribution. The maximum deviation of n value with respect to default is taken as systematic uncertainties. The n values for ϕ meson are consistent with measurements in pp collisions ($\pi^\pm$, $K^\pm$ and K^{*0}) within the uncertainties which suggests that ratios of particle spectra attain similar values in p-Pb collisions at the LHC energies. The x_T spectra is scaled by the $(\sqrt{s_{NN}}/\text{GeV})^n$. The best scaling is obtained in the quoted fitting range with an exponent of $n = 5.12 \pm 0.07$ (sys.) for ϕ meson. The x_T -scaled spectra for ϕ meson in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ and 8.16 TeV are shown in Fig. 3.26. These measurements suggest that ϕ meson yields in p-Pb collisions at LHC energies follow x_T scaling for $x_T > 10^{-3}$. Similar studies were performed in pp collisions at LHC energies for identified hadrons ($\pi^\pm$, $K^\pm$, p ($\bar{p}$) and K^{*0}) with ALICE [39] and for charged hadrons with CMS [40]. The n values obtained in pp collisions for all hadron species except proton are comparable to those reported here for ϕ meson in p-Pb collisions. In Ref. [39], proton takes a larger value of exponent n which was discussed in context of decrease of the baryon to meson ratio with increasing p_T in contrast to the nearly constant behavior of meson to meson ratios. The n value obtained at LHC energies is also observed to be lower compared to RHIC energies which suggests the increasing contribution of hard processes at higher centre of mass energies. A combined-fit to the scaled differential cross sections of ϕ meson is performed with a power-law function of the form $ax_T^b(1+x_T)^c$ to verify the quality of the scaling behavior. Here, a , b , and c are free parameters. The fitting is done in region above $x_T > 1.3 \times 10^{-3}$ (shown as black curve in Fig. 3.26), where the x_T scaling is observed. The χ^2/ndf value is 0.6, which confirms the good quality of the fit. In the fitting region, the measurements agree with the combined power law fits within $\approx 20\%$. The measurements at $\sqrt{s_{NN}} = 8.16$ TeV are consistent over the accessible x_T range $1.3 \times 10^{-3} < x_T < 3 \times 10^{-3}$ with empirical x_T scaling and with measurements from p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. This further helps to understand and distinguish the contributions of the soft and hard processes on

particle production.

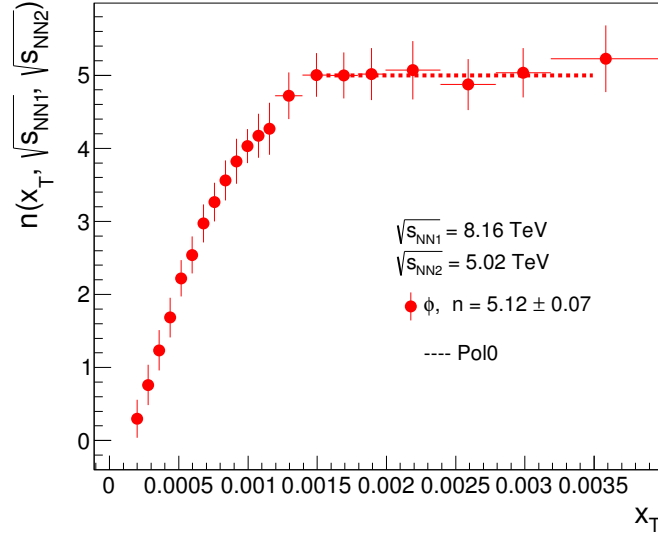


Figure 3.25: The values of n as a function of x_T for ϕ meson in p-Pb collisions. The distribution is fitted with the 1st order polynomial to extract the n value at high x_T shown by dashed red line.

3.6.4 Nuclear modification factor (R_{pPb})

In order to understand the nuclear effects, study of the nuclear modification factor (R_{pPb}) is an important observable in p-Pb collisions. It is calculated as :

$$R_{pPb}(p_T) = \frac{d^2 N_{pPb}/dp_T dy}{\langle T_{pPb} \rangle d^2 \sigma_{pp}^{INEL}/dp_T dy}. \quad (3.20)$$

where $d^2 N_{pPb}/dp_T dy$ is the invariant yield in p-Pb collisions and $d^2 \sigma_{pp}^{INEL}/dp_T dy$ is the invariant cross section in inelastic pp collisions. $\langle T_{pPb} \rangle = \langle N_{coll} \rangle / \sigma^{INEL}$ is the average nuclear overlap function which accounts for the nuclear collision geometry as obtained from a Glauber model [41] and σ^{INEL} is the nucleon-nucleon inelastic cross section extracted from the $\ln^2$ fit using Glauber calculations [41].

If the nuclear modification factor is unity, it suggests that nuclear collisions is an incoherent superposition of nucleon-nucleon collisions.

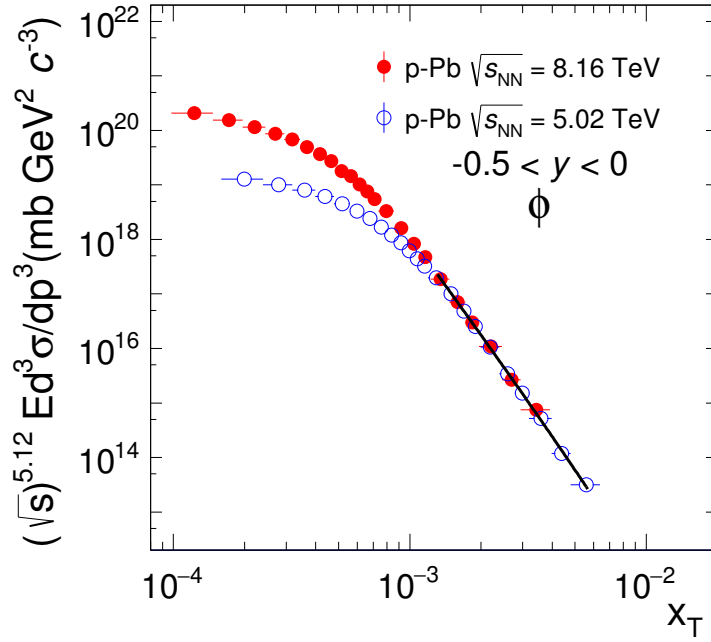


Figure 3.26: Scaled invariant yield of ϕ meson as a function of $x_T = 2p_T/\sqrt{s_{NN}}$ in p-Pb collisions at different energies $\sqrt{s_{NN}} = 5.02$ and 8.16 TeV. The data point are fitted with combined power-law function shown by black line.

In the absence of the availability of ϕ meson measurements at center of mass energy $\sqrt{s} = 8.16$ TeV in pp collisions, the reference p_T spectra are obtained from the measured p_T spectra at $\sqrt{s} = 8$ TeV [9] using simulation approach with PYTHIA 8.230 [42] as shown in Fig. 3.27. In this approach the reference p_T spectra at $\sqrt{s} = 8$ TeV is scaled by a correction factor calculated as the ratio of p_T spectra at $\sqrt{s} = 8.16$ TeV to that at $\sqrt{s} = 8$ TeV, obtained from PYTHIA 8.230. For systematic study the reference pp spectrum is also obtained using the same approach from measured p_T spectrum at $\sqrt{s} = 7$ TeV [3]. The total systematic on the pp reference spectrum is then calculated as the quadrature sum of the systematic uncertainties of the measured p_T spectrum at $\sqrt{s} = 8$ TeV and the difference of the reference spectra obtained using the measured p_T spectra at $\sqrt{s} = 7$ and 8 TeV. The systematic uncertainties on the reference p_T spectra of ϕ meson are 7.3-7.4% for low p_T (< 4.0 GeV/c) to high p_T (> 4.0 GeV/c) region. The systematic and statistical uncertain-

ties in R_{pPb} are calculated as the quadrature sum of respective uncertainties of the p_{T} spectra in p-Pb and pp collisions. The value of nucleon-nucleon inelastic cross section for reference spectra at $\sqrt{s} = 8.16$ TeV is 72.5 ± 0.5 taken from ref [41]. The R_{pPb} of ϕ meson in 5.02 TeV are also calculated from the measured p_{T} spectra in pp and p-Pb collisions published in Refs. [12, 33].

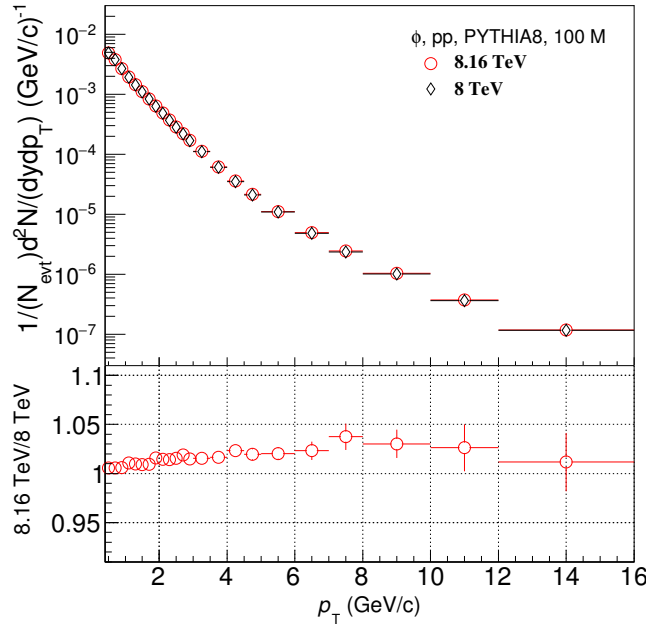


Figure 3.27: ϕ meson p_{T} measured in pp collision at $\sqrt{s} = 8.16$ TeV and $\sqrt{s} = 8$ TeV from Pythia8 model (top panel) and the correction factor (bottom panel).

Figure 3.28 shows the nuclear modification factor of ϕ meson as a function of p_{T} in p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ and 8.16 TeV. At intermediate p_{T} (2–8 GeV/c), a hint of enhancement in R_{pPb} is observed. No significant energy dependence of R_{pPb} is observed for resonances in p-Pb collisions at the LHC energies. Figure 3.29 shows the particle species dependence of nuclear modification factors in p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ and 8.16 TeV. The panels (a) and (b) show R_{pPb} of both K^{*0} and ϕ meson at $\sqrt{s_{\text{NN}}} = 8.16$ and 5.02 TeV, respectively. The comparison with stable mesons π and K at $\sqrt{s_{\text{NN}}} = 5.02$ TeV [46] are shown in panel (b). The panel (c) shows the R_{pPb} of multi-strange baryons (Ξ , Ω) at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. To

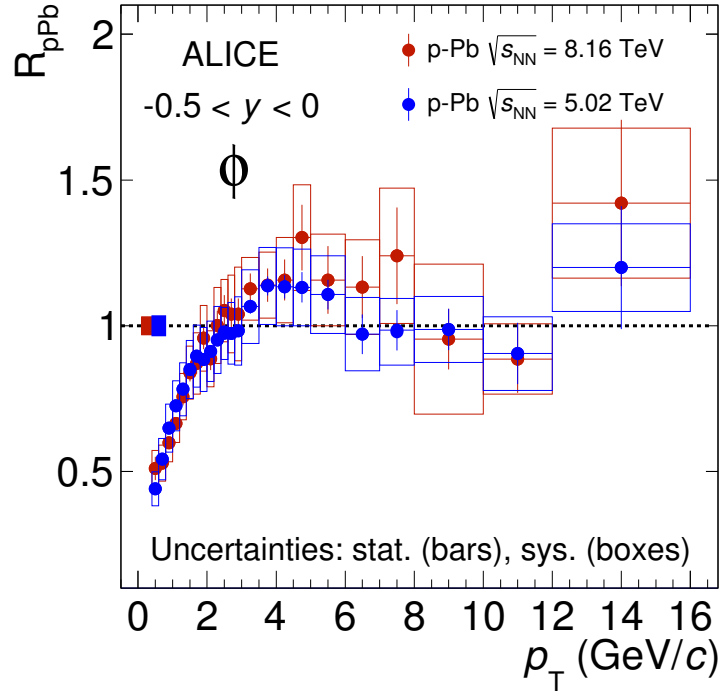


Figure 3.28: Nuclear modification factor of ϕ meson as a function of p_T in p-Pb collisions at different energies $\sqrt{s_{NN}} = 5.02$ and 8.16 TeV. The statistical and systematic uncertainties are represented by vertical bars and boxes, respectively. The total systematic uncertainties on the normalization are shown as boxes around unity near $p_T = 0$.

study the R_{pPb} mass dependence of baryons and baryon-meson effect, the R_{pPb} of proton taken from [46] and that of ϕ meson are also shown in panel (c). At low p_T (< 2 GeV/c), the R_{pPb} is less than unity for all hadrons. At the intermediate p_T range (2-8 GeV/c), the R_{pPb} of baryons shows a Cronin-like enhancement above unity [47]. The R_{pPb} shows mass ordering and larger values are observed for the baryons with higher mass. The similar mass ordering for baryons in the intermediate p_T region is also reported by CMS in [48] and the results are consistent with the hydrodynamical expectation of radial flow [49]. It is also observed that the R_{pPb} of ϕ meson is smaller than that of proton inspite of similar masses, which may indicate baryon-meson ordering. So, along with the presence of strong radial flow component, there are other effects like different production mechanism of baryons and mesons which are affecting the R_{pPb} in this p_T region. Similar behavior is also observed in

Pb-Pb collisions in this p_T region [50]. At high p_T (> 8 GeV/ c), the R_{pPb} values of all particles are consistent with unity within the uncertainties in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ and 8.16 TeV which suggests that there is no modification in R_{pPb} due to cold nuclear matter effects for different particle species. The similar observation is also reported for charged hadrons by ALICE in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [51, 52], identified strange hadrons by CMS in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [10] and STAR collaboration in d-Au collisions at $\sqrt{s_{NN}} = 200$ GeV [11].

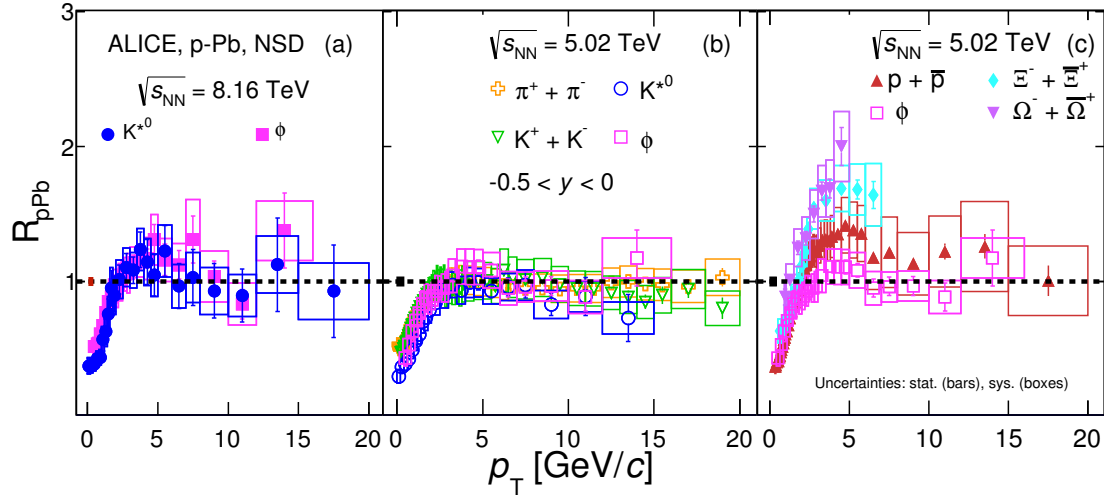


Figure 3.29: The nuclear modification factor R_{pPb} as a function of transverse momentum p_T for different particle species in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ and 8.16 TeV. For comparison the results for π , K, and p [52] are also shown. The statistical and systematic uncertainties are represented by vertical bars and boxes, respectively. The total systematic uncertainties on the normalization are shown as boxes around unity near $p_T = 0$.

3.7 Summary

The production of ϕ mesons as a function of p_T have been measured in the rapidity range ($-0.5 < y < 0$) for various multiplicity classes in p-Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV with the ALICE detector. The EPOS-LHC model including effects of the hadronic phase describe the NSD spectrum qualitatively well as compared to the

DPMJET and HIJING model predictions. A significant evolution of spectral shapes is observed with multiplicity for $p_T < 4$ GeV/ c , a similar behavior is observed in Pb-Pb collisions which can be attributed to the collective radial expansion of the system. The spectral shapes are similar for all multiplicity classes at higher p_T . The scaled p_T integrated yields ($dN/dy / \langle dN_{ch}/d\eta \rangle$) as a function of multiplicity show a smooth evolution from pp and p-Pb to Pb-Pb, and the values are similar for a given multiplicity, irrespective of the colliding systems and energies which shows that ϕ meson particle production is mainly driven by the event multiplicity. The $\langle p_T \rangle$ values of ϕ meson increase as a function of multiplicity and follow a different trend for different collision systems. The EPOS-LHC model which includes parameterized flow gives a good quantitative description of the scaled p_T integrated yields, as well as qualitatively describes the increase in $\langle p_T \rangle$ values with multiplicity for ϕ meson. A universal x_T scaling for ϕ meson is well satisfied (within roughly 20%) in the hard scattering region of the particle production. The obtained value of exponent ($n \sim 5$) is lower compared to RHIC energies which suggests the increasing contribution of hard scattering processes at higher $\sqrt{s_{NN}}$. Furthermore, the value of exponent n in p-Pb collisions is compatible with those in pp collisions for $\pi^\pm$, $K^\pm$ and K^{*0} suggesting that the high- p_T particle production mechanism is similar in both the collision systems. No significant energy dependence in R_{pPb} is observed for ϕ meson in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ and 8.16 TeV. At intermediate p_T ($2 < p_T < 8$ GeV/ c), R_{pPb} values of ϕ meson in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV show Cronin-like enhancement. The R_{pPb} values are consistent with unity within the uncertainties at $p_T > 8$ GeV/ c , which shows the absence of nuclear effects at higher p_T .

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Chapter 4

Rapidity dependence study of ϕ meson production in p-Pb collisions

Hadronic resonances have a lifetime comparable to that of a fireball created in a heavy-ion collision. An abundance of resonances is produced at the LHC in various collision systems. Several aspects of heavy-ion collisions can be studied using hadronic resonances. The hot and dense medium created in such collisions can alter the spectral shape of resonances. As a result of their short lifetimes, resonances are susceptible to re-scattering and regeneration between chemical and kinetic freeze-out. So, the resonance study will help to understand the properties of the hadronic phase. Studying the production of resonances in collision systems such as pp and p-Pb provides a necessary baseline for disentangling initial-state effects from absolute medium effects produced in heavy-ion collisions. Asymmetric collision systems such as proton-nucleus (p-A) and deuteron-nucleus (d-A) where the formation of the QGP phase is not expected, can be used to study the possible effects of cold nuclear matter. At the Large Hadron Collider (LHC), p-A collisions enable to probe the parton distribution function in nuclei at very small values of the Bjorken x variable, in which gluon saturation effects are possible [1–3]. Hadron production can be af-

affected by different effects such as nuclear modification of the distribution functions of partons (nuclear shadowing) as well as parton saturation, multiple scattering, and radial flow. These effects are expected to be influenced by the rapidity of particles produced. We can investigate the mechanism of particle production and shed light on the physics behind the particle production by studying the multiplicity and rapidity dependence of hadron production in p-Pb collisions.

Rapidity asymmetry (Y_{asym}): In p-Pb collisions, it can be expected that the production mechanism will be sensitive to different effects at forward (p-going) and backward (Pb-going) rapidities. Multiple scattering of the partons is expected to occur while the proton traverses the Pb-nucleus and partons on the Pb side will be affected by the nucleus properties. Therefore, it is interesting to investigate the rapidity asymmetry (Y_{asym}) represented by the particle yield ratio between Pb-going and p-going directions:

$$Y_{\text{asym}} = \frac{\left. \frac{d^2N}{dp_T dy} \right|_{-0.3 < y < 0}}{\left. \frac{d^2N}{dp_T dy} \right|_{0 < y < 0.3}} \quad (4.1)$$

where, $d^2N/dp_T dy|_{-0.3 < y < 0}$ is the particle yield in the rapidity (y) interval $-0.3 < y < 0$ (Pb-going direction), and $d^2N/dp_T dy|_{0 < y < 0.3}$ is the particle yield in the rapidity interval $0 < y < 0.3$ (p-going direction). Here, ‘ y ’ corresponds to the center-of-mass rapidity. Y_{asym} is an important observable, as the correlated systematic uncertainties on the ratio will cancel out and hence it becomes more sensitive to the various model calculations. A low Bjorken x value might influence the transverse momentum distribution of hadron production at large rapidities in the p-going direction at LHC energies due to gluon saturation effects. Gluon saturation effects are dependent on colliding nuclei as well as on rapidity as $\sim A^{1/3} e^{\lambda y}$, where A is the mass number and λ is free parameter.

Nuclear Modification factor (Q_{CP}): The nuclear modification factor (Q_{CP}) is the ratio of the yield between the central (high multiplicity) to non-central collisions (low multiplicity), scaled by respective average number of nucleon-nucleon

collisions. It is defined as:

$$Q_{\text{CP}}(p_{\text{T}}) = \frac{\frac{d^2N}{dp_{\text{T}}dy}|_{\text{HM}}}{\frac{d^2N}{dp_{\text{T}}dy}|_{\text{LM}}} \quad (4.2)$$

where, $\langle N_{\text{coll}} \rangle$ is the average number of nucleon-nucleon collisions at low-multiplicity (LM) and high-multiplicity (HM) events, respectively. The rapidity dependent study of Q_{CP} will explore the nuclear phenomena such as Cronin effect [4], dynamical shadowing, and energy loss in cold nuclear matter [5]. In asymmetric systems like p-Pb collisions, multiple scattering, nuclear shadowing, and radial flow are all expected to influence particle production differently in the backward (Pb-going) and forward (p-going) rapidity region. As a result, Pb-going direction is expected to have more radial flow than p-going, resulting in a stronger mass dependence in Pb-going direction. The nuclear shadowing effect is expected to be greater in the p-going direction, since smaller x fractions will penetrate in the nucleus. As a result, Pb-going directions should have higher Q_{CP} values than p-going directions. There is no clear understanding of the effects of parton multiple scattering and studies have shown that they depend on different factors, such as the scatterings being inelastic, elastic, coherent/incoherent. Tests of these predictions can be performed by measuring Q_{CP} separately in the p-going and Pb-going directions.

In this chapter, we present the first measurement of the rapidity dependence of $\phi(1020)$ mesons production in p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV by the ALICE experiment at the LHC. The availability of large statistics data and excellent particle identification of ALICE detector provides us to study rapidity dependence of $\phi(1020)$ mesons in various multiplicity classes. This study will help us to investigate the nuclear effects on the particle production mechanism in p-Pb collisions. The results include the p_{T} spectra, rapidity asymmetry (Y_{asym}), p_{T} -integral particle yield, mean transverse momentum and nuclear modification factor in the rapidity range $-1.2 < y < 0.3$ and three multiplicity classes along with the multiplicity-integrated sample. The rapidity range $-1.2 < y < 0.3$ is divided into five equal intervals of

width 0.3. The measurements are also compared with various model calculations such as EPOS-LHC [6], EPOS3 with and without UrQMD [7], HIJING [8], DPMJET [9] and PYTHIA8(Angantyr) [10].

The EPOS-LHC is an event generator incorporating a parameterization of flow based on LHC results [6]. This event generator utilizes the multiple partonic scatterings described by Gribov's Reggeon field theory formalism, including collective hadronization as well as the core-corona mechanism from pp to A-A collisions. EPOS3 event generator uses the Gribov-Regge multiple scattering framework which includes 3+1D viscous hydrodynamical evolution in it, and is used to understand hadronic resonances and their interactions in the partonic and hadronic medium. The UrQMD within the EPOS3 model introduced the description of regeneration and re-scattering effects in the hadronic phase. The DPMJET is a QCD-inspired dual parton model based on the formalism of the Gribov Glauber approach that treats the soft and hard scattering interactions differently. HIJING is used to study jet and the associated particle production in high energy collisions and is based on QCD-inspired models, including multiple minijet production, soft excitation, nuclear shadowing of parton distribution functions, and jet interaction in dense matter. PYTHIA8(Angantyr) is an event generator based on the Fritiof model, which includes the features of multi-parton interactions and diffractive excitation in each nucleon-nucleon (NN) sub-collision. It acts as a baseline for understanding the non-collective background in the observables sensitive to collective behavior, as PYTHIA8 does not include a collective expansion stage in its description of pp collisions. The comparison of data with the results from these phenomenological models helps to understand the relative contribution of the nuclear effects on the particle production in p-Pb collisions.

4.1 Analysis details

The $\phi(1020)$ mesons measurement are performed in p-Pb collisions at center-of-mass energy in nucleon-nucleon collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. The high statistics

data was collected during ALICE Run-2 in 2016. The ϕ meson is reconstructed through invariant-mass method by using their decay daughters. The ϕ resonance is reconstructed by the following decay channel $\phi \rightarrow K^+ K^-$ having branching ratio 49.2% [11]. In the p-Pb configuration, the ^{208}Pb beam with energy of 1.58 TeV per nucleon collides with a proton beam with an energy of 4 TeV resulting in collisions at a nucleon-nucleon center-of-mass energy $\sqrt{s_{\text{NN}}} = 5.02$ TeV [11]. It leads to the rapidity in the center-of-mass frame being shifted by $\delta y = -0.465$ in the direction of the proton beam with respect to the laboratory frame. As a result of shifting in rapidity, the measurements are performed in the rapidity range $-1.2 < y < 0.3$ (center-of-mass frame) divided into five rapidity intervals having equal width of 0.3, and in three multiplicity classes along with a multiplicity-integrated class. The ϕ signal is obtained in the p_{T} region from 0.8 to 16 GeV/ c for different rapidity intervals and multiplicity classes. The measurements are carried out with the ALICE central barrel detectors, which are utilized for tracking, particle identification, and primary vertex reconstruction and housed inside a solenoidal magnet with a magnetic field of 0.5 T. The main detectors used for reconstructing the track and primary vertex in this analysis are the ITS [12], TPC [13], and TOF [14] detectors. All three detectors have common pseudorapidity coverage of $|\eta| < 0.9$, with full azimuthal coverage.

4.1.1 Event, track selection and particle identification

The event, trigger and track selection criteria used in this analysis are similar as those discussed in previous chapter 3. The events are selected with a minimum bias trigger (kINT7) based on the coincidence of signals in two arrays of 32 scintillator detectors covering full azimuth and the pseudorapidity regions $2.8 < \eta < 5.1$ (V0A) and $-3.7 < \eta < -1.7$ (V0C) [4]. The charged particle track reconstruction information from ITS and TPC detectors is used to reconstruct the primary vertex. The primary vertex of selected events should lie within ± 10 cm from the center of ITS detector along the beam direction (z-direction). The distribution of primary vertex (V_z) position is shown in Fig. 4.1. The Silicon Pixel Detector (SPD) which

is the innermost detector layers of the ITS, is used to reject events in which multiple collision vertices are found (pile-up) [12]. In this analysis, approximately 540 million events are selected after implementation of the selection criteria described above. The multiplicity selection is performed using the total charge deposited in V0A detector. The minimum bias events are further divided into three multiplicity classes, 0-10%, 10-40% and 40-100%. The ϕ meson yield is measured in five rapidity intervals $-1.2 < y < -0.9$, $-0.9 < y < -0.6$, $-0.6 < y < -0.3$, $-0.3 < y < 0$ and $0 < y < 0.3$, in three multiplicity classes 0-10%, 10-40% and 40-100% along with the minimum-bias events (0-100%). The events distribution as a function of charged particle multiplicity classes is shown in Fig. 4.2 All the events cut implemented in the analysis are listed below:

1. kINT7 trigger.
2. InComplete Data Acquisition (DAQ) check. It is used to check if DAQ has set the incomplete event attributes.
3. Pileup Rejection using `AliAnalysisUtils::IsPileUpEvent()`. The events are rejected which have multiple vertices while reconstruction in the SPD.
4. SPD Cluster vs Tracklet Check using `AliAnalysisUtils::IsSPDClusterVsTrackletBG()` with default parameters. It is used to check the correlation between number of clusters and number of tracklets.
5. Event has a track or SPD primary vertex identified. Events that have a primary collision vertex that has been reconstructed using the SPD detector are chosen.
6. SPD vertex-z resolution < 0.25 cm. This cut is optimized for successfully matching tracks between the ITS and the TPC and reject the events with poor vertex-z resolution.
7. SPD vertex dispersion < 0.04 . This is the size of the window opened to define the tracklets used in the determination of the vertex.
8. z-position difference between track and SPD vertex < 0.5 cm. This cut is applied to reject events with badly reconstructed track vertex, typically events with true collision at very large z with badly reconstructed track vertex.
9. Vertex-z position : $|v_z| < 10$ cm. This v_z cut value is optimized using the real

data and Monte Carlo (MC) simulation and it is varied while estimating the systematic uncertainty.

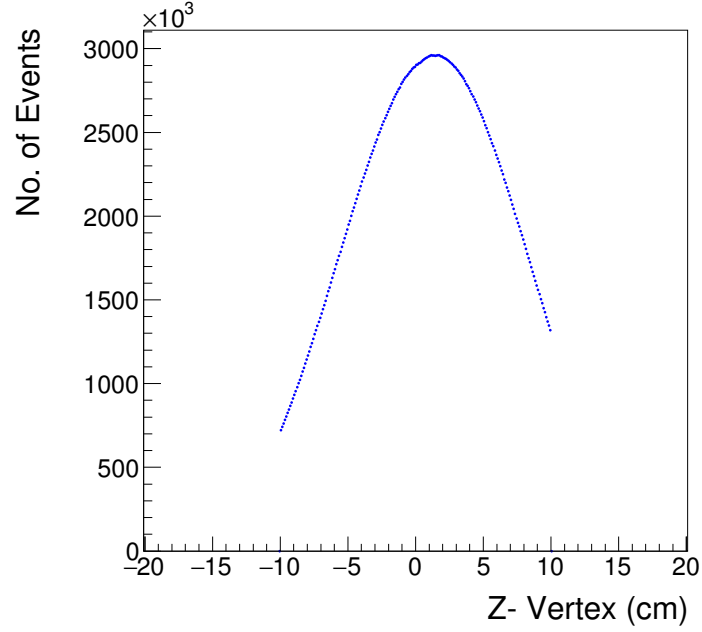


Figure 4.1: The primary vertex (V_z) distribution in p-Pb collision at $\sqrt{s_{NN}} = 5.02$ TeV.

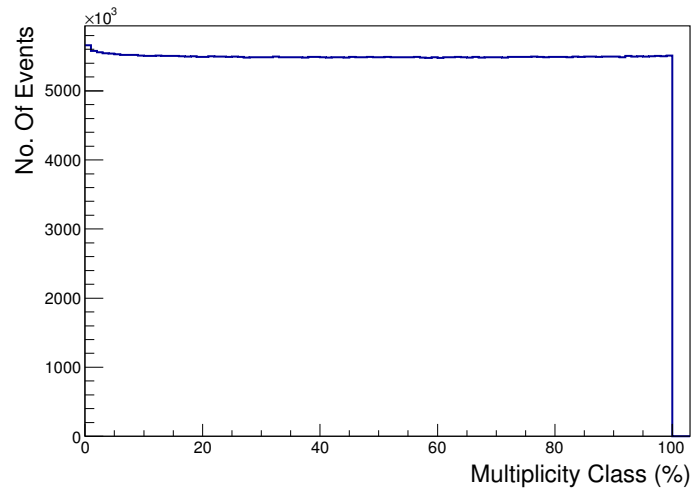


Figure 4.2: The number of events as a function of multiplicity classes from V0A detector in p-Pb collision at $\sqrt{s_{NN}} = 5.02$ TeV.

The charged particle tracks with $p_T > 0.15$ GeV/ c and pseudorapidity $|\eta| <$

0.8 are selected in the TPC for better reconstruction of tracks. The selected charged tracks should pass at least 70 TPC readout pad rows out of maximum 159 rows. The distance of closest approach of the track to the primary vertex in the longitudinal direction (DCA_z) is required to be less than 2 cm. A p_T -dependent selection criteria is applied in the transverse plane of $DCA_{xy}(p_T) < 0.0105 + 0.035 p_T^{1.1}$ cm. The decay daughter (kaons) of ϕ mesons are identified by measuring the specific ionization energy loss (dE/dx) in the TPC [13] and their time-of-flight information using TOF [14] detector. For the kaons selection, the measured $\langle dE/dx \rangle$ is required to be within $n\sigma_{\text{TPC}}$ from the expected $\langle dE/dx \rangle$ values for a given mass hypothesis, where σ_{TPC} is the TPC $\langle dE/dx \rangle$ resolution. A momentum dependent criteria is applied on the value of n as following; a $6\sigma_{\text{TPC}}$, $3\sigma_{\text{TPC}}$ and $2\sigma_{\text{TPC}}$ cut is applied in the momentum interval $p < 0.3$ GeV/ c , $0.3 < p < 0.5$ GeV/ c , and $p > 0.5$ GeV/ c , respectively. If TOF information is available for the selected track, the TOF signal is also used for kaon identification in addition to the TPC one by requiring the time-of-flight of the particle to be within $3\sigma_{\text{TOF}}$ from the expected value for the considered mass hypothesis, where σ_{TOF} is the time-of-flight resolution of the TOF. The dE/dx distribution of kaons in TPC after implementation of PID cut is shown in Fig. 4.3. The $n\sigma$ distribution of kaons in TPC and TOF detector before and after implementation of selection criteria are shown in Fig. 4.4.

4.2 Signal extraction

The ϕ meson is reconstructed by invariant mass technique from its decay daughters using the hadronic channel $\phi \rightarrow K^+ K^-$ with branching ratio 48.9%. The invariant mass distribution in terms of energy and momentum is expressed as,

$$M_{KK} = \sqrt{(E_{KK} + E_{KK})^2 - |\vec{p}_{KK} + \vec{p}_{KK}|^2} \quad (4.3)$$

where, E is the energy and $\vec{p}$ is the momentum of the kaon (K) particle.

For each event, the invariant mass (M_{KK}) distribution of the ϕ meson is constructed

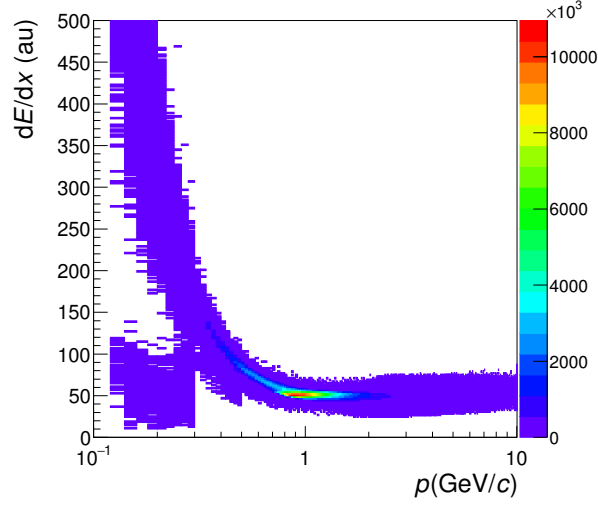


Figure 4.3: The dE/dx distribution of kaons in TPC after particle identification (PID).

using all combinations of K^+ with K^- (called the same-event or signal distribution). Since not all charged $K^\pm$ in each event originate from the ϕ meson decays, the ϕ meson signal extracted in this way sits above a large combinatorial background of uncorrelated pairs. The estimation of the combinatorial background is performed by two methods: event mixing technique and like sign technique.

Event mixing technique:

In event mixing technique, the combinatorial background is constructed by choosing $K^\pm$ from one event and paired with $K^\mp$ from other events. To minimize effects from statistical fluctuations, each event is mixed with five other similar events. The two events that are mixed must have similar characteristics in order to reproduce the combinatorial background. Effects from multiplicity fluctuations are minimized by selecting two events to be mixed with a multiplicity difference less than five. The resultant mixed event background will be around five times higher than the unlike-sign (signal) pairs distribution. So, the mixed event background is normalized in the range $1.06 < M_{KK} < 1.09 \text{ GeV}/c^2$, which is away from the ϕ mass peak position.

Like sign technique:

In like sign technique, the combinatorial background is constructed through the invariant mass distribution of pairs of same charges from the same event. Background

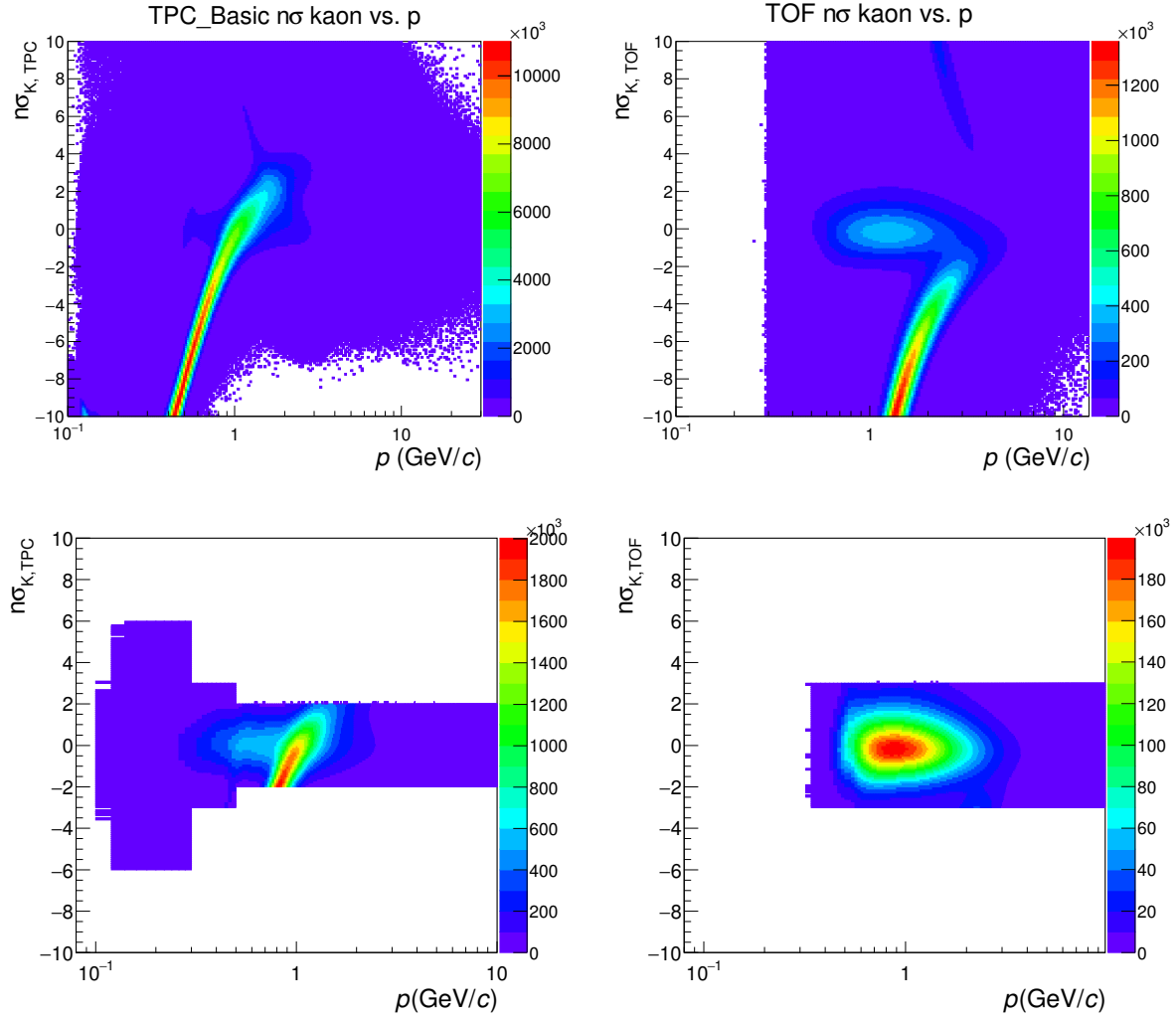


Figure 4.4: Upper panel shows $n\sigma_{\text{TPC}}$ (left) and $n\sigma_{\text{TOF}}$ (right) distributions for kaons before PID cut and lower panel shows distributions of $n\sigma_{\text{TPC}}$ (left) and $n\sigma_{\text{TOF}}$ (right) after implementation of PID cut ($n\sigma$ cut).

is normalized by factor $2\sqrt{(++)\times(--)}$. Here $(++)$ is the invariant mass of K^+K^+ pairs and $(--)$ is the invariant mass distribution of K^-K^- pairs. The signal is obtained by subtracting the like-sign background from the same-event unlike-sign $K^\pm$ invariant mass distribution. The signal after like-sign background subtraction in various p_T bins in rapidity interval $0 < y < 0.3$ for 0-100% multiplicity class are shown in Fig. 4.5.

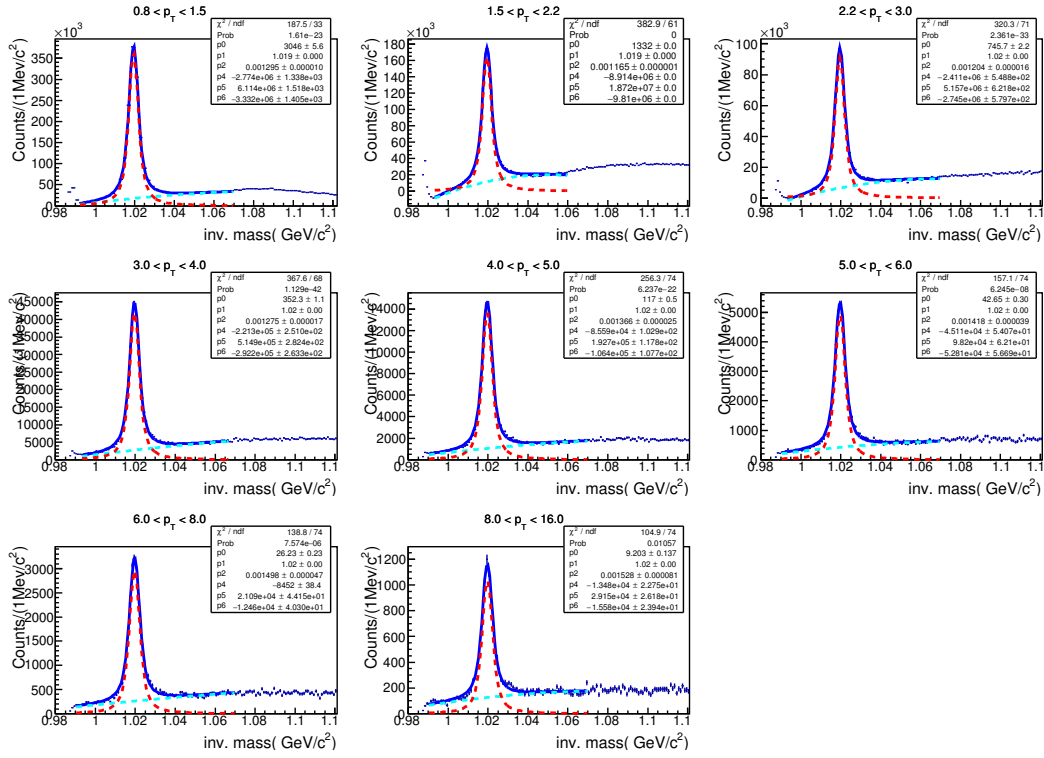


Figure 4.5: Invariant mass distribution M_{KK} after like-sign background subtraction in various p_T bins in the p_T region $0.8 < p_T < 16.0$ GeV/c in the rapidity range $0 < y < 0.3$ for multiplicity class (0-100%). The signal peak is fitted by a Voigtian function (blue line) and the residual background (cyan dotted line) of 2nd order polynomial function.

The mixed-event technique is used as default method to extract the ϕ meson yield. The absolute difference arising in the yield by using the combinatorial background from the like sign method with respect to the default method is taken care in systematic uncertainty. After the subtraction of the combinatorial back-

ground, the invariant-mass distribution consists of a resonance peak sitting on the top of a residual background of correlated pairs. The residual background originates from correlated pairs from jets, misidentification of kaons from ϕ meson decays, and partially reconstructed decays of higher-mass particles [11]. The invariant mass distributions of unlike $K^\pm$ of both same events and normalized mixed event background in p_T region $2.2 < p_T < 3.0$ GeV/ c for the rapidity interval $0 < y < 0.3$ (panel a) and $-0.3 < y < 0$ (panel c) in the multiplicity class 0-10% are shown in Fig. 4.6. The signals after mixed event background subtraction are shown in panel (b) and (d) in Fig. 4.6. The signal peak is fitted by a Voigtian function (convolution of Breit-Wigner and Gaussian functions) and the residual background is fitted by 2nd order polynomial function in the mass range from 0.99 GeV/ c^2 to 1.07 GeV/ c^2 . The Voigtian function along with 2nd order polynomial function is described as:

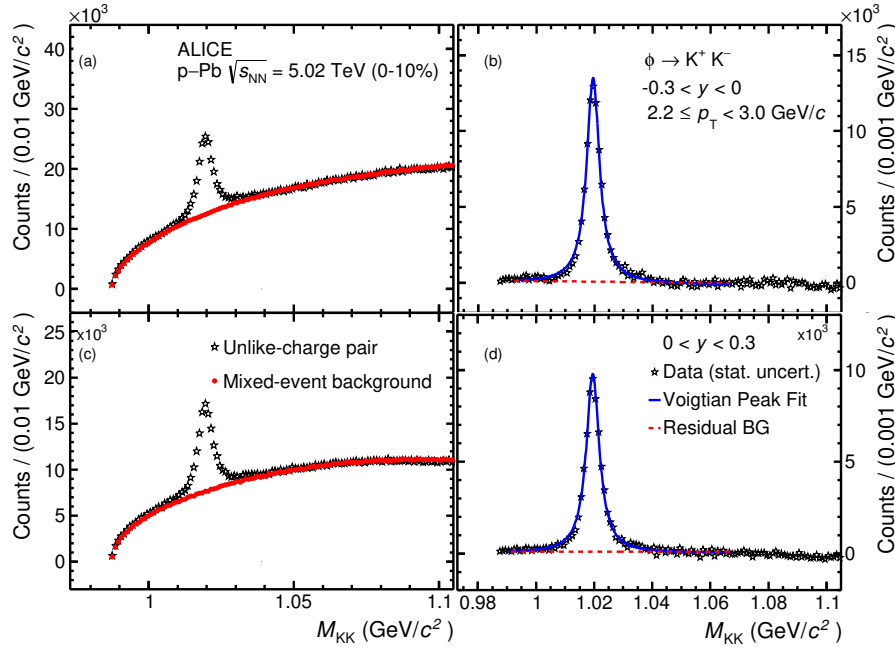


Figure 4.6: Invariant mass distribution M_{KK} of both same event (black marker) and normalized mixed event (red marker) for p_T region $2.2 < p_T < 3.0$ GeV/ c in the rapidity range $-0.3 < y < 0$ (a) and $0 < y < 0.3$ (c) for multiplicity class (0-10%). The invariant mass distribution M_{KK} after mixed event combinatorial background subtraction is shown in panels (b) and (d). The signal peak is fitted with a Voigtian function (blue line) and the residual background (red dotted line) with a 2nd order polynomial function.

$$f(M_{KK}) = \frac{Y\Gamma}{2\pi^{3/2}\sigma} \int_{-\infty}^{\infty} \exp\left(\frac{(m_{KK} - m')^2}{2\sigma^2}\right) \frac{dM_{KK}}{(M_{KK} - M_0)^2 + \frac{\sigma^2}{4}} + AM_{KK}^2 + BM_{KK} + C \quad (4.4)$$

where, M_0 , Γ and σ are the mass, width and mass resolution of ϕ meson, respectively. Y parameter represents the area under the Voigtian distribution and corresponds to ϕ raw yield. The Voigtian function as implemented in ROOT is given below.

A TMath:: Voigt($M_{\text{inv}} - M_0, \Gamma, \sigma$)

where, A , M_0 , Γ , σ are the fit parameters representing the integral of the function (from 0 to ∞), mass of the ϕ , width of the ϕ and detector resolution, respectively. The width of ϕ meson is fixed to the PDG value and resolution (σ of gaussian function) is kept as free parameter. It is observed that the mass and width obtained from the fit are independent of rapidity and multiplicity class. The mass and resolution as a function of p_T for various rapidity interval in 0-100% multiplicity class is shown in Fig. [4.7](#) and [4.8](#), respectively. ϕ meson peak significance is defined as:

$$\text{Significance} = \frac{\text{Sig}}{\sqrt{\text{Sig} + \text{Bkg}}} \quad (4.5)$$

For calculation of ‘Sig’ we integrate the signal after background subtraction over the mass region (1.011, 1.028) GeV/ c^2 (which is within 2Γ from mass peak position) and ‘Sig+Bkg’ is calculated by integrating the unlike sign (signal+background) over the mass region (1.011, 1.028) GeV/ c^2 . ϕ meson signal significance as a function of p_T for various rapidity intervals in multiplicity class (0-100%) is shown in Fig. [4.9](#).

4.2.1 Yield extraction

Raw yield can be extracted from either bin counting method or function integration. Bin counting is used as default and function integration is used for systematic study.

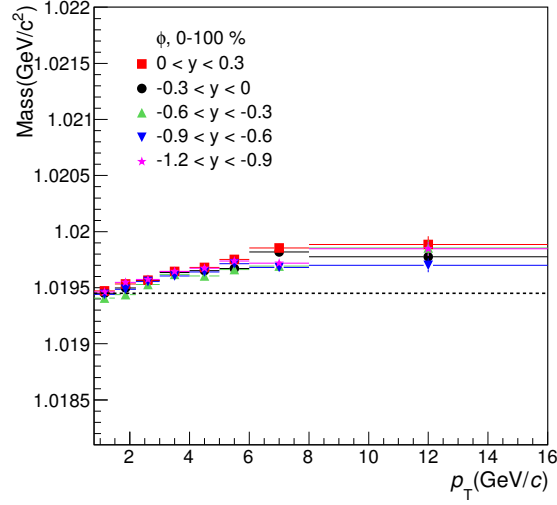


Figure 4.7: ϕ meson mass as a function of p_T for p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in multiplicity class (0-100%). The dashed line represent the PDG value $1019.45 \text{ MeV}/c^2$.

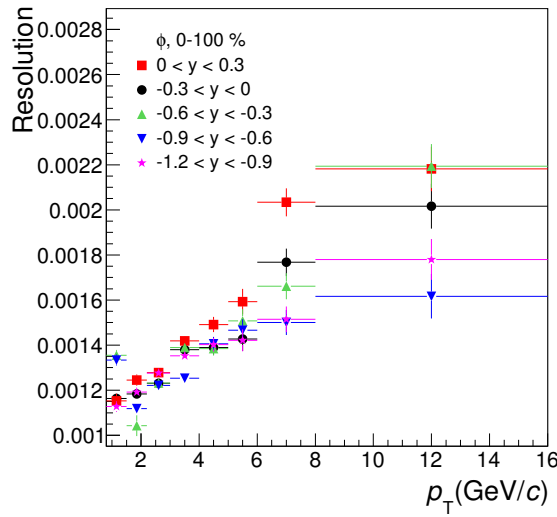


Figure 4.8: ϕ meson resolution as a function of p_T for p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in multiplicity class (0-100%).

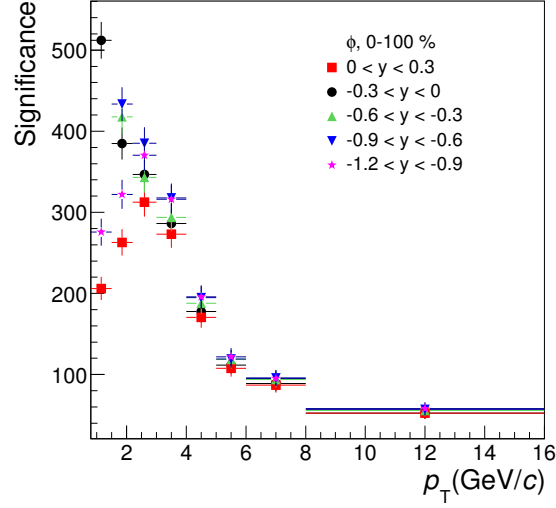


Figure 4.9: ϕ significance as a function of p_T for p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in multiplicity class (0-100%).

Bin Counting (Y_{BC}) :

To extract the yield, first the invariant-mass histogram (after the combinatorial background subtraction) is integrated over the mass region (1.011, 1.028) GeV/ c^2 and then the integral of the residual background contribution (from the polynomial function which is used to describe the residual background) over the same interval is subtracted from the integrated yield.

$$N_{\text{raw}} = N_{\text{counts}} - N_{\text{RB}} \quad (4.6)$$

where, N_{counts} is the total number of counts in signal histogram in mass bins which satisfy the condition: lower value (lval) $\leq$ Bin Center $\leq$ upper value (hval). These lower and upper values are equivalent to $M(\text{PDG}) - 2\Gamma$ and $M(\text{PDG}) + 2\Gamma$ respectively, where Γ is the width of ϕ meson. N_{RB} is integral of the polynomial (used for residual background) in the same mass range mentioned above. The errors from the N_{counts} and N_{RB} are propagated to the N_{raw} . As we only count the yield in a limited mass range ($M(\text{PDG}) - 2\Gamma$ and $M(\text{PDG}) + 2\Gamma$) so we need to correct the same for the tail part. We estimate the tail contribution from the peak fit function in the mass region $(2M_{K^+}) < M_{KK} < 1.011 \text{ GeV}/c^2$ and $1.028 < M_{KK} < \infty \text{ GeV}$

$/c^2$

$$N_{\text{low}} = \int_{2M_K}^{M_{\text{PDG}} - 2\Gamma} \text{fit}(M_{\text{KK}}) dM_{\text{KK}} \quad (4.7)$$

$$N_{\text{high}} = \int_{M_{\text{PDG}} + 2\Gamma}^{\infty} \text{fit}(M_{\text{KK}}) dM_{\text{KK}} \quad (4.8)$$

We added the lower and the higher invariant mass tail contribution to the bin counting yield. The final yield is

$$Y_{\text{BC}} = N_{\text{low}} + N_{\text{raw}} + N_{\text{high}} \quad (4.9)$$

The uncertainty on Y_{BC} is quadrature sum of the uncertainties on N_{low} , N_{raw} and N_{high} .

Function Integral (Y_{FI})

The yield is extracted by integrating the peak fitting function over the region $2M_K < M_{\text{KK}} < \infty$

$$Y_{\text{FI}} = \int_{2M_K}^{\infty} \text{fit}(M_{\text{KK}}) dM_{\text{KK}} \quad (4.10)$$

The raw yield of ϕ meson extracted by bin counting method as a function of p_{T} for various rapidity intervals in p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV in 0-100% multiplicity class is shown in Fig. 4.10. The ϕ meson raw yield spectra for other multiplicity classes is shown in Fig. 4.11.

4.3 Monte Carlo Simulations

Due to inefficiency of detector we need to apply some correction factors like, efficiency, acceptance etc. to the measured ϕ meson yield. These factors can not be obtained from the real data. So a simulated data set is analyzed in order to extract the ϕ reconstruction Efficiency $\times$ Acceptance (this calculation is described in next section). In this study we use two official Monte Carlo productions (LHC17f2b.cent wsdd and fast) from ALICE, which are produced by DPMJET event generator, while

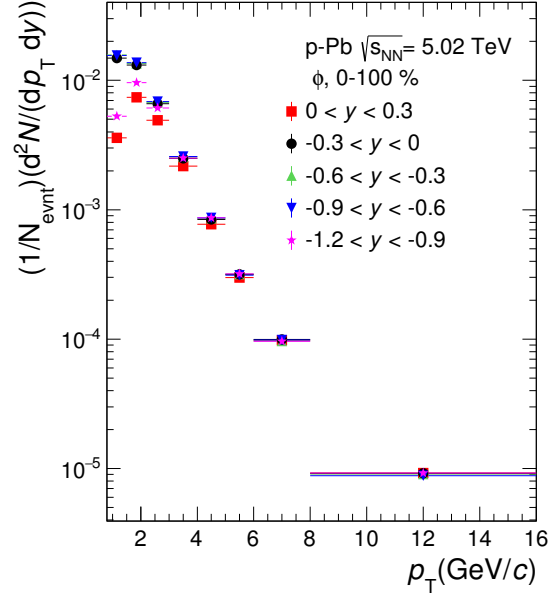


Figure 4.10: The raw p_T spectra of ϕ meson in various rapidity intervals in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in multiplicity class (0-100%).

the particle interactions with the ALICE detector are simulated using GEANT3. The tracks which are identified by the reconstruction algorithms and which pass the track selection and PID cuts (same as data) are referred to as reconstructed tracks. A Tune On Data option is used while selecting the kaon particles.

4.3.1 Reconstruction Efficiency $\times$ Acceptance

The reconstructed efficiency is used to correct the raw spectra. The reconstructed efficiency is defined as the ratio of number of ϕ mesons reconstructed to the number of ϕ mesons generated in each transverse-momentum bin.

$$\epsilon_{\text{rec}} = \frac{N_{\text{rec}}}{N_{\text{gen}}} \quad (4.11)$$

The N_{rec} are the reconstructed ϕ mesons which include the detector effects, pass the analysis cuts and reconstruction algorithms and N_{gen} are the generated ϕ mesons by the event generator DPMJET. Both numbers are counted within a corresponding

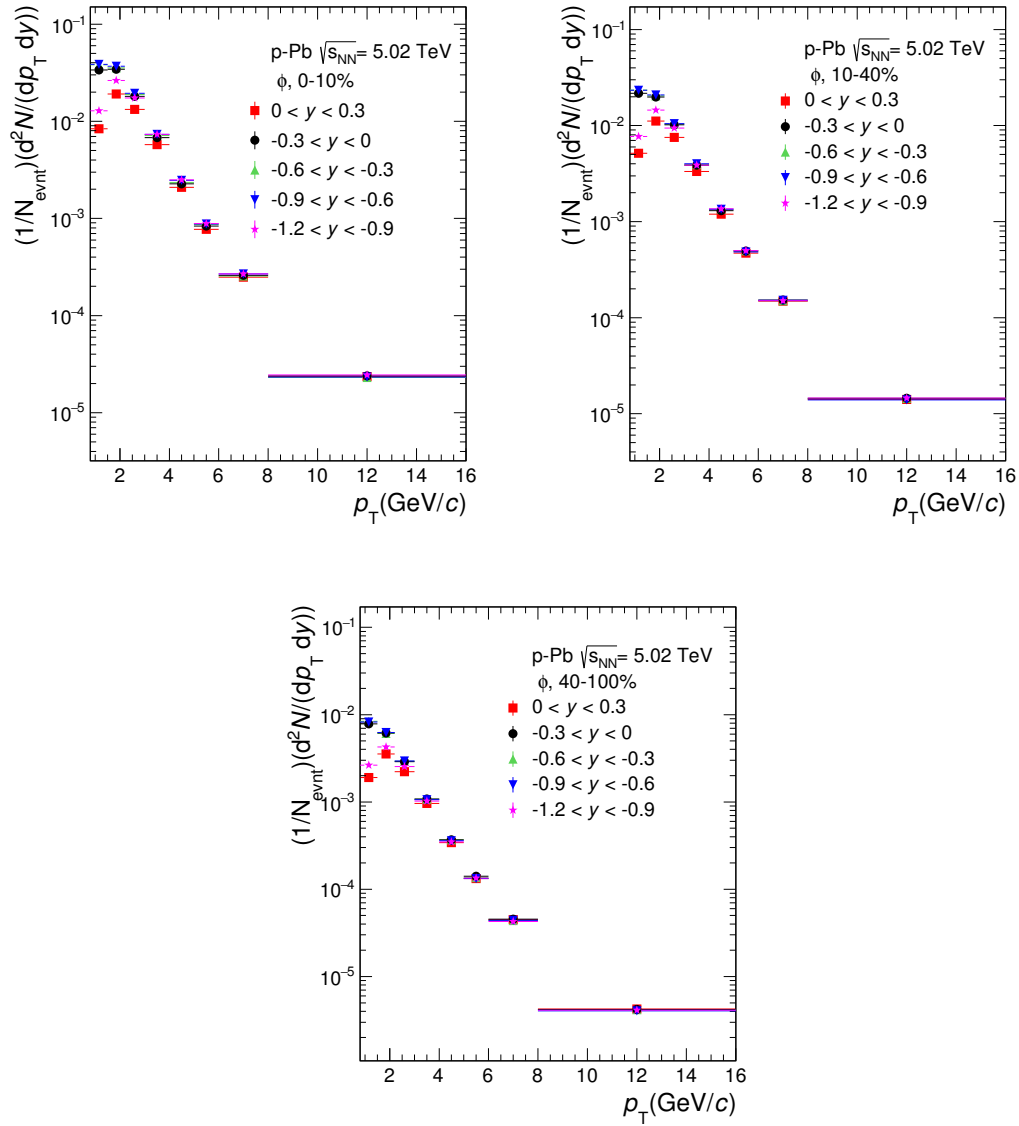


Figure 4.11: The raw p_T spectra of ϕ meson in various rapidity intervals in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in multiplicity classes 0-10%, 10-40% and 40-100%.

rapidity interval. The weighted average reconstructed Efficiency $\times$ Acceptance from two productions for various rapidity intervals in centre of mass frame is shown in Fig. 4.12. The efficiencies among various rapidity intervals have strong dependence on transverse momentum at low p_T .

The uncertainty in ϵ_{rec} is calculated using the Bayesian approach described in [16]. The standard deviation in an efficiency $\epsilon_{\text{rec}} = k/n$, where the numerator k is a subset of the denominator n is defined as;

$$\sigma_{\epsilon} = \sqrt{\frac{k+1}{n+2} \left(\frac{k+2}{n+3} - \frac{k+1}{n+2} \right)} \quad (4.12)$$

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

The Efficiency $\times$ Acceptance is measured for both MC productions. A weighted average Efficiency $\times$ Acceptance is calculated from the Efficiency $\times$ Acceptance of the above two productions (LHC17f2b_cent wsdd and fast). The formula for calculating the weighted average Efficiency $\times$ Acceptance is as follows: $(e_1 * n_1 + e_2 * n_2)/n$, where e_1 and e_2 represent the efficiency, n_1 and n_2 represent the number of events in the corresponding productions, and n equals the sum of n_1 and n_2 . The weighted average Efficiency $\times$ Acceptance is used to correct the raw spectra in various multiplicity classes. It is to be noted that due to large statistical uncertainties at high p_T , we have fitted the Efficiency $\times$ Acceptance with sigmoid function $(a/(1+\exp(-b(p_T-c))))$ where a , b and c are free parameters. We have used the value of efficiency from the fitting function for all p_T bins at $p_T > 4$ GeV/ c with the statistical error propagated from the corresponding MC data p_T bins. The Efficiency $\times$ Acceptance for various rapidity intervals is shown in Fig. 4.12.

The Efficiency $\times$ Acceptance is calculated for all multiplicity classes and no multiplicity dependence is observed. So, a minimum bias (0-100%) Efficiency $\times$ Acceptance is used to correct all multiplicity classes raw p_T spectra. The same

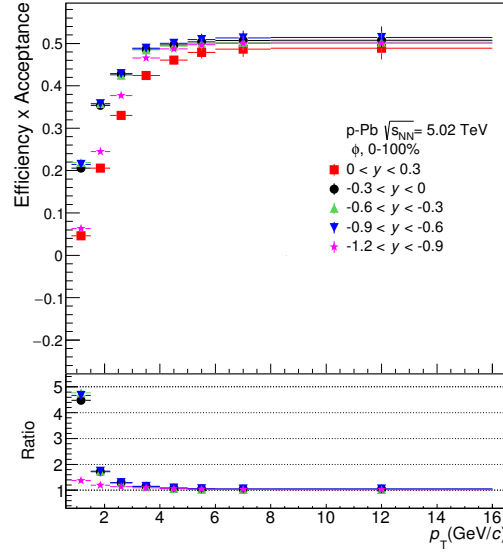


Figure 4.12: The Efficiency $\times$ Acceptance of ϕ meson as a function of p_T for various rapidity intervals in multiplicity class 0-100% for p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The below panel shows the ratio w.r.t. the rapidity window $0 < y < 0.3$.

procedure is applied for the calculation of Efficiency $\times$ Acceptance in all rapidity intervals. The comparison of Efficiency $\times$ Acceptance for both MC production and weighted average method for two rapidity intervals $0 < y < 0.3$ and $-1.2 < y < -0.9$ is shown in Fig. 4.13.

4.3.2 Re-weighted efficiency

It is observed that at low p_T the generated ϕ meson spectrum has different shape than the measured p_T spectra. So it is necessary to weight the generated and reconstructed ϕ meson spectra in these simulations. Fig. 4.14 shows the generated and reconstructed ϕ meson spectra plotted with the (corrected) measured ϕ spectrum in 0-100% multiplicity class and the Levy-Tsallis fit of that measured spectrum.

An iterative procedure is performed to determine the correct weighting (and therefore the correct ϵ_{rec}) as described below:

1. The unweighted ϵ_{rec} is calculated.

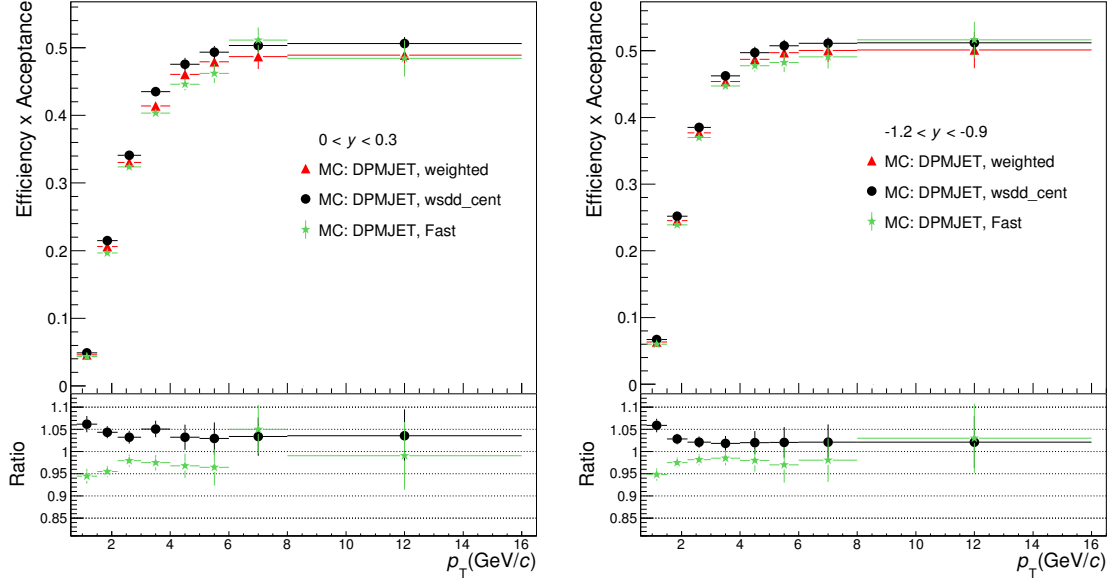


Figure 4.13: The Efficiency $\times$ Acceptance for DPMJET (LHC17f2b cent wsdd and fast) production are compared with weighted average Efficiency $\times$ Acceptance for rapidity intervals $0 < y < 0.3$ and $-1.2 < y < -0.9$ in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in 0-100% multiplicity class.

2. This ϵ_{rec} is used to correct the measured ϕ meson p_T spectrum.
3. The corrected ϕ meson spectrum is fitted with Levy-Tsallis function.
4. This fit is used to weight the MC generated ϕ spectra. A p_T dependent weight is applied to the generated ϕ spectrum so that it follows the fit (see Fig. 4.15). The same weight is applied to the reconstructed ϕ spectrum.
5. The (weighted) ϵ_{rec} is calculated.
6. Steps 2-5 are repeated (with the weighted ϵ_{rec} from step 5 used as the input for step 2) until the ϵ_{rec} values are observed to change by $< 0.1\%$ (relative) between successive iterations. It is observed that two iterations are usually sufficient for this procedure to converge. The procedure is implemented in the macro inside the Aliroot framework,

ALICE PHYSICS/PWGLF/RESONANCES/macros/utls/ReweightEfficiency.C

The net effect of the weighting procedure is very small except at low p_T , as shown in Fig. 4.16. At low p_T weighting factor varies from 5-17% among various rapidity

intervals. Here weighting factor only upto $p_T = 8 \text{ GeV}/c$ is shown as we expected no change at high p_T . The new Efficiency $\times$ Acceptance (corrected with weighting factor) is used to correct the raw p_T spectra for various multiplicity classes and the corresponding rapidity interval.

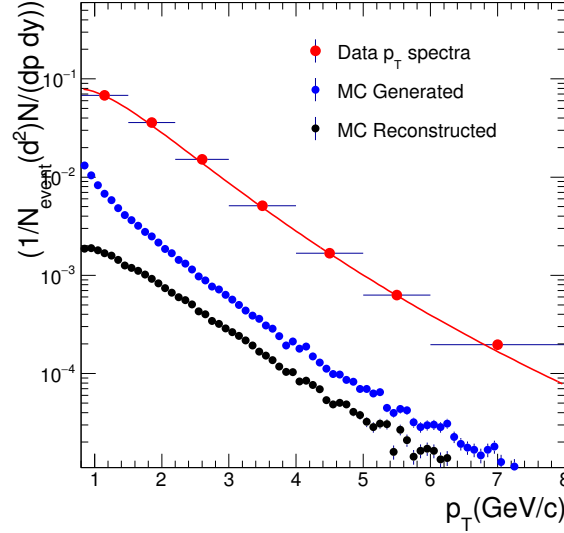


Figure 4.14: The corrected ϕ meson spectrum fitted with Levy-Tsallis function in 0-100% multiplicity class. The generated and reconstructed ϕ meson spectra from MC production is shown by blue and black marker respectively.

4.4 Corrected p_T spectra

The raw spectra is corrected for the Efficiency $\times$ Acceptance of the detector and branching ratio for corresponding decay channel of ϕ meson. The normalized corrected p_T spectra of ϕ mesons is obtained by using the following formula:

$$\frac{d^2N}{dp_T dy} = \frac{\text{Raw Counts}}{N_{\text{evt}} \times \text{BR} \times dp_T \times dy \times \epsilon_{\text{rec}}} \quad (4.13)$$

Where, ‘Raw Counts’ represent the raw yields obtained from invariant mass distributions, N_{evt} is the total number of selected events, BR is branching ratio and is 0.489 for decay channel ($\phi \rightarrow K^+ K^-$) and dy is rapidity interval in which the spectra are measured. The other correction factors such as Vertex correction (f_{vtx}), Signal loss

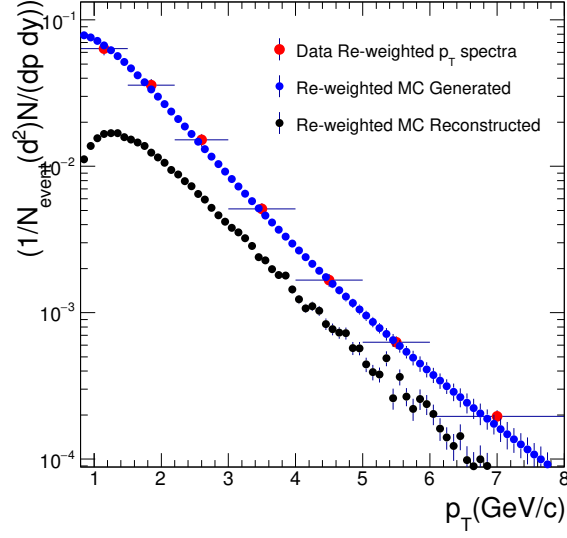


Figure 4.15: The weighted corrected ϕ meson spectrum in 0-100% multiplicity class. The weighted generated and reconstructed ϕ meson spectra after iteration 2 is shown by blue and black marker respectively.

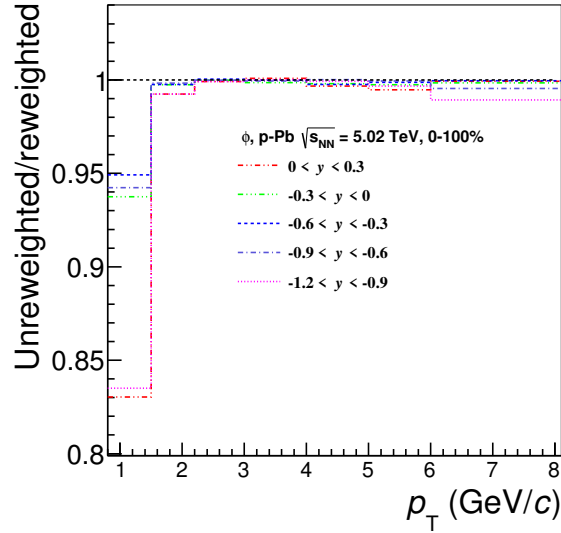


Figure 4.16: Ratio of ϕ meson re-weighted to unweighted Efficiency $\times$ Acceptance after 2 iteration for various rapidity intervals in 0-100% multiplicity class in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

correction (f_{SL}) and Normalization correction factor (f_{Norm}) are negligible for p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV [11]. The corrected p_{T} spectra for various rapidity intervals in 0-10% (left panel) and 10-40% (right panel) multiplicity classes in p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV are shown in Fig. 4.17. Similarly, Fig. 4.18 shows the corrected p_{T} spectra for various rapidity intervals in 40-100% (left panel) and 0-100% (right panel) multiplicity classes in p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. These spectra are scaled with various factors for clear visibility as shown in Figs. 4.17 and 4.18.

4.5 Systematic Uncertainty

The ϕ meson spectra are measured in the rapidity range $-1.2 < y < 0.3$ in various multiplicity classes in p-Pb $\sqrt{s_{\text{NN}}} = 5.02$ TeV. The systematic uncertainties are estimated by varying the default analysis selection criteria. Barlow check is performed as discussed in chapter 3 to check whether the variation comes under systematic uncertainty. If it fails the barlow check criteria, then it is considered in total systematic uncertainty.

The main sources of systematic uncertainties on the spectra are signal extraction, track selection criteria, particle identification, global tracking efficiency, uncertainty in the material budget of the ALICE detector, and the hadronic interaction cross-section in the detector material. In this analysis uncertainty due to global tracking efficiency, material budget, and hadronic interaction cross-section are used from the analysis described in chapter 3.

4.5.1 Systematic uncertainty due to signal extraction

The uncertainties due to signal extraction include variations of the signal peak fitting range, variations of width and mass resolution, mixed event background normalization region, choice of a residual background function, and type of combinatorial background. The like-sign method is used for estimation of combinatorial back-

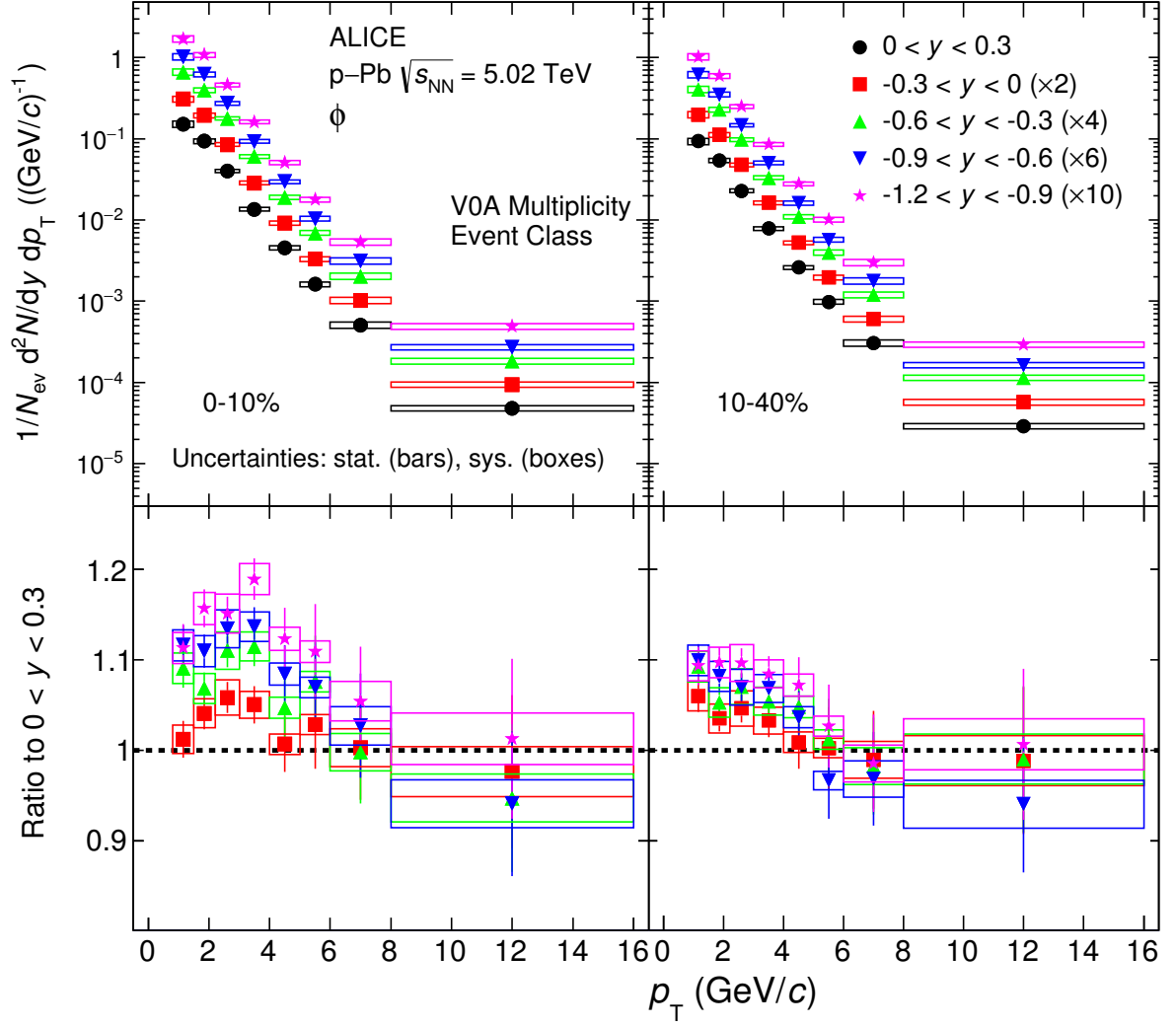


Figure 4.17: ϕ meson spectra in five rapidity intervals within $-1.2 < y < 0.3$ in 0-10% (left panel) and 10-40% (right panel) multiplicity classes in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The bottom panels show the ratios of spectra in various rapidity intervals with respect to the rapidity $0 < y < 0.3$. The statistical and systematic uncertainties are represented by bars and boxes, respectively.

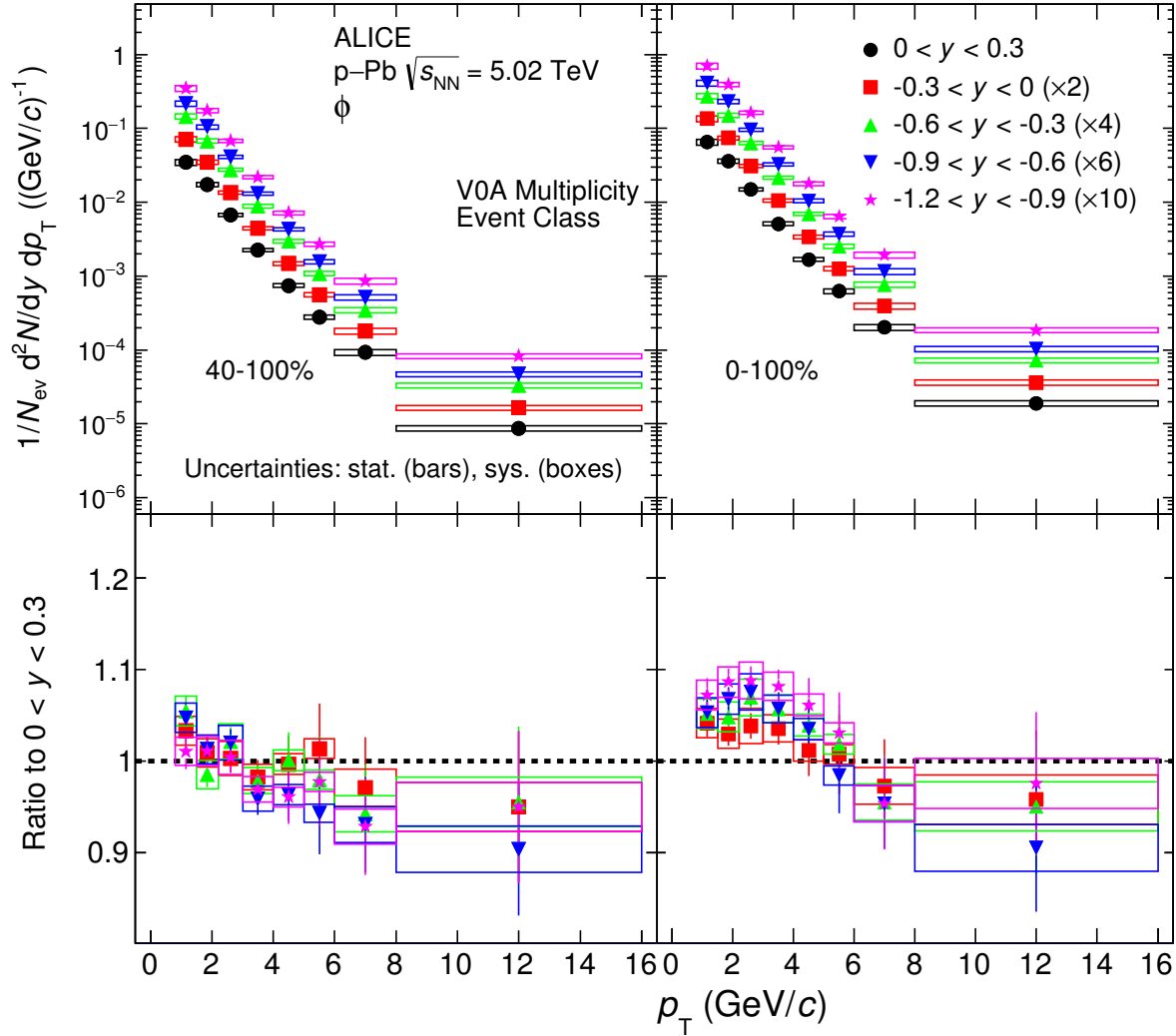


Figure 4.18: ϕ meson spectra in five rapidity intervals within $-1.2 < y < 0.3$ in 40-100% (left panel) and 0-100% (right panel) multiplicity classes in p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. The bottom panels show the ratios of spectra in various rapidity intervals with respect to the rapidity $0 < y < 0.3$. The statistical and systematic uncertainties are represented by bars and boxes, respectively.

ground while the mixed-event method is used as default. The fitting range is varied on both sides of the signal peak while fitting the ϕ meson invariant mass distribution with the Voigtian function. The residual background fit function is varied from 2^{nd} order (default) to 1^{st} and 3^{rd} order for systematic uncertainty. The normalization range of the mixed-event background is varied away from the ϕ meson signal peak. The resolution is fixed to the value obtained from simulations and the width is kept as a free parameter. The estimated systematic uncertainty that comes out due to signal extraction is around 3.3%.

4.5.2 Systematic uncertainty due to particle identification

For the estimation of PID systematic uncertainty, the $n\sigma$ cut in TPC and TOF is varied from the default value for the selection of kaons. Two momentum-independent selections: $2\sigma_{\text{TPC}}$ with $3\sigma_{\text{TOF}}$ and $2\sigma_{\text{TPC}}$ only, while selecting the kaons are used. The estimated systematic uncertainty is 1.7% for ϕ meson.

4.5.3 Systematic uncertainty due to event and track selection

By varying the default selection criteria as discussed in [4.1.1](#), systematic uncertainty due to track selection and event selection is estimated. The variation includes the changes in the number of crossed readout rows from 70 (default) to 80 in the TPC and the distance of the closest approach to the primary vertex of the collision from 7σ (default) to 4σ . The variations also include the variations of χ^2 of ITS from 36 (default) to 25 and TPC from 4 (default) to 3 while reconstruction of the track, and the variations of the cross row over findable clusters from 0.8 (default) to 0.9 in the TPC detector. The primary vertex position cut is also varied from 10 (default) to 8 for systematic uncertainty. The relative contribution of uncertainties due to the tracks and events selection is about 5%.

The systematic uncertainties exhibit a few fluctuations from bin to bin, while

Table 4.1: Relative systematic uncertainties for ϕ meson yields in p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. The quoted relative uncertainties are averaged over p_{T} in the range 0.8-16 GeV/ c . The total systematic uncertainty is the sum in quadrature of the uncertainties due to each source.

Systematic variation	ϕ
Yield extraction (%)	3.3
Track selection (%)	5.0
Particle identification (%)	1.7
Global tracking efficiency (%)	2.1
Material budget (%)	2.2
Hadronic Interaction (%)	2.4
Total (%)	7.3

one might expect a smooth behavior of the systematic uncertainties. We smoothed the dips and spikes in systematic uncertainties by averaging over the nearest bins in order to obtain a more uniform set of systematic uncertainties. The total systematic uncertainty is taken as the quadrature sum of all contributions leading to 7.3% for ϕ mesons. The total systematic uncertainties including contribution from various source of systematics after smoothing are shown in Fig. 4.19 in rapidity interval $0 < y < 0.3$ in 0-100% multiplicity class. No multiplicity and rapidity dependence of the systematic uncertainties is observed. Therefore, the systematic uncertainties on the p_{T} spectra determined for minimum bias events in the rapidity interval $0 < y < 0.3$ are assigned in all rapidity intervals and multiplicity classes. A summary of the systematic uncertainties on the p_{T} spectra is given in Table 4.1.

Y_{asym} systematic uncertainty : Y_{asym} is the ratio of p_{T} spectra in backward rapidity (Pb-going direction) to that in forward rapidity (p-going direction). As a result, some of the systematic errors will cancel out in the ratio. The systematic uncertainties on Y_{asym} are estimated by considering the same approaches and variations as for the corrected yields. The systematic uncertainties due to signal extraction and PID are uncorrelated among different rapidity intervals whereas the other sources of systematic uncertainties such as track selections, global tracking uncertainties, material budget, and hadronic interactions are correlated and can-

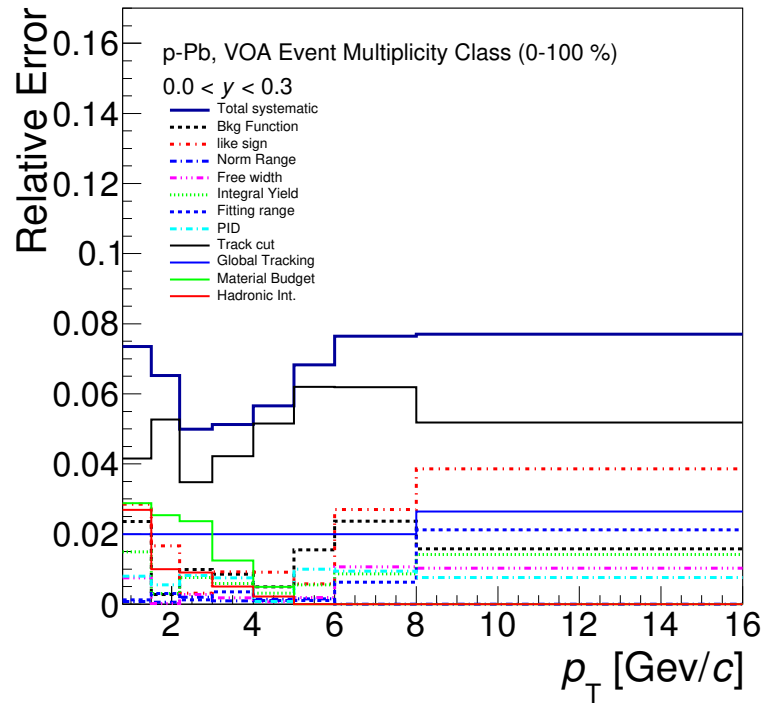


Figure 4.19: Relative total systematic uncertainty on ϕ meson yields as a function of p_T in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in the rapidity interval $0 < y < 0.3$. Different color lines correspond to various sources of systematic uncertainties.

cel out in the Y_{asym} ratio. For the uncorrelated sources of uncertainty, the same variations considered for the yields were studied by estimating their effects on the Y_{asym} ratio. The resulting uncertainty was estimated to be about 2% for ϕ mesons. No multiplicity and rapidity dependence of the uncertainties is observed for Y_{asym} . Therefore, the systematic uncertainties determined for minimum bias events are assigned to the ratios in the different rapidity intervals and multiplicity classes. Total systematic uncertainty on Y_{asym} is shown in Fig. 4.20.

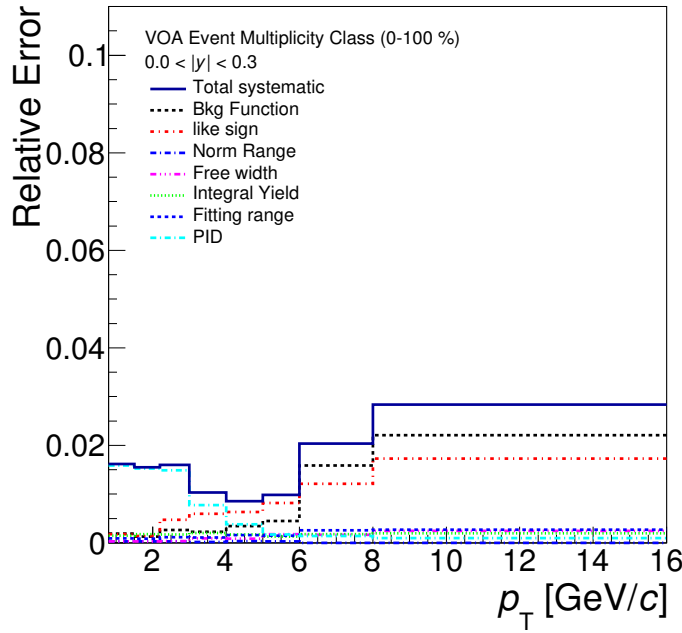


Figure 4.20: Relative total systematic uncertainty on Y_{asym} as a function of p_T in p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV in the rapidity interval $0 < |y| < 0.3$.

Systematic uncertainty on the ratio of dN/dy and $\langle p_T \rangle$: The systematic uncertainties on the ratios $(dN/dy)/(dN/dy)_{y=0}$ and $\langle p_T \rangle/\langle p_T \rangle_{y=0}$ as a function of rapidity are calculated in a similar way as for Y_{asym} . For each uncorrelated source of systematics the ratio is calculated and the variation from the default value is considered as systematic uncertainty due to that particular variation. The systematic uncertainties on $(dN/dy)/(dN/dy)_{y=0}$ and $\langle p_T \rangle/\langle p_T \rangle_{y=0}$ are 2% and 1% for ϕ meson, respectively. The total systematic uncertainty on $(dN/dy)/(dN/dy)_{y=0}$ and $\langle p_T \rangle/\langle p_T \rangle_{y=0}$ are shown in Fig. 4.21.

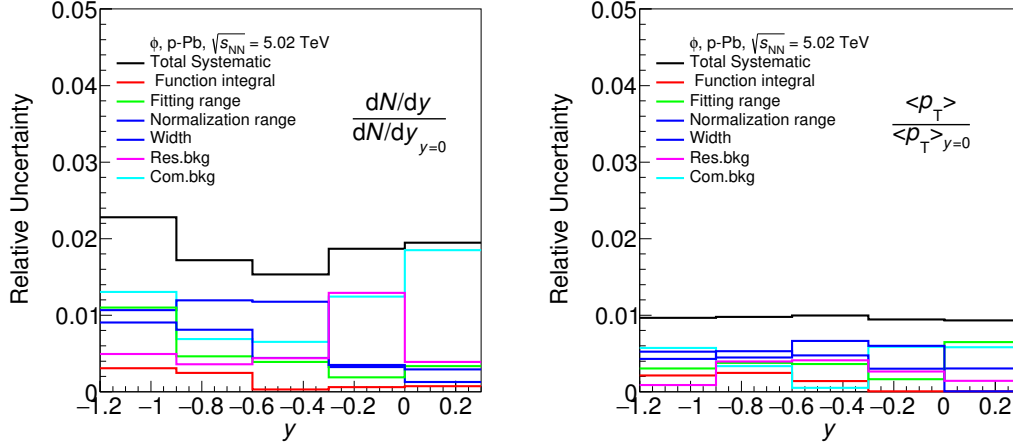


Figure 4.21: The systematic uncertainty on $dN/dy/dN/dy_{y=0}$ (left panel) and $\langle p_T \rangle / \langle p_T \rangle_{y=0}$ (right panel) for 0-100% multiplicity class in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

4.6 Results

4.6.1 Transverse momentum spectra

The ϕ meson p_T spectra is measured in five rapidity intervals within $-1.2 < y < 0.3$ and four multiplicity classes 0-10%, 10-40%, 40-100%, and minimum bias (0-100%) in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with ALICE at the LHC as shown in Figs. 4.17 and 4.18. The spectra are scaled with different factors for clear visibility for different rapidity intervals. The ratios of the p_T spectra in various rapidity intervals to that in the interval $0 < y < 0.3$ are shown in the bottom panels of the Figs. 4.17 and 4.18. The measured spectra at low p_T (< 5 GeV/c) show rapidity dependence for 0-10%, 10-40%, and 0-100% multiplicity classes, indicating that the production of the ϕ mesons is higher in the Pb-going direction ($y < 0$) than in the p-going direction ($y > 0$). For high p_T , and in 40-100% multiplicity class, no rapidity dependences are observed.

4.6.1.1 Model comparison

The measured ϕ meson spectra is compared with the predictions from the models such as HIJING with and without shadowing factor, EPOS-LHC, EPOS3 with and without UrQMD, DPMJET and PYTHIA8 (Angantyr) in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The events are generated locally for p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. In the HIJING model we have generated events with two different shadowing parameter values 0 and 0.1. In EPOS, the events are generated for two cases, one with UrQMD and another without UrQMD. The p_T spectra, dN/dy , mean transverse momentum and Y_{asy} are calculated for all models (HIJING, EPOS-LHC, EPOS3, DPMJET and PYTHIA8 (Angantyr)) for similar rapidity intervals as in data. Figure 4.22 shows the ϕ mesons p_T spectra comparison with the predictions from HIJING, EPOS-LHC, EPOS3, DPMJET and PYTHIA8 (Angantyr) models in the rapidity intervals $0 < y < 0.3$ (left plot) and $-0.3 < y < 0$ (right plot) in 0-100% multiplicity class. The bottom panels show the model to data ratios and bands around one correspond to the statistical and systematic uncertainties on the measured data points. None of the above mentioned model describes the measured p_T spectra in data in full p_T range. EPOS-LHC model describes the measurements better than other models.

4.6.2 Integrated particle yield and mean transverse momentum

The integrated yield (dN/dy) and the mean transverse momentum ($\langle p_T \rangle$) are calculated by the official macro "YieldMean.C" which is part of the PWGLF/SPECTRA aliroot directory. The measured spectra are fitted using the Levy-Tsallis function. The dN/dy and $\langle p_T \rangle$ are obtained from the transverse momentum spectra in the measured p_T interval and using Levy-Tsallis fit function to account for the contribution of ϕ mesons in the unmeasured region. The dN/dy are obtained in the unmeasured region at low p_T (< 0.8 GeV/c) from fitting function. The obtained yield in the extrapolated region accounts for 33% (39%) of the total yield in the 0-

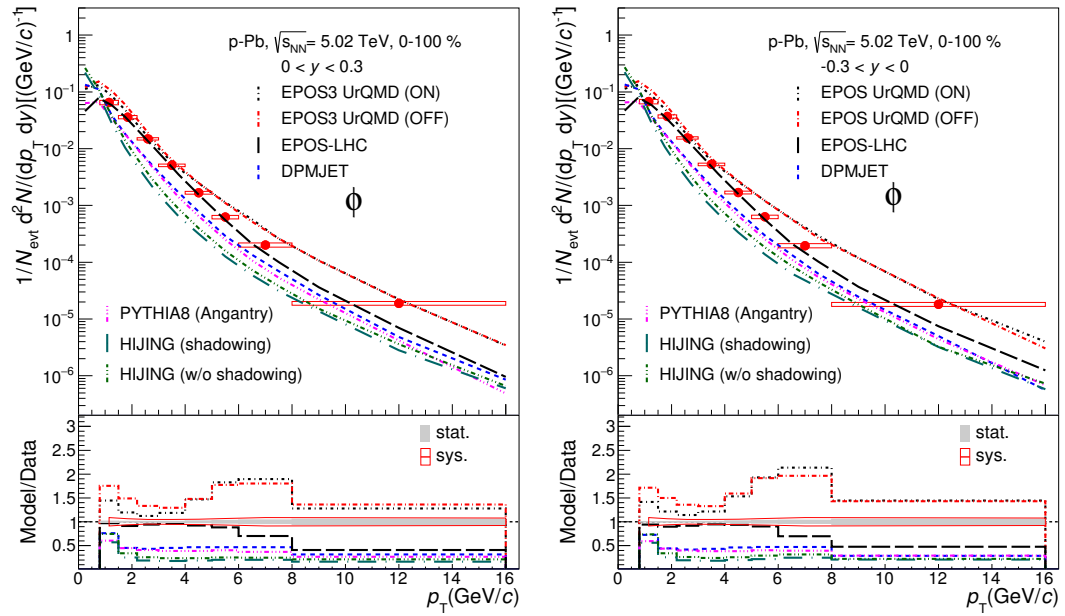


Figure 4.22: The comparison of measured p_T spectra of ϕ meson with predictions from EPOS-LHC, EPOS3, HIJING, DPMJET and PYTHIA8 (Angantyr) model in rapidity intervals $0 < y < 0.3$ (left plot) and $-0.3 < y < 0$ (right plot) in 0-100% multiplicity class for p-Pb collision at $\sqrt{s_{NN}} = 5.02$ TeV. The bottom panels show the ratios of various models to data. The bands around one correspond to the statistical and systematic uncertainties on the measured data points.

10% (40-100%) multiplicity class for ϕ mesons. The contribution of the extrapolated yield at low p_T is the same for all rapidity intervals. The contribution of the yield in the unmeasured region at high p_T ($p_T > 16$ GeV/ c) is negligible for ϕ mesons. The difference between the extrapolated yield contribution at low p_T obtained with different fitting functions (i.e. m_T -exponential, Bose-Einstein and Boltzmann-Gibbs Blast-Wave function) and that obtained with the default Levy-Tsallis function is included in the systematic uncertainties.

Figure 4.23 shows dN/dy (left panel) and $\langle p_T \rangle$ (right panel) of ϕ mesons as a function of rapidity (y) for minimum bias p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The central values of the dN/dy of ϕ mesons decrease slightly from the rapidity interval $-1.2 < y < -0.9$ to $0 < y < 0.3$ even though within the systematic uncertainties all the data points are compatible among each other. Nevertheless, considering that the systematic uncertainties are mostly correlated among the rapidity intervals, the measured dN/dy values suggest a decreasing trend with increasing y in the rapidity interval covered by the measurement. The $\langle p_T \rangle$ shows a constant behaviour as a function of rapidity for ϕ mesons. The measured dN/dy and $\langle p_T \rangle$ are compared with the model predictions from EPOS-LHC, EPOS3 with and without UrQMD, DPMJET, HIJING and PYTHIA8(Angantyr) are shown in Fig. 4.23. In general, the models show a similar trend with rapidity as the data except for calculations from EPOS3 with and without UrQMD for $\langle p_T \rangle$ that show a decreasing trend with rapidity. All the model predictions discussed above underpredict the $\langle p_T \rangle$ of ϕ mesons. EPOS-LHC model $\langle p_T \rangle$ is more closer to the data than the other models. For dN/dy , EPOS-LHC and DPMJET models better describe the data. PYTHIA8(Angantyr) model underpredict the ϕ yield, whereas HIJING and EPOS3 overpredict the measured ϕ mesons yield.

Figure 4.24 shows the dN/dy (left panel) and $\langle p_T \rangle$ (right panel) of ϕ mesons as a function of rapidity (y) in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for various multiplicity classes. The dN/dy and the $\langle p_T \rangle$ increase with multiplicity for a given rapidity interval. The dN/dy shows a weak rapidity dependence with large un-

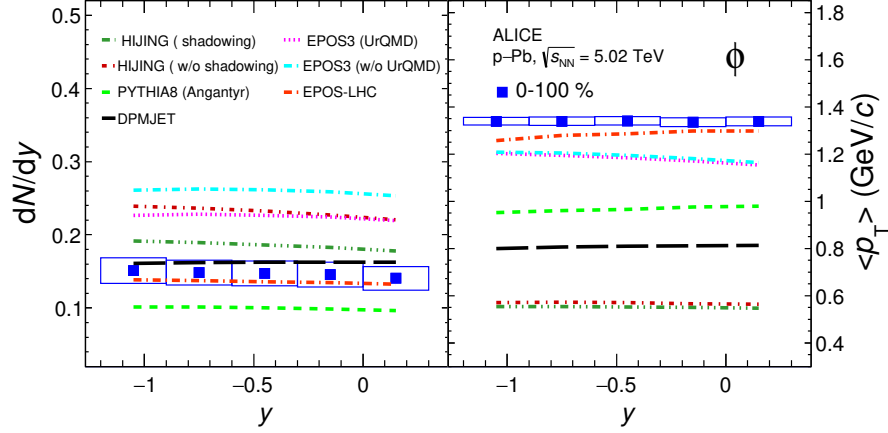


Figure 4.23: The p_T integrated yield (dN/dy) (left panel) and mean transverse momentum ($\langle p_T \rangle$) (right panel) for ϕ meson as a function of y measured for the multiplicity class 0-100% in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The predictions from EPOS-LHC, EPOS3 with and without UrQMD, DPMJET, HIJING and PYTHIA8(Angantyr) are shown as different curves. The statistical uncertainties are represented as bars whereas the boxes indicate total systematic uncertainties on measurements.

certainties, and suggests a more pronounced dependence for events in the highest multiplicity class (0-10%). The $\langle p_T \rangle$ shows a flat behavior as a function of rapidity for all multiplicity classes in the measured rapidity interval. Similar behavior in the average transverse kinetic energy ($\langle KE_T \rangle = \langle m_T \rangle - m$, where $m_T = \sqrt{m^2 + p_T^2}$) as a function of rapidity for strange hadrons was reported in [3].

In order to investigate in more detail the dependence of dN/dy and $\langle p_T \rangle$ for ϕ mesons in the multiplicity class 0 to 100%, the dN/dy and $\langle p_T \rangle$ values in a given rapidity interval are divided by the corresponding values at $y = 0$, as shown in Fig. 4.25. The dN/dy and $\langle p_T \rangle$ value at $y = 0$ is computed from the p_T spectrum measured in the rapidity interval $-0.3 < y < 0.3$. For systematic uncertainties the ratio is obtained for each systematic variation and the difference with respect to default case is taken in systematic uncertainty. The systematic uncertainties on these ratios were estimated by studying the effects of the variations directly on the ratios in similar way as discussed in 4.5.3. Since some of the systematic uncertainties are correlated across rapidity bins, these ratios have a smaller systematic

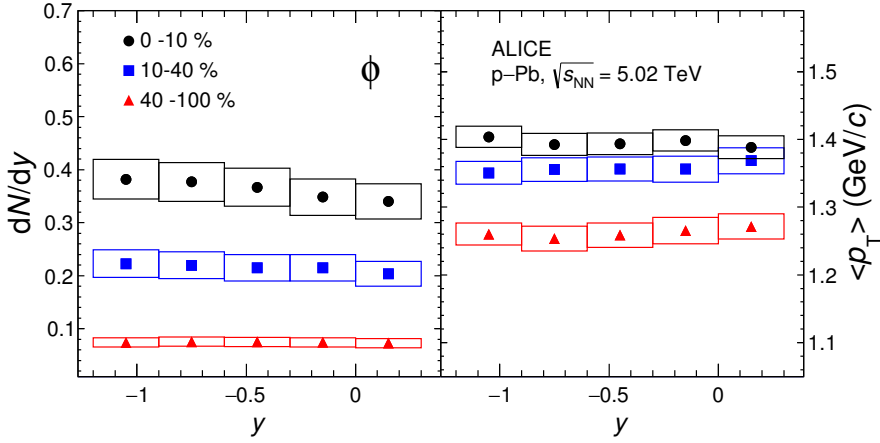


Figure 4.24: The p_T integrated yield (dN/dy) (left panel) and mean transverse momentum ($\langle p_T \rangle$) (right panel) for ϕ meson as a function of y measured for the multiplicity classes 0-10%, 10-40% and 40-100% in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The statistical uncertainties are represented as bars whereas the boxes indicate total systematic uncertainties.

uncertainties than those on the dN/dy and $\langle p_T \rangle$ and so provide more insight into y dependence. The ratio $(dN/dy)/(dN/dy)_{y=0}$ decreases with rapidity, whereas $\langle p_T \rangle / \langle p_T \rangle_{y=0}$ shows a flat behavior within uncertainties as a function of rapidity for ϕ mesons. The measurements are also compared with various model predictions as shown in Fig. 4.25.

For $(dN/dy)/(dN/dy)_{y=0}$, all models except EPOS3 and DPMJET explain the data. EPOS3 explains the data except in $-1.2 < y < -0.9$ rapidity region. For $\langle p_T \rangle / \langle p_T \rangle_{y=0}$, HIJING(with and without shadowing) explains the data, whereas other models do not describe the data towards the negative rapidity region.

Similar studies of the ratio $\langle p_T \rangle / \langle p_T \rangle_{y=0}$ of charged hadrons in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV compared with the predictions of hydrodynamics and color-glass condensate (CGC) model were reported in [17]. Predictions from hydrodynamic calculations show a decrease in $\langle p_T \rangle$ with rapidity, whereas CGC predicts an increase in $\langle p_T \rangle$ with rapidity [17], while the data are flat within uncertainties.

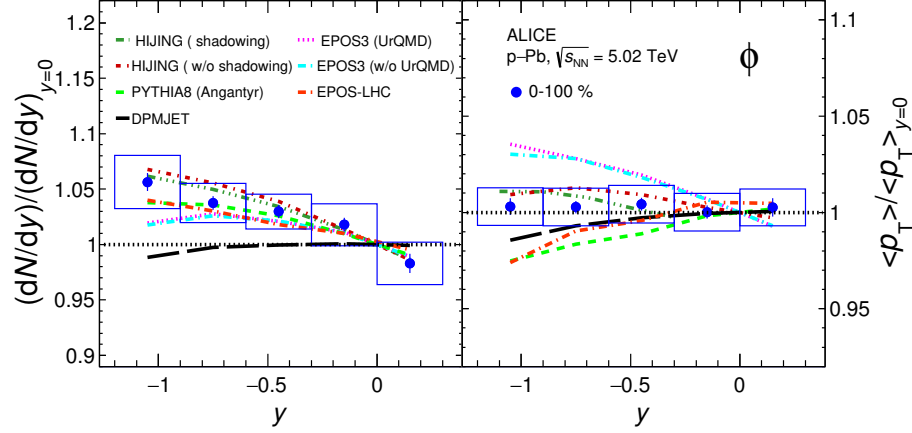


Figure 4.25: The p_T integrated yield (dN/dy) (left panel) and mean transverse momentum ($\langle p_T \rangle$) (right panel) for ϕ meson as a function of y , divided by the dN/dy and $\langle p_T \rangle$ at $y = 0$ measured for the multiplicity class 0-100% in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The predictions from EPOS-LHC, EPOS3 with and without UrQMD, DPMJET, HIJING and PYTHIA8(Angantyr) are shown as different curves. The statistical uncertainties are represented as bars whereas the boxes indicate total systematic uncertainties.

4.6.3 Rapidity asymmetry

The rapidity asymmetry (Y_{asym}) of ϕ mesons is measured from the p_T spectra in the rapidity interval $-0.3 < y < 0$ and $0 < y < 0.3$, as defined by equation [4.1](#). Figure [4.26](#) shows the Y_{asym} of ϕ mesons as a function of p_T for various multiplicity classes in the rapidity interval $0 < |y| < 0.3$ in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The Y_{asym} values deviate from unity at low p_T (< 5 GeV/ c), suggesting the presence of a rapidity dependence in the nuclear effects. The deviations are more significant for events with high multiplicity. The Y_{asym} values are consistent with unity at high p_T (> 5 GeV/ c) for all multiplicity classes, suggesting the absence of nuclear effects at high p_T for the production of ϕ mesons in pPb collisions. Similar results have been reported for charged hadrons, pions, and protons in dAu collisions at $\sqrt{s_{NN}} = 200$ GeV by the STAR Collaboration [\[18\]](#) and for charged hadrons and multi-strange hadrons in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV by the CMS Collaboration as discussed in [\[3, 12\]](#).

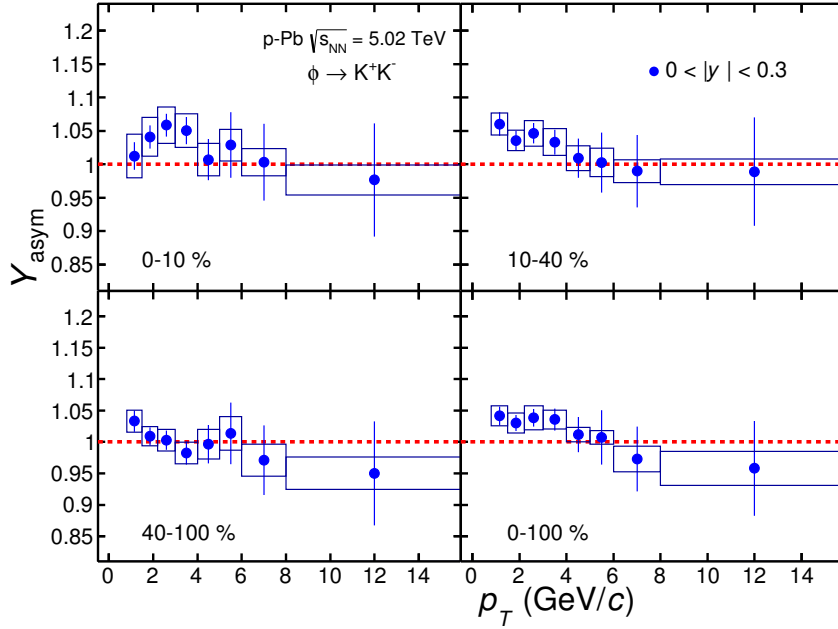


Figure 4.26: Rapidity asymmetry (Y_{asym}) of ϕ meson production as a function of p_T in the rapidity interval $0 < |y| < 0.3$ for various multiplicity classes in p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. The statistical and systematic uncertainties on the measurements are represented as bars and boxes, respectively.

Y_{asym} measurements for ϕ mesons are shown in Fig. 4.27 as a function of p_T in minimum bias events (0-100%) compared to predictions from EPOS-LHC, DPMJET, HIJING with and without shadowing, PYTHIA8(Angantyr), and EPOS3 with and without UrQMD. The HIJING with and without shadowing, and the EPOS3 with and without UrQMD describe the measured Y_{asym} at low p_T within uncertainties, but they overestimate it at high p_T , predicting an increasing trend despite the observations which are consistent with a flat or decreasing trend. EPOS-LHC, PYTHIA8(Angantyr) model predictions at mid p_T and DPMJET at high p_T are in agreement with the data within uncertainties.

4.6.4 Nuclear modification factor

The nuclear modification factor (Q_{CP}) is defined as the ratio of ϕ meson yields in high multiplicity (central) to that in low multiplicity (peripheral) class, normalized

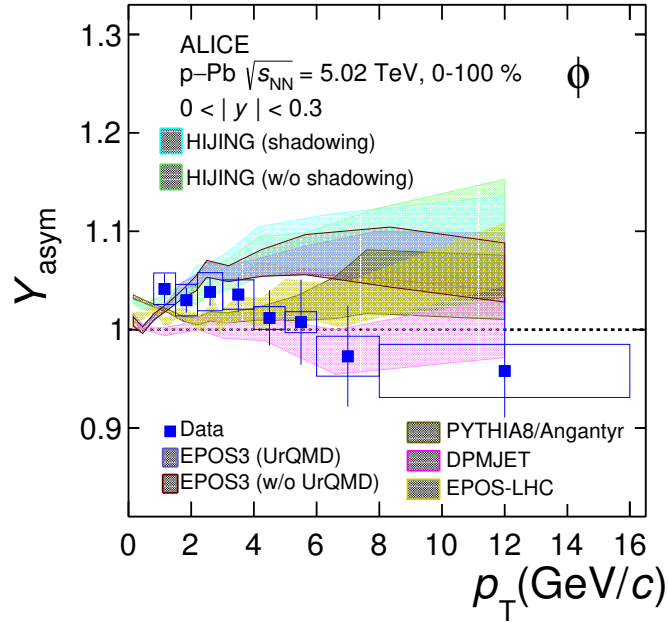


Figure 4.27: The comparison of Y_{asym} for ϕ meson production as a function of p_T in the rapidity interval $0 < |y| < 0.3$ with the model predictions from EPOS-LHC, EPOS3, HIJING, DPMJET and PYTHIA8 (Angantyr) for p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The data points are shown with blue marker, and model predictions are shown by different color bands, where bands represent the statistical uncertainty of the model. The statistical and systematic uncertainties on the data points are represented as bars and boxes, respectively.

with corresponding $\langle N_{\text{coll}} \rangle$ as described by equation 4.2.

Figure 4.29 shows the Q_{CP} of ϕ mesons as a function of p_{T} for 0-10%/40-100% (solid marker) and 10-40%/40-100% (open marker) in five rapidity interval within the range $-1.2 < y < 0.3$ for p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. An enhancement at intermediate p_{T} ($2.2 < p_{\text{T}} < 5.0$ GeV/c), reminiscent of the Cronin effect, is seen. This enhancement is more pronounced at high negative rapidities, i.e. in the Pb going direction, and for high multiplicity events. The more pronounced Cronin-like enhancement for the 0-10% multiplicity class suggests that the multiple scattering effects are more relevant for high multiplicity (central) collisions. At high p_{T} (> 5 GeV/c), the Q_{CP} values are greater than unity, which is a known feature of Q_{pPb} and Q_{CP} when the centrality or multiplicity classes are defined with the V0 detector, and it is interpreted as a selection bias due to the multiplicity estimator [19].

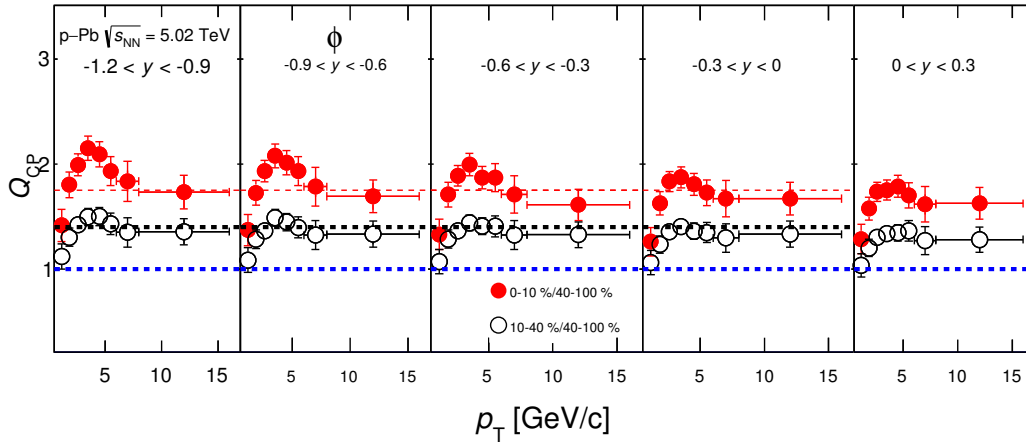


Figure 4.28: The Q_{CP} of ϕ mesons as a function of p_{T} for 0-10%/40-100% (solid circles) and 10-40%/40-100% (open circles) in various rapidity intervals within the range $-1.2 < y < 0.3$ in p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. The statistical and systematic uncertainties on the data points are represented as bars and boxes, respectively.

In order to quantify the rapidity dependence of the nuclear modification factor Q_{CP} , we plotted the Q_{CP} values of ϕ mesons for intermediate p_{T} ($2.2 < p_{\text{T}} < 5.0$ GeV/c) as a function of rapidity in Fig. 4.29. The values of Q_{CP} at intermediate p_{T} show a faster decrease from the rapidity interval $-1.2 < y < -0.9$ to $0 < y <$

0.3 for 0-10%/40-100% than for 10-40%/40-100%, indicating a stronger rapidity dependence of the Cronin-like enhancement in events with high multiplicity. The stronger rapidity dependence for 0-10%/40-100% can be inferred from the slope parameter (m) of the linear function fit to the Q_{CP} of ϕ mesons reported in Fig. 4.29. The bottom panel of the Fig. 4.29 shows the decreasing trend of the double ratio (ratio of 0-10%/40-100% to 10-40%/40-100%) as function of y , which also indicate the stronger rapidity dependence for 0-10%/40-100%. A similar conclusion on the η dependence of nuclear modification factors of charged hadrons was reported by the BRAHMS Collaboration [20].

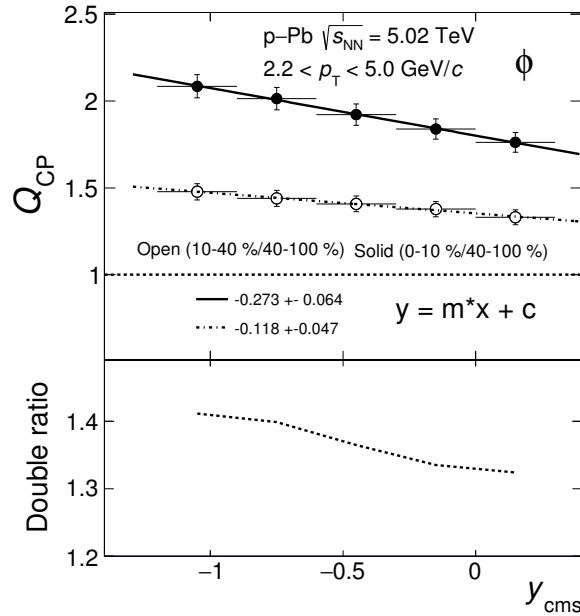


Figure 4.29: The Q_{CP} of ϕ meson as a function of rapidity for 0-10%/40-100% (solid circles) and 10-40%/40-100% (open circles) in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The solid and dotted lines represent the linear fit to data. The statistical and systematic uncertainties on the data points are represented as bars and boxes, respectively.

4.7 Summary

The transverse momentum differential yields of ϕ mesons have been measured in the rapidity interval $-1.2 < y < 0.3$ for various multiplicity classes over the transverse

momentum range $0.8 < p_T < 16$ GeV/ c in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the ALICE detector. The p_T spectra of ϕ mesons show a multiplicity and rapidity dependence at low p_T , whereas the spectral shapes are similar for all multiplicity classes and rapidity intervals at high p_T (> 5 GeV/ c). This suggests that nuclear effects influence ϕ meson production at low p_T . The $(dN/dy)/(dN/dy)_{y=0}$ ratios decreases with increasing rapidity in the measured interval $-1.2 < y < 0.3$, whereas the average transverse momentum ($\langle p_T \rangle$) and the $\langle p_T \rangle / \langle p_T \rangle_{y=0}$ ratios show a flat behavior for ϕ mesons. The rapidity dependence of dN/dy , $\langle p_T \rangle$ and their ratios with respect to the corresponding values at $y = 0$ are compared with model predictions for minimum bias events. The EPOS-LHC model, which includes parameterized flow, is the one that provides the best description for the magnitude of ϕ meson dN/dy and $\langle p_T \rangle$, whereas HIJING predictions are the ones in closest agreement with the measured rapidity dependence, which is studied via the ratios $(dN/dy)/(dN/dy)_{y=0}$ and $\langle p_T \rangle / \langle p_T \rangle_{y=0}$. The Y_{asym} ratios for ϕ mesons as a function of p_T show deviations from unity at low p_T for high multiplicity events, while, their values are consistent with unity within uncertainties at high p_T in the measured multiplicity and rapidity intervals. The measured deviations of Y_{asym} from unity at low p_T suggest the presence of rapidity dependent nuclear effects such as multiple scattering, nuclear shadowing, parton saturation, and energy loss in cold nuclear matter. None of the models presented here is able to describe the Y_{asym} of ϕ mesons at low p_T . The nuclear modification factor for central with respect to peripheral collisions Q_{CP} for ϕ mesons as a function of p_T show an enhancement, with a maximum around $p_T = 3$ GeV/ c , suggestive of the Cronin effect. This Cronin-like enhancement is more pronounced for large negative rapidities (in the Pb-going direction) and for more central (higher multiplicity) collisions. The measurements reported in this chapter suggest that nuclear effects play an important role in particle production in p-Pb collisions at the LHC energies and they will contribute, along with previous and upcoming measurements of other hadron species, to constrain models and event generators.

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Chapter 5

Summary

CERN's main objective since its inception was to understand the physics behind the universe creation and how it is evolving with time. Felix Bloch, then the Director-General of CERN, laid the first foundation stone of the CERN laboratory in July 1955. Since its inception, CERN has made numerous breakthroughs, both in particle physics and technology. The ALICE collaboration, which is a part of the CERN collaboration, is focused on studying the physics of strongly interacting matter (QGP) with the highest energy density ever measured in a laboratory. An intensive study of the production of hadrons in heavy-ion collisions is ongoing to understand Quark-Gluon-Plasma (QGP) properties. Asymmetric collision systems such as proton-nucleus (p-Pb), where the formation of the QGP phase is not expected can be used to study the possible effects of cold nuclear matter. A study of the production of hadrons (which differ in properties such as mass, charge, spin and lifetime) in different collision systems and energies will provide new insights into particle production mechanisms. In this thesis, we have reported the first measurements of ϕ meson productions in mid-rapidity ($-0.5 < y < 0$) p-Pb collisions at center of mass energy $\sqrt{s_{NN}} = 8.16$ TeV [1] with ALICE at the LHC. The measurements are performed in various multiplicity classes (0-5%, 5-10%, 10-20%, 20-40%, 40-60%, 60-80%, 80-100% and 0-100%), selected based on the total charge deposition in the V0A detector. The ϕ resonance has net spin-zero and a lifetime of the

order of 10^{-23} s. The resonances are short-lived particles. The lifetimes of various resonances are comparable to the evolution time of dense matter to the hadronic final state and can be used to probe the matter at different stages of evolution. As the ϕ meson has strange quark and antiquark, its study will help to understand the strangeness production in small systems like p-Pb. The inclusive study of hadrons as a function of multiplicity in p-Pb collisions will help to understand the particle production mechanism from pp to Pb-Pb collisions.

The ϕ meson results including the transverse momentum spectra, integrated yield, mean transverse momentum, x_T scaling and nuclear modification factor in p-Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV are discussed in this thesis. The NSD spectra is compared with the predictions from the EPOS-LHC, HIJING and DPMJET models. The EPOS-LHC model including effects of the hadronic phase describes the NSD spectrum quantitatively well in full p_T range in comparison to the DPMJET and HIJING model predictions. Both DPMJET and HIJING models overpredict the data at low p_T and underpredict the data at high p_T . The NSD spectrum of ϕ mesons at $\sqrt{s_{NN}} = 8.16$ TeV is compared with NSD spectrum at $\sqrt{s_{NN}} = 5.02$ TeV. The differential yield ratio between these two energies are also compared with the predictions from EPOS-LHC, HIJING and DPMJET models. The ratio is independent at low p_T (< 1 GeV/ c) within systematic uncertainty and its value is close to one. It suggests that the particle production in the soft scattering region is not strongly dependent on collision energy. The slope of the differential yield ratios increases as a function of p_T for $p_T > 1$ GeV/ c . Similar behavior is also observed in pp collisions [2]. The p_T differential yield ratios obtained from EPOS-LHC, DPMJET, and HIJING are consistent with the measurements within the systematic uncertainties and reproduce the energy dependence trend for ϕ in p-Pb collisions. The ratios of p_T spectra in various multiplicity classes to the p_T spectrum for NSD events show that at low p_T (< 4 GeV/ c), the slopes of the p_T spectra increase from low to high multiplicity classes, whereas the spectral shapes are similar at high p_T for all multiplicity classes. This indicates that the processes like radial flow, which lead to a change in the shape of the p_T spectra for various multiplicity classes, dominate mainly at low

p_T . The p_T -integrated yields and mean transverse momentum ($\langle p_T \rangle$) extracted from the p_T spectra shows increasing trend with charged particle multiplicity. The $\langle p_T \rangle$ of ϕ mesons seems to be saturated at high charged particle multiplicity. The dN/dy and $\langle p_T \rangle$ measurements are compared with other ALICE measurements in pp collisions at $\sqrt{s} = 7$ and 13 TeV [3,4], in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [5], and in Pb-Pb collisions at 2.76 TeV and 5.02 TeV [6-8]. The multiplicity scaled integrated yields ($dN/dy/\langle dN_{ch}/d\eta \rangle_{|\eta|<0.5}$) evolve smoothly as a function of multiplicity from pp, p-Pb to Pb-Pb collision systems. For similar $\langle dN_{ch}/d\eta \rangle_{|\eta|<0.5}$, these values are consistent within uncertainties for different colliding systems and at various LHC energies. This indicates that the event multiplicity drives the resonance production, irrespective of the colliding systems and energies.

It is observed that the $\langle p_T \rangle$ is increasing faster for pp and p-Pb than Pb-Pb collisions, and for a common multiplicity coverage, the values of $\langle p_T \rangle$ in pp and p-Pb are larger than Pb-Pb collisions. At similar multiplicity, the difference in $\langle p_T \rangle$ values among Pb-Pb, p-Pb, and pp collisions indicate that the geometry of collisions and dynamics of systems are different. The p-Pb measurements are important as it is shown that $\langle p_T \rangle$ of charged hadrons as a function of multiplicity shows similar behavior as pp in low multiplicity, whereas it seems to approach a similar but less prominent trend of saturation as Pb-Pb at high multiplicity. The model comparison to p-Pb data shows that EPOS-LHC describes the increasing trend of $\langle p_T \rangle$ with multiplicity for ϕ , and it gives a better agreement for ϕ to higher multiplicity values. DPMJET and HIJING models fail to describe the observed trend in $\langle p_T \rangle$ for ϕ and they underpredict the data for all multiplicities.

Invariant cross section of particle production have been found to follow a universal scaling at high p_T , which is known as x_T scaling. In this thesis, first time the validity of x_T scaling is tested for ϕ mesons in p-Pb collisions at LHC energies are reported. The invariant cross sections were determined from the measured invariant yield as $Ed^2\sigma/d^3p = \sigma_{inel} Ed^2\sigma/d^3p$, where σ_{inel} is the inelastic cross section in pp collisions. At fixed x_T , the invariant cross section scales as p_T^n , where the exponent of scaling n depends on x_T and $\sqrt{s_{NN}}$. A universal x_T scaling for ϕ is well

satisfied (within roughly 20%) in the hard scattering region (at $x_T > 10^{-3}$) of the particle production. The obtained value of exponent ($n = 5$) is lower compared to that at RHIC energies which suggests the increasing contribution of hard scattering processes at higher $\sqrt{s_{NN}}$. Furthermore, the value of exponent n in p-Pb collisions for ϕ is compatible with those in pp collisions for $\pi^\pm$, $K^\pm$ and K^{*0} suggesting that the high p_T particle production mechanism is similar in both the collision systems.

The nuclear modification factor (R_{pPb}) is reported here to understand the nuclear effects in p-Pb collisions. If the nuclear modification factor is unity, it suggests that nuclear collisions is an incoherent superposition of nucleon-nucleon collisions. In the absence of the availability of ϕ measurements at center of mass energy $\sqrt{s} = 8.16$ TeV in pp collisions, the reference p_T spectra are obtained from the measured p_T spectra at $\sqrt{s} = 8$ TeV [9] using simulation approach with PYTHIA 8.23. Cronin-like enhancement is observed in R_{pPb} values (above unity) at intermediate p_T ($2 < p_T < 8$ GeV/ c) region in p-Pb collision at $\sqrt{s_{NN}} = 8.16$ TeV. The ϕ meson R_{pPb} in p-Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV and 5.02 TeV are comparable and no energy dependence is observed in R_{pPb} . The R_{pPb} of ϕ mesons is compared with that of K^{*0} , π , K , p , Ξ and Ω particles. At intermediate p_T , R_{pPb} shows Cronin-like enhancement, which is more pronounced for baryons having higher mass. The results are consistent with the observation reported by CMS [10] and hydrodynamical expectation of radial flow [11]. It is also observed that the R_{pPb} of ϕ meson is smaller than that of proton inspite of similar masses, which may indicate baryon-meson ordering. So, along with the presence of strong radial flow component, there are other effects like different production mechanism of baryons and mesons which are affecting the R_{pPb} in intermediate p_T region. At high p_T (> 8 GeV/ c), the R_{pPb} values of all particles are consistent with unity within the uncertainties in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ and 8.16 TeV which suggests that there is no modification in R_{pPb} at high p_T .

In p-Pb collisions, it can be expected that the production mechanism will be sensitive to different effects at forward (p-going) and backward (Pb-going) rapidities. The transverse momentum spectra of ϕ mesons have been measured in five

rapidity intervals ($-1.2 < y < -0.9$, $-0.9 < y < -0.6$, $-0.6 < y < -0.3$, $-0.3 < y < 0$ and $0 < y < 0.3$) in range $-1.2 < y < 0.3$ for various multiplicity classes (0-10%, 10-40%, 40-100% and 0-100%) over the transverse momentum range $0.8 < p_T < 1.6$ GeV/c in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with ALICE detector at the LHC. The p_T spectra of various rapidity intervals are compared with the spectra in rapidity interval $0 < y < 0.3$ for various multiplicity classes. It is observed that the ϕ meson production is higher in Pb-going direction ($y < 0$) than p-going direction ($y > 0$). The p_T spectra of ϕ mesons show a multiplicity and rapidity dependence at low p_T , whereas the spectral shapes are similar for all multiplicity classes and rapidity intervals at high p_T (> 5 GeV/c). This suggests that nuclear effects influence ϕ meson production at low p_T . The minimum bias (0-100 %) ϕ mesons spectra in various rapidity intervals are compared with the predictions from EPOS-LHC, HIJING with and without shadowing, DPMJET, EPOS3 with and without UrQMD and PYTHIA8/Angantyr models. The EPOS-LHC model describes the measurements better than the other mentioned models in full p_T region. Integrated yield (dN/dy) and mean transverse momentum ($\langle p_T \rangle$) shows increasing trend with multiplicity classes for a given rapidity interval. The results are consistent with the previous measurements in p-Pb collisions from the ALICE. The dN/dy shows a less pronounced decreasing trend with rapidity in high multiplicity classes. Although the dN/dy looks similar across rapidity within systematic uncertainty. The $\langle p_T \rangle$ shows flat behavior with rapidity across all multiplicity classes. Similar behavior in the average transverse kinetic energy as a function of rapidity for strange hadrons was reported in [12]. The dN/dy and $\langle p_T \rangle$ in minimum bias (0-100%) events are compared with the predictions from EPOS-LHC, HIJING with and without shadowing, DPMJET, EPOS3 with and without UrQMD and PYTHIA8/Angantyr models. EPOS3 with and without UrQMD shows a decreasing trend of $\langle p_T \rangle$, whereas all other models show a similar trend as data. The EPOS-LHC and DPMJET model predictions for ϕ mesons dN/dy are closer to data and EPOS-LHC model better describes the $\langle p_T \rangle$ than the other models.

The $(dN/dy)/(dN/dy)_{y=0}$ and $\langle p_T \rangle / \langle p_T \rangle_{y=0}$ ratios are measured in 0-

100% multiplicity class to quantify the rapidity dependence. The ratio $(dN/dy)/(dN/dy)_{y=0}$ decreases with rapidity, whereas $\langle p_T \rangle / \langle p_T \rangle_{y=0}$ shows a flat behaviour within uncertainties as a function of rapidity for ϕ mesons. The measurements are compared with the predictions from EPOS-LHC, HIJING with and without shadowing, DPMJET, EPOS3 with and without UrQMD and PYTHIA8/Angantyr models. The predictions from HIJING qualitatively reproduce the trend and are the closest to the measurements. The predictions from PYTHIA8/Angantyr, DPMJET, EPOS-LHC, EPOS3 with and without UrQMD show a decreasing trend of $(dN/dy)/(dN/dy)_{y=0}$ with increasing y , but the rapidity dependence is less pronounced than that in the measured data. The EPOS3 with and without UrQMD, overestimates the measurements at the low y and predicts a decreasing trend of $\langle p_T \rangle / \langle p_T \rangle_{y=0}$ with rapidity, which is not supported by the data. The HIJING model predicts a slightly decreasing $\langle p_T \rangle / \langle p_T \rangle_{y=0}$ with increasing rapidity, while PYTHIA8/Angantyr, DPMJET, and EPOS-LHC predict a slightly increasing trend. Hydrodynamic calculations suggests a decreasing trend in $\langle p_T \rangle$ with rapidity, whereas CGC predicts an increasing trend in $\langle p_T \rangle$ with rapidity [13].

The rapidity asymmetry (Y_{asym}) which is the ratio of yield in rapidity interval $-0.3 < y < 0$ to that in $0 < y < 0.3$ is measured for ϕ meson for various multiplicity classes in p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. The Y_{asym} is observed at low p_T (< 5 GeV/ c), suggesting the presence of nuclear effects. At high p_T (> 5 GeV/ c) for all multiplicity classes and in 40-100% multiplicity class the ϕ mesons Y_{asym} values are consistence with unity within uncertainty, suggesting the absence of nuclear effects at high p_T and low multiplicity class (40-100 %) in p-Pb collisions. The Y_{asym} in minimum bias events (0-100%) are compared with the predictions from EPOS-LHC, HIJING with and without shadowing, DPMJET, EPOS3 with and without UrQMD and PYTHIA8/Angantyr models. The HIJING and EPOS3 models describe the Y_{asym} at low- p_T and overestimate the data at high p_T . The DPMJET model describes the Y_{asym} at high p_T within uncertainties. None of the above mentioned models describe the data in the full p_T range.

The nuclear modification factor (Q_{CP}) of ϕ meson is studied for various rapid-

ity intervals in the range $-1.2 < y < 0.3$ for 0-10%/40-100% and 10-40%/40-100% multiplicity classes in p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. The Cronin-like effects are observed at intermediate p_{T} region ($2.2 < p_{\text{T}} < 5$ GeV/ c) for ϕ mesons for the Q_{CP} . The Cronin-like effects are more pronounced at high negative rapidity (Pb-going direction) and for high multiplicity events. It suggests that multiple scattering effects are more relevant for high multiplicity collisions. At high p_{T} (> 5 GeV/ c), the Q_{CP} values are higher than unity, which is a known feature of Q_{pPb} and Q_{CP} when the centrality or multiplicity classes are defined with the V0 detector, and it is interpreted as a selection bias due to the multiplicity estimator [14]. The Q_{CP} values at intermediate p_{T} region show a faster decrease as a function of rapidity at 0-10%/40-100% than 10-40%/40-100% multiplicity classes.

The further study of ratios of ϕ mesons yield to the stable particles yields such as kaons and pions will shed light on the re-scattering/regeneration effects and strangeness enhancement in p-Pb collisions at $\sqrt{s_{\text{NN}}} = 8.16$ TeV. The comparison of mean transverse momentum with other hadrons will help to understand the mass ordering and baryon-meson splitting mechanism. Further study of the rapidity asymmetry of other hadrons will help to understand the nuclear effects in p-Pb collisions. The ϕ mesons Q_{CP} shows rapidity dependent Cronin-like enhancement, further study of Q_{CP} for other hadrons, at higher energy and rapidity will help to understand the various nuclear phenomena. Since most of the studied models do not describe the ϕ meson rapidity asymmetry measurements, this study highlights the need for further theoretical or phenomenological research to understand the physics of p-Pb collisions.

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Appendix A

A.1 Invariant mass distributions

The Invariant mass distributions (M_{KK}) of unliked charged KK pairs in different p_{T} bins at mid rapidity $-0.5 < y < 0$ for various multiplicity classes 0-5%, 5-10%, 10-20%, 20-40%, 40-60%, 60-80%, 80-100% and 0-100% p-Pb collisions at $\sqrt{s_{\text{NN}}} = 8.16$ TeV are shown in the Fig. [A.1](#) to Fig. [A.16](#).

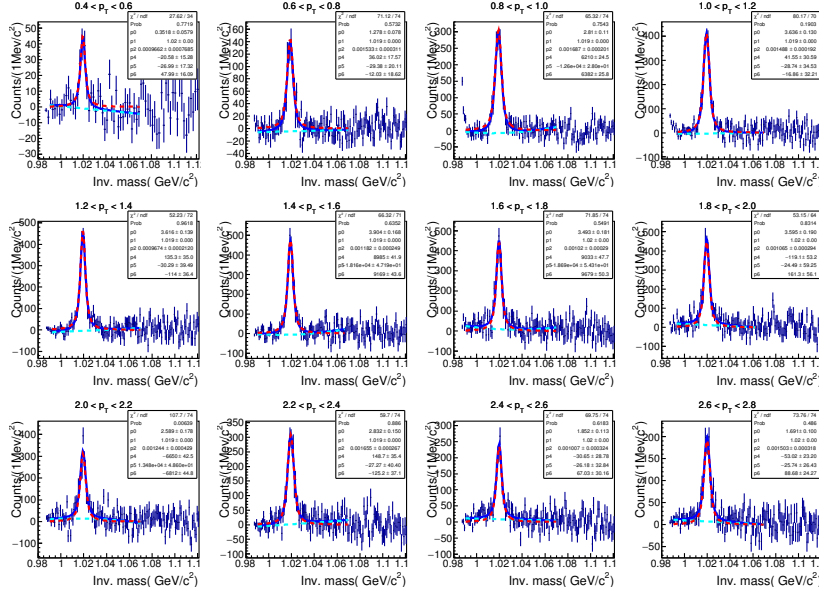


Figure A.1: Invariant mass distribution M_{KK} after mixed-event background subtraction in various p_T bins for multiplicity class 0-5% in p-Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV in rapidity interval $-0.5 < y < 0$. The signal peak is fitted by a Voigtian function (blue line) and the residual background (cyan dotted line) of 2nd order polynomial function.

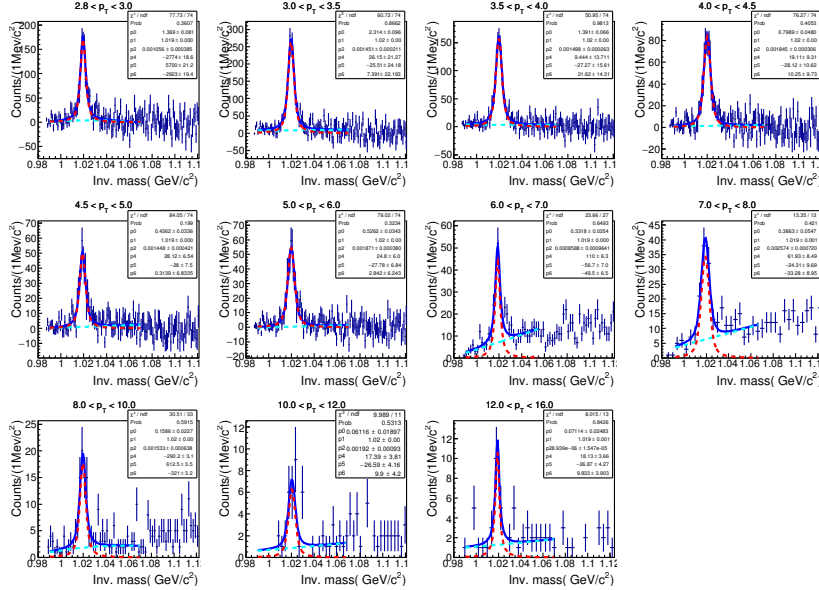


Figure A.2: Invariant mass distribution M_{KK} after mixed-event background subtraction in various p_T bins for multiplicity class 0-5% in p-Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV in rapidity interval $-0.5 < y < 0$. The signal peak is fitted by a Voigtian function (blue line) and the residual background (cyan dotted line) of 2nd order polynomial function.

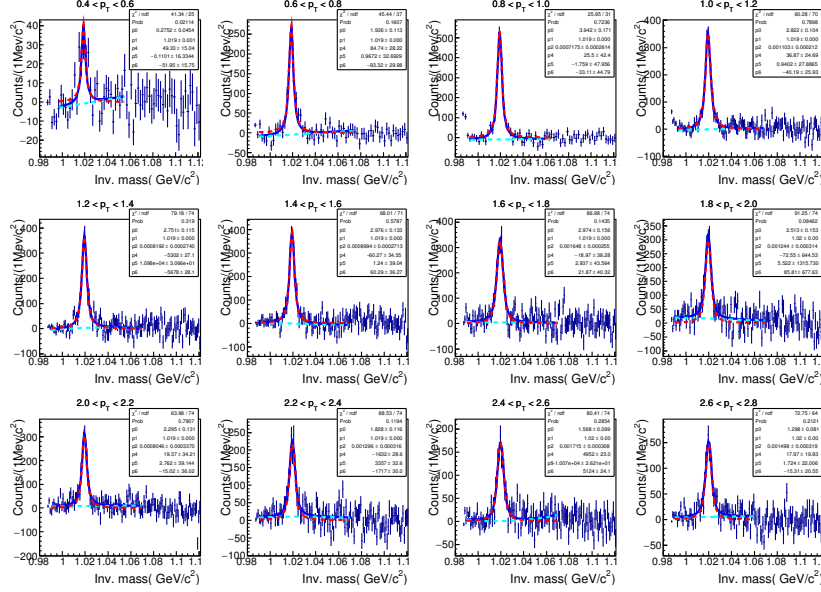


Figure A.3: Invariant mass distribution M_{KK} after mixed-event background subtraction in various p_T bins for multiplicity class 5-10% in p-Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV in rapidity interval $-0.5 < y < 0$. The signal peak is fitted by a Voigtian function (blue line) and the residual background (cyan dotted line) of 2nd order polynomial function.

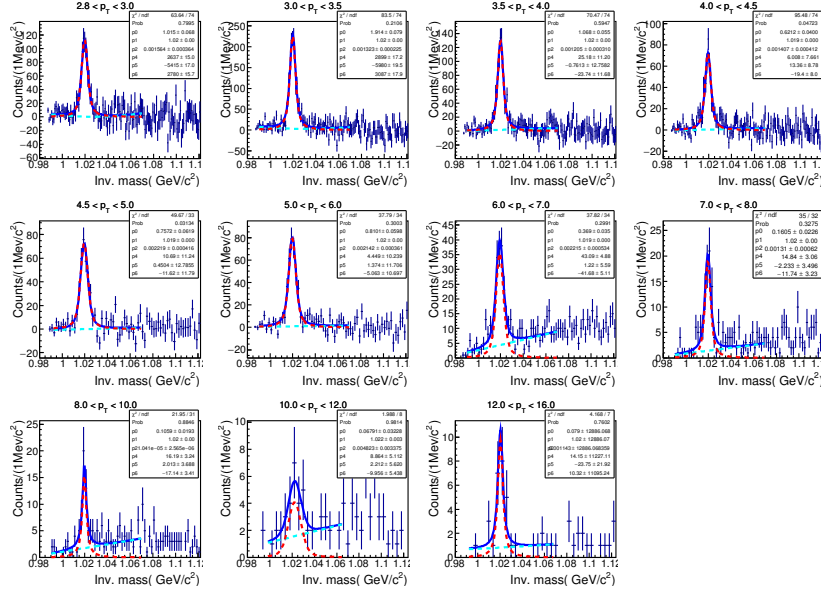


Figure A.4: Invariant mass distribution M_{KK} after mixed-event background subtraction in various p_T bins for multiplicity class 5-10% in p-Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV in rapidity interval $-0.5 < y < 0$. The signal peak is fitted by a Voigtian function (blue line) and the residual background (cyan dotted line) of 2nd order polynomial function.

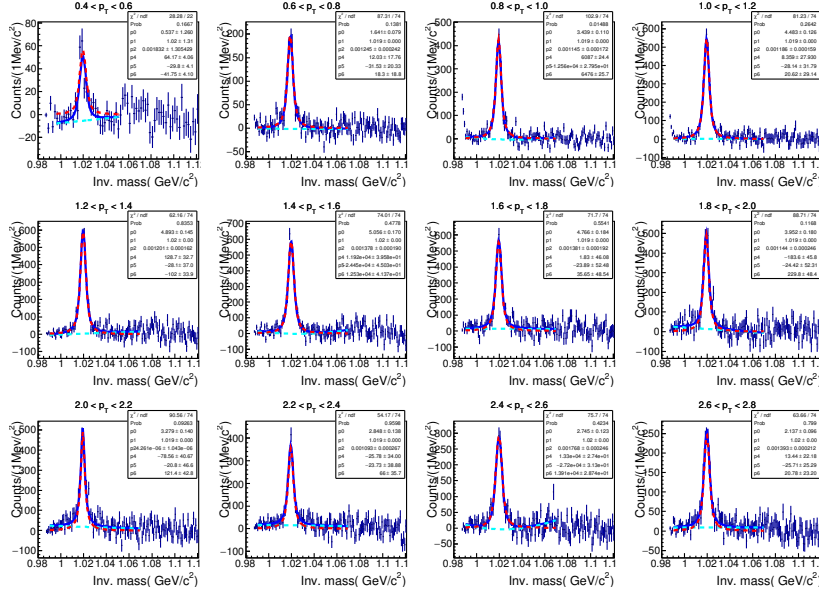


Figure A.5: Invariant mass distribution M_{KK} after mixed-event background subtraction in various p_T bins for multiplicity class 10-20% in p-Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV in rapidity interval $-0.5 < y < 0$. The signal peak is fitted by a Voigtian function (blue line) and the residual background (cyan dotted line) of 2nd order polynomial function.

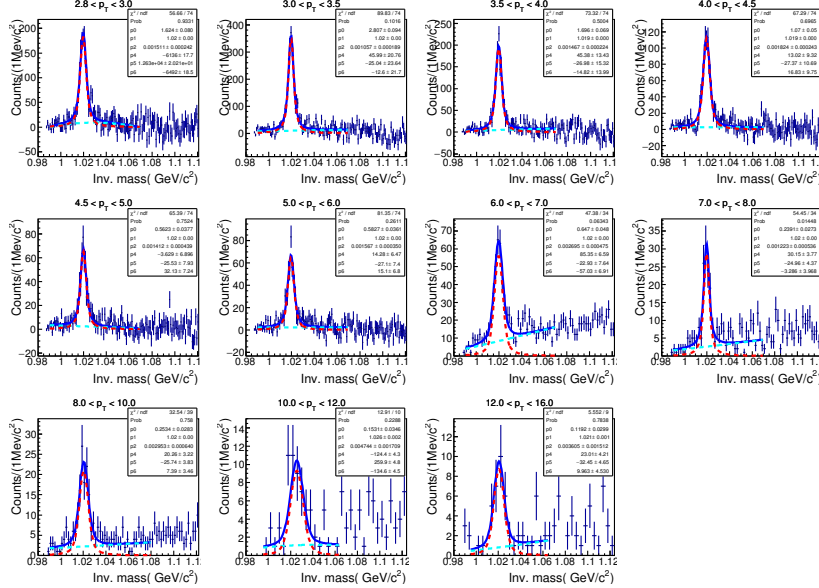


Figure A.6: Invariant mass distribution M_{KK} after mixed-event background subtraction in various p_T bins for multiplicity class 10-20% in p-Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV in rapidity interval $-0.5 < y < 0$. The signal peak is fitted by a Voigtian function (blue line) and the residual background (cyan dotted line) of 2nd order polynomial function.

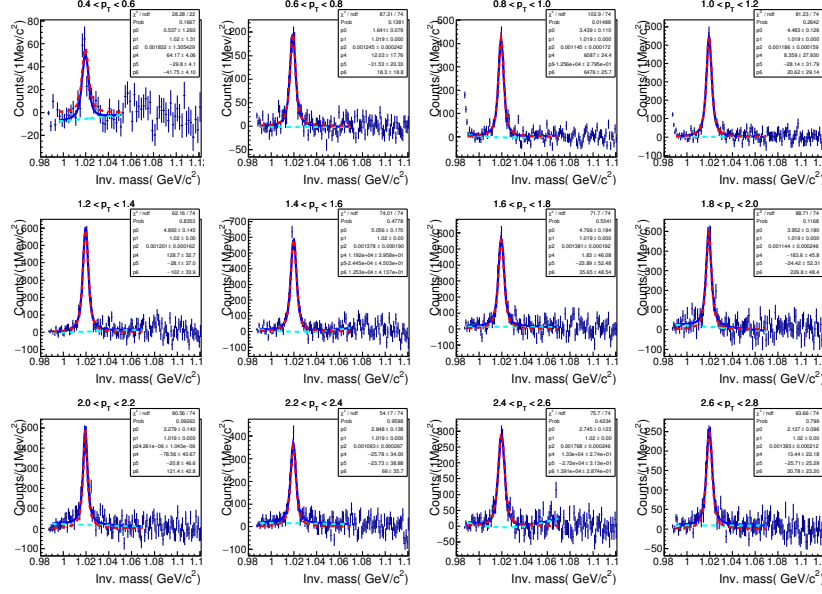


Figure A.7: Invariant mass distribution M_{KK} after mixed-event background subtraction in various p_T bins for multiplicity class 20-40% in p-Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV in rapidity interval $-0.5 < y < 0$. The signal peak is fitted by a Voigtian function (blue line) and the residual background (cyan dotted line) of 2nd order polynomial function.

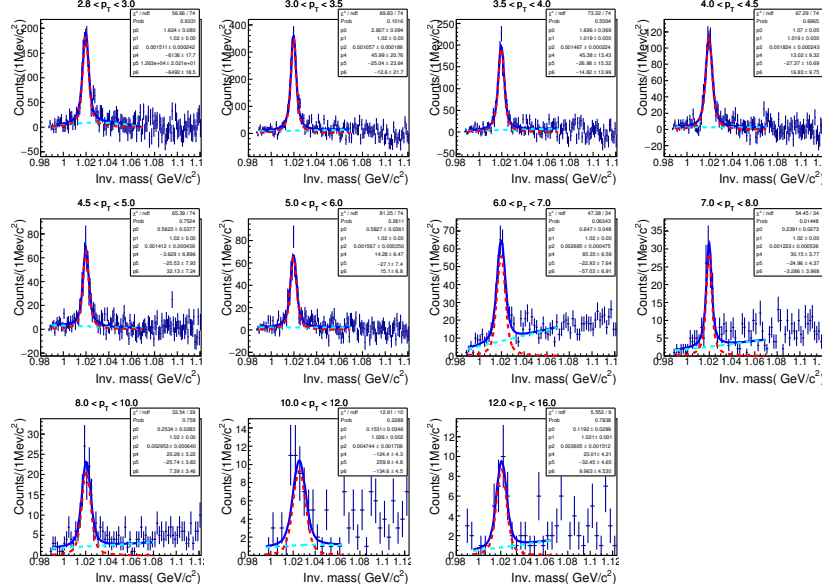


Figure A.8: Invariant mass distribution M_{KK} after mixed-event background subtraction in various p_T bins for multiplicity class 20-40% in p-Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV in rapidity interval $-0.5 < y < 0$. The signal peak is fitted by a Voigtian function (blue line) and the residual background (cyan dotted line) of 2nd order polynomial function.

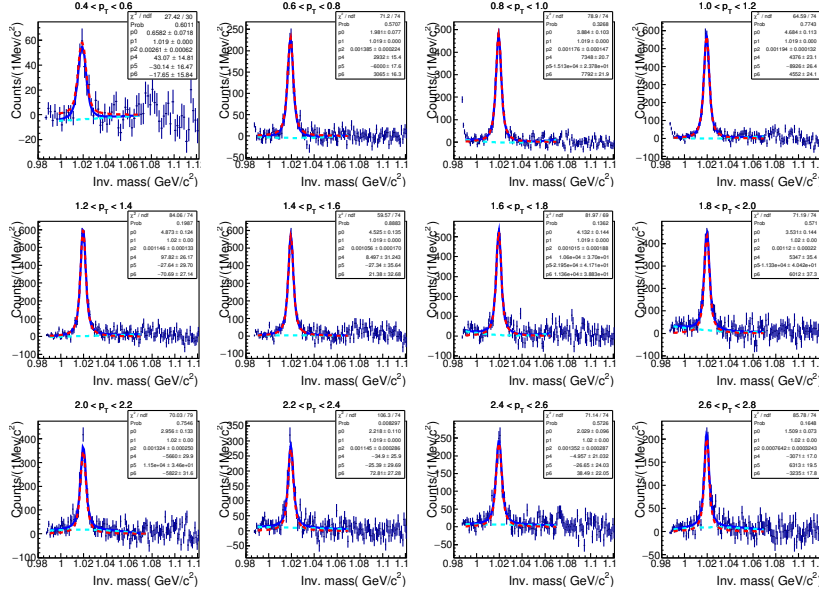


Figure A.9: Invariant mass distribution M_{KK} after mixed-event background subtraction in various p_T bins for multiplicity class 40-60% in p-Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV in rapidity interval $-0.5 < y < 0$. The signal peak is fitted by a Voigtian function (blue line) and the residual background (cyan dotted line) of 2nd order polynomial function.

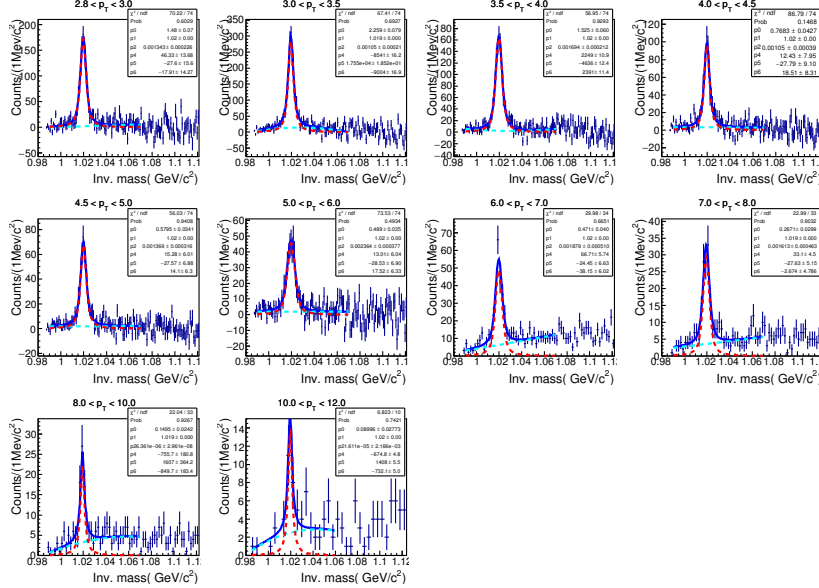


Figure A.10: Invariant mass distribution M_{KK} after mixed-event background subtraction in various p_T bins for multiplicity class 40-60% in p-Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV in rapidity interval $-0.5 < y < 0$. The signal peak is fitted by a Voigtian function (blue line) and the residual background (cyan dotted line) of 2nd order polynomial function.

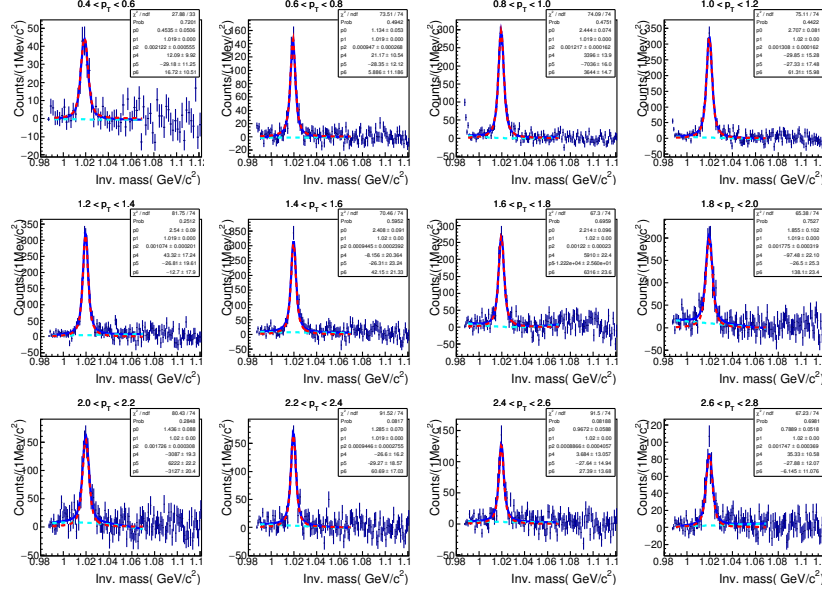


Figure A.11: Invariant mass distribution M_{KK} after mixed-event background subtraction in various p_T bins for multiplicity class 60-80% in p-Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV in rapidity interval $-0.5 < y < 0$. The signal peak is fitted by a Voigtian function (blue line) and the residual background (cyan dotted line) of 2nd order polynomial function.

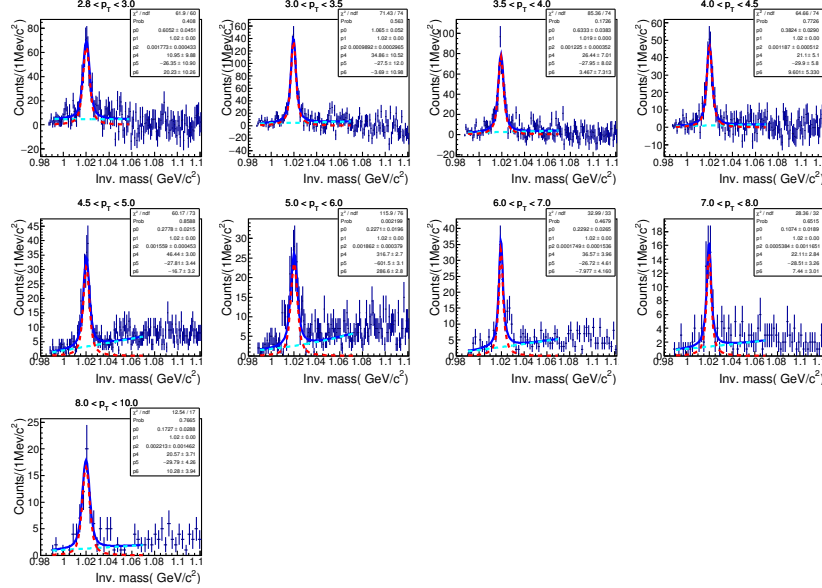


Figure A.12: Invariant mass distribution M_{KK} after mixed-event background subtraction in various p_T bins for multiplicity class 60-80% in p-Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV in rapidity interval $-0.5 < y < 0$. The signal peak is fitted by a Voigtian function (blue line) and the residual background (cyan dotted line) of 2nd order polynomial function.

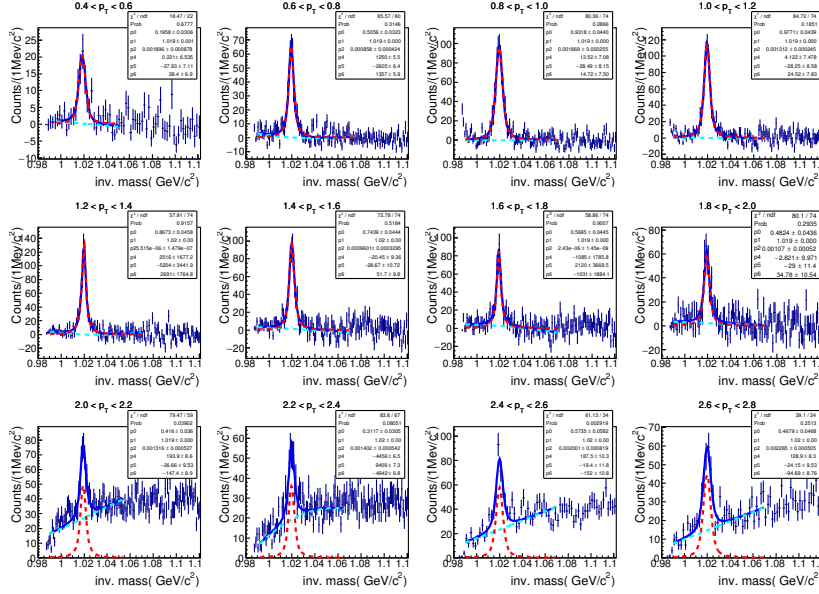


Figure A.13: Invariant mass distribution M_{KK} after mixed-event background subtraction in various p_T bins for multiplicity class 80-100% in p-Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV in rapidity interval $-0.5 < y < 0$. The signal peak is fitted by a Voigtian function (blue line) and the residual background (cyan dotted line) of 2nd order polynomial function.

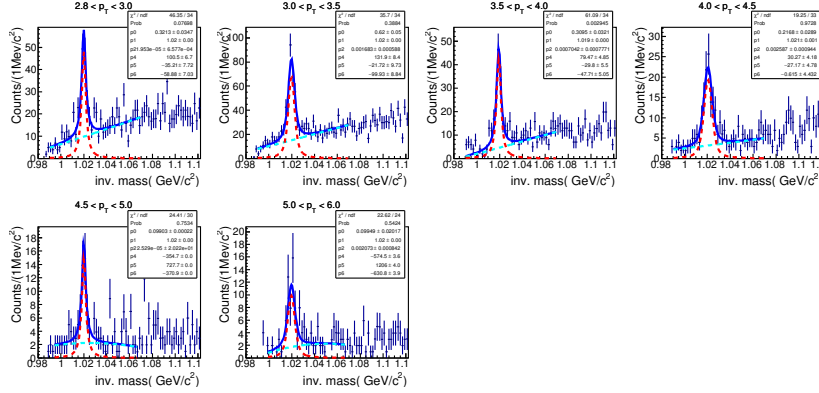


Figure A.14: Invariant mass distribution M_{KK} after mixed-event background subtraction in various p_T bins for multiplicity class 80-100% in p-Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV in rapidity interval $-0.5 < y < 0$. The signal peak is fitted by a Voigtian function (blue line) and the residual background (cyan dotted line) of 2nd order polynomial function.

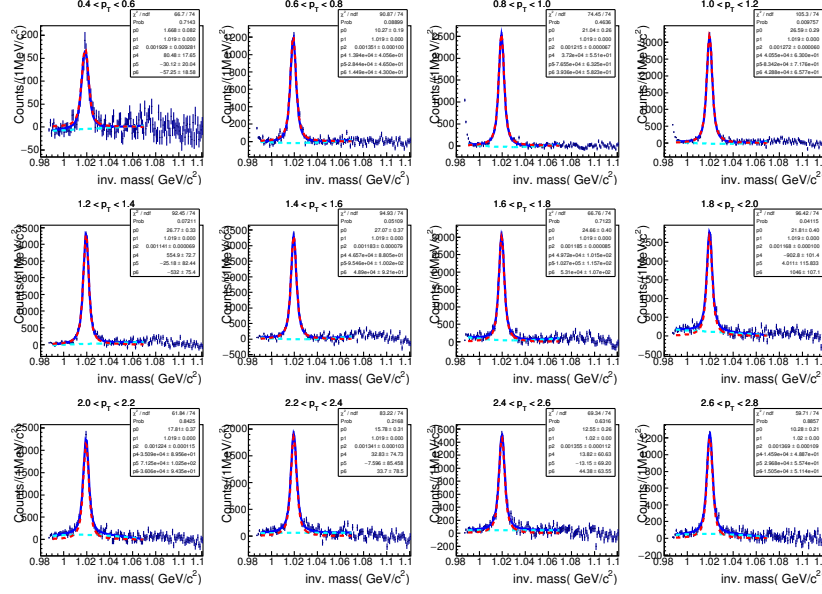


Figure A.15: Invariant mass distribution M_{KK} after mixed-event background subtraction in various p_T bins for multiplicity class 0-100% in p-Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV in rapidity interval $-0.5 < y < 0$. The signal peak is fitted by a Voigtian function (blue line) and the residual background (cyan dotted line) of 2nd order polynomial function.

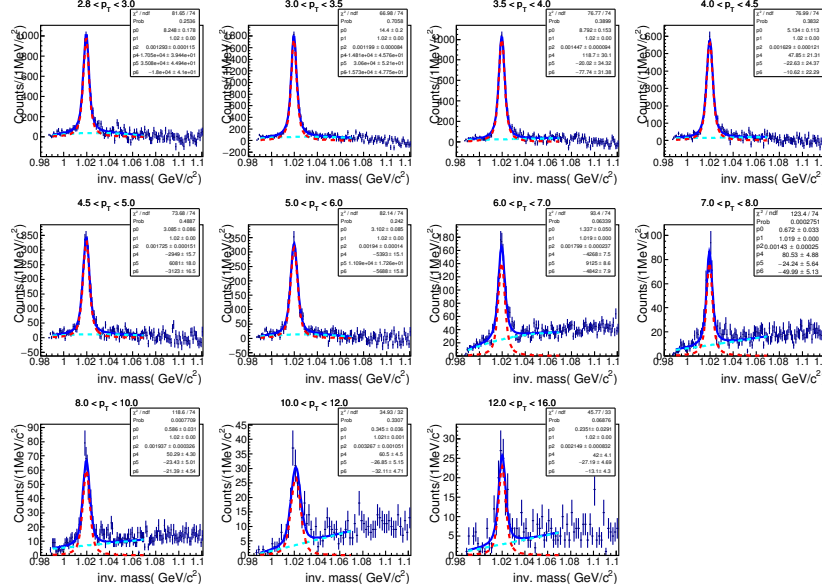


Figure A.16: Invariant mass distribution M_{KK} after mixed-event background subtraction in various p_T bins for multiplicity class 0-100% in p-Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV in rapidity interval $-0.5 < y < 0$. The signal peak is fitted by a Voigtian function (blue line) and the residual background (cyan dotted line) of 2nd order polynomial function.

Appendix B

B.1 Invariant mass distributions

The Invariant mass distributions (M_{KK}) of unliked charged KK pairs in different p_T bins for various multiplicity classes 0-100%, 0-10%, 10-40% and 40-100% p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in the rapidity region $-1.2 < y < 0.3$ are shown in the Fig. [B.1](#) to Fig. [B.20](#).

B.2 Efficiency $\times$ Acceptance

The Efficiency $\times$ Acceptance as a function of p_T for various rapidity interval in rapidity range $-1.2 < y < 0.3$ for multiplicity class 0-100% in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV are shown in Figs. [B.21](#). The Efficiency $\times$ Acceptance is fitted by a sigmoid function($a/(1+\exp(-b(p_T-c)))$) (red line).

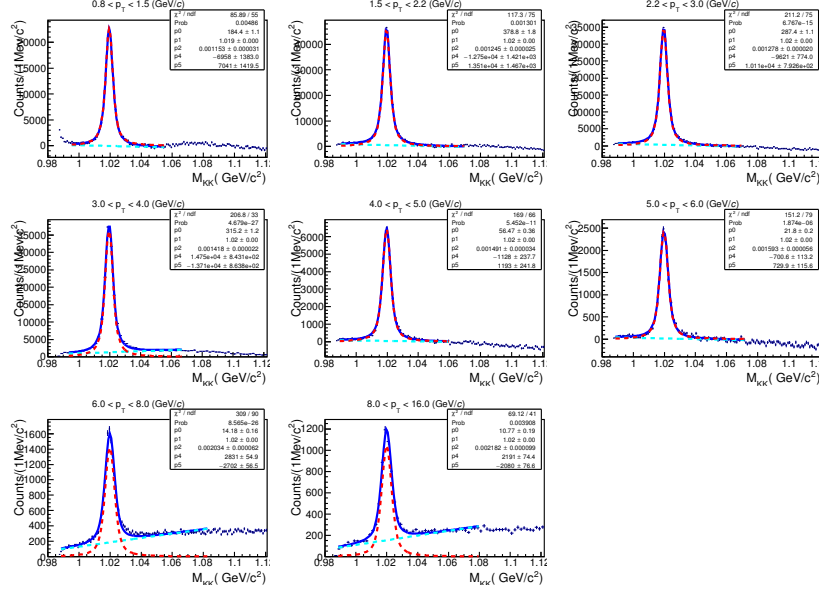


Figure B.1: Invariant mass distribution M_{KK} after mixed-event background subtraction in various p_T bins for multiplicity class 0-100% in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in rapidity interval $0 < y < 0.3$. The signal peak is fitted by a Voigtian function (blue line) and the residual background (cyan dotted line) of 2nd order polynomial function.

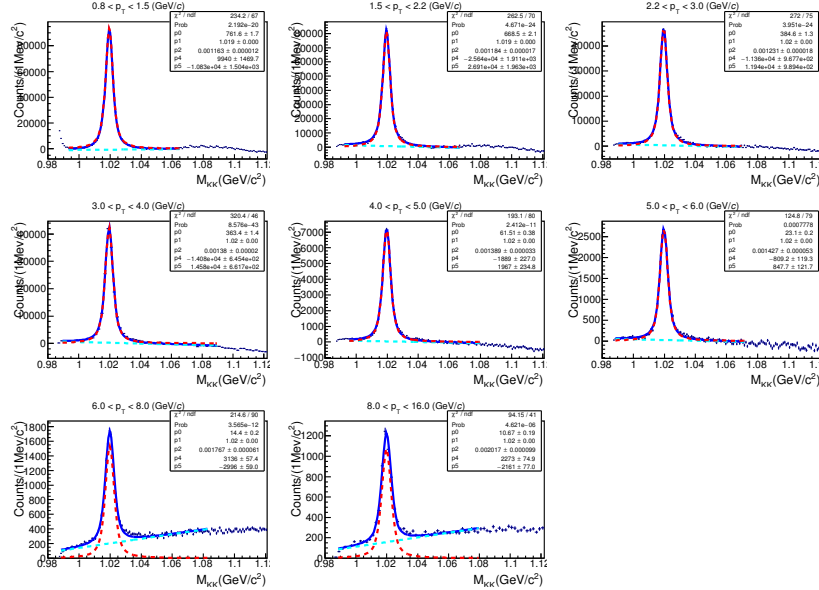


Figure B.2: Invariant mass distribution M_{KK} after mixed-event background subtraction in various p_T bins for multiplicity class 0-100% in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in rapidity interval $-0.3 < y < 0$. The signal peak is fitted by a Voigtian function (blue line) and the residual background (cyan dotted line) of 2nd order polynomial function.

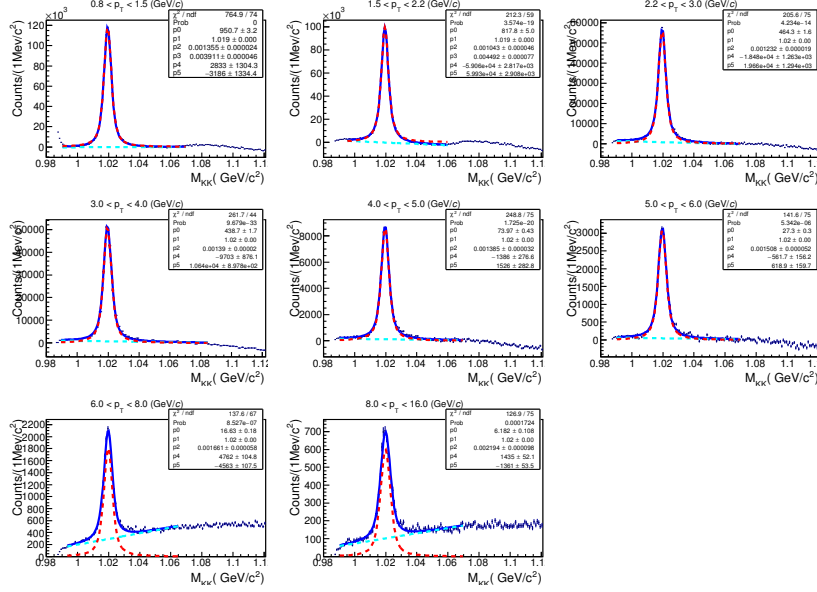


Figure B.3: Invariant mass distribution M_{KK} after mixed-event background subtraction in various p_T bins for multiplicity class 0-100% in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in rapidity interval $-0.6 < y < -0.3$. The signal peak is fitted by a Voigtian function (blue line) and the residual background (cyan dotted line) of 2nd order polynomial function.

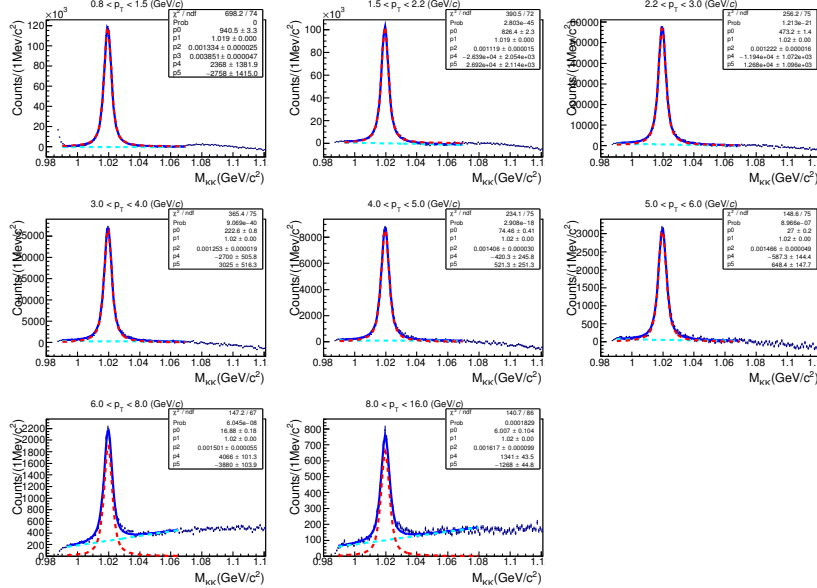


Figure B.4: Invariant mass distribution M_{KK} after mixed-event background subtraction in various p_T bins for multiplicity class 0-100% in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in rapidity interval $-0.9 < y < -0.6$. The signal peak is fitted by a Voigtian function (blue line) and the residual background (cyan dotted line) of 2nd order polynomial function.

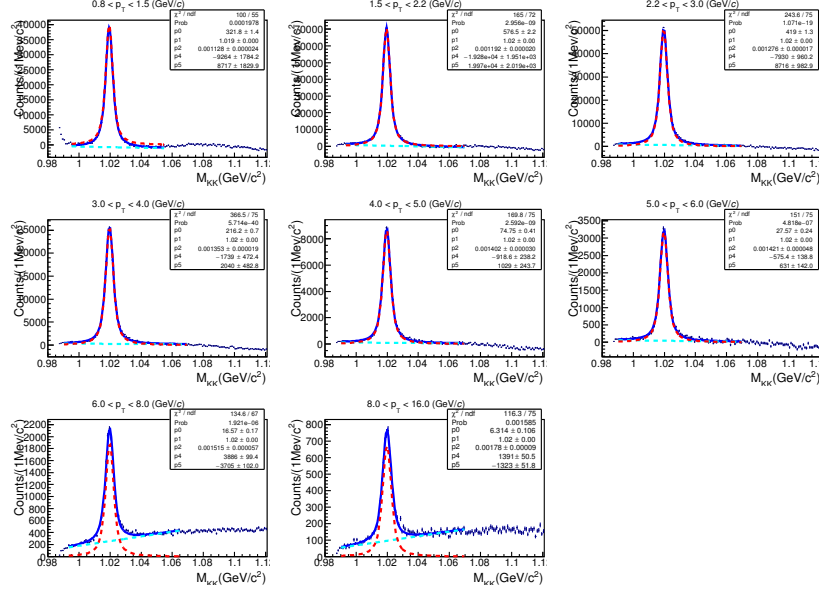


Figure B.5: Invariant mass distribution M_{KK} after mixed-event background subtraction in various p_T bins for multiplicity class 0-100% in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in rapidity interval $-1.2 < y < -0.9$. The signal peak is fitted by a Voigtian function (blue line) and the residual background (cyan dotted line) of 2nd order polynomial function.

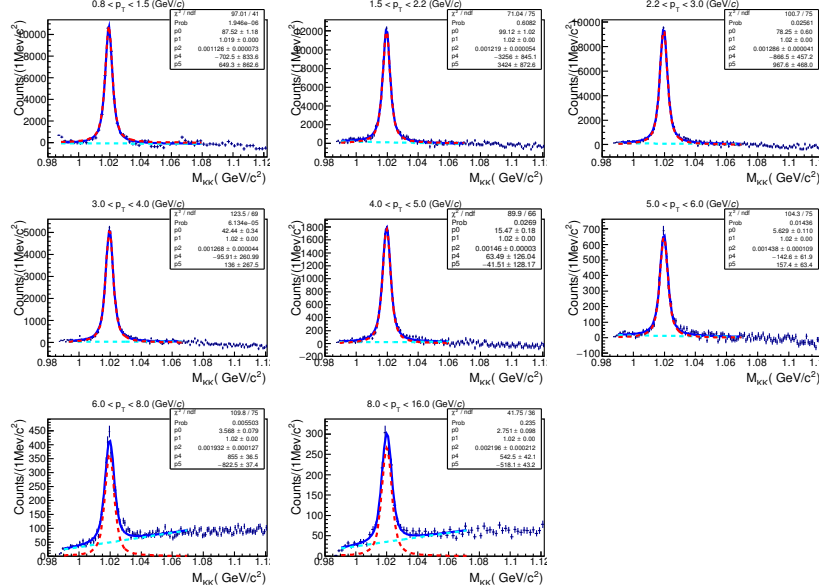


Figure B.6: Invariant mass distribution M_{KK} after mixed-event background subtraction in various p_T bins for multiplicity class 0-10% in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in rapidity interval $0 < y < 0.3$. The signal peak is fitted by a Voigtian function (blue line) and the residual background (cyan dotted line) of 2nd order polynomial function.

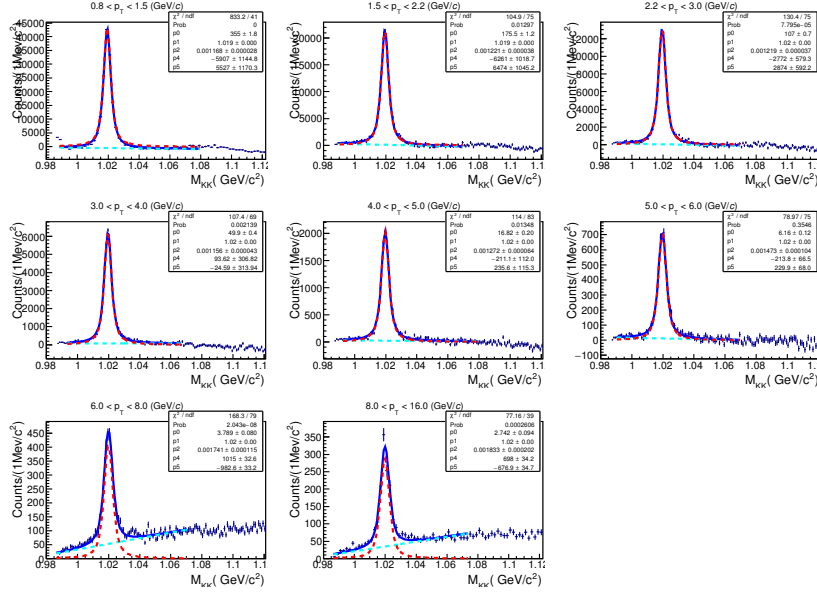


Figure B.7: Invariant mass distribution M_{KK} after mixed-event background subtraction in various p_T bins for multiplicity class 0-10% in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in rapidity interval $-0.3 < y < 0$. The signal peak is fitted by a Voigtian function (blue line) and the residual background (cyan dotted line) of 2nd order polynomial function.

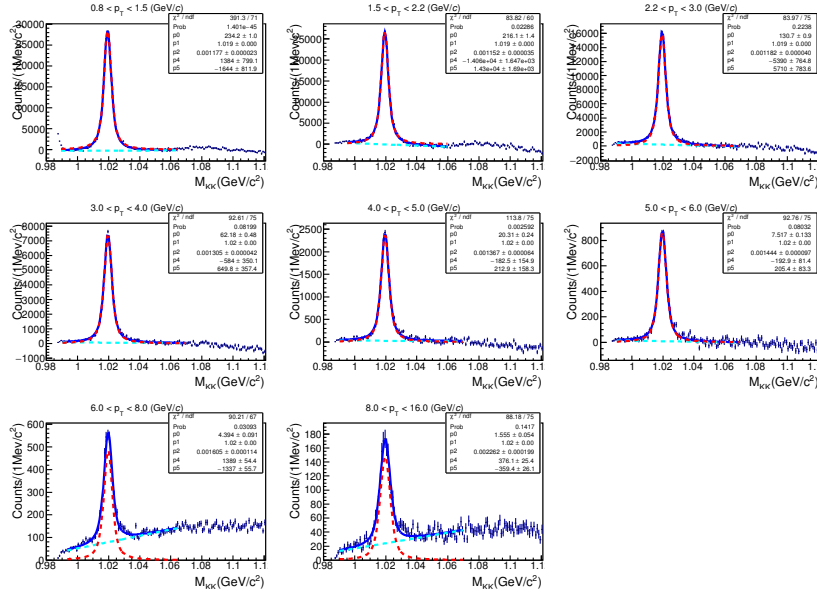


Figure B.8: Invariant mass distribution M_{KK} after mixed-event background subtraction in various p_T bins for multiplicity class 0-10% in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in rapidity interval $-0.6 < y < -0.3$. The signal peak is fitted by a Voigtian function (blue line) and the residual background (cyan dotted line) of 2nd order polynomial function.

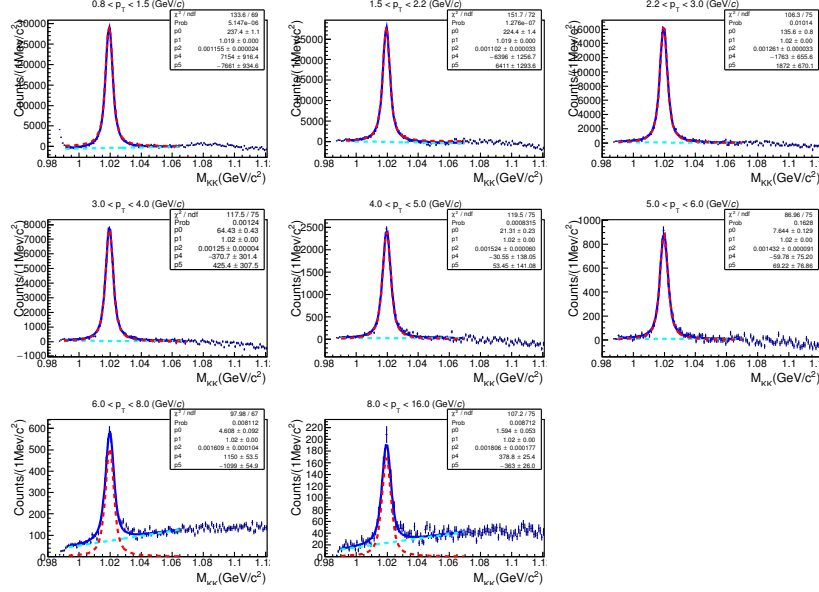


Figure B.9: Invariant mass distribution M_{KK} after mixed-event background subtraction in various p_T bins for multiplicity class 0-10% in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in rapidity interval $-0.9 < y < -0.6$. The signal peak is fitted by a Voigtian function (blue line) and the residual background (cyan dotted line) of 2nd order polynomial function.

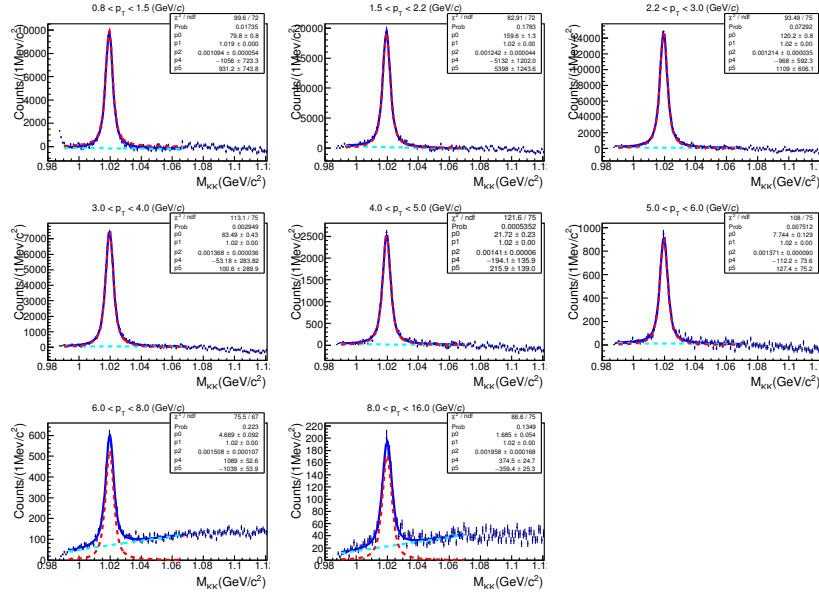


Figure B.10: Invariant mass distribution M_{KK} after mixed-event background subtraction in various p_T bins for multiplicity class 0-10% in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in rapidity interval $-1.2 < y < -0.9$. The signal peak is fitted by a Voigtian function (blue line) and the residual background (cyan dotted line) of 2nd order polynomial function.

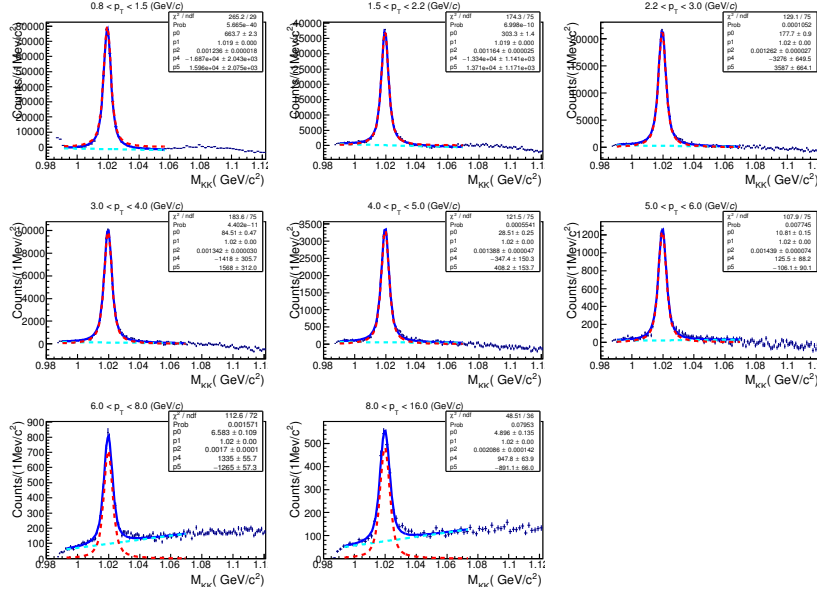


Figure B.11: Invariant mass distribution M_{KK} after mixed-event background subtraction in various p_T bins for multiplicity class 10-40% in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in rapidity interval $0 < y < 0.3$. The signal peak is fitted by a Voigtian function (blue line) and the residual background (cyan dotted line) of 2nd order polynomial function.

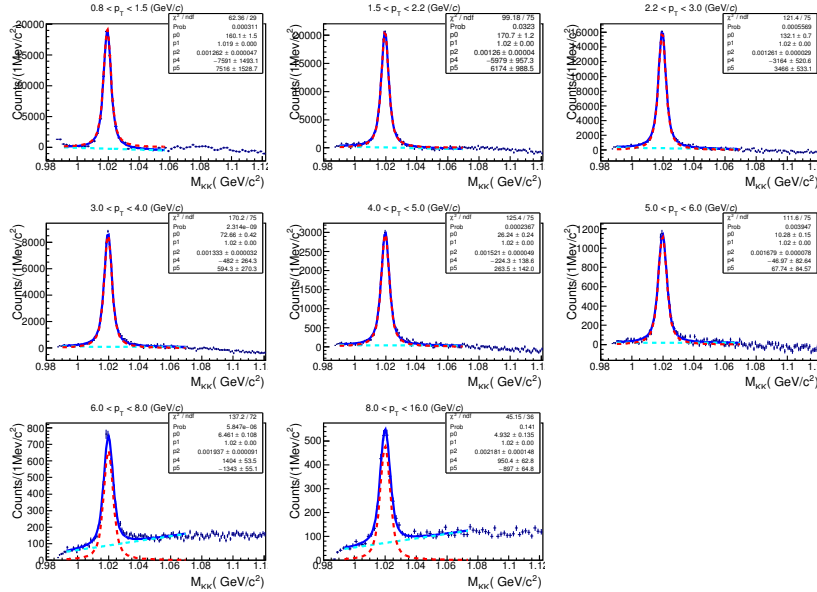


Figure B.12: Invariant mass distribution M_{KK} after mixed-event background subtraction in various p_T bins for multiplicity class 10-40% in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in rapidity interval $-0.3 < y < 0$. The signal peak is fitted by a Voigtian function (blue line) and the residual background (cyan dotted line) of 2nd order polynomial function.

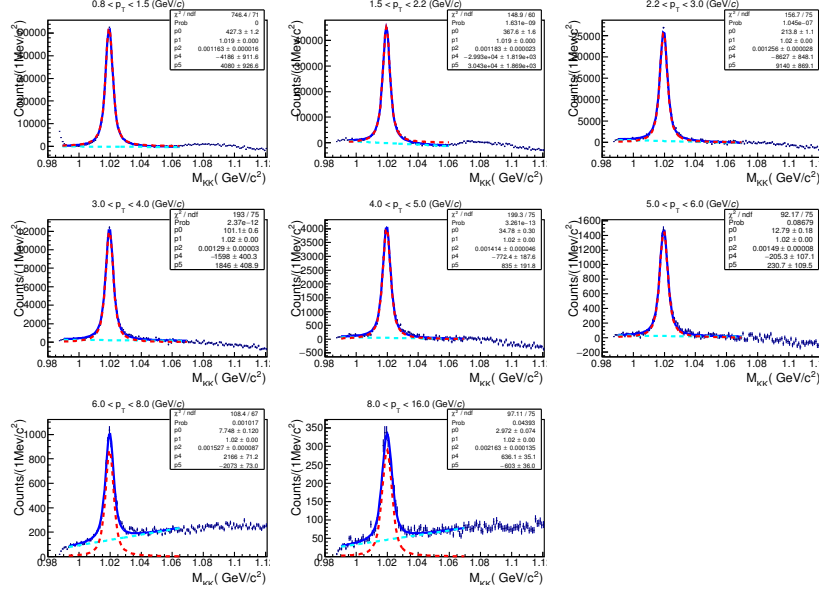


Figure B.13: Invariant mass distribution M_{KK} after mixed-event background subtraction in various p_T bins for multiplicity class 10-40% in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in rapidity interval $-0.6 < y < -0.3$. The signal peak is fitted by a Voigtian function (blue line) and the residual background (cyan dotted line) of 2nd order polynomial function.

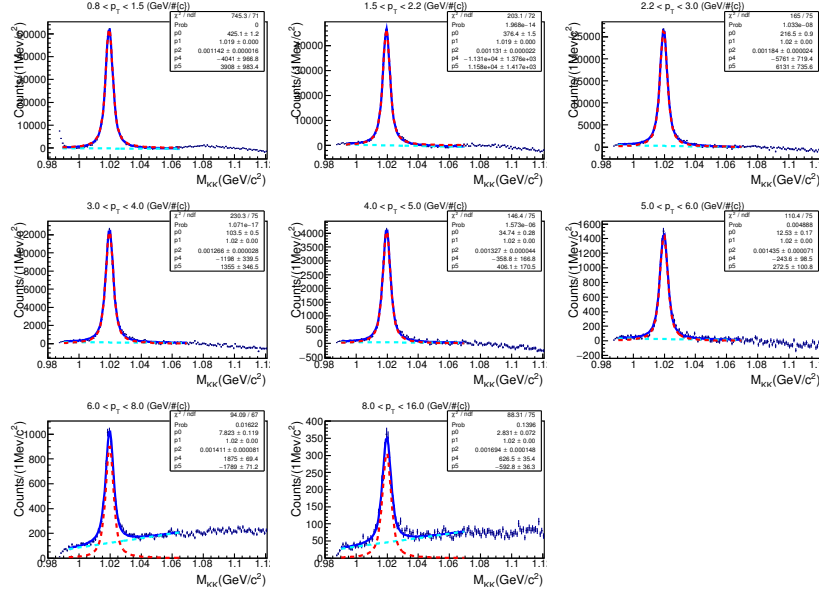


Figure B.14: Invariant mass distribution M_{KK} after mixed-event background subtraction in various p_T bins for multiplicity class 10-40% in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in rapidity interval $-0.9 < y < -0.6$. The signal peak is fitted by a Voigtian function (blue line) and the residual background (cyan dotted line) of 2nd order polynomial function.

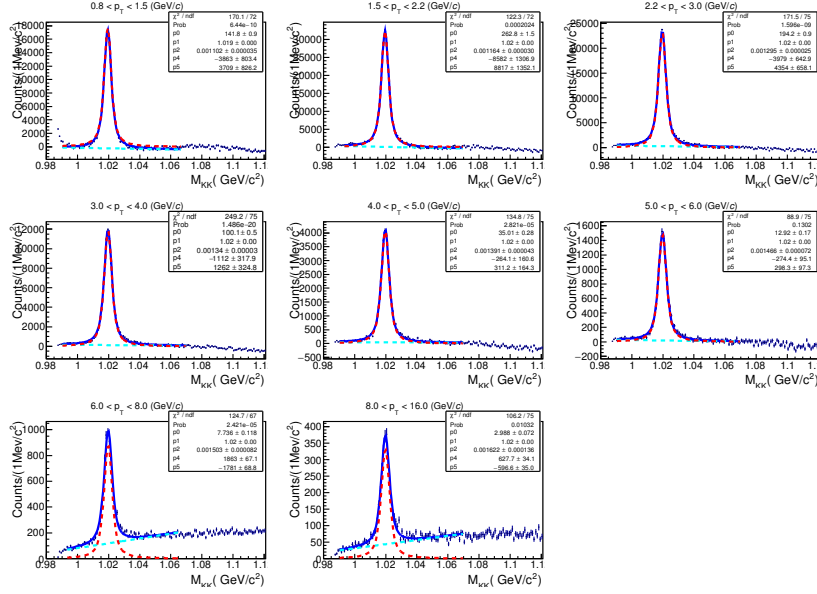


Figure B.15: Invariant mass distribution M_{KK} after mixed-event background subtraction in various p_T bins for multiplicity class 10-40% in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in rapidity interval $-1.2 < y < -0.9$. The signal peak is fitted by a Voigtian function (blue line) and the residual background (cyan dotted line) of 2nd order polynomial function.

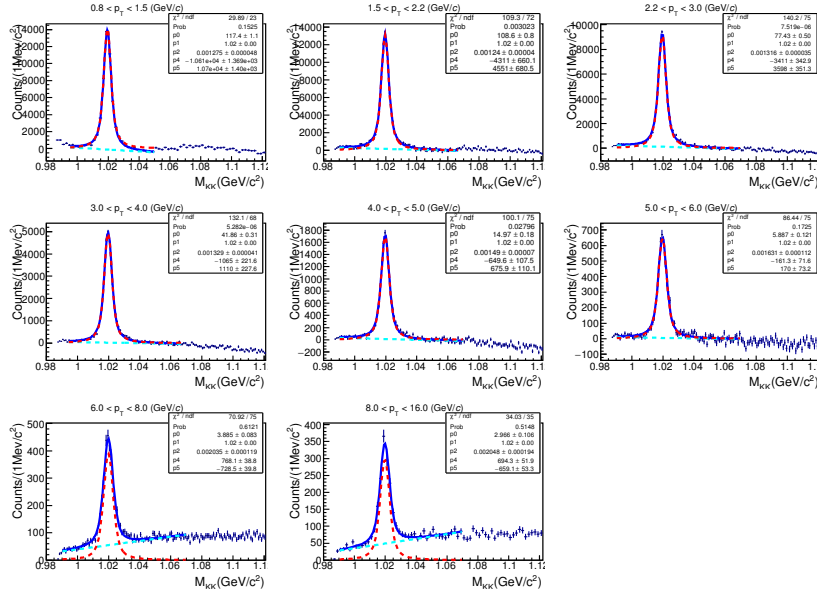


Figure B.16: Invariant mass distribution M_{KK} after mixed-event background subtraction in various p_T bins for multiplicity class 40-100% in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in rapidity interval $0 < y < 0.3$. The signal peak is fitted by a Voigtian function (blue line) and the residual background (cyan dotted line) of 2nd order polynomial function.

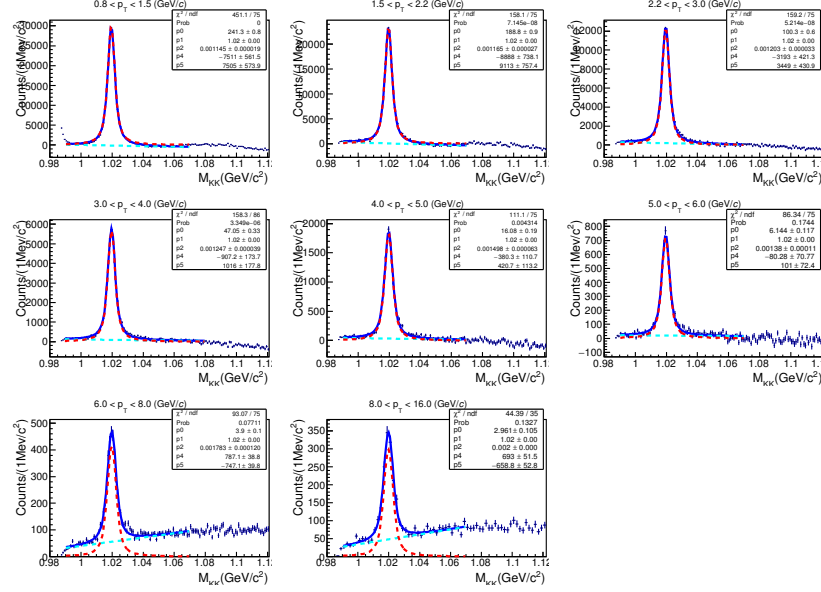


Figure B.17: Invariant mass distribution M_{KK} after mixed-event background subtraction in various p_T bins for multiplicity class 40-100% in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in rapidity interval $-0.3 < y < 0$. The signal peak is fitted by a Voigtian function (blue line) and the residual background (cyan dotted line) of 2nd order polynomial function.

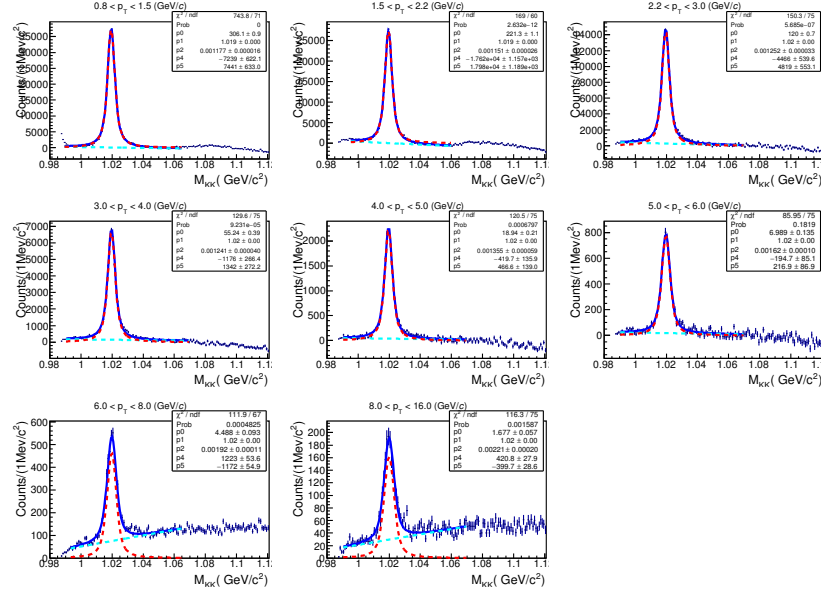


Figure B.18: Invariant mass distribution M_{KK} after mixed-event background subtraction in various p_T bins for multiplicity class 40-100% in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in rapidity interval $-0.6 < y < -0.3$. The signal peak is fitted by a Voigtian function (blue line) and the residual background (cyan dotted line) of 2nd order polynomial function.

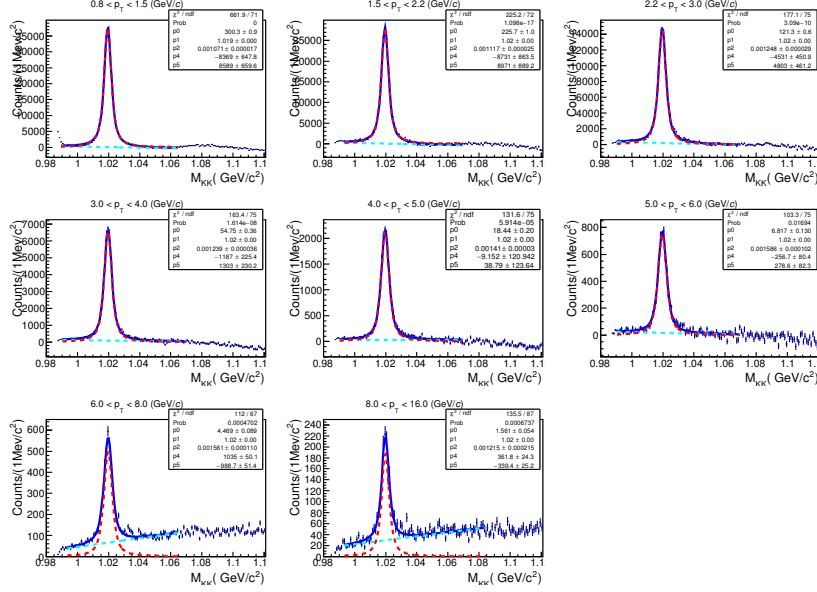


Figure B.19: Invariant mass distribution M_{KK} after mixed-event background subtraction in various p_T bins for multiplicity class 40-100% in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in rapidity interval $-0.9 < y < -0.6$. The signal peak is fitted by a Voigtian function (blue line) and the residual background (cyan dotted line) of 2nd order polynomial function.

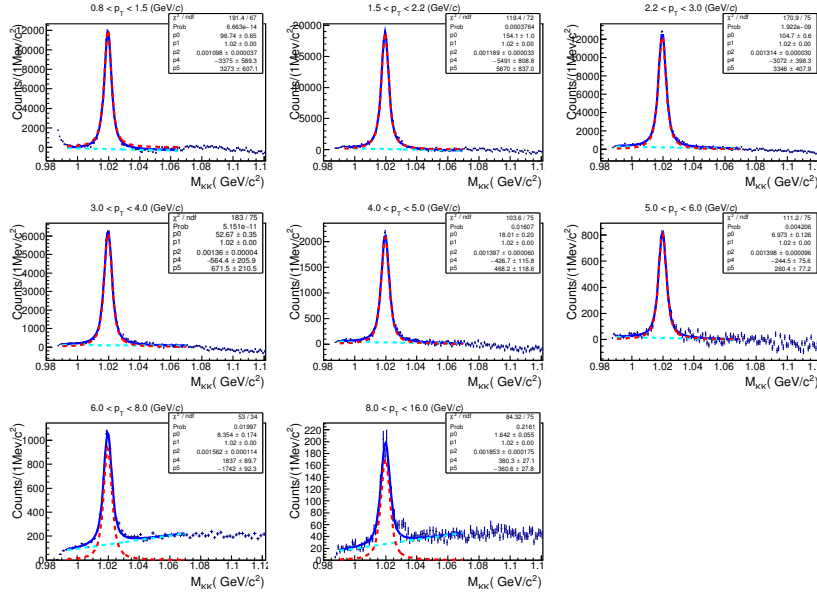


Figure B.20: Invariant mass distribution M_{KK} after mixed-event background subtraction in various p_T bins for multiplicity class 40-100% in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in rapidity interval $-1.2 < y < -0.9$. The signal peak is fitted by a Voigtian function (blue line) and the residual background (cyan dotted line) of 2nd order polynomial function.

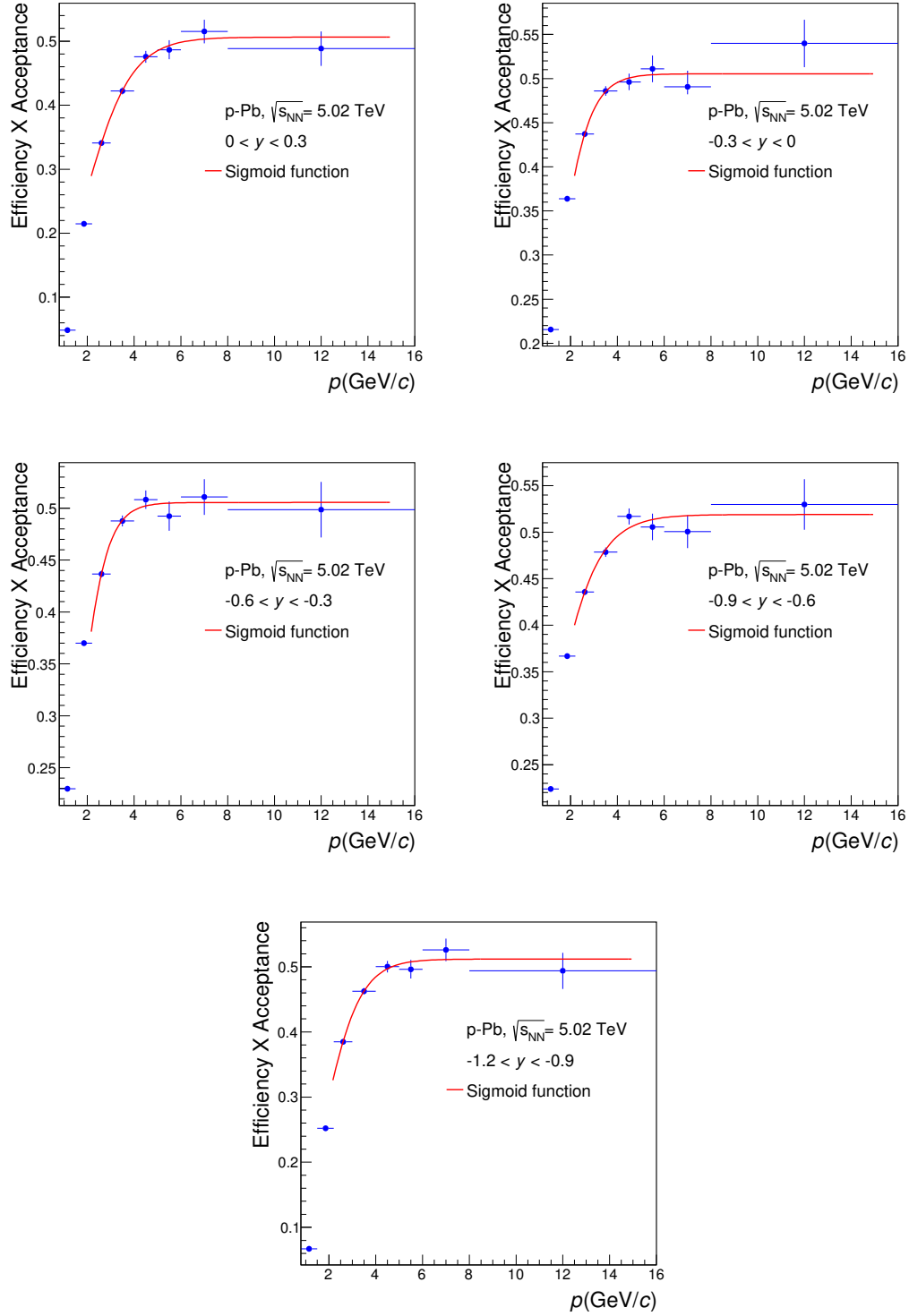


Figure B.21: Efficiency $\times$ Acceptance as a function of p_T for various rapidity interval in rapidity range $-1.2 < y < 0.3$ for multiplicity class 0-100% in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The Efficiency $\times$ Acceptance is fitted by a sigmoid function (red line).

PUBLICATIONS/CONFERENCES

Publications and ALICE Analysis Notes with Direct Contribution

1. Sandeep Dudi *et al.* [ALICE], “ $K^{*0}(892)$ and $\phi(1020)$ Production in pPb Collisions at $\sqrt{s_{NN}} = 8.16$ TeV”, <http://arxiv.org/abs/2110.10042>.
2. Sandeep Dudi *et al.* [ALICE], “Multiplicity and rapidity dependence of $K^{*0}(892)$ and $\phi(1020)$ production in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV”, <https://arxiv.org/abs/2204.10263>.
3. Sandeep Dudi *et al.* [ALICE], “Measurement of ϕ (1020) resonance production in p-Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV”, <https://alice-notes.web.cern.ch/node/766>
4. Sandeep Dudi *et al.* [ALICE], “Rapidity dependent study of ϕ (1020) resonance production in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV”, <https://alice-notes.web.cern.ch/node/978>.

Papers presented in Conferences, Workshops, Symposiums

1. Sandeep Dudi *et al.* [ALICE], “ ϕ and K^{*0} Production in pPb and PbPb Collisions with ALICE at the LHC, DAE-BRNS High Energy Physics Symposium, 10-14 December, 2018.
2. Sandeep Dudi *et al.* [ALICE], “Insight into ϕ meson production in small systems with ALICE at the LHC, DAE-BRNS Symposium on Nuclear Physics, 23-27 December, 2019.
3. Sandeep Dudi *et al.* [ALICE], “Identified particle production in pPb collisions with ALICE at the LHC, International Conference on Hard and Electromagnetic Probes, 1-5 October, 2018.
4. Sandeep Dudi *et al.* [ALICE], “Strangeness and Rapidity-Dependent Studies in Small Systems with ALICE at the LHC”, DAE-BRNS High Energy Physics Symposium, 14-18 December, 2020.

Conferences, Schools, Workshops attended

1. 4-10 April, 2022 **XXIX International Conference Quark Matter 2022**, Krakow, Poland.
2. 5-16 September, 2021 **MCnet-CTEQ Summer School**, Virtual.
3. 14-18 December, 2020 **XXIII DAE-BRNS High Energy Physics Symposium**, NISER Odisha, India.
4. 23-27 December, 2019 **DAE-BRNS Symposium on Nuclear Physics**, Lucjnow Uttar Prades, India.
5. 10-14 December, 2018 **XXIII DAE-BRNS High Energy Physics Symposium**, IIT Madras, India.
6. 1-5 October, 2018 **International Conference on Hard and Electromagnetic Probes**, Aix-Les-Bains, France.
7. 07-27 November, 2017 **Xi SERC School on Experimental High Energy Physics**, NISER Odisha, India.
8. 7-12 August, 2017 **ALICE-India Training Program**, VECC Kolkata, India.

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1. S. Acharya *et al.* [ALICE], “Multiplicity dependence of charged-particle jet production in pp collisions at $\sqrt{s} = 13$ TeV,” *Eur. Phys. J. C* **82** (2022) no.6, 514 doi:10.1140/epjc/s10052-022-10405-x [arXiv:2202.01548 [nucl-ex]].
2. S. Acharya *et al.* [ALICE], “First study of the two-body scattering involving charm hadrons,” *Phys. Rev. D* **106** (2022) no.5, 052010 doi:10.1103/PhysRevD.106.052010 [arXiv:2201.05352 [nucl-ex]].
3. S. Acharya *et al.* [ALICE], “Forward rapidity J/ψ production as a function of charged-particle multiplicity in pp collisions at $\sqrt{s} = 5.02$ and 13 TeV,” *JHEP* **06** (2022), 015 doi:10.1007/JHEP06(2022)015 [arXiv:2112.09433 [nucl-ex]].
4. S. Acharya *et al.* [ALICE], “Neutral to charged kaon yield fluctuations in Pb – Pb collisions at sNN=2.76 TeV,” *Phys. Lett. B* **832** (2022), 137242 doi:10.1016/j.physletb.2022.137242 [arXiv:2112.09482 [nucl-ex]].
5. S. Acharya *et al.* [ALICE], “Production of light (anti)nuclei in pp collisions at $\sqrt{s} = 5.02$ TeV,” *Eur. Phys. J. C* **82** (2022) no.4, 289 doi:10.1140/epjc/s10052-022-10241-z [arXiv:2112.00610 [nucl-ex]].
6. S. Acharya *et al.* [ALICE], “Observation of a multiplicity dependence in the p_T -differential charm baryon-to-meson ratios in proton-proton collisions at $\sqrt{s} = 13$ TeV,” *Phys. Lett. B* **829** (2022), 137065 doi:10.1016/j.physletb.2022.137065 [arXiv:2111.11948 [nucl-ex]].
7. S. Acharya *et al.* [ALICE], “KS0KS0 and KS0K $\pm$ femtoscopy in pp collisions at s=5.02 and 13 TeV,” *Phys. Lett. B* **833** (2022), 137335 doi:10.1016/j.physletb.2022.137335 [arXiv:2111.06611 [nucl-ex]].
8. S. Acharya *et al.* [ALICE], “Characterizing the initial conditions of heavy-ion collisions at the LHC with mean transverse momentum and anisotropic flow correlations,” *Phys. Lett. B* **834** (2022), 137393 doi:10.1016/j.physletb.2022.137393 [arXiv:2111.06106 [nucl-ex]].

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9. S. Acharya *et al.* [ALICE], “Investigating charm production and fragmentation via azimuthal correlations of prompt D mesons with charged particles in pp collisions at $\sqrt{s} = 13$ TeV,” *Eur. Phys. J. C* **82** (2022) no.4, 335 doi:10.1140/epjc/s10052-022-10267-3 [arXiv:2110.10043 [nucl-ex]].
 10. S. Acharya *et al.* [ALICE], “Measurement of prompt D_s^+ -meson production and azimuthal anisotropy in Pb–Pb collisions at $\sqrt{s_{NN}}=5.02$ TeV,” *Phys. Lett. B* **827** (2022), 136986 doi:10.1016/j.physletb.2022.136986 [arXiv:2110.10006 [nucl-ex]].
 11. S. Acharya *et al.* [ALICE], “Prompt D^0 , D^+ , and D^{*+} production in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV,” *JHEP* **01** (2022), 174 doi:10.1007/JHEP01(2022)174 [arXiv:2110.09420 [nucl-ex]].
 12. S. Acharya *et al.* [ALICE], “General balance functions of identified charged hadron pairs of (π ,K,p) in Pb–Pb collisions at $s_{NN}= 2.76$ TeV,” *Phys. Lett. B* **833** (2022), 137338 doi:10.1016/j.physletb.2022.137338 [arXiv:2110.06566 [nucl-ex]].
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Production of $K^*(892)^0$ and $\phi(1020)$ in pp and Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

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The production of $K^*(892)^0$ and $\phi(1020)$ mesons in proton–proton (pp) and lead–lead (Pb–Pb) collisions at $\sqrt{s_{NN}} = 5.02$ TeV has been measured using the ALICE detector at the Large Hadron Collider (LHC). The transverse momentum (p_T) distributions of $K^*(892)^0$ and $\phi(1020)$ mesons have been measured at midrapidity ($|y| < 0.5$) up to $p_T = 20$ GeV/ c in inelastic pp collisions and for several Pb–Pb collision centralities. The collision centrality and collision energy dependence of the average transverse momenta agree with the radial flow scenario observed with stable hadrons, showing that the effect is stronger for more central collisions and higher collision energies. The K^{*0}/K ratio is found to be suppressed in Pb–Pb collisions relative to pp collisions: this indicates a loss of the measured $K^*(892)^0$ signal due to rescattering of its decay products in the hadronic phase. In contrast, for the longer-lived $\phi(1020)$ mesons, no such suppression is observed. The nuclear modification factors (R_{AA}) of $K^*(892)^0$ and $\phi(1020)$ mesons are calculated using pp reference spectra at the same collision energy. In central Pb–Pb collisions for $p_T > 8$ GeV/ c , the R_{AA} values of $K^*(892)^0$ and $\phi(1020)$ are below unity and observed to be similar to those of pions, kaons, and (anti)protons. The R_{AA} values at high p_T (> 8 GeV/ c) for $K^*(892)^0$ and $\phi(1020)$ mesons are in agreement within uncertainties for $\sqrt{s_{NN}} = 5.02$ and 2.76 TeV.

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I. INTRODUCTION

Experiments at the Large Hadron Collider (LHC) at CERN have recorded Pb–Pb collisions at the center of mass energy $\sqrt{s_{NN}} = 5.02$ TeV, to date the highest energy for collisions of heavy ions, that has allowed for the creation of a long-lived, hot, dense, and strongly interacting QCD matter [1,2]. One of the physics interests of ALICE experiment is to study the properties of the deconfined state of quarks and gluons (the quark-gluon plasma, QGP) produced in the early stages of the collision relative to the confined state of hadrons and resonances (excited state hadrons) [3–5]. In these collisions, several kinds of hadrons and resonances with different flavors of valence quark content, mass, spin, and lifetime are produced. Each of these hadrons and resonances possesses unique characteristic features that can be exploited to study the properties of the medium [6]. Strongly decaying resonances like $K^*(892)^0$ and $\phi(1020)$ with strange valence quarks have similar masses and spin = 1, but different lifetimes of 4.16 ± 0.05 fm/ c and 46.3 ± 0.4 fm/ c [7], respectively. The large difference in the lifetimes of these resonances allows one to probe the system formed in heavy-ion collisions at different timescales [8–22].

Experiments usually measure the transverse momentum (p_T), rapidity (y), and azimuthal angle (φ) distributions of the produced particles. Other observables are mostly derived from these basic measurements. The total yields of the resonances like $K^*(892)^0$ and $\phi(1020)$ dominantly come from the low transverse momentum ($p_T < 3$ GeV/ c) particles and are sensitive to the rescattering and regeneration processes in the hadronic phase of the heavy-ion collisions [10,14,18,20,21]. Further, the p_T -integrated yields have been used to construct various particle ratios to understand strangeness enhancement in high-energy collisions [10,12–14,18,19,21,23]. In the intermediate p_T range (3–6 GeV/ c), effects of radial flow and recombination have been probed [24,25]. Different kinds of particle ratios, particularly baryon-to-meson, have been used to understand these dynamics [18,19,21,26–29]. At high p_T , the phenomenon of energy loss by energetic partons traversing the dense medium formed in high-energy heavy-ion collisions has been studied [27,30–38]. The energy loss process depends on the initial medium density, on the lifetime of the dense matter, on the path length traversed by the parton, and on the quark flavor. The contributions of these parameters can be understood by studying the identified hadron p_T spectra for various collision centralities and collision energies relative to pp collisions.

ALICE has previously measured the $K^*(892)^0$ and $\phi(1020)$ meson production in pp and Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [18,21]. The low- p_T physics phenomena of rescattering of resonance decay products and regeneration of resonances in hadronic medium, radial flow, and strangeness enhancement are addressed through the measurements of the particle yield (dN/dy), yield ratios, and mean transverse momentum ($\langle p_T \rangle$). The measured $\langle p_T \rangle$ in central

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Pb–Pb collisions is observed to be 15–20% higher than in peripheral collisions and is also higher than the $\langle p_T \rangle$ measured in nucleus–nucleus collisions at RHIC energies [10,12–14], suggesting a stronger radial flow effect at the LHC. In Ref. [27], it is shown that $\langle p_T \rangle$ of π , K , and p in central Pb–Pb collisions is slightly higher at 5.02 TeV than at 2.76 TeV. This effect is consistent with the presence of a stronger radial flow at the highest collision energy in Pb–Pb collisions. The $K^*(892)^0$ and $\phi(1020)$ resonances, having a mass similar to the mass of the proton, can further be used to test this effect. The p_T -integrated yield of $K^*(892)^0$ relative to kaons is observed to be suppressed in central Pb–Pb collisions compared to pp and peripheral Pb–Pb collisions. No such suppression is observed for the $\phi(1020)$ meson. This suggests that the rescattering of the decay products of the short-lived resonance $K^*(892)^0$ in the hadronic phase is the mechanism that determines the reduced measurable yield. This characteristic is further supported by the expectations from thermal model predictions for Pb–Pb collisions with a chemical freezeout temperature of 156 MeV, which does not include rescattering effect [39]. A detailed study on the energy and system size dependence of p_T -integrated particle yield ratios, K^{*0}/K and ϕ/K is performed. For current measurements, these ratios are calculated with the average of particle and anti-particle yields i.e. $(K^{*0} + \bar{K}^{*0})/(K^+ + K^-)$ and $2\phi/(K^+ + K^-)$, which are denoted as K^{*0}/K and ϕ/K , respectively throughout this paper unless specified otherwise. The reader is referred to Ref. [22] for more elaborate discussions on the observation of rescattering in Pb–Pb collisions, lifetime of the hadronic phase and physics related to p_T dependence of particle ratios involving $K^*(892)^0$ and $\phi(1020)$ resonances in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

The comparison of $K^*(892)^0$ and $\phi(1020)$ p_T distributions to the expected p_T distributions from a blast-wave function [40] with parameters obtained from combined fits to $\pi^\pm$, $K^\pm$, and $p(\bar{p})$ [41], which does not include rescattering effects, shows a suppression of the $K^*(892)^0$ yield by $\approx 40\%$ for $p_T < 3$ GeV/c. However, it is not yet established if the observed p_T -dependence of the $K^*(892)^0$ suppression is only due to the rescattering effect. No such suppression is observed for the $\phi(1020)$ meson, suggesting that $\phi(1020)$ mesons typically decay outside the fireball (lifetime ≈ 10 fm/c [42]) because of their longer lifetime.

The high- p_T parton energy loss is studied by measuring the nuclear modification factor (R_{AA}). It is defined as

$$R_{AA} = \frac{1}{\langle T_{AA} \rangle} \frac{d^2 N^{AA}/(dy dp_T)}{d^2 \sigma^{pp}/(dy dp_T)}, \quad (1)$$

where $d^2 N^{AA}/(dy dp_T)$ is the yield of particles in heavy-ion collisions and σ^{pp} is the production cross section in pp collisions. $\langle T_{AA} \rangle = \langle N_{\text{coll}} \rangle / \sigma_{\text{inel}}$ is the average nuclear overlap function, where $\langle N_{\text{coll}} \rangle$ is the average number of binary nucleon–nucleon collisions calculated using MC Glauber [43] simulations, and σ_{inel} is the inelastic pp cross section equal to (67.6 ± 0.6) mb at $\sqrt{s_{NN}} = 5.02$ TeV [27,44]. The R_{AA} measurements in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [10,31] show that at high transverse momentum ($p_T > 8$ GeV/c) nuclear modification factors for π , K , p , $K^*(892)^0$, and $\phi(1020)$

are consistent within uncertainties. This suggests that the partonic energy loss in the dense medium produced in heavy-ion collisions does not change the relative particle abundancies at $p_T > 8$ GeV/c in the light quark sector (u, d, s). The new measurements in pp and Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV will be useful in the study of energy dependence of R_{AA} and in further testing the flavor dependence of partonic energy loss in the dense medium produced in heavy-ion collisions. The centrality, collision energy and flavor dependence of the R_{AA} are studied using precise measurements at the highest beam energy available for Pb–Pb collisions at the LHC.

In this article, $K^*(892)^0$ and $\phi(1020)$ meson production is studied at midrapidity, $|\eta| < 0.5$, over a wide transverse momentum range up to 20 GeV/c in Pb–Pb and inelastic pp collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Throughout this article, the results for $K^*(892)^0$ and $\bar{K}^*(892)^0$ are averaged and denoted by the symbol K^{*0} , and $\phi(1020)$ is denoted by ϕ unless specified otherwise. The article is organized as follows: Section II describes the data analysis techniques, which include the event and track selection, the technique adopted to obtain the yields of the resonances, correction factors and systematic uncertainties. Section III presents results related to the K^{*0} and ϕ meson p_T spectra, yields, mean transverse momentum, particle ratios and nuclear modification factors. A summary of the work presented in the article is given in Sec. IV.

II. DATA ANALYSIS

The measurements of K^{*0} and ϕ meson production in pp and Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV have been performed on data taken with the ALICE detector in the year 2015. The resonances are reconstructed via their hadronic decay channels, $K^{*0} \rightarrow \pi^\pm K^\mp$ (B.R. = 66.6% [7]) and $\phi \rightarrow K^+ K^-$ (B.R. = 49.2% [7]). In pp collisions, K^{*0} and ϕ mesons are measured in inclusive inelastic events, whereas in Pb–Pb collisions they are measured in eight collision centrality classes 0–10%, 10–20%, 20–30%, 30–40%, 40–50%, 50–60%, 60–70%, and 70–80% [45].

A. Event and track selection

A detailed description of the ALICE detector can be found in Refs. [46,47]. The measurements are obtained with the ALICE central barrel detectors, which are located inside a solenoidal magnet providing a magnetic field of 0.5 T, and are used for tracking, particle identification and reconstruction of the primary vertex. The measurements have been performed by using central barrel detectors: the inner tracking system (ITS), the time projection chamber (TPC), and the time-of-flight (TOF) detector. These detectors have full azimuthal coverage around midrapidity, at pseudorapidity $|\eta| < 0.9$. The primary vertex position is determined from global tracks [47]. Global tracks are reconstructed using both the TPC and ITS, and are used to determine the primary vertex position [47]. Events are selected according to the position of the primary vertex along the beam axis (v_z), which is required to be within 10 cm from the nominal interaction point to ensure a uniform acceptance and reconstruction efficiency in the pseudorapidity region $|\eta| < 0.8$. In addition, the difference between the

vertices reconstructed with the two innermost layers of the ITS and those reconstructed with global tracks ($|v_{z,\text{Track}} - v_{z,\text{SPD}}|$) is required to be less than 0.5 cm. This selection is required to reject pile-up events in pp collisions, which are less than 1% of the overall number of events. Pb-Pb collisions have negligible pile-up. A pair of scintillator arrays (V0 detector) that cover the pseudorapidity region $2.8 < \eta < 5.1$ (V0-A) and $-3.7 < \eta < -1.7$ (V0-C), is used for the interaction trigger both in pp and in Pb-Pb collisions. The trigger is defined as a coincidence between the V0-A and the V0-C. In addition, at least one hit in the central barrel detector SPD is required for the minimum bias trigger in pp collisions. The V0 detector signal is the total charge collected (VOM amplitude) in the detector, which is proportional to the charged particle multiplicity in its acceptance, and it is used to classify the Pb-Pb events into centrality classes, defined in terms of percentiles of the hadronic cross section. A Glauber Monte Carlo model is fitted to the V0 amplitude distribution to compute the fraction of the hadronic cross section corresponding to any given range of V0 amplitudes. Based on these studies, the data are divided into several centrality classes [48]. The number of events analyzed after the event selections are $\approx 110 \times 10^6$ and $\approx 24 \times 10^6$ in minimum bias pp and Pb-Pb collisions, respectively.

K^{*0} and ϕ mesons are reconstructed using global tracks. To ensure high tracking efficiency and to limit the contamination due to secondary particles and tracks with wrongly associated hits, global selected tracks are required to have a minimum number of TPC hits associated to the track (70 of a maximum of 159). The reconstructed track χ^2 normalized to the number of TPC clusters is required to be lower than 4. To reduce the contamination from beam-background events and secondary particles coming from weak decays, selection criteria on the distance of closest approach to the primary vertex in the transverse plane (DCA_{xy}) of the selected tracks and in the beam direction (DCA_z) are applied [47]. The value of DCA_{xy} is required to be $\text{DCA}_{xy}(p_T) < 0.0105 + 0.035p_T^{-1.1}$ cm (p_T in GeV/c) which corresponds to 7 times the DCA_{xy} resolution, and DCA_z is required to be less than 2 cm. The p_T is requested to be larger than 0.15 GeV/c. The charged tracks are selected within the pseudorapidity range $|\eta| < 0.8$, which ensures uniform acceptance and the best reconstruction efficiency. Furthermore, the charged tracks from the decay of weakly decaying kaons are rejected.

The TPC and TOF are used to identify pions and kaons by measuring the specific ionization energy loss (dE/dx) in the TPC and their time-of-flight in the TOF, respectively. Whenever the TOF information for a given track is not available, only the TPC information is used for particle identification. The dE/dx resolution of the TPC is denoted as σ_{TPC} . For K^{*0} and ϕ meson reconstruction in Pb-Pb collisions, and K^{*0} reconstruction in pp collisions, pion and kaon candidates are required to have $\langle dE/dx \rangle$ within $2\sigma_{\text{TPC}}$ of the expected dE/dx values for each particle species over the whole momentum range. To further reduce the number of misidentified particles, the measured time-of-flight is required not to deviate from the expected value for each given mass hypothesis by more than $3\sigma_{\text{TOF}}$ ($\sigma_{\text{TOF}} \approx 60$ ps) [27]. For ϕ meson reconstruction in pp collisions, the kaon candidates are selected using the

TPC with selection criteria of $6\sigma_{\text{TPC}}$, $4\sigma_{\text{TPC}}$, and $2\sigma_{\text{TPC}}$ on the measured $\langle dE/dx \rangle$ distributions in the momentum ranges $p < 0.3$ GeV/c, $0.3 < p < 0.4$ GeV/c, and $p > 0.4$ GeV/c, respectively. In addition, a $3\sigma_{\text{TOF}}$ selection criterion is applied on the time-of-flight over the measured momentum range whenever the TOF information is available.

B. Yield extraction

The raw yields are extracted in each p_T bin and centrality class as done in previous work [18,21,49–51]. The p_T spectra for K^{*0} (ϕ) mesons cover the range 0–20 GeV/c (0.4–20 GeV/c) for pp collisions. For Pb-Pb collisions, the p_T spectra of K^{*0} and ϕ mesons are measured from $p_T = 0.4$ GeV/c up to 20 GeV/c in all centrality classes. The K^{*0} and ϕ mesons are reconstructed via their hadronic decay channels by calculating the invariant mass of their decay daughters. For each event, the unlike-sign kaons and pions are paired for K^{*0} , and unlike-sign kaons are paired for the ϕ meson to construct the invariant-mass distribution. The rapidity of the daughters pair is required to lie in the range, $|y| < 0.5$. An event mixing technique is used to estimate the combinatorial background where the kaons and pions from one event are mixed with oppositely charged kaons and pions from other events. Two events are mixed only if they have similar multiplicity ($|\Delta n| < 5$) and collision vertex ($|\Delta v_z| < 1$ cm). To reduce the statistical uncertainties from the background distribution, each event is mixed with five other events. Then the mixed-event invariant mass distribution is normalized in the mass region outside of the mass peak, namely $1.1 < M_{K\pi} < 1.15$ GeV/ c^2 and $1.035 < M_{KK} < 1.045$ GeV/ c^2 for K^{*0} and ϕ mesons, respectively. The left panels of Figs. 1 and 2 show the invariant mass distributions of unlike-sign $K\pi$ and KK pairs from the same event (black marker) and the normalized mixed event background (red marker) for the transverse momentum ranges $1.2 < p_T < 1.6$ GeV/c and $0.8 < p_T < 1.0$ GeV/c, respectively. The invariant mass distributions are shown for the 0–10% and 70–80% centrality classes in Pb-Pb collisions. The combinatorial background subtracted invariant-mass distributions are fitted using a combined function to describe the signal peak and the residual background. As shown in the right panels of Figs. 1 and 2, respectively, a Breit-Wigner function [Eq. (2)] is used to describe the K^{*0} peak and a Voigtian function [a convolution of a Breit-Wigner and a Gaussian function, Eq. (3)] is used to describe the ϕ peak. A second order polynomial is used to describe the residual background in both cases. The residual background is what remains after the combinatorial background subtraction and it is mainly due to correlated pairs from real resonance decays where the daughter particles are misidentified as K or π . The signal peak fit functions for K^{*0} and ϕ are

$$\frac{dN}{dM_{K\pi}} = \frac{N_{\text{raw}}}{2\pi} \frac{\Gamma}{(M_{K\pi} - M_0)^2 + \frac{\Gamma^2}{4}}, \quad (2)$$

$$\frac{dN}{dM_{KK}} = \frac{N_{\text{raw}}}{2\pi} \int \frac{\Gamma}{(M_{KK} - m')^2 + \Gamma^2/4} \frac{e^{-(m' - M_0)^2/2\sigma^2}}{\sqrt{2\pi}\sigma} dm', \quad (3)$$

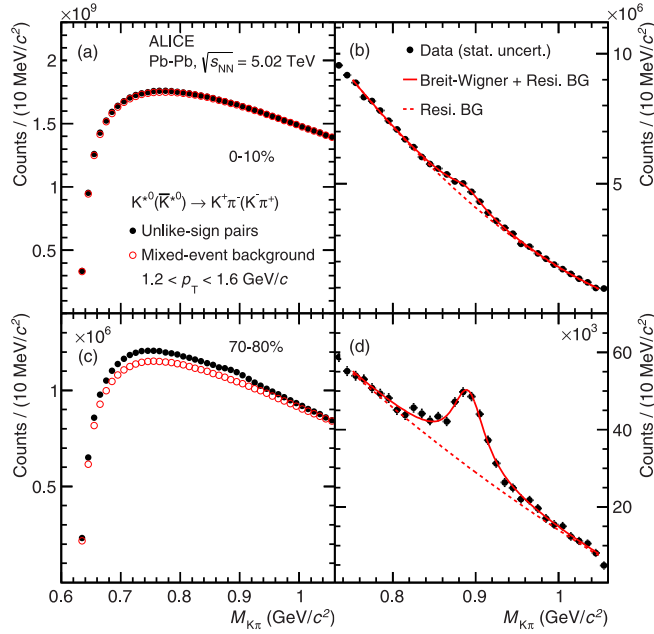


FIG. 1. Invariant-mass distributions of πK pairs for the 0–10% and 70–80% centrality classes in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for the transverse momentum range $1.2 < p_T < 1.6$ GeV/c. The left panels show the unlike charge πK invariant-mass distribution from the same event and the normalized mixed event background. The right panels report the invariant-mass distribution after subtraction of the combinatorial background for K^{*0} . The solid curves represent fits to the distributions and the dashed curves are the components of the fits that describe the residual background. The statistical uncertainties are shown by bars.

where $M_{K\pi}$ and M_{KK} are the reconstructed invariant masses of K^{*0} and ϕ mesons. M_0 , Γ , and N_{raw} are the mass, width and raw yield of the resonances, respectively. The parameter σ in Eq. (3) represents the mass resolution, which depends on p_T . The widths of K^{*0} and ϕ are fixed to the vacuum values [7] while fitting the invariant mass distributions. For the ϕ meson, the σ is kept free. The measured σ on the ϕ mass is p_T dependent, varies between 1–2 MeV/c² and its values are consistent with the values obtained from Monte Carlo simulations. The raw particle yields are extracted by integrating the invariant mass distribution within the mass interval approximately $M_0 \pm 2\Gamma$ and subtracting the integral of the residual background function in the same mass region. The resonance yields beyond the integration region are obtained by integrating the tail part of the signal fit function; these yields are then added to the yields extracted by integrating the invariant mass distribution.

C. Yield correction

1. Acceptance and reconstruction efficiency

The raw transverse momentum distributions are corrected for the detector acceptance and reconstruction efficiency ($A \times \epsilon_{\text{rec}}$). These correction factors are evaluated by using Monte Carlo (MC) events generated with PYTHIA8 (Monash 2013 Tune) [52] for pp and HIJING [53] for Pb–Pb collisions,

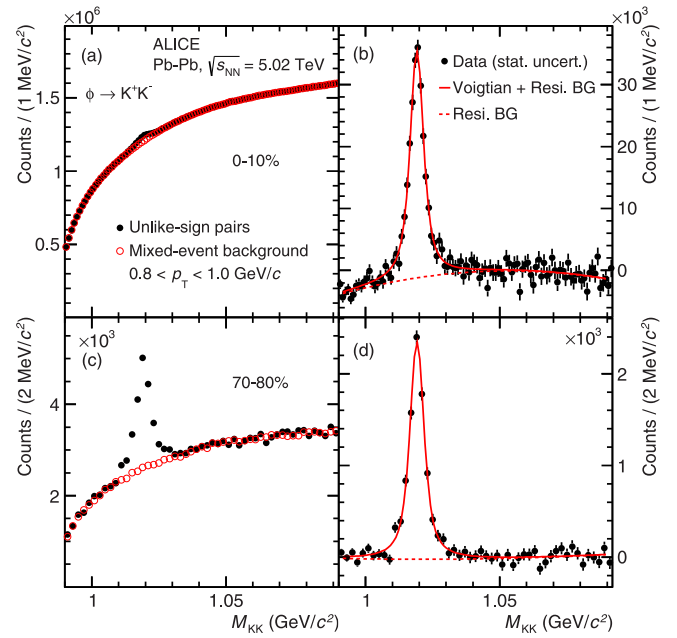


FIG. 2. Invariant-mass distributions of KK pairs for the 0–10% and 70–80% centrality classes in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for the transverse momentum ranges $0.8 < p_T < 1.0$ GeV/c. The left panels show the unlike charge KK invariant-mass distribution from the same event and the normalized mixed event background. The right panels report the invariant-mass distribution after subtraction of the combinatorial background for ϕ . The solid curves represent fits to the distributions and the dashed curves are the components of the fits that describe the residual background. The statistical uncertainties are shown by bars.

and by transporting the particles through a full simulation of the ALICE detector with GEANT3 [54]. The $A \times \epsilon_{\text{rec}}$ has a centrality dependence in Pb–Pb collisions and a deviation of ≈ 5 –7% is observed from the most central to the most peripheral centrality classes. As the real data and the generated MC spectral shapes are different, the p_T spectra of the generated mesons are reweighted to the respective p_T spectra from the data in an iterative method to re-estimate the efficiency [55]. The effect of re-weighting the generated p_T spectra on $A \times \epsilon_{\text{rec}}$ is ~ 4 –6% at low- p_T (< 1 GeV/c) and is negligible at high p_T (> 1 GeV/c).

2. Normalization

The normalized yield is given by

$$\frac{1}{N_{\text{event}}} \frac{d^2N}{dy dp_T} = \frac{1}{N_{\text{event}}^{\text{acc}}} \frac{N_{\text{raw}}}{\Delta y \Delta p_T} \frac{\epsilon_{\text{trig}} \epsilon_{\text{vert}} \epsilon_{\text{SL}}}{(A \times \epsilon_{\text{rec}}) BR}, \quad (4)$$

where Δy and Δp_T are the widths of rapidity and p_T bins, respectively. The raw spectra are corrected for the branching ratio (BR). The extracted yields are normalized to the number of analyzed events ($N_{\text{event}}^{\text{acc}}$). In order to obtain the absolute resonance yields per inelastic pp collision, the factor $\epsilon_{\text{trig}} = 0.757 \pm 0.019$ due to trigger efficiency is used. This is the ratio between the V0 visible cross section [56] and the inelastic cross section [44].

The correction factor ϵ_{vert} accounts for the vertex reconstruction efficiency, which is calculated as the ratio of the number of events having good vertex to the total number of triggered events. This is estimated to be 0.958 in pp collisions. The signal loss correction, ϵ_{SL} accounts for the loss in K^{*0} and ϕ yields that is caused by the event selection with minimum bias trigger, rather than all inelastic events. The ϵ_{SL} has a p_T dependence and is only significant for low p_T (< 2.5 GeV/ c). It is calculated as the ratio of the p_T spectrum from inelastic events to the p_T spectrum from triggered events. The value of ϵ_{SL} is less than 1.05 for both K^{*0} and ϕ mesons in pp collisions. The effects of inelastic trigger, vertex reconstruction efficiency and signal loss corrections are negligible in Pb-Pb collisions [28,41] and, hence, are not considered.

D. Systematic uncertainties

The systematic uncertainties in the measurement of K^{*0} and ϕ production in pp and Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV have been estimated by considering uncertainties due to signal extraction, track selection criteria, particle identification, global tracking efficiency, uncertainty in the material budget of the ALICE apparatus and the hadronic interaction cross section in the detector material. To study the systematic uncertainty for K^{*0} and ϕ in Pb-Pb and K^{*0} in pp , an approach similar to that described in Refs. [18,21,49,51] has been adopted. For the estimation of systematic uncertainties for ϕ in pp , a similar approach is followed as in Refs. [57,58].

A summary of the systematic uncertainties from various sources, for K^{*0} and ϕ in pp and Pb-Pb collisions is given in Ref. [22] where the values of relative systematic uncertainties are quoted for low, intermediate, and high p_T . The track selection criteria have been varied to study the systematic effect due to the track selection. In order to study the effect of the choice of particle identification criteria of the daughter tracks on raw yield extraction, the selection criteria on TPC and TOF have been varied. To estimate the systematic uncertainty of particle identification (PID), the $N\sigma_{\text{TPC/TOF}}$ cut is varied by $1\sigma_{\text{TPC/TOF}}$ from the default PID selection criterion.

The uncertainty due to the signal extraction includes variations of the event mixing background normalization range, signal fit range, residual background fit function, choice of combinatorial background, and mass resolution. The mixed event background distributions for K^{*0} and ϕ have been normalized in different invariant-mass regions excluding the signal peaks; the change in yield is considered as the systematic uncertainty. The $K\pi$ invariant-mass fitting ranges are varied by 10–50 MeV/ c^2 for K^{*0} whereas for the ϕ the KK invariant-mass fitting ranges are varied by 5–10 MeV/ c^2 . The residual background is fitted with a third-order polynomial for Pb-Pb collisions, and in pp collisions, a first- and third-order polynomial is used for systematic studies. The systematic uncertainties due to the combinatorial background are estimated by changing the method of background reconstruction (like sign and event mixing).

Another source of uncertainty comes from the determination of the global tracking efficiency, which arises from the ITS-TPC track matching efficiency. The systematic uncertain-

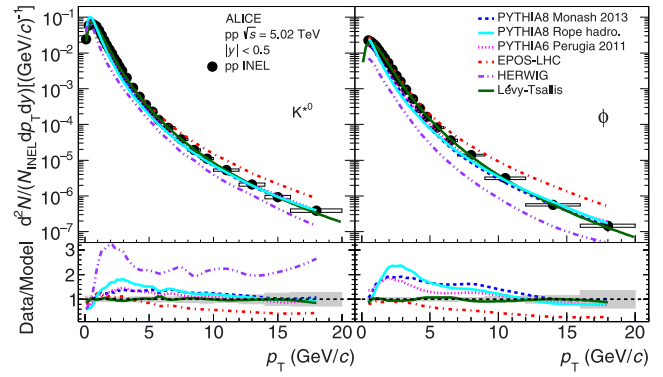


FIG. 3. Transverse momentum spectra of K^{*0} (left panel) and ϕ (right panel) for inelastic pp collisions at $\sqrt{s} = 5.02$ TeV. The statistical and systematic uncertainties are shown by bars and boxes, respectively. The results are compared with model calculations from PYTHIA 6.4 (Perugia 2011 Tune) [62,63], PYTHIA 8.1 (Monash 2013 Tune) [52,64], PYTHIA 8.2 (Rope hadronization) [65], EPOS-LHC [66], and HERWIG 7.1 [67], which are shown as different dashed lines. The lower panels show the data to model ratio.

ties due to global tracking efficiency are calculated from the corresponding values for single charged particles uncertainty and by combining the two charged tracks used in the invariant mass reconstruction of K^{*0} and ϕ . In both pp and Pb-Pb collisions, this contribution has been estimated to be p_T dependent for charged particles [28].

The material budget of the ALICE detector setup is known with an uncertainty of 7% in terms of radiation length, determined on the basis of γ conversion measurements [59]. The systematic uncertainty contribution due to material budget is thus estimated by varying the amount of material by $\pm 7\%$ in the Monte Carlo simulation. The systematic uncertainty due to the hadronic interaction cross section in the detector material is estimated by comparing different transport codes: GEANT3 [54], GEANT4 [60], and FLUKA [61]. The effects of material budget and hadronic interactions are evaluated by combining the uncertainties for a pion and a kaon (in case of K^{*0}), and for two kaons (in case of ϕ) according to the kinematics of the decay [28]. These effects are found to be negligible at intermediate and high p_T for both K^{*0} and ϕ .

Raw yield extraction and global tracking efficiency dominate total uncertainties in the lowest and highest p_T intervals. The total systematic uncertainties for K^{*0} and ϕ amount to 10.9–12.3% (9.1–13.0%) and 6.4–9.2% (5.4–9.5%) in Pb-Pb (pp) collisions, respectively. Among the sources of systematic uncertainty, the yield extraction is the only fully uncorrelated source, while track selection, PID, global tracking efficiency, material budget and hadronic interaction are correlated across different centrality classes.

III. RESULTS

A. p_T spectra in pp collisions

Figure 3 shows the invariant yields of K^{*0} and ϕ mesons as a function of p_T for inelastic pp collisions at $\sqrt{s} = 5.02$ TeV. These first measurements at $\sqrt{s} = 5.02$ TeV extend to

TABLE I. Lévy-Tsallis fit parameters for K^{*0} and ϕ meson p_T spectra in pp collisions at $\sqrt{s} = 5.02$ TeV. The errors on the fit parameters result from the total (quadrature sum of statistical and systematic) uncertainties on the data.

Resonance	n	C (GeV)	χ^2/ndf
K^{*0}	7.05 ± 0.14	0.267 ± 0.006	0.23
ϕ	7.47 ± 0.16	0.309 ± 0.006	0.62

$p_T = 20$ GeV/c in the rapidity range of $|y| < 0.5$. The shape of both spectra is well described by a Lévy-Tsallis function [68] whose form is given by

$$\frac{d^2N}{dp_T dy} = p_T \frac{dN}{dy} \frac{(n-1)(n-2)}{nC[nC + m(n-2)]} \left[1 + \frac{m_T - m}{nC} \right]^{-n}, \quad (5)$$

where dN/dy , n , and C are the parameters of the function that are determined from the fit to the measured spectra, m is the mass of the hadron, and m_T is the transverse mass defined as $\sqrt{p_T^2 + m^2}$. The Lévy-Tsallis function provides a fair description of the shape of the transverse momentum spectrum over a wide p_T range, thanks to its two parameters: the exponent n and the inverse slope C . The parameters obtained from the fit to K^{*0} and ϕ spectra in pp collisions at $\sqrt{s} = 5.02$ TeV are given in Table I. They are similar to the parameters obtained in pp collisions at $\sqrt{s} = 7$ and 8 TeV [57]. The χ^2/ndf values are less than unity because the bin-to-bin systematic uncertainties taken in the fit could be correlated. The data are compared to the corresponding results from the QCD inspired Monte Carlo event generators like PYTHIA6 [62], PYTHIA8 [64], HERWIG [67], and EPOS-LHC [66]. In PYTHIA model hadronization of light and heavy quarks is simulated using the Lund string fragmentation model [69]. Various PYTHIA tunes have been developed on the basis of extensive comparisons of Monte Carlo distributions with the minimum bias data from different experiments. Perugia tunes of PYTHIA6 include the revised set of parameters of fragmentation and flavor which improves the overall description of the Tevatron data as well as the reliability of the extrapolations to the LHC measurements [63]. Perugia 2011 takes into account the minimum bias and underlying event data from the LHC at $\sqrt{s} = 0.9$ and 7 TeV. The Monash 2013 Tune of PYTHIA8 uses the updated set of hadronization parameters compared to the previous tunes [52]. It gives an overall good description of kaon data but significantly underestimates the baryon yields at the LHC. The Rope Hadronization model within the framework of PYTHIA8 assumes that instead of independent string fragmentation, the strings overlap to form ropes in the high multiplicity environment [65]. In the Rope Hadronization model, the larger and denser collision systems form color ropes that hadronize with larger string tension leading to enhanced production of strange hadrons with increasing charged particle multiplicity. The HERWIG model includes processes such as coherent parton showers for initial and final state QCD radiation, an eikonal multiple parton-parton interaction model for the underlying event and a cluster hadronization model for the formation of hadrons from the quarks and gluons produced in the parton shower [67]. EPOS-LHC, which is built on the

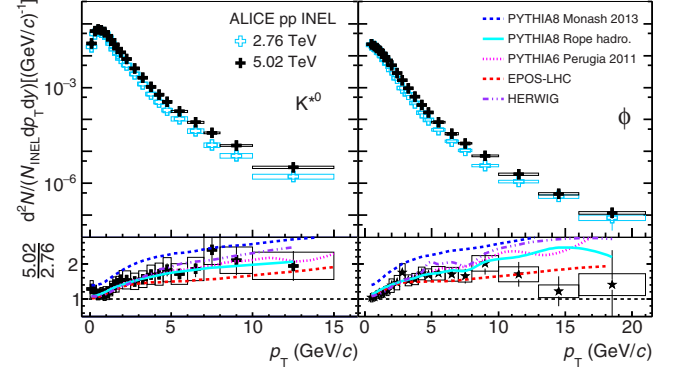


FIG. 4. Comparison of transverse momentum spectra of K^{*0} (left panel) and ϕ (right panel) for inelastic pp collisions at $\sqrt{s} = 5.02$ TeV (solid markers) and 2.76 TeV (open markers) [21]. The lower panels show the ratio of the p_T spectra at $\sqrt{s} = 5.02$ TeV to those from $\sqrt{s} = 2.76$ TeV. The statistical uncertainties on the data are shown by bars and the systematic uncertainties by boxes. The ratios are compared with model calculations from the PYTHIA 6.4 (Perugia 2011 Tune) [62,63], PYTHIA 8.1 (Monash 2013 Tune) [52,64], PYTHIA 8.2 (Rope hadronization) [65], EPOS-LHC [66], and HERWIG 7.1 [67], which are shown as different dashed lines.

Parton-Based Gribov Regge Theory, implements a different type of radial flow for pp collisions, where a very dense system is created in a small volume. The model, utilizing the color exchange mechanism of string excitation, is tuned to LHC data [66]. In this model, the part of the collision system that has high string or parton densities becomes a “core” region that may evolve as a quark–gluon plasma; this is surrounded by a more dilute “corona” for which fragmentation occurs as in the vacuum. The strangeness production is higher in the core region that results in strangeness enhancement with increasing multiplicity.

For K^{*0} , all the tunes of PYTHIA model overestimate the data for $p_T < 0.5$ GeV/c, underestimate the data in the intermediate p_T region and give a better description for $p_T > 10$ GeV/c. For ϕ , all the tunes of PYTHIA model give a better description of the data for $p_T > 10$ GeV/c and underestimate the data for lower p_T region. The deviations in limited p_T ranges observed between data and PYTHIA for both K^{*0} and ϕ are similar to those reported for $\sqrt{s} = 2.76$ [21] and 7 TeV [49]. The EPOS-LHC model results are in agreement with the data for $p_T < 5$ GeV/c (3.5 GeV/c) and overestimate the data at higher p_T for K^{*0} (ϕ). HERWIG does not describe the data for both K^{*0} and ϕ over the measured p_T region.

Figure 4 shows the comparison of p_T spectra of K^{*0} and ϕ mesons between $\sqrt{s} = 5.02$ and 2.76 TeV. The yields of both K^{*0} and ϕ mesons are higher at $\sqrt{s} = 5.02$ TeV compared to $\sqrt{s} = 2.76$ TeV. The ratio of the p_T spectra at $\sqrt{s} = 5.02$ to 2.76 TeV as a function of p_T shows that the differential yield ratio increases with p_T for both K^{*0} and ϕ mesons and show a hint of saturation at higher p_T . These results further help in understanding the nuclear modification factor (derived using pp reference spectra) for Pb–Pb collisions that will be discussed in Sec III E. The ratios are compared to the corresponding calculations from the PYTHIA6 (Perugia 2011

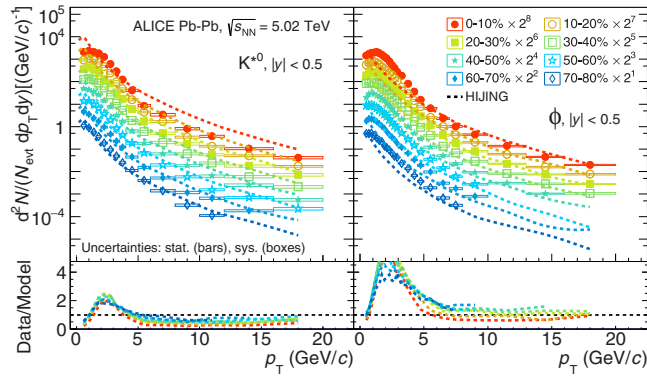


FIG. 5. Transverse momentum spectra of K^{*0} (left panel) and ϕ (right panel) at midrapidity in various centrality classes in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The statistical uncertainties on the data are shown by bars and the systematic uncertainties by boxes. The results are compared with model calculations from HIJING 1.36 [53], which are shown as dashed lines. The lower panel shows the data to model ratios.

Tune), PYTHIA8 (Monash 2013 Tune), PYTHIA8 (Rope hadronization), EPOS-LHC, and HERWIG models. For the K^{*0} meson, all the models except PYTHIA8-Monash 2013 Tune are in good agreement with the measurements within uncertainties for the whole p_T range. For the ϕ meson, all the models except PYTHIA8-Monash 2013 Tune are in good agreement with the measurements within uncertainties for $p_T < 8$ GeV/c. The ratio of the p_T spectra for K^{*0} and ϕ from the Monash 2013 Tune of PYTHIA8 are higher than the measurements for all p_T . All the models presented here fail quantitatively and/or qualitatively to describe the K^{*0} and ϕ data over the entire measured p_T range. It has proven challenging for event generators to accurately model the p_T distributions of such resonances [21,49,57,58]. Thus, the data and model comparisons may provide valuable inputs to tune the MC event generators so that one get a unified physics description of present results.

B. p_T spectra in Pb-Pb collisions

Figure 5 shows the p_T distributions for K^{*0} and ϕ mesons in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The measurements are carried out at midrapidity ($|y| < 0.5$) for eight different centrality classes. For the most central collisions (0–10%), the measurements extend up to $p_T = 20$ GeV/c for both K^{*0} and ϕ mesons. The HIJING model was used to calculate the reconstruction efficiency of K^{*0} and ϕ mesons in Pb-Pb collisions, hence the data are compared to the corresponding results from the HIJING model [53]. For K^{*0} meson, HIJING does not describe the data for all centrality classes over the whole measured p_T region. For ϕ meson, the model gives a good agreement with the data in mid-central collisions for $p_T > 7$ GeV/c, however does not describe the data for most of the centrality classes. The p_T spectra are further characterized by the integrated yields (dN/dy) and the average transverse momentum ($\langle p_T \rangle$) which are discussed in the next subsection. Figure 6 shows the comparison of the p_T spectra for K^{*0} and

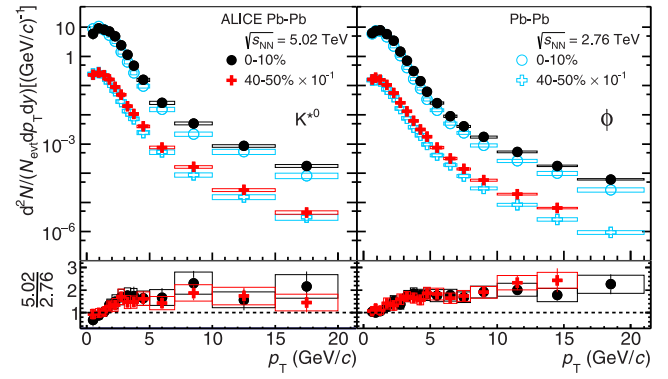


FIG. 6. Comparison of transverse momentum spectra of K^{*0} (left panel) and ϕ (right panel) in central (0–10%) and mid-central (40–50%) centrality classes in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ (solid marker) and 2.76 (open marker) TeV [18,21]. The lower panels show the ratio of the p_T spectra at $\sqrt{s_{NN}} = 5.02$ TeV to those from $\sqrt{s_{NN}} = 2.76$ TeV. The statistical uncertainties on the data are shown by bars and the systematic uncertainties by boxes.

ϕ mesons in Pb-Pb collisions for the 0–10% and 40–50% centrality classes at $\sqrt{s_{NN}} = 5.02$ and 2.76 TeV. The ratios of the p_T spectra increase with p_T and then tend to saturate at high p_T for both mesons in central as well as in peripheral collisions, as also observed in pp collisions (Fig. 4). These results are useful in understanding the energy dependence of the nuclear modification factor which is discussed in Sec III E. For $p_T > 5.0$ GeV/c, the p_T differential yields at 5.02 TeV are ≈ 1.8 times higher than those measured at 2.76 TeV.

A blast-wave model, which does not include rescattering effects, is used to investigate the p_T dependence of resonance yield suppression. Previously, in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [18], the K^{*0} and ϕ p_T spectra were compared to the expected distributions based on the blast-wave model [40] using parameters obtained from the combined fit to $\pi^\pm$, $K^\pm$, and $p(\bar{p})$ spectra. A suppression of the K^{*0} yield with respect to the blast-wave distribution was observed for $p_T < 3$ GeV/c in central collisions. This suppression is attributed to rescattering of resonance decay products in the hadronic phase that reduces the measurable yield of K^{*0} mesons [22]. The lack of similar suppression for the ϕ meson is interpreted as being due to the absence of rescattering, as it mostly decays outside the fireball because of its longer lifetime. We have carried out a similar exercise for Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The Boltzmann-Gibbs blast-wave function is a three parameter simplified hydrodynamic model, which assumes that the emitted particles are locally thermalized in a uniform-density source at a kinetic freezeout temperature T_{kin} and move with a common collective transverse radial flow velocity field. It is given by [40]

$$\frac{1}{p_T} \frac{dN}{dp_T} \propto \int_0^R r dr m_T I_0 \left(\frac{p_T \sinh \rho}{T_{kin}} \right) K_1 \left(\frac{m_T \cosh \rho}{T_{kin}} \right), \quad (6)$$

where I_0 and K_1 are the modified Bessel functions, R is the fireball radius, and r is the radial distance in the transverse

TABLE II. Blast-wave parameters from fit to charged pion, kaon, and proton spectra in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

Centrality	T_{kin} (GeV)	$\langle\beta_T\rangle$	n
0–10%	0.091 ± 0.003	0.662 ± 0.003	0.735 ± 0.013
70–80%	0.147 ± 0.006	0.435 ± 0.011	1.678 ± 0.088

plane. The velocity profile ρ is defined as

$$\rho = \tanh^{-1} \beta_T(r) = \tanh^{-1} \left[\left(\frac{r}{R} \right)^n \beta_s \right], \quad (7)$$

where $\beta_T(r)$ is the transverse expansion velocity and β_s is the transverse expansion velocity at the surface. The free parameters in the fits are T_{kin} , β_s , and the velocity profile exponent n . For the current study, the above parameters, listed in Table II, are fixed to the values from fits to the charged pion, kaon, and (anti)proton p_T distributions in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [27].

Figure 7 shows the expected K^{*0} and ϕ p_T distributions from the blast-wave model (as solid lines), the measured resonance p_T distributions, and the ratios of the measurement to the blast-wave model for central (0–10%) and peripheral (70–80%) collisions. The expected distributions are normalized so that their integrals are equal to the measured yield of charged kaons in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [27] multiplied by the K^{*0}/K and ϕ/K ratios from pp collisions at $\sqrt{s} = 5.02$ TeV. A similar procedure of normalization was used in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [18]. The ratio for the ϕ meson p_T distribution is close to unity and no significant differences are observed in central or peripheral collisions for $p_T < 2$ GeV/c. However, the data/blast-wave ratio for the K^{*0} is lower than unity with a deviation of 40–60% for $p_T < 3$ GeV/c in central collisions. In peripheral collisions, the data/blast-wave ratio for the K^{*0} shows a significantly smaller deviation from unity for $p_T < 2$ GeV/c relative to central collisions. Both K^{*0} and ϕ show a similar deviation

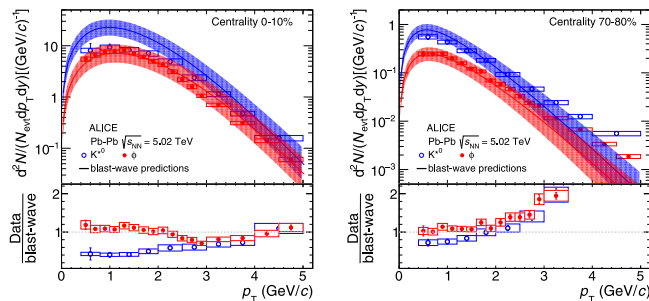


FIG. 7. Transverse-momentum distributions of K^{*0} and ϕ resonances in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV along with expected distributions for central (left) and peripheral (right) collisions. The shapes of the expected distributions are given by Boltzmann-Gibbs blast-wave functions [40] using parameters obtained from fits to pion, kaon, and (anti)proton p_T distributions [27] (see text for details). The shaded bands indicate the uncertainties in the fit parameters of the model distributions. The lower panels show the ratios of the measured distribution to the values from the model.

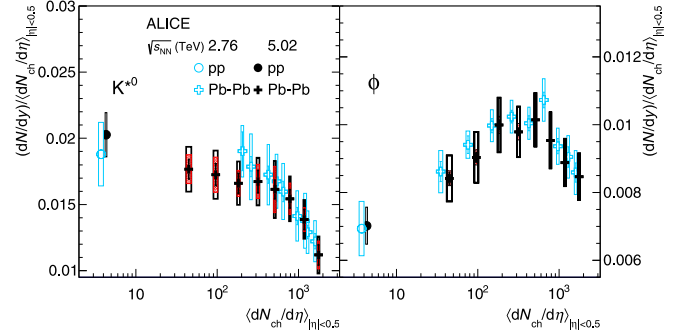


FIG. 8. Transverse momentum integrated yield (dN/dy) of K^{*0} and ϕ as a function of the averaged charged particle density ($\langle dN_{\text{ch}}/d\eta \rangle_{|\eta|<0.5}$) in pp and Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and compared with result from Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [18,21]. The statistical uncertainties on the data are shown by bars and the systematic uncertainties by boxes. The shaded box shows the uncorrelated systematic uncertainties.

for $p_T > 3$ GeV/c (>2.5 GeV/c) in central (peripheral) collisions. The blast-wave model is expected to describe the measured p_T distributions over the entire p_T range if these are driven purely by the collective radial expansion of the system. The model describes the data over a wider p_T interval for central Pb–Pb collisions than for peripheral collisions as observed for π , K , p in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [27]. For Pb–Pb collisions, the average transverse velocity $\langle\beta_T\rangle$ is observed to increase with centrality while T_{kin} decreases [27]. For central Pb–Pb collisions, the shape of the p_T distributions of K^{*0} and ϕ mesons for $p_T < 2$ GeV/c are consistent with the blast-wave parameterization within uncertainties. The suppression of yields of K^{*0} with respect to the blast-wave model expectation in central collisions, relative to peripheral collisions and ϕ mesons, is consistent with the dominance of rescattering effects in the medium formed in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

C. dN/dy and $\langle p_T \rangle$

Figure 8 shows the p_T -integrated yield dN/dy of K^{*0} and ϕ mesons scaled by the average charged particle multiplicity measured at midrapidity ($\langle dN_{\text{ch}}/d\eta \rangle_{|\eta|<0.5}$) as a function of $\langle dN_{\text{ch}}/d\eta \rangle_{|\eta|<0.5}$ for Pb–Pb and pp collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The p_T -integrated yields (dN/dy) have been obtained by integrating the spectra over p_T using the measured data and a blast-wave function (Lévy-Tsallis function) in the unmeasured regions for Pb–Pb (pp) collisions. The fraction of the yields from the extrapolation to the total for K^{*0} (ϕ) mesons is 0.09 (0.08) in the 0–10% centrality class, and is 0.16 (0.12) in the 70–80% centrality class. This fraction is 0.17 for ϕ in pp , whereas no extrapolation is needed for K^{*0} . For comparison, the corresponding results from $\sqrt{s_{NN}} = 2.76$ TeV are also shown in Fig. 8. The dependence of the normalized dN/dy on $\langle dN_{\text{ch}}/d\eta \rangle$ is found to be the same regardless of the beam energy.

The average transverse momentum $\langle p_T \rangle$ values for the K^{*0} and ϕ resonances are obtained by using the data in the measured region and a blast-wave function (Lévy-Tsallis function)

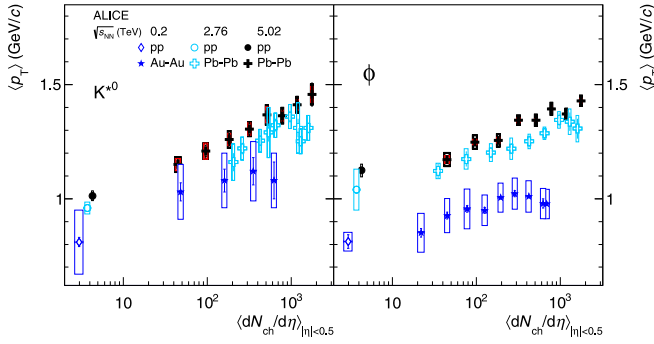


FIG. 9. Mean transverse momentum of K^{*0} and ϕ as a function of the averaged charged particle density $\langle dN_{ch}/d\eta \rangle_{|\eta|<0.5}$ in Pb-Pb and pp collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Also shown for comparison are the corresponding values from Pb-Pb and pp collisions at $\sqrt{s_{NN}} = 2.76$ TeV [18,21], and Au-Au and pp collisions at $\sqrt{s_{NN}} = 200$ GeV [9,10,12,13]. The statistical uncertainties on the data are shown by bars and the systematic uncertainties by boxes. The shaded box shows the uncorrelated systematic uncertainties.

in the unmeasured regions for Pb-Pb (pp) collisions. Figure 9 shows $\langle p_T \rangle$ values obtained at midrapidity ($|\eta| < 0.5$) as a function of $\langle dN_{ch}/d\eta \rangle_{|\eta|<0.5}$ for Pb-Pb and pp collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The $\langle p_T \rangle$ values increase with charged particle multiplicity. The $\langle p_T \rangle$ of K^{*0} and ϕ mesons, which have similar masses, are similar for events with the same

$\langle dN_{ch}/d\eta \rangle_{|\eta|<0.5}$ in Pb-Pb collisions. Both of these features are consistent with the picture of a growing contribution of radial flow with increasing $\langle dN_{ch}/d\eta \rangle_{|\eta|<0.5}$ for the system formed in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [27]. These results are also compared to the corresponding results from Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [18,21], and to Au-Au and pp collisions at $\sqrt{s_{NN}} = 200$ GeV [9,10,12,13]. The $\langle p_T \rangle$ values are larger for higher energy collisions at similar values of $\langle dN_{ch}/d\eta \rangle_{|\eta|<0.5}$, although the uncertainties are also larger at lower collision energies for K^{*0} . The qualitative features of the dependence of K^{*0} and ϕ meson $\langle p_T \rangle$ on $\langle dN_{ch}/d\eta \rangle_{|\eta|<0.5}$ are similar at RHIC and LHC energies. The values of dN/dy and $\langle p_T \rangle$ of K^{*0} and ϕ measured in Pb-Pb and pp collisions at $\sqrt{s_{NN}} = 5.02$ TeV are given in Table III.

Figure 10 compares the $\langle p_T \rangle$ of K^{*0} and ϕ as a function of $\langle dN_{ch}/d\eta \rangle_{|\eta|<0.5}$ with the respective values for $\pi^\pm$, $K^\pm$, and $p(\bar{p})$ [27] for Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. All the hadrons exhibit an increase in $\langle p_T \rangle$ from peripheral to central Pb-Pb collisions: the largest increase is observed for protons, followed by the K^{*0} and ϕ mesons, and then by K and π . The rise in the $\langle p_T \rangle$ values is steeper for hadrons with higher mass, as expected in presence of a radial flow effect. For $\langle dN_{ch}/d\eta \rangle_{|\eta|<0.5} > 300$, the $\langle p_T \rangle$ values of K^{*0} , p , and ϕ hadrons follow a similar trend and have quantitatively similar values within uncertainties at a given $\langle dN_{ch}/d\eta \rangle_{|\eta|<0.5}$ value. The masses of these hadrons are similar, $K^{*0} \approx 896$ MeV/ c^2 , $p \approx 938$ MeV/ c^2 , and $\phi \approx 1019$ MeV/ c^2 . The hadron mass

TABLE III. The values of dN/dy and $\langle p_T \rangle$ measured in Pb-Pb and pp collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Pb-Pb results are shown for the different centrality classes. In each entry the first uncertainty is statistical and the second one is systematic.

K^{*0}		
Centrality class	dN/dy	$\langle p_T \rangle$
0–10%	$19.726 \pm 1.357 \pm 2.475$	$1.457 \pm 0.053 \pm 0.044$
10–20%	$16.363 \pm 0.895 \pm 1.725$	$1.411 \pm 0.039 \pm 0.035$
20–30%	$12.129 \pm 0.547 \pm 1.331$	$1.364 \pm 0.031 \pm 0.034$
30–40%	$8.260 \pm 0.361 \pm 1.111$	$1.368 \pm 0.030 \pm 0.043$
40–50%	$5.321 \pm 0.268 \pm 0.574$	$1.305 \pm 0.034 \pm 0.032$
50–60%	$3.039 \pm 0.140 \pm 0.300$	$1.259 \pm 0.030 \pm 0.037$
60–70%	$1.661 \pm 0.079 \pm 0.176$	$1.209 \pm 0.028 \pm 0.035$
70–80%	$0.793 \pm 0.033 \pm 0.076$	$1.150 \pm 0.024 \pm 0.033$
ϕ		
Centrality class	dN/dy	$\langle p_T \rangle$
0–10%	$14.937 \pm 0.154 \pm 1.210$	$1.429 \pm 0.008 \pm 0.023$
10–20%	$10.483 \pm 0.113 \pm 0.828$	$1.371 \pm 0.008 \pm 0.024$
20–30%	$7.497 \pm 0.083 \pm 0.647$	$1.393 \pm 0.009 \pm 0.027$
30–40%	$5.192 \pm 0.056 \pm 0.404$	$1.344 \pm 0.008 \pm 0.024$
40–50%	$3.113 \pm 0.038 \pm 0.237$	$1.343 \pm 0.009 \pm 0.021$
50–60%	$1.829 \pm 0.024 \pm 0.148$	$1.256 \pm 0.010 \pm 0.027$
60–70%	$0.870 \pm 0.013 \pm 0.072$	$1.248 \pm 0.011 \pm 0.029$
70–80%	$0.378 \pm 0.008 \pm 0.031$	$1.171 \pm 0.014 \pm 0.029$
pp collisions		
Particle specie	dN/dy	$\langle p_T \rangle$
K^{*0}	$0.0872 \pm 0.0006 \pm 0.0072$	$1.0131 \pm 0.0038 \pm 0.0216$
ϕ	$0.0302 \pm 0.0002 \pm 0.0024$	$1.1239 \pm 0.0047 \pm 0.0282$

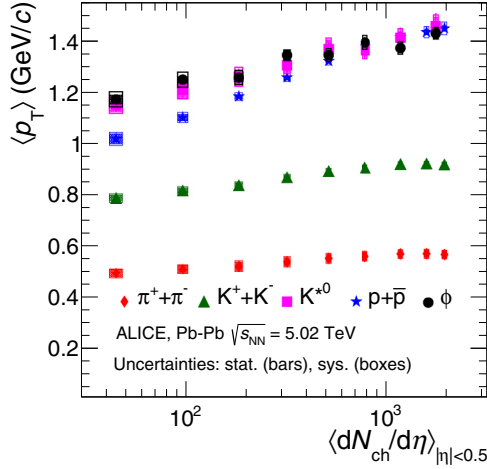


FIG. 10. Mean transverse momentum of K^{*0} and ϕ as a function of the averaged charged particle density ($\langle dN_{ch}/d\eta \rangle_{|\eta|<0.5}$) in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV compared with the corresponding values for other identified particles such as $\pi^\pm$, $K^\pm$, and $p(\bar{p})$ [27]. The statistical uncertainties on the data are shown by bars and the systematic uncertainties by boxes. The shaded boxes show the uncorrelated systematic uncertainties.

dependence of $\langle p_T \rangle$ is consistent with the expectation from a hydrodynamic evolution of the system formed in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for $\langle dN_{ch}/d\eta \rangle_{|\eta|<0.5} > 300$. In peripheral collisions ($\langle dN_{ch}/d\eta \rangle_{|\eta|<0.5} < 300$), $\langle p_T \rangle$ of proton is lower than those of K^{*0} and ϕ , indicating the breaking of mass ordering while going toward peripheral Pb-Pb collisions.

D. Particle ratios

Figure 11 shows the K^{*0}/K ratio in panels (a) and (b) for different collision systems at RHIC [9,10,12–14,49] and at the LHC [18,21,50,51,70] as a function of $\langle dN_{ch}/d\eta \rangle^{1/3}$ and $\sqrt{s_{NN}}$, respectively. The K^{*0}/K ratio in heavy-ion collisions is smaller than those in pp collisions, with the results from p -Pb lying in between. The K^{*0}/K ratio decreases when the system size increases, as reflected by the values of $\langle dN_{ch}/d\eta \rangle^{1/3}$ (a proxy for system size [42]). To quantify the suppression of K^{*0}/K ratio in central Pb-Pb collisions with respect to pp collisions, we calculate the double ratio $(K^{*0}/K)_{PbPb}/(K^{*0}/K)_{pp}$. The K^{*0}/K double ratio in Pb-Pb collisions at 5.02 TeV (2.76 TeV) is 0.483 ± 0.082 (0.585 ± 0.122), which deviates from unity by 6.2 (3.4) times its standard deviation. The same ratio in Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV gives 0.571 ± 0.147 , which deviates from unity by 2.9 times its standard deviation. Figure 11(b) shows K^{*0}/K ratio as a function of $\sqrt{s_{NN}}$ for pp collisions, as well as for central p -Pb, Cu-Cu, Au-Au, and Pb-Pb collisions. The K^{*0}/K ratio is higher in pp collisions than in central Au-Au and Pb-Pb collisions at various center of mass energies. The value of the K^{*0}/K ratio is larger in central Cu-Cu than in central Au-Au collisions, as expected because of the smaller Cu-Cu system size.

Figures 11(c) and 11(d) show the ϕ/K ratio for different collision systems at RHIC [9,10,12–14,49] and LHC [18,21,50,51,70] as a function of $\langle dN_{ch}/d\eta \rangle^{1/3}$ and $\sqrt{s_{NN}}$,

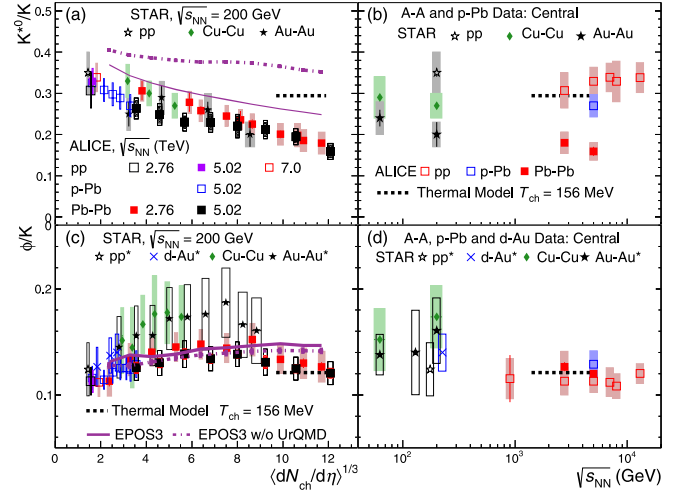


FIG. 11. Particle ratios K^{*0}/K [panels (a) and (b)] and ϕ/K [panels (c) and (d)] in pp , d-Au, p -Pb, Cu-Cu, Au-Au, and Pb-Pb collisions [9,10,12–14,18,21,49–51,70]. In panels (a) and (c) these ratios are presented as a function of $\langle dN_{ch}/d\eta \rangle^{1/3}$. These ratios are measured as K^{*0}/K^- and ϕ/K^- in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV and in STAR experiment. The values of $\langle dN_{ch}/d\eta \rangle_{|\eta|<0.5}$ were measured at midrapidity. In panels (b) and (d), these ratios are presented for pp , central d-Au, p -Pb, and heavy-ion collisions as a function of $\sqrt{s_{NN}}$. The values given by a grand-canonical thermal model with a chemical freezeout temperature of 156 MeV are also shown [39]. For quantities marked “*”, boxes represent the total uncertainty (separate uncertainties are not reported). Otherwise, bars represent the statistical uncertainties and boxes represent the systematic uncertainties (including centrality-uncorrelated and centrality-correlated components). EPOS3 model predictions [20] of K^{*0}/K and ϕ/K ratios in Pb-Pb collisions are also shown as violet lines.

respectively. In contrast to the K^{*0}/K ratio, the ϕ/K ratio is approximately constant as a function of $\langle dN_{ch}/d\eta \rangle^{1/3}$. The values of the ϕ/K ratio in Au-Au and Cu-Cu collisions are slightly larger than the corresponding results from Pb-Pb collisions, but agree within uncertainties. The ϕ/K ratio is found to be independent of collision energy and system from RHIC to LHC energies.

Figures 11(a) and 11(c) also show the K^{*0}/K and ϕ/K ratios from EPOS3 model calculations with and without a hadronic cascade phase modeled by UrQMD [20], and thermal model calculations with chemical freezeout temperature $T_{ch} = 156$ MeV [39]. The thermal or statistical hadronization model assumes that the system formed in heavy-ion collisions reaches thermal equilibrium through multiple interactions and undergoes a rapid expansion followed by the chemical freezeout. The freezeout surface is characterized by three parameters: the chemical freezeout temperature T_{ch} , the chemical potential μ and the fireball volume V . The value of the K^{*0}/K ratio in central Pb-Pb collisions is smaller than the thermal model expectation, however ϕ/K ratio is in fair agreement with the model calculations. The EPOS3 event generator is based on 3 + 1D viscous hydrodynamical evolution where the initial stage is treated via multiple scattering approach based on Pomerons and strings and the reaction

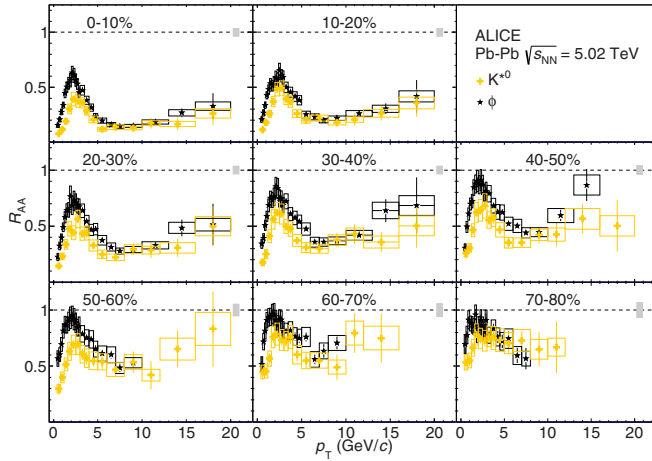


FIG. 12. The nuclear modification factor, R_{AA} , as a function of p_T for K^{*0} and ϕ mesons at midrapidity ($|y| < 0.5$) for different centrality classes in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The statistical and systematic uncertainties are shown as bars and boxes, respectively. The boxes around unity indicate the uncertainty on the normalization of R_{AA} .

volume is divided into two parts, “core” and “corona.” It is the core part that provides the initial condition for QGP evolution, described by viscous hydrodynamics. The corona part is composed of hadrons from the string decays. In EPOS3 + UrQMD approach [20], the hadrons separately produced from core and corona parts are fed into UrQMD [71,72], which describes the hadronic interactions in a microscopic approach. The chemical and kinetic freezeouts occur during this phase. The model predictions from EPOS3 and EPOS3 + UrQMD are shown for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. As the ratios are shown as a function of $\langle dN_{ch}/d\eta \rangle$, no significant qualitative differences are expected between the two energies. The observed trends of the K^{*0}/K and ϕ/K ratios are reproduced by the EPOS3 generator with UrQMD. However, EPOS3 model without hadronic interactions is unable to reproduce the suppression of K^{*0}/K ratios toward the higher $\langle dN_{ch}/d\eta \rangle^{1/3}$ values or central collisions.

E. Nuclear modification factor

The nuclear modification factor, R_{AA} , of K^{*0} and ϕ mesons are studied as a function of centrality and center-of-mass energy. The R_{AA} values of resonances are also compared to those of π , K , and p to investigate the hadron species dependence of R_{AA} .

1. Centrality dependence of the nuclear modification factor

The centrality dependence of R_{AA} helps in understanding the evolution of parton energy loss in the medium as a function of the system size. Figure 12 shows the R_{AA} for K^{*0} and ϕ mesons as a function of p_T for different centrality classes at midrapidity ($|y| < 0.5$) for Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The R_{AA} values are lower for K^{*0} compared to ϕ for $p_T < 5$ GeV/c for most of the collision centralities studied. This can be attributed to the dominance of rescattering effects

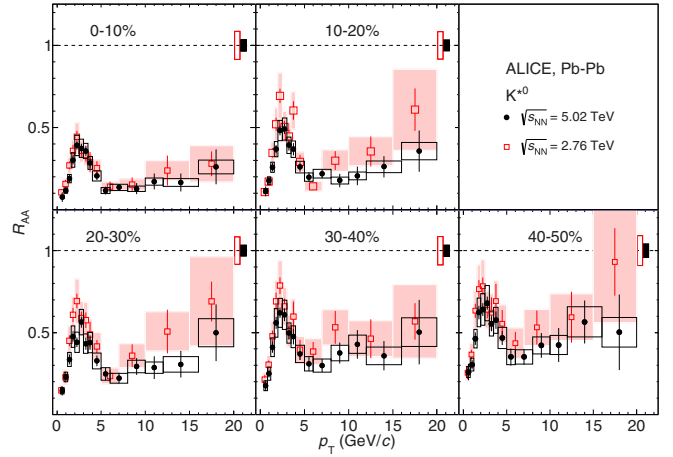


FIG. 13. The nuclear modification factor, R_{AA} , as a function of p_T for K^{*0} for different centrality classes in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV compared with the results from Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [21]. The statistical and systematic uncertainties are shown as bars and boxes, respectively. The boxes around unity indicate the respective uncertainty on the normalization of R_{AA} .

at lower p_T . At higher p_T (> 6 GeV/c) the R_{AA} values for K^{*0} and ϕ mesons are comparable within uncertainties. The R_{AA} values below unity at high p_T support the picture of a suppression of high p_T hadron production due to parton energy loss in the medium formed in heavy-ion collisions. For all the collision centralities studied, the R_{AA} values are below unity and the values increase for $p_T > 6$ GeV/c. The average R_{AA} values at high p_T (> 6 GeV/c) are found to decrease when going from peripheral to central collisions for both K^{*0} and ϕ mesons. The dependence of R_{AA} on collision centrality at high p_T provides information on the path length dependence of parton energy loss in the medium formed in high energy heavy-ion collisions [21,31,73–76]. This is reflected as a more pronounced suppression of R_{AA} in the most central collisions, as expected from the longer path length traversed by the hard partons as they lose energy via multiple interactions.

2. Center-of-mass energy dependence of the nuclear modification factor

Figure 13 (Figure 14) show the p_T -differential R_{AA} for the K^{*0} (ϕ) meson for five different collision centrality classes (0–10%, 10–20%, 20–30%, 30–40%, and 40–50%) in Pb-Pb collisions. The R_{AA} values for $\sqrt{s_{NN}} = 5.02$ TeV are compared to the corresponding values at $\sqrt{s_{NN}} = 2.76$ TeV. No significant differences are observed between 5.02 and 2.76 TeV for both the K^{*0} and ϕ resonances. This is supported by Figs. 4 and 6, which show that the ratios of p_T spectra of K^{*0} and ϕ at 5.02 TeV to that at 2.76 TeV are similar for both pp and Pb-Pb collisions. The results from Figs. 12–14 indicate that within uncertainties, the nuclear modification factor is independent of the resonance species at high p_T and compatible with measurements at $\sqrt{s_{NN}} = 2.76$ TeV for different centrality classes. However, the R_{AA} measurements of other mesonic and baryonic resonances like $\rho(770)^0$, $\Delta(1232)^{++}$, $\Sigma(1385)$, and

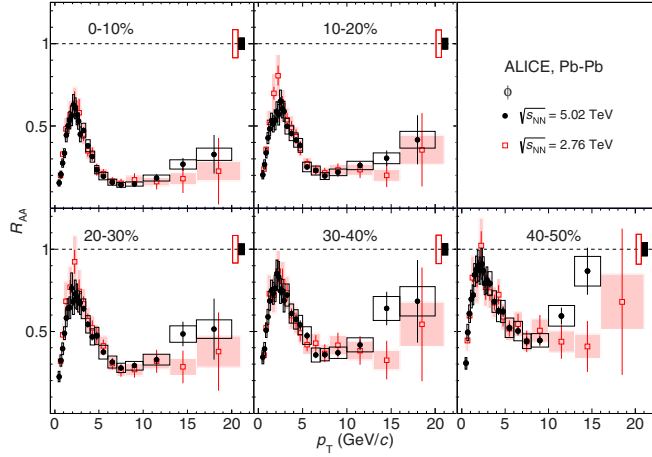


FIG. 14. The nuclear modification factor, R_{AA} , as a function of p_T for ϕ mesons in different centrality classes in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV compared with the results in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [21]. The statistical and systematic uncertainties are shown as bars and boxes, respectively. The boxes around unity indicate the uncertainty on the normalization of R_{AA} .

$\Lambda(1520)$ which differ in lifetime, mass, quark content, and particle type are required to further support these results.

3. Hadron species dependence of the nuclear modification factor

Figure 15 shows the hadron species dependence of R_{AA} for various collision centrality classes in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The hadron species considered here are charged pions, kaons, (anti)protons, K^{*0} and ϕ mesons. They vary in mass from about 140 to 1019 MeV, both baryons and mesons are considered, and their valence quark contents are also different. At low p_T (< 2 GeV/c), the K^{*0} R_{AA} val-

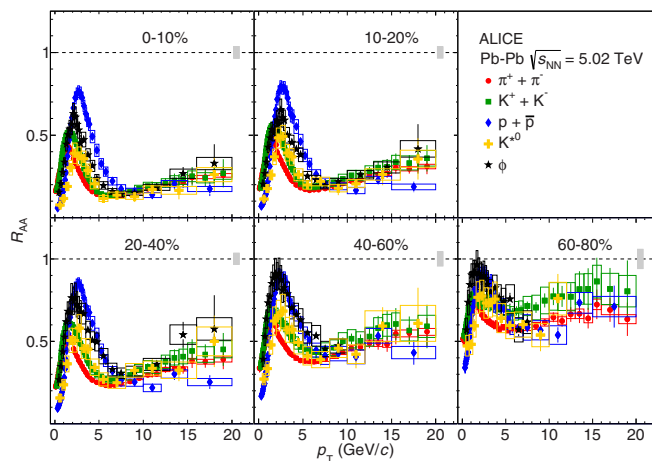


FIG. 15. The nuclear modification factor, R_{AA} , as a function of p_T for K^{*0} and ϕ mesons in Pb–Pb collisions for different centrality classes at $\sqrt{s_{NN}} = 5.02$ TeV. The results are compared with the R_{AA} values of π , K , and p measured by ALICE [27]. The statistical and systematic uncertainties are shown as bars and boxes, respectively. The boxes around unity indicate the uncertainty on the normalization of R_{AA} .

ues are the smallest for central collisions; this is attributed to the rescattering effect as discussed earlier in the article. For the p_T range 2–8 GeV/c, there appears to be a hadron mass dependence for mesons. It is also observed that R_{AA} of proton is higher than all mesons including ϕ . This indicates a baryon-meson ordering. So, even in the presence of strong radial flow in this p_T region, there are other effects which can affect R_{AA} . For p_T larger than 8 GeV/c, all the particle species show similar R_{AA} values within uncertainties for all the collision centralities studied. This suggests that, despite the varying degree of energy loss at different collision centralities, the relative particle composition at high p_T remains the same as in vacuum.

IV. CONCLUSIONS

The transverse momentum distributions of K^{*0} and ϕ mesons have been measured in inelastic pp and Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV using the ALICE detector. The measurements are carried out at midrapidity ($|y| < 0.5$) up to $p_T = 20$ GeV/c and for Pb–Pb collisions in various collision centrality classes.

The p_T distributions for K^{*0} and ϕ mesons in pp collisions are well described by a Lévy-Tsallis function and are compared to results from the PYTHIA6, PYTHIA8, EPOS-LHC, and HERWIG event generators. None of the models are able to describe the transverse momentum distributions of K^{*0} and ϕ in the measured p_T range. The $\langle p_T \rangle$ values are found to increase with $\langle dN_{ch}/d\eta \rangle_{|y| < 0.5}$, with the mass of the hadron and with $\sqrt{s_{NN}}$. These measurements are consistent with the observation that radial flow effects are larger for more central collisions and increased high- p_T production at higher collision energies.

The p_T -integrated particle ratios as a function of $\sqrt{s_{NN}}$ and $\langle dN_{ch}/d\eta \rangle^{1/3}$ in Pb–Pb and inelastic pp collisions have been compared. The K^{*0}/K and ϕ/K ratios as a function of $\sqrt{s_{NN}}$ and $\langle dN_{ch}/d\eta \rangle^{1/3}$ taken together indicate the dominance of the rescattering effect in the hadronic phase in Pb–Pb collisions. EPOS3 and thermal models that do not include hadronic interactions are unable to describe the suppression of K^{*0}/K ratio. EPOS3 + UrQMD, where the hadronic phase is described by the UrQMD model, is able to reproduce the decreasing trend of K^{*0}/K ratio as a function of multiplicity in the Pb–Pb collisions. In contrast, the ϕ/K ratios in Pb–Pb collisions are quite comparable to those from pp collisions, and agree well with all model calculations. The dissimilarity in the behavior of K^{*0}/K and ϕ/K ratios is dominantly attributed to the lifetime of K^{*0} , which is a factor of 10 smaller than the lifetime of the ϕ meson. Hence, K^{*0} decay daughters are subjected to a greater rescattering in the hadronic medium. The comparison of transverse momentum distributions of K^{*0} and ϕ in central Pb–Pb collisions with blast-wave predictions, which does not include rescattering effects, show a suppression of K^{*0} yield for $p_T < 3$ GeV/c.

At low p_T (< 5 GeV/c), the nuclear modification factor values for K^{*0} are lower with respect to those obtained for ϕ mesons, chiefly because of rescattering effects. The R_{AA} values at high p_T (> 6 –8 GeV/c) for K^{*0} and ϕ mesons are comparable within uncertainties. The average R_{AA} values

at high p_T are found to decrease when going from peripheral to central collisions. The R_{AA} values at high p_T for K^{*0} and ϕ mesons at $\sqrt{s_{NN}} = 5.02$ TeV are comparable to the corresponding measurements at $\sqrt{s_{NN}} = 2.76$ TeV for most of the collision centralities studied. At the same time, the transverse momentum spectra at high p_T in both pp and Pb-Pb collisions are found to be higher by a factor of about 1.8 at $\sqrt{s_{NN}} = 5.02$ TeV compared to $\sqrt{s_{NN}} = 2.76$ TeV. Further, we find that the R_{AA} values at high p_T for the hadrons π , K , K^{*0} , p , and ϕ are similar within uncertainties for all the collision centrality classes studied. This suggests that the energy loss in the medium which leads to the suppression does not modify the particle composition in the light quark sector.

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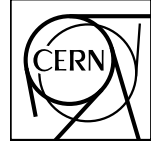
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Multiplicity and rapidity dependence of $K^*(892)^0$ and $\phi(1020)$ production in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

ALICE Collaboration

Abstract

The transverse-momentum (p_T) spectra of $K^*(892)^0$ and $\phi(1020)$ measured with the ALICE detector up to $p_T = 16$ GeV/ c in the rapidity range $-1.2 < y < 0.3$, in p–Pb collisions at the center-of-mass energy per nucleon–nucleon collision $\sqrt{s_{NN}} = 5.02$ TeV are presented as a function of charged particle multiplicity and rapidity. The measured p_T distributions show a dependence on both multiplicity and rapidity at low p_T whereas no significant dependence is observed at high p_T . A rapidity dependence is observed in the p_T -integrated yield (dN/dy), whereas the mean transverse momentum ($\langle p_T \rangle$) shows a flat behavior as a function of rapidity. The rapidity asymmetry (Y_{asym}) at low p_T (< 5 GeV/ c) is more significant for higher multiplicity classes. At high p_T , no significant rapidity asymmetry is observed in any of the multiplicity classes. Both $K^*(892)^0$ and $\phi(1020)$ show similar Y_{asym} . The nuclear modification factor (Q_{CP}) as a function of p_T shows a Cronin-like enhancement at intermediate p_T , which is more prominent at higher rapidities (Pb-going direction) and in higher multiplicity classes. At high p_T (> 5 GeV/ c), the Q_{CP} values are greater than unity and no significant rapidity dependence is observed.

1 Introduction

The primary goals of high-energy heavy-ion (A–A) collisions are to create a system of deconfined quarks and gluons known as quark–gluon plasma (QGP) and to study its properties [1–4]. Asymmetric collision systems like proton–nucleus (p–A) and deuteron–nucleus (d–A) can be considered as control experiments where the formation of an extended QGP phase is not expected. These collision systems are used as baseline measurements to study the possible effects of cold nuclear matter and disentangle the same from hot dense matter effects produced in heavy-ion collisions [5–14]. In addition, p–A collisions at Large Hadron Collider (LHC) energies enable probing the parton distribution functions in nuclei at very small values of the Bjorken x variable, where gluon saturation effects may occur [15–17]. Recent measurements in high-multiplicity pp, p–Pb, p–Au, d–Au, and ^3He –Au collisions at different energies have shown features such as anisotropies in particle emission azimuthal angles, strangeness enhancement, and long-range structures in two-particle angular correlations on the near and away side, which previously have been observed in nucleus–nucleus collisions [18–29]. The origin of these phenomena in small systems is not yet fully understood. A systematic study of multiplicity and rapidity dependence of hadron production allows us to investigate the mechanism of particle production and shed light on the physics processes that contribute to the particle production [15]. Similar studies have been reported by the experiments at the LHC [9, 10, 16, 17] and Relativistic Heavy Ion Collider (RHIC) [6, 7, 19–21]. The mechanism of hadron production may be influenced by different effects such as nuclear modification of the parton distribution functions (nuclear shadowing) and possible parton saturation, multiple scattering, and radial flow [16, 30–32]. These effects are expected to depend on the rapidity of the produced particles. In p–Pb collisions, one can expect that the production mechanism may be sensitive to different effects at forward (p-going) and backward (Pb-going) rapidities [9, 10, 16, 17, 32, 33]. The partons of the incident proton are expected to undergo multiple scattering while traversing the Pb-nucleus. It is thus interesting to study the ratio of particle yields between Pb- and p-going directions, represented by the rapidity asymmetry (Y_{asym}) defined as:

$$Y_{\text{asym}}(p_T) = \frac{\left. \frac{d^2N}{dp_T dy} \right|_{-0.3 < y < 0}}{\left. \frac{d^2N}{dp_T dy} \right|_{0 < y < 0.3}} \quad (1)$$

where $d^2N/dp_T dy|_{-0.3 < y < 0}$ is the particle yield in the rapidity (y) interval $-0.3 < y < 0$, considered as the Pb-going direction, and $d^2N/dp_T dy|_{0 < y < 0.3}$ is the particle yield in the rapidity interval $0 < y < 0.3$, corresponding to the p-going direction. From the experimental point of view, the Y_{asym} is a powerful observable because systematic uncertainties cancel out in the ratio and hence it can better discriminate rapidity-dependent effects among models [16–18]. Gluon saturation effects at low Bjorken x values [7, 18] may affect the transverse momentum distribution of hadron production at large rapidities in the p-going direction in p–Pb collisions at LHC energies. The gluon saturation effects depend on the colliding nuclei and rapidity as $A^{1/3}e^{\lambda y}$, where A represents the mass number [18], and λ is a parameter whose value lies between 0.2 and 0.3, and is obtained from fits to the HERA measurements [8]. The effect of rapidity dependence on particle production is tested by measuring the ratios of integrated yield (dN/dy) and mean transverse momentum ($\langle p_T \rangle$) at given y to the values at $y = 0$, i.e. denoted as $(dN/dy)/(dN/dy)_{y=0}$ and $\langle p_T \rangle / \langle p_T \rangle_{y=0}$. It is also important to study the variation with rapidity of the nuclear modification factor between central and non-central collisions. This factor ($Q_{\text{CP}}(p_T)$) is defined as

$$Q_{\text{CP}}(p_T) = \frac{\left. \frac{d^2N}{dp_T dy} \right|_{\text{HM}}}{\langle N_{\text{coll}} \rangle} \bigg/ \frac{\left. \frac{d^2N}{dp_T dy} \right|_{\text{LM}}}{\langle N_{\text{coll}} \rangle}, \quad (2)$$

where $\langle N_{\text{coll}} \rangle$ is the average number of nucleon–nucleon collisions in low-multiplicity (LM) and high-multiplicity (HM) events, respectively. The multiplicity dependence of K^{*0} and ϕ meson production at

midrapidity was studied in pp, p-Pb, and Pb-Pb collisions at LHC energies and reported in Refs. [14, 26, 27, 34]. The lifetime of the K^{*0} meson is about 4 fm/c, which is comparable to the lifetime of the hadronic phase. In contrast, the lifetime of the ϕ meson is 10 times higher. The K^{*0} and ϕ mesons are thus useful probes of the late-stage evolution of high-energy hadronic collisions. As they have similar mass but differ in their strangeness content by one unit, they are suitable candidates to understand the modification of particle production due to rescattering effects and the role of the strangeness content, as discussed in Refs. [26, 28, 29, 34].

This article reports the first measurements of the rapidity dependence of $K^*(892)^0$ and $\phi(1020)$ mesons production in p-Pb collisions at center-of-mass energy per nucleon–nucleon collisions at $\sqrt{s_{NN}} = 5.02$ TeV by the ALICE experiment at the LHC. The large size of the data sample and the excellent particle identification (PID) provide opportunities to extend these measurements in a wider rapidity interval and multiplicity classes compared to earlier measurements [23, 24, 26–29]. This enables the investigation of the nuclear effects on the particle production in p-Pb collisions. The p_T spectra, $Y_{\text{asym}}(p_T)$ and $Q_{\text{CP}}(p_T)$ are studied in the rapidity range $-1.2 < y < 0.3$ and three multiplicity classes along with a measurement on the multiplicity-integrated sample. Similar measurements for charged particles and strange hadrons at RHIC and the LHC energies were reported in Refs. [7, 16, 18].

The measurements presented here are compared with various model predictions such as EPOS-LHC [35], EPOS3 with and without UrQMD [36–39], DPMJET [40], HIJING [41] and PYTHIA8/Angantyr [42]. EPOS-LHC is an event generator for minimum-bias hadronic interactions that incorporates a parameterization of flow based on LHC data [35]. It is an event generator based on multiple partonic scatterings described using Gribov’s Reggeon field theory formalism, supplemented with collective hadronization and the core-corona mechanism from pp to A–A collisions [35]. EPOS3 is an event generator based on 3+1D viscous hydrodynamical evolution in the Gribov-Regge multiple scattering framework, which is used to understand hadronic resonances and their interactions in the partonic and hadronic medium. The UrQMD model introduces the description of rescattering and regeneration effects in the hadronic phase [36, 38, 39]. DPMJET is a QCD-inspired dual parton model based on the formalism of the Gribov-Glauber approach that treats the soft- and hard- scattering interactions differently [40]. HIJING is used to study jet and the associated particle production in high energy collisions and is based on QCD-inspired models, including multiple minijet production, soft excitation, nuclear shadowing of parton distribution functions, and jet interaction in dense matter. Due to nuclear shadowing, the parton distribution functions of quarks and gluons are expected to differ from the simple superposition of their distribution in a nucleon. The initial nuclear shadowing effect on particle production is tested using two shadowing depth constant values 0.1 and 0 that represent the HIJING model predictions with and without shadowing [41]. PYTHIA8/Angantyr is an event generator based on the Fritiof model [43], which includes the features of multi-parton interactions and diffractive excitation in each nucleon–nucleon (NN) sub-collision. It acts as a baseline for understanding the non-collective background in the observables sensitive to collective behavior, as PYTHIA8 does not include a collective expansion stage in its description of pp collisions [42]. The comparison of data with the results from these phenomenological models helps to understand the relative contribution of the nuclear effects on the particle production in p-Pb collisions.

For the results presented here, $K^*(892)^0$ and $\bar{K}^*(892)^0$ are averaged and denoted by the symbol K^{*0} , while $\phi(1020)$ is denoted by ϕ . The article is organized as follows. In Section 2, the data sample, event and track selection criteria, the analysis techniques, the procedure of extraction of the yields, and the study of the systematic uncertainties are discussed. In Section 3, the results on the p_T spectra, the dN/dy , the $\langle p_T \rangle$, the Y_{asym} and the Q_{CP} in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV are presented. Finally, the results are summarized in Section 4.

2 Data analysis

Measurements of K^{*0} and ϕ meson production are carried out on the data sample collected in 2016 during the second LHC run with p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The resonances are reconstructed from their decay products by using the invariant-mass method. The considered decay channels are $K^{*0} \rightarrow K^+\pi^-$ and its charge conjugate, and $\phi \rightarrow K^+K^-$ with respective branching ratios (BR) of 66.6 % and 49.2 % [26, 27]. In the p-Pb configuration, the ^{208}Pb beam with energy of 1.58 TeV per nucleon collides with a proton beam with an energy of 4 TeV resulting in collisions at a nucleon-nucleon center-of-mass energy $\sqrt{s_{NN}} = 5.02$ TeV [26]. It leads to the rapidity in the center-of-mass frame being shifted by $\Delta y = -0.465$ in the direction of the proton beam with respect to the laboratory frame. The measurements are performed in the rapidity range $-1.2 < y < 0.3$ for five rapidity intervals with width of 0.3 units and three multiplicity classes along with a multiplicity-integrated class. The details of the ALICE detector setup and its performance can be found in Refs. [44, 45]. The measurements are carried out with the ALICE central barrel detectors, which are utilized for tracking, PID, and primary vertex reconstruction and are housed inside a solenoidal magnet with a magnetic field of 0.5 T. The main detectors that are used for the analyses presented here are the Inner Tracking System (ITS) [46], the Time Projection Chamber (TPC) [47], and the TOF (Time-Of-Flight) [48] detectors. These detectors have full azimuthal coverage and have a common pseudorapidity coverage of $|\eta| < 0.9$.

2.1 Event and track selection and particle identification

The trigger and event selection criteria are the same as those discussed in previous publications [26, 27]. The events are selected with a minimum-bias trigger based on the coincidence of signals in two arrays of 32 scintillator detectors covering full azimuth and the pseudorapidity regions $2.8 < \eta < 5.1$ (V0A) and $-3.7 < \eta < -1.7$ (V0C) [49]. The primary vertex of the collision is determined using the charged tracks reconstructed in the ITS and the TPC. Events are selected whose reconstructed primary vertex position lies within ± 10 cm from the center of the detector along the beam direction. The Silicon Pixel Detector (SPD) which is the innermost detector of the ITS, is used to reject events in which multiple collision vertices are found (pile-up) [46]. In this work, approximately 540 million events are selected with the criteria described above. The minimum-bias events are further divided into three multiplicity classes, which are expressed in percentiles according to the total charge deposited in the V0A detector [49]. The yield of K^{*0} and ϕ mesons is measured in five rapidity regions $-1.2 < y < -0.9$, $-0.9 < y < -0.6$, $-0.6 < y < -0.3$, $-0.3 < y < 0$ and $0 < y < 0.3$ for the multiplicity classes 0–10%, 10–40%, 40–100% in addition to the multiplicity-integrated (0–100%) measurement, corresponding to all minimum-bias events. The 10% of the events with the highest multiplicity of charged particles correspond to the 0–10% class and similarly, the 40–100% class corresponds to the lowest multiplicity. The $\langle N_{\text{coll}} \rangle$ values are estimated from a Glauber model analysis [50] of the charged particle multiplicity distribution in the V0A detector, and they are 13.8 ± 3.8 , 10.5 ± 3.9 and 4.0 ± 2.6 , respectively for 0–10%, 10–40%, and 40–100% multiplicity classes taken from Ref. [51]. Charged-particle tracks reconstructed in the TPC with $p_T > 0.15$ GeV/c and pseudorapidity $|\eta| < 0.8$ are selected for the analysis. The selected charged tracks should have crossed at least 70 out of 159 readout-pad rows of the TPC. The distance of closest approach of the track to the primary vertex in the longitudinal direction (DCA_z) is required to be less than 2 cm. In the transverse plane (xy) a p_T -dependent selection of $\text{DCA}_{xy}(p_T) < 0.0105 + 0.035 p_T^{-1.1}$ cm is applied. The K^{*0} and ϕ mesons are reconstructed from their decay daughters (pions and kaons), which are identified by measuring the specific ionization energy loss (dE/dx) in the TPC [47] and their time-of-flight information using the TOF [48]. For the selection of pions and kaons, the measured $\langle dE/dx \rangle$ is required to be within $n\sigma_{\text{TPC}}$ from the expected $\langle dE/dx \rangle$ values for a given mass hypothesis, where σ_{TPC} is the TPC $\langle dE/dx \rangle$ resolution. The values of n are momentum-dependent (p) and are set to $6\sigma_{\text{TPC}}$, $3\sigma_{\text{TPC}}$, and $2\sigma_{\text{TPC}}$ in the momentum intervals $p < 0.3$ GeV/c, $0.3 < p < 0.5$ GeV/c and $p > 0.5$ GeV/c, respectively. If the TOF information is available for the considered tracks, it is used for pion and kaon identification in addition to the TPC one by

requiring the time-of-flight of the particle to be within $3\sigma_{\text{TOF}}$ from the expected value for the considered mass hypothesis, where σ_{TOF} is the time-of-flight resolution of the TOF.

2.2 Yield extraction

The K^{*0} and ϕ resonances are reconstructed from their decay products using the invariant-mass reconstruction technique described in Refs. [26, 27]. The invariant-mass distributions of $K^\pm\pi^\mp$ and K^+K^- pairs in the same event are reconstructed. The shape of uncorrelated background is estimated using two techniques, namely mixed-event and like-sign methods. In the mixed-event method, the shape of the uncorrelated-background distribution for K^{*0} (ϕ) is obtained by combining pions (kaons) from a given event with opposite-sign kaons from other events. Each event is mixed with five different events to reduce the statistical uncertainties of the estimated uncorrelated-background distribution. The events which are mixed are required to have similar characteristics, i.e. the longitudinal position of the primary vertices should differ by less than 1 cm, and the multiplicity percentiles, computed from the V0A amplitude, should differ by less than 5%. The mixed-event distributions for K^{*0} (ϕ) candidates are normalized in the invariant mass interval $1.1 < M_{K\pi} < 1.15$ GeV/c^2 ($1.06 < M_{KK} < 1.09$ GeV/c^2), which is well separated from signal peak.

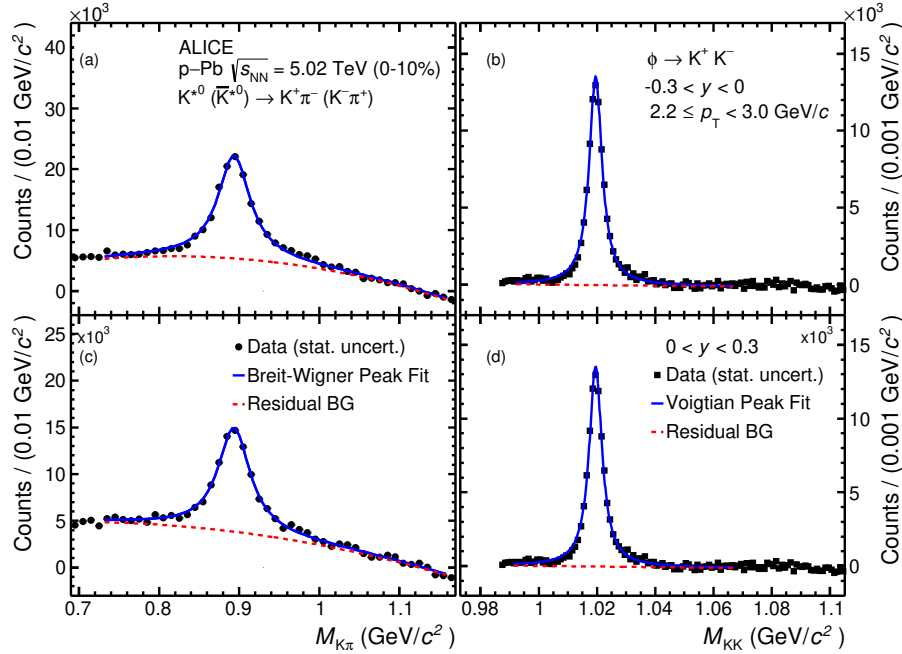


Figure 1: Invariant-mass distributions after combinatorial background subtraction for K^{*0} and ϕ candidates in the multiplicity class 0–10% and transverse momentum range $2.2 \leq p_T < 3.0$ GeV/c in the rapidity interval $-0.3 < y < 0$ (panels (a) and (b)) and $0 < y < 0.3$ (panels (c) and (d)). The K^{*0} peak is described by a Breit-Wigner function whereas the ϕ peak is fitted with a Voigtian function. The residual background is described by a polynomial function of order 2.

In the like-sign method, tracks with the same charge from the same event are paired to estimate the uncorrelated background contribution. The invariant-mass distribution for the uncorrelated background is obtained as the geometric mean $2\sqrt{n^{++} \times n^{--}}$, where n^{++} and n^{--} are the number of positive-positive and negative-negative pairs in each invariant-mass interval, respectively. The mixed-event technique is used as the default method to extract the yields for both K^{*0} and ϕ mesons, while the difference with

respect to the yield obtained using the combinatorial background from the like-sign method is included in the estimation of the systematic uncertainty. After the subtraction of the combinatorial background, the invariant-mass distribution consists of a resonance peak sitting on the top of a residual background of correlated pairs. The residual background originates from correlated pairs from jets, misidentification of pions and kaons from K^{*0} and ϕ meson decays, and partially reconstructed decays of higher-mass particles [26]. Figure 1 shows the $K^\pm\pi^\mp$ and K^+K^- invariant-mass distributions after subtraction of mixed-event background in the transverse momentum interval $2.2 \leq p_T < 3.0$ GeV/c for the rapidity intervals $-0.3 < y < 0$ (panels (a) and (b)) and $0 < y < 0.3$ (panels (c) and (d)) in the 0–10% multiplicity class.

The signal peak is fitted with a Breit-Wigner and a Voigtian function (convolution of Breit-Wigner and Gaussian functions) for K^{*0} and ϕ resonances, respectively. For the K^{*0} , a pure Breit-Wigner is used because the invariant mass resolution is negligible with respect to the natural width of the resonance peak. A second-order polynomial function is used to describe the shape of the residual background for both resonances. The fit to the invariant-mass distribution is performed in the interval $0.75 < M_{K\pi} < 1.15$ GeV/c² ($0.99 < M_{KK} < 1.07$ GeV/c²) for $K^{*0}(\phi)$. The widths of K^{*0} and ϕ peaks are fixed to their known widths $\Gamma(K^{*0}) = 47.4 \pm 0.6$ MeV/c², $\Gamma(\phi) = 4.26 \pm 0.04$ MeV/c² [52], whereas the resolution parameter of the Voigtian function for ϕ is kept as a free parameter. In the estimation of the systematic uncertainties, the width of the Breit-Wigner is taken as a free parameter. The mass and width values extracted from the fit have similar magnitude and trend with p_T as reported in previous publications [26, 27, 34, 53]. In the present study, it is found that the mass and width obtained from the fit are independent of rapidity and multiplicity for both K^{*0} and ϕ mesons. The sensitivity of the systematic uncertainty to the choice of the fitting range, normalization interval of the mixed-event background, shape of the residual background function, width, and resolution parameters have been studied by varying the fit configuration, as described in Section 2.3. The raw yields of K^{*0} and ϕ mesons are extracted in the transverse momentum range from 0.8 to 16 GeV/c for various rapidity intervals and multiplicity classes.

To obtain the transverse momentum spectra, the raw yields are normalized by the number of accepted non-single-diffractive (NSD) events and corrected for the branching ratio and the detector acceptance (A) times the reconstruction efficiency (ϵ_{rec}). The $A \times \epsilon_{\text{rec}}$ is obtained from a Monte Carlo (MC) simulation based on the DPMJET [40] event generator and the GEANT3 package to model the transport of the generated particles through the ALICE detector [54]. The $A \times \epsilon_{\text{rec}}$ is defined as the ratio of the reconstructed p_T spectra of $K^{*0}(\phi)$ mesons in a given rapidity interval to the generated ones in the same rapidity interval. The track and PID selection criteria applied to the decay products of resonances in the MC are identical to those used in the data. Since the efficiency depends on p_T and the p_T distributions of K^{*0} and ϕ mesons from DPMJET are different from the real data, a re-weighting procedure is applied to match the generated p_T shapes to the measured ones.

The effect of the re-weighting on $A \times \epsilon_{\text{rec}}$ depends on p_T and amounts to $\sim 5\text{--}17\%$ at $p_T < 1.5$ GeV/c. At higher p_T , the effect is negligible. The effect of re-weighting also depends on rapidity at low p_T . The re-weighted $A \times \epsilon_{\text{rec}}$ is used to correct the raw p_T distribution. The $A \times \epsilon_{\text{rec}}$ is calculated for each rapidity interval and multiplicity class considered in the analysis. The $A \times \epsilon_{\text{rec}}$ as a function of p_T shows a rapidity dependence for a given multiplicity class, however, no significant multiplicity dependence of $A \times \epsilon_{\text{rec}}$ is observed for a given rapidity interval.

2.3 Systematic uncertainties

The procedure to estimate the systematic uncertainties is similar to the one adopted in previous analyses [26, 27]. The sources of systematic uncertainties on the measured yield of K^{*0} and ϕ mesons are signal extraction, track selection criteria, PID, global tracking efficiency, uncertainty on the material budget of the ALICE detector, and the hadronic interaction cross section in the detector material. A summary of the systematic uncertainties on the p_T spectra is given in Table 1. The uncertainty due to signal extraction is estimated from the variation of the yields when varying the invariant mass fit range,

Table 1: Relative systematic uncertainties for K^{*}0 and ϕ yields in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The quoted relative uncertainties are averaged over p_T in the range 0.8–16 GeV/c. The total systematic uncertainty is the sum in quadrature of the uncertainties due to each source.

Systematic uncertainty	K [*] 0	ϕ
Yield extraction (%)	5.2	3.3
Track selection (%)	2.5	5.0
Particle identification (%)	3.0	1.7
Global tracking efficiency (%)	3.0	2.1
Material budget (%)	1.2	2.2
Hadronic Interaction (%)	1.9	2.4
Total (%)	7.5	7.3

the treatment of the Breit-Wigner width in the fits, the mixed-event background normalization interval, the choice of residual background function, and the method to determine the combinatorial background. The fitting range is varied by 50 MeV/c² for K^{*}0 and 10 MeV/c² for ϕ . The normalization interval of the mixed-event background is varied by 150 (50) MeV/c² with respect to the default value for K^{*}0 (ϕ). The width of K^{*}0 and ϕ resonances is left as a free parameter in the fit, instead of fixing it to the world-average value. For ϕ resonances, the effect on the yield due to the variation of resolution parameter (σ of the Gaussian function in the Voigtian distribution) is also considered. The residual background is parameterized using first-order and third-order polynomial functions for estimating its contributions to the systematic uncertainties. The combinatorial background from the like-sign method is used instead of the one from event mixing. The estimated systematic uncertainties due to the yield extraction is 5.2% for K^{*}0 and 3.3% for ϕ . The systematic effects due to charged track selection have been studied by varying the selection criteria on the number of crossed rows in the TPC, the ratio of the numbers of TPC crossed rows to findable clusters, and the DCA to the primary vertex of the collisions. The estimated uncertainties due to the track selection is 2.5% for K^{*}0 and about 5% for the ϕ mesons. To estimate the systematic uncertainty due to the PID, the selections on the dE/dx and time-of-flight of the pions and kaons are varied. Two momentum-independent selections: $2\sigma_{\text{TPC}}$ with $3\sigma_{\text{TOF}}$ and $2\sigma_{\text{TPC}}$ only, are used for both K^{*}0 and ϕ . The estimated systematic uncertainties are 3% for K^{*}0 and 1.7% for ϕ . The uncertainty due to the global tracking efficiency, description of the detector material budget in the simulation, and the cross sections for hadronic interactions in the material are taken from Ref. [26]. The total systematic uncertainty is taken as the quadratic sum of all contributions leading to 7.5% for K^{*}0 and 7.3% for ϕ mesons. No multiplicity and rapidity dependence of the systematic uncertainties is observed. Therefore, the systematic uncertainties on the p_T spectra determined for minimum-bias events in the rapidity interval $0 < y < 0.3$ are assigned in all rapidity intervals and multiplicity classes.

The systematic uncertainties on Y_{asym} are estimated by considering the same approaches and variations as for the corrected yields. The systematic uncertainties due to signal extraction and PID are uncorrelated among different rapidity intervals whereas the other sources of systematic uncertainties such as track selections, global tracking uncertainties, material budget and hadronic interactions are correlated and cancel out in the Y_{asym} ratio. For the uncorrelated sources of uncertainty, the same variations considered for the yields were studied by estimating their effects on the Y_{asym} ratio. The resulting uncertainty was estimated to be about 2.5% (2%) for K^{*}0 (ϕ) mesons. No multiplicity and rapidity dependence of the uncertainties is observed for Y_{asym} . Therefore, the systematic uncertainties determined for minimum-bias events are assigned to the ratios in the different rapidity intervals and multiplicity classes. The systematic uncertainties on the ratios $(dN/dy)/(dN/dy)_{y=0}$ and $\langle p_T \rangle / \langle p_T \rangle_{y=0}$ as a function of rapidity are calculated in a similar way as for Y_{asym} . The systematic uncertainties on $(dN/dy)/(dN/dy)_{y=0}$ and $\langle p_T \rangle / \langle p_T \rangle_{y=0}$ are 2.2% (2%) and 1.2% (1%) for K^{*}0 (ϕ), respectively.

3 Results and discussion

The rapidity and multiplicity dependence results on the p_T spectra, the dN/dy , the $\langle p_T \rangle$, the Y_{asym} , and the Q_{CP} in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV are discussed. The measurements are also compared with various model predictions.

3.1 Transverse momentum spectra

Figure 2 and Fig. 3 show the p_T spectra of K^{*0} and ϕ mesons in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for five rapidity intervals within $-1.2 < y < 0.3$ and for two multiplicity classes 0–10% and 40–100%, respectively. The ratios of the p_T spectra in different rapidity intervals to that in the interval $0 < y < 0.3$ are presented in the bottom panels of Fig. 2 and Fig. 3. The measured p_T spectra of K^{*0} and ϕ mesons in the 0–10% multiplicity class show a rapidity dependence at low p_T (< 5 GeV/c) indicating that the production of these resonances is higher in the Pb-going direction ($y < 0$) than in the p-going direction ($y > 0$). For high p_T , no rapidity dependences are observed.

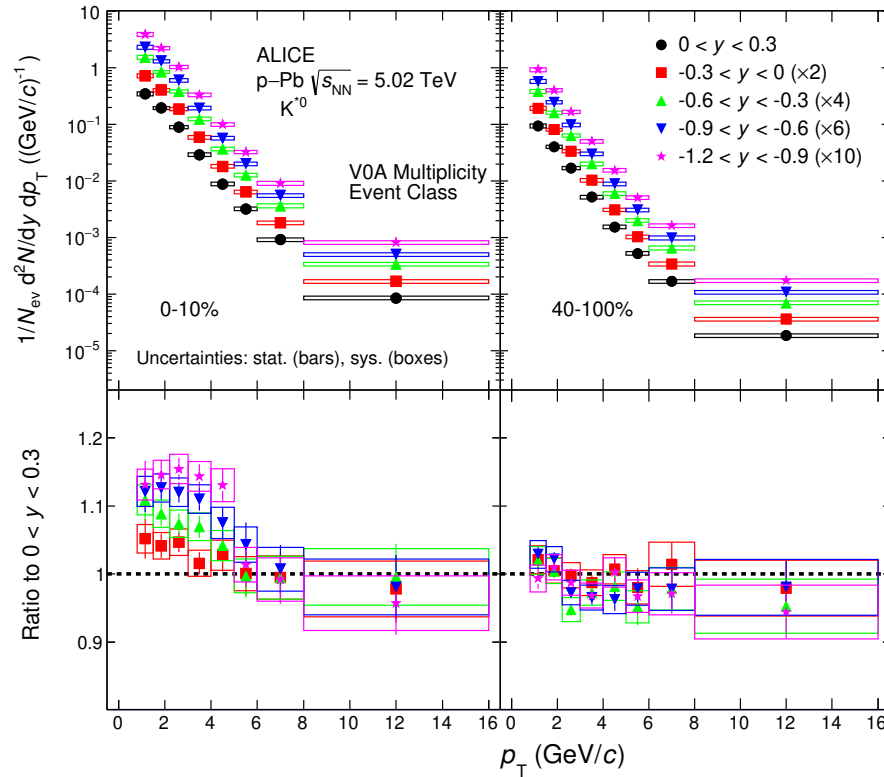


Figure 2: Top panels: The transverse momentum spectra of K^{*0} for five rapidity intervals within $-1.2 < y < 0.3$ and for two multiplicity classes (0–10%, 40–100%) in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The data for different rapidity intervals are scaled for better visibility. Bottom panels: The ratios of the p_T spectra in various rapidity intervals to that in the interval $0 < y < 0.3$ for a given multiplicity class. The statistical and systematic uncertainties are shown as bars and boxes around the data points, respectively.

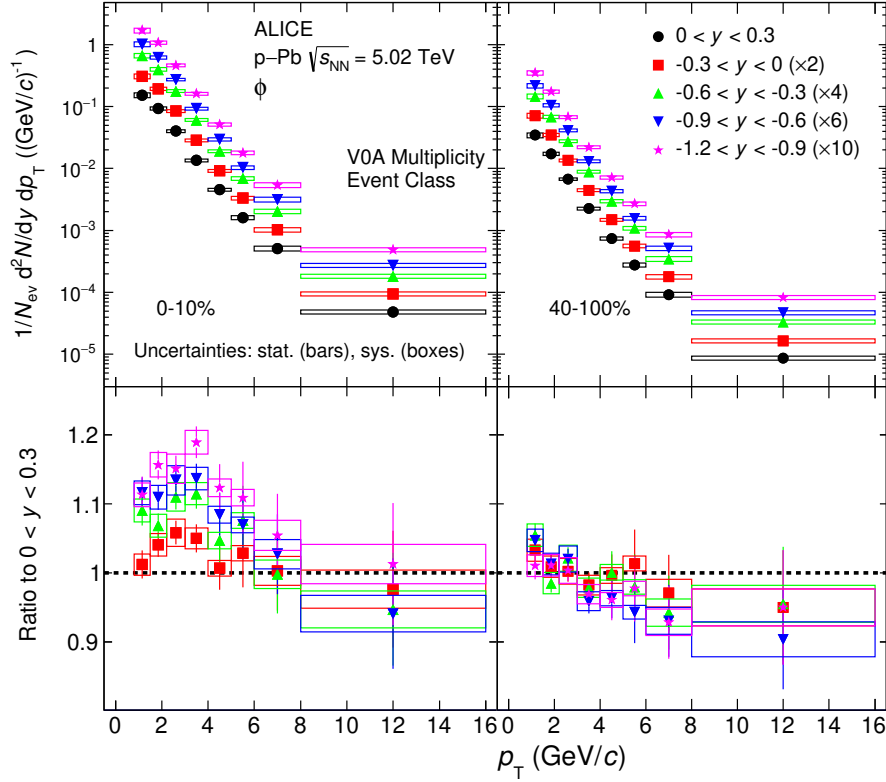


Figure 3: Top panels: The transverse momentum spectra of ϕ for five rapidity intervals within $-1.2 < y < 0.3$ and for two multiplicity classes (0–10%, 40–100%) in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The data for different rapidity intervals are scaled for better visibility. Bottom panels: The ratios of the p_T spectra in various rapidity intervals to that in the interval $0 < y < 0.3$ for a given multiplicity class. The statistical and systematic uncertainties are shown as bars and boxes around the data points, respectively.

3.2 Integrated particle yield and mean transverse momentum

The dN/dy and the $\langle p_T \rangle$ are obtained from the transverse momentum spectra in the measured p_T interval and using a fit function to account for the contribution of K^{*0} and ϕ mesons in unmeasured regions. The spectra are fitted with a Lévy-Tsallis function [55] and the fit function is extrapolated to unmeasured regions at low p_T (< 0.8 GeV/c). The integral of the fit function in the extrapolated region accounts for 33% (39%) of the total yield in the 0–10% (40–100%) multiplicity class for both K^{*0} and ϕ mesons. The contribution of the extrapolated yield at low p_T is the same for all rapidity intervals. The contribution of the yield in the unmeasured region at high p_T (> 16 GeV/c) is negligible for both K^{*0} and ϕ mesons. The extrapolated yield contribution at low p_T obtained with different fitting functions (i.e., m_T -exponential, Bose-Einstein and Boltzmann-Gibbs Blast-Wave function [56]) and that obtained with the default Lévy-Tsallis function is 5% (8%) for the 0–10% (40–100%) included as the systematic uncertainties in the dN/dy and it varies by 2–5 % for the $\langle p_T \rangle$. In Fig. 4 the dN/dy (top panels) and $\langle p_T \rangle$ (bottom panels) of K^{*0} (left) and ϕ (right) mesons are shown as a function of y for minimum-bias p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The central values of the dN/dy of both K^{*0} and ϕ mesons decrease slightly from the rapidity interval $-1.2 < y < -0.9$ to $0 < y < 0.3$ even though within the systematic uncertainties all the data points are compatible among each other. Nevertheless, considering that the systematic uncertainties are mostly correlated among the rapidity intervals, the measured dN/dy values suggest a decreasing trend with increasing y in the rapidity interval covered by the measurement. The $\langle p_T \rangle$ is constant as a function

of rapidity for both K^{*0} and ϕ resonances.

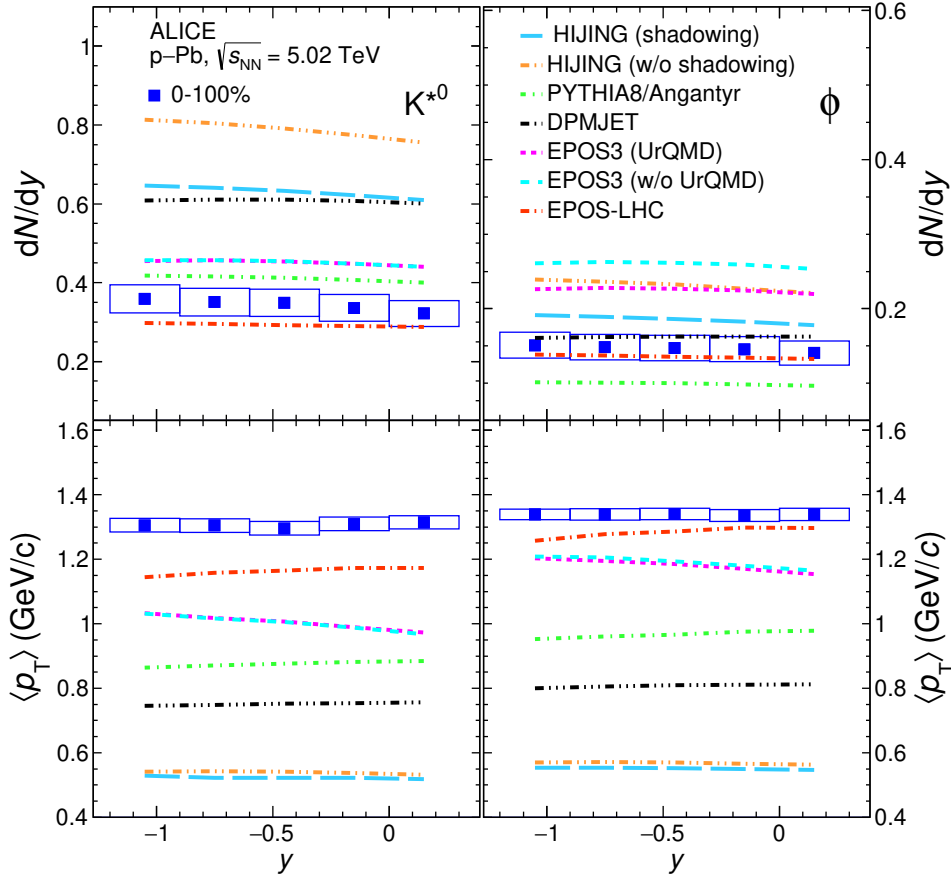


Figure 4: The p_T integrated yield (dN/dy) (top panels) and mean transverse momentum ($\langle p_T \rangle$) (bottom panels) for K^{*0} (left) and ϕ (right) mesons as a function of y measured for the multiplicity class 0-100% in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The predictions from EPOS-LHC [35], EPOS3 with and without UrQMD [38, 39], DPMJET [40], HIJING [41], and PYTHIA8/Angantyr [42] are shown as different curves. The statistical uncertainties are represented as bars whereas the boxes indicate total systematic uncertainties.

The model predictions from EPOS-LHC [35], EPOS3 with and without UrQMD [38, 39], DPMJET [40], HIJING [41], and PYTHIA8/Angantyr [42] are also shown in the Fig. 4. In general, the models show a similar trend with rapidity as the data except EPOS3 with and without UrQMD for $\langle p_T \rangle$, which shows a pronounced decreasing trend with rapidity. All the model predictions shown in Fig. 4 underestimate the $\langle p_T \rangle$ of both meson species. For the dN/dy , HIJING and EPOS3 with and without UrQMD overpredict the measured values for both K^{*0} and ϕ , while PYTHIA8/Angantyr overpredicts the K^{*0} and underpredicts the ϕ yield. EPOS-LHC provides the best overall description of the dN/dy and $\langle p_T \rangle$ measurements for K^{*0} and ϕ mesons. The $\langle p_T \rangle$ also shows a flat behavior as a function of rapidity for all the considered multiplicity classes as it can be seen in Fig. A.1 of Appendix A.

A similar behavior in the average transverse kinetic energy as a function of rapidity for strange hadrons was reported in Ref. [16]. The rapidity dependence of dN/dy and $\langle p_T \rangle$ for K^{*0} and ϕ mesons in the multiplicity class 0-100% is further studied by dividing the dN/dy and $\langle p_T \rangle$ values in a given rapidity

interval by the corresponding values at $y = 0$, as shown in Fig. 5. The dN/dy and $\langle p_T \rangle$ value at $y = 0$ is computed from the p_T spectrum measured in the rapidity interval $-0.3 < y < 0.3$. The systematic uncertainties on these ratios are estimated by studying the effects of the variations directly on the ratios as discussed in Section 2.3. This procedure takes into account the correlation of the systematic uncertainties across rapidity bins: as a result, these ratios have smaller systematic uncertainties than those on the dN/dy and $\langle p_T \rangle$, and allow for a better insight into the y dependence. The ratio $(dN/dy)/(dN/dy)_{y=0}$ decreases with rapidity, whereas $\langle p_T \rangle / \langle p_T \rangle_{y=0}$ shows a flat behavior within uncertainties as a function of rapidity for K^{*0} and ϕ mesons. The measurements are compared with various model predictions. The predictions from HIJING qualitatively reproduce the trend and are the closest to the data for both K^{*0} and ϕ . The predictions from PYTHIA8/Angantyr, DPMJET, EPOS-LHC, EPOS3 with and without UrQMD show a decreasing trend of $(dN/dy)/(dN/dy)_{y=0}$ with increasing y , but the rapidity dependence is less pronounced than the one in data, as it can be seen by the fact that they all tend to underestimate the measured yield ratios in the lowest rapidity intervals, especially for K^{*0} meson.

For $\langle p_T \rangle / \langle p_T \rangle_{y=0}$ as a function of y , also shown in Fig. 5, EPOS3 with and without UrQMD overestimate the measurements at low y and predict a marked decreasing trend of $\langle p_T \rangle / \langle p_T \rangle_{y=0}$ with rapidity, which is not supported by the data. From the other models, less pronounced trends are expected, which are consistent with the data. In particular, HIJING predicts a slightly decreasing $\langle p_T \rangle / \langle p_T \rangle_{y=0}$ with increasing rapidity, while PYTHIA8/Angantyr, DPMJET, and EPOS-LHC predict a slightly increasing trend.

Similar studies of the ratio $\langle p_T \rangle / \langle p_T \rangle_{y=0}$ of charged hadrons in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV compared with the predictions of hydrodynamics and color-glass condensate (CGC) model were reported in [33]. Predictions from hydrodynamic calculations show a decrease in $\langle p_T \rangle$ with rapidity, whereas CGC predicts an increase in $\langle p_T \rangle$ with rapidity [33], while the data are flat within uncertainties. The dN/dy and $\langle p_T \rangle$ increase with multiplicity at midrapidity as observed for light-flavor hadrons and resonances in pp and p-Pb collisions [26, 27, 56]. A similar behavior is observed in this article for K^{*0} and ϕ in all the different rapidity intervals shown in Fig.A.1 in Appendix A.

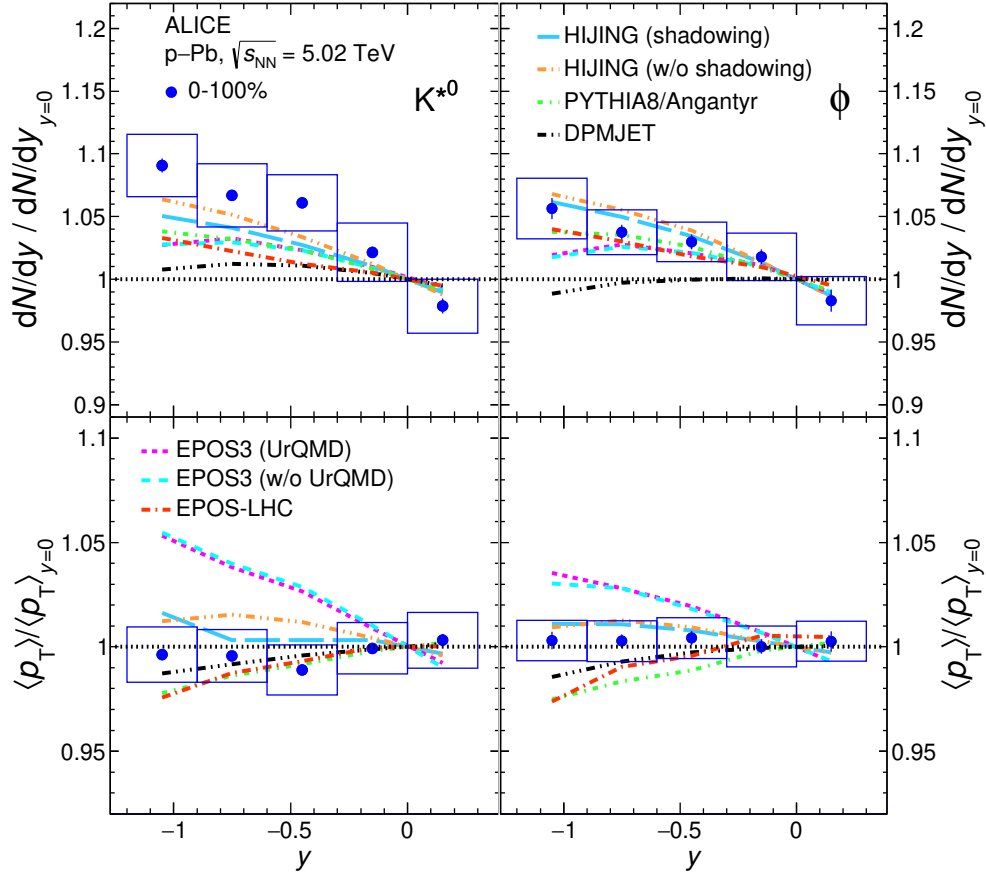


Figure 5: The p_T integrated yield (dN/dy) (upper panels) and mean transverse momentum ($\langle p_T \rangle$) (bottom panels) for K^{*0} (left) and ϕ (right) mesons as a function of y , divided by the dN/dy and $\langle p_T \rangle$ at $y = 0$ for the multiplicity class 0–100% in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The predictions from EPOS-LHC [35], EPOS3 with and without UrQMD [38, 39], DPMJET [40], HIJING [41], and PYTHIA8/Angantyr [42] are shown as different curves. The statistical uncertainties are represented as bars whereas the boxes indicate total systematic uncertainties.

3.3 Rapidity asymmetry

The rapidity asymmetry (Y_{asym}) is calculated from K^{*0} and ϕ mesons yields in $-0.3 < y < 0$ and $0 < y < 0.3$, as defined by Equation 1. Figure 6 shows the Y_{asym} of K^{*0} and ϕ mesons in the measured p_T intervals for various multiplicity classes in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

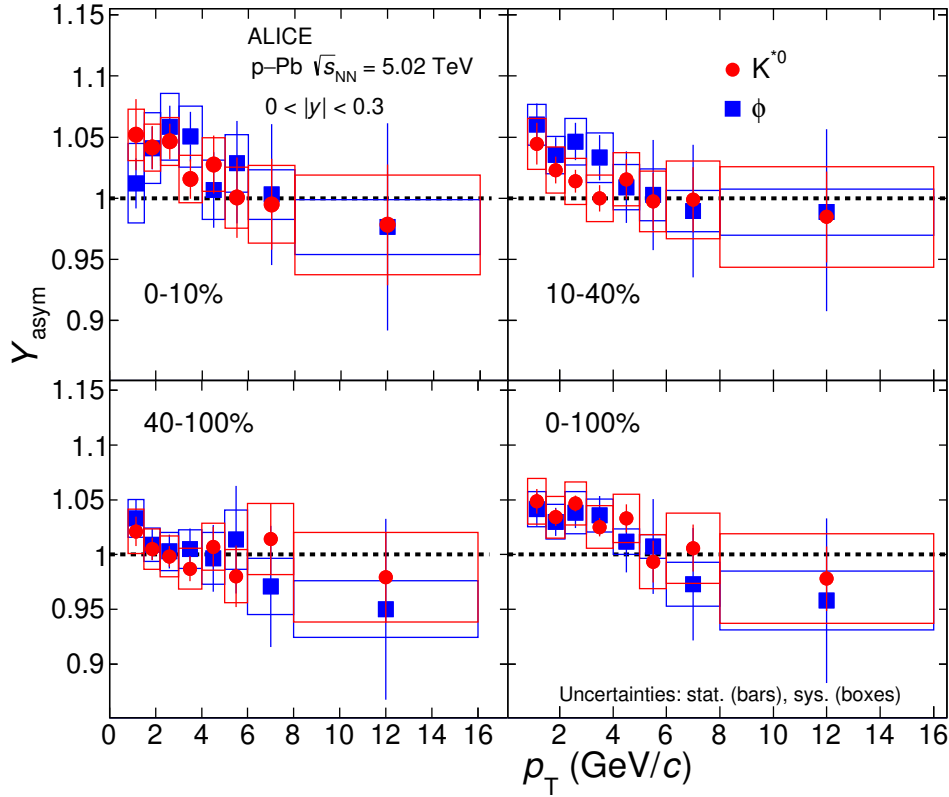


Figure 6: Rapidity asymmetry (Y_{asym}) of K^{*0} (red circles) and ϕ (blue squares) meson production as a function of p_T in the rapidity range $0 < |y| < 0.3$ for various multiplicity classes in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The statistical uncertainties are shown as bars whereas the boxes represent the systematic uncertainties on the measurements.

The Y_{asym} values for K^{*0} and ϕ as a function of p_T are consistent within uncertainties for all multiplicity classes. The Y_{asym} values deviate from unity at low p_T (< 5 GeV/c), suggesting the presence of a rapidity dependence in the nuclear effects. The deviations are more significant for events with high multiplicity. The Y_{asym} values are consistent with unity at high p_T (> 5 GeV/c) for all multiplicity classes, suggesting the absence of nuclear effects at high p_T for the production of K^{*0} and ϕ mesons in p-Pb collisions. Similar results have been reported for charged hadrons, pions, protons in d-Au collisions at $\sqrt{s_{NN}} = 200$ GeV by the STAR Collaboration [18] and for charged hadrons and multi-strange hadrons in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV by the CMS Collaboration as discussed in Refs. [16, 17]. Figure 7 shows the comparison of the measured Y_{asym} for K^{*0} and ϕ mesons as a function of p_T in minimum-bias events (0-100%) with the model predictions from EPOS-LHC, HIJING with and without shadowing, DPMJET, PYTHIA8/Angantyr, and EPOS3 with and without UrQMD.

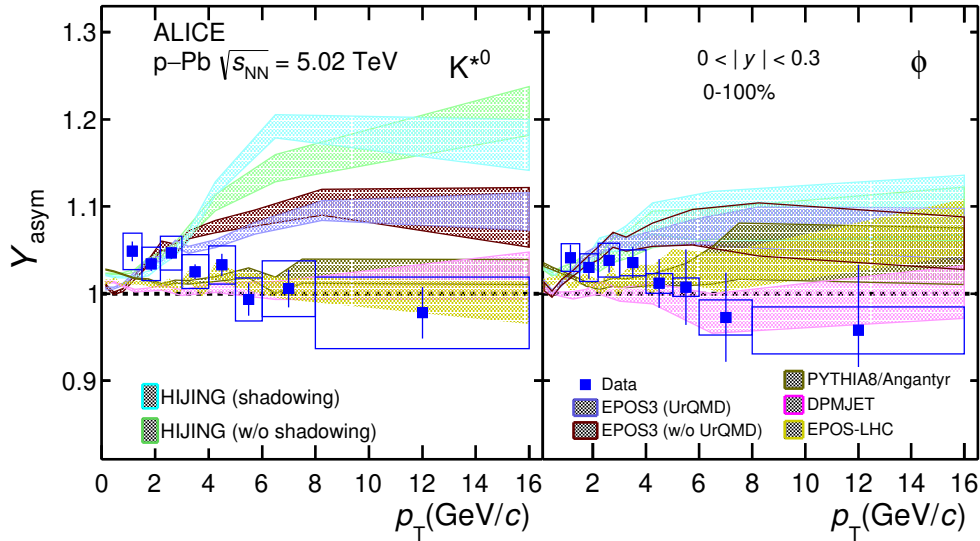


Figure 7: The comparison of experimental results of Y_{asym} for K^{*0} and ϕ meson production as a function of p_T in the rapidity range $0 < |y| < 0.3$ with the model predictions from EPOS-LHC [35], EPOS3 with and without UrQMD [38, 39], DPMJET [40], HIJING [41], and PYTHIA8/Angantyr [42]. Data points are shown with blue markers, and model predictions are shown by different color bands, where bands represent the statistical uncertainty of the model. The statistical uncertainties on the data points are represented as bars whereas the boxes indicate total systematic uncertainties.

HIJING with and without shadowing, and EPOS3 with and without UrQMD describe the measured Y_{asym} at low p_T within uncertainties, but they significantly overestimate the data at high p_T , predicting an increasing trend with p_T (more pronounced for K^{*0} than for ϕ) that is not supported by the measurements, which are consistent with a flat or decreasing trend for both meson species. Model predictions from EPOS-LHC, PYTHIA8/Angantyr, and DPMJET for K^{*0} and DPMJET for ϕ at high p_T are in agreement with the data within uncertainties.

3.4 Nuclear modification factor

The nuclear modification factor Q_{CP} is calculated from the K^{*0} and ϕ yields normalized to $\langle N_{\text{coll}} \rangle$ in high multiplicity (central) and low multiplicity (peripheral) collisions, as defined by Equation 2. Figure 8 shows the Q_{CP} of K^{*0} (red circles) and ϕ (blue squares) mesons as a function of p_T for 0–10% / 40–100% (top panels) and 10–40% / 40–100% (bottom panels) in various rapidity intervals within the range $-1.2 < y < 0.3$ for p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The Q_{CP} of ϕ mesons seems to be slightly higher than the K^{*0} one for the ratio of 0–10% / 40–100%, however, the results for the two meson species are consistent within uncertainties for the ratio 10–40% / 40–100% for all measured rapidity intervals. An enhancement at intermediate p_T ($2.2 < p_T < 5.0$ GeV/c), reminiscent of the Cronin effect, is seen for K^{*0} and ϕ mesons in the Q_{CP} . This enhancement is more pronounced at high negative rapidity, i.e., in the Pb-going direction, and for high multiplicity events. The more pronounced Cronin-like enhancement for the 0–10% multiplicity class suggests that multiple scattering effects are more relevant for high multiplicity (central) collisions. At high p_T (> 5 GeV/c), the Q_{CP} values are greater than unity, which is a known feature of Q_{pPb} ¹ and Q_{CP} when the centrality or multiplicity classes are defined with

¹It is defined as the ratio of the yield per equivalent number of nucleon–nucleon collisions at a given centrality or multiplicity class in p-Pb collisions to the yield in minimum-bias pp collisions at the same center-of-mass energy.

the V0 detector, and it is interpreted as a selection bias due to the multiplicity estimator [51]. The results for K^{*0} and ϕ mesons are consistent between each other within uncertainties.

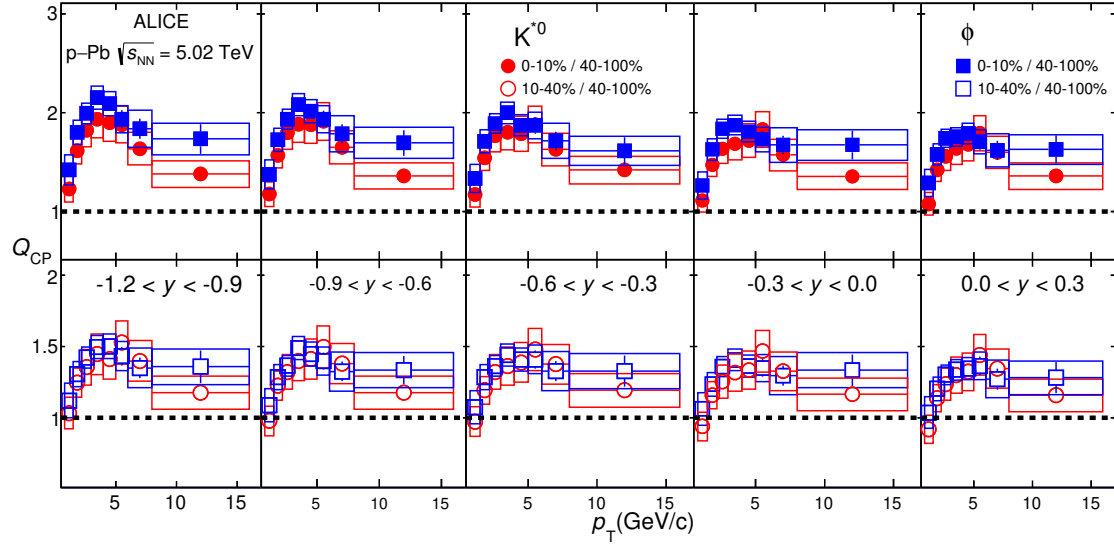


Figure 8: The Q_{CP} of K^{*0} (red circles) and ϕ (blue squares) mesons as a function of p_T for 0–10% / 40–100% (top panels) and 10–40% / 40–100% (bottom panels) in various rapidity intervals within the range $-1.2 < y < 0.3$ in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The statistical and systematic uncertainties are represented by vertical bars and boxes, respectively.

To quantify the rapidity dependence of the nuclear modification factor, the Q_{CP} values of K^{*0} and ϕ mesons for intermediate p_T ($2.2 < p_T < 5.0$ GeV/c) are shown as a function of rapidity in Fig. 9. The values of Q_{CP} at intermediate p_T show a faster decrease from the rapidity interval $-1.2 < y < -0.9$ to $0 < y < 0.3$ for 0–10% / 40–100% than for 10–40% / 40–100%, indicating a stronger rapidity dependence of the Cronin-like enhancement in events with high multiplicity. The stronger rapidity dependence for 0–10% / 40–100% can be inferred from the slope parameter (α) of the linear function fit to the Q_{CP} of K^{*0} and ϕ mesons reported in Fig. 9. The slope of the ϕ meson Q_{CP} is slightly larger than the K^{*0} one. A similar conclusion on the η dependence of nuclear modification factors of charged hadrons was reported by the BRAHMS Collaboration [7].

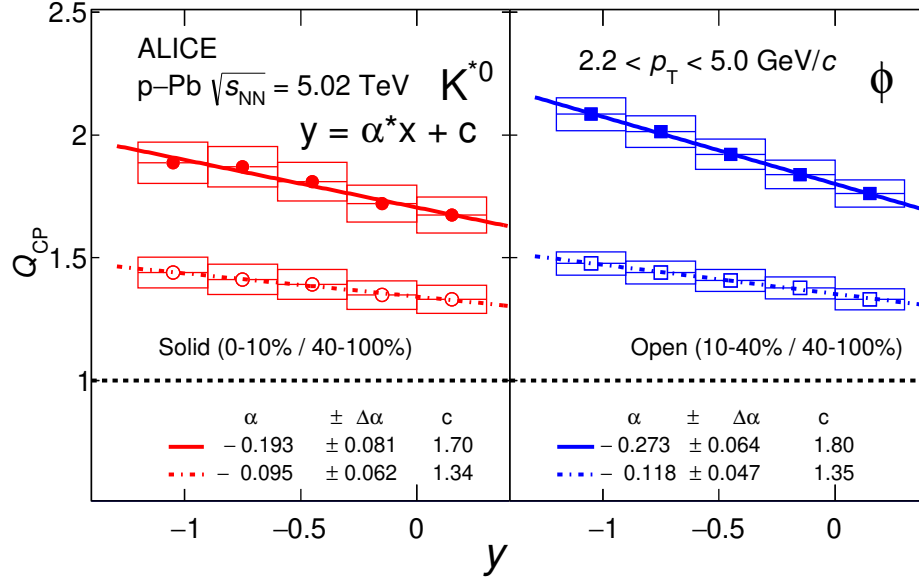


Figure 9: The Q_{CP} of K^*0 (red circles) and ϕ (blue squares) mesons as a function of rapidity for 0–10% / 40–100% (solid markers) and 10–40% / 40–100% (open markers) in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The solid and dotted lines represent the linear fit to data. The statistical and systematic uncertainties are represented by vertical bars and boxes on the measurements, respectively.

4 Summary

The transverse momentum differential yields of K^*0 and ϕ mesons have been measured in the rapidity interval $-1.2 < y < 0.3$ for various multiplicity classes over the transverse momentum range $0.8 < p_T < 16$ GeV/c in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the ALICE detector. The p_T spectra of K^*0 and ϕ mesons show a multiplicity and rapidity dependence at low p_T , whereas the spectral shapes are similar for all multiplicity classes and rapidity intervals at high p_T (> 5 GeV/c). This suggests that nuclear effects influence K^*0 and ϕ meson production at low p_T . The $(dN/dy)/(dN/dy)_{y=0}$ ratios decrease with increasing rapidity in the measured interval $-1.2 < y < 0.3$, whereas the average transverse momentum $\langle p_T \rangle$ and the $\langle p_T \rangle / \langle p_T \rangle_{y=0}$ ratios show a flat behavior for both K^*0 and ϕ mesons. The rapidity dependence of dN/dy , $\langle p_T \rangle$ and their ratios with respect to the corresponding values at $y = 0$ are compared with model predictions for minimum-bias events. The EPOS-LHC model, which includes parameterized flow, provides the best description for the magnitudes of K^*0 and ϕ dN/dy and $\langle p_T \rangle$, whereas HIJING predictions are in closest agreement with the measured rapidity dependence, which is studied via the ratios $(dN/dy)/(dN/dy)_{y=0}$ and $\langle p_T \rangle / \langle p_T \rangle_{y=0}$. The Y_{asym} ratios for K^*0 and ϕ mesons as a function of p_T show deviations from unity at low p_T for high multiplicity events, while, their values are consistent with unity within uncertainties at high p_T in the measured multiplicity and rapidity intervals. The Y_{asym} ratios of K^*0 and ϕ mesons are found to be consistent between each other within uncertainties in the measured kinematic region. The measured deviations of Y_{asym} from unity at low p_T suggest the presence of rapidity dependent nuclear effects such as multiple scattering, nuclear shadowing, parton saturation, and energy loss in cold nuclear matter. None of the models presented here is able to describe the Y_{asym} of K^*0 and ϕ mesons at low p_T . The nuclear modification factors between the central and peripheral collisions Q_{CP} for K^*0 and ϕ mesons as a function of p_T show a bump, with a maximum around $p_T = 3$ GeV/c, suggestive of the Cronin effect. This Cronin-like enhancement is more pronounced for large

negative rapidities (in the Pb-going direction) and for more central (higher multiplicity) collisions. The measurements reported in this paper confirm that nuclear effects play an important role in particle production in p-Pb collisions at the LHC energies. They will contribute, along with previous and upcoming measurements of other hadron species, to constrain models and event generators.

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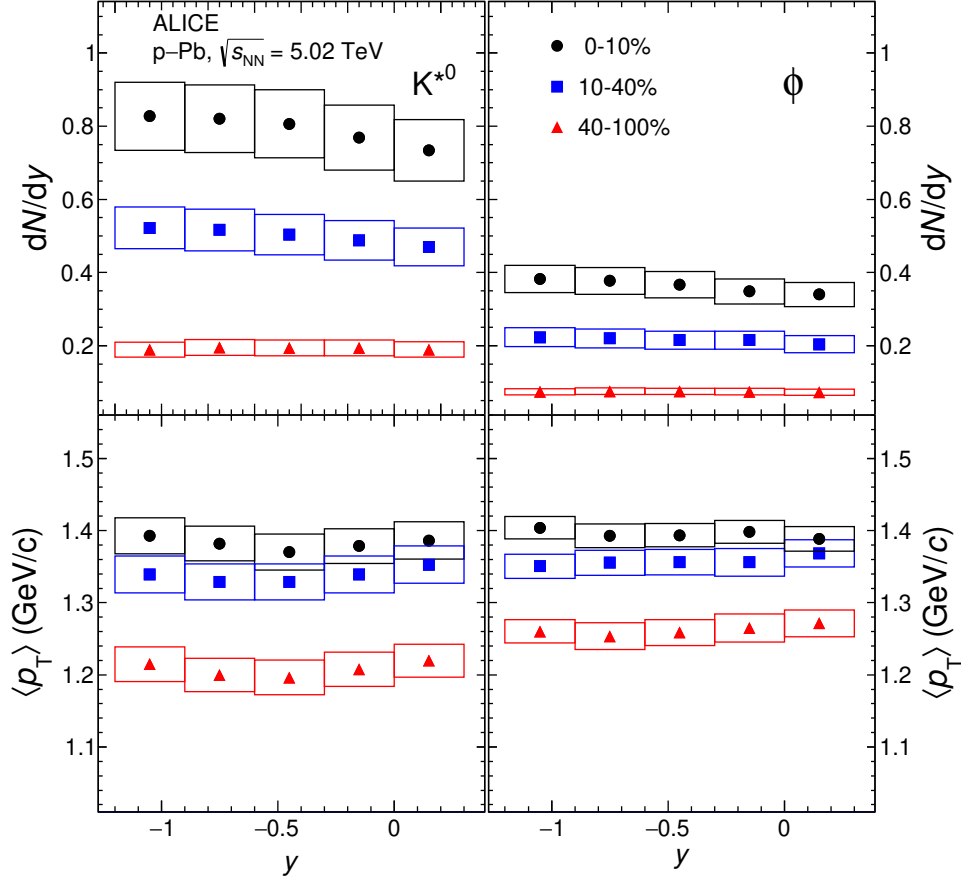


Figure A.1: The p_T integrated yield (dN/dy) (top panels) and mean transverse momentum ($\langle p_T \rangle$) (bottom panels) for K^{*0} (left panels) and ϕ (right panels) mesons as a function of y measured for the multiplicity classes 0–10%, 10–40% and 40–100% in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The statistical uncertainties are represented as bars whereas boxes indicate the total systematic uncertainties on the measurements.

A Multiplicity and rapidity dependence of dN/dy and $\langle p_T \rangle$

Figure A.1 shows the multiplicity dependence of the dN/dy and $\langle p_T \rangle$ of K^{*0} and ϕ mesons as a function of y in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The dN/dy and the $\langle p_T \rangle$ increase with multiplicity for a given rapidity interval. The dN/dy shows a weak rapidity dependence with large uncertainties, and suggesting a more pronounced dependence for events in the highest multiplicity class (0–10%). The $\langle p_T \rangle$ shows a flat behavior as a function of rapidity for all multiplicity classes in the measured rapidity interval. Similar behavior in the average transverse kinetic energy as a function of rapidity for strange hadrons was reported in Ref. [16].

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Insight into ϕ meson production in small systems with ALICE at the LHC

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Introduction

The measurement of hadronic resonance production in high-energy heavy-ion collisions provides an important contribution for understanding particle production mechanisms. Measurements in smaller collision systems such as pp and p-Pb act as a reference for the interpretation of the heavy-ion results. Due to their short lifetime, resonances are ideal candidates to probe the dynamics of the hadronic phase formed in heavy-ion collisions. The lifetime of ϕ meson (46.3 fm/c) is long compared to that of other hadronic resonances as well as the lifetime of the fireball produced in the heavy-ion collisions. The ϕ meson is useful for the study of strangeness enhancement. The ϕ meson contains strange quark and antiquark ($s\bar{s}$), with net strangeness content equal to zero. Its production should therefore not be canonically suppressed, while the production of hadrons with open strangeness (*e.g.* kaons or Ξ) may be canonically suppressed [1]. Recent results obtained by using the ALICE detector show that although the ϕ meson has zero net strangeness content, it behaves like a particle with open strangeness in large collision system. Measurements of ϕ -meson production as a function of the multiplicity may help to distinguish between the various explanations of strangeness enhancement in small systems.

Analysis details

The ϕ vector meson is reconstructed through an invariant mass analysis using the hadronic decay channel into K^+K^- (branching ratio: 49.2%) [2]. The ϕ meson signals in

different transverse momentum (p_T) intervals and multiplicity classes is obtained by subtracting the combinatorial background from unlike-sign pair invariant-mass distributions. After the combinatorial background subtraction a residual background remains, which mainly arises from other sources of correlated pairs and mis-identified particle-decay products. The extracted ϕ signal is fitted with a Voigtian function (which is a convolution of Breit-Wigner and Gaussian functions). A polynomial function is used to describe the residual background. In each p_T interval, the raw yield is obtained from the fit to the signal peak for the various multiplicity classes. To determine the final p_T spectra the raw yields are corrected for detector acceptance, reconstruction efficiency and decay branching ratio. Recent measurements of ϕ mesons in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ and 8.16 TeV and in pp collisions at $\sqrt{s} = 7$ and 13 TeV, are presented.

Results and Discussion

Figure 1 shows the p_T integrated ϕ -meson yield (dN/dy) as a function of charged-particle multiplicity in different colliding systems and at different energies. dN/dy increases with increasing charged-particle multiplicity. It also appears that the event multiplicity drives the particle production, irrespective of the colliding system type and energies.

Figure 2 shows the ratios of the yields of p, K_s^0 , Λ , ϕ , Ξ , and Ω to pions as a function of charged particle multiplicity in various systems at different energies. A significant enhancement of strange to non-strange hadron production is observed with increasing charged particle multiplicity in pp and p-Pb collisions [3]. No significant energy dependence is observed in these ratios. The larger the strangeness content of the particle, the

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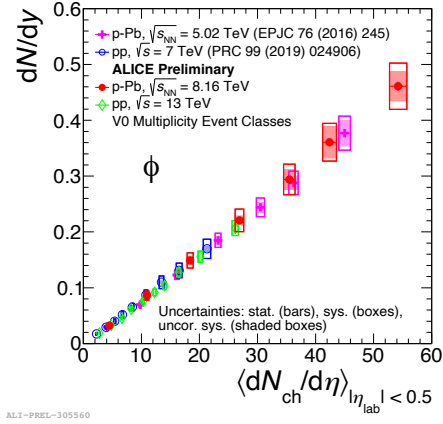


FIG. 1: Transverse momentum Integrated yield (dN/dy) of ϕ as a function of $\langle dN_{ch}/d\eta \rangle_{|\eta_{lab}| < 0.5}$ in pp collisions at $\sqrt{s} = 7$ and 13 TeV and in p-Pb collisions at $\sqrt{s} = 5.02$ and 8.16 TeV.

stronger the observed enhancement. This effect is due to strangeness and not due to the baryon number or mass of the hadron. At high multiplicity in pp and p-Pb collisions the yield ratios have similar values to those observed in Pb-Pb collisions.

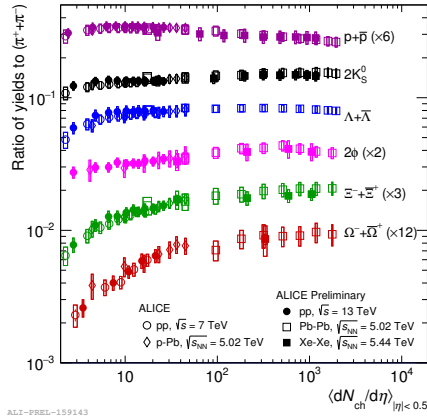


FIG. 2: Ratio of yields of hadrons (p , K_s^0 , Λ , ϕ , Ω , Ξ) to pions as a function of $\langle dN_{ch}/d\eta \rangle_{|\eta_{lab}| < 0.5}$ in pp collisions at $\sqrt{s} = 7$ and 13 TeV, in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ [4], in Xe-Xe collisions at $\sqrt{s_{NN}} = 5.44$ and in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

The Ξ/ϕ ratio as a function of charged-particle multiplicity for three different collision systems and energies is shown in Fig. 3. The net strangeness content of ϕ meson is 0, while net strangeness of Ξ is 2. In Fig. 3 it is possible to see that Ξ/ϕ ratio slightly increases in pp and p-Pb as a function of the charged particle multiplicity, but is fairly constant or slightly increases across a wide range of multiplicities. This indicates that the ϕ meson behaves as if it had an effective strangeness ≤ 2 . Comparing the ϕ with particles having strangeness 1 or 2, one observe that the ϕ meson behaves like a particle with open strangeness.

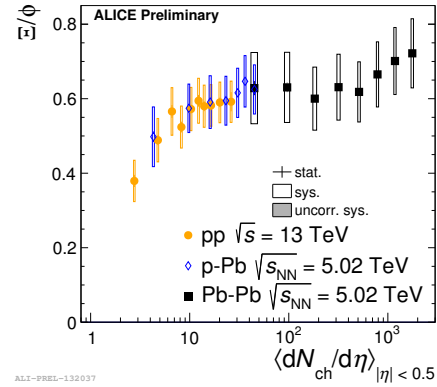


FIG. 3: Ξ/ϕ ratio as a function of $\langle dN_{ch}/d\eta \rangle_{|\eta_{lab}| < 0.5}$ in pp collisions at $\sqrt{s} = 13$ TeV, in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

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Chapter 93

Φ and K^{*0} Production in p–Pb and Pb–Pb Collisions with ALICE at the LHC



Sandeep Dudi

Abstract We report recent measurements of ϕ and K^{*0} production in p–Pb and Pb–Pb collisions at $\sqrt{s_{NN}} = 8.16$ and 5.02 TeV, respectively. The integrated yield and mean transverse momentum are reported as a function of charged particle multiplicity to explore the particle production mechanism. Particle ratios K^{*0}/K and ϕ/K are studied as a function of charged particle multiplicity to explore rescattering and regeneration effects. The nuclear modification factor (R_{AA}) as a function of p_T is studied to explore parton energy loss.

93.1 Introduction

It has been established that in high-energy heavy-ion collisions, a hot and dense, strongly interacting matter, often described as a strongly coupled quark-gluon plasma (sQGP), is created [1–3]. The $K^*(892)^0$ ($d\bar{s}$) and $\phi(1020)$ ($s\bar{s}$) particles produced in these collisions contain strange (anti-strange) quarks and they can be used for the systematic studies of the particle-species dependence of partonic energy loss in the medium. The K^{*0} and ϕ have lifetimes in vacuum of 4.16 ± 0.05 fm/c and 46.3 ± 0.4 fm/c, respectively [4]. Due to their short lifetimes, resonance particles can be used to probe the system at different timescales during its evolution. Resonance yields measured by hadronic decay channels can be affected by particle rescattering and regeneration in the hadron gas phase.

A Large Ion Collider Experiment (ALICE) [5] is a multi-purpose heavy-ion detector, which has excellent tracking and particle-identification capabilities [6]. Resonances ϕ and K^{*0} are reconstructed from their hadronic decay daughters ($\phi \rightarrow KK$ and $K^{*0} \rightarrow K\pi$) using an invariant mass technique. The details of the analysis can be found in [7].

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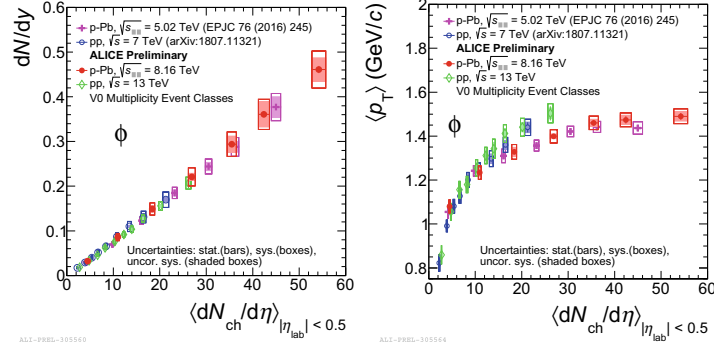


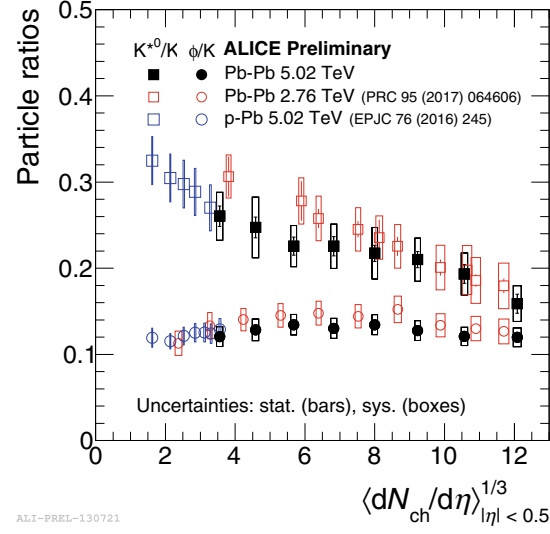
Fig. 93.1 (Left) The integrated yield (dN/dy) and (right) the mean transverse momentum ($\langle p_T \rangle$) of ϕ meson as a function of charged particle multiplicity ($\langle dN_{ch}/d\eta \rangle$) in pp collisions at $\sqrt{s} = 7$ and 13 TeV and in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ and 8.16 TeV

93.2 Results

Figure 93.2 (left panel) shows the integrated yield of ϕ as a function of the charged particle multiplicity in pp collisions in rapidity ($|y| < 0.5$) at $\sqrt{s} = 7$ and 13 TeV and in p-Pb collisions in rapidity ($-0.5 < y < 0$) at $\sqrt{s_{NN}} = 5.02$ [8] and 8.16 TeV. The integrated yield increases with increasing charged particle multiplicity ($\langle dN_{ch}/d\eta \rangle$) independently of the identities of the colliding ions and their energies. The right panel of Fig. 93.1 shows the mean transverse momentum ($\langle p_T \rangle$) of ϕ as a function of $\langle dN_{ch}/d\eta \rangle$ in pp collisions at $\sqrt{s} = 7$ and 13 TeV and in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ and 8.16 TeV. The $\langle p_T \rangle$ increases as a function of the charged particle multiplicity and seems to saturate at high multiplicity in p-Pb collisions. A similar trend of $\langle p_T \rangle$ dependence on multiplicity is also observed for other resonances [8]. The new results for $\langle p_T \rangle$ may lead to a better understanding of the mass ordering (particles with similar masses have similar $\langle p_T \rangle$) observed in central and semi-central Pb-Pb collisions, which is consistent with expectations from the hydrodynamic expansion of the system [7]. The mass ordering in $\langle p_T \rangle$ is not observed in small collision systems [9].

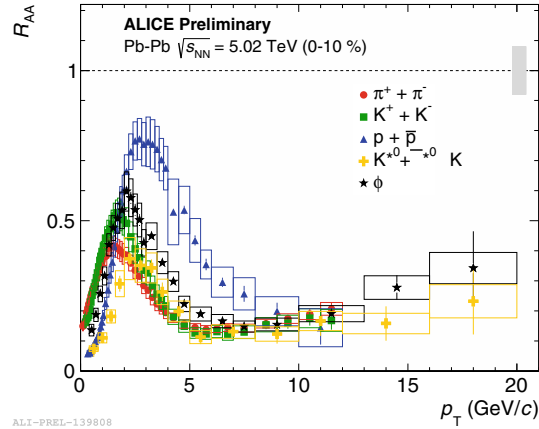
The K^{*0}/K and ϕ/K ratios as a function of charged particle multiplicity ($\langle dN_{ch}/d\eta \rangle$) in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV are shown in Fig. 93.2. The results are compared with p-Pb and Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ and 2.76 TeV, respectively. The K^{*0}/K ratio decreases as we go from p-Pb and peripheral Pb-Pb collisions to the most central Pb-Pb collisions. This decrease in the K^{*0}/K ratio can be understood as the rescattering of K^{*0} decay daughters in the hadronic medium [7]. The ϕ/K ratio shows no suppression in p-Pb and Pb-Pb collisions and almost no dependence on $\langle dN_{ch}/d\eta \rangle$. The ϕ/K ratio suggests that the ϕ (which has a lifetime of an order of magnitude larger than the K^{*0}) might decay predominantly outside the hadronic medium.

Fig. 93.2 p_T integrated K^{*0}/K and ϕ/K ratios as a function of charged particle multiplicity in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV



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Fig. 93.3 Nuclear modification factor (R_{AA}) of π , K , p , ϕ and K^{*0} as a function of p_T in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in the 0–10 % multiplicity or centrality class



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The nuclear modification factor (R_{AA}) of π , K , p , ϕ and K^{*0} as a function of p_T in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in the 0–10 % collision centrality class is shown in Fig. 93.3. In the intermediate p_T range (2–6 GeV/c), the R_{AA} of ϕ and K^{*0} are similar to that of the charged kaons, whereas protons and ϕ exhibit a different trend despite their similar masses [10]. For $p_T > 8$ GeV/c, all the light flavoured species, π , K , p , ϕ and K^{*0} , show a similar suppression within uncertainties.

93.3 Conclusions

The production of ϕ and K^{*0} mesons in p–Pb and Pb–Pb collisions in various centrality classes at $\sqrt{s_{NN}} = 8.16$ and 5.02 TeV, respectively, has been measured. The integrated yields (dN/dy) of ϕ and K^{*0} mesons (only the ϕ measurement is shown here) are independent of collision system and energy, indicating that particle production is driven by multiplicity. The $\langle p_T \rangle$ of the ϕ meson saturates at high multiplicity in p–Pb collisions. The suppression in K^{*0}/K ratio indicates that rescattering dominates over regeneration. The R_{AA} value of ϕ mesons and protons differ at intermediate p_T despite similar masses. At high p_T ($p_T > 8$ GeV/c), all particles show similar suppression within uncertainties.

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Identified particle production in p–Pb collisions with ALICE at the LHC

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The study of identified particle production in p–Pb and pp collisions provides a baseline measurement to be compared with Pb–Pb results. The excellent tracking and particle identification capabilities of the ALICE detector allow the study of identified particle production up to a very high transverse momentum (p_T). We report recent results on ϕ and K^{*0} in p–Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV along with measurements of π , K, p, Ξ , Λ and Ω in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Integrated yields, mean transverse momenta, and particle ratios as a function of the charged particle multiplicity are studied to understand the particle production mechanism. The nuclear modification factor (R_{pPb}) as a function of p_T is studied to understand the parton energy loss mechanism and the Cronin effect.

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†A footnote may follow.

1. Introduction

Measurements of identified particle production as a function of the charged particle multiplicity in pp and p-Pb collisions are important tools for understanding the similarities and differences between small and large interacting systems. Because of their short lifetimes, resonances are good candidates to understand the mechanism of particle production and properties of the hadronic phase. The yields of resonances might be modified by in-medium effects such as re-scattering and regeneration [1]. The multiplicity dependent studies in pp and p-Pb collisions can be used to search for the onset of collectivity similar to what is observed in heavy ion collisions. The nuclear modification factors (R_{pPb}) can be used to study the parton energy loss mechanism, cold nuclear matter effects such as the Cronin enhancement at intermediate p_T and shadowing effects [2]. The p-Pb collision system allows a study of the particle productions mechanisms in the multiplicity range intermediate between elementary pp and peripheral Pb-Pb collisions.

We present measurements of integrated particle yields, mean transverse momenta and p_T integrated yield ratios of $\phi(1020)$, $K^*(892)^0$, π , K, p, Λ , Ω and Ξ in p-Pb collisions at LHC energies. In addition, nuclear modification factors (R_{pPb}) of π , K, p, Ω and Ξ in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV are discussed.

2. Analysis

The detailed description of the ALICE detector can be found in Ref. [3]. The measurements of π , K, p, ϕ and K^{*0} production are performed in p-Pb collision as a function of the charged particle multiplicity at $\sqrt{s_{NN}} = 5.02$ and 8.16 TeV in the rapidity range $-0.5 < y_{cm} < 0$. Resonances (ϕ , K^{*0}) and multi-strange baryons (Ω , Ξ) are reconstructed by using an invariant mass technique [1]. The ϕ and K^{*0} are reconstructed in the following decay channels $\phi \rightarrow K^+ K^-$ (BR = 48.2%) and $K^{*0}(\bar{K}^{*0}) \rightarrow K^+ \pi^- (K^- \pi^+)$ (66.6 %) while Ω and Ξ are reconstructed in the decay channel $\Omega^-(\bar{\Omega}^+) \rightarrow \Lambda K^- (\bar{\Lambda} K^+)$ (67.8%) , $\Xi^-(\bar{\Xi}^+) \rightarrow \Lambda \pi^- (\bar{\Lambda} \pi^+)$ (99.9%) with a subsequent $\Lambda \rightarrow p \pi^-$ (63.9%) decay [4]. Long-lived particles like π , K, p and $\bar{p}$ are identified with the help of various ALICE sub-detectors: the Inner Tracking System (ITS), the Time Projection Chamber (TPC) and the Time-Of-Flight (TOF), by using different PID techniques [5]. The centrality classes are defined based on the signal amplitude measured in the V0A scintillator. The resonance peaks reconstructed by the invariant-mass method sit on top of a large combinatorial background, which is estimated by using like-sign and event-mixing techniques. In the mixed-event method the shape of the uncorrelated background is estimated from the invariant-mass distribution of $h^+ h^-$ combinations from five different events having similar characteristics like multiplicity, collision vertex position etc. In the like-sign technique, the background is evaluated by using invariant mass distribution of like-charge pairs from the same event [1]. After background subtraction the raw yield is extracted from the invariant-mass distribution and is then corrected for detector acceptance, tracking efficiency and branching ratio. The first two corrections are determined from Monte Carlo simulations of the ALICE detector response [6].

3. Results

Figure 1 (left panel) shows the integrated yields of ϕ as a function of the charged particle

multiplicity in pp collisions at $\sqrt{s} = 7$ and 13 TeV and in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ and 8.16 TeV. The integrated yield increases with increasing $\langle dN_{ch}/d\eta \rangle$. The right panel of Fig. 1 shows the mean transverse momentum ($\langle p_T \rangle$) of ϕ as a function of $\langle dN_{ch}/d\eta \rangle$ in pp collisions at $\sqrt{s} = 7$ and 13 TeV and in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ and 8.16 TeV. The $\langle p_T \rangle$ increases as a function of the charged particle multiplicity and seems to saturate at high multiplicity in p-Pb collisions. A similar trend of $\langle p_T \rangle$ dependence on multiplicity is also observed for other resonances [7]. In the most central p-Pb collisions, $\langle dN_{ch}/d\eta \rangle$ has the same order of magnitude as in peripheral heavy ion collisions. The new results for $\langle p_T \rangle$ may lead to a better understanding of the mass ordering (particles with similar masses have similar $\langle p_T \rangle$) observed in central and semi-central Pb-Pb collisions, which is consistent with expectations from the hydrodynamic expansion of the system [1]. The mass ordering is not observed in small collision systems [6].

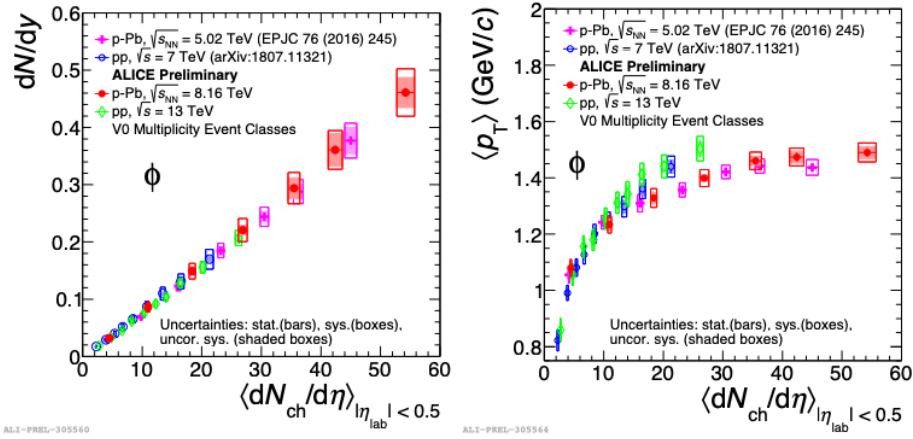


Figure 1: (Left) The integrated yield (dN/dy) and (right) the mean transverse momentum ($\langle p_T \rangle$) of ϕ meson as a function of charged particle multiplicity ($\langle dN_{ch}/d\eta \rangle$) in pp collisions at $\sqrt{s} = 7$ and 13 TeV and in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ and 8.16 TeV.

Figure 2 (left panel) shows the ratios of the yields of p, K_s^0 , Λ , ϕ , Ξ , and Ω to pions as a function of charged particle multiplicity in various systems at different energies. A significant enhancement of strange to non-strange hadron production is observed with increasing charged particle multiplicity in pp and p-Pb collisions [8]. No significant energy dependence is observed. The larger the strangeness content of the particle, the stronger the observed enhancement. This effect is due to strangeness and not due to baryon number or mass. At high multiplicity in pp and p-Pb collisions the yield ratios have similar values as observed in Pb-Pb collisions. The Ξ/ϕ ratio as a function of charged particle multiplicity for three different collision systems and energies is shown in Fig. 2 (right panel). The net strangeness of ϕ is 0 (the ϕ , as an $s\bar{s}$ state, has hidden strangeness) while net strangeness of Ξ is 2. From the figure we can see that Ξ/ϕ ratio slightly increases in pp and p-Pb as a function of the charged particle multiplicity, but is fairly constant over a wide range of multiplicities. This indicates that ϕ behaves as if it had an effective strangeness $S_\phi \leq 2$. From ϕ/K ratio (not shown here), the effective strangeness of ϕ is $S_\phi \geq 1$.

The nuclear modification factor for π , K, p, Ω and Ξ as a function of p_T in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV is shown in Fig. 3. At intermediate p_T ($3.0 < p_T < 6$ GeV/c) a Cronin peak

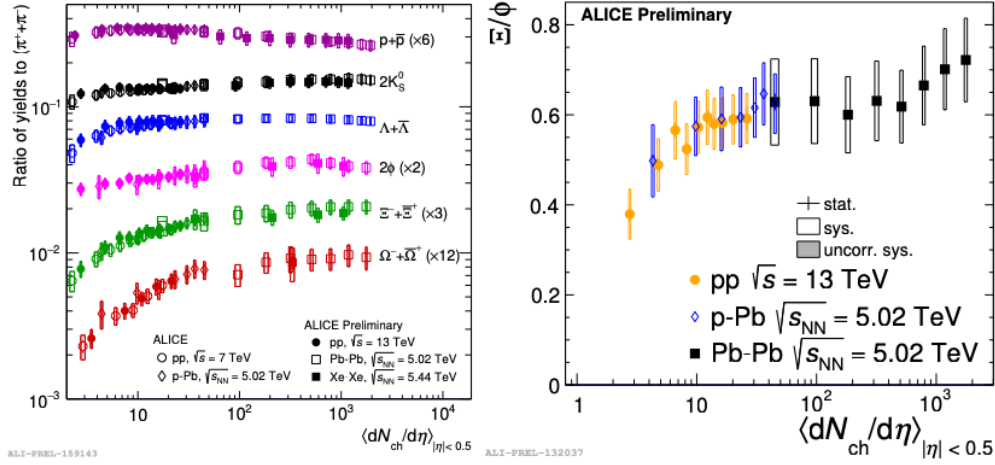


Figure 2: (Left) The ratio of yields of hadrons (p, K_s^0 , Λ , ϕ , Ω , Ξ) to pions as a function of charged particle multiplicity ($\langle dN_{ch}/d\eta \rangle$) in pp collisions at $\sqrt{s} = 7, 13$ TeV, in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ [9], in Xe-Xe collisions at $\sqrt{s_{NN}} = 5.44$ and in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. (Right) Ξ/ϕ ratio as a function of $\langle dN_{ch}/d\eta \rangle$ in pp collisions at $\sqrt{s} = 13$ TeV, in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

is observed in R_{pPb} for p, Ξ and Ω . At intermediate p_T baryons and mesons show different R_{pPb} and the enhancement for p, Ξ and Ω is stronger. R_{pPb} at high p_T ($p_T > 8$ GeV/c) is consistent with unity within uncertainty, suggesting that final state effects do not play a role. The R_{pPb} for the proton has a peak at $p_T \sim 4$ GeV/c. A similar enhancement of protons was observed in Pb-Pb collisions and similar pattern was observed at RHIC [10].

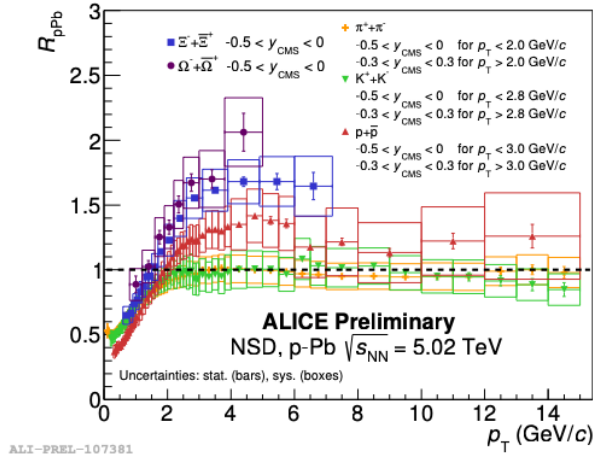


Figure 3: The nuclear modification factor (R_{pPb}) of π , K, p, Ω and Ξ as a function of p_T in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

4. Conclusions

We have reported the measurements of identified particle production as a function of the charged particle multiplicity in p–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ and 8.16 TeV. The integrated yields (dN/dy) of ϕ and K^{*0} mesons are independent of collision system and energy, indicating that particle production is driven by multiplicity. The $\langle p_T \rangle$ of the ϕ meson saturates at high multiplicity in p–Pb collisions. In the ratios of p, K_s^0 , Λ , ϕ , Ω , Ξ yields to that of pions, a significant enhancement of strange to non-strange hadron production is observed with increasing charged particle multiplicity in pp and p–Pb collisions. The yield ratios are independent of the energies. While the net strangeness of ϕ is zero, it behaves as a particle with an effective strangeness of 1-2. The R_{pPb} is independent of particle species at high momentum, it is consistent with unity within uncertainty. The enhancement at intermediate p_T is stronger in case of p, Ξ and Ω . In the future, new results for R_{pPb} from p–Pb collisions at $\sqrt{s_{\text{NN}}} = 8.16$ TeV may help to study the energy dependence of R_{pPb} .

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CERTIFICATE OF PARTICIPATION

THIS IS TO CERTIFY THAT

Mr. Sandeep Dudi

FROM

ALICE Collaboration

HAS SUCCESSFULLY PARTICIPATED AND PRESENTED A TALK IN THE

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